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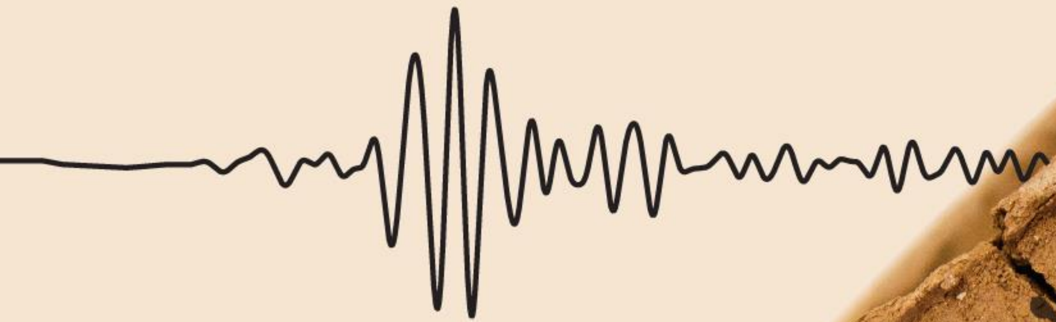
IASPEI
International Association of Seismology and Physics of the Earth's Interior

VIRTUAL

37th General Assembly of the European Seismological Commission

ESC2021

19-24 September



Book of Abstracts

Welcome Message

Dear Colleagues,

I welcome you, on behalf of the Local Organizing Committee and the Executive Committee, to the 37th General Assembly (GA) of the European Seismological Commission which is delivered fully virtually between 19-24 September 2021.

I would like to thank all of the members of LOC, the international scientific committee and the ESC-ExeCom for their valuable help for the best possible organization of the event. I am also grateful to all the invited speakers, conveners and authors for their excellent work. The conference benefited greatly from their contribution.

The 37th General Assembly (GA) of the European Seismological Commission will be focusing in all recent advances in seismology, where early-career and senior researchers from more than 60 countries from Europe and all over the world will virtually meet to discuss different modern fields of seismology and related applications. The sessions and the more than 600 submitted abstracts, a really significant number given that the event is fully virtual, cover broad fields of seismology, such as seismic networks, seismic hazard and risk, physics of earthquakes, study of the Earth's interior, array seismology, engineering seismology, induced seismicity, seismic anisotropy, earthquake forecasting, statistical seismology, historical seismology and microseismology, recent significant earthquakes, earthquake secondary effects, as well as education, outreach and societal implications, making the 2021 ESC General Assembly one of the largest meetings ever.

In addition, The “Peter Bormann Young Seismologist Training Course of 2021: Seismology for Science and Society” will host some 40 students from all over the world, providing a unique opportunity to learn and exchange ideas about a great variety of seismological issues, such as seismotectonics of Greece and the Eastern Mediterranean, faults and seismic risk, the recent Croatian earthquakes, macroseismology, induced seismicity, computational seismology, machine learning, earthquake catalogues, citizen seismology and seismic waveform archives.

Your active participation will undoubtedly contribute to a successful and productive 2021 ESC General Assembly.

Looking forward to welcoming you in our virtual conference!

Professor Nicholas Voulgaris
Vice-President of the European Seismological Commission
Vice Rector of the National and Kapodistrian University of Athens

Committees

Local Organizing Committee

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VIRTUAL 37th

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Keynote Lectures

Seismology of Greece: present knowledge and open challenges for seismic hazard assessment

Anastasia Kiratzi
Aristotle University of Thessaloniki, Department of Geophysics, Thessaloniki, Greece

The Eastern Mediterranean Sea is one of the most rapidly deforming areas on the planet, due to the complex interactions of the Arabian, African, and Eurasian tectonic plates. Greece lies in the crossroads of this interaction, encompassing subduction of African lithosphere beneath the Aegean Sea, an active volcanic arc, extension across the Aegean Sea, lateral extrusion of Anatolia along the North Anatolian Fault, and high levels of seismicity. Without any doubt, the Aegean Sea and the surrounding lands, is one of the best places in the world to study distributed continental deformation.

Because strong earthquakes frequently struck Greece, imposing a threat to humans and infrastructure, Seismology and the related engineering fields, have flourished. Since 1911, when the first seismograph was installed in Athens, marking the beginning of the instrumental era, the broader area is nowadays monitored by 11 seismic networks (nine of which permanent) and from two virtual networks. Data are distributed through EIDA@NOA adopting an open-data policy, providing unlimited and unrestricted access, for research purposes, to waveform data archives from Greece, Cyprus, southeastern Mediterranean, and the Balkans.

The upgraded instrumentation, offering denser seismic and geodetic monitoring, the new processing tools that are now freely available, the long-standing cooperation of Greek scientists with colleagues from abroad, the gradual change of our mentality towards data sharing and team work, provided unprecedented opportunities to advance our knowledge on the characteristics of the Aegean seismicity. Since 2006, during the last 15 years, a cascade of 25 strong (Mw>6.0) earthquakes occurred in Greece remarkably delineating the boundaries of the Aegean microplate. The most memorable of these earthquakes are the ones which occurred on land and close to urban settlements, as for example the 2014-2015 sequence in Cephalonia and Lefkada (Ionian Islands), which provided the strongest strong ground motions ever recorded in the Aegean, and proved the concept of asperities, with a 12yr delay in the breakage of a strong asperity. A number of these recent events occurred along the cross-border region of Greece-Turkey, and their impact was significant in both countries. The 2017 Lesvos and Kos-Bodrum earthquakes occurred in the peak of the tourist season for both countries, while the most notorious example is the 2020 Mw7 Samos earthquake, which dramatically affected the city of Izmir, 70 km away from the epicentre. The most recent earthquakes are the 2021 doubled of Mw6.3/6.0 mainshocks, which occurred in eastern Thessaly Basin (central Greece). These earthquakes revealed the hazard imposed from unmapped fault segments, which are members of a fault system of mapped faults, composing an extensional fault population alike in other areas in back arc Aegean region. These (minor) faults are capable to host strong (M>6.0) earthquakes and can invoke substantial ground motions and significant damage to nearby settlements, especially in the cases of constructions that were not built according to the current building code standards.

In terms of seismic hazard, in Greece, as in other parts of the world, the most memorable and risky earthquakes are those with epicentres on land or near the shoreline and close to urban areas. In the near field, even moderate magnitude events can be hazardous, as was the case for the deadliest earthquakes of the past decades in Greece, as, for example, the 1999 Mw5.9 Athens earthquake. Along the Hellenic subduction interface, although we have not experienced such a disaster in instrumental times, the historical information indicates that large-magnitude earthquakes (M~8.5) have occurred, with dramatic consequences for the broader eastern Mediterranean area. Even though the frequency of these events is not sufficiently constrained, partially due to unknown degree of locking of the interface, however, the contemporary earthquake disaster mitigation planning should account for this important hazard. Furthermore, the intermediate depth earthquakes, if strong enough, can potentially affect distant sites. These earthquakes, connected with subduction process, pose an infrequent but dramatic threat for the wider southern Aegean Sea region, sparsely inhabited during winter but densely populated during the touristic summer period in Greece.

ESC2021-KL02

Review of Various ISC earthquake datasets and their best intended use by the community

Dmitry A. Storchak, James Harris, Domenico Di Giacomo, Thomas Garth and Kathrin Lieser
International Seismological Centre (ISC), Thatcham, Berkshire, United Kingdom

The mission of the International Seismological Centre (ISC) is to produce the most long-term and complete Bulletin of instrumentally recorded seismicity on a global scale. We describe recent achievements in rebuilding the entire ISC Bulletin using the new ISC locator, ak135 velocity model, more robust magnitudes and inclusion of the first motion based source mechanisms.
In addition, we produce several specially designed data products that stemmed from the ISC Bulletin and allowed ISC to assist several distinct areas of seismological research. These datasets include recently re-worked ISC-EHB dataset (1964-2018), ISC-GEM catalogue (1904-2018), IASPEI Reference Event List (GT), ISC Event Bibliography (1904-2021) and Seismological Contacts.
We also show the ISC efforts in collecting individual network articles describing the history, current status and earthquake monitoring procedures and standards used by seismic networks around the world. These articles are part of the printed/on-line Summaries of the ISC Bulletin.
Finally, we describe the ISC Dataset Repository which allows researchers to submit for safe keeping and long-term availability their catalogues/bulletins of seismic events as well as results of critical review of regional seismicity, earth structure studies, velocity models, notable earthquake observations etc. This long-term secure repository is designed to be recognised by scientific journals as one of the legitimate independently maintained places for depositing author processed datasets to satisfy editorial board requirement of open access to data.

ESC2021-KL03

Advancing global earthquake monitoring through machine learning

William Yeck
U.S. Geological Survey, Golden, United States

The U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC) detects, locates, and produces source parameters for tens of thousands of earthquakes per year. NEIC is the sole United States federal agency responsible for documenting and cataloging earthquake source parameters for global earthquakes that are used in a wide variety of earthquake hazards assessment and research activities. The monitoring mission at NEIC primarily focuses on: 1) modeling earthquake source parameters that include creating many high-level products (e.g., moment-tensor solutions, finite fault models, and impact estimates), 2) monitoring domestic earthquakes at a finer scale and acting as the primary backup to many regional seismic networks, and 3) assisting in US government response to large, damaging foreign and domestic earthquakes. To support this monitoring effort, the NEIC ingests 2100+ global seismic stations representing a wide variety of tectonic settings and noise environments. The rapid analysis of fundamental earthquake properties, including location, depth, magnitude, and other source characteristics is critical to allow NEIC to rapidly estimate the impact and seismotectonic context of an earthquake. In 2018, the USGS Powell Center hosted a multi-day international meeting on "Future Opportunities in Regional and Global Earthquake Monitoring and Science" to help prioritize NEIC future science and development directions. One of the outcomes of this meeting was the recommendation that NEIC begin to explore the role of machine learning in helping fulfill its mission. Clear advantages of machine learning tools are their accuracy, speed, and ability to generalize across a diverse set of observations. In this presentation, I will provide an overview of NEIC's monitoring system, discuss where machine learning tools may contribute significantly, and provide insights into potential problems with their implementation. I will discuss NEIC's current operational use of machine-learning tools and ongoing research. Lastly, I will describe NEIC's long-term vision for implementing machine-learning tools into a robust operation.

ESC2021-KL04

Paleoseismology in Europe: what's next?

Daniela Pantosti
Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

Paleoseismology is the geological study of the earthquakes of the past up to several millennia; integrating with instrumental and historical seismology it provides the observation of seismicity for very long time windows.

Paleoseismology landed in Europe ca. 30 yr from US and Japan. This relatively young discipline is based on the observation that M6+ earthquakes produces permanent modifications at the Earth surface such as surface faulting, liquefaction, landslides, tsunami deposits, uplift/subsidence. These modifications, if preserved in time, become the geological records of past earthquakes and can be deciphered and dated similarly to what is done with the historical documentation.
Trenching, coring, outcrops, and bedrock exhumed fault planes, coupled with geochronology are the common targets for the analysis of paleoseismologists. They make use of a wide range of tools from very basic to high tech, but it is undoubtful that the exponential technological growth of the past decades has made possible relevant improvements and the development of new approaches for the study of deformed stratigraphic sequences and their dating.

Paleoseismological data have several applications for hazard assessment, e.g., from local land-use planning directly related to coseismic effects, to regional time-dependent hazard estimates and development of predictive models of earthquakes at scales of time and magnitude. Although these applications have a direct impact on land use planning, infrastructure setting, and society safety, in Europe paleoseismological results are rarely included in hazard evaluations. Recently, a few papers have highlighted the possibility to use the paleoseismological data for the characterization of fault ruptures in time, stressing the potential of these investigations in more robust assessments.

What are the reasons for this under-use of paleoseismological data, although all agree these can be very effective for hazard calculations? I will review these past 30 years of paleoseismology in Europe to try to focus on these reasons and consider possible counteractions. (or solutions).

ESC2021-KL05

The main developments of Seismology and Earthquake Engineering since middle 1700´s and the new challenges for a sustainable society

Carlos Sousa Oliveira
CERis/Instituto Superior Técnico, Universidade de Lisboa, Portugal

A look to the evolution of both Seismology and Engineering Construction since mid-1700´s until mid-1900´s is presented to understand the main accomplishments achieved. Then, I perspective the new advancements towards future mitigation of earthquake impacts with a clear proposal in the direction of sustainability and ecological challenge.

I will concentrate in the analysis of the phase 1755-1950, because not enough attention has been paid recently to this interesting period. Next, I jump to our days to look into a few great problems that require the involvement of the scientific, technical and political communities. In particular:

(i) I will look into the developments that Intensity Scales should pursue to reduce uncertainties, since more than 20 years have passed since the last upgrade and to the fact that today the information that results from new events is much more extensive and reliable than in the past. Several examples will be presented to illustrate how the frequency of motion should be included in the main categories (Building typologies and Vulnerabilities; Damage Grade; Quantity definition), and how it could be very helpful to add a few more descriptors to the Scale, namely shaking of objects and sloshing of water in recipients.

(ii) I will analyze the lines of development to mitigate earthquake impacts, responding to present and future needs, concentrating on the new scientific developments that are changing seismology from a “back-analyst” science (indirect contribution to earthquake engineering) into a more pro-active one, with direct contributions to reduce risk, such as the EEWS, and low-cost instrumentation. And changing earthquake engineering with the revolutionizing health monitoring, as a precautious indicator of mal-function of structures, complemented with the citizen science. Finally, all these ingredients need to be merged into simple recommendations for which only data mining will be able to extract new reliable information.

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Scientific Sessions

Session 01

Machine learning solutions to seismic problems: Joint Session ESC-SSA

Conveners:
William Yeck[1], Mostafa Mousavi[2], Léonard Seydoux[3], Martijn van den Ende[4]
[1]US Geological Survey, [2]Stanford University, [3]Université Grenoble-Alpes, [4]Université Côte d'Azur, Géoazur

In the past few years, there has been a resurgence in the application of machine learning techniques to seismological problems, leveraging state-of-the-art advancements in machine learning algorithms. Recent examples of seismic processing that attest to the massive potential of these techniques include automated event detection and association, denoising, phase picking, polarity determination, magnitude estimation, and location determination. Further, unsupervised learning techniques are improving the ability to extract novel information from continuous waveform data. Many of these applications have leveraged the enormous datasets collected by seismologists over the last decades, yet many more remain untapped, opening the way to the development of new machine learning techniques and applications. In this session we invite contributions discussing the exploration and application of machine learning in all seismic problems, and invite contributors to discuss successes, challenges, and lessons learned in the application of these developing technologies.

Session 02

Open and FAIR seismology - consequences, challenges and opportunities

Conveners:
Florian Haslinger[1], Lars Ottemöller[2], Carlo Cauzzi[3], Remy Bossu[4], Fabrice Cotton[5] and the EPOS Seismology Consortium Assembly
[1] EPOS Seismology & ETH Zurich, [2] UiB, Bergen, Norway, [3] ORFEUS & SED@ETH, Zurich, [4] EMSC-CSEM, [5] EFEHR & GFZ Potsdam

Funding agencies and policy makers put increasing emphasis on Open and FAIR (Findable, Accessible, Interoperable, Reusable) seismological data, products and infrastructures. Adherence to the INSPIRE directive or the concept of certified Trusted Digital Repositories gain importance and attention. Journals are changing their policies towards openness of data and software connected to publications, and national, European and global initiatives and institutions are developing more and more services around Open and FAIR data, covering curation, distribution and processing. EPOS is based on the concepts of Open Access and FAIRness, and the European seismological infrastructures ORFEUS, EMSC and EFEHR that together form EPOS Seismology have adopted this as well. Infrastructure operators, academic institutions and individual researchers struggle with the requirements and conditions they encounter in this evolving environment. An inclusive and integrated approach to Open and FAIR still needs to be developed, with consistent policies, standards and guidelines covering the whole research data lifecycle, and addressing also basic legal frameworks e.g. for intellectual property and licensing. The research community needs to further develop a common understanding of best practices and appropriate scientific conduct adequate for this new era. We solicit contributions from researchers, service providers,
infrastructures and institutions that have a story to share on their experience with this evolving Open and FAIR research environment. Contributions are welcome across all aspects, including but not limited to the technical implementation of data management and access, the use of persistent identifiers, policy development, licensing and IP issues, interaction with funders and policy makers.

Session 03

Challenges due to massive generation of seismic data. Large-N experiments, fiber optic cables, and how users, data centres and applications will cope with data in the near future

Conveners:
Javier Quinteros[1], Helle Pedersen[2], Andreas Rietbrock[3]
[1] GEOFON / Deutsches GFZ Potsdam, Germany, [2]University of Grenoble, France, [3]KIT / Karlsruhe, Germany

Within the seismological community, the last decades have been characterised by large amount of new additional conventional seismic stations becoming available. Dense observations due to new technologies include Large N deployments, cheap sensors, and fibre-optic cables. All of them are starting to show their great potential in providing quality data with a wide spectrum of applications ranging from Tsunami early warning to Infrastructure monitoring. Although data quality and resolution of the examples mentioned above are different, they have in common the potential to produce large volumes of data in a very short period of time due to both the extremely dense spatial and temporal resolutions.

This considerable increase in the data generation is challenging for seismological data centres hosting data, because there are still no standard policies on how this should be managed by our standard web services, which are very stable and mature, but have never faced the need to support an on-the-fly conversion of such a big volume of data from proprietary to standard formats.

Some data centres are already using particular data formats to archive these data (e.g. PH5) or to provide it to users (e.g. ASDF), but additionally to this a change in the way our web services process and provide such amount of data would be needed.

The scope of this session is to present the latest advances on this topic, on-going coordinated efforts between big data centres (e.g. IRIS, GFZ, RESIF), and to collect feedback and requirements from the community.

We expect contributions related, but not limited to:

- Best practices for seismologists and data centres producing data.
- Users processing big amounts of seismic data.
- Developers working on cloud processing to minimize data transfer or other novel approaches.
- Data producers of DAS and Large-N experiments.
- Data Centre Operators archiving and providing big datasets.

Session 04

The cycle of observational seismology from Waveform Data Collection to scientific products

Conveners:
Carlo Cauzzi[1], Susana Custódio[2], Christos Evangelidis[3], Giovanni Lanzano[4], Lars Ottemöller[5]

[1] ORFEUS and SED@ETH, Zurich, Switzerland, [2] FCUL, Lisbon, Portugal, [3] IG-NOA, Athens, Greece, [4] INGV, Milan, Italy
[5] UiB, Bergen, Norway

Observational seismology has witnessed tremendous advances in the last two decades in Europe and worldwide. The establishment of EIDA marked a change of paradigm in seismic data dissemination in Europe. The deployment of dense modern accelerometer networks has blurred the boundary between broadband and strong-motion seismology. Geophysical site characterization has become standard practice, and open databases have been created to host basic and advanced station metadata. In this dynamic landscape, ORFEUS (http://orfeus-eu.org/) carries out since 1987 its mandate to promote and coordinate waveform seismology in Europe. ORFEUS services (http://orfeus-eu.org/data/) currently provide access to the waveforms acquired by more than 10,000 stations in Pan-Europe, including dense temporary experiments, with strong emphasis on open and high data quality. The data and services are collected or developed at the national level and further standardized, homogenized and promoted through ORFEUS, including full integration with EPOS. Contributing data to ORFEUS archives means long-term archival, state-of-the-art quality control, enhanced data access and usage, especially through webservices. This means, in turn, increased scientific impact of seismic waveform data. This session aims at discussing the latest advances in seismological observation in Pan-Europe and the challenges ahead. Focus is not limited to the participants to ORFEUS, their hardware and software infrastructure, technical and scientific products. Contributions from other global / international / national agencies and scientists working in the broad domain of observational seismology are welcome, as are suggestions for innovative developments and ideas to be considered for integration into the EPOS Seismology domain.

Session 05

The structure of the central Mediterranean: insights from seismological and geophysical data

Conveners:
Giuliana Rossi[1], Irene Molinari[2], Irene Bianchi[3], Josip Stipcevic[4], Andrea Magrin[1], Mark R. Handy[5]
[1]Istituto Nazionale di Oceanografica e di Geofisica Sperimentale–OGS, Trieste, Italy, [2]Istituto Nazionale di Geofisica e Vulcanologia INGV, Bologna, Italy, [3]University of Vienna, Vienna, Austria, [4]Department of Geophysics, Faculty of Science, University of Zagreb, Zagreb, Croatia, [5]Institut für Geologische Wissenschaften, Freie Universitδt Berlin, Berlin, Germany

The mountain chains of the Central Mediterranean (the Apennines, the Alps, Dinarides, Albanides, Hellenides) are shaped and modeled by the complex tectonic processes induced by the relative movements and collision of several different microplates. The intense onshore and offshore seismic activity puts at risk the rich cultural heritage characterizing the entire region. A better understanding of the lithospheric and crustal structures coupled with the knowledge about the interaction between different tectonic units is the key to unravel the processes governing the distribution of the seismic activity. In the last years, seismological field projects (e.g., AlpArray and its complementary seismic experiments) collected new top-quality seismological data thus bringing new insight into the Alps-Apennines-Carpathians-Dinarides orogenic system. One of the aims of this session is to present the research stemming from these field projects thus encouraging future research proposals to extend this desirable approach to other parts of the circum-Mediterranean region.

We aim to collect contributions from the Earth Science community to highlight new and recent results identifying and bringing on key open questions related to the structure and dynamics of the tectonic plates in the central Mediterranean. We also aim to shed light on still unresolved questions about collision vergence and the relative motions of the plates. We welcome disciplinary and multidisciplinary works based on geophysical imaging, seismotectonics, geodesy, geodynamics, gravimetry, tectonics, and structural geology, from the crust to the upper mantle. Contributions focused on other regions that have some similarity and analogy with the central Mediterranean area, are also welcome.

Session 06

Bringing seismological issues to the public: a way to foster seismic risk best practice

Convener:
Remy Bossu[1], Gemma Musacchio[2], Stefano Solarino[2]
[1]European-Mediterranean Seismological Centre - EMSC, France, [2]INGV, Italy

Seismological institutions worked hard in the last years to make information on earthquakes promptly available as they occur. They also made efforts to respond to the increasing demand of the society for more knowledge about the scientific issues behind the natural phenomenon. This raised the consciousness of the public about earthquakes but contributed only a little to mitigation.
Surprisingly, preparedness and prevention are still, at least in Europe, second priority issues; there is a lot more to do to foster seismic risk awareness in a lazy society that pays attention to the topic mostly, and sometime only, after a destructive earthquake occurs.

The session aims at opening a debate about the role of seismologists in educating people to seismic risk. It also aims at discussing efficient ways to transfer knowledge and to educate the public to the best practices.

In order to do this, the session welcomes contributions to update the audience on the education initiatives, planned or ongoing, for the public, schools and stakeholders. In this perspective, the session is open to description of projects about risk education in schools, information campaigns, education initiatives, exhibitions, movies, apps, internet sites, communication on the internet and social networks, relationships with the press.

Session 07

Seismicity and Seismotectonics in Central and Eastern Europe

Conveners:
Istvan Bondar[1], Damiano Pesaresi[2], Wolfgang Lenhardt[3]
[1]Research Centre for Astronomy and Earth Sciences, Hungary, [2]OGS, Italy, [3]ZAMG, Austria

Central and Eastern Europe is an ideal seismic laboratory for seismotectonic studies that can benefit for the coexistence in the area of the triple junction of the Alps, Dinarides and the Pannonian Basin, the Vrancea subduction region, the Bohemian Massif, the Carpathians, the collision zone of the Adriatic Plate and the southern part of the Trans- European Suture Zone.

Hence, in such a relatively small region, significant spatial variability of the seismicity, the stress fields and the focal mechanisms, occur, that affect the seismic hazard and consequently the seismic risk.

In particular, a better understanding of the seismicity in the region can be obtained by more accurate analysis of the seismic events, and a more reliable identification of quarry blasts.

The session aims at collecting presentations regarding analyisis of seismic data for the region and in particular:

- methods for separating natural seismicity from quarry blasts and mining activity
- improved seismic catalogs of historical and instrumental seismicity

- crustal and deep structure
- developments in - real-time data exchange, including cross-border exchange of macroseismic queries

Session 08

Seismic arrival time determination: The reliability of established and innovative automatic picking techniques compared to manual picking

Conveners:
Thomas Garth[1], Thomas Meier[2], Kostas Lentas[1]
[1]International Seismological Centre, Thatcham, United Kingdom, [2]Institute of Geosciences, Christian-Albrechts-Universität zu Kiel, Kiel, Germany

The amount of seismic waveform data that is openly accessible or available to national earthquake monitoring agencies has vastly increased in the past decade, a trend which continues thanks to the ongoing establishment and improvement of national monitoring seismic networks. This influx of data has hugely increased the number of earthquakes that are detected globally, but also presents challenges as this volume of data cannot be analysed and picked manually.

Increasingly therefore both national and international earthquake monitoring agencies have relied upon automatic detection algorithms to identify seismic arrivals and attribute them to a given seismic event. These automated picks are then reviewed and reported along with the associated earthquake locations by numerous earthquake monitoring agencies, with the majority of these observations being reported to and curated by International Seismological Centre (ISC, www.isc.ac.uk). This forms a key data set with the reported earthquake locations and seismic phases used in many areas of seismology including earthquake hazard, and seismic imaging.

In this session we invite presentations that give an overview of automatic picking techniques that are used systematically in seismic monitoring and earthquake detection, along with examples where automatic detections and picking are used. We also welcome submissions outlining new and improved techniques for earthquake detections and phase picking. Particularly we would like to encourage submissions that consider the impact of automatic arrival picking on the fidelity of the final results they inform.

Session 09

Advancing the (Re)use and preservation of Analog Seismic Data

Conveners:
Josep Batlló[1], Lorraine J. Hwang[2], Allison Bent[3], Dmitry A. Storchak[4]
[1]Institut Cartogrũfic i Geolçgic de Catalunya, ICGC, [2]University of California, Davis, [3]Natural Resources Canada, [4]International Seismological Centre, ISC

Analog seismograms have formed the basis for seismological research for almost 100 years. These data contain unique earthquakes and almost all atmospheric nuclear tests. With the wide availability of digital seismic data, researchers have recognized nontraditional phenomena such as slow-slip events, storm surges, tectonic tremors, acoustic phases, landslides, icequakes, and avalanches. In addition, these newly recognized connections between Earth's systems – atmospheres, ocean, and cryosphere have increased the importance of contributions from seismology to understand and mitigate the threat from both natural and anthropogenic hazards.

These and yet to be recognized phenomena have been recorded for decades on analog media but many of these records are underutilized due to their inaccessibility.

Analog seismograms are at risk from inadequate storage conditions or institutional neglect. A growing movement for their preservation alongside the development and adaptation of techniques to use them is gaining momentum worldwide as the value of old data is recognized. Better coordination, sharing experiences, definition of standards and applying FAIR (Findable, Accessible, Interoperable, Reusable) standards can greatly improve, even overturn, their precarious situation. If available, information on recordings of particular seismic events in digital form may become standard part of seismic event bulletins distributed by global, regional, and local agencies.

We invite abstracts on a wide range of topics related to the use and preservation of analog seismic data including: research using analog data; approaches, methods and
lessons learned in preservation and digitization; issues, challenges, case studies in preservation and use; and vision and needs for preservation and standards.

Session 10

Seismic anisotropy and shear-wave splitting: Achievements and perspectives

Conveners:
George Kaviris[1], Yuan Gao[2], Lucia Margheriti[3]
[1]Assistant Professor of Seismology – Seismic Anisotropy, Section of Geophysics – Geothermics, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, Athens, Greece, [2]Research Professor, Key Laboratory of Earthquake Prediction, Institute of Earthquake Forecasting, China Earthquake Administration, Beijing, China, [3]Senior researcher at Osservatorio Nazionale Terremoti Istituto Nazionale di Geofisica Vulcanologia, Roma, Italy

Seismic anisotropy has played a crucial role in investigating the Earth's interior from the
upper crust to the inner core and is a useful tool to study dynamic processes in the Earth's interior. Shear-wave splitting, one of the most effective way to study seismic anisotropy, can identify the properties and the geodynamics of the upper mantle analysing core phases, such as SKS and PKS. Shear-wave splitting in the upper crust can be intrinsic or due to the presence of fluid-saturated microcracks, oriented according to the stress regime, as observed in tectonic, seismic or volcanic environments worldwide, as well as in exploration seismology. Temporal variation of shear-wave splitting is a challenging topic, associated with changes of the stress regime and possibly with earthquake occurrence and the gradual inflation and deflation of magma chambers. Azimuthal anisotropy and radial anisotropy can be extracted from earthquake or ambient noise records to detect the seismic layered features and to rebuild the 3D seismic structure. This session aims to present modern research on topics related to seismic anisotropy and shear-wave splitting, including new methods for analysing anisotropic parameters, tectonic implications, geodynamic modeling, laboratory experiments, relations with seismic and volcanic phenomena and novel approaches on the subject. Submissions concerning the different facets of this topic are welcome.

Session 11

From school seismology to citizen science

Conveners:
Gerasimos Chouliaras[1], Dragos Tataru[2]
[1] Institute of Geodynamics, National Observatory of Athens (NOA), Greece, [2] National Institute for Earth Physics (NIEP), Romania

Educational seismology groups from several countries in Europe and around the globe work closely together with specific interests in developing collaborations and finding synergies with the growing citizen science movement in seismology.

In the last decade, citizen seismology has achieved a number of important goals, combining the interest for citizen science in general but especially in the field of disaster management and preparedness. Numerous initiatives in citizen seismology demonstrate that it is highly valuable for providing data from and to citizens quickly in time-sensitive cases, for providing data in poorly monitored locations, or for providing scientists, authorities and disaster managers with data related to earthquakes and its human elements.

In this session, we would like to invite contributions from citizen science projects in seismology and also from STEM related seismology projects. We welcome studies that are related but not limited to engage the public in gathering or obtaining insights from various earthquake observations, such as low cost seismic sensors, social networks, internet-based information and other sources.

Session 12

Seismological and structural studies in Polar Regions and the cryosphere

Conveners:
Myrto Pirli[1], Nicolas Celli[2], Peter Voss[3], Fabian Walter[4]
[1]Independent Researcher, Norway, [2]Dublin Institute for Advanced Studies, Ireland, [3]Geological Survey of Denmark and Greenland – GEUS, Denmark, [4]ETH Zürich, Switzerland

The Polar Regions attract increased scientific, social and economic attention and hold special significance as regions strained the most by the consequences of climate change. Unanswered questions on the regions' tectonic evolution, implications of their natural resources and the UN Law of the Sea Treaty stimulate further interest in them. Among the seismological challenges in the Polar Regions are the origin and properties of intraplate seismicity, the mechanisms of ultraslow seafloor spreading, the structure and dynamics of aseismic ridges and subglacial cratons and orogens, the role of glacial rebound in seismicity triggering, seismogenic glacier sliding and iceberg production, and the exploration for oil and gas. As an imaging tool both in depth and on the surface, apart from revealing the Earth's structure, seismology contributes to studies of paleoclimate and ice and permafrost structure. Seismology has also proven itself as an effective instrument to study ice dynamics and monitor glacier-related natural hazards, the rich cryoseismological wavefield providing unrivalled insights into iceberg detachment, crevassing, subglacial water flow and basal stick-slip phenomena.

We invite submissions on seismology and Earth structure in the Polar regions and glaciated environments with temperate climates. All seismological topics are welcome, including monitoring and analysis of seismicity (tectonic and cryogenic) and related hazards, near-surface processes, studies of recent larger seismic events, seismotectonics and seismic imaging of crustal and mantle structure. We welcome contributions on recent research results and their interpretation, and on passive and active experiments under the special conditions of the polar environment and mountain glaciers.

Session 13

Seismological and geophysical imaging of shallow geological structures at different scales: challenges and perspectives

Conveners:
Sebastiano D'Amico[1], Francesco Panzera[2], Fabio Villani[3], Stéphanie Gautier[4]
[1]University of Malta, Department of Geosciences, [2]Swiss Seismological Service - ETH Zurich, [3]Istituto Nazionale di Geofisica e Vulcanologia, [4]Université Montpellier, Géosciences Montpellier, Université Montpellier II

There is an increasing need for high-resolution imaging of shallow geological structures as well as characterization of their physical properties. This stems not only from purely scientific perspectives, but also from correct land planning in areas subject to a wide range of environmental risks. In this regard, seismological and geophysical techniques represent the main tools for achieving a deep understanding of inaccessible subsurface structures. The improvement of such imaging techniques is related to the growing computational capability in the solution of inverse problems, and to the theoretical development of modelling algorithms. Among their countless applications, we seek contributions on the study of active fault zones (crucial in tectonic geomorphology, and in the analysis of seismic sources, surface faulting hazard and fluids flow), fracture networks (in reservoirs, volcanic areas and geothermal fields), landslides (from shallow fractured rock masses to deep sliding surfaces) and seismological engineering problems (site effects and ground shaking amplification).

The aim of this session is to collect the most recent results of seismological and geophysical imaging of shallow crustal structures in a wide range of environmental applications, including also discussions on methodological challenges and new perspectives. We encourage submitting works dealing with multi-disciplinary high-resolution methods together with new developments in data processing, imaging strategies and field acquisition layouts. Case studies from active tectonic settings are welcome.

Session 14

Imaging and modeling 3D fault complexities in FAULT2SHA

Conveners:
Francesco Visini[1], Bruno Pace[2], Laura Peruzza[3], Oona Scotti[4], Graeme Weatherill[5]
[1]Istituto Nazionale di Geofisica e Vulcanologia, sezione di Pisa, [2]Università degli Studi "G. D'Annunzio" di Chieti-Pescara, [3]Istituto Nazionale di Oceanografia e Geofisica Sperimentale - Centre for Seismological Research, [4]Institut de Radioprotection et de Sûreté Nucléaire - BERSSIN - Seismic Hazard Assessment Section, [5]GeoForschungsZentrum - Seismic Hazard & Risk Dynamics

Defining the 3D geometries of faults and their structural and rheological complexities not only presents challenges for field geologists, but also for seismic hazard assessment (SHA). Roughness of the fault plane, friction, asperities and bends constitute primary controlling parameters in physicsbased earthquake rupture models. Advanced seismic-cycle and earthquake rupture simulations incorporating these variables in 3D models have shown the occurrence of complex earthquake ruptures. Meanwhile, structural and field geologists are analyzing data at micro- and macro-scales, revealing that microscale observables can influence earthquake ruptures, or that, for example, strain partitioning, propagation of earthquake rupture or the seismic/creeping behavior can be influenced by steps, bends, gaps and barriers within and between faults. Modeling the 3D geometry incorporating the variability of these fault parameters along-strike and down-dip is the new frontier that earthquake scientists are beginning to explore, and a key scientific target of the Fault2SHA community. Finally, as the assessment of seismic hazard is ultimately concerned with the expected ground motion, to what extent are empirical ground motion prediction equations and physics-based ground motion simulations capable of capturing these complexities?

This session welcomes contributions from: (i) earthquake geologists, seismologists and structural geologists exploring fault geometry and behavior, including detailed imaging of fault properties along-strike and down-dip; (ii) simulations of complex ruptures and earthquake recurrence through dynamic and multi-cycle simulations; (iii) incorporation of characteristic of 3D faultbased ruptures into SHA; (iv) and ground motion modelers (empirical and physics-based) investigating the influence of such complex micro- and macroscale 3D complexities.

Session 15

Earthquake hazard assessment towards seismic risk mitigation in Urban Areas

Conveners:
Aybige Akinci[1], Karin Sesetyan[2], Simone Barani[3], Dario Albarello[4]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, [2]Boğaziçi University, Kandilli Observatory and Earthquake Research Institute, Dept. of Earthquake Engineering, Istanbul, Turkey, [3]University of Genoa – DISTAV, Genova, [4]University of Siena, Department of Physics, Earth and Environmental Sciences, Siena, Italy

Recent seismic events (like Van 2011, Turkey; Amatrice-Norcia 2016-2017, Italy; Canterbury 2010-2011, New Zealand; Puebla-Morelos 2017, Mexico) have shown that urban areas are increasingly vulnerable to earthquake-induced damage and present remarkable levels of risk. In many cases, large metropolitan areas in the world (such as the San Francisco bay area, Istanbul, and Lisbon) are situated close to the seismic sources that are capable of producing large earthquakes and, consequently, pose considerable threat to such areas. Developing risk reduction measures requires detailed seismic hazard models and a quantitative description of the ground shaking on a fine spatial scale. To this end, great efforts have been spent to increase the knowledge about site response through detailed ground response analyses and
microzonation studies aimed at defining areas that are susceptible to site effects. Nowadays, such effects can be incorporated into seismic hazard using probabilistic or deterministic approaches.

In this session, we would like to welcome different and innovative methodologies and practices aimed at improving standards in seismic hazard and risk assessments throughout the presentation of databases, models, and applications that are suited to the urban areas. This session covers many earthquake engineering aspects and topics, including strong ground motion observations and estimations, broadband ground motion simulations, extensive estimation of site effects in urban areas of earthquake prone regions together with risk management issues based on the implementation of local hazard estimates in building codes and urban planning practices.

Session 16

Advances in models, observations and verification towards operational earthquake forecasting

Conveners:
Antonella Peresan[1], Dimitar Ouzounov[2], Vladimir G Kossobokov[3], Angelo De Santis[4], Gerassimos Papadopoulos[5], Sergey Pulinets[6]
[1]Istituto Nazionale di Oceanografia e Geofisica Sperimentale, Centro Ricerche Sismologiche, OGS-CRS, [2]Center of Excellence in Earth Systems Modeling & Observations, Chapman University, Orange, CA, USA, [3]Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences, Moscow, Russia, [4]Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy, [5]International Society for the Prevention & Mitigation of Natural Hazards, Athens, Greece, [6]Space Geophysics Department, Space Research Institute, Russian Academy of Sciences, Moscow, Russia

Which are the physical processes that take place in the Earth crust before the earthquake nucleates? How can we observe, describe and model them statistically and physically? Significant steps have been made towards assessing earthquake space-time correlations, clustering, and the emergence of seismicity patterns, showing the potential for reproducible and testable earthquake forecasting. But seismicity is only one manifestation of Earth's complex dynamics preceding catastrophic earthquakes. Besides identified patterns and probabilistic models of earthquake occurrence, a large amount of newly available data provide nowadays opportunities for systematic analysis and model testing. A variety of physical observables, ranging from ground-related deformation patterns (GPS, SAR, etc.) to pre-earthquake changes
(be they geochemical, electromagnetic, hydrogeological or thermodynamic), may be related to stress variations in the lithosphere prior to a large earthquake.

With this session, we intend to better understand the feasibility and practical relevance of earthquake forecasting methods. Contributions addressing the following theoretical and practical issues are welcome:

- State-of-the-art and novel observations from ground based or satellite based techniques;
- Systematic analysis, physical interpretation and modeling of pre-earthquake processes;
- Models validation and statistical assessment of the proposed physical-based precursors;
- Statistical methods and issues in earthquake forecast validation;
- Earthquake forecasting experiments for real-time model testing at global scale and in specific test areas;
- Time-dependent seismic hazard assessment, based on reproducible earthquake forecast;
- Dissemination and use of earthquake forecasting information;
- Possible extension to seismic risk and loss forecasting.

Presentations addressing these problems, in both probabilistic and deterministic approaches, are welcomed

Session 17

Crowdsourcing and macroseismology: reliability, applications and developments

Conveners:
Valerio De Rubeis[1], Ina Cecić[2]
[1]Istituto Nazionale di Geofisica e Vulcanologia, Italy, [2]Agencija RS za okolje, Slovenia

The contribution of citizens is an important aspect of research in macroseismology as past experience showed the reliability of this kind of data. Furthermore, this approach opens new developments. The aim of this session is to highlight the following key topics: crowdsourced data collection through questionnaires, thumbnails or icons; pros and cons of simplicity and completeness of information; key diagnostics in intensity evaluation and comparison among values obtained with different methods; differences between traditional and web-based intensity; web platforms for data visualization and exchange; correlations among intensities and ground motion; the contribution of intensities for the definition of the seismic source even in real-time.

Contributions concerning other aspects of citizen science in macroseismology are welcome.

Session 18

Towards operational forecasting of earthquakes and early warning capacity for more resilient societies

Conveners:
Johannes Schweitzer[1], Sarah Dryhurst[2], John Douglas[3], Stefan Wiemer[4]
[1]NORSAR, [2]University of Cambridge, [3]University of Strathclyde, [4]ETH Zürich

To help mitigate the risks related to earthquakes, citizens need additional protection that goes beyond building codes and retrofitting actions. These include Earthquake Early Warning (EEW) approaches and operational earthquake forecasting (OEF), but also Rapid Response to Earthquake (RRE) systems. Besides scientific and technological advances, a focus must be on improved preparedness due to more effective two-way communication of forecasts, early warning and uncertainties for users and the public. In 2019, two new seismology and earthquake engineering related projects were awarded by the European Commission, RISE and TURNkey. In these two projects, more than 40 European institutions are collaborating on numerous aspects of improving real time seismology and its communication, and seismic risk reduction capacity. This session will give the opportunity to present and discuss first project results with the wider community. In addition, we welcome contributions on all aspects of improving earthquake resilience, including the scientific background, actual implementation scenarios and problems in communicating OEF, EEW and RRE results to stakeholders and public.

Session 19

Physics of earthquakes and seismic sources

Conveners:
Efthimios Sokos[1], Christos Evangelidis[2], Václav Vavryčuk[3], Jiří Zahradník[4]
[1]Department of Geology, University of Patras, Greece, [2]Institute of Geodynamics, National Observatory of Athens, Greece, [3]Institute of Geophysics, Czech Republic, [4]Charles University, Prague, Czech Republic

Earthquake physics attempts to answer fundamental questions in seismology as how do earthquakes prepare, how does seismic rupture start, propagate and stop, what is the role of the long-term and short-term processes in the Earth, what is the role of fluids in earthquake triggering, and what is the link between fault dynamics, energy, friction and other physical parameters of the focal zone. Recent advances in seismological, geodetic and satellite observations provide a vast amount of data, which, linked with advances in computational methods, have significantly expanded our ability to study earthquake related phenomena on various scales. Nevertheless, despite the achieved progress, earthquake source processes are not often sufficiently understood and in some cases the results are controversial, calling for increased efforts towards source studies.

The goal of this session is to attract scientific contributions related to broad aspects of methodological as well as data-oriented earthquake source studies. Submissions focusing on earthquake source parameters, focal mechanisms and their inversion for stress, non-doublecouple components of moment tensors, source slip inversions, finite fault inversions, back-projection techniques and their applications, resolution limits and related uncertainties are particularly welcome as well as physics-based simulations. In addition, the session is suitable for studies of source imaging as well as frequency-dependent source parameters, imaging of dynamic rupture, characterization of source complexity, statistical properties of earthquake source parameters as scaling laws etc.

Session 20

New seismological workflows: from event detection to earthquake forecasting

Conveners:
Margarita Segou[1], William Ellsworth[2], Lauro Chiaraluce[3]
[1]British Geological Survey, [2]Stanford University, [3]Istituto Nazionale di Geofisica e Vulcanologia

Deep learning applications in seismological practice provide now a dramatically increase in the number of detections revolutionizing the way we describe and understand fault systems. The improvements touch upon pre-processing, event detection, phase picking, and association techniques allowing us to develop comprehensive earthquake catalogs that include seismic parameters and rupture characteristics. These catalogs are critical for advancing our knowledge about earthquake behaviour and triggering mechanisms. Ultimately these workflows support rapid analysis capabilities and will transform standard seismological practice. The existence of high-resolution data products translates into improved predictability of short-term earthquake forecasts that track the evolution of earthquake sequences using physics-based or statistical simulations. In this session we focus on induced and natural seismicity cases with high-resolution catalogs, machine learning applications, ranging from event detection to model development, existing labelled long-term datasets for algorithm training, how data quality may influence forecast predictability, what is the information gain for advanced operational forecasts based on machine learning catalogs and how these workflows can be adapted for different spatial scales from monitoring microseismicity in observatory sites, evolving aftershock seismicity to national level earthquake detection. We will close the session with an open discussion with a panel of experts focusing on recent European and US examples of high-resolution earthquake development with machine learning applications.

Session 21

Physics of earthquake preparation process: From laboratory experiments to earthquake forecast

Conveners:
Eleftheria Papadimitriou[1], Alexey Zavyalov[2], Rodolfo Console[3], Ramon Zuniga[4]
[1]Aristotle University of Thessaloniki, Greece, [2]Institute of Physics of the Earth RAS, Moscow, Russia, [3]Centro di Geomorfologia Integrata per l'Area del Mediterraneo, Potenza, Italy; Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy, [4]Centro de Geociencias, Campus Juriquilla, UNAM, Queretaro, Mexico

The skepticism connected with earthquake forecasting, both deterministic and probabilistic, is related with the complexity of earthquake generation process that puts limitations in scientific knowledge and incomplete insights. These latter prevent a reliable estimation of the occurrence place, time and magnitude of an ensuing earthquake. Meanwhile, it is known that the earthquake process is not momentary, but on the contrary there are several gradually evolving stages that take place in time and space. Before the main rupture occurs, the destruction process is going through a number of levels (stages), starting with the micro–scale and ending on macro–scale, including earthquake focal area. In this session, we invite researchers to discuss the results and directions for further studies on the physics of the seismic process – from experiments in laboratory conditions, to rock bursts in mines and seismically active regions during the preparation phase of strong earthquakes.

Special emphasis will be given to quantitative physical models of the seismic process at different scales, observations on earthquake triggering by other earthquakes or nearby faults, and synchronization between nearby faults with positive stress coupling, fault system interactions controlling earthquake occurrence, the connection of smaller magnitude seismicity with stress changes as expressed through the Rate/State model, calculation of stress changes from changes in earthquake occurrence. Modeling and simulations across a wide range of spatial and temporal scales provide a better understanding of the source processes and interactions, and advance predictive capabilities.

Session 22

The 2020 European Seismic Hazard and risk model: new developments and future directions for seismic hazard and risk assessment in Europe

Conveners:
Stefan Wiemer[1], Domenico Giardini[2], Fabrice Cotton[3]
[1]Swiss Seismological Service, ETH Zürich, Zürich, Switzerland, [2]Domenico Giardini, Energy Science Centre, ETH Zürich, Zürich, Switzerland, [3]Fabrice Cotton, Seismic Hazard and Risk Dynamics, GFZ German Research Centre for Geosciences, Potsdam, Germany

The session showcases the innovations and outcomes of the 2020 European Seismic Hazard and Risk Models (ESHM20 and ESRM20), an end-product of the three-year SERA project (www.sera-eu.org) tasked with an assessment of earthquake risk in Europe and the development of regionwide maps of seismic design inputs for Eurocode 8.

Building upon preceding national and European initiatives including the Seismic Hazard Harmonisation in Europe (SHARE) project, the ESHM20 and ESRM20 begins with a compilation of new data and models for seismic risk assessment including updated instrumental and historical earthquake catalogues, active faults, strong motion recordings, ground motion models, building exposure (residential, commercial and industrial) and vulnerability functions. This wealth of data provides deeper insights into the characteristics the earthquake process and of the built environment across Europe and the surrounding countries. To ensure that this information is integrated into the hazard and risk models, the ESHM20 and ESRM20 have spurred development of innovative methodologies for characterizing the earthquake sources, ground motions and building response.

In addition to presenting the results of this latest generation model, the session will also look to the future of seismic hazard and risk activities in Europe within the framework of the European Facility for Earthquake Hazard and Risk (EFEHR, www.efehr.org), a new pillar of the EPOS Seismology Thematic Core Service, and emphasise the role that earthquake scientists and engineers across Europe can play in the development and harmonisation of the next generation of models for mitigation of seismic risk both at a national and European scale.

Session 23

Swarm-like and earthquake sequences driven by local transients in tectonic and volcanic areas

Conveners:

Maria Mesimeri[1], Luigi Passarelli[2], Federica Lanza[3], Gian Maria Bocchini[4]

[1]University of Utah, United States of America, [2]King Abdullah University of Sciences and Technology – KAUST Kingdom of Saudi Arabia, [3]ETH Zurich, Switzerland, [4]Ruhr-University Bochum, Germany

Earthquake swarms and complex earthquake sequences generally lack a clear mainshock, initiated by several small magnitude events with larger earthquakes that occur later in the sequence. Thus, resulting in a more complex temporal evolution compared to typical mainshock-aftershock sequences. In addition, they exhibit spatio-temporal migration patterns and extend over larger areas than expected considering the magnitude of the largest earthquake. Spatial migration and complex temporal evolution have been associated to transient forcing such as slow slip, creeping and/or
pressurization of crustal fluids in tectonic environments, or due to magma migration and hydrothermal fluid redistribution in volcanic areas. However, the physical mechanisms and the rheological conditions leading to such complex seismic sequences are still largely elusive. This session aims to host studies on earthquake swarms and complex seismic sequences related to transient forcing. We invite contributions focusing on characterizing the spatio-temporal evolution of such sequences, their scaling properties, and the underlying physical processes. Microseismicity studies in volcanic regions, areas of geothermal activity as well as complex earthquake sequences in active tectonic areas, are also welcome.

Session 24

Physical and statistical models and pattern recognition techniques applied to foreshocks, aftershocks and multiplets at different scales, from laboratory experiments to real-scale observations

Conveners:

Stefania Gentili[1], Rita Di Giovambattista[2], Filippos Vallianatos[3], Álvaro González[4]

[1]Centro Ricerche Sismologiche, OGS, Italy, [2]INGV, Italy, [3]Department of Geophysics–Geothermics, Faculty of Geology and Geoenvironment, National and Kapodistrian University of Athens, Athens, Greece, [4]Centre de Recerca Matemàtica, Spain

Seismicity can occur with great spatio-temporal variability, dominated by background activity or several kinds of earthquake clusters, from swarm-like to burst-like types. In many regions where complex fault systems exist, clusters are characterized by multiple mainshock sequences, with potentially large aftershocks. Foreshock occurrence is still poorly understood: some events are preceded by significant foreshock activity, while others occur suddenly. A persistent behavior of the seismicity and cluster properties has been observed in some seismotectonic areas. The increasing amount of earthquake data available on local to global scales provides new opportunities for model testing.

In this session, we invite researchers to present the latest results on physical and statistical models for foreshocks, aftershocks and multiplets, including experimental results based on laboratory experiments on rock fracture and friction, along with theoretical and numerical models, and methods for seismic hazard analysis related to the complex patterns of seismicity. Strongly encouraged contributions will be those dealing with spatio-temporal correlations, scaling laws and clustering, variations of seismicity style correlated to geological or tectonic characteristics, the emergence of seismicity patterns, and pattern recognition techniques applied to earthquake sequences.

Session 25

Research on array seismology and earthquake mechanisms at seismic experimental sites

Conveners:
Zhongliang Wu[1], Ke Jia[2], Fabio Romanelli[3], Jiancang Zhuang[4], Shiyong Zhou[5]
[1]Institute of Earthquake Forcasting, China Earthquake Administration, China, [2]School of Automation, Northwestern Polytechnical University, China, [3]Department of Mathematics and Geosciences, University of Trieste, Italy, [4]The Institute of Statistical Mathematics, Japan, [5]School of Earth and Space Science, Peking University, China

The recent deployments of dense seismic and geodetic observation networks in some Seismic Experimental Sites have revealed detailed pattern of crustal stress and strain rate in tectonically active regions all over the world. Modeling and interpretation of physics of the earthquake process across a wide range of spatial and temporal scales provide a better understanding of source processes and interactions, and advance predictive capabilities.

This session will cover theories, methodologies, techniques, and applications related to earthquake mechanisms based on multiple types of data, from seismic to GPS arrays. We welcome studies aimed at characterizing individual earthquake events and crustal deformations to explore active tectonics, seismic hazard, and earthquake behaviors at different scales. We encourage contributions from scientists involved in a broad range of disciplines, including geology, seismology, geodesy, geodynamics, active tectonics, crustal stress, seismic hazard assessment and numerical modeling to enrich our understanding of dynamics and mechanisms of earthquakes at seismic experimental sites.

Session 26

Seismicity and geodynamics in Corinth Gulf and other Near Fault Observatories

Conveners:
Panagiotis Elias[1], George Kaviris[2], Athanassios Ganas[3], Helene Lyon Caen[4]
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The Corinth rift is among the fastest extending continental regions in the world. It has one of the highest seismicity rates in the Euro-Mediterranean region, with frequent moderate and strong (M≥6.0) earthquakes. With its high extension rate of 12-14 mm per year (which can't be explained by seismicity alone) it is included among the fastest extending areas in continental regions. In addition, lower magnitude earthquakes and seismic swarms sometimes are very frequent.

The combination of strong, shallow earthquakes during the 20th century and high crustal deformation gave rise to the installation and densification of local seismological and geodetic permanent as well as campaign networks. This infrastructure provides observations of continuous slow, possibly aseismic deformations, not linked to recordable seismicity, by use of space geodetic data. Since 2014 the Corinth Rift Laboratory (CRL) is included as a Near Fault Observatory (NFO) within EPOS.

This session primarily targets scientific observations related to the understanding of the geodynamic evolution and the seismotectonic properties of the rift.

We also invite new advancements of research in the fields of geophysics, seismology,
geodesy, geology and their synergy exploiting the NFO operational network at their most, source studies and kinematic modeling, seismic anisotropy, active deformation, and new observations on the properties of the medium and the earthquake nucleation phase. Relative studies from other Near Fault Observatories will also be considered.

Session 27

Networks and open data in seismology the example of HELPOS: HELLENIC PLATE OBSERVING SYSTEM

Conveners:
Panagiotis Papadimitriou[1], George Drakatos[2], Anastasia Kiratzi[3], Efthimios Sokos[4]
[1]Section of Geophysics – Geothermics, Department of Geology and Geoenvironment, National and Kapodistrian University of Athens, Athens, Greece, [2]Geodynamic Institute, National Observatory of Athens, Athens, Greece, [3]Department of Geophysics, School of Geology, Aristotle, University of Thessaloniki, Thessaloniki, Greece, [4]Section of Applied Geology and Geophysics, Department of Geology, University of Patras, Patras, Greece

The understanding of physical processes underlying earthquake generation, volcanic eruptions, surface and tectonic activities, ground motion, wave propagation, seismic response of engineering structures and tsunamis, require the prompt and long-term availability of high-quality data and services.

HELPOS project aims to form a network of geosciences and earthquake engineering observatories, run by the Greek Research Institutions and Universities, following the EPOS example in Europe. The backbone of the project is formed by permanent stations involved in global, regional and local networks, which feed high-quality services, mostly in real time. Permanent observatories are complemented with local stations and networks in regions of interest. The in-situ monitoring and forecast modeling services of HELPOS is essential for earthquake, earthquake engineering, volcano and tsunami earlywarning systems, as well as for disaster relief, risk assessment, management and prevention. Open access to this multidisciplinary research infrastructure stimulates innovative research on earth dynamics and processes leading to catastrophic events and results in new developments in engineering seismology towards more effective disaster prevention.

In light of these advances, this session welcomes recent results on any of the above fields from a broader community, and not only HELPOS participants. We especially welcome contributions that highlight the importance of existing infrastructure, of the value-added from unified networks and open access data for multidisciplinary studies in the field of earth sciences.

Session 28

Fast seismo-geodetic rupture inversion for early warning and rapid impact assessment

Conveners:
Torsten Dahm[1], Stefano Lorito[2], K. Chousianitis[3], Susan Custodio[4], Aandrey Babeyko[1]
[1] GFZ German Research Centre for Geosciences, Germany, [2] INGV Rome, Italy, [3] NOA, Athens, Greece, [4] IDL, FCUL, Portugal

Retrieving earthquake rupture parameters in (near) real time is essential for more reliable early warning accounting for cascade effects, such as tsunami generation and landslide triggering, as well as for rapid impact assessment with an ultimate goal to support civil protection decisions. Multisensor seismo-geodetic data streaming and real-time joint processing allows generation of coseismic displacements necessary to invert for finite source rupture models of different complexity. Rupture inversion methods need to be simple and flexible in their parameterization to allow fast and robust results. The latter, in turn, may be used to generate synthetic ground motion and landslide susceptibility maps to rapidly, within minutes, assess earthquake-affected areas as well as to assimilate source information for reducing tsunami forecasting uncertainty for early warning.

We invite presentations along the entire workflow-chain including but not limited to: real-time GNSS and joint seismo-geodetic data processing; fast and robust source inversion into rupture models of different complexity (from point source centroid moment tensors to finite faults); simulation of ground motion and landslide susceptibility maps based on source parameters; fast implementation of rupture parameters into tsunami forecasting for early warning.

Session 29

GNSS/InSAR inputs for geodynamic modeling, tectonic strain and seismic hazard in the Mediterranean

Conveners:
Athanassios Ganas[1], Nicola D' Agostino[2]
[1]NOA, [2]INGV

The aims of the proposed session are:

1) Present new research on geodynamics, tectonics and seismology that makes use of space geodesy products such as integration of high-rate GNSS & InSAR measurements, GNSS velocity maps, tectonic strain rates and seismic data
2) Present results and current research on deformation, geodynamics and tectonics of the Eurasian – African Plate Boundary
3) Contribute towards the dissemination of geodetic products of the EPOS project (https://epos-ip.org/
4) Establish connections and priorities for the expansion of space geodesy and EPOS in west Balkans (Serbia, Croatia, Montenegro, North Macedonia, Albania, and Bosnia) and SE Europe – East Mediterranean (Cyprus, Israel, Turkey) and
5) to attract contributions on the use of geodesy time series towards the study of fault creep, interseismic coupling and seismic hazard assessments.

Session 30

New challenges for urban engineering seismology

Conveners:
Philippe Gueguen[1], Stefano Parolai[2], Adrien Pothon[3], Roberto Paolucci[4], Dimitris Pitilakis[5]
[1]ISTerre, Grenoble, [2]OGS Trieste, [3]GIE AXA, [4]Politecnico di Milano, [5]Aristotle University

Devastating earthquakes and induced seismicity near infrastructures must become in the coming decades the centrepiece of analysis in reducing risk and increasing resilience, facing up to global urban population growth and the concentration of wealth in cities. The accurate forecasting of seismic ground motion and response of structures are key issues in reduction of seismic urban risk. A comprehensive set of transferable skills must be developed through innovative and interdisciplinary joint research projects between academic and non-academic partners on the prediction of seismic hazard in urban areas considering low probability/high consequences events and induced seismicity related to the exploitation of energy resources; the seismic ground motion prediction within the non-freefield urban area; the coupling between ground motion and structures/infrastructures responses for natural and induced seismicity including time dependency vulnerability; and the systemic risk of interconnected urban systems. The aim of this session is to provide a multi-disciplinary session, in particular for young scientists, in order to share their individual projects (like the ITN MSCA URBASIS EU) related to the urban seismology domain. Advanced capacities in modelling and predicting seismic impact in cities must be captured putting the urban environment as the centrepiece of URBASIS.

Session 31

When science meets industry: Advances in engineering seismology stemming from practice

Conveners:
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In recent years, the challenges faced in major industrial projects have provided a springboard for research and innovation that have brought about numerous advances in the Engineering and Seismological communities. In the US, it has been the case for a long time that cutting-edge research in engineering seismology does not only originate in a purely academic context but also from practice in large-scale projects between academia and industry aimed at solving real casespecific challenges, not least in the domain of seismic hazard assessment. In more recent years, large national and international industrial projects in Europe have also begun to shape the state-ofthe-art in science, technology and practice, developing new approaches and innovative techniques in several topics, including ground motion models, uncertainty quantification, site-specific hazard assessment, site characterisation, site effects and attenuation, but also seismic hazard of lowseismicity regions, induced seismicity, and more.

This session aims to bring together the Engineering and Seismological communities and create a platform for discussion and exchange concerning recent advances in any aspect of engineering seismology where innovation in data, models or methods has been driven by the needs of industry. We welcome contributions from academics and practitioners, national bureaux rendering expert services, organisations from the energy and other sectors, leading companies that practice research-led consulting. We also seek to hear from those developing new products, sensors, or software that are changing the state-of-the-art and to discuss exciting new possibilities for applications.

Session 32

Induced seismicity: observations, modelling, monitoring, discrimination and risk management strategies

Conveners:
Enrico Priolo[1], William L. Ellsworth[2], Antonio Pio Rinaldi[3], Tony Alfredo Stabile[4], Simone Cesca[5], Serge Shapiro[6]

[1]OGS, Italy, [2]Stanford Univ., CA, [3]ETHZ, Switzerland, [4]CNR, Italy, [5]GFZ, Germany, [6]Frie Univ. Berlin, Germany

Industrial activities perturb the balance between stresses acting on faults and their frictional strength can induce minor seismicity or trigger larger earthquakes. Most activities are related to development and production of energy (e.g. unconventional hydrocarbon and enhanced geothermal systems, underground gas storage, mining, water impoundment) while others are being developed in response to the climate change and global warming (e.g. underground CO2 sequestration).

Induced seismicity has become a global phenomenon with clear implications for seismic hazard and risk. Real concern exists about larger earthquakes that might be triggered, especially in densely populated areas or communities with high seismic vulnerability. Public and regulatory concerns about the potential hazard from induced earthquakes continues to evolve in response to a deepening scientific understanding of the underlying mechanisms and improvements to probabilistic seismic hazard models. Guidelines for monitoring are being revised and improved, in order to make more data available in the shortest time possible to feed analysis procedures aimed at understanding the possible connections between seismicity and activity, and take steps to reduce the hazard. In this framework, the integration of industrial, community and research infrastructures in the field of anthropogenic seismicity plays an important role.

This session focuses on theoretical, experimental and observational advances in understanding, detecting, discriminating the seismicity induced by industrial, as well as hazard management strategies for reducing the risk and actions for improving the synergy among research institutions, academy and industry.

We welcome contributions on advances in seismic and deformation monitoring (e.g., network deployment, sensors installation, automatic/real time detection and location methodologies including the application of machine learning, DInSAR analysis and optical fiber DAS); case studies and modelling of induced seismicity, as well as the triggering of existing faults, at different spatial and temporal scales; studies from laboratory and underground labs; discrimination between natural, triggered and induced seismicity; multidisciplinary studies combining different data types and observations; assessment of seismic hazard and seismic risk in areas where such activities are carried out; existing regulations and interface between monitoring, regulation and operations (in particular, cases of success or failure of the traffic light system); and public perception and concern.

Session 33

Advances in single station and array methods for subsurface characterization onshore and offshore

Conveners:
Agostiny Marrios Lontsi[1], Manuel Hobiger[2], Cécile Cornou[3]
[1]Swiss Seismological Service, ETH Zurich, Switzerland, [2]Federal Institute for Geosciences and Natural Resources (BGR), Hanover, Germany, [3]Institut des Sciences de la Terre ISTerre, Université Grenoble Alpes, France

The use of ambient seismic noise has significantly increased over the last decades. Controlled source signals are also widely used and can complement ambient noise measurements. Taking advantage of the large wavelength range of these signals, the subsurface structure can be investigated in a broad depth range from few meters to several hundreds of meters. The analysis of the subsurface structure of the Earth is a necessary step towards mitigating natural hazards such as earthquake, landslide, instable rock slopes, or non-linear site behavior such as liquefaction. However, the approach is not limited to the Earth's solid surface, but can also be applied in marine
or lake environments, on the Lunar surface or, on Mars. We invite contributions that address single-station and/or array data modeling, processing and applications.

Methods may range from:

1. Single-station methods, e.g. microtremor horizontal-to-vertical (H/V) spectral ratio, ellipticity estimation, receiver functions, transfer functions;
2. Array methods using single- or multi-component data processing (passive or active sources), e.g. frequency-wavenumber, spatial autocorrelation, Multichannel Analysis of Surface Waves (MASW), Interferometric-MASW;
3. Any combination of (1) and (2) and innovative techniques.

Methods based on the Diffuse Wavefield approach or using cross-correlation techniques are also welcome, as well as any contribution concentrating on the inversion of any of the aforementioned methods on any depth-scale range.

Session 34

Earthquake Induced Landslides: from triggering to stabilization, methods and techniques of monitoring

Conveners:
Ioannis K. Koukouvelas, Konstantinos Nikolakopoulos, Vassiliki Zygouri
Sector of Physical, Marine Geology and Geodynamics, Department of Geology, University of Patras, Patras, Greece

Landslides are common secondary effects during earthquakes. Their classification is difficult representing the complexity of their underlying triggering mechanism. Recent examples from New Zealand and Wenchuan strong earthquakes indicate that landslides are widespread but also during less strong earthquakes (i.e. recent Cephalonia and Lefkada), equally important and disastrous landslides took place. In now days it is recognized worldwide the increasing role of geology along with the seismic ground motion in the landslide inventory. Remote sensing inventory, UAVs, monitoring systems and statistical analysis are used to determine how the occurrence of landslides correlates with the following factors: distance from the earthquake epicenter, slope steepness and aspect, drainage pattern, seismic intensity, rock type and tectonic setting. Thus, inventory and monitoring of earthquake-induced landslides contribute in understanding social and economic impact of the earthquakes.

We separate earthquake induced landslide inventory in large and small scale. Notably several discussions and approaches exist, regarding the best research methodology for mitigation practice of the ongoing earthquake-induced landslides when their number is enormous. When the affected area is quite big satellite imagery is applicable. However, in cases of landslides affecting man-made structures, UAV data are more effective. In this session we welcome papers focusing on both large and small scale inventory, monitoring and transient evolution of earthquake induced landslides based on different methodologies in complex growing talus slopes and isolated landslides. In our session welcome also papers with a special focus on achieving inventory maps based on remote sensing data in combination with ground control points (GCPs) measured using Global Navigation Satellite System (GNSS) sensors, papers focusing on UAV, SAR and Terrestrial Laser Scanner data and processing.

Session 35

Tsunamis in Europe and worldwide: Observations, theory and numerical analyses for hazard and risk assessment and risk reduction

Conveners:
Fabrizio Romano[1], Finn Løvholt[2], Jacopo Selva[1], José Manuel González Vida[3]
[1]Istituto Nazionale di Geofisica e Vulcanologia, Italy, [2]Norwegian Geotechnical Institute, Norway, [3]University of Malaga, Spain

A surge of great earthquakes worldwide in the last fifteen years has caused a significant number of damaging tsunamis, some of which will be remembered among the worst natural disasters ever occurred. This has been a grave natural warning that tsunami risk should not be underestimated but, at the same time, these events offered a number of clues for a deeper understanding of tsunami generation, propagation and impact mechanisms. In response, the continuously growing interdisciplinary tsunami science community has put an unprecedented effort in: understanding tsunami physics, addressing tsunami hazard and risk, and contributing to tsunami risk reduction primarily through the development of regional and national tsunami warning systems, input to longterm coastal planning and public awareness raising. This session aims to gather tsunami scientists in the broad sense, and we encourage contributions on all the themes ranging from fundamental tsunami science, through case-studies worldwide, towards hazard- risk- and early warning methodologies.

Contributions concerning tsunamis in Europe will be particularly welcome as well as progress reports on NEAMTWS are also especially encouraged.

Session 36

Functionality of seismometer and accelerometer in ground-motion recording

Convener:
Izidor Tasič
Slovenian Environment Agency, Ljubljana, Slovenia

The number of locations, where seismometers and accelerometers are installed, is constantly increasing, and the locations are not always optimal. Continuous measurements allow the use of seismic signals for purposes other than earthquakes, and weak seismic signals are playing an increasingly important role. However, when detecting seismic signals, certain irregularities may occur due to known or unknown non-seismic sources. Therefore, by exchanging experiences (both positive and negative) on the installation of measuring equipment at seismic stations, experts from various fields would gain.

The purpose of this session is to cover all areas related to the functionality of measurements at the seismic stations: from the design of the seismic station, the choice of material, the choice of power supply systems, how to install instruments in atypical locations, how environments affect on the measurements, how to isolate individual measuring parts, orientations in shafts and tunnels, about problems that were subsequently identified on individual parts of seismic equipment, the method of protection against lightning, ...

In your presentations, we invite you to present your good practices in setting up individual seismological measuring systems, as well as tricks and traps that you have experienced in various cases and scenarios.

Session 37

Historical earthquake data in seismology practice

Conveners:
Paola Albini[1], Christa Hammerl[2], Vasiliki Kouskouna[3], Andrea Rovida[1]
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This session promotes and invites contributions as widely ranging as possible on the topics of collection, interpretation, treatment and storing of historical earthquake data and related phenomena, as well as their use and exploitation in many fields of the seismological research and practice. We welcome reviews of past and ongoing experiences, proposals for future research developments and fresh applications of historical seismological data. We especially encourage contributions focused on bringing up the discussion and the exchange of ideas among experts in different disciplines.

In line with 2018 ESC General Assembly's resolution, we prompt all young scientists to participate and be involved in learning the distinctive methods and skills of Historical Seismology, and take care of transmitting this knowledge asset to the future generations of historians and seismologists by means of the appropriate repositories and tools.

The session results from the ongoing co-operation between the ESC Working Group “Archive of historical earthquake data for the European-Mediterranean area" and the IASPEI Working Group “Historical Seismology”.

Session 38

General Seismology - Recent strong earthquakes

Conveners:
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This session is intended to cover any topic in seismology which may not be directly relevant to any of the other sessions. We welcome contributions dealing with seismicity and seismotectonics of regions in or outside the Euro-Mediterranean area, global and planetary seismology, novel ideas or improvements to conventional methodologies, theoretical or applied aspects of seismology, etc as well as abstracts on recent notable earthquakes.

VIRTUAL 37th

General Assembly of the European Seismological Commission

ESC2021

19-24 September

Session 01

Machine learning solutions to seismic problems: Joint Session ESCSSA

ESC2021-S01-040

Modeling repeating events using manifold learning techniques: application to seismic mine blasts identification

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This work focuses on the problem of identifying arrivals of mine blasts that originate from a specific mine from a stream of seismic data. Identification and masking of such arrivals should reduce the number of false associations in automatic bulletins and may help to lighten the analysts' burden.

The mine pattern to identify is complex, as the mine spans several kilometers and the recorded blasts may be of different type, magnitude and location. Furthermore, identification of such single blasts from ongoing recordings that contain many other types of seismic signals, may be a challenging task.

In this work, manifold learning techniques, which faithfully model high-dimensional data into a compact, low-dimensional space, are utilized. In particular, an extension of diffusion maps is applied for creating a compact representation of the mine patterns. This representation is stable with respect to the changing waveforms that hold new seismic data. We demonstrate the model on several different datasets and highlight its computational and explainable properties. In particular, at the station EIL we identify arrivals that were caused by the blasts at the nearby Eshidiya mine in Jordan. The framework may be adapted to other types of seismic machine learning problems.

ESC2021-S01-086

A self-supervised Deep Learning approach for blind denoising of Distributed Acoustic Sensing data

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Fibre-optic Distributed Acoustic Sensing (DAS) is an emerging technology for vibration measurements with numerous applications in seismic signal analysis as well as in monitoring of urban and marine environments, including microseismicity detection, ambient noise tomography, traffic density monitoring, and maritime vessel tracking. Unfortunately, incoherent random noise originating from e.g. thermal or electronic sources may obscure signals of interest, such as microearthquakes. But, as opposed to isolated seismometers or sparsely distributed seismic arrays, DAS offers a spatio-temporal view of the ground motions that can be leveraged to perform blind separation of spatio-temporally coherent signals (like earthquakes) from incoherent noise.

In this work, we adopt a self-supervised Deep Learning algorithm to extract locally-coherent signal components. Owing to the similarity of coherent signals along a DAS system, one can predict the coherent part of the signal at a given channel based on the signals recorded at other channels, referred to as "J-invariance". Following the recent approach proposed by Batson & Royer (2019), we leverage the J-invariant property of earthquake signals recorded by two submarine fibre-optic cables. A U-net auto-encoder is trained to reconstruct the earthquake waveforms recorded at one channel based on the waveforms recorded at neighbouring channels. Repeating this procedure for every measurement location along the cable yields a J-

invariant reconstruction of the dataset that strongly suppresses incoherent noise and maximises the local coherence of the data, without requiring a clean, noise-free ground truth.

ESC2021-S01-092

New Unsupervised Machine Learning Model for Seismic event Discrimination and its application to discriminate Icequakes and Tectonic quakes in Southeastern Alaska

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Seismic observatories around the world often require a classification system that can discriminate tectonic and non-tectonic seismicity, e.g. for seismic hazard assessment, especially in the areas where these events overlap in magnitude, space and time. Although many machine learning models have been proposed for event detection and location, very few models are being reported for providing a reliable automatic classification of events.

Automatic classification systems have the potential to out-performing approaches that rely on individual human judgement, while providing considerably more efficient workflows.

In this study, we present a new unsupervised machine learning model for seismic event discrimination which is based on applying Principal Component Analysis to absolute frequency spectrum of different event series and labelling the clusters using Gaussian Mixture Models. The model can work on data from a single station using just a single component and provide reliable classification in near real time.

We have done synthetic tests where we have shown the separations of synthetic sine curves having different frequency contents at different signal to noise ratios ranging from 0.1 to 5. We also applied our model to show the discrimination of 300 well reviewed icequakes and tectonic quakes in southeastern Alaska with a very high accuracy. Our model thus has a potential to come out as a general automatic event classifier and can also be used to discriminate other non-tectonic events such as quarry blasts, mining events and explosions from tectonic events.

ESC2021-S01-106

Separating and denoising seismic signals with dual-path recurrent neural network architecture

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Separation of overlapping signals is an important task in signal processing, with application in music, speech, and seismic signal processing. We show that separation is possible also for seismic recordings, using techniques from machine learning (and even those recorded with a single sensor). This may have an impact on seismic applications such as ambient noise tomography, induced seismicity, earthquake analysis, aftershock analysis, nuclear verification, and seismoacoustics/infrasound.

The machine learning technique that we use for seismic signal separation is based on a dual-path recurrent neural network which is applied directly to the time domain data.

We train the network on seismic data produced by trains, and recorded with a Raspberry Shake sensor at the University of Vienna. We demonstrate that the network predicts the signals from a synthetic mixture very well.

We then use a transfer learning approach to fine-tune this pre-trained network for earthquake signals and denoise them. We also perform a task outside of its initial training domain - a P- and S- wave arrival picking, demonstrating the wide potential for applications of such a network. Furthermore, we argue that a network built this way can serve as a Bidirectional Encoder Representation (BERT) pre-training step in waveform Machine Learning applications, thus reducing necessary training time for potential applications. This work proves the concept and steers the direction for further research of earthquake-induced source separation. We have therefore aimed to describe the technicalities in detail. We provide a reproducible research repository with algorithms and datasets.

ESC2021-S01-130

Application of recurrent neural networks for detection of reservoir-triggered seismic events

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Recurrent neural network detection has been applied to regions of moderate and low seismicity at regional and local scales. Monitoring such areas requires the detection of sparse and small events recorded below the noise level.

The multi-stage learning process has been applied for event detection. In the subsequent stages, the previously trained detection is validated in the successive recording periods. False detections are added to the training set along with new seismic events and the detection is retrained. The multi-step process significantly reduces false detections.

Good examples of such regions are the Lai Chau and Song Tranh 2 areas of reservoir-triggered seismicity in Vietnam. They are monitored with small networks. Therefore, a relatively small number of examples can be used to train the network. An additional difficulty in detection is the anthropogenic origin of seismicity observed in regions where seismicity is non-stationary and occurs in locations without prior seismic activity.

ESC2021-S01-154

Application of a general regression neural network to ground motion prediction models

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The general regression neural network (GRNN) is used to build the nonparametric ground motion model (GMM), which is simply a function of pairs of previous ground motion (GM) value measurements and corresponding GM parameters describing features of events, recording sites, and wave paths.

The creation of GRNN-GMMs focuses on the selection of various GM parameters and the creation of the best conditional probability distribution of these parameters given GM values. The conditional probability distribution is estimated by kernel estimators, which reduces the problem of creating GMMs to the study of different metric distances between parameters. The criterion for choosing the metric spaces of the parameters is to minimize a cross-validation error.

This approach allows us to study the GMMs containing focal mechanisms and other event parameters such as epicentral coordinates or azimuth between the source and the site. The impact of different metric spaces on the effectiveness of GMMs is presented.

ESC2021-S01-183

Unsupervised Deep Representation Learning for Icequake Detection at Neumayer Station, Antarctica

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With the growing amount of uncurated continuous waveform data and the increasing interest in environmental signals like icequakes for which labelled data is rare, unsupervised machine learning methods are gaining attention in the seismological community. While many approaches work with hand-crafted features to discriminate different types of seismic signals, we want to train an automatic feature extractor using neural networks. Given recent success of contrastive learning for unsupervised feature learning in various domains, we aim to transfer these methods to the domain of seismology. In particular, we use SimCLR and MoCo which work by using data augmentation to contrast similar samples against dissimilar ones. We discuss methods of data augmentation for seismological data and apply contrastive learning methods to automatically learn features. The methods are trained on a dataset containing various waveforms detected by an STA/LTA algorithm on one year of continuous waveform recordings from the geophysical obervatory at Neumayer station, Antarctica. The quality of the features is evaluated on a small hand-labelled dataset containing icequake events, spikes and noise using a classical clustering method, k-means. First experiments show that the different groups are cleary separated and on a simple dataset, the clustering can achieve an accuracy of up to 100%.

ESC2021-S01-201

Seismo-acoustic applications of Machine Learning in The Netherlands

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The increased popularity of Artificial Intelligence (AI) is pervading many geophysical applications supported by a growing abundance of high quality data and building on successful results in several domains.
Recent developments have demonstrated how innovative data-driven approaches can effectively complement and often outperform traditional methods, thereby offering new insights and opening up to novel scientific pathways.

At the KNMI R&D Seismology and Acoustics department we research how Machine Learning, and in particular Deep Learning, can aid us to fulfil our primary tasks which include the monitoring of natural and induced seismicity in The Netherlands and the assessment of risks due to geophysical phenomena.

To this end we have investigated a broad range of methods targeting specific goals. For instance, we applied supervised learning for the classification of seismo-acoustic events; and unsupervised learning in order to automatically assess the quality of our extensive sensor networks.

Current investigations also include the application of Recurrent Neural Networks (RNNs), Graph Convolutional Networks (GCNs) and generative methods such as Generative Adversarial Networks (GANs).

As an ultimate goal we envisage a system that could support us in providing society with timely and accurate information about natural and anthropogenic hazards, thus contributing to the realisation of an Early Warning Centre.

Our strategy is to combine multiple dedicated ML-based pipelines in order to exploit the potential of each method and effectively tackle outstanding challenges.

As the application of such methods in a production environment requires to enable understanding and confidence in processes and results our recent research focus includes Explainable AI (XAI).

In this contribution we will provide an overview of our current applications, the main results achieved, the challenges encountered and future plans.

ESC2021-S01-225

SeisBench: A framework for machine learning in seismology

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Machine learning methods have seen widespread adoption within the seismological community in recent years. Their ability to effectively process large amounts of data, while equalling or surpassing the performance of human analysts or classic algorithms make them an ideal choice for future-proofed algorithms. However, building and evaluating machine learning methods for seismology often requires significant work not directly related to the machine learning models, e.g., dataset collection, data loading, or preprocessing steps. Similarly, practitioners seeking to apply published machine learning solutions often need to bridge the gap between the standard formats in seismology and those in machine learning. Whilst a number of benchmark datasets in machine learning friendly formats have been published, no standard exists, making it difficult to test across a wide range of data or benchmark differing algorithms across new datasets.

We present SeisBench, an open-source framework for machine learning in seismology. SeisBench offers a unified API for downloading and using already published datasets, a set of standard machine learning models for seismology together with pretrained weights, e.g. GPD, PhaseNet or EQTransformer, and a simple API for building training pipelines. SeisBench is written in Python and can easily be extended: datasets can be added by converting them to the SeisBench format, models can be written directly using PyTorch, and custom training augmentations can be defined. The SeisBench source code will be published with an open license and explicitly encourages community involvement.

SeisBench removes a lot of the overhead of using machine learning in seismology, enabling researchers to focus on the key machine learning aspects. Furthermore, due to the availability and interoperability of models and datasets, we expect that SeisBench enables more robust results by evaluating models across datasets and comparing their performance to previous approaches.

ESC2021-S01-230

Forecasting the Preparatory Phase of Induced Earthquakes by Recurrent Neural Network

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Earthquakes prediction is considered the holy grail of seismology. After almost a century of efforts without convincing results, the recent raise of machine learning (ML) methods in conjunction with the deployment of dense seismic networks has boosted new hope in this field. Even if large earthquakes still occur unanticipated, recent laboratory, field, and theoretical studies support the existence of a preparatory phase preceding earthquakes, where small and stable ruptures pro-gressively develop into an unstable and confined zone around the future hypocenter. The problem of recognizing the preparatory phase of earthquakes is of critical importance for mitigating seismic risk for both natural and induced events. Here, we focus on the induced seismicity at The Geysers geothermal field in California. We address the preparatory phase of M~4 earthquakes identification problem by developing a ML approach based on features computed from catalogues, which are used to train a recurrent neural network (RNN). We show that RNN successfully reveal the preparation of M~4 earthquakes. These results confirm the potential of monitoring induced microseismicity and should encourage new research also in predictability of natural earthquakes.

ESC2021-S01-243

Automatic classification of seismo-volcanic events by means of Machine Learning techniques: application to Stromboli volcano signals

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The real time interpretation on the dynamics underlying seismo-volcanic activity, along with tracking its temporal and spatial patterns are some of the primary tools to monitor active volcanoes and forecast eruptions. While the detection of events can be accomplished by automatic systems, the classification (or labeling) of the seismo-volcanic events is generally manually performed by experts. The strong increase of seismo-volcanic activity before an eruption makes a fast manual classification during a major unrest and/or an eruptive episode impossible to achieve. Moreover, manual classification often suffers a lack of unified criteria and eventually results in poorly reliable labeled databases. In order to efficiently detect and classify seismo-volcanic events, there is a need of automatic techniques able to operate in nearly real-time. These difficulties can now be overcomed thanks to the application of modern Machine Learning (ML) techniques. Classification techniques are among the basic methods of supervised ML, currently much improved thanks

to the use of deep neural networks. In this work, we present an automatic procedure for the recognition and near real-time classification of seismo-volcanic signals based on ML techniques. This procedure was applied to the signals recorded by the Stromboli volcano (Sicily) permanent seismic network, which allowed us to automatically detect and classify the seismic signals associated with mild explosive eruptions, volcanic degassing, and rockfalls, by using their different time-spectra features. Given the persistent mild explosive activity characterizing Stromboli volcano, our performed automatic procedure may help to better characterize seismo-volcanic seismicity and related hazards in real time through a continuous data processing of the large datasets produced by Stromboli's permanent seismic network.

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Automatic inspection and analysis of digital waveform images by means of convolutional neural networks

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Analysing seismic data to get information about earthquakes has always been a major task for seismologists and, more in general, for geophysicists. Recently, thanks to the technological development of observation systems, more and more data are available to perform such tasks. However, this data "grow up" makes "human possibility" of data processing more complex in terms of required efforts and time demanding. That's why new technological approaches such as artificial intelligence are becoming very popular and more and more exploited. In this paper we explore the possibility of interpreting seismic waveform segments by means of pre-trained deep learning. More specifically, we apply convolutional networks to seismological waveforms recorded at local or regional distances without any pre-elaboration or filtering. We show that such an approach can be very successful in determining if an earthquake is "included" in the seismic wave image and in estimating the distance between the earthquake epicentre and the recording station.

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Machine Learning to Illuminate the Mechanics of Laboratory Earthquake Prediction and Precursors to Failure

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I summarize works showing that stick-slip failure events –lab earthquakes– are preceded by a cascade of acoustic emission (AE) events that foretell catastrophic failure. These works include traditional machine learning (ML) methods based on regression and deep learning (DL) approaches. The original studies used continuous measurements of AE to predict the timing of labquakes. This was extended to predict the end time of labquakes, their duration and stress drop and the fault zone stress state. Recently, DL has been used to predict and autoregressively forecast labquakes and fault zone shear stress. In addition, ML methods using AE catalogs can predict labquakes. Such catalogs document the evolution of frequency magnitude statistics during the lab seismic cycle, which provides an opportunity to use ML to interrogate the physics of impending failure. Here, one finds that seismic b-value begins to decrease as faults unlock and start to creep. This provides a sensible connection between the ML-based predictions, based on AE, and the physics of failure. In the lab, AE events represent a form of foreshock and, not surprisingly, the rate of foreshock activity correlates with fault slip rate and its acceleration toward failure. Recent works show that lab earthquakes can also be predicted using active source acoustic measurements. In this case, ML predicts labquakes using

changes in fault zone wave speed and the amplitude of transmitted elastic waves. Such measurements of precursory changes in wave speed prior to labquakes are well known, but ML predicts with fidelity the time of impending failure. This suggests the possibility of physics-based models for prediction, by connecting the evolution of fault zone elastic properties to frictional contact mechanics and constitutive laws. A central goal of this work is to learn from lab earthquake prediction to improve forecasts of earthquake precursors and tectonic faulting.

ESC2021-S01-363

Earthquake detection in Iberia based on dense seismic deployments using deep learning and matched filter techniques

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Iberia is a region of slow tectonic deformation (≲1 mm/yr) in Southwest Europe, except for the Betics near the plate boundary between Nubia and Eurasia. Understanding the seismic behavior of slow deforming regions remains a challenge to seismologists due to the low tectonic loading rates, complex systems of non-linear faults and episodic and migrating seismic activity that complicate the imaging of the seismic cycle and hazard assessment. Moderate to high magnitude earthquakes are infrequent in the region (documented mostly in the historical and geological records). To better understand this region, we will focus on lower magnitude earthquakes that can be missed by analysts and not listed in standard earthquake catalogs. From 2007 to 2014 several dense temporary seismic networks were deployed in the region. The untapped data from these deployments can significantly reduce the current magnitude of completeness, resulting in more detected microearthquakes.

We will analyze 7 years (2007-2014) of seismic data using both a convolutional neural network-based phase-identification classifier (CNN; Zhu et al., 2019) followed by phase association (REAL; Zhang et al., 2019) and a matched filter detection technique (Peng and Zhao, 2009). We trained our CNN using data from permanent seismic networks in the region and their respective phase catalogs, for a best model with 95% recall and 66% precision. We tested both techniques in a smaller region of the Lower Tagus Valley, Portugal. Preliminary results show that template matching is more robust than our CNN approach. Matched filter returns 13 times more events than the original catalog while our CNN approach returns 25 times more events. However, an analysis of the CNN approach detections reveals several many of the newly detected signals are false events. Updated results will be presented at the meeting.

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Performance of a predefined sentiment analysis (SA) model on tweets related to emergency response and early recovery. The case of the 2019 Albanian earthquake

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On the 26th November 2019 two major earthquakes struck the northwest region of Albania. Most of the damages took place in the city of Durrës, the village of Thumanë and the town of Laç. The earthquake caused 51 deaths and 3,000 injured. After an earthquake, it is essential to understand its impact on the population

and physical assets. Social media (SM) has become a valuable tool for quickly collecting large amounts of first-hand data after a disaster, essential for an efficient emergency response. 695 tweets with the hashtags: #Albania #AlbanianEarthquake #albanianearthquake from the 26th November 2019 to the 3rd February 2020 were collected. Those tweets were used to test the accuracy of the predefined sentiment analysis (SA) machine learn algorithm developed by MonkeyLearn to identify polarity in text data related to the earthquake. We explore the feasibility to use this predefined model for assessing emergency response and early recovery. Comparing the polarity of tweets allocated considering rules defined by authors, we identified the machine learning algorithm's performance accuracy of 63% and a misclassification rate of 37%. Solidarity messages, in-kind contributions, encouraging messages, international support and actions to collect funds are accurately classified as positive. Seismic information and technical details of humanitarian items are accurately classified as neutral. Reports of tremors, injuries and casualties, xenophobic messages and criticism to the emergency management are accurately classified as negative. However, text data related to damages in buildings, problems with the distribution of humanitarian aid and rescue efforts are misclassified as neutral. Prominent people visiting survivors and expressions of condolence are misclassified as negative. We conclude that to improve the classification accuracy, we need to run the SA analysis at the sentence level. To assess emergency response and early recovery progress using SA, it would be necessary to first make a topic classification.

ESC2021-S01-381

Blending Physics-Based numerical simulations and seismic record and meta-data databases using Generative Adversarial Network

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A strategy to blend the outcome of physics-based numerical simulations with massive and poorly labeled databases has been proposed by Gatti and Clouteau.[1] This strategy is based on the encoding of seismic signals into a reduced manifold, which decoded back into the physics space, conditioned by the numerical simulation. This hybrid scheme is capable of enhancing low-frequency numerical simulations with realistic high-frequency content, directly learned from large seismic databases. However, this approach does not account for the available pieces of information carried out by meta-data such as magnitude. Moreover, it does not allow the disentangling between hidden variables and experimental data and those being specific to each type of entries.

The present approach is an extension of [1], in the sense that it is still based on convolutional auto-encoders trained with adversarial training technique, but hidden variables are disentangled with respect to the type of entries and the available meta-data. The method used here takes into account a single encoder that transforms broadband (respectively filtered) signal into its hidden variable, in the latent space. Once this has been done two separate generators are used to decode. A first generator converts the hidden variables into broadband signals. A second generator does the same job for the filtered signals. Then the same adversarial learning techniques will trick the discriminators to make the false signals indistinguishable from the true ones. Once the reconstruction of the hidden variables allows us to reconstruct all the signals, we add to the hidden variables data such as magnitude and source-to-site distance in the data reconstruction. As a results, this new auto-encoder is capable of generating any type of output, including fake experimental data, from whichever entry available, including fine or coarse physics-based results and even meta-data only, since a meta-data vector.

[1] 10.1016/j.cma.2020.113421

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Fast seismic moment tensor estimation using Bayesian Neural Networks applied to the 2019 Ridgecrest sequence and induced seismicity in southern Germany

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Fast estimation of earthquakes' source mechanism is essential for near real time hazard assessments. The model and data uncertainties associated to the estimated source mechanism are also crucial. We propose a Baysian Machine Learning algorithm trained on normalized synthetic waveforms for estimating the full moment tensor of earthquakes almost instantaneously with associated source parameter uncertainties using variational inference.

The learned labels, which are the information learned associated to the data, are the moment tensor components, described with five unique parameters. For predefined locations in an area of interest we train a set of fully independent Bayesian Convolutional Neuronal Networks (BNN). With variational inference the weights of the network are not scalar but represent a distribution of weights for the activation of neurons, allowing inherently to consider data and model errors.

As a test set, we trained our models for an area south of the Coso geothermal field in California for a fixed set of broadband stations. We validate our approach with a subset of earthquakes from the Ridgecrest 2019-2020 sequence. For this data set we compare the results of the estimates of our Machine Learning based approach with independently determined focal mechanism and moment tensors. Overall, we benchmark our approach with data unseen during the training process of the Machine Learning models and show its capabilities for generating similar source mechanism estimations as independent studies within only a few seconds processing time per earthquake.

We finally apply the developed method to seismic data of a research network monitoring the area around two south-german geothermal power plants as part of the SEIGER project. Our approach demonstrates the potential of Bayesian Machine Learning in operational frameworks for fast earthquake source mechanism estimation, with associated uncertainties.

ESC2021-S01-403

Automated detection and machine learning-based classification of seismic tremors associated with non-volcanic gas emission

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Seismic tremors associated with gas emissions have been extensively studied in volcanic areas to understand the interaction between magmatic fluids and the surrounding rocks. Conversely, in non-volcanic areas, seismic tremors from gas emissions have been rarely observed and quantitatively analyzed. Given the rising

interest in the role of crustal fluids in large earthquakes generation, better understand non-volcanic gas emissions areas becomes essential.

In this work we investigate the Mefite D'Ansanto site: known since the first century BC and located in one of the highest seismic hazard areas in Europe (Southern Apennines, Italy), it is the largest natural emission on Earth of non-volcanic, CO2-rich gases with an estimated total gas flux of about 2000 tons per day.
Employing a dense temporary seismic network (4 Broadband and 7 Short-Period sensors) deployed at the site between 30-10-2019 and 02-11-2019, we implemented and tested an automated detection algorithm based on non-parametric statistics of the recorded amplitudes at each station, collecting a total dataset of 8561 events.

Spectral analysis of the signals was carried out, defining a characteristic frequency band of 6-20 Hz. Both unsupervised (DBSCAN-Density-Based Spatial Clustering of Applications with Noise) and supervised (KNN-k-nearest neighbors classification) machine learning techniques were applied, based on specific parameters (duration, RMS-amplitude and arrival slope) of the detected events. DBSCAN algorithm allowed to determine characteristic bivariate correlations among tremors parameters: an high linear correlation (r≈0.8) between duration and RMS-amplitude and a lower one (r≈0.4) between amplitude and arrival slope (first arrival parametrization). These relationships let us define training samples for the KNN algorithm, which allowed to classify tremor signals at each station and to automatically discriminate between tremors and accidentally detected anthropogenic noise.

Further analyses will be directed to exploit the information provided by seismic tremor to monitor the tectonically complex Mefite D'Ansanto gas emission site.

ESC2021-S01-426

Picking and associating seismic activity in regional and local networks using Deep Learning

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Seismological networks, whether global, regional or local, have the objective of monitoring seismic activity. This implies the detection of seismic events and their location (latitude, longitude, depth and origin time) with an acceptable level of uncertainty. To achieve this, continuous data of multiple stations needs to be processed to detect and pick seismic phases (the P and S waves in each station). In many networks this process is carried out by an analyst who, looking at the traces on a computer, determines the arrival time of a wave at a station. However, for dense seismic networks or temporary deployments, this task may require the work of several analysts and a lot of time. Considering the need to automate processes, we use two pre-trained Deep Learning models (EQTransformer & PhaseNet) to detect and pick the seismic phases. For association of phases and earthquake location a density-based spatial clustering (DBSCAN) is used. We apply these two steps (detection and association) to a regional (Colombian Seismological Network, station separation ~ 100 km), and two local and temporary networks (station separation ~ 10-20 km) in Northern South America.

Based on the above, some statistics were made that seek to compare the performance of the autopicking algorithms with respect to the seismological analyst picks. In addition, the obtained catalog is compared with the network catalog. Preliminary results show that this implementation is reliable enough to generate automatic seismic catalogs, and better yet, it can improve manual catalogs due to its good performance in small earthquakes and aftershocks.

ESC2021-S01-481

Towards Automated Real-time Discrimination of Deep Earthquakes from Earthquake Energy using Deep Learning

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Rapid and robust identification of deep earthquakes is useful in the application of more accurate real-time analysis, location and warning, particularly at teleseismic distances where real-time estimates of depth differ from reviewed calculations by up to tens of kilometers. In Barama and Newman (2018), we developed a method using the first-derivative of the per-station energy time series of earthquakes (occurring from 2008 to 2018) to identify distinct double-peaks of energy associated with the direct-P phase followed by the combined energy of the depth phases (sP and pP). This was a promising result from automatic processing of initial energy pulses without any additional processing of the waveforms, and allows us now to characterize independent parameters for real-time energy and duration calculations of deep events. However, a larger dataset will be fruitful for improving assessment, too, by applying Machine Learning (ML) to this problem, we suspect we will further improve these determinations with a deep earthquake classifier that is able to independently identify features not readily apparent to human observers. Using over 2000 earthquakes (> 70km depth) that occurred between 1989-2019 with moment magnitude greater than 5.5 from the Reviewed International Seismological Centre (ISC) bulletin, we calculated the per-station energy flux (of the P-wave group energy) in the frequency domain. We will show results for a deep earthquake discriminator built from a 10-layer convolutional neural network trained on original time-dependent broad-band (0.5 -70 s) and short-period (0.5 - 2 s) energy growth per station. Because rapid network determinations of location provide reasonably accurate station-event distances, we perform training runs within binned distance-windows, and only train on depth labels as determined by the ISC catalog. We will also compare results using the first-order derivative of energy flux to determine if the human-visible differentiation (mentioned above) makes any significant improvement when using ML.

ESC2021-S01-483

INSTANCE - The Italian seismic dataset for machine learning

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We have assembled a dataset for machine learning (ML) applications using the seismological data acquired in Italy. The dataset includes 1.2 million three-component (3C) waveform traces from about 50,000 earthquakes and more than 130,000 noise 3C waveform traces, for a total of about 43,000 hours of data. An average of 21 3C traces per earthquake are provided.
The earthquakes have been selected from Italian seismic bulletin (http://terremoti.ingv.it/bsi) of the ``Istituto Nazionale di Geofisica e Vulcanologia'' between January 2005 and January 2020. The dataset includes events in the magnitude range between 0.0 and 6.5. The waveforms come from both weak (HH, EH channels) and strong motion recordings (HN channels).

All the waveform traces have been trimmed to a length of 120 s, and sampled at 100 Hz. Waveform data are available both in counts and ground motion units (after deconvolution of the instrument transfer functions) in separate HDF5 files.

The waveform dataset is accompanied by metadata consisting of 114 parameters providing comprehensive information on the earthquake source, the recording stations, the trace features, and other derived quantities.

This rich set of metadata allows the users i) to target the data selection for their own purposes; ii) to select some of them as labels in supervised ML applications and iii) to exploit directly the metadata for studies requiring only parametric information. The dataset can be also used for unsupervised ML applications.

The expectation is that this dataset can prove useful to address several seismological topics spanning from trace noise reduction and earthquake detection to earthquake early warning and rapid ground motion estimations. The dataset, assembled in HDF5 format, is available at http://doi.org/10.13127/instance.

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Deep learning for predicting laboratory earthquakes and autoregressive forecasting fault zone stress

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Laboratory earthquakes are ideal targets for machine learning (ML) and deep learning (DL) because they can be produced in long sequences under a wide range of controlled conditions. Indeed, recent work shows that labquakes can be predicted from fault zone acoustic emissions (AE). A central goal of current work is to generalize these results and to assess possible application to tectonic faulting. Key questions include whether improved ML/DL methods can outperform existing models, including prediction based on limited training, or if such methods can successfully forecast beyond a single seismic cycle for aperiodic failure. Here, we describe significant improvements to existing methods of labquake prediction using simple AE statistics (variance) and DL models such as Long-Short Term Memory (LSTM) and Convolution Neural Network (CNN). We demonstrate that LSTMs and CNNs predict labquakes under a variety of conditions, including pre-seismic creep, aperiodic events and alternating slow and fast events. Shear stress is predicted with fidelity confirming that the acoustic energy is a fingerprint of the fault zone stress. We predict also Times To Failure (TTF) and Time To the end of Failure (TTeF). Interestingly, TTeF is successfully predicted in all seismic cycles, while the TTF prediction varies with the amount of creep before an event. We also report on a novel autoregressive forecasting method to predict the future fault zone stress state. Our forecasting model is distinct from existing predictive models, which only predict the current state. We compare three modern approaches: LSTM, Temporal Convolution Network (TCN) and Transformer Network (TF). Results are encouraging, especially for the use of TCN and TF to forecast at long-term future horizons. Our methods for labquake prediction outperform the state of the art and our forecasting models yield promising results that suggest a framework for advancement.

VIRTUAL 37th

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Session 02

Open and FAIR seismology - Consequences, challenges and opportunities

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The Seismica initiative: a community-led Diamond Open Access journal for seismological research

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On 24 November 2020, the Springer Nature publishing group announced the introduction of Open Access (OA) journals in Nature and its sibling journals. The corresponding OA publication fee (charged directly to the authors) was set to €9,500/$11,390/£8,290, an amount that may be well out of reach for researchers with limited financial means. This is especially a problem for researchers in developing countries, and for early-career researchers on small, personal fellowships. Funding agencies often demand that research be published under an OA license, forcing authors to accept the high publication fees.

The high cost of these and similar OA fees for other Earth science journals prompted a discussion among the seismological community on Twitter, during which the idea was raised to start a free-to-publish, free-to-read journal for seismological research. The concept of Diamond Open Access was previously adopted by Volcanica (www.jvolcanica.org) for volcanological research, providing a precedent and directives for similar initiatives (like Seismica, but also Tektonika for the structural geology community). Following the community discussion on Slack with over 150 participants, a small "task force" was formed to investigate in detail the possibility of starting a Diamond OA seismology journal, taking Volcanica as a model. In this contribution, we report the progress that has been made by the task force and the seismological community in the conceptualisation of the journal, and the steps that remain to be taken. Once the initiation of the journal is completed, Seismica will offer a platform for researchers to publish and access peer-reviewed work with no financial barriers, promoting seismological research in an inclusive manner. We invite all interested members of the seismological and earthquake community to participate in the discussions and development of this OA journal, by contacting the authors listed on this abstract.

ESC2021-S02-174

QQuake: seismological data in QGIS made easy

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Knowledge of seismic phenomena has always benefited from sharing data, and the seismological community has a long tradition of that. The availability of data increased in recent years, but it is becoming difficult to identify reliable sources. With the advent of modern communication technologies and open data, any user should be provided with convenient tools that could make basic tasks such as searching and plotting trustworthy data on a map as easy as a blink of an eye.

Dealing with many types of data needs standardised technologies able to support its use by a heterogeneous community. A great effort is still ongoing in seismology to establish and disseminate data formats such as QuakeML, miniSEED and StationXML. These formats are community-specific standards, and they can be too complex for students or scientists with inadequate skills. On the other hand, adoption of generic standards

such as those promoted by the Open Geospatial Consortium is still limited in seismology due to reasons such as the non-geographical nature of a large part of seismological data (i.e., waveforms) and the existence of specific, well-established, and well-performing formats. Furthermore, there is a lack of a strong interaction among different scientific communities so that any change in the existing workflows is not always welcome. Several initiatives especially at the European level are pushing for the progressive adoption of the Open Science paradigm. Activities carried out within the EPOS ERIC (https://www.epos-eu.org) are challenging scientific communities to interact with each other.

In this framework, we developed QQuake (https://www.emidius.eu/qquake/), a QGIS plugin written in Python that makes access to seismological data easy to anyone with basic GIS knowledge. QQuake is open source, anyone can contribute to it, and its current version supports these standards: fdsnws-event, macroseismic data service, fdsnws-station, OGC WFS and WMS.

ESC2021-S02-177

Staying fair while being FAIR - challenges with FAIR and Open data and services for distributed community services in Seismology

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The European Plate Observing System EPOS is the single coordinated framework for solid Earth science data, products and services on a European level. As one of the science domain structures within EPOS, EPOS Seismology brings together the three large European infrastructures in seismology, ORFEUS for seismic waveform data & related products, EMSC for parametric earthquake information, and EFEHR for seismic hazard and risk information. Across these three pillars, EPOS Seismology provides services to store, discover and access seismological data and products from raw waveforms to elaborated hazard and risk assessment. The initial data and product are contributed by academic institutions, government offices, or (groups of) individuals, and are generated as part of academic research as well as within officially mandated monitoring or assessment activities. Further products are then elaborated based on those initial inputs by small groups or specific institutions, usually mandated for these tasks by 'the community'. This landscape of coordinated data and products services has evolved in a largely bottom-up fashion over the last decades, and led to a framework of generally free and open data, products and services, where formats, standards and specifications continue to be emerging and evolving from within the community under a rather loose global coordination.

The advent of FAIR and Open concepts and the push towards their (formalized) implementation from various directions has stirred up this traditional setting. While the obvious benefits of FAIR and Open have been readily accepted in the community, issues and challenges are surfacing in their practical application, concerning identification, attribution, licensing, reproducibility and overall service governance.

In this presentation we show how the community organization behind EPOS Seismology is tackling these issues, what approaches towards addressing them are being considered, and where the major hurdles on the way towards a truly fair FAIR and Open environment still are.

ESC2021-S02-205

Towards FAIR seismological data and services with ENVRI-FAIR

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The FAIR principles are widely recognised as fundamental pillars for mature data management.
The EPOS Seismology (EPOS-S) community has been actively involved in FAIR related initiatives since the early days. For instance, by investigating and piloting solutions for the assignments of Persistent Identifiers (PIDs) to seismological data and products; by establishing community standard APIs for data access; and by developing and promoting the use of metadata and catalogues to support data discovery.
Such activities favourably positioned the community on the FAIR pathway.

Nevertheless, as the FAIR principles leave room for their specific implementation, a shared application of FAIR is not yet achieved in the community. Several factors play a role in the current situation. Presumably, one of the reasons is that despite advances and growing availability of technological solutions, sustainability and consistent support in a highly distributed community and infrastructures remain major issues.

The ENVRI-FAIR project aims at advancing the findability, accessibility, interoperability and reusability of the data and services offered by the research infrastructures of the ENVRI cluster.
In particular, the EPOS-S community represented in the project by ORFEUS-EIDA has the task to increase awareness and develop a FAIR roadmap.

Starting from a systematic assessment of data and services a number of activities have been identified and planned in order to improve their level of FAIRness.
Those include:
- Investigating solutions and policies for feasible and flexible persistent identification
- Supporting customisable data management practices
- Developing community vocabularies

Moreover, we addressed the challenges of supporting the researchers and data analysts of the EPOS community in generating reproducible science. This is obtained by combining a variety of interactive tools for development and visualisation, which are controlled and orchestrated on the cloud, by a provenance-aware API.

In this contribution we will present details of these activities and discuss future plans.

ESC2021-S02-283

What's keeping the EIDA staff busy?

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These two past years, EIDA nodes have been working hard in order to improve the integration of seismological data management in Europe.
This presentation will focus on the realizations that can help end users to access the data, metadata within Orfeus and EPOS, getting closer to compliance with all the FAIR criteria. Including :
- Integration of our services in EPOS
- European Routing system to advertise the localisation of the data
- FDSNWS-Availability webservice implementation
- DOI advertisement in the metadata
- Central logging system

ESC2021-S02-285

Résif-SI : The french seismological data management, from 0 to FAIR

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The Résif-SI for seismology is the french organisation for managing seismological data. It manages over 70 seismological networks in a distributed way.

We will present the collective work done so far in order to manage the data and metadata of all the french sismological experiments and, not only distribute it under the FAIR principles, but also overlook the global quality of data, metadata and services.

VIRTUAL 37th

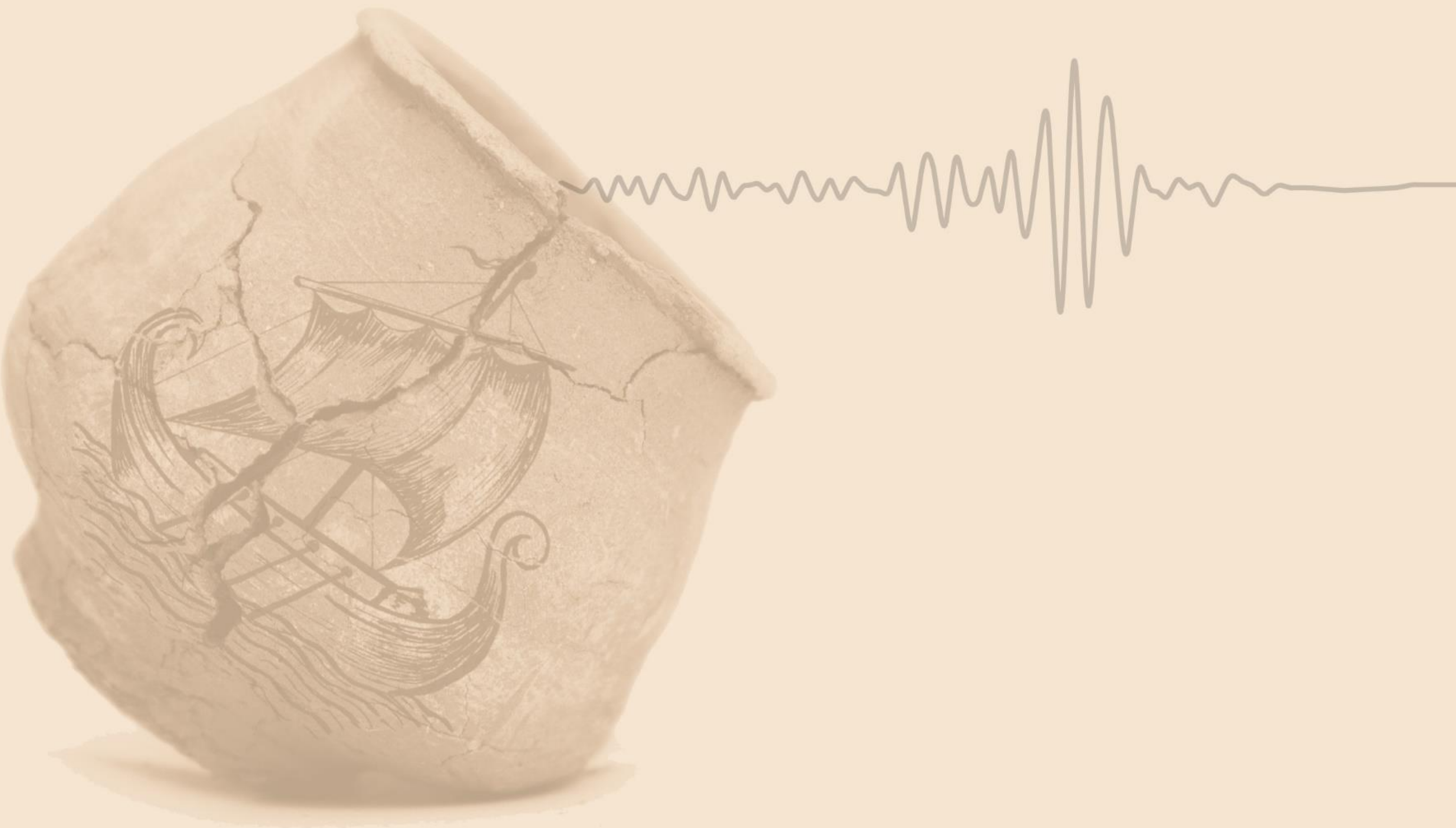
General Assembly of the European Seismological Commission

ESC2021

19-24 September

Session 03

Challenges due to massive generation of seismic data. Large-N experiments, fiber optic cables, and how users, data centres and applications will cope with data in the near future



ESC2021-S03-594

SeiSpark: A computational archive for seismology

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The seismology data archive at Istituto Nazionale di Geofisica e Vulcanologia (INGV), a node of the EIDA federation, currently holds more than 100 TB of seismological waveform data. The infrastructure for archiving and distribution of these data is well-established, functional and robust. However, it is getting increasingly more challenging to make good use of all these data assets, because the currently established workflows require users to download the dataset of interest (usually a rather small portion of the archive), and to process them on local resources. This approach gets at its limits when a more significant portion of the data holdings should be processed, both for the user and for the data centre. The user would need to ensure adequate local resources for storage, I/O and computation, while the datacentre gets challenged by the immense amount of data requests for which the provided services and infrastructure were not designed.

We are adding significant computational resources and an adequate processing and analysis framework to the seismological data archive, creating a "computational archive" where storage resources and computational resources converge. This concept follows the paradigm of data locality, thereby avoiding unnecessary data transfers on every level. The processing framework leverages existing solutions from the BigData ecosystem, notably Apache Spark, and combines them with the popular open source Scientific Python framework which is well established in seismological research. ObsPy, the well-known Python framework for processing seismological data, provides the domain-specific functionality. We present the technical details of the implemented platform, both the hardware setup, and the software architecture. We discuss various design choices, the underlying Resilient Distributed Datasets abstraction and we provide first testing results. Ultimately, we outline how specific algorithms and applications would be implemented.

ESC2021-S03-615

Challenges and new approaches for very Large Data in Seismology: User and data center perspective

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In the last years, new methods of measuring ground motion generate data at much finer temporal and spatial resolution, compared to traditional seismic experiments. Experiments making use of a high number of observation points using low-cost sensors are becoming common. Also, a new technology called distributed acoustic sensing (DAS), which uses a fiber-optic cable as sensor, is being applied in many experiments, and can provide a resolution as fine as 2 m between sampling points in cables of tens of km.

Despite that these technologies are different, they have in common the potential to produce large volumes of data in a very short period of time, due to both the extremely dense spatial and temporal resolutions.

Some of the largest collections of seismological data (e.g. managed by IRIS, RESIF, GEOFON) measure their whole volumes in hundreds of terabytes, while a single large DAS experiment could acquire much more than a hundred terabytes.
The situation is similar to that from the mid-80s, when the amount of data generated was much bigger than the data centers could safely and sustainably archive. At that moment, the temporary solution was to keep only time windows of interest (e.g., waveforms related to an event) and discard the rest of the data after some time. What has been learned from this experience is that discarding data is not the best option to consider, as illustrated by present day research in data mining, new types of seismic signals, and imaging techniques using seismic noise.

We have attempted to identify the needs of members of the community working with these large datasets by means of a survey, with requests and expectations, regarding data formats, data volumes, programming languages, and use of different types of infrastructures.

We present some common solutions and best practices for managing very large data sets. We take into account not only the user needs, but also the perspective of the data centers regarding the archival, creation, and distribution of data sets, while maintaining their standard data services and formats. We also consider many issues related to the creation of the metadata for DAS experiments, which doesn't fit in the current standard StationXML definition.

ESC2021-S03-616

Fibre optic distributed acoustic sensing for seismology and volcanology

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Fundamental advances on understanding geophysical signals prior to and during volcanic eruptions and earthquakes have been achieved in recent years. Yet, uncertainties about subsurface structures distorting observed signals and undetected subtle processes prevent seismologists and volcanologists to infer accurately triggering mechanisms of earthquakes or volcanic phenomena. Disruptive progress in eruption and earthquake forecasting requires reliable descriptions of both magmatic and mechanical processes and volcano and crust structures. This has been possible for volcanic eruptions only with observations as close as possible to their source, where danger clearly exists. Here, we demonstrate that Distributed Acoustic Sensing (DAS) with optical fibres can be used to identify very small volcanic events from a remote safe location and image hidden volcanic structural features. We describe and quantify strain signals associated with explosions and tiny intra-crater transients. We locate explosions using a 2D-template matching between picked and theoretical wave arrival times. Based on coherence arguments, we perform wavefield separation and systematically investigate the ground response to various excitation mechanisms and quantify the thickness of the upper layer of scoriae in which the cable is buried. We validate our findings with conventional sensors and by applying array techniques and waveform modelling. Those results provide the basis for improved volcano monitoring and hazard assessment using Distributed Acoustic Sensing. Although fibre optic methodologies allow clear improvement in understanding structure and dynamics of the Earth at several scales, it generates large amount of data. While this work focuses on scientific results for volcanology and seismology, we also discuss challenges in the implementation for efficient monitoring and data management.

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Session 04

The cycle of observational seismology from Waveform Data Collection to scientific products

ESC2021-S04-029

The footprint of “lockdown” measures to curb COVID-19 spread in Greece on seismic noise

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The recently discovered coronavirus (COVID-19) first broke out in China in December 2019 and since then the virus has rapidly spread around the world causing thousands of deaths. The World Health Organization has declared the COVID-19 outbreak a pandemic. Greece, aiming to prevent the spread of the virus, imposed public health scenarios, including restrictive measures on the movement of people. The implementation of the measures concluded to a nationwide lockdown in March 23th 2020.

Human activity is considered as one of the principal sources of seismic noise energy for frequencies above 1Hz (human-induced seismic noise). The suspension of economic, cultural and numerous everyday-life activities, due to the “lockdown”, resulted in a significant and unprecedented reduction of the background noise levels, as this latter is continuously being monitored by the Hellenic Unified Seismological Network. In this study, we provide evidence of the effect of lockdown measures on seismic noise levels from different cities in Greece. The initiation of the lockdown measures caused a reduction of the noise levels, especially within urban environments. The magnitude of the observed variations largely depends on factors, such as the environment type (urban, suburban) or the proximity of the seismic stations to main roads, schools, public facilities. The observed noise levels are compared with those that are usually observed during public or summer holidays in Greece. The effect of the lockdown on the detection of small magnitude earthquakes by city-based seismometers is also discussed.

Since COVID-19 pandemic triggered restrictions on movement throughout the whole planet, “lockdown-induced” seismic noise reduction was upgraded to a global scale phenomenon. The observations of this study include evidence that permanent seismic stations, especially within urban environments, can be used as an efficient monitoring tool for non-seismic activities, highlighting the potential development of a new branch of seismology, that of Social Seismology.

ESC2021-S04-060

Promoting Observational Seismology in Europe and Beyond: Overview of ORFEUS Services and Activities

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Observational seismology in Europe is deeply rooted in national and regional observatories in charge of managing more than 100 permanent seismic networks and more than 200 temporary deployments. This large community is also at the core of ORFEUS (http://orfeus-eu.org/), a non-profit foundation that promotes observational seismology in the Euro-Mediterranean area through the collection, archival and distribution of seismic waveform data, metadata, and closely related services and products. The data and services are collected or developed at national level by more than 60 contributing Institutions and further enhanced, integrated, standardized, homogenized and promoted through ORFEUS. The goals of ORFEUS are achieved through the development and maintenance of services like: (i) the European Integrated Data Archive (EIDA; https://www.orfeus-eu.org/data/eida/); and (ii) the European Strong-Motion databases (SM; https://www.orfeus-eu.org/data/strong/). New emerging groups within ORFEUS are focused on mobile pools and computational seismology. ORFEUS services currently provide access to the waveforms acquired by ~ 14,500 stations with strong emphasis on open, high-quality data. Contributing to ORFEUS data archives means benefitting from long-term archival, state-of-the-art quality control, improved access, increased usage, and community participation. Access to data and products is via state-of-the-art information and communication technologies, with strong emphasis on federated web services that considerably improve seamless and automated user access to data. Particular attention is paid to adopting clear policies and licenses, and acknowledging the crucial role played by data providers / owners, who are part of the ORFEUS community. There are significant efforts by ORFEUS participating Institutions to enhance the existing services to tackle the challenges posed by the Big Data Era. All ORFEUS services are developed in coordination with EPOS and are largely integrated in the EPOS Data Access Portal, as ORFEUS is one of the founding Parties and fundamental contributors of the EPOS Thematic Core Service for Seismology (https://www.epos-eu.org/tcs/seismology).

ESC2021-S04-138

The ISC Rebuild Project: Creating Consistency in the World’s Most Comprehensive Seismic Bulletin

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The Bulletin of the International Seismological Centre (ISC) is widely regarded as the most comprehensive record of Earth’s seismicity, and has been in production for over 55 years. With the support and cooperation of more than 150 agencies worldwide we are able to integrate and combine data from many sources, from global agencies with permanent networks to local temporary deployments. Our position as a not-for-profit and non-governmental entity allows us to create a unique product that is openly distributed to the global community. The ISC Bulletin is used by thousands of seismologists worldwide for seismic hazard estimation, for tectonic studies and for regional and global imaging of the Earth’s structure.

This presentation focuses on the ISC Rebuild project that was introduced in order to bring the earlier period of the Bulletin (1964-2010) into line with more recent years and homogenise our methods across more than four decades of data guaranteeing consistency of locations and error estimates through the entire period. Improvements we were able to make include:
- Relocating hypocentres with the latest ISC locator using the ak135 velocity model and all phases from IASPEI Standard Phase List where Jeffreys-Bullen travel time tables with only P phases (and later S phases) were used before

- Recomputing magnitudes using an alpha-trimmed median and a minimum of three stations
- Introduction of additional datasets from permanent and temporary deployments
- Performing quality checks to remove poorly constrained events, duplicate readings in more than one event, bogus events etc.
- Introduction of ISC fault plane solutions (Lentas et al., 2019)

The Rebuild project is now completed and the entire reviewed part of the ISC Bulletin (1964–2018) is based on the same procedures. This presentation shows the results and clear improvement of the rebuilt data set as part of the ISC Bulletin.

ESC2021-S04-179

Implications of site characterisation of the UK seismic monitoring stations to ground motion modelling

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Although site characterisation has become standard practice in observational seismology, most of the monitoring stations in the United Kingdom (UK) are uncharacterised in terms of first-order local conditions. This information would result in better modelling the ground motion and therefore improve the estimation of seismic hazard in the UK.

Ground motion prediction equations (GMPEs) generally include terms to account for source, path, and site effects to model the ground motion from an earthquake at a site. In particular, the site component in ground motion modelling is expressed by two elements: the elastic amplification often described by the shear wave velocity of the top 30 m (Vs30) and the near-surface site-specific attenuation modelled by the parameter κ_0. The elastic amplification is included in the site term of many recent GMPEs, whereas the near-surface attenuation is implicitly accounted for in the GMPEs through the data used to derive the equations.

This work aims to investigate the impact of better site characterisation on the ground motion modelling for the UK and whether realistic site terms improve the predictions for the UK data by the GMPEs. Using the Vs30 values estimated for selected seismic strong motion stations in the UK in Tallett-Williams (2017) and the κ_0 values computed from the seismic ambient noise method of Butcher et al. (2019), we adjust the ground motion predictions by selected GMPEs using the host-to-target adjustment. Then, we compare them with the observed ground motions using statistical methods. Our results show that the ground motions predicted by the GMPEs for the appropriate Vs30 and corrected for the host-to-target adjustment improve slightly the agreement with the UK data. However, there is still a significant scatter between the strong motion observations and predictions suggesting that many empirical GMPEs are not calibrated for the source parameters of the UK earthquakes.

ESC2021-S04-188

Nonstationary stochastic simulation of strong ground motions: Application to the Italian database

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The selection of the input motion in the earthquake engineering practice has become progressively more important with the growing use of nonlinear dynamic analyses. Despite the increasing availability of large strong motion databases, ground motion records are not always available for all given earthquake scenarios and site conditions, requiring the adoption of simulated time series. In this work we focused on the methods based on stochastic simulations, considering the time-frequency decomposition of the ground motion. We updated the non-stationary stochastic model initially developed by Sabetta & Pugliese (1996) and later modified by Pousse et al. (2006) and Laurendau et al. (2012). The model is based on the S-transform that implicitly considers both the amplitude and frequency modulation. The amplitude modulation in time is obtained using time envelopes for the P, S, and coda waves. The frequency modulation is achieved with a lognormal function calibrated with the Brune's ω-square model. The four model parameters required for the simulation are obtained from regression analyses on a strong motion dataset of shallow active crustal events in Italy (Lanzano et al. 2019) and are embedded in the simulation code: Arias intensity, significant duration, central frequency, and frequency bandwidth. The proposed model is simple, fast, it takes into account the basic concepts of seismology, and gives a good fit with the target response spectrum even for a small number of simulations. The simulated accelerograms show a good match with the ground motion model prediction of several amplitude and frequency measures, such as Arias intensity, peak acceleration, peak velocity, Fourier spectra, and response spectra. The results presented are specific for Italy, although the approach is general and can be adapted to other databases if predictive equations for Arias intensity and significant duration are available.

ESC2021-S04-207

Road-map for compiling instrumental catalogs homogeneous in magnitude suitable for seismic hazard assessment

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Along with hypocentral information, earthquake magnitude is a key entry point for a wide spectrum of applications, ranging from real-time natural and induced seismicity monitoring, to long-term seismic hazard assessment. Since magnitude is used to measure the earthquake size, or its strength, different magnitude scales are defined depending on which source property is considered or which wavefield feature is analyzed. Whereas the different scales complement each other, providing a more complete view of the source characteristics, the standard practice for seismic hazard assessment requires the compilation of seismic catalog homogeneous in magnitude, assuming the moment magnitude Mw as the reference scale. This practice often requires the application of conversions from other scales to Mw, possibly considering regional dependencies. Motivated by the effort spent over the last decades to compile and update the European-Mediterranean earthquake catalogue (EMEC), in this study we present a road-map to a procedure for updating the instrumental catalogue for hazard assessment in Europe. The procedure assumes Mw from the GEOFON Program as reference magnitude for the updates. To ensure the consistency with previous studies, the compatibility between GEOFON and EMEC moment magnitudes is investigated, as well as the consistency with Mw disseminated by other regional or global agencies. To include events with magnitude smaller than the Mw completeness of GEOFON in Europe, a local magnitude scale harmonized for central-southern Europe is also considered, and its scaling with Mw investigated. Finally, in view of the complementarity of magnitudes derived from either seismic moment or radiated energy, teleseismic energy magnitudes are also introduced with the long term aim of investigating a possible reduction of uncertainties relevant to event-specific ground-shaking predictions. We present here the current status of our effort with the aim of stimulating a discussion with various stakeholders at a wider international context.

ESC2021-S04-245

Empirical shaking-scenarios for Europe

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Over the past two decades, standardization of seismological data format for archiving and dissemination, and technological developments in data acquisition and transmission, have facilitated the development of trans-network studies. In this work, we take advantage of EIDA, the European Integrated Data Archive of ORFEUS (Observatories and Research Facilities for European Seismology) to develop pan-European harmonized seismological models used, in turn, for generating empirical shaking scenarios. Guided by an event catalog generated through the ISC-International Seismological Centre web-services, we used an in-house developed software (https://geofon.gfz-potsdam.de/software/stream2segment/) to populate a local data base with a few millions data segments and relevant metadata, and to process the waveform. The computed Fourier amplitudes are used to set up a large scale spectral decomposition based on a non-parametric approach where source, propagation and site effects are isolated without imposing any functional form to their shapes. The high density of station coverage is used to generate frequency dependent amplification maps and a regionalization in macro-regions is adopted for calibrating the spectral attenuation models. Both non-parametric and parametric source are derived, considering standard omega-square spectral shapes. Results are exemplified in term of frequency-dependent empirical shaking-scenarios for different earthquakes. Future developments will look at coupling the spectral models to broad-band simulations (e.g., 0.3-25 Hz) in order to account for finite fault effects, moving in this way from pure empirical to empirical & physics-based scenarios, in the framework of Urbasis (https://urbasis-eu.osug.fr/) and METIS (https://metis-h2020.eu/) European projects.

ESC2021-S04-253

Seismic evidence of mid-mantle water transport beneath the Yellowstone region

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The mantle transition zone (MTZ) has been proposed as a major reservoir for water in the solid Earth. Transport of water across the 410-km and 660-km discontinuities could lead to water-induced partial melting and generate seismic low-velocity zones (LVZs) above and below the MTZ. We estimated receiver functions (RFs) for the mantle transition zone (MTZ) beneath the Yellowstone region using earthquakes recorded by ~200 stations of the Earthscope Transportable Array. Around the Yellowstone hotspot, a mantle plume is juxtaposed with the descending fragments of the Farallon slab. We estimated RFs targeted at specific depths, using time-delayed data windows, according to a 3-D tomographic model. We stacked the RFs in the frequency domain with multiple-taper correlation technique, using frequency cutoffs between 0.25 and 1 Hz. We formed multiple transects to isolate negative-polarity Ps converted waves, exceeding 2[illegible] jackknife uncertainty, above the 410-km discontinuity and below the 660-km discontinuity, consistent with sharp velocity inversions caused by the presence of partial melt. We interpret these features with water release upon phase transformation of hydrated MTZ rock into hydrophobic upper- and lower-mantle mineral assemblages. We also observe significant topography on both the 410-km and the 660-km discontinuity. The locations of LVZs and discontinuity topography are consistent with mid-mantle flow induced by descent of a Farallon-slab fragment and ascent of the Yellowstone plume as imaged by seismic tomography. Our study

validates the MTZ water-filter hypothesis in this complicated geodynamical environment below the western US.

ESC2021-S04-341

Local Magnitude for Earthquakes in the NE of the Iberian Peninsula

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Local magnitude, Ml, as defined by Richter depends on the seismic wave's attenuation. Thus, assessment of the local magnitude, Ml, for earthquakes occurred in outside California must be adjusted to the attenuation of the studied region. At present, the seismic network of Catalonia, managed by the Institut Cartogràfic i Geològic de Catalunya (ICGC) asses the magnitude Ml of the earthquakes occurred in this region using Richter's original definition. The seismicity database (DB) of the network currently contains more than 10,000 earthquakes recorded in a homogeneous way. Using this DB, a new formula of magnitude Ml has been calibrated for the events occurring in the NE area of the Iberian Peninsula and the Eastern Pyrenees and it is presented here. In its development many tests were performed to evaluate critical factors in the definition of the new formula influencing the earthquake Ml assessment, such as the influence of the recording distance and the possible variations introduced by the different geological units of the region, as well as station static corrections. The result is a new formula is better suited to regional conditions. The different steps of its development are presented and discussed here.

ESC2021-S04-400

Improving the Automatic Processing of the Engineering Strong Motion database

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The rapid increase of seismic waveforms, due to the increment of seismic stations and continuous real-time streaming to data centres, leads to the need for automatic procedures aimed at supporting data processing and data quality control.

In this work, we improve the automatic processing of the Engineering Strong Motion database (ESM, https://esm-db.eu) to facilitate and reduce the time-consuming manual revisions. ESM is developed under the general coordination of the ORFEUS (Observatories and Research facilities for European Seismology; http://orfeus-eu.org/) strong-motion management committee with the aim to enables users to access daily updated strong-motion waveforms related to events with magnitude greater than 4, mainly recorded in the Pan-European regions. ESM is fully compatible with the European Integrated Data Archive (EIDA; http://orfeus-eu.org/data/eida/) and disseminates waveforms and related metadata according to the Federation of Digital Seismograph Networks (FDSN, https://www.fdsn.org/networks/).

Accelerometric waveforms uploaded in the ESM database are routinely processed following a standard procedure and are subsequently inspected by manual revision. Although the expert judgment on both the data quality and the processing settings is an undeniable added value, the ever-increasing rate of growth (currently about 2,000 records per year) requires the development of an automated protocol that reduces the need for manual intervention. To this end, the improvement of the automatic processing leads to four

main targets: (1) refinement of the automatic waveform cutting; (2) definition of a quality index that allows discarding bad quality data and reduces the waveforms to be manually revised; (3) setting of low-cut and high-cut frequencies for the band-pass filter based on the signal-to-noise ratio; and (4) automatic recognition of multiple events in the traces. The accuracy of the updated automatic processing is evaluated by comparison with the manual processing available for thousands of records.

ESC2021-S04-440

ISC Datasets for Seismology

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The mission of the International Seismological Centre (ISC) is to produce the most long-term and complete Bulletin of instrumentally recorded seismicity on a global scale. We describe recent achievements in rebuilding the entire ISC Bulletin using the new ISC locator, ak135 velocity model, more robust magnitudes and inclusion of the first motion based source mechanisms.

In addition, we produce several specially designed data products that stemmed from the ISC Bulletin and allowed ISC to assist several different areas of seismological research. These datasets include recently re-worked ISC-EHB dataset (1964-2017), ISC-GEM catalogue (1904-2018), IASPEI Reference Event List (GT), ISC Event Bibliography (1904-2021) and Seismological Contacts.

We also show the ISC efforts in publishing individual network articles describing the history, current status and earthquake monitoring procedures used by seismic networks around the world.

Finally, we describe the ISC Dataset Repository which allows researchers to submit for safe keeping and long-term availability their catalogues/bulletins of seismic events as well as results of critical review of regional seismicity, earth structure studies, velocity models, notable earthquake observations etc. This long-term secure repository is designed to be recognised by scientific journals as one of the legitimate independently maintained places for depositing author processed datasets to satisfy editorial board requirement of open access to data.

ESC2021-S04-449

CARAVEL: A New Seismic Monitoring System

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Data of the Italian seismic networks and the ones of the neighbouring countries are collected in the EIDA node at the Istituto Nazionale di Geofisica e Vulcanologia for the Italian Seismic Surveillance Service; to improve this task, a new software architecture based on a new database schema capable of representing all information coded in the QuakeML format and a set of OpenAPI specifications has been redesigned and developed in order to standardise the interaction of software that produce and review scientific products.
Real-time earthquake evaluation consists of phase picks, preliminary and automatic hypocenters, local magnitudes and ground-motion parameters. The real-time analysis system presently in use at INGV (AIDA) was the starting point for Caravel a new compound system that relies on four main components: automatic earthquake detection and location systems based on multiple instances of Earthworm; a new seismological

relational database for parametric data called QuakeDB; a full set of new web services application programming interface specifications to share information and provide data at the application level called Dante and; finally, a multiplatform interactive revision tool developed to analyse, use, and review the seismic parameters in real-time called PickFX. Such a system has been engineered to access the EIDA data, interact with the International FDSN (Federation of Digital Seismic Networks) standard web services.
INGV personnel are now testing the Caravel system for bulletin analysis to be ready in the next future to use it for the Italian Seismic Surveillance and the review of the Italian Seismic Bulletin.

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ISMDq, a web portal for real-time quality monitoring of Italian strong-motion data

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We present the INGV Strong Motion Data-quality (ISMDq), a new automatic system that provides parameterized Italian-earthquake ground-motion information, as well as real-time data-quality report within minutes of the occurrence of any Italian earthquake with M ≥ 3.0. The new system also provide a detailed daily-picture about the performance of the available strong motion stations in terms of metrics and data availability, allowing the end-users to check the goodness of the recordings during the last six months.

The ISMDq represents an update of ISMD, the real-time INGV (Italian National Institute for Geophysics and Vulcanology, see Data and Resources) Strong-Motion Data web portal, published on line in January 2012, now including more than 180.000 three-component waveforms, from about 1.800 Italian earthquakes, with magnitude from 3.0 to 6.5.

The ISMDq arose with a different idea with respect to the traditional real time or manually revised-based platforms for disseminating earthquake strong-motion data in Italy and Europe. The main scope of the new system is to provide high quality raw data that are automatically selected through quality indices estimated on the based of the comparisons with the background ambient noise level, performed both in time and in the frequency domains. Therefore, very broadband (0.01 Hz to 40 Hz) high- and low-noise reference levels were derived for the overall Italian strong motion stations, for each single station and for stations grouped in the same soil classes, as described in the available seismic code (EC8, NTC18).

The ISMDq is accessible online (see Data and Resources) from August 2020 and it provides the rapid open access to the available high quality raw strong motion data and metadata recorded by more than 300 Italian accelerometric stations, managed both by INGV and other Italian public authorities and Universities.

ESC2021-S04-555

Exist-fdsn-station, XML-native database providing fdsn-station web service

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The International Federation of Digital Seismograph Networks (FDSN) has specified several standards describing seismic data formats and the access to data and metadata based on web services. These standards are widely adopted in the community and many seismological data centers around the world now use them for data distribution. Various implementations of standard compliant web services exist, with different levels of support for optional features. Seismic stations metadata in StationXML format is provided by the fdsnws-station web service.

We propose the use of the XML database eXist-db to store StationXML documents natively and a new implementation of the fdsnws-station web service based on it. Our solution is scheme-less and provides the flexibility to add any Station XML element without changes to the implementation. One of the most remarkable features of the database is the fact that it is versioned and provides all the functionality to support the “updatedafter” optional query parameter of the standard. By extending the standard web service API using the PUT method we manage StationXML document updates and new stations insertion. Leveraging this feature we are able to easily replicate or clone any other fdsnws-station web service instance. Performance is comparable with existing solutions for smaller queries, but scales better as query output size grows. The package is publicly available on GitHub, licensed under AGPL-3.0 and easily deployable as a docker container.

ESC2021-S04-585

A scalable and flexible station inventory management and monitoring system

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Seismic network inventory management is one of the most challenging tasks in a seismological data center. It involves many stakeholders with diverse backgrounds and requires keeping track of all station and network related information and metadata, e.g. the setup and configuration of scientific instrumentation, servers and transmission system based on heterogeneous technologies, status of the various components, responsibilities, contacts or further information necessary for the management of such a complex system.

In 2010 the data center at Istituto Nazionale di Geofisica e Vulcanologia, which also operates the Italian EIDA node, introduced its seismic network management system Seisface and its companion database Seisnet. Seisface created one single environment to deal with the complexity of network management, however, due to its monolithic design it cannot be easily extended to respond to new requirements, the growth of the inventory and related operations.

The new station management system, presently under development, has a modular design. The purpose of this is to facilitate future evolution by adding or replacing single modules. Functionally distinct components are implemented, whenever possible, by leveraging existing open-source solutions configured or adapted for our purpose. A customized Tuleap implementation is used to realize the ticketing system, for tracking of station and transmission faults and to establish an updating workflow for station information and metadata. Station metadata and channel responses are managed natively in XML, exploring Yasmine as template and metadata editor, and adopting eXist-db to store and serve documents through web services. We employ a micro services architecture and use web API as a glue layer to support the creation of an integrated environment. The GUI leverages Grafana to create a dashboard and to present an overview of the system status of all components.

ESC2021-S04-604

Seismological observations to study crustal structure and mantle anisotropy beneath Kamchatka

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We use seismological data collected from a recently deployed seismological network around the Kamchatka volcanic region to study the crustal structure and mantle anisotropy beneath the region. In order to improve and extend the data coverage, we combined this data set with data from previous temporary deployments and permanent stations to reach a total number of XXX stations covering a region defined in the geographic coordinates 150°-167°E and 50°-61°N.

We use common-conversion-point (CCP) and H-k stacking of receiver functions to investigate crustal structure beneath the network. The hybrid approach of the CCP and H-k stacking methods provide a better constraint on the lateral variation of crustal Vp/Vs ration and Moho depths. We find a relatively complex crustal structure beneath the region with two main interfaces beneath the active volcanic region that lateral merges to a simpler structure to the west.

The splitting analysis of core-refracted shear waves (SKS) indicates a trench-normal mantle flow beneath the eastern edge of the Kamchatka peninsula that converts to a more complex pattern beneath the active volcanic region. The SKS splitting analysis of long-term (longer than one decade) data at permanent stations suggests that the idea of a trench-.parallel flow as suggested by previous studies needs to be re-assessed.

ESC2021-S04-619

Exploiting Marine Seismology Data

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Mobile marine seismology data has proven difficult to access and exploit by the seismological community, because it is still too rarely present in EIDA-compliant data centers and it has atypical noise, timing and orientation characteristics. We present a two-pronged approach to remedy these problems. The first is a suite of rules and data-transformation tools to help provide FAIR-compliant data and metadata to data centers with minimum pain. The second is a suite of tools to improve marine seismology data once it is on the data center. We will present the nascent French Marine Data transformation center (RESIF A-node), which will implement the first approach using open-source software and workflows, as well as recent German efforts in the same direction. We will also present existing and needed software for data improvement and discuss how to make them and their outputs easilyaccessible to the scientific community.

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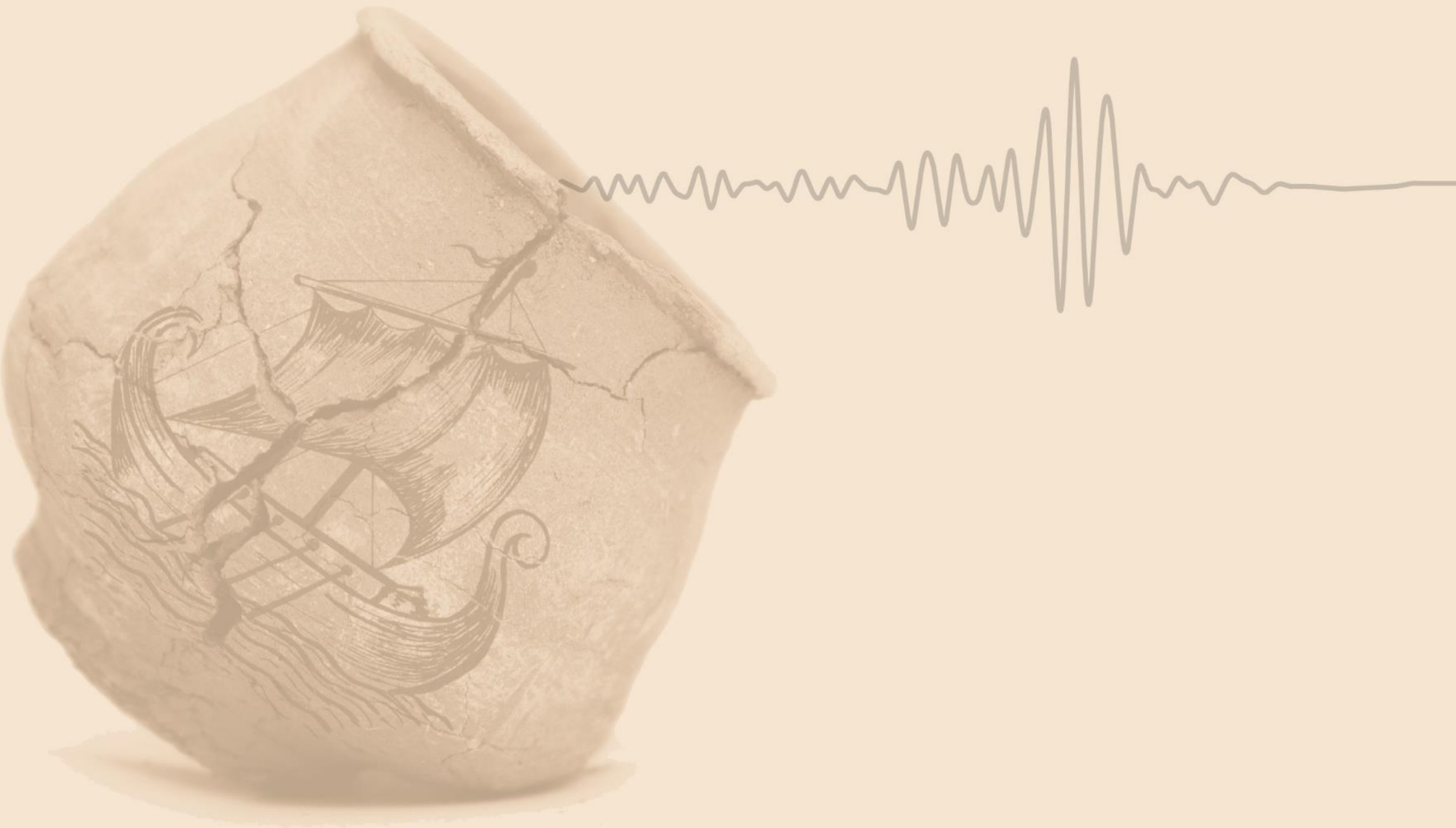
The structure of the central Mediterranean: insights from seismological and geophysical data



ESC2021-S05-045

Seismic tomography in the broader area of Atalanti

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Central Greece is characterized by a complex geotectonic regime and important seismicity which relates to the area's main fault zones. The study area, which focuses on the broader area of Atalanti, distinguished by the alternation of mountain massifs and basins separated by significant shear zones. The geotectonic study which is presented as well as the fault zones help the interpretation of the Seismic tomography's exported results.

A Local Earthquake tomography study was performed, using body-wave (P and S) travel-time data, derived by the analysis of waveform data recorded in local stations of the Hellenic Unified Seismological Network (HUSN) from the Seismological Laboratory of the National and Kapodistrian University of Athens (SL-NKUA). The data cover a time period of six years, between 2012 and 2017.

The LOTOS algorithm (Koulakov, 2009) was used in order to perform an iterative tomographic inversion and obtain a local 3-D velocity model for VP and VS (Koulakov, 2009). More specifically, 2996 seismic events were selected corresponding to 54351 and 34852 rays of P-waves and S-waves, respectively. The size of the fidelity area was defined through several checkerboard tests that were performed before the initiation of the real-data inversion (Humphreys and Clayton, 1988).

The results of the 3D inversion assisted in identifying local tectonic structures from regional to local scale, as well as a possible connection between geothermal fluid circulation and the increase in microseismicity rates in areas such as North Evia and Sperchios River basin where there are numerous geothermal fields thermal springs which have been extensively studied by previous geological and geophysical surveys.

ESC2021-S05-113

Deriving a new crustal model of Northern Adria: the Northern Adria Crust (NAC) model

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The area of transition between Eastern Alps and External Dinarides occupies the northernmost edge of the convergent margin between Eurasia and the Adria microplate. This area undergoes a complex stress field with a resulting heterogeneous deformation pattern and is the seismically most active area of the Alps.

Here, we present NAC (Northern Adria Crust): a 3D model of the geophysical crustal properties in this area (Magrin, Rossi, 2020). NAC has been built by critically choosing and integrating all available information about the depth of the main interfaces and the physical properties of the crust. Uncertainties and reliability of the model are quantified, taking into account the data quality and the interpolation procedure. NAC has two versions, with a different structure of the Moho: the first version considers one continuous surface for the whole area, while the second one implies three separate surfaces for the Adria microplate, Eurasia, and the Pannonian fragment. The differences between the two models are minimal, but the available data better sustain the solution of the fragmented crust. For its characteristics of multiparametric information and resolution, NAC can be precious for any purpose and use where a detailed knowledge of the crustal structure of this area is required. Moreover, it is easy to improve NAC, including new data on structures or crustal properties. In the last year, new information on the crustal structures became available (e.g., Molinari et al., 2020; Qorbani et al., 2020; Stipčević et al., 2020; Sadeghi-Bagherabadi et al., 2020). We compare NAC to some of them, in order to discuss its strengths, limitations, and possible developments.

ESC2021-S05-117

Anisotropic P-wave tomography of the Central Mediterranean region

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The Mediterranean represents one of the most complex convergent margins on Earth and its recent tectonic history was characterized by the coexistence of different compressional and extensional phases associated with episodes of orogenesis, slab rollback, slab tearing and oceanic spreading.

Since the late 1990s, numerous seismological studies have been carried out in the region aiming at imagining the isotropic and anisotropic structures of the upper mantle. Among the various imaging techniques, isotropic P-wave travel-time tomography was largely used. However, seismic anisotropy is widespread throughout the Mediterranean area and neglecting its effects could introduce significant artefacts in the inversions that could bias our understanding of the Earth's interior structure and dynamics. Here we discard the isotropic approximation and invert for both P-wave isotropic velocity anomalies and seismic anisotropic by using the method proposed by VanderBeek & Faccenda (2021).

We find that the magnitude of the isotropic P-wave velocity anomalies are substantially reduced when inverting for seismic anisotropy. This suggests that lateral variations in temperature and/or composition are smaller that what can be inferred from isotropic tomographies.

P-wave fast azimuths orient mostly parallel to the trend of the Balcanic and the Alpine orogens in Eastern and Central Europe, respectively. In the Central Mediterranean the P-wave fast azimuths are sub-parallel to the Oligocene/Miocene-to-present retreating direction of the Ionian trench which led to the opening of the Liguro-Provençal and Thyrrenian basins and rotation of the Corsica-Sardinia block. In synthesis, the pattern of the P-wave fast azimuths is largely consistent with the S-wave fast azimuths determined from the splitting of SKS waves and from Rayleigh waves. This poses further constraints on the interpretation of the regional geodynamic evolution and on the accuracy of the employed inverse method.

ESC2021-S05-118

Micro and macro-scale geodynamic modelling of the recent dynamics of the Central Mediterranean region

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The Central Mediterranean region in the Tertiary was characterized by intermittent phases of subduction and collision, the opening of back-arc extensional basins (i.e., Liguro-Provençal, Alboran, and Tyrrhenian basins) and episodes of slab lateral tearing, segmentation and break-off that led to the currently complex geological setting. Although the shallow tectonic evolution of the region has been relatively well constrained by

abundant geological data, several uncertainties persist about the mechanisms that generated the present-day surface morphology and deep slab geometry.

In this study, we reproduce the recent large-scale evolution of the Central Mediterranean and the associated strain-induced upper mantle fabrics and seismic anisotropy combining geodynamic and seismological numerical modelling techniques. 3D thermo-mechanical subduction models were designed and calibrated according to paleogeographic-tectonic reconstructions of 30 Ma and seismological observations from the Mediterranean region available in the literature. It is found that the opening of back-arc extensional basins in response to the south-eastward retreat of the Ionian slab is a common feature in all models and slab lateral tearing or break-off occurs when Adria continental margin enters the trench. More importantly, we show that structural heterogeneities within the Adria plate and/or the geometry of its Tyrrhenian passive margin have a profound impact on (i) the development of a slab window below the Central Apennines, (ii) the retreat of the Northern Apenninic trench till the Adriatic Sea, and (iii) the retreat of the Ionian slab till the present-day position. More in general, this study highlights the importance of coupling macro-scale geodynamic modelling with micro-scale simulations of strain-induced upper mantle fabrics and seismological synthetics in order to better constrain the tectonic evolution of complex convergent margins such as the Central Mediterranean.

ESC2021-S05-158

Present-day uplift of the European Alps: mechanisms and relative contributions

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The most updated measurements of surface vertical displacements of the European Alps show widespread rock uplift at rates of up to ~2.5 mm/a in the north-western and central Alps and ~1 mm/a across a continuous region from the eastern to the south-western Alps. Such uplift rate pattern is at odds with the horizontal strain rate field, characterized by shortening and crustal thickening in the eastern Alps and very limited deformation in the central and western Alps. Proposed climate- or tectonic-controlled mechanisms of uplift include lithospheric adjustment to the deglaciation, erosion and/or detachment of the western Alpine slab, as well as lithospheric and surface deflection due to the sub-Alpine asthenospheric flow. Here, I critically resume previous quantifications and present new estimates of the contributions from all potential mechanisms. The lithospheric adjustment to deglaciation and erosion accounts for the majority of the observed surface uplift rate budget in the eastern Alps, which suggests that topographic growth by horizontal shortening and crustal thickening is hampered by subsidence due to the eastern Alpine slab pull or lateral escape of crustal material. In the central and western Alps, the lithospheric adjustment to deglaciation and erosion accounts for roughly half of the uplift rate budget, which points to a noticeable contribution by possible mantle-related processes such as detachment of the European slab and/or asthenospheric upwelling. Although to date it is difficult to constrain even the first order pattern and magnitude of mantle-controlled contributions to ongoing Alpine vertical displacements, cooperative tectonics- and climatic-controlled processes, rather than an individual forcing, best explain current measurements of Alpine uplift.

ESC2021-S05-218

Seismic anisotropy and geodynamics in the Central Mediterranean inferred from ambient seismic noise – Results from GEOMED

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Radial and azimuthal seismic anisotropy provide important information on the past and/or ongoing geodynamic processes of a region. We look into the anisotropic patterns across the Central Mediterranean, from the Central Apennines to the African foreland. We use ambient seismic noise data recorded on 83 stations to compile >2,000 Rayleigh- and Love-wave dispersion curves spanning the period range 5-100 seconds. The radial anisotropy is determined from the inversion of phase velocities for 1-D and 3-D shear-velocities with depth, whereas the azimuthal anisotropy is determined from the inversion of the phase velocities to 2-D tomographic maps.

We find that shallow areas experiencing extension (<10 km depth) have positive radial anisotropy (VSH>VSV), intraplate volcanism and subsidence. In contrast, areas experiencing compression have negative radial anisotropy (VSV>VSH), subduction volcanism and rising elevation. In the mantle, the Tyrrhenian Sea and the Sicily Channel are both characterised by negative radial anisotropy - the origin of each respective anisotropy may, however, differ. The latter is related to the rifting processes, while the Calabrian arc slab rollback may influence the former.

Between 10-20 s period, the Rayleigh-wave azimuthal anisotropy is WE oriented west of the Vavilov Basin and oriented NW-SE east of the Vavilov Basin, reflecting the extension pattern of the Tyrrhenian Sea. The Sicily Channel is divided between SSE—NNW west of the Channel to SW-NE east of the Channel. The western part reflects Africa's plate motion, and the eastern part reflects the rifting process.

We discuss the relevance of these findings together with other geophysical studies such as the shear-velocity structure, regional seismicity, earthquake focal mechanisms, and GPS velocity vectors to resolve the different tectonic processes that characterise the study region.

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ESC2021-S05-256

3D segmentation of the Hellenic-Aegean subduction zone

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The Hellenic-Aegean subduction zone in the Eastern Mediterranean is the area of highest seismic activity and hazard in Europe. It has attracted since very early investigations mainly focused on the Aegean surface morphology and geology and the deep slab roll back beneath. Though, detailed subsurface structure at shallower depths (up to 100-150km) has remained unresolved, and little was known on the geometry of the presently subducting Ionian oceanic lithosphere. Dense receiver-function acquisition on a 300-km-long seismic network constrained the 3D geometry of the slab Moho underneath Peloponnesus, central Greece, and the western coast of the Aegean Sea (THALES WAS RIGHT, EU project). This imaging revealed that the subducting oceanic crust is segmented by 9 trench-normal subvertical faults which are seismically active at intermediate depths. Observations imply relations between the intra-slab tearing, slab fluids-related embrittlement, and fluids exit and propagation within the overlying mantle wedge. These faults appear also to impact upper plate seismicity and they mark its kinematics evolution. Offshore the SW Peloponnesus, they segment the backstop updip limit and may control the location and size of large Mw~7.0 historical and instrumental-era megathrust earthquakes. Previous and new results allow to discuss relationship between the active slab dynamics, the deformation of the fast advancing Aegean domain and seismicity of both plates.

ESC2021-S05-272

Correlation of the tectonic structural elements of the Gökova Gulf region with deep seismic velocity structure: Primary results

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The Gulf of Gökova and its vicinity are located at the northeastern end of the Aegean (Hellenic) Arc, where the Aegean, Mediterranean and Anatolian blocks meet. This is one of the most seismo-active regions of Western Anatolia. It is observed that the activity has increased even more in the region especially after the 20th of July 2017 Bodrum Earthquake (Mw 6.6). The main purpose of this work is to determine the crustal 1-Dimensional and 3-Dimensional seismic velocity structure of the region in high resolution by using tomographic methods, to re-locate earthquakes and to calculate the focal mechanism solutions of earthquakes of certain size of the region. In order to obtain 1-D and 3-D seismic velocity structure, P and S wave arrival times of the stations established in the region were required. The phase data between 2010-2029 used in the study were retrieved from the bulletin of the International Seismological Center (ISC), where catalog data was retrieved. There are a number of AFAD (Disaster and Emergency Management Presidency) accelerometer stations in the area that would contribute significantly to the work, but the phase readings of these stations are not included in the bulletin of the ISC. To improve the accuracy of the results, the number of rays passing through the crustal volume should be increased. For this purpose, obtaining the waveform data of the accelerometer stations of AFAD-TDVMS (Turkey Earthquake Data Center System) and reading the phase arrivals has been deemed necessary. In addition, earthquakes over a certain magnitude (M 2.5) was selected in order to make the phase readings properly. In this case, the necessity of providing sufficient number and distribution of data for tomographic studies was taken into consideration. It is predicted that this study will cover an important gap in the literature in terms of its results.

ESC2021-S05-322

Earthquake location in Central Mediterranean area by means of pseudo 3D velocity model: a procedure for velocity models optimization

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The quality of hypocenters locations is controlled by several factors, including network geometry, number of available phases, arrival-time reading accuracy and information about the crustal structure. Hypocentral parameters determined from existing algorithms contain errors, which are largely influenced by velocity models. In regions with strong lateral variations and irregular topographic surfaces, significant errors or systematic shifts in earthquake locations can be introduced by the use of simplified 1-D velocity parametrization. Accurate earthquakes location is of primary importance for studying the seismicity and seismogenetic volume, especially in a very complex geodynamical area like the Central Mediterranean. In this work we present an automatic procedure for velocity model optimization and a first application to the Central Mediterranean area. For this purpose, we iteratively relocated the seismic events that occurred from 2000 to 2020 in Sicily and the surrounding region. Based on a priori geological/geophysical information, the study area was divided into a set of homogeneous 1D lithospheric models. At each location round, the optimization procedure involves a perturbation of the model's parameters. The perturbations are carried out in a systematic and random manner, both globally (on the whole pseudo 3D velocity model) and locally (on a single 1D lithospheric model). The optimization procedure also allows to optimize the station corrections. The objective function was defined as a weighted product of root-mean square travel time residual, estimated horizontal and depth location errors. We relocated 26197 events recorded by about 300 seismic stations. As result, a set of optimized velocity models for the Central Mediterranean area (pseudo 3D model) was obtained. The optimized velocity models were employed in precise and accurate earthquake location to return an unbiased image of the seismicity of Sicily and Central Mediterranean.

ESC2021-S05-379

Lithospheric architecture of the Ligurian Basin from amphibious seismic AlpArray data

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The Ligurian Basin is located at the transition from the western Alpine orogen to the Apennine system and was generated by the southeast trench retreat of the Apennines-Calabrian subduction zone. Extension led to extreme continental thinning. It is highly debated whether oceanic or atypical oceanic crust was formed or if the crust is continental. Active and passive seismic data have been recorded on ocean bottom seismometers (OBS) in the framework of SPP2017 4D-MB, the German component of AlpArray. Two refraction seismic profiles were shot in the Ligurian Basin. Furthermore, we present seismicity recorded during the deployment from June 2017 to February 2018.

The Vp velocity model from refraction seismic data shows a crust-mantle boundary in the central basin at ~12 km depth that deepens to ~24 km within a narrow necking zone of ~30 km towards Corsica. However, extremely thinned continental crust indicates a long-lasting rifting process that possibly does not initiate oceanic spreading before the opening stopped.

We calculated cross-correlation functions for the OBS and surrounding land stations. The group velocity maps show heterogeneities for short periods (5-15 s). Shear-wave velocity results show a Moho deepening from 12 km at the southwestern basin centre to 20–25 km at the Ligurian coast and to over 30 km at the Provençal coast. We find no hint on mantle serpentinisation. We see a separation of the southwestern and northeastern Ligurian Basin that coincides with the promoted prolongation of the Alpine front.

Two seismic clusters occurred between 10-16 km depth, within the lower crust and uppermost mantle. Thrust faulting focal mechanisms indicate compression and inversion of the basin. The seismicity suggests reactivation of pre-existing rift-related structures. High mantle S-wave velocity and a low Vp/Vs ratio support the hypothesis of strengthening of crust and uppermost mantle during rifting-related extension and thinning of continental crust.

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The AlpArray Research Seismic Catalog

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We take advantage of the new large seismic data set provided by the AlpArray Seismic Network (AASN) as part of the AlpArray research initiative (www.alparray.ethz.ch), to provide consistent and precise hypocenter locations and uniform magnitude calculations across the greater Alpine region (GAR).The AASN is composed of 1117 stations with more than 650 broadband seismic stations, 311 of which are temporary. The uniform station coverage provides a unique opportunity to study the laterally and heterogeneous seismicity distribution that is currently monitored and reported by a dozen of national individual observatories.
A precise, consistent and complete earthquake catalog in terms of location and magnitude estimation is a prerequisite to better understand and investigate the Alpine seismotectonic and the relative seismic hazard of such complex yet interesting region.

We created a dedicated machine for the SeisComP3 (SC3) seismic-monitoring software and run it in the so-called playback mode to repick the entire continuous data collected in the 4 years (~20Tb). SC3 was also responsible for the events detection and initial locations thus providing an initial automatic seismic catalog.
Such catalog is then reprocessed with a new multi-step, semi-automatic method for the creation of highly consistent seismic catalog applying two different software. We first used the new ADAptive Picking Toolbox (ADAPT) python library to develop a new multi-picking algorithm for highly consistent and precise phase identification and recognition. Then, we used of the powerful joint-hypocenter determination (JHD) implemented in the VELEST algorithm to obtain the most reliable earthquakes locations thus providing a quantitative error estimation.

Our final catalog contains more than 3000 earthquakes covering four years seismicity inside GAR with a targeted magnitude of completeness of 3.0 MLv assessed by a comparison with seismic bulletins provided by national and regional agencies.

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An updated 3D upper crustal velocity model for Cyprus by non-linear inversion of travel times and its correlation with surface geology

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A new three-dimensional velocity model has been obtained for the crust of the island of Cyprus using a seismic tomography approach. This P and S wave 3-D velocity structure was estimated by inverting travel-times of local earthquakes mainly recorded by the Cyprus Seismological Network, using data collected from

the ISC catalogue during the period 1964–2019. To assess the reliability of the results, we applied several resolution tests using a checkerboard pattern reconstruction tests on synthetic data. These tests suggest that for large crustal depths (>12km) the resolution is rather poor, due to the insufficient data coverage (relatively small epicentral distances) and the quality of data. The results provide new information on the structure of the dominant ophiolitic Troodos complex. More specifically, a high velocity-zone is identified for the whole upper crust, in excellent correlation with the NW-SE trending ophiolitic zone of Troodos. The results also show that the root of the ophiolite zone of Troodos complex is well observed up to the depth of at least 7 Km. These observations are confirmed by the analysis of the recovered station corrections, showing that negative residuals (early arrivals, due to the high surface velocities) are also strongly associated with the ophiolitic Troodos complex. Moreover, the results also identify a strong velocity contrast between the tectonic unit of the Troodos complex and the low-velocity areas located in the SW and NE parts of the Cyprus region. The distribution of these upper crustal low-velocity anomalies shows a good correlation with the Pachna and Lefkara formation in SW Cyprus, while a very low-velocity anomaly extends in the Mesaoria Basin between two topographic highs of Cyprus, the Kyrenia Range in the north and the Troodos Massif.

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Contemporary kinematics and distributed block deformation in the South Aegean (Greece), inferred from Differential GNSS measurements and geophysical/geotectonic data

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We examine the kinematics of crustal deformation in the broader southern Aegean region using 47 GNNS stations distributed across the eastern Peloponnesus, Attica, Cyclades, Dodecanese, Crete and the coast of western Anatolia. The analysis is based on velocity vectors relative to local reference points at the western and eastern halves of the study area, the strain field computed from absolute velocity vectors, geomagnetic and isostatic anomaly data, a recent base of active fault data and the constraints set by the focal mechanisms of recent earthquakes. The results demonstrate that the South Aegean region undergoes complex distributed block deformation, the most significant of those being the Southern Cyclades, Cretan Sea and Dodecanese blocks. A major defining feature of the study area appears to be a right-lateral tectonic line running north of the Ikaria, Naxos, Paros and Milos islands, possibly associated with past magmatism. This comprises the northern boundary of the Southern Cyclades Block, in turn comprising a NE-SW oriented series of structures that include the Amorgos – Santorini Basin. The southern boundary appears to be a significant normal-sinistral series of tectonic lineaments between south Kalymnos, Astypalaea and Anafi islands. By this configuration, the Southern Cyclades Block undergoes NE-SW translation with simultaneous counter-clockwise rotation. The same goes for the Cretan Sea block. The third major block (Dodecanese) appears to undergo very high rate south-westward extension, which commences at the Kalymnos – Astypalaia – Anafi line; its eastern boundary is thought to be a tectonic feature or features extending between the Kasos/Karpathos and Anafi islands, whose nature is yet to be identified.

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A Moho depth model for the Central and Eastern Mediterranean derived from 3d flexural model and controlled by gravity data

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The central Mediterranean region is a geodynamically complex domain in which three plates converge and form two neighboring subduction zones that exhibit opposite directions of motion. Accordingly, the lithosphere of the region is far from isostatic equilibrium. This is apparent in the Gravity Anomaly maps of the area, where even the free air anomaly is dominated by a broad and significant low. This departure from the gravity figure of an isostatically balanced area can by no means be explained by topography alone.

Herein we present a new model of the depth to the Moho in the Central-Eastern Mediterranean, based on gravity data. Instead of using the conventional isostatic techniques, we implement 3-D flexural modeling based on Finite Elements. At the expense of computational time, this allowed us to construct a versatile model of the entire African oceanic plate, its lateral discontinuities (e.g. crustal scale faults) and its thickness and flexural rigidity variations (such as those along the Ionian-Adriatic basins and the Ionian Basin-Pelagic platform and the Mediterranean-African plates borders). It also facilitated the formulation of a realistic scenario of the plate loading and allowed the incorporation of inner crustal loads that are not directly related to the loads implied by topography and bathymetry alone, (e.g. thrust faults s in the area of the Mediterranean Ridge). Finally, it facilitated the investigation for the existence of possible large scale discontinuities that may have been very important to past plate deformation, but are not recognizably active today. We also examine the relation of our model with the present seismicity distribution and active faulting.
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Bringing seismological issues to the public: a way to foster seismic risk best practice

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Use of ambient vibration measurements in Earthquake Protection of Historical Buildings - Case study: Castle Trakošćan, Croatia

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Castle Trakošćan, built on the rocky peak of the hill in the late 13th century, is the protected cultural heritage as a historical entity by the Republic of Croatia. Trakošćan is constructed as a highly irregular brick masonry structure with timber or shallow masonry arch, vault or dome floors. It was substantially renewed and upgraded in the late 16th and 19th century. On 16 March 1982, the Tower Castle and a part of the second floor were severely damaged by the M4.5 (VII °EMS) earthquake with the hypocentre below Mt. Ivančica (approx. 20 km from the Castle). The observed damage was found to be the most significant from an earthquake in the past 50 years, and until year 2020. The Castle was subjected to repair and partial retrofitting until year 2000. The Zagreb M5.5 (VIII °EMS) and Petrinja M6.2 (VIII-IX °EMS) earthquakes, which occurred in March and December 2020, respectively, had strongly shaken the Castle's structure. The earthquake damage was observed and assessed by a visual inspection accompanied by ambient vibration measurements. As observed, the Castle Trakošćan suffered slight cracking throughout the original and added structure, including the retrofitted parts due to their poor performance. However, the slight cracks that appeared on masonry arches were found to be critically positioned, which can likely lead to their collapse if their spreading is not prevented. The ambient vibration measurements performed, which were compared to pre-earthquake measurements (from year 2016), revealed the decrease in the fundamental period of the castle central tower unit and the second floor, thus indicating the loss of structural stiffness as a consequence of the earthquake damage. The Castle earthquake performance and protection for the purpose of retrofitting and withstanding the future earthquakes, requires careful investigation by use theoretical analysis and empirical data.

ESC2021-S06-211

Teaching Social-Emotional learning through an earthquake lesson

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The project "Supporting Social and Emotional Learning", funded by the Citizen Diplomacy Action Fund (U.S. State Department) and implemented in partnership with Partners of the Americas, seeks to strengthen resiliency among youth-facing trauma and train educators in trauma-responsive practices. Fulbright Alumni from US and Greece collaborate in developing and implementing this training in U.S and Greek schools and in NGOs and refugee camps.

The coping strategies in managing traumatic responses to earthquakes can be applied to interpersonal traumas many children and adults are often reluctant to deal with. Learning to cope with one kind of trauma helps to cope with other ("contagion effect"). Serving as a perfect model for domestic violence and/or

refugee trauma, the earthquake lesson incorporates earthquake basics, simulation of a real earthquake at a shake table developed for this project and recommended self-protection measures. Woven throughout the content are best practices in supporting social and emotional health. Stress accumulation in the fault corresponds to stress accumulation from other severe traumatic situations, with similar coping and survival strategies. The project deliverable is a unified training, addressing both interpersonal traumatic events and natural disasters, especially those made worse by human negligence and incompetence.

ESC2021-S06-288

When color theory meets seismology: Principled visualization design for seismic hazard maps

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Probabilistic seismic hazard estimates are a key ingredient of earthquake risk mitigation strategies and are usually communicated through seismic hazard maps. Though evidence exists that visual design properties are critical for effective communication using such maps, few authors describe their approach in visualizing seismic hazard. Current maps use colors, legends and data classification schemes which are suboptimal, from the visualization perspective. As such, they have the danger of miscommunicating seismic hazard. We present a set of principles regarding color choice, legend design, and classification of the continuous hazard estimate for categorical mapping.

These principles are based on (1) communication goals regarding the seismic hazard phenomenon, (2) empirically-validated recommendations from the visualization literature and (3) other best practices in map design. We discuss the process of redesigning the German seismic hazard map using these principles. A set of prototype maps adhering to these principles are presented. We also describe efforts to test the redesigned maps, as well as how to use them to further communicate the uncertainty around probabilistic hazard estimates.

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Evidence-based recommendations to effectively combat misinformation

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"When will the earthquake happen?" or "My dog can predict earthquakes." are commonly heard phrases about earthquakes. Due to the rise of social media, misinformation about earthquakes can be spread quickly nowadays and can lead to inappropriate behavior during and after severe seismic events, potentially increasing harm. The origin of this misinformation is manifold, ranging from confirmation biases to lack of knowledge to lacking trust in the source of information. In addition, the understanding of non-experts of what seismology can and cannot do is understandably limited.

To tackle this issue, we as an international group of social scientists, seismologists and statisticians started a project one year ago. We sought to address the questions i) what seismology can and cannot do and ii) how much truth is there to common earthquake myths. To this end, we first chose seven earthquake myths that are most common among the non-experts. Second, we elicited expert input from a group of seismologists and geologists to better understand the current research on each myth. Third, we formulated statements per myth in a way non-experts would phrase them (e.g., "Earthquakes can be predicted"). To assess the scientific consensus on the accuracy of each statement, we conducted a survey with at the end 167 earth scientists. In the survey, the seismologists were asked to rate each statement on an ordinal scale between 1 (completely false) and 7 (completely true). We discussed survey results with a smaller group of seismologists to gain further insights about their thoughts and contextualize their feedback. We will use these insights to compile a communications guide which should help seismologists, emergency managers and science communication practitioners to combat earthquake misinformation.

We will present the communications guide and key insights from the results of the expert elicitation.

ESC2021-S06-294

One hundred years after: The results of an educational project

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We present the results of an earthquake education project whose forthcoming launch we announced at the ESC 2016 in Trieste. Over the next five years the centenaries of five major historical earthquakes of the Northern Apennines were about to fall: 1916 Rimini (Mw 6.1), 1917 Valtiberina (Mw 5.9), 1918 Romagna Apennines (Mw 5.9), 1919 Mugello (Mw 6.3) and 1920 Garfagnana (Mw 6.5).

We wished to use these anniversaries as a starting point for leading Northern Apennines people to reacquaint themselves with their past in a positive way, improving their awareness of earthquakes as a natural feature of their environment but above all their appreciation of the stamina with which their ancestors coped with and overcame them.

To this end we cooperated with schools, encouraging students to look for traces of the earthquakes of a century ago in the man-made environment and the memories and traditions of the communities, and to find creative ways to involve the grownups in this process.

The project is now ending and we wish to share the lessons learned. An important one is probably the need for adaptability. The involved communities did not share the same level of risk awareness: in the tourist-oriented Adriatic coast earthquakes are something best forgotten, both by citizens and administrations. On the contrary, as one moves inland towards the Apennines ranges, where social cohesion matters more than economic wealth, earthquakes are a constant presence and the people are more easily involved in an active process of risk reduction and daily attention. This prompted us to progressively and constantly adapt our approaches and procedures within the project. Having learned this lesson ourselves, even the Covid-induced restrictions proved a stimulus to adapt our teaching activities to the new constraints, allowing us a closer and immediate contact with students and teachers.

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The effects of the earthquake of February 28, 1969 as a theme for promoting work in the subject of Citizenship and Development in Basic Education

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In the teaching-learning process, the experiences of students, families, and society in general can, and should, be used to enhance a more participatory and self-constructive learning. It was in this context that in a class of the 8th year of schooling in the Central Region of mainland Portugal, within the scope of the subject of Citizenship and Development, it was proposed to the students to work on the theme of seismic risk, and in particular the case of the earthquake of February 28, 1969, which had a magnitude of 7.9 Ms, was felt across the continental country, having caused numerous damages, countless injuries and 13 fatalities. Within the scope of the aforementioned work proposed, a questionnaire and interview to the population was applied by the students, which was based on a survey prepared by the Portuguese Institute of the Sea and Atmosphere (IPMA). This work allowed the students to hear with a loud voice what they families and the population of the city where they live, and study felt and how this telluric event affected the people who experienced it. On the other hand, the preservation of documentary records, for future memory, had a great impact on the training of students, making them more interested in this type of geological phenomena and more resilient.

ESC2021-S06-479

Assessment of source parameters from individual intensity data points

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The georeferenced intensities of the Individual Data Points intensities (IDPs), provided by non-expert users through the EMSC LastQuake application, are a tool that allows to quickly obtain quantitative assessment of the effects (i.e. felt reports) of an earthquake. Although IDPs allow a quick evaluation of the damage scenario, some IDPs can be incorrect or unreliable for various reasons and only slightly changeable using filters (e.g. based on distance). Programs to derive source parameters from the intensity distribution are strongly sensitive to the presence of outliers, especially for high intensities.

To avoid the influence of outliers, IDPs can be combined by areas (e.g. cells, cities) using spatial clustering techniques and a “statistical” intensity (e.g. mean or median of the IDP distribution) can then be assessed. Such macroseismic data point (MDP) intensity for each cluster is more similar to the definition of intensity of the macroseismic scales, i.e. a value assessed to medium-sized cities.

We apply various spatial clustering techniques to the available EMSC IDPs for some thousand earthquakes occurring around the world in the last 10 years to achieve MDP intensities similar to the intensities assigned in historical catalogs (such as the Italian CPTI). The available MDP intensities are then processed with the BOXER code obtaining the source parameters (in particular location and magnitude) to be compared with the instrumental data.

Our procedure of spatial clustering and subsequent processing with the BOXER code can also be applied to IDPs collected in near real time.

ESC2021-S06-522

Assessment of Non-Geoscientist's understanding of real-time earthquake information products

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Scientists recognize public engagement is needed to communicate societal impacts of government-funded science, and educators identify outreach as a key mechanism for learning about science. However, outreach effectiveness could be limited if approaches are not evidenced-based. Partnerships with cognitive scientists who study fundamental learning processes can help. For example, cognitive science suggests that helping people to learn how and why earthquakes happen would significantly improve understanding of earthquake hazards and reasons for preparedness. We recently developed a cognitive science partnership to investigate the IRIS Ground Motion Visualizations (GMVs) widely used for outreach after large earthquakes. However, non-geoscientists do not have improved understanding of fundamental seismology concepts after viewing GMVs. In our current study, we utilized a similar strategy to evaluate understanding by non-geoscientists of key USGS realtime products ShakeMap and PAGER that are widely viewed after large earthquakes. Based on discussions with USGS staff, we focused on three key aspects of these products: 1) What do people learn from PAGER? 2) How well can people read contoured information on ShakeMaps? and 3) Do people understand macroseismic intensity? Poor performance on Zoom interviews about PAGER and ShakeMap that probed modeled fatalities and location of damage led us to develop alternative visualization of the fatality and damage probabilities and maps of shaking intensity. We used a Qualtrics survey to assess participant understanding using the original and new visualizations, revealing some modest improvement with the new visualizations. With a separate Qualtrics survey we assessed how well participants associate macroseismic intensity terms (moderate, strong, and severe shaking) with their corresponding observational cues (e.g., felt by a few people, furniture moved slightly), but again success was lower than expected. Together, these findings suggest additional work is needed to continue developing strategies for educating non-geoscientists about basic earthquake principles and terminology when disseminating scientific information.

ESC2021-S06-618

Serious games: an alternative and appealing mean to foster best practices

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Despite the recent scientific and technological advances in disaster research studies the devastating impact of some disasters shows that both concept and practice on disaster preparation are not adequately conveyed to the society.

In the last decades, in the effort to at least partly overcome the limitations to effective risk communication and relief provision, bottom-up strategies of risk education have raised importance The bottom-up approach is based on a paradigm shift towards a more participatory and community-based strategies. The main advantage is that end-users are treated not merely as a target audience but as partners in co-learning through processes and products that reflect their own contributions The participatory style of education has taken to use games/simulations as an alternative, or complementary, teaching tool to enhance collaborative and adaptive skills and response to social-ecological challenges. In particular, serious games are designed to foster knowledge, learn about certain subjects and expand concepts. Their success is based on the fact that playing a game involves inductive reasoning, memory, concentration, often also teamwork and cooperation, which are all requisites of learning. Serious games and simulations have the potential to enhance the process of remembering information and, as a consequence, to foster best practices.

We describe how we designed serious games within two recent projects and discuss their impact in terms of acquired preparedness.

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Seismicity and Seismotectonics in Central and Eastern Europe

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Seismic and tectonic activity in the Alps from CMT inversion of weak to moderate earthquakes

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The European Alps are mostly characterized by weak to moderate seismicity. A heterogeneous crustal structure and high topography challenge centroid moment tensor (CMT) inversions in this region. Thanks to the dense AlpArray network (>600 stations) and the adoption of the bootstrap-based inversion tool Grond, we reduced the magnitude threshold for CMT inversion to Mw 3.1. Systematic inversion tests were conducted to define guidelines for frequency ranges and input data types, and to study the effects of azimuthal gaps. Furthermore, we assessed the reliability of potential non double couple components. We present ~75 CMT solutions for 2016-2019 and compare our results to strain rates and both historic and recent seismicity.

We identify seismically active regions of the Alps and adjacent areas like the Western Alps, the region around Lake Garda, the SE Alps, the northern Dinarides and the Apennines. Seismicity is particularly low in the E Alps north of the Periadriatic line and in parts of the central Alps. While typical E-W to ENE-WSW striking thrust faulting is observed in the SE Alps, strike-slip faulting with a similarly oriented pressure axis is observed along the central Alps and in the Dinarides. NW-SE striking normal faulting is typical in the NW Alps. Our centroid depths confirm that Alpine seismicity is predominantly shallow, with 80 % of the events shallower than 10 km. In a joint analysis with GNSS data we study the distribution of P and T axis and perform stress inversions. While typical N-S shortening and thrust faulting is observed in the SE Alps, the Western Alps show little horizontal strain rates. Normal faulting events indicate extensional regimes. Our results confirm that observed high uplift rates in the W Alps are unlikely to be directly related to the convergence of Europe and Africa.

ESC2021-S07-075

Seismological and geodetic analysis of the June 12th,2017 Lesvos Island seismic sequence and the February 2021 seismic swarm

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A strong and destructive earthquake occurred in the offshore area, south–westerly of Lesvos Island (North Aegean region; Mw6.3, 12th June 2017), resulting in one human loss, injuries and extended building damage. A vigorous aftershock sequence including remarkable aftershocks (Mw5.2, Mw4.7, Mw4.9), affected even more Lesvos Island. Focal mechanisms, the aftershock sequence relocation and the regional tectonic setting indicate a NW-SE, SW-dipping fault. The relocated seismicity initially constrains the activated fault of the mainshock, and a secondary structure southeast striking, accommodating the largest aftershock. The majority of the aftershocks occupied the northwest part of the activated area during the first four days of the

sequence and then the activity was migrated to the southeastern part of the aftershock area, where the largest aftershock was occurred, forming a smaller but distinctive cluster.

Geodetic raw data were collected by three permanent GPS/GNSS stations (AGPA, LESV, MYTI), located on Lesvos Island, as well as by stations of adjacent islands (Chios and Samos Islands) and analysed. The displacements, recorded by stations located to the north of the main rupture, are characterized by a NE direction, while the ones recorded by stations located on the hanging wall, show SW direction. These results further confirm the faulting properties of the main rupture.

More recently, in February 2021, the activity in the study area is rejuvenated with several events ranging between M4.6 and M5.1). This seismic swarm is located north–west of the 2017 main rupture leading to the conclusion that the 2017 main rupture is a segment of a fault zone, extended north-westerly. The Coulomb stress changes due to the 2017 mainshock, is explored as a possible triggering mechanism of the recent activity.

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The crustal structure of the Pannonian Basin and wider region from P-to-S receiver function analysis

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We present the results of P-to-S receiver function analysis to improve the 3D image of the sedimentary layer, the upper and lower crust in the Pannonian Basin area. The Pannonian Basin hosts deep sedimentary depocentres superimposed on a complex basement structure and it is surrounded by mountain belts. We processed waveforms from 221 three-component digital broadband stations. As a result of the dense station coverage, we were able to achieve so far unprecedented spatial resolution in determining the velocity structure of the crust. We applied a three-fold quality control process; the first two being applied to the observed waveforms and the third to the calculated radial receiver functions. This work is the first uniform and comprehensive receiver function study of the investigated region.

The 1D, non-linear inversions provided the depth of the discontinuities, shear-wave velocities and Vp/Vs ratios of each layer per bundle, and we calculated uncertainty values for each of these parameters. We then developed a 3D visualization method based on natural neighbour interpolation to obtain the 3D crustal structure from the local inversion results. We present the sedimentary thickness map, the first Conrad depth map and an improved, detailed Moho map, as well as the first upper and lower crustal thickness maps obtained from receiver function analysis.

Our Moho depth map presents local variations in the investigated area: the crust-mantle boundary is at 20-26 km beneath the sedimentary basins, while it is situated deeper below the Apuseni Mountains, Transdanubian and North Hungarian Ranges (28-33 km), and it is the deepest beneath the Eastern Alps and the Southern Carpathians (40-45 km). These values well reflect the Neogene evolution of the region, such as crustal thinning of the Pannonian Basin and nappe stacking in the neighbouring orogens.

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Comparison of swarm localization methods with the help of temporary local stations in Mór Graben, Hungary

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The Mór Graben is a seismically active area active region in Hungary, earthquakes, doublets and sometimes swarms with M < 1 can be regularly observed here. The epicenter determination is particularly challenging because of the small events, and the few nearby stations. We improved the detection of small earthquakes by installing 4 temporary stations in Mór Graben region. The objective of this study was to test the different swarm localization methods. We applied waveform cross-correlation, the Fingerprint and Similarity Thresholding and the HypoDD methods. The tested fourth method for identifying swarms was the subspace detector. This method is excellent for identifying seismic signals of the swarm source to a prior cluster data system. Master event(s) can be used to investigate the origin and signal characteristics of time-varying swarm(s).

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Relative P-wave residuals from three DPRK tests: exceptionally noticeable effects of lithospheric inhomogeneities in the Central Europe

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Lateral inhomogeneities of the Earth's interior (crust and mantle) have significant influence on the arrival time of detected seismic signal. Due to these inhomogeneities, observed arrival times differ from values presumed on the basis of a homogeneous velocity model, these differences are quantified by relative arrival time residuals.

P-wave signal originated by DPRK nuclear tests and detected by European seismic stations gives extraordinary opportunity for regional study of relative P-wave residuals. Very precise knowledge of hypocentre position, exceptionally sharp beginnings of P-waves, high amplitude of signal and possibility to compare the results obtained for three strongest DPRK tests (from years 2016-2017) allow very accurate determination of relative P-wave time residuals. In the most cases, differences between residuals obtained on single station from three DPRK tests not exceed 0.1 s (while values of residuals themselves are in order of up to seconds), only in a few cases this difference was greater than 0.2 s.

The area selected for time residual study in the Central Europe covers the Bohemian Massif, Eastern Alps and Western Carpathians regions. Most significant relative arrival time delay was observed in the Western Carpathians, including central parts of this region. Even though the flysch units undoubtedly contribute to the discussed time delay, there has to be some additional cause of this delay in the deeper layers. Another time delays are observed in the Pannonian Basin. In the Eastern Alps, only small area close to Salzburg exhibits relative time delay. Another expected effects of low-velocity flysch layer and thicker crust are probably compensated by effects of mantle units in the Eastern Alps. Significantly higher values of average seismic velocity (relative time-shifts exceed one second) are observed in the Southern Alps.

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Stress-field orientation inferred from ambient seismic noise in the Northern Alpine foreland

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The stress-field orientation acting in the crust is commonly estimated from in-situ borehole breakouts and earthquake focal mechanisms. These measurements are generally sparse, and often they pertain to local stress-field conditions. Here we examine two approaches to derive an approximation to the stress-field orientation. Both are based on the analysis of seismic ambient noise, in the first case from recovered Rayleigh waves, and in the second from temporal velocity variations in coda waves. The first approach considers azimuthal seismic anisotropy of Rayleigh-waves group-velocity residuals after isotropic inversion. For the upper crust, this anisotropy may be interpreted in terms of the orientation of stress-induced cracks. The second approach infers the stress-field orientation by differencing coda waves in empirical Green's functions. This approach relies on the stress-induced anisotropy in nonlinear anelastic behavior under tidal deformation. Both approaches are applied to data from the AlpArray in the Alpine foreland region, where the orientation of maximum horizontal compressive stress is well-known from borehole breakouts and drilling-induced fracture.

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Coda waves attenuation in Racha (Georgia) using different coda methods

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The Racha region is situated in the western Greater Caucasus and is notable for its high level of seismicity. During the instrumental period, the strongest earthquake in the Caucasus (M7) occurred in Racha in 1991.

The main goal of the study was to calculate the quality factor (QC) using the single-scattering model in the frequency range of 1-32 Hz, comparing received results and connecting them to the tectonics and seismicity of the study region. Eighty local earthquakes in 2009-2017 were analyzed and Qc values were estimated by applying three different methods in time and frequency domains. Earthquakes magnitudes varied from 1.2 to 3.7; epicentral distances and depth were smaller than 50 km and 15 km, respectively; coda window ranged from 20 sec to 60 sec. These earthquakes were recorded by five digital seismic stations equipped with broadband Guralp CMG40T and Trillium 40 seismometers.

The QC values were fitted to a power-law, QC (f)= Q0 (f)n , where Q0 is the quality factor at 1Hz and n is the frequency parameter, which depends on the heterogeneity of the medium. In our study QC increases both with respect to lapse time and frequency for all methods. The frequency dependent QC relations obtained for different coda windows are the following estimates:

Qc = (20.4±1.6)f(1.25±0.54) - (20sec);
Qc =(32.5±3.6)f(1.16±0.040) - (30sec); Qc = (39.6±4.5)f(1.13±0.053) - (40sec);
Qc =(65.9±4.0)f(0.99±0.062) - (50sec); Qc = (82.4±9.9)f(0.95±0.077) - (60sec).

These empirical relations represent the average attenuation properties of the region obtained by all seismic station data. We also evaluated those volumes of the earth where studied coda waves formed. Observed

QC, Q0 and n values indicate that the studied region is seismic and tectonically active with high heterogeneities.

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Localization of historical earthquakes in the Pannonian Basin

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The aim of this research is to determine the epicentres, focal depths, and magnitudes of historical earthquakes in the Pannonian Basin based on contemporary sources and literature that recorded the effects, damage and accompanying events. In the course of present study, a historical intensity value for a given place was estimated only if it could be determined based on several contemporary damage data, and accompanying event data from the same place. Based on intensity values obtained this way in different locations, the position of the hypocentre and magnitude of the historic earthquake was determined using an empirical equation:

$$M=(I+a\cdot \ln R+b)/c \qquad (1)$$

where R=(h2+d2)1/2 (h- focal depth (km); d- epicentral distance (km), I - EMS intensity at a R hypocentral distance from the earthquake source). The values of the constants a, b, and c were determined with the use of recent earthquakes data (instrumental magnitude values and intensity databases used to complete isoseismal maps) of eight earthquakes: Kecskemét, 2011 (5.6); Várpalota, 1927 (M3.4); Dunaharaszti, 1956 (M5.6); Békés, 1978 (M4.6); Berhida, 1985 (M4.9); Ebreichsdorf, 2000 (M4.8); Oroszlány, 2011 (M4.5); Tenk, 2013 (M4.8). Based on the constant values a, b and c defined in this way became possible to localize the epicenters and define magnitudes of the events of Komárom 1763, 1783 and Érmellék 1829, 1834. To confirm calculated with the use of equation (1) epicenter positions, focal depth and magnitude values the reports about felt aftershocks, surface cracks, and soil liquefaction as well as the average losses of taxpayers in the villages are taken into consideration to pinpoint the location of the earthquake.

ESC2021-S07-180

Regional attenuation of amplitudes in a structurally complex crust at the orogenic front: case of Mw3.7 Alland 2016 earthquake

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Unique set of dense instrumental and macroseismic records of ML4.2/Mw3.7 Alland 2016 earthquake (SE of Vienna) offers a possibility to study in detail the propagation of seismic waves in the tectonically complex junction region of the Alps, Carpathians, Alpine foreland and Pannonia.

In this contribution we illustrate the contrasting amplitude decay in different tectonic domains and present its best fitting models as a function of geometrical spreading, anelastic attenuation and frequency-filtering structural barriers.

We give possible explanation of the long-known and incompletely understood elongation of isoseismals from East Alpine earthquakes towards the Bohemian Massif in the Alpine foreland. In the latter, the slope of amplitude (and intensity) decay is reduced at near to middle distances, probably due to interference of Lg with waves reflected at rather shallow intracrustal reflectors and the Moho. Resemblance with observations in eastern North America is striking. On the contrary, high-frequency energy of the direct and guided waves passing towards the orogen is strongly attenuated at crustal barriers likely related to orogenic paleosuture.
We emphasise the advantages of combining instrumental and macroseismic data which allows correct description of amplitude decay at local distances. We argue that similar locally-derived amplitude attenuation models based on few well-sampled earthquakes may give better input for regional SHA than those based on larger datasets and extrapolated from other regions.

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Monitoring of seismicity in Central Europe: Contributions of the IPE Brno

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Since its establishing 40 years ago, the Institute of Physics of the Earth, Masaryk University Brno (IPE) has become an integral part of the Czech seismological service and a regional hub of Central European observational seismology. Its present monitoring infrastructure includes 22 seismic stations located in the S and E parts of the Czech Republic and the data centre in Brno.

5 broadband stations contribute to CZ network and are partly integrated in monitoring systems of ZAMG, GEOFON and CTBTO. 17 short-period stations form the local networks M1, T1 and D1, the latter two established to monitor the areas of both Czech nuclear power plants. Records from most stations are shared in near-real time with partner seismological institutions and archived with open access in GFZ EIDA node. Using our data and 100+ surrounding real time stations for a detailed manual data analysis, we monitor seismicity at the contact area of the Alps, the Carpathians and the Bohemian Massif and thus contribute to the knowledge of the slow deformation in the external part of the Alpine orogen and its forefield.

As the parameters of areas with low-rate, low-magnitude seismicity are essential for seismic hazard assessment in the Czech Republic, our main goal is the production of catalogues with the greatest possible completeness in small magnitudes, the careful separation of explosions and the absence of fake events.

Recently, all Czech earthquakes, both historical and instrumental, have been revised in cooperation with our partners. A Czech instrumental earthquake catalogue for 2000-2019 and an open access database of historical earthquakes till 1999 will be completed in 2021. Then we aim to initiate the compilation of a harmonized cross-border catalogue covering the Czech territory and adjacent parts of Austria, Slovakia, Hungary, Germany and Poland.

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Revaluation of the Romanian earthquake catalogue

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The high seismic risk profile of the Romanian territory has two main sources: Vrancea intermediate-depth source (major events up to 7.9 magnitude) and various crustal seismogenic areas (generally affected by moderate earthquakes, i.e., magnitudes smaller than 7.0).

A comprehensive and homogeneous earthquake catalogue, based on accurate historical information and instrumental data, is crucial in the analysis of seismicity and seismic hazard. We present the first phase of the revaluation of the Romanian earthquakes catalogue (ROMPLUS) –analysis and reassessment of the seismicity registered between 1000 and 2005. The following actions have been taken for the considered time interval: (1) comparative analysis between the seismic events locations in ROMPLUS and the solutions from other catalogues for the 1000 – 1900 time period; (2) completing ROMPLUS with sequences and swarms of earthquakes produced in Romania and analysed in scientific studies; (3) adding to ROMPLUS the events observed during seismic tomography or reflection and refraction experiments; (4) completing ROMPLUS with events that occurred in different seismic regions (western and south-western Romania) and had not been included in the current catalogue.

The information gathered during the ROMPLUS revaluation process will be organized into a database containing the parameters of the analysed events (origin time, location, intensity, types of magnitude), confirmation of the existence of focal mechanisms and macroseismic maps, reference studies, documents, and photos of the effects produced by the major earthquakes. An important section of this database, the “event type” (earthquake/explosion), will allow identification of the anthropic events (military and industrial explosions) in an attempt to decontaminate the reevaluated ROMPLUS by discriminating blasts and tectonic earthquakes. A distinct catalogue containing quarry/mine blasts produced on the Romanian territory will be compiled.

Comparative tests and statistical analysis between the original version of the ROMPLUS and the revised catalogue are presented.

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Improving the view of the seismicity in the Pannonian Basin with the Bayesloc algorithm

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We relocated the entire seismicity of the Pannonian Basin with the Bayesloc algorithm. We have used instrumentally recorded events between 1996 and 2017 in the Pannonian Basin and its surrounding area. The magnitudes and the hypocenter coordinates are determined with the iLoc algorithm using 3D global RSTT predictions in the Hungarian National Seismological Bulletin. hypoDD solutions are also available for some major event clusters. The initial hypocenters for the Bayesloc were constructed as a combination of hypoDD and iLoc solutions. Using satellite images and GIS tools we have identified hundreds of probably anthropogenic events originally identified as earthquakes in the Hungarian National Seismological Bulletin. In our work, we have used several hundreds of ground truth events (anthropogenic quarry blasts, explosions, and earthquakes) to tie down the seismicity pattern relative to ground truth locations. The results show that the Bayesloc using prior constraints produces an improved view of seismicity.

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Potential archeoseismological evidence of historical earthquakes in Lower Silesia, Poland

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Completeness of seismic catalogs is always in doubt, therefore seismic hazard modeling is a specifically challenging task in intraplate regions, such as Lower Silesia in Central Europe, due to the low deformation rate and associated low to moderate seismicity with usually long recurrence period. This results in the lack of historical data and significant gaps in the records that might underestimate the seismogenic potential of these regions. Worldwide examples prove the occurrence of large earthquakes in such stable continental regions.
Lower Silesia in the north-eastern part of the Bohemian Massif is cut by the 200-km long Sudetic Marginal Fault (SMF), i.e., one of the most prominent tectonic zones in central Europe that exhibits the pronounced morphotectonic escarpment of the Sudetic Mountains front. Previous paleoseismological studies confirmed its Quaternary activity with a prehistoric earthquake of minimum moment magnitude M 6.3 and the inferred slip rate of about 0.03 mm/year (Štěpančíková et al., 2010). Several historical earthquakes since the XV century have been reported in the areas adjacent to this fault structure (e.g., Guterch and Kozák, 2015), i.e., the 11 June 1895 Mid-Silesia earthquake with the highest intensity of VII on the modified Mercalli intensity scale (Sana et al., 2021). However, their actual source and relation with the SMF or associated structures have not been corroborated.
Here, we propose a comprehensive archeoseismological study of churches, castles, and other historical buildings in Lower Silesia, especially close to Strzelin, Nysa, Dzierżoniów, Brzeg, etc. These were selected due to the historical and archive data, and preliminary reconnaissance studies, having unusual buttresses. The results of this study should fill the gaps in the historical records, allow re-evaluation of the intensity of historical earthquakes, and provide insights into the potential seismogenic source of these events.

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Determinaton of the 1-D Crustal seismic velocity structure and active seismic sources around Bursa, Turkey

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One of the major neotectonic elements of Turkey, North Anatolian Fault Zone (NAFZ) is a right lateral strike-slip fault zone extended from eastern Anatolia to the Aegean Sea. Bursa and surroundings, experienced 1855 destructive earthquakes, is located on another important branch of the NAFZ in terms of slip values. Although the faults formed pull-apart basins in the east and west of Bursa are determined, locations and geometries of active faults are not well defined in the vicinity of Bursa. Activity of the faults can be revealed by the past and recent seismicity which provides information such as locations and characteristics of the faults and their relationship with lithology, basin geometry and basement depth. In order to determine this information by seismological methods, data of the earthquakes that occurred in the region recorded by the stations belonging to the national observation centers (Kandilli Observatory and Earthquake Research Institute, AFAD, etc.) were used. 1-D Vp and Vs structures were determined to be used as a reference model in the determination of the 3-D tomographic velocity structure. At this stage, the 1-D velocity structure that best represents the region was obtained and the earthquake hypocentral parameters were recalculated. 3-D

velocity model was determined considering the 1-D velocity determined in the previous stage as the reference model and using quality travel time data selected according to certain criteria (such as GAP, number of P- and S-phase readings, RMS residuals). The bulletin data of 19885 earthquakes that have occurred since 1990 were retrieved from the International Seismological Center (ISC). Number of earthquakes to be used in 1-D velocity model determination was decreased to 13264 after relocation process. The resulting velocity model was obtained up to a depth of 15 km by using 2211 earthquakes that were selected with the criteria of minimum 8 P-phase readings.

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Preliminary results of attenuation tomography in the Carpathian-Pannonian region revealed by the analysis of ambient seismic noise

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The Carpathian-Pannonian region (CPR) is one of the geologically most exciting areas of Europe due to a high diversity of tectonic processes in very close proximity, extensional basin evolution, oceanic subduction, post-collisional volcanism, as well as active crustal deformation associated with the push of the Adria plate or the pull of the actively detaching Vrancea slab making an excellent natural laboratory to study the behaviour of the lithosphere-asthenosphere system in a special tectonic setting.

A new national project “Eastern European Ambient Seismic Noise” (EENSANE) was recently funded by The Executive Agency for Higher Education, Research, Development and Innovation Funding, Romania (UEFISCDI) aiming to investigate the physical properties of the crust in the CPR at the highest possible resolution. In this framework, we analyze the broadband vertical recordings from the stations that have been operational during 2020 in CPR provided by the Romanian Seismic Network and European Integrated Data Archive (EIDA). With the advent of this large amount of data and by applying a new processing method of ambient seismic field based on the continuous wavelet transform, we computed cross-correlations between various station pairs to extract waves propagating between the stations We further determined the coda quality factors and mapped the attenuation features at the crustal level, within the study region, in two different period ranges (2–10 s and 10–20 s).

Our results emphasized high attenuating features along the Carpathians orogen and within the Neogene volcanic area in the Transylvanian Basin shaping as well the boundaries of the East European Craton and the Eastern edge of the Pannonian Basin. We also revealed the efficiency of noise correlation techniques in analyzing the coda quality factors for lower frequencies than the ones previously pointed out by the earthquake data analyses.

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Revision of the instrumental seismicity occurred from 1951 to 2019 in the Lodi area (Po Plain, Italy)

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We revised the instrumental seismicity occurred in the period 1951-2019 in a sector of the Po Plain (Italy), which is usually considered aseismic. The study area is an 80x80km square centered on the depleted gas reservoir of Cornegliano Laudense (near Lodi). Our goal was to establish a baseline to recognize seismicity variations possibly connected with the gas storage in the reservoir before the activity starts.

We collected all the data made available by various agencies, specifically all P- and S-phase readings related to more than 300 earthquakes occurred in the study area. We relocated these seismic events homogeneously, through absolute location codes and velocity models used by seismic networks at global, national and regional scale.

The new seismicity picture results rather different from what shown by the previously existing catalogues for this area: earthquakes are rare, weak and deep, with a clear separation between the Alpine and Apennines domains. Through the investigated period (~70 years), only 2 weak events occur within a distance of 15 km from the Cornegliano Laudense reservoir; the strongest events are those of the 1951 Caviaga seismic sequence, and they are deep events located at about 30 km from the reservoir. The main shock of this sequence has hypocentral location and focal mechanism that match those of the M4.2 Milan earthquake of Dec 17, 2020, relocated in this study too; therefore, we hypothesize a common tectonic stress for these two events.

Our results suggest that the deep seismicity in this sector of Po Plain originates from the convergence between the Southern Alps and Northern Apennine, even though the geological structures capable of generating earthquakes are not distinguishable yet.

We believe that the improvement in the seismic monitoring capabilities of the very last years will be crucial to define better the seismogenic sources hypothesized for this area.

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A focal mechanism catalogue of earthquakes that occurred in the southeastern Alps and surrounding areas from 1928 – 2019

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We present a catalogue of focal mechanisms related to seismicity in the southeastern Alps and surrounding areas from 1928 to 2019. The area - involved in the convergence of the Adria and Eurasia microplate - is one of the most seismically active regions in the Alpine Belt. Although the seismicity is minor, the 1976 Friuli earthquake (Ms 6.5) being the strongest event recorded in the area, the seismic risk is significant because it is a highly populated region.

Numerous studies have been conducted to investigate the area's stress field and geodynamic characteristics using focal mechanisms. To provide a comprehensive set of revised information, which is challenging to build quickly because the data are dispersed in many articles, we have collected and reviewed focal mechanisms that have been previously published in the literature. In addition, depending on the quality and availability of the data, we computed new focal mechanisms through first-arrival polarity inversion or seismic moment tensor. Finally, we combined all fault plane solutions to obtain a catalogue of 772 earthquakes with $1.8 \le M \le 6.5$. For each earthquake, we reported all available focal mechanisms obtained from different authors. However, we have also suggested a preferred solution for users who need quick information.
The catalogue is available at https://doi.org/10.5281/zenodo.4284970

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Real Time network performance and data exchange for improving seismic monitoring in Romania

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The National Institute for Earth Physics (NIEP) operates and maintains a dense real time seismic network that covers most part of the Romanian territory. NIEP shares with the international scientific community seismic waveforms and parametric data in real time via European Integrated Data Archive (EIDA), where NIEP is the primary node. Furthermore, NIEP is part of the Central and Eastern Europe Earthquake Research Network (CE3RN), established under the collaboration between seismological institutions based in Central and Eastern Europe. The quality of the seismic waveform data and related metadata is essential for the scientific analysis and data interpretation. At NIEP, algorithms were created to automatically check the data quality parameters and to handle a big amount of data. This will allow to monitor changes and variations in data quality over different time and scales which will lead to the best quality data. The performance of the Romanian seismic stations is monitored both in frequency and time domain, by computing the probability density functions (PDF) and of the power spectral densities (PSD). This way, the overall station quality and a baseline level of Earth noise at each site can be accurately estimated. The permanent development of the National Seismic Network in Romania contributes to the enhancement of the detection capability, resulting in the increasing of the quality of different products like moment tensor computation and seismic bulletins for local, regional and teleseismic events.

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Join study of the Neunkirchen (30th of March 2021) and the Gloggnitz (20th of April, 2021) SE Austria, Seismic Sequences

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We examine two seismic sequences near Neunkirchen and Gloggnitz, about 50 km from Vienna, Austria, and around 10 km apart from each other. Despite the moderate magnitudes, the recent earthquakes near Neunkirchen, in the south-eastern part of the Vienna Basin, were felt in the epicentral region and up to 300 km away.

The Neunkirchen sequence started on the 11th of March 2021. The last recorded earthquake being on the 12th of May 2021, according to the Austrian Seismological Service at ZAMG. Until mid of May 2021, over 245 earthquakes with local magnitudes ranging from 0.52 to 4.6 have been recorded. Among the earthquakes analyzed, 21 were felt (1.8 ≤ ML ≤ 4.4), and one caused damage (ML4.6) in Wiener Neustadt, the capital of the province of Lower Austria, and 12 km from the epicenter. According to initial evaluations, the depths of this series range from 7 to 12 km.

The Gloggnitz sequence started on the 1st of April 2021, the last recorded earthquake (ML1.1) on the 8th of May 2021. A total of 65 earthquakes were localized, of which the population felt four, and no damage was caused. The local magnitudes in this seismic series range from -0.34 to 3.8. Earthquakes of this sequence are slightly shallower than the ones in Neuenkirchen, between 4 and 7 km.

The relocation of the earthquakes of both series was carried out using the NonLinLoc by Lomax (2019). The focal mechanisms of the largest earthquakes were also calculated with the Seismic Moment-Tensor inversion. For the rest of the events, a joint fault-plane solution was investigated. Additionally, we compiled and analyzed the macro-seismic questionnaires for all felt earthquakes in the series to produce intensity maps (EMS-98) and to calculate the intensity attenuation as a function of distance for later comparison.

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Seismic activity and one-dimensional velocity structure in the South West Carpathians Bend, from accurate hypocenter relocations

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The seismic activity in Romania is mostly distributed along the Carpathians orogen reaching its maximum at the south-eastern Carpathians bending. In addition, a particular region with notable seismic activity is highlighted at the contact between the western edge of the South Carpathians with the Tisza Dacia block, where weak to moderate crustal earthquakes are frequently recorded. The crustal seismicity is linked by the active deformations and formation of pull-apart basins as a result of the right lateral movement of the southern Carpathians relative to the stable Moesian Platform. To better understand the dynamic and sedimentary processes that continuously shape the Earth's crust in this area we carried out a travel-time inversion of 408 well-located local crustal events consisting of 4300 P and 43000 S arrivals. The resulted one-dimensional (1D) velocity model together with the station's corrections used further to relocate 3100 events recorded by the Romanian earthquakes catalogue (ROMPLUS) between 2000 and 2018, time interval. Our results show a good correlation with the local geology, emphasizing clusters of events following the orientation of the major faults existing in the area and a significant amount (~75%) of relocated hypocentres distributed in the upper part of the crust (< 20km). In addition, we showed an improvement in earthquake locations by decreasing the location RMS error up to 15%.

ESC2021-S07-497

Local site effects investigations along the Pannonian Basin

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Pannonian Basin is one of the largest Miocene sedimentary basins located in Central Europe and local site investigations are necessary in the estimation and mitigation of the seismic hazard and risk. The seismicity in this area is moderate with rare large events, a magnitude 6 earthquake is about once every 100 years, while a magnitude 5 event appears on average every 20 years.

The present study is focused on identifying and mapping the fundamental frequency of S-wave resonance using the non - invasive Horizontal - to - Vertical Spectral Ratios (HVSR) method. The data sets consists in ambient vibration and local/regional earthquakes signals recorded from more than 150 seismic stations, among this ones are online/offline stations of the national seismic network of Romania, Hungary, Slovakia and ones were deployed during temporary international projects (Carpathian Basin Project, 2005 – 2007; South Carpathian Project, 2009 - 2011). The events magnitude is in the range of 4 - 6.4 Mw.

The HVSR curves show multiple peaks along the study zone: a fundamental one that is very well defined and is interpreted as the fundamental frequency of resonance (0.11 – 10 Hz) and higher peaks that are related to the complex geological structure. A second peak was observed in the frequency domain 0.4 - 5 Hz. For some stations, a third peak with a low amplitude can be noticed on the resulting curves. It can be interpreted as a mixture of the higher modes of Rayleigh waves and SH waves. From the HVSR resulting curves, one can identify similarities in the case of ambient vibration and earthquake signals. For the majority of the stations, the fundamental frequency of resonance extracted from the ambient vibrations coincides with the predominant frequency identified from the earthquake analysis.

ESC2021-S07-529

Seismic discrimination of anthropic and tectonic events in the Targu-Jiu quarry area (Romania)

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Targu-Jiu city is located on the western side of Romania at the contact of the Moesian Platform with South Carpathians, the so-called Getic Depression. The region is characterized by both crustal tectonic earthquakes (for example, the seismic sequence of December 2011 – January 2012 with a mainshock of 4.5 local magnitude) and anthropic events related to the numerous quarries. Due to the increase of the seismic station number and the improvements in the quality of the sensor, the network capabilities to detect and locate seismic events increased significantly, and the magnitudes of the recorded events decreased. A direct consequence of the decrease in the magnitude threshold was the significant increase in the number of events in the Romanian catalogue (Romplus) with seismic events of probably anthropic nature leading to strong catalogue contamination that affects any further investigation on seismicity, interpretation and modelling of the geodynamics of the area. Therefore, discriminating natural from anthropic events is of the highest importance to assess seismic hazard and to model and interpret regional seismicity patterns. We test and apply a set of discrimination procedures in order to implement them for further decontamination of Romplus catalogue for the Targu-Jiu area. An imaginary 10km diameter ellipse was traced around the quarries. The techniques applied to discriminate on these data are based on statistics, waveform cross-correlation and infrasound processing. Our approach in seismic discrimination reveals that more than 70% of the events recorded in the catalogue are potential quarry blast events.

ESC2021-S07-531

First evidence of paleoearthquakes along the eastern Rhine Graben Boundary Fault (Germany)

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The eastern Rhine Graben Boundary Fault (RGBF) is located in the center of the European Cenozoic rift system as part of the Upper Rhine Graben (URG). The URG is one of the most seismically active areas in the stable continental interiors of Central Europe. It is characterized by low intra-plate seismicity where several strong historical earthquakes occurred in its central part, without documented surface ruptures. Several paleoseismological studies have been carried out only along the western RGBF. Our research aims to characterize the eastern RGBF to evaluate its seismic history and establish a chronology of seismic events combining shallow geophysics and paleoseismological trenching. The eastern RGBF consists of several parallel transtensional left-lateral strike-slip fault strands marked by topographic steps and varying hydrogeological conditions as evidenced by geophysical anomalies. We excavated six trenches along and across the NNE-SSW topographical fault scarp of one of the secondary fault strands associated with the main scarp of the border fault, north of Ettlingen-Oberweier (south of Karlsruhe, Germany). The exposed fault zone has a negative flower structure and spreads within 6 m in several en-echelon branches, slightly oblique to the main fault. The whole sedimentary sequence (consisting of colluvium and periglacial deposits), except for the youngest layer (AD 1030-1160), is displaced by moderate to steep (60° to 85°) faults that are downthrown to the west. The displacement on free faces is on the order of 30 – 60 cm per event vertically and amounts to c. 2m left-laterally (cumulative). From cross-cutting relationships and dating based on the radiocarbon and optically stimulated luminescence methods, we identify a minimum of three seismic events with a minimum magnitude M of 6; two of these events occurred within the last 65.1 ka. Our findings contribute significantly to the completeness of the earthquake history in the URG.

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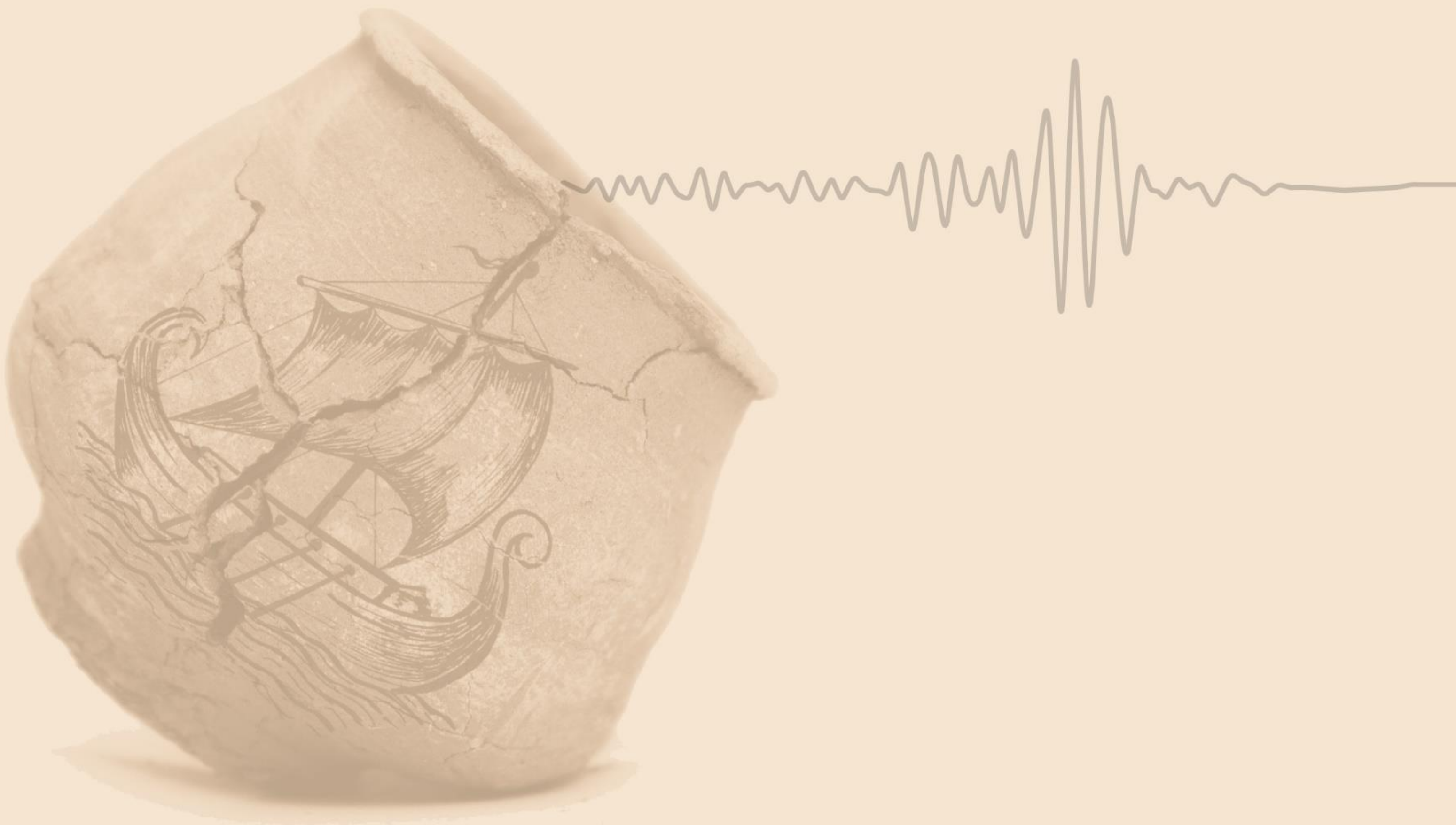
Session 08

Seismic arrival time determination: The reliability of established and innovative automatic picking techniques compared to manual picking



ESC2021-S08-182

P-wave arrival picking with deep learning and uncertainty quantification

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The task of picking the arrival time of seismic P-waves is crucial to the work of seismologists. With the growing amount of seismological data, more automated algorithms are developed and used but they may not be as trusted as picks by expert seismologists. Still, several deep learning approaches have been developed for the task. We build upon previous work by adding the component of uncertainty quantification to the deep learning model: In addition to predicting an arrival time, our model outputs a level of uncertainty. This will allow a hybrid approach, where the machine may pick the most certain arrivals, while those with a higher uncertainty may be checked by a human analyst. We use 1D convolutional neural networks on single component seismograms and two methods for uncertainty quantification: direct uncertainty prediction and Monte-Carlo-Dropout. We train and test the model on the seismological archive from Neumayer Station, Antarctica. On the test set, 83% of automatic picks of teleseismic P phases are within 0.5s of the analyst pick; when discarding the 20% of picks with highest predicted uncertainty, the accuracy improves to 93% of picks within 0.5s of the analyst pick.

ESC2021-S08-284

Real time picking with Transformer Networks

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The widely used SeisComp observatory software has a number of automatic pick algorithms implemented, which we will review briefly. While these standard automatic picks often provide us with an early approximation of the P-wave onset and allow fast event detection, they are often too late compared to the manual pick, or overlook weak first arrivals such as from Pn phases. Nevertheless, they play an important role for the early localisation of an event. Improving automatic picks to the approximate level of manual picks could facilitate the work of human analysts facing larger and larger amounts of seismic data. Particularly, errors due to missed onsets can lead to large localisation errors. We refine standard automatic picks by feeding the associated waveform to the “Transformer Earthquake Picker” (TEP). While the first rough automatic pick is usually done by an STA/LTA picker, the second-stage picker, TEP, is a Deep Learning network that was trained on 289,162 manual picks from about 3,500 events. Its architecture combines convolutional and Transformer networks and returns a time series of P-wave onset probabilities, which in addition to providing an estimate of the pick time as peak probability have the potential to represent multi-modal distributions in case of ambiguity. Compared to the standard autopicker in SeisComp, the results show a significant reduction of mean error and standard deviation of the automatic pick treating the manual picks as gold standard. TEP picks tend strongly to have a higher confidence when they lie close to the manual pick, and only very low confidences are returned for traces with no discernible picks. We are establishing a workflow, where incoming automatic picks are refined essentially in real time, and evaluate the performance of those picks without a gold standard using measures such as number of well-fitting picks and residual rms values.

ESC2021-S08-317

Assessing automatic pwith machine learning at the USGS National Earthquake Information Center

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The U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC) has an interest in operationalizing deep-learning tools in order to improve our ability to automatically detect and characterize earthquake source parameters. As a first step, the NEIC developed machine learning models to classify the source characteristics of waveforms surrounding standard short-term-average / long-term-average (STA/LTA) picks in order to improve picking accuracy, estimate phase-type, and estimate source-station distance. In this framework, the NEIC is still reliant on STA/LTA algorithms to initially detect seismic events. In this presentation, we will examine the performance of our machine learning models in improving automatic arrival-time estimates as compared to human analyst picks. We will examine the variability in both algorithms and human-derived picks and the significance of these gains on our downstream processing. While NEIC still uses STA/LTA algorithms, machine learning models have been shown to have powerful detection capabilities. Therefore, the NEIC is exploring the use of machine learning models at all distance ranges to directly detect and pick seismic phases from continuous waveform streams. We will discuss the current state of these capabilities and their implications for improved performance in NEIC's global seismic monitoring mission.

ESC2021-S08-323

Automatic picking of teleseismic P- and S-Phases using an autoregressive prediction approach

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In the recent decade, the amount of available seismological broadband data has increased steeply. Picking later arriving phases such as S-phases is difficult, and there are few manual picks available for these phases. Data sets of manual picks can also be problematic, since phase arrival picks are sensitive to the parameters of the filtering, which are often unknown, and the individual picking behavior of the analysts. However, accurate arrival times, especially for these phases, could be used to improve the accuracy of velocity models obtained from seismic tomography. This necessitates the adoption of automatic techniques for determining teleseismic phase arrival times consistently over a large data set.

In this work, a robust automatic picking algorithm based on autoregressive prediction is examined with regards to its accuracy. For this, a series of tests were carried out, using synthetic waveforms as well as real data in conjunction with manual picks obtained from the reviewed ISC-catalog.

Picking errors are estimated by comparing the automatic picks with manual picks, automatic picks at the neighboring stations as well as statistical meth- ods. The quality evaluations suggest potential of using these automatically determined phase arrival times for a travel time tomography.

ESC2021-S08-331

Refinement of automatic arrival-time measurements based on cross-correlation and Hierarchical clustering

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The accuracy of arrival-time measurements is crucial for travel-time-based seismological applications, such as earthquake location and travel(delay)-time tomography, in particular when double-difference time are used. Due to the huge amount of real-time data, the monitoring networks are implementing single-station, automatic event detection/location procedures, which produce inconsistent arrival-times of the same phase among stations. To overcame this problem, several refined cross-correlation (CC) techniques for time picking have been recently developed. Their basic approach is to use CC to refine picks of event pairs with high waveform similarity. Similar events are grouped considering the max CC values, the inter-distance and/or the focal mechanism similarity. For each family, a reference trace (RT) is computed using conventional linear stacking. Then, RT is cross-correlated with traces in the family to obtain coherent pick adjustments. Two drawbacks of this common approach are (1) the impact of noise from individual receiver levels on the quality of RT and (2) the inability to adjust the systematic shift of automatic picks.

Here we propose a new, fully automatic approach to refine the phase time picks. The medium is discretized in cubes, in which we use the CC to identify family members with a hierarchical clustering procedure. In each family, after the trace alignment, we build a RT by stacking the events weighted by the signal-to-noise ratio. To remove the systematic shift, we perform an automatic pick to be used for the picks refinement within the family. We tested this technique on a calatog of 157 events obtained by the application of an automatic platform in the Northern Nagano prefecture (Japan). The results indicate that we are able to improve the consistency of phase picks among similar events and to adjust the systematic shift introduced by the automatic picker with differences between refined and automatic picks up to 0.5-1 s.

ESC2021-S08-364

Deep learning for phase picking and earthquake monitoring

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Developing effective and efficient earthquake detection techniques is of interest for both routine earthquake monitoring and in-depth study of intense earthquake sequences. The complexity in earthquake waveforms that occurs due to combined source, path, and site effects makes it challenging to manually design optimal characteristic functions or set thresholds for earthquake detection and seismic phase picking. Deep learning provides a new approach to automatically learn universal features that characterize earthquake waveforms from decades of training labels picked by analysts. These complex features that distinguish earthquake waveforms can be effectively learned through supervised training of deep neural networks, and can be further enhanced by careful data augmentation and regularization techniques. We have developed several deep-learning-based detection and phase-picking models, including PhaseNet, CRED, and EQTransformer, which have significantly improved earthquake detection performance and picking of P-wave and S-wave arrivals. These models have been applied to studying both tectonic and induced earthquake sequences around the world. We have further extended our deep-learning earthquake monitoring pipeline by developing a new phase association method, GaMMA, which helps aggregate collections of picks observed across a seismic network into individual events. Combining these modules together with cloud computing, we have an automated deep-learning-based workflow, QuakeFlow, for monitoring earthquakes at local and regional distances. We applied QuakeFlow for both real-time monitoring and processing of archived seismic datasets for studying intense earthquake sequences. We used auto-scaling in Kubernetes to parallelize the workflow on Cloud platforms, enabling the technique to efficiently process large datasets with many stations and long observation times. The output earthquake catalog lowers the magnitude of completeness and improves resolution of earthquake catalogs, demonstrating how deep learning quickly reveals details of seismic activity and provides new insights into the earthquake processes.

ESC2021-S08-458

A practical tool for consistent seismic picking in local and regional networks: the ADAPT library

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Phase arrival picking is one of the most important and fundamental task for many seismological studies. Among these tasks, earthquake's locations, moment–tensor inversion and traveltime tomographies requires precise and consistent phase identification with associated arrival time and error assessment.

The amount of earthquake signals recorded by local and national seismic networks is rapidly increasing and analyzing such large amounts of data manually has become a burden for routine operators occasionally leading to inconsistencies in the review process.

For this reason the use of automatic pickers is becoming more and more important in real time and offline observatory tasks. We face these challenges by creating tools for stable and smoother workflows. The ADAptive Picking Toolbox (ADAPT) is an object-oriented python library aiming to provide an efficient, customizable toolbox for high consistent and high quality seismic picking procedures. Its modular architecture makes it applicable for different time-series transient detection, easy to implement and versatile for different.

With the help of such library we developed a new semi-automatic multi-picking algorithm for consistent and precise first-arrival phase identification, the so-called ADAPT-JHD-VELEST picking algorithm. This method combines several well-established picking algorithms for phase identification, and it uses the Joint Hypocenter Determination developed in VELEST software for quantitative error-assessment and precise event locations.

We successfully applied such framework in the creation of a regional seismic catalog and a traveltime tomography dataset in the framework of AlpArray project (www.alparray.ethz.ch), that provided unprecedented amount of data (~20 Tb) for the Alpine Region spanning the Jan.2016 – Dec.2019 time period.

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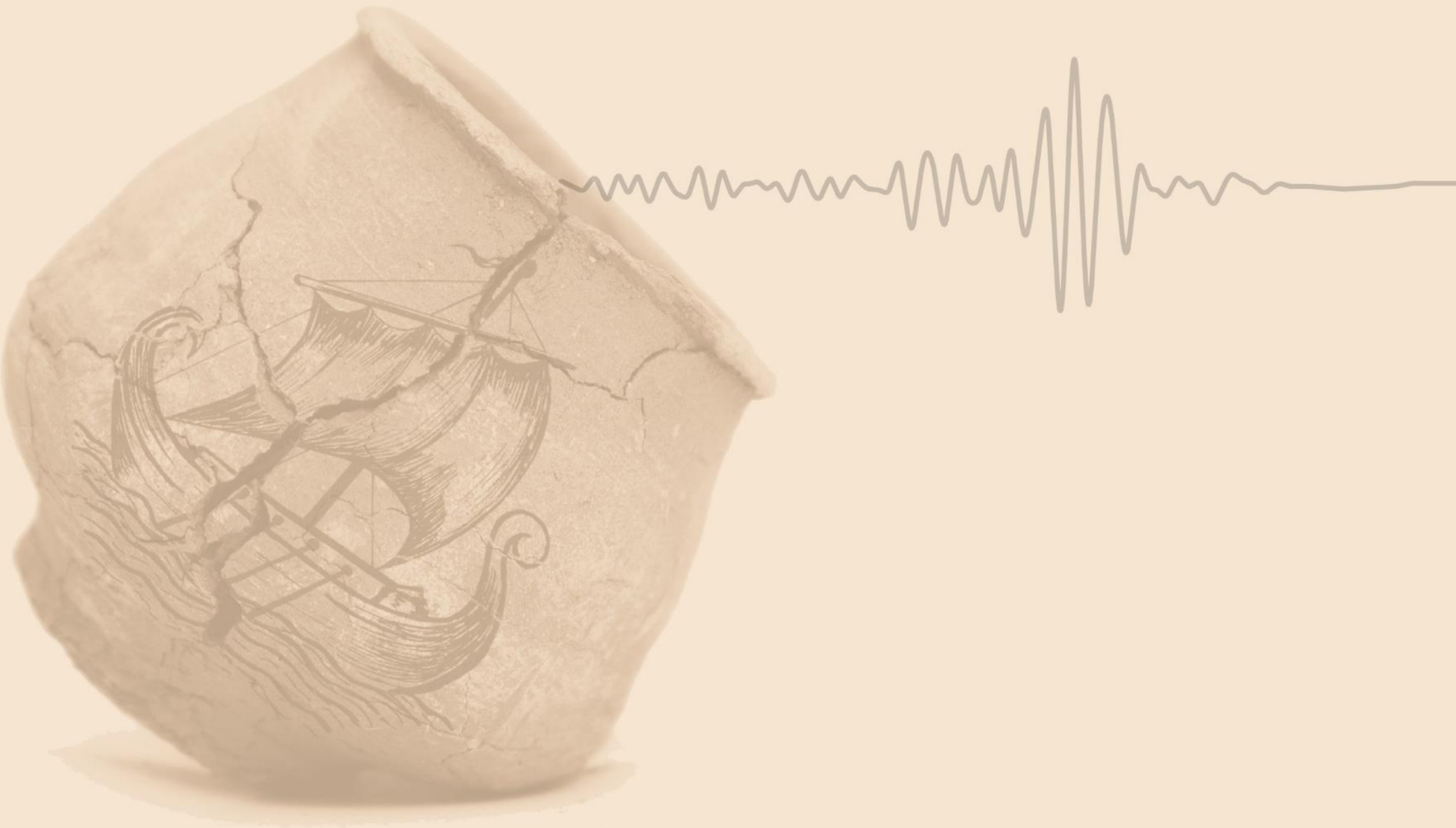
Session 09

Advancing the (Re)use and preservation of Analog Seismic Data



ESC2021-S09-053

Advancing the reuse of Legacy Seismic Data FAIR'ly

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Efforts to preserve analog seismic data and make them available digitally are underway at a number of institutions world-wide. While these preservation efforts provide leadership in best practices in conservation, imaging, and vectorization, community discussions have been initiated on standards and how the collections can meet FAIR data principles. That these data be Findable, Accessible, Interoperable, and Reusable provides guidance for data management and stewardship in the modern digital ecosystem allowing centers managing these products to develop uniform tools for discovery and return legacy data in formats accompanied with metadata to ensure its usability. Establishing standards before significant work begins will help ensure continuity and consistency in data preservation projects, high-quality products, and comprehensive capture of key information.

The 2019 Securing Legacy Seismic Data to Enable Future Discoveries workshop held September 18-19, 2019 in Albuquerque, New Mexico was convened to discuss the framework for preservation of longitudinal seismic data and create an interdisciplinary network of data, domain, and computational scientists to facilitate management, access, and use of digitally imaged legacy data. Towards these goals, participants outlined community needs: creating a catalog of analog data, creating a publications database that use analog data, identifying metadata standards, establishing a pilot project, enabling future research, identifying enabling technologies, attracting a cross-disciplinary community of users, and enlarging the user community through outreach. They also provided feedback on proposed core metadata for legacy data preservation and use. Subsequently, the international community was surveyed on the metadata elements revised by workshop participants. Elements were grouped into broad categories that parameterized the data: 1) Time of Data, 2) Station/Channel, 3) Sensor, 4) Recording System, 5) Image File, and 6) Other. These metadata elements and survey results will be presented. The goal is to set the stage for FAIR legacy data adoption by the larger international community.

ESC2021-S09-096

Seismic Patrimony Preservation Tutorial

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Fabra Observatory has been devoted to astronomical, meteorological and seismological observations and studies since 1904. Besides, holds a small museum, regular courses, conferences, scholar visits, and many other divulgation activities. Seismic observations started in 1906 and have been maintained active since then. Our seismic patrimony includes original instruments and diverse documentation, instrumental registers and macroseismic data collected from a number of sources. Thanks to the inestimable advice, help and support from other particular and institutions, we have performed inventories, restorations, studies and scannings to preserve, use and share as much of our scientific heritage as possible . Extense summaries of our patrimony and some of those projects up to that date were already presented in the past.

Observatori Fabra is a relatively small and independent institution with a limited budget and personnel but with a significant historical scientific patrimony and a remarkable interest to use it for both scientific and

divulgation purposes. Since much of the pre-WWSSN data is still owned and maintained by similar institutions, we think that sharing our related experiences, problems and ideas could be of great interest and useful to help others to identify, preserve and use their own seismic patrimony. Therefore, we decided to use them together with the deeper knowledge of restoration professionals and other interested institutions also willing to share theirs to prepare a brief and useful compendium of best practices and problems to avoid about identification, inventory, conservation/preservation, restoration, use and exposition of seismic patrimony. We plan to shortly release a first complete version of this tutorial to be shared freely to the interested community.
Here we aim to expose in detail the current status of this project to a potentially interested audience and to enrich it with as many contributions, doubts, and observations from our colleagues as possible.

ESC2021-S09-192

The 1928 Oaxaca, Mexico large-earthquakes sequence(M6.5-M7.8): preliminary results from the re-analysis of legacy seismograms and seismic bulletins information.

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In 1928, an unusual five large earthquakes seismic sequence (M6.5-M7.8) occurred in Oaxaca, Mexico. Three of these earthquakes have magnitude M≥7.5.

We gathered the legacy seismograms and metadata from the seismic bulletins of this seismic sequence, through the SISMOMex project of the Mexico's National Seismological Service (SSN), the International Seismological Centre (ISC) online seismological bulletin, and 1928 seismological bulletins, from other different international seismological agencies.

In this work we present the preliminary results for the seismic source analysis based on the regional smoked paper seismograms recorded at the (SSN) stations in 1928. To vectorize and obtain the evenly sampled ground motion time-series of these seismograms we use TIITBA software developed by one the authors at the Institute of Geophysics of UNAM, Mexico. We also, present the seismic sequence relocation using the SEISAN software and a Bayesian inversion method. With TIITBA software, we obtained a SEISAN S-file for relocation by picking the P and S phases directly on the scanned regional smoked paper seismograms. Finally, we present the uncertainty between the obtained results and the source and hypocenter information reported, considering the absolute time limitations that legacy seismic data have.

ESC2021-S09-195

Reevaluating the 1968 Belice seismic sequence (South Italy) from analog data

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Using digitized waveforms we estimated moment tensor solutions for the most energetic earthquakes occurred during the January-June 1968 Belice sequence, western Sicily, in a sector of the Nubia-Eurasia margin previously considered aseismic. Focal mechanism solutions and poorly constrained hypocenter locations proposed in the literature led to controversial interpretations of the possible geometry and kinematics of the seismogenic source. In particular, the two main fault models proposed alternatively suggest thrust faulting on ca. E-trending structures and dextral strike-slip movements on ca. N-S oriented faults.

Aiming to solve this ambiguity, we focused on the starting phase of the sequence and computed the moment tensor solutions for three of the strongest earthquakes (M≥5) by using digitized seismograms and a time-domain waveform inversion technique properly calibrated for analog data. Our results indicate that the sequence was characterized by a mainly thrust faulting activity occurring on ca. E-to-NE trending structures, thus solving the dualism between the previously proposed models. We were also able to obtain the first estimate of Mw for the analyzed events, that indicate an overall overestimation of previous assessments. Moreover, we collected the arrival times from original bulletins and catalogs to analyze, by means of a Bayesian hypocenter location method, the spatial distribution of most energetic earthquakes and our results well agree with the moment tensor solutions and structural features of the area. The improved knowledge we achieved for the most relevant seismic activity of western Sicily may have primary effects on regional seismotectonic modeling and seismic hazard evaluations.

ESC2021-S09-333

Assembling and Preservation in digital format of Analogue Seismograms and Other Documents at Institut Cartogràfic i Geològic de Catalunya (ICGC)

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Catalonia, in the NE of the Iberian Peninsula, has a long tradition on seismic recording. The first seismic station in this region, EBR, was installed in 1904. The second one, FBR, started in 1906. Both keep their seismograms and a large amount of complementary information. Since 1984, the Catalan seismic network, presently managed by the Institut Cartogràfic i Geològic de Catalunya (ICGC), was deployed. Analog recording on thermal paper was used up to the end of the XX Century. Altogether, these seismic stations have been generating and preserving a large number of seismograms recorded in analog records (smoke, ink and thermal paper, analog tapes, etc.) and related documents (station notebooks, seismic bulletins, correspondence, etc.). To preserve these records and documents for the future, a campaign to scan them as images was undertaken years ago. At present, around seventy thousand seismograms have been scanned as well as several thousands of pages of bulletins and other records. Access to these data (seismograms, bulletins, etc.) can be obtained at the ICGC website. We show the present status of the project, the adopted strategies for scanning, classification and dissemination of the acquired data and future planning.

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ESC2021-S09-346

Rescue of Analog Data for Nuclear Explosions

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Our data rescue project is based on a process of inventory, identification, scanning, and aggregation of metadata and data quality control, followed by collecting the scans and their associated metadata into a common repository to prevent potential loss of digital information.

Analog nuclear explosion paper recordings (photographic paper, ink on paper, smoked paper) belonging to the archives of four national institutes in Central and Eastern Europe are used: Central Institute for Meteorology and Geodynamics – Austria, National Institute of Geophysics, Geodesy and Geography – Bulgaria, Institute of Geology and Seismology – Republic of Moldova, National Institute for Earth Physics – Romania. These archives cover the entire nuclear explosion era and contain recordings from 78 seismic stations. Most of the nuclear explosions occurred before digital data recording became common, so rescuing these analog data is an important task. The analog paper recordings suffer progressive degradation which is resulting in data loss with time, so their rescue is also an urgent task for the community.

Each participating institution compiles inventories of nuclear explosion recordings, based on their national bulletins and seismic catalogues of the time, then recordings are identified in the seismogram archives. These recordings are scanned with high resolution and stored as image files in a data repository. For each scanned recording, a comprehensive set of metadata is prepared, including detailed information on station, instrument and paper recording, as collected from old station books, national catalogues, instrument documentation, and technical publications of the time. The resulted data set can be converted to digital time-series in the future, via digitization, allowing the application of modern signal-processing techniques.

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The TRI-117 WWSSN-LP recordings of the October 9, 1963 Vajont Catastrophe

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We retrivied from the OGS archive the seismic signal generated by the 1963 Vajont catastrophic landslide recorded at the Worldwide Standardized Seismographic Station Network-LP station (TRI-117) of Trieste (Italy). The landslide (nearly 260–270 million m3) invaded an artificial reservoir designed for electrical production, and generated a 220 m high wave that flowed over the dam and claimed the lives of approximately 2000 people. The original three-component seismograms have been digitized and analyzed using time–frequency tools and numerical simulations. The results indicate that a seismic signal comparable to that generated by an Ms 3.7 earthquake was generated by the landslide. Furthermore, the calculated nearly 2×1014 J of frictional energy, considering the known parameter of the mass movement, is compatible with a friction coefficient of 0.29, in excellent agreement with the values from literature. The seismic efficiency that we calculate (1.12 × 10−4 – 4.45 × 10−4), is within the range of values previously published. Finally, by means of numerical simulations and adopting an ad hoc crustal model for the area, we first

checked the capability of reproducing the signal generated by the landslide and we re-estimated the origin time of the event at 21 hr 41 min 42 s UTC, that is 12 second after to what was originally proposed. The results confirm the importance of the reanalysis of analog seismograms with modern tools within a multihazard context.

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Identifying specific events from historical seismograms of the first decade of the 20th century – case studies of COI seismic station (Coimbra, Portugal)

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The Meteorological and Magnetic Observatory of the University of Coimbra (OMMUC) was the first Portuguese institution equipped with an instrument for record the seismic activity at the end of the 19th century. However, only in May 1903, after the installation of a Milne horizontal pendulum, the seismological recording in COI seismic station started in a regular way. Nevertheless, most part of the seismograms of the first decade of that century were not analysed.

The revisitation of historical seismograms of the Milne horizontal pendulum installed in COI allowed to identify two phenomena occurred in the European continent during the first decade of the 20th century: the Tunguska explosion, on June 30, 1908, and the Croatia earthquake on October 8, 1909, this last one allowed Andrija Mohorovicic to prove the existence of a discontinuity in the velocity of the P and S seismic waves. Both events were not identified as seismic signals by the OMMUC's observers at that time, due to the very small recorded oscillations.

These two case studies confirm the great importance of the historical patrimony of the COI seismic station in the identification of new data, thus contributing to the seismic catalogues updating and improvement of the scientific knowledge.

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Analogical seismic data at the Spanish Geophysical Data National Archive

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The Spanish Geophysical Data National Archive (Toledo Geophysical Observatory) is a centre created by Instituto Geográfico Nacional to preserve all the geophysical documentation produced in all of the observatories that IGN has had in operation throughout its history.

Since 1909 seismic data has been produced in 8 observatories that IGN has operated in Spain along the twentieth century. All this historical information has been transferred to the Geophysical Data National Archive where it has been reviewed, classified and catalogued in a database, to be eventually filed in the records repository of the Archive, with the appropriate conditions for their future preservation. Its contents are being digitized as backup and to meet the data requests received in this Archive.

For the study of earthquakes throughout the twentieth century, this Archive has a large volume of information. The documents most consulted by researchers are the seismic records from the IGN Geophysical Observatories, but also the Archive houses an important collection of complementary information. For example, the Archive is implementing a great collection of seismic bulletins. Historically an active interchange of bulletins was made between international institutions, and now we are collecting all the bulletins located in all IGN observatories, and putting them in value for the international community.

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Seismic anisotropy and shear-wave splitting: achievements and perspectives

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Mantle dynamics in the SE Tibetan Plateau revealed by teleseismic shear-wave splitting analysis

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The tectonic evolution of the southeastern Tibetan Plateau is key to understanding the mechanism of growth of the whole Tibetan Plateau. Its imprint on lithospheric and asthenospheric mantle rock fabrics is expected to have a strong signature on seismic anisotropy. In this study, we measure the splitting delays and fast polarization directions (FPD) with the minimum-transverse-energy and the splitting intensity methods using core-refracted phases (e.g., SKS, SKKS, PKS) recorded by the ChinArray experiment. The potential complex anisotropic structures, i.e., the frequency-dependent splitting and two-layer anisotropy, are investigated in particular. The FPDs are consistent in different frequency bands, but the delay times measured at low frequency (8-20 s) are often larger than those measured at high frequency (2-8 s). The measurements can be better explained by a two-layer anisotropy model at many stations. Splitting intensities are also inverted to constrain the depth distribution of seismic anisotropy in the upper mantle. Combined with the two-layer anisotropy models, these results suggest different patterns of seismic anisotropy in the lithosphere and asthenosphere. In the lithosphere, anisotropy shows distinct patterns in the different tectonic blocks. The FPDs are oriented along the major tectonic boundaries. In the asthenosphere, continuous NW-SE FPDs spread from the Tibetan plateau to the Youjiang Orogen along the southwestern margin of the Yangtze craton, implying asthenospheric extrusion from the high plateau. In the northern Indochina block, the dominant E-W FPDs may indicate asthenospheric flow driven by the eastern subduction and subsequent rollback of the Indian plate.

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Temporal evolution of shear-wave splitting properties before an Mw=6.3 event in the Eastern Aegean (Greece)

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Shear-wave splitting studies in the upper crust have debated the possibility of treating time-delay variations as earthquake precursors. The Anisotropic Poro-Elasticity (APE) model suggests the existence of a fractured upper crust, pervaded by vertical microcracks saturated with fluids. The delicate balance between fluid properties and the regional stress field can be sampled by shear-wave splitting. Accumulation and relaxation of stress in the rock volume affected by an impending earthquake are monitored as an increase and decrease in observed time-delay, respectively. Moreover, increased pore pressure in areas adjacent to the future causative fault can cause a change to the aspect ratio of microcracks, indicated by 90° flips in the polarization direction.

The occurrence of a strong Mw=6.9 earthquake in 2020 near Samos Island (Greece), and its rich aftershock sequence, offered a unique opportunity to investigate the anisotropic properties of the upper crust in the Eastern Aegean. We analyzed seismic waveforms recorded by stations located on and near Samos, using

events since 2015, including the 2020 aftershocks. Results indicate a complex state of stress on Samos, with polarization being influenced by different sources of anisotropy.
The initial intent was to establish the state of the fast S-wave polarization in the region and discover possible temporal variations of splitting properties related to the recent 2020 event, but this was not feasible due to lack of local events in the immediate time preceding the earthquake. Nevertheless, we uncovered a sequence of increase and decrease of time-delays, possibly related to the occurrence of an Mw=6.3 event in 2017, approximately 130 km away, which is well correlated with existing models. We discuss the reliability of our findings and offer insight on the role of both splitting parameters in achieving a so-called "stress-forecast".

ESC2021-S10-101

Upper mantle deformation signatures of craton–orogen interaction in the Carpathian–Pannonian region from SKS anisotropy analysis

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During the Mesozoic, central and eastern European tectonics were dominated by the closure of the Tethys Ocean as Adria and Europe collided, forming the Alpine-Carpathian Orogen. In the Miocene, the edges of the East European Craton and Moesian Platform were reworked in collision during the Carpathian orogeny and coeval lithospheric extension formed the Pannonian Basin. To investigate the mantle deformation signatures associated with this complex collisional-extensional system we analyse SKS splitting at 123 broad-band seismic stations in the region. Fast polarization directions are mostly NW–SE oriented across the seismically slow West Carpathians and Pannonian Basin and are independent of geological boundaries, absolute plate motion direction or an expected palaeo-slab roll-back path. Instead, they are systematically orthogonal to maximum stress directions, implying that the indenting Adria Plate, the leading deformational force in Central Europe, reset the upper-mantle mineral fabric in the past 5 Ma beneath the Pannonian Basin, overprinting the anisotropic signature of earlier tectonic events. Towards the east, fast polarization directions are perpendicular to steep gradients of lithospheric thickness and align along the edges of fast seismic anomalies beneath the thick Precambrian terranes outside the Carpathians, supporting the idea that craton roots exert a strong influence on the surrounding mantle flow. Within the Moesian Platform, SKS measurements become more variable with Fresnel zone arguments indicating a shallow fossil lithospheric source of anisotropy likely caused by older tectonic deformation frozen in the Precambrian. In the Southeast Carpathian corner, in the Vrancea Seismic Zone, a lithospheric fragment that sinks into the mantle is sandwiched between two slow anomalies, but smaller SKS delay times reveal weaker anisotropy occurs mainly to the NW side, consistent with asymmetric upwelling adjacent to a slab, slower mantle velocities and recent volcanism.

ESC2021-S10-104

Shear-Wave Splitting in the Alpine Region

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We study SKS shear-wave splitting from the region densely covered by the AlpArray seismic network, to constrain seismic anisotropy under and around the Alps. Our technique is based on measuring the splitting intensity, using several stabilization measures to deal with the inherent tradeoff between bias and measurement instability that is controlled by the degree of (accepted) noise level.

4 years of teleseismic earthquake data were processed automatically (without human intervention), from 724 temporary and permanent broadband stations of the AlpArray deployment including ocean-bottom seismometers. We have thus obtained a reproducible image of anisotropic structure, at a spatial resolution that is unprecedented in the study region. As in earlier studies, we observe a coherent rotation of fast axes in the western part of the Alpine chain, and a region of homogeneous fast orientation in the central Alps. The spatial variation of splitting delay times is particularly interesting. On one hand, there is a clear positive correlation with Alpine topography, suggesting that part of the seismic anisotropy (deformation) is caused by the Alpine orogeny. On the other hand, anisotropic strength around the mountain chain shows a distinct contrast between Western and Eastern Alps. This difference is best explained by the more active mantle flow around the Western Alps. We discuss earlier concepts of Alpine geodynamics in the light of these new observational constraints.

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Seismic anisotropy study of the upper crust in the Bransfield Strait (Antarctica)

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In the present study 380 seismic events were located in the Bransfield Strait area, which is a rift where active extension is ongoing, located in the Antarctic Ocean, between the South Shetland Islands and the Antarctic Peninsula. The Strait is approximately 120 km wide and 500 km long with a maximum depth of 2 km. The events were recorded during 2018-2019 by twelve seismological stations, nine of which are temporally installed by the BRAVOSEIS project, two are permanently installed by the same group in previous projects, while one belongs to the Argentinean-Italian Network. The majority of the events were intermediate-shallow (focal depth< 30 km), of small magnitude (Md< 3) and were located in the proximity of the South Shetland Islands and in the Bransfield Strait. The goal of the study was to investigate the area's upper crust seismic anisotropy. For that purpose, the shear-wave splitting phenomenon was examined and evidence about the direction of the dominant stress field and the degree of anisotropy in the crust was acquired. We obtained reliable measurements for 41 event-station pairs for 10 stations. Four stations had enough results to define a mean anisotropy direction. The obtained fast shear-wave polarization direction under BYE station suggests that seismic anisotropy is caused by the ongoing rifting or by the compression that occurs west of the station. Under FRE and JUBA stations seismic anisotropy is due to compression, probably by periodical movement lock of the subduction to the north, or by the inflation of the magma chamber of the Orca Volcano. Under AST station, the mean polarization direction suggests that it might be caused by an unmapped structure. Although further investigation is required, the results show that shear-wave splitting may play an important role to understand the stress distribution in the Bransfield Strait.

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Layered mantle flow beneath the Japan Sea and NE China from inversion of surface wave dispersion using rj-MCMC method

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Surface wave dispersion data with azimuthal anisotropy can be used to invert for wavespeed azimuthal anisotropy, which provides essential dynamic information about depth-varying deformation of the Earth's interior. The traditional method to solve this inversion problem is a two-step scheme, i.e. inverting the isotropic wavespeed first, based on which the anisotropic part is solved successively. In this study, we simultaneously invert both the isotropic and anisotropic shear wave velocity using the rj-MCMC (reversible jump Markov Chain Monte Carlo) algorithm, which allows sampling the model space in a transdimensional way.

We apply the method to obtain crustal and upper mantle azimuthal anisotropy of Northeast Asia, including the Eastern North China Craton, Northeast China, Korean Peninsula and the Japan Sea. The data used in this study is from a recent two-station surface wave tomographic research by Fan et al. (2020). The 3-D isotropic shear wave velocity model we obtained reveal some local mantle upwellings related to some intraplate volcanoes, as well as convective systems associated with lithospheric subsidence. Moreover, a two-layer anisotropic model is firstly proposed in this study, which exhibit a large-scale dynamic characteristic of the Northeast Asia together with previous SKS studies.

ESC2021-S10-196

Seismic anisotropy on volcanoes and geothermal areas

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Seismic anisotropy is used as a tool to determine the crustal stress state, and its changes have been attributed to magmatic activity and geothermal extraction. We present preliminary results from a systematic review of crustal anisotropy in volcanic and geothermal regions. The objective is to provide a database of anisotropy measurements and their error bars. We will use the database to test hypotheses about the origin of anisotropy, and about its utility for monitoring magmatic unrest or geothermal production. Of the 764 articles that matched our search terms, 242 were deemed relevant. The majority of these examined shear-wave splitting in volcanic regions.

S-wave anisotropy was also determined from surface waves and receiver functions. These methods were both helpful for determining the depth distribution of anisotropy and surface waves determined the difference in wave speed between vertically versus horizontally polarised waves. P-wave anisotropy was best determined from earthquake body wave tomography or from controlled source experiments.

Generally, the highest values of anisotropy (>10%) were measured in the near surface and the lower crust, relating to cracks closing rapidly with depth and to the most anisotropic minerals occurring as schistose material in the lower crust. The shallow crust often has velocities fastest in the vertical plane due to vertically aligned cracks, dikes and aligned vents, while deeper regions are fastest in the horizontal plane, due to layered materials, horizontal deformation or aligned sills.

Shear wave splitting fast directions are most often interpreted in terms of regional stress directions, but local stress changes due to topography, and structural controls such as fault orientations are increasingly considered important. Almost all of the studies examining temporal variation used shear-wave splitting. Stress changes can explain some of the observed parameter variations, but changes in gas or liquid content in cracks may also be important.

ESC2021-S10-210

Shear wave Splitting in Central Apennines (Italy): anisotropic parameters and seismic sequences

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Central Apennines (Italy) is a region of high seismic hazards and in the last decades was affected by moderate to strong earthquakes followed by seismic sequences of thousands of aftershocks (i.e. L'Aquila 2009, Amatrice-Visso-Norcia 2016-2017). The Apennines chain is a fold-and- thrust belt characterized by NE-SW extensional tectonics and NW-SE-trending active normal faults mostly parallel to the dominant SHmax. This area is affected by widespread CO2 degassing occurrences and deep fluid circulation, which could facilitate fault reactivation and reduce the recurrence time of an earthquake.

In areas where active faults are present tectonic stress variation influences fracture field orientation and fluid migration processes and the state of the fluid in the rock, whose evolution with time can be monitored through the changing in anisotropic properties measurement providing useful information about fault failure process.

The anisotropic datasets, analysed in the last years, have been explained considering the main interpretative models proposed in the literature. In the structural anisotropy model the local stress field and cracks are aligned by past tectonics phases and are not necessarily related to the presently active stress field. Therefore, the variations of the anisotropic parameters are only space-dependent.

In the EDA and APE models fluid-filled micro-cracks are aligned or 'opened' by the active stress field and the variation of the stress field might be related to the evolution of the pore pressure in time; therefore, in this case the variation of the anisotropic parameters are both space- and time-dependent.

In our review analysis, we collect different datasets of crustal seismic anisotropy related to earthquakes that occurred in the last two decades along the central Apennines and use them to analyse the state of stress and the fracture field associated with the distribution of earthquakes, the lithology, the fluid migration and the pore pressure state in the crust.

ESC2021-S10-217

Peeking inside the deep structure through seismic anisotropy: a review in the Italian region

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Over the years, seismic anisotropy has become one of the most popular methods to study and understand the Earth's deep structure. Starting from more than 20 years ago, considerable progress has been made to map the anisotropic structure beneath the Central Mediterranean area. In particular, several past and current international projects (such as RETREAT, CATSCAN, CIFALPS, CIFALPS-2, AlpArray) focused on retrieving the anisotropic structure beneath Italy and surrounding regions, promoting advance in the knowledge of geological and geodynamical setting of this intriguing area. Indeed, the reason for the improvement of these studies is the attempt to better understand the complex active geodynamics of Apennines, Alps and Dynaric

belts, together with the extensional Tyrrhenian basin and the active and remnant subductions characterizing this region.

Dense high-quality seismic networks, permanent run by INGV and other institutions, and temporary deployed in the framework of international projects, joined with the improvements in data processing and the use of various and even more sophisticated methods proposed to quantify the anisotropy, allowed to collect a huge amount of anisotropic parameters from different seismic phases.

Here, a parade of all measurements done on core refracted phases (SKS, SKKS) or on S-direct phases when possible (e.g. southern Tyrrhenian slab), seismic anisotropy detected through harmonic receiver function studies, together with Pn anisotropy maps and results of elaborations on multilayered or complex anisotropy patterns, will be shown. Images of anisotropy patterns, paired with tomographic images, identify well-developed mantle flows around the sinking European and Adriatic slabs. Slab retreat and related mantle flows are interpreted as the main driving mechanism of the Central Mediterranean geodynamics.

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Identifying Seismic Anisotropy Patterns and Improving Tomographic Images in the Alps and Apennines with Splitting Intensity

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Active and past subduction systems influence the interpretation and understanding of current tectonics and velocity structures of the upper mantle of the Alps and Apennines. Computational advances over the years made it possible to identify remnant and active slabs up to great depths and large seismic deployments revealed mostly clockwise rotation of SKS splitting measurements in the Alpine region.. The complexity of layered anisotropy, upper mantle flow through possible slab detachments, and subduction related anisotropy with a dipping axis of symmetry is still not completely recovered. In this study we intend to identify anisotropic depth dependencies and improve tomographic images of the upper mantle by mapping and comparing existing and new anisotropy measurements (e.g., SKS, Pn anisotropy, azimuthal anisotropy from surface waves tomography, and splitting intensities). In particular, splitting intensities will be analyzed with the aim to be used to correct velocities in a full-waveform tomography. Furthermore, we try to improve the handling of splitting intensity data with tests on synthetic models. One goal is to automate the data filtering and processing, making it possible to apply the method to larger regions without being very time consuming. Secondly the study aims to analyze the effects of dipping and complex anisotropy on splitting intensity values and splitting parameter calculations.

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The Expression of Seismic Anisotropy in Ps and Sp Converted Waves

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Many researchers have used the birefringence of P-to-S converted waves from the Moho discontinuity to constrain the anisotropy of Earth's crust. However, this practice ignores the substantial influence that

anisotropy has on the initial amplitude of the converted wave, in addition to the splitting acquired during its propagation from interface to the seismometer. We find that large amplitude variations with back-azimuth occur for P-wave anisotropy, as well as S-wave anisotropy, and that the variations are largest for crustal anisotropy with a tilted axis of symmetry, a geometry that is often neglected in birefringence interpretations. The S-P receiver functions also constrain anisotropy at depth via the back-azimuth variation of Sp-phase amplitude on the vertical component. This Sp behavior is not typically studied, but it has the potential to test the hypothesis that the seismic lithosphere-asthenosphere boundary (LAB) is caused by a transition in anisotropic layering at the base of Earth's tectonic plates. Simulations of these wave-propagation effects with the ANIMATIVITY reflectivity code, a public software package based on Matlab, suggest that the practical use of S receiver functions to investigate anisotropy will depend on accurate determination of the initial S-wave polarization.

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Azimuthal anisotropy of receiver functions in the Central South China Block and its tectonic implications

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South China Block is located in the south of Chinese mainland. By the H-κ stacking of the receiver functions and the splitting of the Pms phases, this study obtained crustal structures of the central South China Block, using seismic data from the HN Array, a dense temporary seismic array deployed for 2 years. The result shows strong lateral heterogeneity in crustal structures in the central South China block. Crustal thickness reduces from northwest to southeast, with significant differences across boundary of sub-blocks. The average crustal Vp/Vs ratio gradually increases from west to east, leading to high values in the coastal region, which suggests the subduction of the Pacific plate has possibly caused the underplating of magma or the upwelling of upper mantle material. Affected by the tectonic confinement of the surrounding plates and the orogenic belts including faults, the complex anisotropic structure in the crust has evolved inside the South China block. The crustal azimuthal anisotropy of the Qinling-Dabie orogenic belt and the Jiangnan orogenic belt is generally consistent with the strike of the tectonic belt as well as the direction of absolute plate movement. It suggests that the crustal azimuthal anisotropy of the orogenic belt is related to the extension and deformation of the lithosphere. During the collision between the Middle and Lower Yangtze block and the North China block, strong nappe structural deformation occurred along the Qinling-Dabie-Sulu orogenic belt. The anisotropy in the crust is closely related to the crustal deformation. The direction of fast S wave in the crust and the upper mantle in the Cathaysia block is generally consistent with the direction of absolute plate motion, indicating that the azimuthal anisotropy of the Cathaysia block is related to lithospheric deformation and the under-invasion of upper mantle material. This study is supported by NSFC Project (41604038).

ESC2021-S10-255

Imaging crustal structure and azimuthal anisotropy in the southeast margin of Tibetan Plateau from ambient noise data

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Southeast margin of Tibetan Plateau is related to the collision of Indian and Eurasian Plates and has been uplifted and deformed since Quaternary. The models on the uplifting and the deformation mechanisms are still in arguement.

This study collected continuous seismic data for 6 years (2007-2009, 2011-2013) recorded by 153 broadband stations from China Digital Seismic Network (CDSN) to image the crustal structure and the azimuthal anisotropy beneath the southeast part of Tibetan Plateau. Phase velocities and azimuthal anisotropy are obtained from the empirical Green's functions in the periods of 5 s to 35 s. Then adopting the pure-path Rayleigh-wave dispersion curves for each grid node, we finally construct the 3D shear wave velocity in this area.

The results show that, at periods 5 s and 10 s, the sediments feature much slower seismic velocities than crystalline rocks so Sichuan basin and Simao basin show low velocity. The azimuthal anisotropy in same periods is close related to the regional fault that the polarization direction of the fast wave generally goes along the strike of the fault. At periods of 20 s, 25 s up to 30 s, Sichuan-Yunnan rhomboid block becomes low velocities gradually, but it begins to become high velocity anomaly. At periods of 30 s to 35 s, the patterns of azimuthal anisotropy is different from those at periods 5 s to 10 s, but gradually consistent with the fast wave directions of SKS (including PKS and SKKS) phases. It suggests that the azimuthal anisotropy at periods 30 s to 35 s has reflected the influence from the upper mantle. Combining other independent studies, these observations suggest that there may be different deformation style in the crust and upper mantle in the southeast margin of Tibetan Plateau. This study is supported by NSFC Project 4180040231 and 41730212.

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3D Anisotropic tomography: A novel method and its application in SW Iceland

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A new algorithm and computer code for seismic tomography in anisotropic inhomogeneous media was developed. The new tomographic approach is a generalization of classical isotropic seismic tomography introducing spatially and directionally varying slowness. The velocity model is considered as a stack of homogeneous blocks in contact, each block being individually parametrized by background velocities of P- and S-waves and a set of 21 anisotropy parameters. Inverse problem is solved sequentially in five steps when velocity model provided by previous step is used as the starting model for the next step. These steps form a chain with increasing complexity: (1) isotropic homogeneous model; (2) isotropic velocity model with vertical velocity gradient; (3) 3-D inhomogeneous isotropic velocity model; (4) 3-D inhomogeneous model with uniform anisotropy; (5) 3-D inhomogeneous generally anisotropic model. The new algorithm was applied to real bulletin data of 18 seismic stations deployed in SW Iceland and operated preferably for monitoring of local swarm-like seismicity. Next the resolution, robustness and accuracy of the inversion were discussed using real and synthetic data. Real data inversion revealed predominantly depth-dependent isotropic velocity background and additional general 3-D anisotropy. Parametrization of the medium is too flexible to enable credible interpretation of the anisotropy inside elementary blocks and, cluster analysis was applied to stabilize the inversion results. Three important clusters were identified. Orientation of the anisotropy (fast and slow P-wave propagation directions) of two clusters coincides with the strike of documented faults. The orientation of the anisotropy in the third cluster is considered as a consequence of fluid dynamics around the Kleifarvatn Lake. The P-wave anisotropy strength reaches the value of ±5 – 8%.

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High-resolution lithospheric shear-wave structure beneath the central-southern Tanlu fault: implications for its initiation and geodynamics

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Tanlu fault is a well-known lithosphere-cutting strike-slip fault in eastern China, playing a crucial role in regional plate tectonics since the Middle Mesozoic. However, there are still many controversies especially on the origin and tectonic evolution of the Tanlu fault, partially due to the lack of constraints from deep structures. In this study, we extracted 5–150 s surface wave dispersion data from 253 permanent stations and 111 temporal stations surrounding the central-southern Tanlu fault. We applied an approach of direct surface wave tomography to obtain the isotropic and azimuthally anisotropic shear-wave velocity (Vs) models simultaneously. The Vs models reveal unprecedented and interesting structures, including arc-shaped Vs fast directions in the southeast corner of the Dabie orogen, a half-circle-shaped pattern of Vs fast directions around the crust of the Luxi uplift, fault-parallel Vs fast directions in the Tanlu fault throughout the crust, a fan-shaped pattern of Vs fast directions and wide-spread low-velocity anomalies in the asthenospheric mantle, and orogen-parallel high-velocity anomalies presented near both the Dabie and Sulu orogens at depths larger than 130 km. Based on these new discoveries and previous tectonic frameworks, we envisage a possible tectonic model of the Tanlu fault. The tectonic model suggests an abrupt termination of the Tanlu fault at the south end, anti-clockwise rotation in the eastern areas (relative to the Tanlu fault) while clockwise rotation in the western areas, decoupled deformations between the crust and mantle, and break-off oceanic slabs from the subduction of the SCP beneath the NCP. The high-resolution Vs models obtained in this study provide important constraints for the regional deformations and plate tectonics of the Tanlu fault.

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Pn wave velocity and anisotropy beneath the central segment of the North-South Seismic Belt in China

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In the central segment of the North-South Seismic Belt in China there are numerous stable basins and active faults, making this segment attractive for extensive studies. We present a Pn wave velocity and anisotropy model of this region, obtained by a tomographic analysis of 49973 Pn wave phase readings collected by the China Earthquake Networks Center and temporary stations in Yunnan and Sichuan. The tomographic velocity model shows that the average Pn wave velocity is 8.06 km/s; prominent high-velocity (high-V) anomalies are visible under the Sichuan Basin, the Zoige Basin and the Ordos block, which clearly outline their tectonic margins. A pronounced low-velocity (low-V) zone is observed from the Songpan-Ganzi block to the Chuan-Dian and Daliangshan blocks, suggesting the presence of hot material upwelling. The station delay data show a gradual variation from negative to positive values, possibly reflecting a crustal thickness variation from the southwest to the northeast of the study region. A correlation between the Pn wave anisotropy and the distribution of velocity anomalies is observed: anisotropy is relatively weaker in the high-V anomaly zones beneath stable basins, while it is stronger in the low-V anomaly zones and the high-to-low-V anomaly transition zones. The high-resolution velocity and anisotropy tomographic model that we obtained could also

provide a better understanding of the study region seismicity, since the occurrence of strong earthquakes seems to be related to the presence and strength of lateral heterogeneities at the uppermost mantle level.

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Seismic anisotropy around the north segment of Xiaojiang faults in the SE margin of Tibetan Plateau and its tectonic implications

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The Xiaojiang faults (XJF) located in the SE margin of the Tibetan Plateau is a fault system of left-lateral strike-slip and striking N-to-S between the 2nd-order Sichuan-Yunnan rhombic tectonic block and the 1st-order South China block. The area around the XJF is characterized by strong tectonic movement and high seismicity because of the collision between the Indian plate and the Eurasian plate and the resistance of the South China block. Using data from 62 stations of the Qiaojia Temporary Seismic Array (QJ Array), deployed by the Institute of Geophysics, China Earthquake Administration, this study obtains the seismic anisotropy characteristics by the shear-wave splitting (SWS) analysis, using the seismic records of small local earthquakes from January 2013 to November 2020, and discusses the deformation patterns in the upper crust in the north segment of XJF. The preliminary results show that the predominant polarization of fast shear-wave (PFS) in the study area is in NNW orientation. The predominant direction is consistent with the direction of the regional principal compressive stress. According to the PFS pattern, the study area would be divided into two subzones, the subzone S and the subzone N. In the subzone S, the predominant PFS orientation is in NS direction, parallel to the strike of XJF. The PFS orientations in the subzone N are complicated, and the predominant PFS orientation is in NNW, which is consistent with the direction of the regional compressive stress. It suggests that the seismic anisotropy in the upper crust in the subzone S is caused by XJF. But in the subzone N, the seismic anisotropy in the upper crust is associated with both the regional compressive stress and the local tectonics.

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Shear-wave splitting in the upper crust revealed by a temporary linear seismic array in the southern Sichuan-Yunnan block, SE margin of Tibetan Plateau

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The southern Sichuan-Yunnan rhombic block (SYB), intersected by the Xiaojiang fault (XJF) striking NS and the Honghe fault (HHF) striking NW, is a crucial zone for material escape. The HX Array (i.e., the Honghe-Xiaojiang temporary linear seismic array) was deployed in December 2017. With seismic data recorded by the HX Array and permanent seismic stations over 22 months, this study conducts investigation of shear-wave splitting parameters of local earthquakes. Based on results of seismic data analysis, the study area can be divided into two subzones. The PFS (i.e., the polarization of the fast shear wave) along the observation line has obvious deviation in the area of Yimen. In the west subzone, across the HHF and Lancangjiang fault, the dominant PFS orientations in NW are consistent with the direction of regional principal compressive

stress as well as the strikes of faults, which suggest the joint effect of faults and stress. However, in east subzone across the XJF, the dominant PFS orientations in NE are inconsistent with the faults or stress, which may indicate strong distortions of the South China block. Interestingly, the upper crustal anisotropy has good consistency in PFS orientations in a belt of zone at both sides of the HHF or the XJF. One reason for this phenomenon is that these two large faults could tectonically control wide range and influenced significantly on the anisotropic pattern in the crust. With reference to the data from Pms anisotropy and XKS (SKS, SKKS and PKS) splitting, we infer that there might be multiple mechanisms in the crust and the upper mantle as well as in the upper and the lower crust. This study demonstrates an effective way to study upper crustal anisotropy with dense temporary seismic array [supported by NSFC Project 41730212 and National Key R&D Project of China 2017YFC1500304].

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Quantifying uncertainty in radial anisotropy models based on two-step Bayesian inversion of Love and Rayleigh wave dispersion and receiver function: case study Sri Lanka

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Radial seismic anisotropy (RA) designates the difference between the speeds of vertically and horizontally polarized shear waves. RA in the crust can provide information on past tectonic events. In the inversion problem, data uncertainty must be quantified to balance the data fitting ability of the model and its complexity. The transdimensional Bayesian approach is able to quantify non-uniqueness resulting from this tradeoff and thus to provide uncertainty estimates taking fully into account the nonlinearity of the forward problem. Traditionally, two-step RA inversion of surface wave dispersion and receiver function only takes account of the uncertainty in the second step. In our study, we first determined period-wise group and phase velocity maps for Love and Rayleigh waves. To remove outliers, data uncertainty distribution is expressed as a mixture of a Gaussian and a uniform distribution. In both steps, a hierarchical transdimensional Bayesian Monte Carlo search with coupled uncertainty propagation is being applied. The number of layers and data errors are treated as unknown. Then, probabilistic profiles of the isotropic average Vs and RA as a function of depth across stations are obtained by inverting local dispersion curves and receiver functions jointly. Model errors are propagated from the 2D velocity tomography to the 1D shear velocity inversion as relative uncertainties for the 1D joint inversion.

We applied our methods to a temporary broadband array covering all of Sri Lanka. Our two-step Bayesian inversion effectively quantifies the uncertainty of the final RA model and shows robust results in regions with good ray coverage, except a slight increase of uncertainty at interfaces which should be the trad-off between layering and anisotropy. The negative RA (Vsh > Vsv) found in the middle of Sri Lanka may indicate the existence of vertically oriented shear zones during the amalgamation of Gondwana.

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Characteristics of crustal medium anisotropy and tectonic significance in the Qinghai Lake Basin, northeastern margin of the Tibetan Plateau

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The northeastern margin of the Tibetan Plateau is the frontier of the outward expansion of the Tibetan Plateau, and the unique tectonic pattern of basin-range interval is developed. The study of the fine crustal structure of the basin and the basin-range coupling relationship is important for understanding the outward expansion of the plateau. In this paper, the seismic data from nine stations of the Himalayan II mobile array were analyzed using the method of post-azimuth weighted superposition of radial and tangential receiver functions to determine the crustal anisotropy parameters of the Qinghai Lake Basin at the northeastern margin of the Tibetan Plateau. The results show that the crustal medium in the study area is strongly anisotropic, with a mean fast and slow wave delay time of 0.48 s. The fast wave direction is controlled by the mountain range, with two stations on the northwest side parallel to the Datong Shan, four stations on the southwest side parallel to the Qinghainan Shan, and three stations on the east side parallel to the Riyue Shan, and overall, the anisotropic fast wave direction surrounds Qinghai Lake in a circle. The above results reveal that the Qinghai Lake basin is a stable block, and there are weak zones in the combination with the circumferential mountains, which also exists in the Xining basin and the Gonghe basin. The essence of the current basin-ridge tectonic pattern on the northeastern margin of the Tibetan Plateau is a soft zone orogeny between rigid block extrusions.

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Seismic anisotropy from S waves in the SE margin of Tibetan Plateau: Probing into lithospheric deformation in different scales

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Strong tectonic movement and high seismicity, appears in SE (southeast) margin of Tibetan Plateau, due to the confliction between the Indian plate and the Eurasian plate and the obstruction of South China block. In order to investigate the lithospheric deformation in SE margin of Tibetan Plateau, this study reveals the seismic anisotropy of S waves in three scales, the upper crust, the whole crust and the lithosphere.

Firstly, the S wave splitting of local earthquakes indicates seismic anisotropy in the upper crust. The polarizations of fast S waves (PFS) show the dominant orientation nearly in NS in the study area, but in NNW, NNE or other orientations in different subzones. The PFS is generally consistent with the principal compressive stress, although more scattered by station.

Secondly, this study shows the azimuthal seismic anisotropy in the whole crust, detected from the receiver functions of the Pms phases. With results by other researchers, the general pattern of the fast orientations harmonizes with the PFS, although different in some specific subzones. Also, the fast orientations at stations are more scattered, maybe partly originated from calculation errors.

Last, the azimuthal seismic anisotropy in the lithosphere, maybe including the topmost asthenosphere, is indicated by the fast orientations of XKS (i.e. SKS, PKS and SKKS phases) splitting. The lithospheric anisotropy is characterized by two subzones. The subzone south and the subzone north is bounded along about 26°20’N. The fast directions are in NS in the north and in EW in the south.

The azimuthal seismic anisotropy in the lithosphere shows the multi-scale pattern of subzones. It reveals different deformation from the shallow thinner upper crust to the deep thicker lithosphere. Further it suggests complicated regional deep tectonics and deep substance migration process. [supported by National Key R&D Project of China 2017YFC1500304 and NSFC Project 41730212].

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On the interpretation of teleseismic shear wave splitting measurements: Lessons learned in North America, Africa, and Australia

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Teleseismic shear wave (mostly SKS, SKKS, and PKS) splitting analysis is a major component of structural seismology. Mostly due to the limited vertical resolution of the splitting measurements, a considerable degree of ambiguity exists in the interpretation of the splitting measurements. To provide constraints on the vertical distribution and layering of the anisotropic structure, we have developed and adopted a number of approaches for the ultimate goal of reliably interpreting the splitting parameters, such as 1) searching for an optimal depth that leads to the maximum spatial coherency of the splitting parameters; 2) conducting splitting analysis of the P-to-S converted phases from the 410 km and 660 km discontinuities to distinguish contributions from the lower mantle, the mantle transition zone, and upper mantle; and 3) relating splitting parameters to surface wave or body wave anisotropic tomography inversion results. Applications of the above techniques at ~4000 stations in North America, Africa, and Australia suggest that the major contributing layer to the observed azimuthal anisotropy is the rheologically transitional layer between the lithosphere and asthenosphere. The fact that the fast orientations are similar to the absolute plate motion (APM) direction implies that 1) the lithosphere is either moving on top of a stationary asthenosphere (relative to the lithosphere) or 2) the two are moving toward the same or opposite directions at different speeds. While it is a common practice to attribute APM-inconsistent fast orientations to lithospheric fabrics, we found that for most cases such inconsistency can be alternatively attributed to deflection of mantle flow by the undulations of the bottom of the lithosphere especially by cratonic keels. The depth contour of the keels and lithospheric fabrics (such as those parallel to orogenic belts surrounding the cratonic core) usually have the same trend, leading to ambiguities in the source of the observed anisotropy.

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Full-wave multiscale tomography for the upper mantle anisotropy under Sichuan-Yunnan, China

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Sichuan-Yunnan region is located in the southeastern margin of the Tibetan Plateau. This region has experienced complex deformation since the Cenozoic and has a relatively high level of seismicity. Seismic anisotropy reveals the deformation of the materials at depth, and knowledge of the anisotropic structure of the upper mantle under Sichuan-Yunnan improves our understanding on the regional seismotectonics. In this study, we use the full-wave multiscale anisotropy tomography method to investigate the seismic anisotropy in the Sichuan-Yunnan region. Our approach uses the full-wave theory to model the SKS waveforms, which enables us to compute the sensitivity kernels of the SKS splitting intensities to the 3D variation of anisotropy. We collect three-component broadband records at ~150 seismic stations in the region from teleseismic events occurring during 2009-2020 and measure the SKS splitting intensities. The 3D anisotropic model obtained from the inversion can help us better understand the distribution and mechanism of the deformation in the southeastern margin of the Tibetan Plateau as well as their implications to the regional seismotectonics.

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From school seismology to citizen science

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New online tools for educational seismology in Romanian Educational Seismic Network

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The National Institute for Earth Physics – NIEP is the leading institution for seismology in Romania, responsible for seismic monitoring and advanced seismological research in Romania. One of the NIEP objectives is to improve the link between research, education and outreach. Operating the educational seismometers in schools and museums opens the opportunities for students to practice in the field of physics, earth sciences, ICT and geography. Presently, the Romanian Educational Seismic Network consist of 10 SEP seismometers, 7 Slinky seismometers, 18 Raspberry Shake 1D seismometers and data from 18 broadband seismometers from Romanian Seismic Network operated by NIEP. A series of educational software's (e.g. jAmaseis, Seisgram2k, Swarm) for earthquake analysis are already familiar to schools that use educational seismometers to teach geosciences. The educational seismic network is able to record local earthquakes from Vrancea seismic area with magnitude Ml=4. With the installation of Raspberry Shake 1D seismometers, the network became able to record earthquakes from teleseismic distances with magnitude 6 and from regional distances with magnitude 5. During the last year the educational seismic network recorded 7 local earthquakes and 5 regional earthquakes. The installation of Raspberry Shake 1D seismometers increased the recording capacity of the network. Data from the educational network are also used in scientific research. Methods and programs of data analysis, which are usually used by researchers, are adapted for application in the learning process of geosciences in schools. Python codes and Jupyter Notebook used by seismologists to analyze seismic data are now available to teachers and students to improve their programing skills using real seismic data and to learn more about Earth sciences. The works capitalize on and at the same time offer sustainability to the results of successful projects (ROEDUSEIS and MOBEE).

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ALARM: a virtual Escape Room combined with a webinar to play seismologist

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Bringing young people closer to science and scientific careers is an ancient problem, linked to how science is communicated, not only within the classroom but also and above all by universities, research institutions and society. For this reason, the interest in Science Communication is increasing more and more. To this purpose, already in 2004, the Italian Ministry of Education, University and Scientific Research activated the Scientific Degree Plan (Piano Lauree Scientifiche - PLS). This program objectives are the dissemination of scientific culture, the encouragement of young people to undertake the study of scientific subjects and the improvement of orientation possibilities through initiatives that offer the opportunity to have a first direct experience with the world of research.

Within the academic year 2020/21 edition of PLS, due to the COVID19 pandemic, we were faced with the need of adapting to the schools approved virtual tools while keeping the overall experience light and interactive, and the learning informal.

We developed a virtual Escape Room to be combined with a webinar. Our goal was to allow the students to be at the center of the action while not only learning the scientific content but also developing problem solving and leadership skills. Pupils played a technical support team with the goal to send help to a community who suffered an earthquake in the southern Apennine area in Italy . To do so, they had to solve two main tasks, e.g. locate the earthquake epicenter using the triangulation method and assess its local magnitude, and some smaller themed puzzles.

We repeated the experience with different schools and number of participants. The final students' evaluation of the event showed that its online characteristic was perceived as positive due to introduction of the virtual Escape Room.

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A tiny box that can do a lot. Lessons learned from Raspberry Shake hosts experience in Haiti

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On January 12th 2010, Haiti was hit by one of largest seismic disasters known to date. This left many political, economic, social and psychological scars and made risk reduction a key issue for the country's future. At the time, seismic risk culture and perception was rather low among the population, and so was seismological knowledge, due to the lack of seismic sensors in Haiti.

Low costs seismic sensors were seized as an opportunity to (1) complement the national seismic network and (2) enhance risk perception, preparedness level and scientific knowledge among the population through a citizen-seismology approach. These were the goals of S2RHAI, which studied a paradigm shift under which we consider that seismic networks are not only composed of sensors, but also of the humans gathering around these tools and information.

We present here the results of a qualitative survey conducted among 15 Raspberry Shake (RS) hosts in Haiti. Semi-directive interviews were led to know more about their experience, assess their motivations, difficulties and expectations. We found that RS hosts expressed pride in being part of the network and actively contributing to risk reduction. Some of them reported a form of empowerment as they could palliate the deficiency of the State, which they generally mistrust. However, RS hosts also formulated a need for technical and scientific support from scientists. Additionally, few of them have engaged mediation activities or discussions with members of their community, mainly because they fear it will awaken their trauma caused by the "goudougoudou". This enabled us to list concrete actions to improve the seismic information system, to integrate volunteers better in the network and to accompany them in their ambassador role.

We conclude that, in a citizen seismology project understanding volunteers' motivations, obstacles and expectations is essential and enhances the chances of sustaining it.

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Can high-school students contribute to seismic risk reduction? The development of a crowdsourced exposure database in northeastern Italy

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Since more than ten years the National Institute of Oceanography and Applied Geophysics - OGS throughout its department, the Seismological Research Center (CRS), is hosting students from regional high school institutes, involving them in educational activities with the aim of stimulating their awareness and proactive contribution to seismic risk reduction. Recently, the Italian Ministry for Education launched an innovative program ("Percorsi Trasversali per le Competenze e l'Orientamento – PTCO") aimed at consolidating the educational programme of high school students, through practical training activities useful for their future professional and personal growth. OGS is thus contributing to this programme through an innovative crowdsourcing project named "CEDAS: Censimento dell'Edificato per la stima del DAnno Sismico". The project consists in the characterization of the main residential buildings typologies of the Friuli Venezia Giulia region (NE Italy), so as to contribute to the improvement of the existing regional seismic exposure database. The accuracy of the damage estimates strongly depends on the quality of the information available on the building typologies present in the area. The information available at regional and national level (eg. population and building census) will be enriched with more specific and targeted information collected by the students. Given the impossibility of hosting students to the CRS premises due to the presently ongoing COVID19 pandemic, OGS has adapted the activity to be delivered fully online, with the possibility for students to work remotely. The pilot activity is divided into four phases: online training, individual survey activity (crowdsourcing) , data processing and critical review of the results. This project contributes to the ongoing research activities of the CRS aimed at mitigating the impact of strong earthquake events in northeastern Italy by producing reliable damage estimates, in strict collaboration with the Civil Protection of the Friuli Venezia Giulia and Veneto Regions (NE Italy).

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School Seismology in Nepal for earthquake risk reduction

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To close the gap between research results in earthquake science and the Nepali population living in a high seismic risk zone, we have developed a local educational seismology program starting 2017 [ref.1]. The program currently involves thirty secondary schools, and focuses on two, connected pillars: (1) an operational low-cost seismic network in schools, (2) teaching earthquake-related topics in classrooms. Since spring 2019, the seismometers have been used to record earthquakes, and allowed various 'learning-by-doing' classroom activities. Individuals outside the schools are invited to observe earthquake records on their smartphones, which motivates them for better earthquake preparation. Beyond our funding efforts, the program convinced local governments to co-fund school's participation. The network operation is monitored online, and repairs feasible on site are carried out by Nepali people with remote advices and sometimes autonomously.

We constructed an event detectability graph in distance–magnitude space, and we calibrated a new magnitude equation. To reach the educational objectives, we prepared and adapted several materials to the Nepali education system, and also trained the teachers for their new challenges in the classroom. The knowledge learnt by students is transferred to their personal environment, which helps building earthquake-

safer communities. Our approach was very well received and we could already measure a positive impact of our program. This is encouraging to continue and expand the efforts across Nepal, for which we recently launched a crowdfunding campaign [ref.2].

Finally, our program has developed the Earthquake Awareness Song [ref.3] which has already been seen by >100’000 visitors online. Lessons learned from Nepal will be applied for developing an educational seismic network in Western Switzerland using Raspberry Shake sensors.

Notes
[ref.1] http://www.seismoschoolnp.org/
[ref.2] https://www.gofundme.com/f/help-save-people-in-nepal-from-big-earthquakes
[ref.3] https://www.youtube.com/watch?v=ymE-lrAK0TI

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Intensity-based sentiment analysis. The case of the Aegean earthquake

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An earthquake with a magnitude MW 6.9 hit the coasts of Turkey and Greece on the 30th October 2020. The earthquake with an epicentre located 14 km northeast of Avlakia in the Greek island of Samos and 25 km southwest of Izmir caused a mini-tsunami, which flooded these areas, and resulted in 119 dead, 1,053 injured, and a further 15,000 left homeless. . After an earthquake, it is essential to understand its impact on the population and physical assets. Social media (SM) has become a valuable tool for quickly collecting large amounts of first-hand data after a disaster, essential for efficient emergency response. This analysis aims to test the feasibility of identifying the intensity reached by an earthquake based on the lexicon included in the comments. Using tex-data provided by the European-Mediterranean Seismological Centre (EMSC) collected through the LastQuake app for the Aegean Earthquake, we undertake a sentiment (SA) analysis according to the intensities reported by their users in the Modified Mercalli Intensity (MMI) scale. 2,518 comments were collected, reporting intensities from I to X being the most frequent intensity reported III. According to a rule-set, we use supervised classification defined by authors and two-tailed Pearson correlation to find statistical relationships between magnitudes reported in the MMI and polarities identified in the comments per intensity reported. The correlation analysis indicates that the positive polarity prevails in the comments associated with the lowest intensities reported: (I-II), while the comments with negative polarity in the remaining intensities (III-X). The correlation analysis identifies a negative correlation between the increase in the MMI intensity reported and the positive polarity in comments. We can conclude that the negative polarity in text data is an indicator of significant intensity in the MMI scale. Additional tests are needed to define a correlation with a specific intensity.

ESC2021-S11-535

Seismology in school education promotes scientific literacy, motivates teachers, engages students and fosters collaborations with local stakeholders. The case of the School Networks Alert Citizens Protection project

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The School Networks Alert Citizens Protection project offered schools in different countries the opportunity to expand their horizons and perspectives of collaboration with other schools, to apply, implement and adopt non-traditional educational methods, to increase their awareness of cutting-edge trends and developments in science, technology and education that have significant impact to society. It focused on the study of a physical phenomenon with great societal impact and proposed pedagogical practices based on inquiry-based methods that are effective in science education. The objective of this combination was, to increase students' interest in science, on how science over the years and how it affects everyday life, but also, to stimulate teacher motivation on up-taking innovative teaching methods and practices to enrich and renew the science curriculum. The project proved that seismology in school education is of pivotal importance, as it serves as a fruitful ground for promoting the development of scientific literacy across school levels. At the same time the learning benefits that result in the context of school seismology move beyond the development of scientific knowledge about this phenomenon, as it provides the ground for informed action to protect lives and property on local, regional, and national levels. Based on the quantitative and qualitative results, it became apparent that the project managed to develop an effective mechanism to help participating schools establish an open schooling approach, changing their culture and impacting positively their students, teachers, while connecting at the same time with the local society, the local stakeholders and citizens, including the parents. Concurrently, seismology proved to be a catalytic factor and the appropriate subject to motivate teachers, engage students and attract local stakeholders. Based on pre and post questionnaires, the project positively impacted students' attitudes towards STEM, as well as their critical thinking and understanding of civic responsibility.

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Bringing scientific research in the classroom and fostering awareness and scientific literacy through the “build your own seismograph” contest.

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The educational contest “Build your own seismograph” is organised the last four years by Ellinogermaniki Agogi in collaboration with the Geodynamic Institute of the National Observatory of Athens and the Institute of Educational Policy.

The contest focuses on the study of a natural phenomenon with a large social impact and promotes pedagogical practices based on the exploratory method. The aim of this combination is, on the one hand, to increase students 'interest in science and how it affects everyday life, and on the other hand, to stimulate teachers' interest in innovative teaching methods.

As research in this area shows that the general public is not well informed about the necessary measures to be implemented to minimize the effects of earthquakes, the pedagogical design of the contest proves that a complex geophysical phenomenon such as earthquakes can be studied in the classroom using a simple instrument while students act as scientists.

According to the pedagogical framework of the contest, innovation is seen as the school's path to digital maturity (e-maturity) and integrated use of ICT, and especially as the school's path to “openness” which becomes apparent in its relationship with external partners, in parental commitment, promoting community well-being as a whole, the school's ability to combine curriculum implementation with a study of local challenges, its willingness and ability to share its achievements with other schools and its commitment to challenges of modern Responsible Research and Innovation. Groups of students in collaboration with their teachers are invited to build an improvised seismograph and record the whole process in a presentation accompanied by photographic or other audiovisual material. Their work must contain scientifically correct explanations, interpretations and descriptions and not refer to sources that create misconceptions or misunderstandings in relation to the phenomenon in question.

ESC2021-S11-560

Seismocitizen: Contribution of Raspberry Shake dense seismic networks hosted by citizens for natural and anthropic seismicity monitoring

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After a first deployment of 8 low cost seismic stations (Raspberry Shake type) in 2017 around Strasbourg, we launched end of 2018 a multidisciplinary project of citizen seismology called SeismoCitizen. It associates Seismology with Social/Human science research. It is intended to build a real network of observation sites in urban and peri-urban areas, based on internet-connected stations hosted by volunteers' citizens. They participate in a survey conducted by sociologists aiming at observing and analyzing the effects of a citizen engagement in scientific research (via hosting a seismometer) on the perception and representation of seismology. Before installation, the instrumental response of the station is fully characterized in respect to a BB station at the instrumental testing platform of EOST.

We deployed about 60 stations widespread in three dense networks: Strasbourg area with recent induced seismicity related to geothermal activity (≈ 15 stations), area at the Upper Rhine graben (URG) close to Mulhouse city with a high seismic hazard for France mainland (≈ 20 stations) and west border of URG where active faults are suspected (≈ 25 stations). These dense seismic networks make it possible to densify the mesh of the permanent observation network (RESIF). Despite a higher noise due to their installation in urban and peri-urban houses, the short station-event distance offers a considerable advantage for 3D earthquake location and discrimination. Since 2017, they provided us more than 5400 "P phases" (1475 for earthquakes, 3442 for induced events, 485 for quarry blasts) with 18 stations contributing to more than 100 events (the station with the highest contribution is for 549 events). It improves the French seismic monitoring activities of BCSF-RENASS and products like "shakemap".

ESC2021-S11-563

Evaluating students' attitudes, civic awareness, civic efficacy and connection to community in an open-schooling and citizen seismology context: The case of the SNAC project

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In the context of the Erasmus+ project School Network Alerts Citizens (SNAC), schools from Greece, Cyprus, Italy, Turkey and Bulgaria implemented projects related to educational seismology and citizen awareness. The project's goal was for schools to become open hubs of innovation, education, training and information to their local society through citizen seismology and open schooling. In order to identify the overall impact of the project on students, teachers and school, an evaluation methodology was developed and enacted. Various evaluation tools and methods were employed to adequately evaluate the project (case study reports, students' questionnaires, Self-Reflection Tool (SRT) for schools) following mainly a pre and post design. The quantitative data were analyzed with the use of IBM SPSS Statistics and Excel (using the Analyse-IT plugin) and the qualitative data were analyzed with the open coding method. During the implementations, teachers in almost all schools collaborated with peers and external stakeholders to introduce or enhance an open school culture through innovative projects with the use of real-time seismic data and educational seismometers. On average, there was an increase of 11,2% in pre and post SRT questionnaires of SNAC School. Students from all the countries had more positive attitudes for science after the implementations than before. This difference was statistically significant for Turkey, Greece and Cyprus. Also, students' civic awareness, civic efficacy and connection to community from all the countries was improved after the implementations. This difference was statistically significant for Greece and Cyprus. Bulgarian and Italian students improved statistically significant their civic efficacy. Overall, the project succeeded to a great extent to meaningfully impact schools, teachers, students and the wider community by providing the opportunity to actively participate projects focusing on open-schooling and citizen seismology.

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School seismology network at the National Observatory of Athens

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The "Schools Study Earthquakes" (SSE) and "School Network Alerts Citizens" (SNAC) educational seismology projects have been coordinated by the Institute of Geodynamics (NOA) under the key action "Cooperation for innovation and the exchange of good practices" of the EU Erasmus+ Program.

The target of both projects is to raise the interest and awareness in science and natural disaster mitigation and we approached this goal by establishing a school network of low cost seismometers that operate in real time for studying the seismic waves produced by the ongoing local and distant earthquakes. Traditional pendulum seismometers are used in elementary physics classroom lessons as well as in seismic wave data acquisition together with Raspberryshake sensors and data analysis software for educational purposes (SeisGram2k, AmaSeis , JamaSeis, SWARM).

The seismic activity during these years was rich in large, intermediate and small, magnitude seismic events with epicentral locations in SE Europe as well as major global seismic events. In addition, nuclear and missile explosions and anthropogenic noise during the 2020-2021 Covid lockdown quiescence were recorded and are available in our database.

In this presentation we will demonstrate the school network's ability to detect and archive seismic events in real time with a SeisComp3 software plugin that has been designed to connect the low cost seismometers to traditional seismological observatories, an added value to the seismological community's research on real time hazard evaluation and disaster mitigation. https://snac.gein.noa.gr

ESC2021-S11-592

Prove and improve using a seismology summer school for high school students and teachers

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Seismology at school is already a well known global program for the past 20 years, mainly aiming to support teachers in the use of educational seismometers and real-time seismic data in the classroom. Also citizen seismology has achieved a number of important goals, combining the interest for citizen science in general but especially in the field of disaster management and preparedness.

The model was also introduced from 2012 in Romania in the framework of ROEDUSEIS project (Romanian Educational Seismic Network) and gave project initiators (a research & education partnership) the opportunity to draw a wealth of conclusions and to define the best ways to continue this initiative, as well as to focus on actions that offer sustainability and maximize the impact.

A clearly identified difficulty in the way of a good functioning, scalability and sustainability of an educational seismological network is the maintenance of contact with teachers and the provision of sufficient training to be able to operate the recording instruments almost autonomously. Also, the proof of the usefulness of the data from the educational networks for the improvement of some research products, an objective that equally motivates the researchers to get involved, start to be no longer just a desideratum, and this especially due to the unprecedented development of semi-seismographs. professional.

In this study we will present how a Summer School of Science and Technology that link education to a real research environment, being conducted by researchers and builds on existing research in the field can be used to improve both the level of knowledge of students and teachers who will use seismographs and recorded data, and continuously improve an educational seismological network.

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School Tune into Mars - an educational journey to the Red Planet

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In order to support teachers in developing STEM skills for students which will be needed in the near future, the Schools Tune Into Mars (STIM) project aims to improve effective and quality teaching of science, technology, engineering and mathematics (STEM) disciplines at secondary level and to increase young students knowledge and interest in STEM education by providing pedagogical materials with high-quality inspirational lessons related to planetary seismology as well as adequate guidance and to underpin innovative activities that are developed in a co-constructive process between researchers and teachers.

STIM is a project that brings together a network of schools and organizations with an interest in space education and studies related to the planet Mars.

To achieve all these goals several complementary blocks of activities have been developed: a programmatic document elaborated based on the STIM resources supported by a study aiming to assess the need and

opportunity of STIM resources for teachers; a pedagogical guide to support the use of resources from space missions in classrooms; a Massive Open Online Course (MOOC) entitled “bring Mars missions into the classroom” which provides online training to teachers in order to use innovative teaching materials related to Mars space missions in classrooms and a report with recommendations for the creation of a Mars-Edu network to set the scene for an innovative and long-term collaborative network on space education related to Mars missions.

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Seismological and structural studies in Polar Regions and the cryosphere

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Glacial Hydraulic Tremor on Rhone Glacier, Switzerland

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The hydrologic conditions beneath a glacier have a large impact on basal motion. Glacial Hydraulic Tremor (GHT) can be monitored to observe changes in location and distribution of waterflow beneath glacial ice, allowing the spatiotemporal evolution of subglacial hydrology to be studied continuously and remotely. We use Frequency Dependent Polarization Analysis (FDPA) to assess the temporal and spatial extent of glacial hydraulic tremor beneath Rhone Glacier, Switzerland, captured by a continuous seismic record through 2018 and 2019 at three moraine-based seismometers. From this we determined back azimuth to subglacial channels and observed frequency bands comprising the GHT. This captured the seasonal shift from a distributed system to a channelized system and allowed comparison of channel locations within and across seasons, with implications for sediment evacuation and bed erosion. Across the three locations, there are notable sources of hydraulic tremor which vary based on locality and time of year, each with distinct frequency bands and back azimuth angels. The GHT clearly reflects the seasonal hydrologic cycle whereby the glacier transitions between an efficient, channelized system during the summer and to a distributed system in the winter. The successful use of GHT to monitor glacial hydrology previously on Taku glacier (the methods of which this project follows) and now Rhone glacier support passive seismic monitoring can be used to continuously and cost-effectively monitor basal hydrology across a variety of glacial systems for the first time ever.

ESC2021-S12-042

Monitoring sea ice thickness and mechanical properties with seismic noise

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In the context of global warming, monitoring the thickness and mechanical properties of sea ice is a major challenge in modern climatology. In particular, the heavy logistical constraints of polar environments, and the lack of accuracy of satellite remote monitoring methods, are obstacles to improving climate models. As a result, the decline of sea ice, which has been accelerating over the last four decades, is difficult to predict on short or longer time scales. For example, while only 5 years ago, the Arctic was expected to be ice-free in summer from the 2050s, the latest forecasts indicate that this could happen as early as the 2030s. Accurate and regular measurements of pack ice properties are crucial to better anticipate future changes.

In this presentation, we introduce methods to demonstrate that it is possible to monitor sea ice passively, based on the ambient seismic field recorded continuously in situ. In particular, I introduce analysis methods based on:

- seismic noise interferometry to extract the Green's function of guided waves in ice
- machine-learning algorithms to classify the recorded signals
- guided wave dispersion for a joint inversion of the thickness, Young's modulus, Poisson's ratio, and density of the ice pack, via Bayesian inference methods

Based on these analyses, we demonstrate that it is possible to monitor the temporal and spatial evolution of these parameters at the scale of a few kilometers, with a temporal resolution of a few hours.

ESC2021-S12-082

Seismic studies of seasonally varying permafrost conditions in the SW Svalbard

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The rapid global climatic change is strongly visible all over the world. One particular place where those changes strongly destabilize the current geosystem is in the Arctic, especially with its permafrost changes. In regions where unique environmental balance is nearly not directly polluted by human existence, every global climatic change is greatly visible and thus can be directly studied.

In the presented work, the time-lapse approach utilizing multiple seismic methods, such as MASW, Refraction Tomography and Reflection Imaging, allowed for estimation of environmental changes occurring in the seasonally frozen ground. The results obtained with those methods were directly aimed at visualizing not only the changes in the active layer but most of all the permafrost thickness. The study site, near the Polish Polar Station in Hornsund (Svalbard), is unique due to its location and environmental processes occurring in this region. The close presence of the retreating Hans glacier induces dynamic geological and environmental processes. Two expeditions conducted at different seasons of the year (Autumn 2017 and Spring 2018) allowed for the collection of unique data on changes taking place in both coastal and mountain zones, as well as in post-glacial moraine.

The results reveal, that changes occurring in the subsurface due to seasonal and climatic changes are greater than expected. The seismic recognition of the permafrost layer, based on dense 2D seismic reflection and refraction methods, allowed for direct comparisons between observations conducted at two different seasons. Such knowledge allowed us to better understand the processes responsible for the dynamic geological and environmental processes taking place in the study site.

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ESC2021-S12-119

Ambient seismic noise under the sea-ice of the Arctic Ocean: First results from a pilot experiment with Ocean Bottom Seismometers at eastern Gakkel Ridge

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Seismic monitoring of the cryosphere is mostly done with land seismometers on the surface of ice masses. Seismic monitoring beneath sea ice at the bottom of ice-covered oceans has hardly been attempted, because ocean bottom seismometers (OBS) are difficult to recover in perennial sea ice. As a result, for example the

tectonic activity of the Arctic mid-ocean ridge system is poorly known. Recently, ambient seismic noise in long-term seismic records proved a useful tool to monitor the state of the sea ice cover.

From September 2018 - September 2019, we deployed a trial network of 4 broadband OBS in Arctic sea ice. OBS were positioned at distances of 10 km at a water depth of 4 km on eastern Gakkel Ridge. Station noise levels from power spectral density analysis are considerably lower for sub-ice stations than for OBS in the Greenland Sea and are comparable to those of Arctic land stations. The network was designed to record local earthquakes along Gakkel Ridge, but it also yielded valuable data on the sub-ice ambient seismic noise in the Arctic Ocean. Spectrograms covering the entire deployment reveal pronounced seasonality in different frequency bands: Above 5 Hz, noise levels increase when sea ice cover is present. In addition, anthropogenic noise is prominently seen. The secondary microseismic noise peak has two clearly separable components with opposite seasonal evolution.

Microseisms at 3-10 s periods relate to swell events outside the Arctic Ocean with a higher incidence of such events during winter time. In contrast, secondary microseisms originating in the Arctic Ocean peak in September during the annual sea ice minimum. Their periods increase from 0.5 s to 5 s as the fetch area for wave evolution increases from June to September.

ESC2021-S12-125

Regional and local scale monitoring of glacier dynamics and permafrost in Svalbard

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Cryoseismology is a rapidly developing research area in Earth Sciences with many applications in Polar regions and high mountain areas. The seismic monitoring infrastructure on the Arctic Archipelago of Svalbard has shown to be particularly useful to map and study the spatiotemporal distribution of near-regional glacier-induced seismic events, benefiting from long observation periods of more than two decades. For example, seismic observations calibrated with satellite and terrestrial remote-sensing observations of iceberg calving allow us to estimate glacier frontal ablation rates at Kronebreen, a tidewater glacier in North-East Svalbard, with unprecedented high temporal resolution. These observations help glaciologists in better understanding processes at the ice-ocean interface.

Cryogenic seismic signals have also been utilized to constrain spatiotemporal evolution of glacier surges, which are common in Svalbard and thereby contribute to enhance process understanding. Furthermore, passive seismic data on a local scale have been used to study en- and subglacial processes such as crevassing, glacier speed-ups, and meltwater discharge. Apart from glacier studies, we have conducted pilot studies to explore ambient noise-based time-lapse monitoring of the subsurface. We used the Horizontal-to-Vertical Spectra Ratio method to monitor the permafrost active layer variability. Furthermore, frost-quakes in the active permafrost layer have been used to monitor seasonal changes. In summary, passive seismic techniques have a huge potential to complement established methods for monitoring the cryosphere in Svalbard. We give an overview of currently ongoing activities in glacier and permafrost research and recommend next steps to further advance cryoseismological research in Svalbard.

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The dynamic component of the alpine glacier drainage system revealed by shear wave splitting

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Fractures contribute to bulk elastic anisotropy of many materials in the Earth's crust. This includes glaciers and ice sheets, whose fracture state controls the routing of water to the base and thus large-scale ice flow. Here we use anisotropy-induced shear wave splitting (SWS) to characterize ice structure and probe subsurface water drainage beneath a seismometer network on an Alpine glacier. SWS observations reveal diurnal variations in S-wave anisotropy up to 3%. Our modelling shows that when elevated by surface melt, subglacial water pressures induce englacial hydrofractures whose volume amounts to 1-2 percent of the probed ice mass. While subglacial water pressures decrease, these fractures close and no fracture-induced anisotropy variations are observed in the absence of meltwater. Consequently, fracture networks, which are known to dominate englacial water drainage, are highly dynamic and change their volumes by 90-180 % over subdaily time scales.

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Macroseismic Data from the eastern Canadian Arctic and Implications for Seismic Hazard

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The eastern Canadian Arctic is a vast, remote region encompassing several active seismic zones where the study of earthquakes is challenging. There is no knowledge of earthquakes in the region from instrumental data, historical documents or oral history prior to the occurrence of an Mw 7.4 earthquake in Baffin Bay in 1933. Despite recent upgrades to seismograph networks in Canada and Greenland, instrumental coverage remains sparse relative to southern Canada. Intensity data are also sparse because of the low population density and historically challenging communications between the Arctic and southern Canada. Nevertheless, there is a body of underutilized intensity data and this is the focus of our study. Of the ten known earthquakes of magnitude 5.9 or greater in this region, five can be considered significant because of their magnitude or impact although none have reported intensities greater than V on the Modified Mercalli Intensity (MMI) scale. The intensity data from these earthquakes as well as several smaller ones have been compiled into an easily used format. Although this data set is not sufficiently dense to produce well-constrained isoseismal maps, it is adequate for direct comparisons to southern Canadian earthquakes of comparable magnitudes and to published intensity-distance relations. These consistently show lower intensities and, by implication, higher attenuation in the eastern Arctic. Lg attenuation studies also show evidence for higher attenuation in the Boothia-Ungava region, the source of many of the felt reports, than in the surrounding areas of the Canadian Shield although more work is needed to refine the attenuation relations. Low intensities from earthquakes occurring in Baffin Bay may be a direct result of oceanic paths, known to attenuate or block Lg propagation. Higher attenuation could reduce the current seismic hazard values that assume Eastern North America ground motion attenuation relations.

ESC2021-S12-167

Seismic structure of the antarctic upper mantle imaged with adjoint tomography

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The upper mantle and transition zone beneath Antarctica and the surrounding oceans are among the poorest-imaged regions of the Earth's interior. Yet knowledge of this structure is important for understanding not only the tectonics of the continent, but also the interactions of the solid Earth and the ice sheets. To that end we use broadband seismic data from 297 Antarctic and 26 additional seismic stations south of ~40°S to image the seismic structure of the upper mantle and transition zone using adjoint tomography. Over the course of 20 iterations, we utilize phase observations from three-component seismograms containing P, S, Rayleigh, and Love waves, including reflections and overtones, generated by 270 earthquakes that occurred from 2001-2003 and 2007-2016. The new continental-scale seismic model (ANT-20, http://ds.iris.edu/ds/products/emc-ant-20/) possesses regional-scale resolution south of 60°S.

In East Antarctica, thinner continental lithosphere is found beneath areas of Dronning Maud Land and Enderby-Kemp Land. A continuous slow wave speed anomaly extends from the Balleny Islands through the western Ross Embayment and delineates areas of Cenozoic extension and volcanism that span both oceanic and continental regions. Slow wave speed anomalies are also imaged beneath Marie Byrd Land and along the Amundsen Sea Coast, extending to the Antarctic Peninsula. These anomalies are confined to the upper 200–250 km of the mantle, except in the vicinity of Marie Byrd Land where they extend into the transition zone and possibly deeper. Finally, slow wave speeds along the Amundsen Sea Coast link to deeper anomalies offshore, suggesting a possible connection with deeper mantle processes. Here we will discuss the tectonic implications of these features and also comment on their implications for solid Earth and cryosphere interactions.

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Knipovich Ridge's Logachev volcanic centre: insights into volcanic activity from seismic tomography

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Ultraslow spreading ridges represent the slowest divergent plate boundaries on Earth. Distinct spreading processes along ultraslow spreading ridges build magmatic segments that are volcanically active in between amagmatic segments that exhibit mantle rocks at the seafloor. Our local seismicity study along the ultraslow spreading Knipovich Ridge in the Greenland Sea gives insights into spreading processes of an entire ridge segment. The more than 8000 with HYPOSAT reliably located events exhibited an undulating brittle-ductile boundary shallowing towards the Logachev volcanic centre in the centre of the study area. Here, we observe a gap, where seismicity is absent apart from two earthquake swarms. Together with numerous earthquake swarms north of the seismicity gap, this indicates current activity of the volcanic centre. To further investigate the Logachev volcanic centre and its activity we perform a local earthquake tomography. The relevant part of the network of ocean bottom seismometers consisted of 14 stations, spaced by 10-20 km, deployed for one year approximately 60 km along the Knipovich Ridge. The tomography revealed a low velocity area underneath the Logachev volcanic centre at a depth of 10-12 km. This anomaly is robust when using different

parameter sets and tomography algorithms. Together with the earthquake swarms and the presence of fresh basalts on the seafloor, this low velocity area could represent a magma chamber feeding the Logachev volcanic centre. From the magma chamber dikes rise to the surface thereby producing swarm activity and heating the surrounding area. The heated area does not allow background seismicity and thereby shows up as a seismicity gap.

ESC2021-S12-204

Improved Seismic Monitoring with OBS Deployment in the Arctic: A Pilot Study from Offshore Western Svalbard

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The mid-ocean ridge system is the main source of earthquakes within the Arctic region. The earthquakes are recorded on the permanent land-based stations in the region, although smaller earthquakes remain undetected. In this study, we make use of three Ocean Bottom Seismographs (OBSs) that were deployed offshore western Svalbard, along the spreading ridges. The OBS arrival times were used to relocate the regional seismicity, using a Bayesian approach, which resulted in a significant improvement with tighter clustering around the spreading ridge.

We also extended the regional magnitude scales for the northern Atlantic region for OBSs, by computing site correction terms. Besides location and magnitude improvement, the OBS network was able to detect hundreds of earthquakes, mostly with magnitude below Mw 3, including a swarm activity at the Molloy Deep. Our offshore observations provide further evidence of a low-velocity anomaly offshore Svalbard, at the northern tip of Knipovich ridge that was previously seen in full-waveform inversion. We conclude that even a single permanent OBS near the ridge would make a significant difference to earthquake catalogs and their interpretation.

ESC2021-S12-221

Using icequakes to quantify basal slip and sliding behaviour at an Antarctic ice stream

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The physics of slip at the bed of glaciers remains one of the greatest unknowns in ice dynamics models. Glacier slip, in combination with ice deformation, controls how fast ice migrates from land into the oceans, with influences on sea-level rise. While one can measure the surface velocity, quantifying of the proportion of ice deformation vs. basal slip from observations remains challenging. We use a dataset from Rutford Ice Stream, Antarctica, comprising of 230,000 icequakes to measure basal slip directly. Icequake magnitude analysis combined with earthquake source models are used to estimate stress-drops and fault slip properties. The displacement due to slip of thousands of icequakes in a number of clusters are used to measure the average slip rate. These slip rates are of the order of 0.8 m / day, for failure within the till. Comparison to surface velocities of approximately 1 m /day suggests that around 80 % of ice displacement at Rutford Ice Stream is due to slip within or at the ice-till interface and 20 % from deformation of the ice column.

Furthermore, we use estimates of effective stress on the fault in attempts to verify sliding laws, as well as evidencing that slip is likely accommodated within the till, close to the ice-till interface. More broadly, our results emphasise the importance of and dependence on knowledge of the velocity structure and attenuation of the medium for stress-drop analysis of earthquakes. In summary, we present a method for measuring basal slip directly, which could provide constraint for ice dynamics models and therefore sea-level rise projections.

ESC2021-S12-227

Seismic monitoring of rock glaciers: observations and modelling

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Rock glaciers are mountain permafrost landforms composed of a heterogeneous mixture of rock debris, ice and liquid water. They can reach surface velocities of several meters per year for the most active ones, and can therefore cause an emerging hazard that needs to be addressed and monitored. Several geophysical methods (GPR, seismic refraction, ERT) provide interesting tools for investigating the subsurface, while in-situ and remote sensing methods make it possible to follow the kinematics of these study objects. However, all these methods do not offer sufficient temporal resolution for an accurate monitoring at depth.

Passive seismic instrumentation can overcome this difficulty by providing continuous ambient noise and microseismicity data. Such instrumentation has been deployed for several years at Gugla (Valais, Switzerland) and Laurichard (Hautes-Alpes, France) rock glaciers.

From these data, interferometry and spectral analysis of the seismic ambient noise provide daily observables (relative change velocity of the surface waves, and resonance frequencies of the glacier's vibration modes) which are directly linked to the elastic properties of the medium at depth, and therefore its stiffness and density.

For the two sites studied, the seasonal variations of these observables show a cyclic freeze-thawing effect on the elastic properties of the medium subjected to seasonal hydro-thermal forcing.

Mechanical modelling using a poroelastic approach was built to quantify the effect of the ice content on the stiffening into the medium at depth, and on the measured seismological observables. A simple viscoelastic model can also be used to explain the seasonal variability of the deformation rate of rock glaciers. In the long term, analyzing the multiannual trend in seismological proxies could help to detect changes in ice content and thus quantify the permafrost degradation.

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The Antarctic Seismographic Argentinean Italian Network (ASAIN): recording earthquakes in the Scotia Sea region

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The Antarctic Seismographic Argentinean Italian Network (ASAIN) is a permanent broadband seismic network that operates from 1995 in the Scotia Sea region, the Antarctic Peninsula and the polar area. It was deployed and managed in the framework of the cooperation between the National Institute of Oceanography and Applied Geophysics (OGS) and Dirección Nacional del Antártico (DNA) - Instituto Antártico Argentino (IAA), financially supported by the Programma Nazionale di Ricerca in Antartide (PNRA). The network consists of 7 seismological stations equipped with broadband sensors . ASAIN provides data to IRIS (Incorporated Research Institutions for Seismology), ORFEUS (Observatories and Research Facilities for European Seismology) and GEOFON (GEOFOrschungsNetz). It improves the worldwide seismic networks detection capabilities and contributes to refine regional earthquake locations released by USGS. The proximity of the seismic stations to the Antarctic continent and their continuous operation in the long term also allows having a privileged observatory on the ice-related seismicity along the Antarctica Peninsula and polar areas.

We present the current configuration of the ASAIN network and the main characteristics of the seismic stations. We also provide information on the ASAIN data exchange and the contribution to the scientific research in Antarctica.

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New Seismic Arrays in the European Arctic

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As part of the EPOS-Norway infrastructure project, NORSAR received funding from the Research Council of Norway for a new small-aperture, regional seismic array on Bjørnøya (Bear Island) in the European Arctic.

After a long planning phase, a six-element broadband array was installed by NORSAR staff in August 2019 and has been providing data to NORSAR in near real-time since then. Due to several logistical and administrative constraints the 6-element array has an aperture of only 300 m. All sites are equipped with MBB-2 sensors and Earth Data EDR-209 digitizers that are installed in near-surface vaults. Data are automatically copied to the Norwegian node of the European Integrated Data Archive (EIDA) and are openly available.

Due to environmental restrictions less than the planned 9 array sites could be installed on Bjørnøya and the non-used instruments are now available to extend the broadband station HSPB to another small aperture broadband array, also with 6 sites. HSPB had been jointly installed at the Polish Polar Station Hornsund, Southern Spitsbergen, by NORSAR and the Geophysical Institute of the Polish Academy of Sciences during the International Polar Year 2007-2008. The new array will also be jointly installed, however, due to the ongoing pandemic this is now postponed to 2022.

This talk will report on planning and installation of the array and on the first analysis results from the Bjørnøya array (BEAR) data. We will try to answer the following questions: How is the array performance of the new station? What are the noise conditions on Bjørnøya? How are the seismic monitoring capabilities in the region changing? How are data from this new installation complementing data from the seismic arrays (ARCES, SPITS and Apatity) already installed in the European Arctic when feeding them in the Generalized Beam Forming (GBF) algorithm?

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Insights into the contemporary stress field in the Svalbard Archipelago from earthquake focal mechanisms

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The Svalbard Archipelago is a geotectonically complex region and a locus of increased seismic activity in the European Arctic, surpassed only by the nearby tectonic plate boundaries. The improvement of seismic network coverage since the mid-2000s has resulted in the enhanced registration of regional seismicity in the area, manifested both as background activity and episodic outbursts. Prominent examples among the latter are the smaller and larger earthquake sequences near the island of Hopen (2003), in the offshore Storfjorden region (2008-2020) and at Hornsund, southern Spitsbergen (2015 and 2017). The occurrence of larger and moderate magnitude events during these episodes (M between ~ 4.0 – 6.0) has facilitated the determination of earthquake double-couple solutions from moment tensor inversion. Combined with older solutions from literature (Heerland, Nordaustlandet), a catalog of focal mechanisms is compiled that can be used to provide insights into the contemporary stress field in the Svalbard region. We discuss stress indicators at local and regional scales, including the results of a formal stress inversion and assess their agreement with the theoretical stress field, based on tectonic plate movement in the area.

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An Improved Catalogue of Glacial Earthquakes at Jakobshavn Isbræ and the Effects of external Forcings

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Jakobshavn Isbrae is the Greenland ice sheet's fastest glacier and is responsible for the highest volume of dynamic discharge (submarine melt and calving). Buoyancy-driven calving, the dominant calving style at Greenlandic tidewater glaciers, produces minute-long low-frequency seismic signals termed glacial earthquakes. Studying these events can provide insight into the short term earth-ocean-ice coupling at the glacier and help constrain ice loss through calving. In addition to new detections from Olsen and Nettles (2019), the Global CMT glacial earthquake catalog counts 117 events from 1993 to 2013, an underestimate as suggest by other studies. The catalog includes 18 events at Jakobshavn from July 2012 to December 2013, 14 of which have centroid single force magnitude Mcsf> 4.6 while 4 have Mcsf ~1-2 within 15 minutes of a large event. We apply a multi-station matched-filter (MMF) method to enhance the glacial earthquake catalog, using these 18 events as templates to cross correlate with continuous waveform data at stations ILULI and JIG1 in the same period. We detect 649 additional glacial earthquakes compared to 61 published events in the same time period; the false detection rate varies from 4 to 14% depending on the MMF parameter setting. We show a higher glacial seismicity rate precedes terminus acceleration based on glacier velocity from InSAR velocity maps. We also run an MMF for seiches (standing waves in the fjord water) and find they correlate with the glacial earthquake occurrence though are only detected half as often. We will discuss calculations of relative magnitudes of detected events and the cumulative seismic moment as compared to local uplift rates. We investigate whether large teleseismic earthquakes may dynamically trigger calving and thus glacial earthquakes. We will also present preliminary results of comparing glacial seismicity records to climate data to explore the drivers of calving events.

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Investigating Seismicity from the fast-flowing trunk of Jakobshavn Isbræ, Greeland

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Outlet glaciers and ice streams are the main channels through which ice sheets transport their mass towards the ocean. In recent years, rapidly increasing velocities of such streaming ice are observed in both Greenland and West Antarctica. Characterizing the underlying mechanisms of fast-moving ice is crucial for our understanding of the stability of ice sheets and their impact on future sea-level rise. Seismology has proven to be a valuable tool for investigating glacier dynamics. It reveals signals accompanying basal sliding, which is the main mechanism facilitating fast ice flow. However, seismological measurements on fast-flowing ice are sparse because of difficult access to heavily crevassed ice surfaces. Jakobshavn Isbræ, on the west coast of Greenland, is an example of a fast flowing ice stream, which recently experienced acceleration episodes. It moved 20 m/day between 1990 and 2000, but has shown accelerations up to 40 m/day in the last two decades (Joughin et al. 2020).

To research the dynamics of Jakobshavn Isbræ, we plan to acquire passive seismic recordings on both the fast-flowing trunk and the surrounding slow moving ice sheet. The seismic measurements target signatures of basal sliding such as discrete stick-slip events and sustained sliding tremor (McBrearty et al., 2020). Combining geophones, interferometric radar, high-resolution drone imagery and high-precision GPS we will investigate temporal and spatial variations in basal sliding related to melt runoff and ice-ocean interface changes.

Here we report on a first instrument deployment planned for July/August 2021. Moreover, we present first steps towards a machine-learning based automatic detector that identifies basal stick-slip signals in the presence of dominating surface crevasse seismicity. We develop and train this algorithm using existing icequake catalogues from Greenland and the European Alps. The driving idea is to reveal dynamic sliding processes, happening on time scales to short for conventional remote sensing measurements.

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New capabilities in polar rated very broadband seismic instrumentation

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Up until now, the choices for researchers wanting low powered, scientific grade records of analog signals in polar environments were stark, either an expensive and large broadband seismic recorder requiring more power and logistics or an inexpensive recorder with poorly defined timing, gain, response, reliability or support. Recently developed polar rated broadband seismic systems have much wider bandwidth, lower self-noise, and greatly reduced SWaP (size, weight, and power). These instruments provide the opportunity to realize higher-density, high quality modern data acquisition that is relevant to solid Earth, glaciological, and/or climate-related studies, and to broadly further the autonomous and real-time collection of extremely low noise observations in polar regions. We will discuss the capabilities of these new instruments and

possibilities in the context of further improving present polar instrument pools to address polar science initiatives that have not yet been realized.

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New insights into the seismic velocity structure of Deception Island from H/V analysis of ambient noise

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The horizontal to vertical (H / V) spectral ratio of ambient seismic noise has been used in many applications, from civil engineering to cryosphere studies, to obtain information on the surface structure. This fast and non-invasive method is based on the interpretation of the ratio between spectral amplitudes of the horizontal and vertical components of the background seismic vibrations.

In this study, we report a successful application of the H / V method to estimate the shallow structure of Deception Island, in Antarctica, using seven years of noise records at the DCP permanent station, seven surveys of about two-three months each performed during the austral summer for five more stations located on the island, and three months of data at four OBS of a temporary array within the Foster Bay. Initial analysis revealed a variety of H / V typologies. Local 1D models of the subsurface seismic-velocity structure have been obtained at each station by inverting the experimental H / V curves. Dispersion curves determined from temporary arrays of apertures of up to ~1 km helped to mitigate non-uniqueness issues. The thickness of the main surface layers was determined at each station. Some of the models include shallow layers attributed to permafrost. This is one of the first applications of this technique to OBS measurements, taking into account the effects of the water layer.

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Seismological and geophysical imaging of shallow geological structures at different scales: challenges and perspectives

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Shallow elastic structure and Vs30 estimates from co-located pressure and seismic data

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In the past 10 years, pressure sensors have been installed at many seismic stations, providing co-located pressure and seismic data at many locations. One of the most grandiose examples is the EarthScope Transportable Array (TA) in the USA (after 2011) but many global seismic networks have also installed pressure sensors and become co-located stations. These data provide critical information on how the atmosphere and solid Earth interact mechanically through surface pressure changes. This interaction can become strong for frequencies between 0.01 Hz and 0.05 Hz and its time intervals can be identified easily by examining the coherence between pressure and seismic data.

When coherence is high between 0.01 Hz and 0.05 Hz, phase difference between pressure and vertical displacements is about 180 degrees. It means that we are observing pressure loading effects on Earth's surface and seismic data are showing an elastic response of solid Earth caused by surface pressure changes.

Using this phenomenon, we developed an algorithm to derive shallow elasticity structure. We first measure the ratios η(f)=Sz(f)/Sp(f), where Sz(f) and Sp(f) are the power spectral densities of vertical seismic velocity and pressure. We developed software to compute the depth sensitivity kernels for this quantity and can now invert η(f) for depth-varying elasticity beneath a co-located station (Tanimoto and Wang, 2019).

We will report the results of this analysis for many co-located stations, including the EarthScope TA stations. We will discuss the nature of shallow structures by this approach and derive our estimates for Vs30, an average S-wave speeds in the uppermost 30 m of the Earth. We will then compare our results to other Vs30 estimates, derived by other methods. Our method provides an alternative approach to measure Vs30 and is quite economical as the only requirement is addition of a pressure sensor to seismometers.

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Constraining the 3D-extent of a deep-seated landslide before and after a rapid acceleration phase using seismic ambient vibrations

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Deep-seated landslides often involve large volumes with complex subsurface structures of shallow sliding surfaces and deep-seated interfaces. Estimating subsurface geometries from surface geodetic surveying or geotechnical measurements are crucial for understanding landslide kinematics, but are a challenging task when using only surface mapping tools. Recent advances in the analysis of ambient-vibration wave fields show a great potential for characterizing unstable rock masses in a fast, relatively inexpensive and non-invasive way. At the Moosfluh deep-seated gravitational slope deformation (DSGSD) in Switzerland, the dynamic behavior of the rock slope instability was studied with passive seismic measurements in 2015, at a time when the central part was moving with around 0.8 m/a. An unexpected and dramatic acceleration of Moosfluh started in September 2016 and lasted until 2018. It caused the opening of large cracks, the formation of numerous uphill-facing scarps, countless rockfall events and displacements of several tens of meters per year, which changed the landslide structure significantly. Therefore, passive seismic measurements were repeated after this active phase of deformation in 2020.

We compare the two measurements before and after the acceleration phase. By using surface-waves dispersion characteristics, we derive the Vs-velocity profile indicating two sliding interfaces, a deep interface identified in a seismic velocity change at a depth of 100 to 120 m, and a shallow interface at a depth of around 50 m. We studied the spatial distribution of wave amplification and polarization, resulting in the highest amplifications between 3-5 Hz, which can be related to a shallow sliding interface of the landslide. Since ambient vibration measurements in 2015 already identified two potential interfaces, this method might be a promising supplement to the present day measurement systems for landslide monitoring and risk assessment, that might help to constrain the depth of the instability and therefore its volume.

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Two dense seismic campaigns in the French Rhône valley for characterizing site effects

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Superficial geological layers can strongly modify the surface ground motion induced by an earthquake. These so-called site effects are highly variable from one site to another and still difficult to quantify for some geological configurations (e.g. deep valleys). That is why site-specific studies can greatly contribute to improve the hazard prediction at a specific site. However site-specific studies have historically been considered difficult to carry out in low-to-moderate seismicity regions.

We present here datasets acquired in the French Rhône valley in the heavily industrialized area surrounding the Tricastin Nuclear Site (TNS). TNS is located above an ancient Rhône Canyon. The strong lithological contrast between the sedimentary filling of the canyon and the substratum, as well as its expected confined geometry make this canyon a good candidate for generating site effects.

In order to characterize the geological medium and its impact on the seismic motion, we conducted two complementary seismic campaigns in the area. The first campaign, carried out by IRSN with the help of EGIS and SISPROBE companies, consisted of deploying 400 nodes over a 10x10 km area for one month and aims at recording the seismic ambient noise. In addition, a second seismic campaign has been carried out within the framework of the French-German DARE project (IRSN; Univ. Potsdam; GFZ Potsdam; Univ. Grenoble Alpes). This second campaign consisted of deploying about 50 broadband stations over the same area for nine months and aims at recording the seismicity. Both dense datasets will be processed within the DARE project (2020-2023) to explore the potential of such acquisitions to improve site effect characterization in low-to-moderate seismicity areas.

In this presentation, we will provide details on the measurement campaigns, the related challenges and perspectives, and further present the acquired datasets in the framework of site effect assessment in an urban and industrialized area.

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Inversion strategy of using microtremor array data for a soft site with two strong impedance contrasts

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A two dimensional microtremor array campaign is carried out as part of a comprehensive ground investigation aiming to characterise a soft site in the UK. A dispersion curve from the arrays is inverted using the neighbourhood algorithm scheme and the complexity of selecting the final solution is explored through sensitivity analyses. The parameter space is constrained using shear and compressional-wave velocities from site-specific intrusive measurements, with the aid of a seismic reflection survey conducted for the site and using data from regional deep boreholes from the British Geological Survey. Joint inversions are performed using alternative input targets from High-resolution Rayleigh three-component beamforming f-k analysis.

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Vs-profile of geological units based on a geophysical database: application to Lisbon

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The geological setting of Lisbon has a complex lithostratigraphic structure composed of diverse lithological units. In the southwest area, Cretaceous formations arise, while Paleogene and Miocene formations appear in the northern and eastern areas of Lisbon. The Cretaceous formations are composed of carbonate rocks – Bica Formation and Caneças Formation – and basaltic rocks – Lisbon Volcanic Complex. The Miocene formations are composed of sands, sandstone, clay, and limestone. The Paleogene Benfica Formation, with a heterogeneous composition, corresponds to the transition between the Miocene formations and the Lisbon Volcanic Complex. The Quaternary deposits represented by alluviums and/or landfills constitute the surface formations.

The high degree of urbanization of Lisbon difficult a comprehensive geological, geotechnical, and geophysical characterization. The combination and complementarity of the different approaches favour a more detailed characterization and a better interpretation, increasing the robustness and reliability of the results.

A geophysical database was created where all the results of available geophysical tests carried out in Lisbon were compiled. These results include shear wave velocity values (Vs) from cross-hole, down-hole, and surface wave tests, such as MASW (Multichannel Analysis of Surface Waves). The natural frequency of ground (f0) from HVSR method (Horizontal to Vertical Spectral Ratio) was also compiled. For each geological formation, it was performed a linear regression analysis of Vs and defined an expression of the linear increase of shear wave velocity with depth. However, the number of geophysical campaigns carried out is few, scarce and sparse.

Recently, some surface wave tests were carried out in several sites with different geological settings around the city. The surface waves seismic profiles to estimate the characteristics and response of the ground profile

were compared with the linear increase of shear wave velocity equations to validate them and prove their effectiveness.

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Ambient vibration techniques and ground motion modelling to derive and to test the quality of a local 3D geophysical model: The example of VISP, Switzerland

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The majority of strong earthquakes in Switzerland occur in the alpine area, and the Canton Valais is one of the most active zones. The Rhone valley dominates the region with sediment deposits of up to 800 m thickness. The shape of the valley and high velocity contrasts between sediments and rock are responsible of important 2D/3D seismic site effects. In the framework of the project Earthquake Risk Model Switzerland, we selected a large area of the Rhone valley around the municipality of Visp and derived a series of local amplification models by combining geological and geophysical data. For this purpose, geophysical data collected in the past as well as newly acquired data were employed. The data consist of 487 single station noise measurements, 10 small aperture seismic arrays, seismic records from 13 seismic stations and 14 boreholes reaching the bedrock depth. Single station measurements were used to compute horizontal to vertical spectral ratios; the array measurements were processed with three-component high-resolution f-k analysis, estimating both Love and Rayleigh wave dispersion curves and ellipticity.

All the available pieces of information were then combined in an inversion procedure to obtain a 3D velocity model for the area. The model was then validated by comparing observed and synthetic H/V and standard spectral ratios. Simulations were carried out up to 4 Hz using a fourth-order finite-difference scheme implementing a curvilinear mesh near the surface to handle realistic topography. We show that spectral ratio techniques can be an efficient and cheap tool for the validation and improvement of subsurface models. Our 3D model for the Visp area well reproduces the observations in the 0.5-4.0Hz frequency range, although some aspects of the numerical modelling must be further investigated.

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Joint interpretation of geophysical results and geological observations for detecting buried active faults: The case of the “Il Lago” plain (Pettoranello del Molise, Italy)

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We describe a study across an active normal fault system at the “Il Lago” Plain (Pettoranello del Molise, Southern Italy) by newly acquired geophysical data and literature geological data. We used low frequency

GPR methods combined with seismic tomography methods. The usefulness of traditional GPR techniques in geological studies is affected by the limited achievable depth of investigation. Previous studies indeed detected only the shallowest portions of faults. Conversely, our study demonstrates the potentialities of the combined use of seismic and deep GPR surveys for investigating buried faults at depth of tens of meters (down to 60 m in this study).

This approach can be applied to young structures that, despite their probable seismogenic potential, have not yet developed mature geomorphic features, or are buried under thick sequences of recent deposits. Even though the “Il Lago” Plain is a small basin within the Bojano fault system, our study allowed insights into the Mt. Patalecchia Fault System, by detecting and characterizing four buried sub-vertical antithetic and synthetic normal faults that form horst and graben structures below the plain filling, previously unknown.

This result is crucial given the seismotectonic importance of the Bojano basin, for improving the knowledge of the Holocene paleoseismological history. The geophysical evidence of Late Pleistocene to Holocene displacement beneath “Il Lago” Plain strongly suggests that recent sedimentation rates at this site are larger than the vertical component of normal faulting rate. A similar result was documented in the San Gregorio Magno (Campania region, Southern Italy) Plain, where paleoseismic evidence of Holocene surface faulting was studied with exploratory trenching across the 1980 earthquake surface ruptures.

In conclusion, our investigations do not rule out that the 1805 surface faulting also affected the “Il Lago” Plain, as suggested by historical literature.

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Directional amplification across the San Jacinto fault, CA

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In the top few kilometers of the crust, fault zones are characterized by the presence of systematic brittle deformation. The locally reduced seismic impedance of the fault damage zones (FDZ) can influence earthquake-induced ground motions, producing directional amplification effects the following signatures: (i) waveforms tend to be polarized in the horizontal plane with horizontal motions largely dominate over vertical ones; (ii) the most persistent direction of polarization does not fit the expected source mechanism, even in active source-controlled experiments; and, (iii) polarization azimuths are not random and tend to form a high angle with the fault strike, being transversal to the predominant fracture strike. Due to the decrease of the polarization intensity moving away from the fault trace, directional amplification effects were ascribed to the locally predominant fracture field, as an effect of stiffness anisotropy. This effect is different from the well-known fault trapped wave generation in FDZ, resulting in the time domain of polarization parallel to the fault strike.

In this work we have investigated directional amplification effects across the San Jacinto Fault using stations belonging to several arrays installed in various fault sectors in Southern California, between the Blackburn Saddle and Borrego Valley (net “YN”), composed by velocimetric and/or accelerometric sensors. For data processing we selected recorded earthquakes with magnitude ranging from 3 and 4.7, recorded in the array working periods, between 2012 and 2021.

Across the Anza seismic gap we found that directional amplification effects are stronger inside the low velocity zone, as identified by other authors. The effect is even stronger with increasing the velocity contrast between the fault damage zone and intact rocks.

Conversely at other locations, interpretation of the results is more challenging, and the contribution of lithological contrasts such as the presence of sedimentary layers, seems to play the main role.

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Crustal structure in the complex seismic area of Romania as seen by attenuation tomography

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The seismic activity in Romania is mainly confined in the Vrancea region, located in the Eastern Carpathians bend, where strong subcrustal earthquakes are generated, causing significant damage over extended areas. Apart from subcrustal seismicity, crustal seismic activity is recorded as well in this region, spread over a larger area, mostly to the outer side of the Eastern Carpathians bend. It is significantly smaller than the intermediate-depth seismicity, raising controversies about the geodynamic and possible coupling processes driving the seismogenic system in the region. The seismicity in the crust partly follows the alignments at the contact between the tectonic blocks that collide in the area. With the advent of new permanent seismic stations of the Romanian Seismic Network (RSN), we were able to lower the earthquake magnitude detection threshold to 0.5 ML, largely expanding the earthquake database.

The goal of the present study is to investigate and differentiate the attenuation features by using local earthquakes that occurred within the crust with local magnitude in the range of 0.8 to 5.7, recorded by the permanent stations of RSN between 2015 and 2021. We applied an absorption tomography technique based on Multiple Lapse Time Window Analysis and scattering tomography followed by a kernel-based inversion for a diffusive regime to map the absorption features with better accuracy.

The main results of the study outline the structural complexity of the study region due to the lateral variation and the dimensions of absorption features. The deeper layers are sampled by the lower frequency ranges revealing an increasing trend of the absorption to the northwest and southeast relative to the Vrancea region while the highest frequency absorption features are prevalent in the deepest sedimentary areas and stable regions (platforms).

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Modelling the S-waves velocity spatial variability within the Amatrice Basin (central Italy) to capture the dominant propagation modes

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The Amatrice Basin is a NW-SE intermountain depression of the central Apennines originated during the Plio-Pleistocene extensional phase.

Many hamlets located inside the basin suffered cumulative damages after the August 24th, 2016, Mw 6.0 earthquake and the following aftershocks.

2D/3D site effects also were recognized due to the presence of fluvial terraces, ridges, hillsides and morphological steps.

This complex framework has been investigated in the uppermost portion (maximum depth about 200 meters) for understanding as the geological setting and the distribution of mechanical parameters (i.e. S-waves velocity) can influence the upward propagation of seismic waves, furthering the possible occurrence of focusing, reflection, refraction and/or amplification effects in the basin.

In particular, this scientific contribution aimed firstly at creating a refined mechanical model, able of integrating geological (i.e. maps and cross-sections) and geophysical (i.e. Down-hole, refraction, seismic tomography, surface waves methods measurements) data.

Once data have been organized in a unique 3D environment, where faults, stratigraphic boundaries and geophysical attributes have been modelled, a posteriori validation of the relationships between the stratigraphy and the areal and depth variability of S-waves velocities was carried out by comparing the ellipticity of Rayleigh waves, computed for selected modelled seismo-stratigraphy profiles, with available noise measurements (HVSR curves).

The adopted procedure allowed investigating the role of the geological setting in controlling the seismo-stratigraphic constraints in the Probabilistic Seismic Hazard Assessment (PSHA) perspective (i.e., analysing the dominant modes and influences of seismic bedrock depth assumptions and the S-waves velocity spatial variability). Hence, the proposed approach may represent a promising methodology in geological modelling devoted to these applications.

The final product will be a 3D model useful for numerical simulations, able to quantitatively estimate the seismic response in the basin, considering both the geological framework and geophysical characteristics of the Amatrice area subsoil.

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Using a seismological approach to monitor cliff instabilities: the NEWS project

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The islands composing the Maltese archipelago (Central Mediterranean) are characterized by a four-layer sequence of limestones and clays. In the western half of the archipelago, we can find the full stratigraphic sequence where the youngest formation is the Upper Coralline Limestone, which overlays a soft Blue Clay layer. When exposed at coastal sections, such geological structures induce instabilities and lateral spreading phenomena associated with falls and topples of different-size rock blocks and are responsible for a typical landscape with a stable plateau of stiff rocks bordered by unstable cliff slopes. Such landforms present spectacular scenery and are highly frequented touristic places. They therefore represent widespread high-risk locations, that occur especially along the north-western coast. The Maltese islands thus offer an important case study investigating such typical cliff settings.

The NEWS project aims (among other activities) to monitor the cliff instability at selected test sites. During the project implementation, engineering-geological surveys and passive seismic measurements (single station and array configuration) were carried out to evaluate the main resonance frequencies of sections of the Selmun promontory (northern part of the island of Malta) and monitor the gravity-induced instability processes.

Additionally, several geo-resistivity profiles were taken to estimate the thickness of the main stratigraphic contacts.

Within the project, a seismic station was installed on one of the partially detached blocks and a few arrays of seismic stations were deployed in different positions on the Selmun Promontory. The goal was to detect possible microseismic events related to slope gravity-induced instabilities involving the edge of the UCL plateau. Furthermore, a detailed 3D digital model of the entire promontory has been created by the means of LiDAR and photogrammetry data.

The NEWS project (Nearshore Hazard Monitoring and Early Warning System) has been funded by Interreg V-A Cross Border Cooperation Italia–Malta projects.

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Shallow geophysical signature of a normal fault-zone in the northern sector of Malta

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The accurate location and characterization of faults are essential factors for site characterization as well as urban development. Depending on the tectonic and geomorphic environment, faults can display complex structure and they may consist of wide band of deformed rock known as fault-zone. Some faults do not reach the surface or overlaying younger sediments can make direct observation impossible. The combination of shallow geophysics methods become essential in the study of such complex underground structures.
In this study, we investigated the signature and structure of a normal fault zone in the northern part of the island of Malta. The geology of the area is characterized by a Tertiary marine stratigraphic sequence typical of the Maltese islands. In some parts, this sedimentary succession is covered by a thin quaternary lay of sediments, which at place conceal the trace of faults. To characterize and map the fault structure and the quaternary sediments in the survey site, we carried out a high-resolution multi-approach geophysical survey. We have combined ambient vibration measurements, active-source seismic and electrical resistivity tomography (ERT) as well as GPR profiles. Measurements have been taken along transects crossing perpendicularly the fault zone area.

We recorded ambient vibrations using 3 component velocimeters at several locations along transects perpendicular to the investigated fault. The signals were analysed employing the HVSR technique and were interpolated to create HVSR tomographic sections. The 2D ERT were obtained with a multichannel resistivity. We tested several configurations in order to obtain good vertical and lateral resolution. The GPR scans were

acquired using two different instruments with different central frequency (400MHZ and 70MHz), to achieve good shallow resolution and deep penetration.

The subsurface images obtained allowed us to discriminate stratigraphic boundaries and fault associated structures that could not be determinate without the combination of several complementary geophysical signals.

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Ambient noise characterization of the Northeast Buenos Aires Province and its implication on the stratigraphy

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Although ambient noise characterization is usually used in areas seismologically active the Horizontal to vertical spectral ratio (HVSR) technique is also a useful tool in cratonic areas to determinate stratigraphic boundaries when does exist a sharp velocity contrast between stratigraphic units. It serves as a proxy to determine the main features of stratigraphic successions.

In this study, we collect several ambient noise measurements with a mobile 3 component seismometer in Northeast Buenos Aires Province, Argentina. The main goal was to identify and discriminate the main stratigraphic boundaries in the area. The geology of the zone is characterized by about 400 m of siliciclastic sediments over a pre-Cambrian craton. The shallowest unit represents the limit of the last quaternary marine ingression and controls the topography and the main geomorphologic units, the Continental Plain and the Coastal Plain.

The stations recorded ambient noise and the recorded signals were cleaned and analysed by applying the horizontal-to-vertical spectral ratio (HVSR) technique. The results were analysed in the range of 0.5-20 Hz and they show peaks with a different patron between the two geomorphological units. We were able to relate the HVSR curve with the Plio-Quaternary sediment sequence of the area and this interpretation was supported by the constraints provided by water well data available in the area.

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Ambient vibrations of a maar structure: insights from observations & modelling

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The Mýtina maar belongs to the series of recently described volcanic maar structures in the Czech Republic. It is located in West Bohemia, 1 km north of the Quaternary volcano Železná hůrka and 10 km SE from the city of Cheb. Although an extensive geophysical survey was performed in past including gravimetric and geomagnetic measurements, the deep structure of the maar crater is not known. In this contribution, we demonstrate the potential of seismic noise methods to study such structures from their local seismic response. In particular, we performed an ambient vibration survey and numerical simulations in order to infer the depth of the crater. In particular, we mapped relative amplification of ground motions at X points

using site-to-reference spectral ratios (SRSR) method. All the stations located on the maar sediment infill show significant amplification reaching the value of 30 in centre and gradual decrease towards edges of the maar. The observed wavefield seems to be dominated by standing waves of the maar infill due to its three-dimensional (3D) structure. In order to explain these observations, we performed a number of 3D seismic wave simulations using finite difference method. The developed 3D velocity model has been constrained by a couple of seismic array measurements performed in the middle and close to edge of the maar. The observed dispersion curves of surface waves were inverted it into 1D seismic velocity profile characteristic for the maar sediment infill. The modelled seismic response fits both the frequencies and shape of the observed amplification curves only for specific geometry of the crater. Therefore, finally, we were able to constrain the dimensions of the crater including its depth.

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Modal analysis of an unstable rock compartment overlooking the A8 highway (Peille, Southern French Alps)

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Following the collapse of a large rock compartment located in calcareous cliff area, overlooking the A8 highway (near Monaco Monte-Carlo in the Southern Alps), a seismic monitoring campaign has been set-up for stability assessment. The upper part of the compartment, with a volume close to 450 m³, has remained in place and its level of stability appears unchanged following the event, but the rockfall hazard remains high to very high. The compartment is part of a limestone massif (late Jurassian) crossed by vertical fractures with East-West azimuth, progressively opened by weathering effects which tend to individualize large rock columns along the cliff area.

Seismic instrumentation was set-up in two one-day campaigns (July 2019 and March 2020) in order to: 1) characterize the dynamic behavior of the actual rock compartment, and 2) investigate the feasibility of long-term monitoring based on ambient vibrations. The instrumentation consisted of two measurement networks of four Lennartz velocimeters (Le3D 5sec) each. The measurement points covered the maximum of the exposed and accessible surface of the block, as well as on the intact rock massif. Data analysis in the frequency domain identified several resonance peaks as well as their preferred azimuths. The analysis of the two networks using modal identification technique by FDD (Frequency Domain Decomposition) highlighted the main modes of vibration of the compartment, including torsion and tilting modes from 4 Hz up to 10 Hz. First results of numerical modeling of the cliff help to constraint the time evolution of the identified modes, as they are sensitive to boundary conditions of the studied rock compartment.

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Bedrock reconstruction in urban areas with single-station microtremor and gravity surveys

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Imaging the shallow subsurface is of primary importance in populated areas for several applications, e.g., for seismological engineering problems. The study of seismic amplification relies on the investigation of the shallow stratigraphy and on the reconstruction of the bedrock morphology below sedimentary covers. This

is often performed with surface geophysical methods, however not all geophysical techniques are easily applicable in urban environments. We focus on two low-impact single-station techniques: microtremor and gravity. These are easily applicable to a broad range of scales and settings as opposed to more traditional seismic methods performed along long profiles that are not always feasible. They allow for extensive mapping of shallow and deep geologic structures and, since they are sensitive to different model parameters, their joint use helps constraining the model and partly overcoming the intrinsic non-uniqueness of geophysical data inversion.

Microtremor and gravity data have been used in previous studies by comparing results independently. We suggest a procedure to combine them into a unique subsoil model. We apply the procedure to the Bolzano sedimentary basin, Northern Italy. We use microtremor data to map the ground resonance frequencies and derive an initial 3D bedrock depth model by assuming a Vs profile for the sediment fill. We then assign density values to sediments and rock and perform a 3D gravity forward modeling. We test several Vs and density models and find the parameters best fitting the observed gravity anomalies. We account for data uncertainties to explore the significance of the results and estimate the final model uncertainty. This procedure is able to overcome some intrinsic limitations of both techniques and reduces the amount of stratigraphic constraints needed to derive a subsoil model. The wide applicability of these single-station techniques makes this approach very efficient in urban areas and in different geological contexts and exploration scales.

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Multi-array and multi-scale ERT cooperative inversion: A tool for higher resolution imaging of subsurface geological structures

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ERT is nowadays frequently applied for fault zone imaging and characterization across surface earthquake related ruptures. Its success is due to fast, accurate and cost-effective subsoil imaging.

In this work, we focus on possible strategies to improve the resolution of 2-D resistivity models and we present novel inversion results of previous data set acquired across a normal fault that ruptured the surface in the Castelluccio basin following the 30 October 2016 Mw 6.5 earthquake in central Italy.

This data set is composed of ERT measurements along the same profile crossing a ~3m-high fault scarp in alluvial deposits with different inter-electrode distances (2, 5 and 10m, respectively) and using both the dipole-dipole and Wenner-Schlumberger arrays. The individual inversion of each ERT dataset (6 total) has put in evidence several characters of the investigated section imaging the fault zone down to about 100-120m depth. The latter appears as a sharp, sub-vertical low-resistivity region (< 100Ωm).

Conscious that model resolution is a close consequence of subsoil sampling that can be enhanced by illuminating targets using different both investigation depth and geometry, all the available measurements were homogenized in a unique multi-array and multi-scale dataset and inverted. Raw data have been filtered for noise measurements and corrected for topography, and subsequently combined to take into account the different electrode spacing and investigation depth.

The new resistivity model is characterized by:
1. A greater resolution in the near surface.

2. An increase of resolution in the middle and deeper part of rupture, with a better sharpness of ground bodies.
3. A new discontinuity at depth as a consequence of the best resolution that are confirmed by independent seismic model.

The resistivity model obtained by full integration of different both arrays and scales of investigation improves the imaging of fault zone refining the reference geological model.

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Bedrock depth variability along the extra - Carpathian area of Romania

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Local site evaluation is an essential step in understanding the amplification of seismic motion induced by the complex geological structure and their estimation for future strong earthquakes in urban regions. One of the critical parameters on evaluating amplification ef ects is the depth of the geophysical bedrock, whose interface to soft sediments is responsible for the development of destructive resonance phenomena. The present study is focused on the estimation of the geophysical bedrock depth along the extra-Carpathian area of Romania (Moesian Platform and surroundings) by correlating and interpolating the results obtained from single station measurements with the available geological/geophysical data. Each site was investigated through the computation of horizontal-to-vertical (H/V) spectral ratios from three-component single station measurements of ambient vibrations. The geophysical bedrock depth was computed using a two-step inversion scheme based on the retrieval of the Rayleigh-wave ellipticity peak at each seismic station using a regional generic velocity profile. The fundamental frequency of resonance reaches the lowest value in the deepest side (0.07 Hz) and is rising to 13 Hz in the South of the Moesian Platform, where a shallow bedrock is present. The computed bedrock depths (from 30 to ~3100m) show a dipping tendency towards the Southern Carpathians and complex features such as local outcrops and lateral depth variations superpose this gradually dipping trend. In the Carpathian foreland, the bedrock is interpreted as the transition between different sediment layers of Neogene, while outside this area as the Neogene - Cretaceous transition.

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Ambient vibration techniques for characterization of 2D/3D sites

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The use of ambient vibration measurements has become attractive in shallow subsurface characterization, because of relatively simple and efficient data acquisition. However, majority of the results depends on the assumption of 1D layered isotropic media (inversion of surface wave dispersion curves, H/V ratio interpretation). We explore the possibility to include 2D/3D effects in the ambient vibration analysis. We simulate noise wave field in realistic 3D complex media by finite difference method and perform a detailed analysis of the synthetics. We apply polarization analysis, three component FK methods and wave field decomposition techniques in order to isolate potential signatures of the local 3D structure in the synthetic noise wave field (e.g., specific polarization features; preferential directions in the wave field). The results are

verified against measured ambient vibrations at sites with the expected 2D/3D effects (basin edges, fault zones, etc.).

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Imaging and modeling 3D fault complexities in FAULT2SHA

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Focal mechanism solution and seismogenic structure of the 17 June 2019 Ms6.0 Sichuan Changning earthquake sequence, Southwestern China

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On June 17, 2019, an Ms 6.0 earthquake hit the Changning County, the southern margin of Sichuan Basin. The mainshock and strong aftershocks caused 13 people died and over 200 people injured. Based on the seismic data provided by Regional Seismic Network, we relocated the early events of the Ms 6.0 earthquake sequence from June 17 to 22, 2019 by using the multi-stage location method. The focal mechanism solutions and centroid depths of 16 Ms≥3.6 earthquakes before 4 July 2019 were calculated from the CAP inversion method. Finally, the seismogenic structure of the sequence is preliminarily analyzed.

The distribution of relocated events shows the aftershock area is 25 km long in a NW-SE trending and 5 km wide. The focal depth ranges from 0 to 10 km with a mean value ~3.2 km, the total sequence is deep in the west and shallow in the east. The focal mechanism solutions show that the seismogenic structure system of the sequence was dominated by thrust and oblique thrust faulting mode; the centroid depths of 16 Ms≥3.6 earthquakes are within 1~7 km with average ~3.5 km, which is consistent with the relocation result and reveals that the Changning earthquake sequence occurred in the shallow part of the upper crust. Based on the spatial distribution of the sequence, focal mechanism solutions and structural characteristics of the seismogenic area, it is inferred that the occurrence of the Ms 6.0 earthquake sequence may be related to two anticlines and their associated fault activities, belonging to the complex Changning-Shuanghe anticlines. The tectonic deformation of the seismogenic structures for the sequence generally presents the characteristics of NE-SW compression with small NW-SE extension component, significantly different from that in the southern area, reveals that the southern margin of the Sichuan Basin is in a complexity tectonic deformation transition region.

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Displacement variation along the Lion King fault is a function of lithology and fault interaction: implications for seismic hazard analysis

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The Lion King fault is a strike-slip fault system that has pierced through a Miocene sedimentary sequence, which is dominantly composed of steeply dipping shallow marine sandstone beds. It is in the Jerudong area of Brunei Darussalam. The outcrop exposes ~60m of the fault trace when viewed from above, and therefore, it is one of the best places to study the brittle faulting in detail, which are routinely difficult in other places because of the forest cover, erosion, etc. We used the drone and field-based mapping to map the fault zone, and we discovered that faulting is continuous for 60 meters, and the amount of strike-slip displacement varies from 0.8m to 1.28 m along a 10m section, which was measured parallel to the strike length of the fault. The details show that smaller amount of along strike displacement is observed in regions where sandstone displays a relatively broad brittle deformation zone with well-developed deformation bands, and in particular the disaggregation bands.

The maximum displacement is observed where the fault has pierced through shale beds, and the deformation bands are not well developed, and often display thin bands (<2mm). Fault bending, curvature, and anastomosing also contribute towards the variations in fault displacement and width and thickness of the fault zone. We, therefore, suggest that seismogenic faults could also display such features, which could greatly influence the slip-rate and recurrence intervals that are routinely used to estimate seismic hazards. Our work clearly shows that displacement measured along the strike of the fault could greatly vary even in a 10m section, which shows that faults displace the marker units differently, which suggests a review of the existing slip models. The field data are crucial to understanding these variations, which must be part of the seismic hazard analysis.

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FAULT2SHA ESC Central Apennines WG - Bridging the gap between Geologic Data-Providers and Seismic Risk Practitioners

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We present results from the Central Apennines laboratory Fault2SHA ESC WG aimed at enhancing the use of geological data in fault-based seismic hazard and risk assessment and promoting synergies between data providers (earthquake geologists), end-users and decision-makers. The Fault2SHA Central Apennines Database is the reference database used. Geologic data is thus provided in the form of characterized fault traces, grouped into faults and main faults, with individual slip rate estimates. The proposed methodology first derives slip rate profiles for each main fault. Main faults (alternatives main faults definitions are possible: epistemic uncertainty) are then divided into distinct sections of length comparable to the seismogenic depth (epistemic uncertainty) to allow in the computations consideration of variable slip rates and associated uncertainties along them as well as exploration of multi-fault ruptures (aleatory uncertainty).

Specific examples will be used to illustrate the methodology and quantify the impact of epistemic choices on the resulting hazard and typological risk (here represented by fragility curves for a single "historic" small edifice). The aim of this presentation is to inform both data providers and end-users the tools we developed to best visualize faults that threaten specific localities the most, appreciate the density of geological observations results are based on, and interrogate the degree of confidence on the fault parameters documented in the database. Finally, closing the loop, the methodology highlights priorities for future geological investigations in terms of where improvements in the density of data within the database would lead to the greatest decreases in epistemic uncertainties in the hazard and risk calculations. Key to this new generation of fault-based seismic hazard and risk methodology are the user-friendly open source codes documenting the link between the geological database and the relative contribution of each section to seismic hazard and risk at specific localities (ESC-2021 Hands-on organized).

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3D structural complexities in the upper crust of the 2016-2017 Central Italy seismic sequence area: the impact of fault segmentation and reactivation on seismotectonics.

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The Retrace-3D project produced a comprehensive 3D geological model of the region struck by the 2016-2017 Central Italy seismic sequence that has been recently released to the public (http://www.retrace3d.it/Contenuti.html).

The 3D model was built by using a large subsurface dataset acquired for hydrocarbon exploration, integrated with the available geological mapping in the area, and is constituted by seven lithostratigraphic units bounded by six horizons recognized in the seismic profiles, separated in fault blocks delimited by the major tectonic discontinuities.

The model shows the relationship between a series of thrusts developed during the Miocene-Pliocene Apennines orogenesis and inherited normal faults developed during the Mesozoic extensional phase and the Miocene foreland flexural process. Most of the normal faults mapped at the surface appear to be segmented both horizontally and vertically and were transported within the thrust sheets.

The analysis of the 3D model allows for a description of the various tectonic events that affected the region highlighting the widespread reactivation of inherited structures, sometimes inverting their kinematics.

This tectonic evolution had a strong impact on the seismicity observed in the area and in particular on the faults activated during the 2016-2017 seismic sequence. The comparison of relocated seismicity with the 3D geometry of the faults within the model demonstrated that mainshocks and aftershocks of the 2016-2017 seismic sequence are often located close or aligned with segments of inherited faults, both compressional and extensional.

The results of the Retrace-3D project provide the scientific community with a tool that can be useful in various applications related to the seismic hazard assessment workflows and in developing seismotectonics interpretations supported by subsurface three-dimensional constraints.

ESC2021-S14-282

Seismicity, structure and evolution of active faults systems in the Alboran Sea: The path to improve the seismic hazard related to offshore areas in the frame of the STRENGTH project

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Great to moderate offshore earthquakes, together with the possibility to generate destructive tsunamis, are geohazards of key societal concern, as they may impact world-economies, can disturb underwater key structures (i.e. submarine pipelines, fiber-optic cables, wind-farms or critical facilities) and affect coastal areas with the associated risk for local populations. The Alboran Sea is a Neogene basin located between Iberian and Nubia plates. The Plio-Quaternary deformation is being accommodated by large strike-slip and thrust faults. Seismicity is characterized by earthquakes of low to moderate magnitude; however, large historical and instrumental earthquakes have also occurred in the region. The STRENGTH project has the main objective to characterize the structure, development and seismicity of the large fault systems in the Alboran Sea. The knowledge on the location and characterization of active structures in this region Sea has been improved by recent studies. Nevertheless, the potential association of offshore seismicity to specific faults has not yet been undertaken in a systematic way.
The STRENGTH project aims to link a more detailed and precise characterizations of active faults in the Alboran Sea to offshore earthquakes to enhance image of the seismicity. To this, we are revisiting and analyzing the historical earthquake records and macroseismic information, and relocating the instrumental earthquakes registered in the last two decades, with a non-linear probabilistic approach jointly with high-resolution local/regional velocity models. The study focus on: a) characterizing the 3D-structure of the fault systems and their evolution, and identify the active faults that may have generated large-earthquakes; b) associating moderate to low magnitude seismicity and seismicity clusters to specific faults; and c) modeling ground motions in coastal areas based on fault characterization and recorded seismicity. The expected results will contribute to an improved assessment of the seismic hazard and risk in the Alboran Sea Region.

ESC2021-S14-350

Probabilistic slip-rate analysis of thrust faults in the northern Adriatic Sea (Italy): implications for the Plio-Pleistocene tectonic activity

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The detection of recent tectonic deformation becomes overly challenging when sedimentation rates overtake tectonic rates. In the Adriatic Sea, Plio-Pleistocene foredeep deposits blanket the fold-and-thrust belt system of the Northern Apennines, concealing the bathymetric expression of the buried structures. Despite the subtle to null geomorphic signature, the tectonic activity in the region is testified by the recorded seismicity, with historical earthquakes peaking at nearly moment magnitude 6. Moreover, following the occurrence of offshore earthquakes, also small tsunamis were reported during the last century.

To tackle this problem, we investigated the Plio-Pleistocene tectonic activity of buried thrusts in an offshore sector of the Northern Apennines orogen by analyzing a large dataset of 2D seismic reflection profiles and wells. We thus reconstructed the 3D geometry of eleven buried thrusts and then documented the last 4 Myr slip-rate histories of four of them by restoring two high-quality regional cross-sections. We determined the slip and slip rates necessary to recover the observed deformation of eight well-constrained stratigraphic horizons (Zanclean to Middle Pleistocene). Slip rates are then presented through probability density functions, including uncertainties derived from the restoration process and horizon ages.

Our results show that the thrust activation proceeds from the inner to the outer sectors of the Northern Apennines. The deformation history reveals an exponential reduction of slip rates over time, with a major

slip-rate change around 1.5 Ma (Calabrian). These findings agree with previous studies in the larger region and suggest that the strong slip rate deceleration of the outer thrust fronts in the last 1.5Ma is widespread throughout the Northern Apennines.

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Constraining the geometry of seismic sources with seismic scenarios: Application to the 1804 Dalías and 1680 Málaga earthquakes (SE Iberia)

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SE Iberia is a tectonically active region with an important historical record of destructive earthquakes (intensity>VIII), such as the 1522 Almeria, the 1829 Torrevieja or the 1884 Arenas del Rey earthquakes. Nevertheless, the fault source of some of the reported events still remains unclear. In this study, we have focused in the 1804 Dalias and 1680 Malaga earthquakes. The goal is to identify the best fault source rupture for each event and to discriminate between different fault candidates when they are spatially close.

Using the Boxer method, we determined the most probable location of the earthquake fault sources, their dimensions and azimuth, and earthquake magnitude. The comparison of these sources with the identified active Quaternary faults has allowed to select those possible fault candidates to have generated the 1804 and 1680 earthquakes. Then, we built different seismic scenarios considering all the possible selected candidates using OpenQuake. These seismic scenarios or simulations consider fault parameters such as rake, dip, length, hypocenter depth, magnitude, and fault geometry in depth to model the intensity fields corresponding to each possible rupture. It is expected that the modeled fault ruptures closer to the actual seismic source may produce intensity field distributions closer to the reported intensities at each location for the 1804 and 1680 earthquakes. The best performing fault for the source of the 1804 Dalias earthquake is the Loma del Viento Fault, a vertical fault running NW-SE through the Campo de Dalias. For the 1680 Malaga earthquake, the best performing fault is a complex rupture of the Montes de Malaga Fault, a hidden reverse E-W fault that controls the relief of the region by folding. In conclusion, the used methodology has proved very valuable to identify and constrain historical seismic fault sources.

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3D complexities of the Baza Fault (S Spain). Consequences for SHA

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The 3D geometric characterization of the normal Baza Fault (S Spain) indicates that this active fault is divided in two sectors: a northern sector characterized by a narrow damage zone (up to 1km width) and striking N–S to NNW–SSE (N175E), and a southern sector characterized by a wide damage zone (up to 7km width) and striking NW–SE (N165E to N135E). We postulate that such differences are the consequence of the combination of three different factors: i) The differences in the structural organization of the basement offset by the Baza Fault (homogeneous basement in the northern sector and with a strong mechanical layering in the southern sector). ii) The different orientation of the two sectors with respect to the regional extension (the northern sector is sub-perpendicular to regional extension while the southern sector is oblique). iii) Interaction of the Baza Fault with other regional structures (leading to an interaction damage zone in the

southern sector). The two last factors (different orientation and interaction with other active structures) present significant consequences for SHA. The change of orientation of the Baza Fault could imply that the fault is segmented. After applying the most common segmentation criteria to the Baza Fault, we propose that the entire fault should be considered as a single master seismogenic fault that is not divided into seismogenic segments. The interaction with other regional structures could indicate a physical linkage between active faults, that could potentially cause complex ruptures, increasing the maximum expected magnitude. Consequently, the 3D complexities of the Baza Fault point to a higher seismic hazard than previously characterized.

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Kinematic fault coherence. Insights from GNSS data and consequences for SHA

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Interaction of synchronously active faults implies a transfer of displacement between them. If the interacting faults present different kinematics, kinematic coherence is expected, which means that displacement rates of the faults should be interdependent. Analyses of kinematic coherence are usually realised by applying field data to elucidate fault attitudes, slip directions and displacement rates. We present GNSS (Global Navigation Satellite System) data from S Spain that provide slip rates for two faults: the normal Baza Fault and the strike-slip Galera Fault. GNSS data permit us to analyse how displacement is transferred between these two active faults, indicating that the fault system is kinematically coherent.

Complex ruptures involving multiple faults with a wide range of orientations, senses of movement, slip rates, recurrence intervals and even crossing tectonic domain boundaries have been documented for several historical earthquakes around the world. The kinematic coherency indicated by our GNSS data points to a physical linkage between the Baza and Galera faults. Consequently, we propose that a complex rupture involving both active faults should be considered in seismic hazard assessment studies.

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SISMOLAB-3D

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SISMOLAB-3D is the nickname of "Laboratorio di sismica a riflessione," a recently established INGV's infrastructure devoted to archiving, processing, and interpreting seismic reflection data and well-log data.

The lab also provides resources to perform numerical modeling and analyses of derived products to validate the three-dimensional reconstructions of the crustal structure and guarantee their reproducibility.

Although the lab's overarching goal is to contribute to any field of geosciences which involves detailed knowledge of the Earth's crust, the 3D reconstruction of potentially seismogenic faults is certainly one of its main subject matter.

The interpretation of seismic reflection data of sufficient penetration is ideal for illuminating the fault geometry at seismogenic depths. This aspect is of first-order importance because sophisticated simulations of earthquake ruptures applied to a poorly defined geometric definition of the hosting fault may lead to under-constrained results, as well as compromise subsequent interpretations and applications, including earthquake hazards analyses in all its various spatial and temporal scales. In addition, the comparison of reliable fault subsurface images with high-resolution catalogs of background seismicity and small seismic swarms/sequences can provide insights into the geometry and seismogenic potential of active faults.

This presentation illustrates the SISMOLAB-3D main data assets and their curation, HW-SW facilities, organization, and access policies. A portfolio of 3D models developed in the framework of recent and current projects will demonstrate the lab potentialities contributing to unveil the intimate aspects of faults at seismogenic depth and stimulate collaborations within the earthquake hazard community and beyond.

A display of the SISMOLAB-3D main features is available on its website (http://sismolab3d.ingv.it/).

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Earthquake hazard assessment towards seismic risk mitigation in Urban Areas

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Amplification study of sites characterised by a buried low-velocity layer using the Standard Spectral Ratio (SSR) and earthquake H/V techniques

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The Maltese islands are geologically characterised by a relatively simple four layer sequence of limestones and clays. A predominant feature in some parts of the islands is a layer of clay (which can be up to 75 m thick) buried beneath Upper Coralline Limestone (UCL). This velocity inversion has been comprehensively studied in the past years using ambient noise techniques. With the extension of the Malta Seismic Network to eight stations, and including three sites characterized by the above-mentioned typology, a new opportunity to study site amplification effects using earthquake data arises. In this work we present the results obtained from analyzing close to 3 years of earthquake data. By comparing the seismograms obtained on rock sites and on the sites characterised by a buried low-velocity layer, it is shown that higher accelerations are obtained on the latter. These effects can be attributed to the local geology structure, and have important implications for the assessment of seismic risk on the islands. The plots with results from the Standard Spectral Ratio (SSR) and earthquake H/V techniques are also used to highlight the amplification effect at particular frequencies. Comparisons with results from previous studies using noise data are also conducted.

ESC2021-S15-083

Near-Fault Ground-Motion observations and 3D Simulations of the Mw6.5, 30 October 2016 Norcia, Italy Earthquake, Italy

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During the 2016 Central Italy earthquake sequence, Amatrice and Norcia towns in the central Apennines were struck by an earthquake with M>6.0 three times over three months. The earthquake sequence destroyed the historic center of Amatrice town and caused major damage in Norcia. The unprecedented density of near-fault seismic stations and the high quality of recorded data made the Norcia earthquake one of the best recorded earthquakes in Italy.

Assessing the ground motion that a structure will endure during its life time is essential when designing seismic facilities for earthquake risk reduction and disaster mitigation. Estimating a realistic ground motion during earthquakes can fill the gap when records of strong ground motion due to large-magnitude earthquakes are missing, especially in near-fault regions.

In this study, we performed deterministic 3D modeling of the Norcia earthquake, using a physics-based rupture model and a 3D velocity model. We used high-performance computing and a fully numerical approach to compute strong ground motion in the frequency range 0-5Hz over eight thousand virtual stations covering a fault distance range of 0-30km. We used SW4, a finite difference code that uses a topography conforming curvilinear mesh, designed to model surface topography including wave scattering and mode conversions.

This research is the first attempt to simulate the 3D near-fault ground motions from the 30th October 2016 Norcia earthquake, based on a kinematic fault model and a 3D velocity structure. Our simulations suggest the topographic effect as an important factor that influenced the ground-motion amplification pattern in the study area. They also show that the recorded ground motion amplitude at near-fault stations was strongly affected by the large slip areas. These findings are essential to explain the extensive damage caused by the earthquake. They directly affect the seismic risk assessment of future earthquakes in the region.

ESC2021-S15-084

An approach to construct a Netherlands–wide ground-motion amplification model

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Local site conditions can strongly influence the level of amplification of ground-motion at the surface during an earthquake. Especially near-surface low velocity sediments overlying stiffer seismic bedrock modify earthquake ground motions in terms of amplitudes and frequency content, the so-called site response. In the Netherlands, earthquake ground-motion is of great concern because it can lead to amplified surface shaking resulting in significant damage on structures despite small magnitude events.

The ambient seismic field and local earthquakes recorded over 69 borehole stations in Groningen are used to define relationships between the subsurface lithological composition and the amplitude of ground shaking. For the Groningen region we show that the earthquake transfer functions match the ambient vibrations (H/V spectral ratios), which can be used as a first proxy for site response.

Based on the learnings from Groningen we constructed sediment type classes for the Dutch subsurface, each class representing a level of expected amplification. Secondly, the HVSR curves are estimated for all surface seismometers in the Netherlands seismic network and a sediment class is assigned to each location. Highest HVSR peak amplitudes are measured at sites with the highest level of amplification of the sediment classification. Based on this correlation and the presence of a detailed shallow geological model at most sites in the Netherlands, an approach is presented to predict amplification at any location with sufficient lithologic information. With this resulting site response map, we can obtain constraints on the seismic hazard and site response in areas that have limited data availability but have potential risk of seismicity, for example due to geothermal energy extraction.

ESC2021-S15-124

Seismic hazard assessment for the regions of low seismicity: example of Sparta, southern Peloponnese, Greek mainland

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Seismic hazard assessment for regions with low seismicity is a complicated task, since information regarding the sources is typically scarce. In cases where strong earthquakes have been reported in the past the issue becomes even more important, since such events point out to large local faults capable of causing extensive damage in possible future events. Deterministic hazard assessment can be carried out, however, by

incorporating data from geophysical field surveys which can point out to the location of local large faults. An example of such a seismically inactive area in Greece is the region of Sparta (southern Peloponnese). In 464 B.C the area was struck by a highly destructive earthquake of proposed magnitude Mw=6.4 which completely devastated the city of Sparta.
In the framework of the presented work, we perform site-specific deterministic seismic hazard assessment by calculating the synthetic ground motion from hypothetical events from the Sparta fault, delineated by seismic geophysical surveys. In our analysis, we also incorporated the VS profiles that were calculated using the Multichannel Analysis of Surface Waves (MASW) methodology in the test sites, in order to better simulate the site response.

For comparative purposes, strong ground motion is first calculated with the stochastic methodology (EXSIM algorithm), based on a variety of parameters that describe the source, the path and the site effect. We also employed the Synthetic Green's function (SGF) method which provides a site specific, broadband, three-component synthetic time series.

The application of these two methodologies allowed us to obtain the soil response at any selected site, to analyze it in frequency domain and to estimate further the effectiveness of each method for the purposes of soil-structure interaction.

ESC2021-S15-137

Seismic Hazard Assessment: A detailed probabilistic approach for the broader Messinia (SW Greece) region

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The region of Messinia is located in SW Peloponnese (Greece), in the vicinity of the Hellenic Arc which is dominated by reverse faulting. The arc is one of the most seismically active areas of Europe. Normal faults are also mapped on land, mainly striking N-S, adding further complexities to the involved seismotectonic processes. The Mw=6.8 2008 Methoni mainshock revealed a thrust focal mechanism, whereas the destructive 13 September 1986 (Ms=6.0) Kalamata earthquake a normal one. A detailed probabilistic seismic hazard study is performed for the broader Messinia region.

Probabilistic Seismic Hazard Assessment (PSHA) is applied to estimate the maximum expected ground motion parameters, i.e. PGA, PGV and PGD, for a mean return period of 475 and 950 years in terms of hazard maps. The results are obtained using the SHARE 2013 seismicity model, taking into account seismicity of the instrumental period, via the R-CRISIS V20 software. GMPEs obtained using Greek data that take into consideration the style of faulting and the soil type were applied. The optimum results for each ground motion parameter are obtained by hybrid models, through a logic-tree approach, that take into account all considered GMPEs and accounts for epistemic uncertainties. In addition, the hazard values are compared with previous studies, as well as with results obtained using historical earthquakes. The Uniform Hazard Spectrum (UHS) for five towns in Messinia, i.e. Kyparissia, Filiatra, Pylos, Messini and Kalamata, are also presented and compared with their seismic histories and the elastic design spectra proposed by the Greek National Building Code and Eurocode 8.

ESC2021-S15-161

Evaluating the amplification model at high resolution for the Sion area by combining earthquake and ambient noise recordings

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Earthquake site effects have a major impact on the seismic hazard. Evaluating the site response in a broad frequency range and with a good spatial resolution remain difficult. Currently, there is still a high demand from the engineering seismology community in having a cost-effective and reliable approach to evaluate the site response.

Empirical site effect assessment has shown good reliability up to high frequency but rely on earthquake recordings at many sites which require long station deployments. In contrary, seismic ambient noise can be rapidly recorded anywhere at any time. Recently, Perron et al. 2018 proposed a hybrid approach (SSRh) using both the spectral ratio on earthquake recordings at a few sites and the spectral ratio on ambient noise recordings between many sites where a short duration deployment has been done. The objective of our study is to evaluate the applicability of SSRh on large areas. To do so we performed 300 short ambient noise measurements of about 1 hour, on a regular grid with about 300m distance between points around the city of Sion, Switzerland; Sion is in a valley prone to complex 2D site effects in a broad frequency range caused by the soft, thick and variable sedimentary deposit of the Rhône River.

We take benefit from the 5 permanent and 5 long-term seismic stations present in the area to evaluate the empirical site response using the Standard Spectral Ratio (Borcherdt, 1970) and the Empirical Spectral Modelling (Edwards et al., 2013) approaches. Based on the site amplification function for 8 of these sites located on sediment, we are able to use the SSRh approach to evaluate the site amplification function at the ambient noise recording points. We obtain a high-resolution amplification model for this densely populated urban area which is in good agreement with the geological model.

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Local site effects in seismic risk mitigation: Case of 30 October 2020 Samos Earthquake

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Exploring the efficacy of the region-specific parameters is vital to make better predictions for the expected future ground shaking as part of the hazard mitigation plans. This argument has become apparent following the 30 October 2020 MW 7.0 earthquake that occurred in the eastern Aegean Sea causing considerable seismic damage and deaths. The extent of damage in Izmir was surprising for an epicenter 70 km away where the alluvial sediments strongly amplified ground motion in the city. The seismic damages showed the importance of local site effects in estimating the potential seismic risk. To clarify the ground motion characteristics, Interferometric Synthetic Aperture Radar (InSAR) and Global Positioning System (GPS) data were included in constraining the source mechanisms of the earthquake. Then, strong ground motions were stochastically generated of 1055 virtual stations on an area including Izmir. The parameters of the generated motions were compared with the observed ground motions as well as the ground motion prediction equations (GMPEs). The comparisons of ground motions' parameters were found consistent whereas the

GMPEs' results fall short at the distance where the local site effects are dominant. Thus, it is essential to compute proper calibration of the site response parameters instead of generic models in areas similar to the Izmir Metropolitan Area, before the conclusion of the next urbanization planning.

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Worldwide Strong motion metadata inspection to select design-compatible waveforms for Switzerland: Preliminary results

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The waveforms selection is a key step for many engineering seismology applications, such as seismic microzonation. The selection and use of earthquake ground motion recordings must be consistent with the seismic hazard level and ideally able to capture the variability and contributions of both local and distant earthquake sources to that specific hazard level and site condition.

In this contribution we inspect available databases of waveforms and related metadata to define standards linked to the quality of 3C-waveforms (compatibility to ground motion models, capturing the duration, energy and frequency content). Furthermore, the quality of metadata is a critical aspect of the entire process (e.g. reliability of magnitude, distance, site condition information, free-field recording). The purpose of the investigation is to assess which site metadata are provided, collate them among different databases, and verify the feasibility of a sub-selection of stations fulfilling the ideal criteria serving the purposes of the project (i.e. free-field stations with a reliable soil classification according to the Swiss building code (SIA261). Among the available strong motion databases, we selected the Engineering Strong Motion database (https://esm-db.eu/#/home), the Japanese database of K-NET and KiK-net (https://www.kyoshin.bosai.go.jp/) and the recordings from NGA-West2 (https://ngawest2.berkeley.edu/).

For each database, we extract a subset of stations suitable for the purposes of the project. These subsets of stations comprise 771 sites classified in terms of Swiss building code soil categories (A-E), inspecting the provided VS profiles. Moreover, the waveform metadata of the selected stations were checked. The resulting subset of waveforms comprise 12,572 recordings, that we analysed in terms of magnitude and Joyner and Boore distance distribution. Finally, using the results of seismic hazard disaggregation we provided for the different national seismic zones a subset of waveforms, trying to cover all the possible magnitude and distance combinations relevant for each seismic zone.

ESC2021-S15-171

An integrated 3D geological-seismological model for urban-scale seismic hazard assessment in Basel, Switzerland

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Assessment of seismic hazard at a local scale is fundamental to the adoption of efficient risk mitigation strategies for urban areas with spatially distributed building portfolios and infrastructure systems. The current work presents an advanced approach to develop a 3D integrated geological-seismological model, which will explicitly account for the complex geological conditions at the surface and at depth, for evaluating

earthquake risk in the Swiss canton of Basel-City. A rich database of ambient vibration measurements is available for the area from several hundred single stations and more than 25 passive seismic arrays. It is complemented by several active seismic measurements and numerous borehole logs. Earthquake recordings are available from an operating network of 22 permanent and 6 temporary stations along with several former stations. A rigorous 3D model of subsurface geological structure of the area has already been developed. We used dispersion characteristics of surface waves from ambient vibration array data for imaging subsurface shear-wave velocity (Vs) profiles. We applied a novel approach based on a Multizonal Transdimensional Inversion, formulated in the Bayesian probabilistic framework, in order to retrieve 1D Vs profiles from ambient vibration arrays. The initial results are very promising in resolving the interfaces corresponding to major velocity contrasts, especially in the complex sedimentary structure of the Rhine Graben formation. The Bayesian inversion also enables model uncertainty to be duly accounted for. The development of a 3D geophysical model, by assigning elastic properties to the subsurface layers and by integrating them with the 3D geological model, is currently ongoing. It will then be used to estimate the amplification of seismic waves, calibrated by empirical amplification obtained from earthquakes, in the area. The developed 3D geological-seismological model will be used for simulating risk scenarios and for revising the microzonation for Basel.

ESC2021-S15-186

Towards regional-scale, site-specific probabilistic seismic hazard analyses: an example in Western Liguria (Northwestern Italy)

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The present study couples up-to-date procedures for probabilistic seismic hazard analysis (PSHA) with the results of microzonation studies to achieve site-specific seismic hazard maps for the westernmost sector of the Liguria region (northwestern Italy), an area where strong earthquakes (of magnitude up to about 6.5) occurred in the past producing hundreds of casualties. The final goal is to produce probabilistic seismic hazard maps for peak ground acceleration and spectral acceleration that incorporate site amplification (by amending existing ground-motion attenuation models for rock conditions with an additional amplification term provided by microzonation studies) on a municipal scale. In the present application, site amplification is quantified through pre-compiled, frequency-independent amplification factors, which were determined through 1D equivalent linear ground response analysis of target soil columns representative of the stratigraphic settings of the Liguria territory.

According to modern practice, seismic hazard is assessed by applying a partially non-ergodic approach. The epistemic uncertainty related to site behavior is modeled via logic tree. Compared to conventional, ergodic hazard assessments for rock conditions and flat topography, the resulting maps provide a finer picture of the actual hazard of the study area, highlighting those sites where the ground motion hazard is dominated by local amplification effects. At these sites, the expect ground motions are up to twice the values resulting from the traditional, ergodic PSHA on rock. Besides hazard maps, results are also presented in terms of uniform hazard spectra for some target sites. Comparison with the isoseismal maps of past earthquakes have revealed a good agreement between the spatial distribution of the assessed hazard and that of felt intensities, with greater damage observed in areas presenting significant amplification effects and, consequently, a higher seismic hazard.

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Enhancing urban resilience in areas after earthquake events- case study in Elassona, Greece

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The ability of a city's social and physical elements to withstand and recover from major disturbances posed by natural disasters such as earthquakes is an important topic in preparedness and recovery of modern society. In cases like the Kobe earthquake of 1995, resilience in the sense of return to normalcy, was only possible after an extended period of extreme social-spatial dislocation. Space is one obvious and important, but little studied, resource for the creation of urban resilience. Open spaces can contribute to urban resilience and should be protected not just for their high value for urban life in normal times, but also because for their qualities in post-catastrophic scenarios.

This study focuses on the space as a valuable resource in urban resilience after earthquake events and examines the case study of Elassona in Greece where in early March 2021 was struck by two earthquakes up to magnitude 6. In this work, the data used are Sentinel-1 radar images in Single Look Complex (SLC) mode, dual-polarization (VV/VH), ascending orbit from the Copernicus Open Access Hub. The data processing was performed using the open-source software Sentinel Application Platform (SNAP) by the European Space Agency (ESA). The image pairs generated two co-seismic interferograms and two displacement maps respectively that represented the deformation caused by the two earthquakes. The methodology to derive the deformation maps will be fully described from co-registration, to interferogram and coherence estimation and phase unwrapping. Geometrical results will be also given along with comparisons using externally measured features by GNSS network measurements. The results included determining the suitability of land currently allocated to urban development and identifying areas that should remain as parks and open spaces, crucial for victims and supporting actors who are involved in tasks like sheltering, debris removal, and essential construction work.

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Near real-time damage assessment for building typologies: a case study in northeastern Italy

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In case of an earthquake, providing a rapid estimation of expected impacts to emergency managers and first responders is extremely important. Current near real-time damage assessment methods rely on ground motion estimates and exposure/fragility data sets, sometimes integrating the shaking recorded at the site (e.g. from strong motion monitoring networks). Here we propose a method for damage assessment of building typologies. The expected damage is estimated from strong motion recordings of a seismic event in the selected area. The dynamic behavior of a specific building typology can in a first approximation be described by a single-degree-of-freedom oscillator, or for more complex structures, by a multi-degree-of-freedom oscillator. Its characteristics, i.e. fundamental frequencies and damping, which approximate the dynamic behavior of the studied building typology are obtained from the analysis of the building stock and a large number of ambient vibration measurements in buildings of this typology. The information can also be

retrieved from frequency-height relations for different building typologies found in literature. The damage proxy is either the maximum drift or the displacement, estimated at the top of a building. The limits for different damage states and building typologies for various regions are defined in the available literature. Since no damaging event has been recorded by our northeastern Italy building monitoring network so far, the method has been verified using a case-study simulating the 1936 Cansiglio event. Additionally, the damage assessment has been validated for a single building which has been monitored by the Italian seismological structural observatory and completely damaged by the Central Italy earthquake sequence in 2016. The method can be applied also in other seismic areas worldwide to provide a quick damage assessment, if information on the building stock is available and a seismic event has been recorded.

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Testing site amplification curves in hybrid broadband ground-motion simulations for the 2016 Amatrice earthquake

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In a recent paper, Pischiutta et al. (2021) produced synthetic broad-band seismograms for the 2016 Mw 6.0 Amatrice earthquake. To infer the low frequency seismograms, they considered the kinematic slip model by Tinti et al. (2016), while the high-frequency seismograms were produced using a stochastic finite-fault model approach. Simulated hybrid ground-motions were validated through the comparison with data recorded at 133 strong-motion stations. Site effects were accounted by the use of generic amplification curves for the different soil classes as prescribed by Italian NTC18. The use of generic site curves led on average to an improvement in the fit with real data. However, under particular site conditions, such curves did not adequately represent the effects of the specific characteristics on shaking. In fact, they do not consider specific geological features and impedance contrasts in the site- characteristic stratigraphy.

Therefore, in this work we select 57 stations potentially affected by site amplification in particular site conditions, as sedimentary basins, topographic irregularities, rock sites in fault zones. We test the use of empirical amplification curves in order to achieve a better fit between observed and simulated ground-motion. The considered curves, available in the Italian Accelerometric Archive v3.1, were obtained from Horizontal-to-Vertical Response Spectra (HVRS), Horizontal-to-Vertical Spectral Ratios calculated from Fourier spectra using earthquakes (HVSR) and ambient Noise (HVNSR) waveforms. We also adopt site curves derived from the Generalized Inversion Technique (GIT).

The GIT empirical amplification curve was very effective in reproducing spectral peak caused by stratigraphic effects at stations installed in sedimentary basins. However, the use of the generic site amplification curve led a better fit with real data than HVSR and HVNSR.

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Analysis of stratigraphic column surface parameters obtained from artificial seismograms

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The construction of strategic engineering structures as dams and nuclear power plants, requires a preliminary seismic hazard assessment study specific to the construction site. However, poor seismicity data in the study region may constitute a real challenge to the completion of site vulnerability study. To address this issue, several potential solutions can be considered, in particular the use of typical reference earthquakes records (El Asnam, Imperial Valley, Northridge… etc) as input in the basement of the stratigraphic column. Another alternative solution is to use an artificial seismogram instead of earthquake records. This study discusses step by step the development of an artificial seismogram in the time- frequency-phase domain. A series of transformations are applied in the three dimentional space of time- frequency-phase domain in order to reproduce the variations observed in the real accelerogram. The target spectrum is tested using the ratio of target and calculated spectra for each frequency of the Fourier transform. Obtained results are discussed based on the comparison of surface parameters, namely PGA, PGV, and PGD obtained from an artificial earthquake and those obtained using real data.

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On the implementation of site effects for the new Seismic Hazard Map of Norway: an Oslo area case study

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In March 2020, NORSAR released the new Seismic Hazard Map of Norway, based on new approaches and harmonized data. Many improvements have been done to the 1998 national earthquake hazard map, that is considered not sufficient in local detail and outdated with respect to data and methodology applied. To estimate the probability of ground shaking from earthquakes, the 2020 map uses a Probabilistic Hazard Analysis approach, with three different realizations for the seismic zonation: based on seismicity, on structural elements and on a zonation free approach (regular grid extracted from earthquake activity rates). All results are evaluated at bedrock conditions using a reference shear wave velocity equal to 1200 m/s.

As part of the GEObyIT (Geodata-based Machine Learning for real-time urban risk reduction systems) project, we aim to compute the seismic risk for the city of Oslo, conducting a microzonation study that will include site effects. More specifically, the Vs30 value has been introduced to become the main attribute to characterize the soil type and subsequently account for soil type related seismic amplification. The input for this study is missing for the Oslo area, therefore we aim to invert H/V spectral ratio of ambient noise as a proxy for S-wave velocity (Vs) profiles. In addition to resulting Vs30 values, this method will also allow to define depth to bedrock estimates, which will likely be required for an updated Eurocode. This procedure will be applied in specific areas in the Oslo urban environment that are susceptible to site effect amplifications.

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Interscale magnitude relationships for the Ibero-Maghreb region

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Magnitude inter-scales relationships for the Ibero-Maghreb region are derived using the International Seismic Centre (ISC) earthquake catalog. Both standard and weighted least square regressions (LSE, WLSE) together with orthogonal regression (OR) have been applied to get the link between the Ms reference scale and other magnitude scales, namely Mb, Ml and Mblg. Based on the correspondence between magnitude and energy, these regressions were performed under the assumption that observed deviation between two

magnitude scales should not exceed a given threshold limit. Such hypothesis is motivated by the fact that large differences between magnitude scales may result from errors in the determination of magnitudes. Accordingly, it is set to avoid the use of bad quality data and to improve regression performance by enhancing linear data tendency by smoothing along the main observed direction. The results show pronounced linear regression fits from different regression methods, obtained as a potential link between Ms and other magnitude scales. The established relationships are used to build an Ms- homogenized earthquake catalog for seismic hazard studies.

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Risk-targeted hazard maps for Spain

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Many studies have shown that using the uniform hazard principle to design structures does not ensure a uniform collapse risk. Due to the structural capacity uncertainties and mainly the shape of hazard curves, even in regions with equivalent peak ground accelerations (PGAs) corresponding to the same mean return period, the seismic risk in terms of failure probability would be substantially different. In this study, the risk targeted hazard mapping is investigated in Spain using a newly revised seismic hazard map. Since risk targeting requires several input parameters, such as model parameters for fragility curves, the variability of these parameters is taken into account using the probability distribution corresponding to the RC moment frame building, which is the most common typology in Spain. The impact of changing these parameters on risk outcomes is investigated, and various assumptions for estimating the model parameters of fragility curves are demonstrated. These assumptions are included in a fixed fragility curve (generic) or building-site-specific fragility curves. Regarding the seismicity level in Spain, various suitable risk thresholds such as collapse, and yielding were considered. Finally, the maps for risk-targeted design ground motion and risk coefficient are shown. It was highlighted due to the variation in shape of the hazard curves across Spain and the uncertainty of structural capacity; the use of risk-targeted hazard mapping led to adjustments for current design ground motions. Furthermore, it was discovered that using building- and site-specific fragility curves could lead in better seismic risk uniformity across the country.

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Ground Motion Prediction Equations (GMPEs) for the Italian territory: a new estimation from ten years RAN accelerometric database and an overview about their application limits

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In the first part of this study we obtained new GMPEs for the Italian territory calibrated on a robust and good quality accelerometric database, correspondent to 1608 ML>3 events occurred in the ten years time-span 2009-2019. All data was recorded by Central Eastern European Earthquake and Research (CE3RN) Network and Rete Accelerometrica Nazionale (RAN) network.

We have estimated relations for the prediction of the peak ground motion parameters (displacement, velocity and acceleration) and of pseudo spectral accelerations at different periods (0.3, 1.0 and 3.0 seconds). In addition, we also included in the analysis some integral ground motion parameters such as the Integral of Squared Acceleration (IA2), Squared Velocity (IV2), Squared Displacement (ID2), the Cumulative Absolute Velocity (CAV), the Housner (IH) and Arias Intensity (IA). All the parameters have been calculated by considering the maximum, the geometrical mean of the two horizontal components and the vertical component. The derived prediction laws have been tested on the one year time-span 2020 RAN accelerometric records constituted by 79 ML>3 earthquakes; their relative residuals showed in first approximation a log-normal distribution.

In the second part of the work, taking as reference our testing database, we compared the performance of our GMPEs functional with the more complex ones recently used for the Italian territory. In addition, in correspondence of three Italian sub-regions, we derived a set of regional GMPEs with the same functional form and then compared their performance on the testing data set with respect to the laws obtained at National level. The results showed that a complex modeling of the ground motion parameter does not provide a significant reduction of the residuals relative to a much simpler GMPE functional. Furthermore, we found that the use of a regional approach for GMPE application is approximately equivalent to the one at National scale.

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Probabilistic seismic hazard assessment in Lebanon

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The present work focuses on Lebanon, a country with a high seismic potential since it is located along the Levant fault system (LFS), a ~1200 km long strike-slip fault that accommodates the northward motion of the Arabian plate relative to the Sinai-Levantine plate (with a slip rate around ~5 mm / year, Le Béon et al 2008). Our aim is to determine probabilistic seismic hazard for the country. In this area, the observation datasets available both to model earthquake recurrence and to select ground-motion models are scarce. The instrumental catalog is typical of a low-seismicity region, and is not representative of the large destructive earthquakes that occurred in the past. We develop a set of smoothed seismicity models based on instrumental data, to forecast off-fault seismicity.

We build a fault model including major and best-characterized faults in the area. For all faults, a Gutenberg-Richter model is assumed with earthquake frequencies inferred from the slip rate of each fault. We show that for most sites in Lebanon, the hazard at 475 years return period is controlled by the faults with a negligible contribution from the background seismicity. In the case of Beirut, the hazard estimates are fully controlled by the Mount Lebanon thrust Fault that underlies the capital city. We set up a logic tree including uncertainties on the b-value, on the maximum magnitude, and on the slip rate and demonstrate that the slip rate uncertainty governs the overall variability on hazard estimates. This study is a first step in a long-term project aim at better understanding and improving seismic hazard assessment in Lebanon.

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Mitigation of seismic risk of architectural monuments in Bucharest

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Bucharest, the capital of Romania is a city experiencing strong earthquakes that originate in the so-called Vrancea-intermediate-depth seismic source. 1977, March 4, the last strong seismic event was of magnitude MW = 7.4, with a lot of collapsed buildings and almost 1500 victims in the city.

Because of this situation architectural monuments built at the beginning of the XX-th century, when there were not in force seismic codes for design and construction, request a special attention. One of these monuments is "Arch of Triumph" built between 1921-1922 in the Northern area of the city, made of concrete and masonry. Along the years it was rehabilitated several times (1935-1936; 2014) being reinforced to withstand strong earthquakes. In the 2014 rehabilitation process was introduced a base isolation system and dampers and from the end of 2016 was monitored by two seismic sensors at the base and on top. In the paper will be presented recordings of acceleration on the arch and free field of several seismic events in the years of monitoring and how the base isolation modifies the amplification of the seismic response in the structure, contributing to the mitigation of seismic risk of the monument. Will be analyzed and discussed the benefits of this extended rehabilitation with base isolation for the preservation of historic monuments.

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Toward a site-specific PSHA in the Po Plain area (Northern Italy)

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The present study deals with a site-specific Probabilistic Seismic Hazard Analysis (PSHA) for the Po Plain area. The main scope is to evaluate the impact of site amplification on the Po Plain seismic hazard, particularly at long response periods. To this end, the work incorporates the results of the recent study of Mascandola et al. (2021), which presents an amplification model based on 1D ground response analyses for the entire Po Plain, and the frequency-dependent correction factors of Lanzano et al. (2016) to account for 3D amplification effects related to surface wave generation at the edge of the basin. These effects were observed to play a significant role on site response, particularly at those sites where the seismic hazard is controlled by distant sources.

According to modern practice, seismic hazard is assessed by applying a partially non-ergodic approach (e.g., Rodriguez-Marek et al., 2011). The epistemic uncertainty related to site amplification is included in the computations via logic tree, while adopting up-to-date assumptions about the seismic catalog (CPTI15, Rovida et al., 2021), seismogenic model (Santulin et al., 2017a,2017b), and ground-motion prediction equations (Lanzano et al., 2016, 2019) in the reference hazard model.

Results are presented both in terms of hazard maps and in terms of uniform hazard spectra for target sites. Compared to conventional, ergodic hazard assessments for rock conditions, the resulting maps provide a finer picture of the actual hazard of the study area, highlighting those sites where the ground motion hazard is dominated by amplification effects.

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Ground Motion Variability across a Small-Aperture Urban Array during the 2008 M6.3 Ölfus Earthquake in South Iceland and its Impact on Seismic Loss Estimation

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Iceland is the most seismically active region in northern Europe and damaging earthquakes repeatedly occur in its two transform zones. The most recent and costliest earthquake was the 29 May 2008 Mw6.3 Ölfus earthquake in the South Iceland Seismic Zone. The town of Hveragerði was in the extreme near-fault region of the earthquake and was subjected to very high peak ground accelerations and large amplitude velocity pulses, recorded on the ICEARRAY I strong-motion urban array in the town. Hveragerði is one of six European testbeds of the TURNkey H2020 European project (www.earthquake-turnkey.eu) and in this study, we investigate the variability of ground-motion intensity measures of the Ölfus earthquake and its impact on the expected seismic loss, with reference to the detailed building-by-building exposure database and the corresponding loss data. We compute all known ground-motion intensity measures (IMs) and quantify their spatial variability by Kriging geostatistical analyses along with accounting for the uncertainties in the spatial interpolation process. The significant variation of different IMs over the small study area (2*2 km²) illustrates that the assumption of uniform distribution of a single IM for a relatively small cell in seismic risk assessment can give deceptive results, especially when looking closer, the geology is shown to be non-uniform with systematic resonance at certain periods. The exposure database combined with the IM distribution enables us to predict losses for the key building typologies, identified according to the SERA classification. The loss estimation factors in the spatially variable uncertainty of the IM through a logic-tree framework. Moreover, loss estimates are computed at the highest spatial resolution at the geographical level, i.e., building-by-building, from global fragility models using the open-source SELENA software (Molina et al., 2010). We show that the estimated losses (mean loss ratio) from the global models are greatly higher than the observed losses.

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A Seismic hazard Model for the Middle East Region

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The middle east region covers a broad spectrum of seismotectonic features due to the northward movements of the Africa Plate, the Arab Plate, and the Indian Plate that converge with the Eurasian Plate. Additionally, the Middle Ocean Ridge drafts the Arab Plate away from the Africa Plate. Historically, middle east region endures significant loss due to seismic hazard. Most previous hazard studies have either covered a single

country or part of the Middle East region. In this study, we take a unified approach to study seismic hazard for the purpose to assess regional earthquake risk. A moment magnitude homogenized historical earthquake catalog is developed from using the ISC bulletin data, ISC-GEM catalogs, GCMT catalog, as well as many other local and regional catalogs. We compiled a fault database covering the entire region to be included as explicit seismicity source. In addition, we developed a kinematic model using recent GPS data along of fault and plate motion information to determine a strain rate and moment rate field, and use such information as constraints for distribution of modeled seismicity and rate. Seismicity model is developed using a combination of areal source and fault zone including both shallow and intermediate depth earthquakes. We reviewed the latest Ground Motion Prediction Equations (GMPE) developed locally and globally for active crustal, oceanic spreading ridge, stable continental, subduction zone interface and intra-slab earthquakes, and evaluated these equations against available strong motion data in the region, selected a proper set of GMPEs for each types of earthquakes for intensity calculation. We will discuss the hazard results in the context of other previous studies, focusing on most areas of most impacted by seismic risks.

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Unravelling resonance patterns in a sedimentary basin: an example from Bolzano (Northern Italy)

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The seismic response of sedimentary basins is an important hazard factor during earthquakes. Its study relies on the measurement of ground resonances, usually by means of the H/V (horizontal to vertical spectral ratio) method applied to single-station microtremor measurements. This method is suitable in the case of 1D plane-parallel stratigraphy, where the dynamic behavior does not change along any horizontal directions. When the 1D assumption does not hold, such as in the case of deep sediment-filled valleys, 2D resonance modes develop along cross-sections of the valley and the dynamic behavior differs along the horizontal directions. 2D resonances appear as peaks in the individual spectral components of motion at different frequencies along the longitudinal and transversal directions of the valley. In addition, while 1D resonance correlates with the local stratigraphy below the measurement site, 2D resonances imply simultaneous vibration of the whole valley slice and depend on the valley cross-section geometry.

In the case of more complex geometries, such as sedimentary basins, resonance modes are more difficult to predict and depend on the unknown complexity of the buried bedrock geometry.

We analyzed several hundred single-station microtremor measurements acquired in the Bolzano alluvial-sedimentary basin (Northern Italy) and attempted to unravel the observed resonance patterns. We first identified frequency and amplitude features that characterize 1D- and 2D-type resonances on individual spectral components of motion and on H/V ratios, on a single measurement and on several measurements acquired along lines across the basin. Then we performed further analysis on 2D resonance modes, by investigating their directionality, frequency and amplitude features. With a simple rotation procedure, we assessed the main axes of motion of the buried geological structures, analyzed 2D resonance mode frequencies and amplitudes along these axes and observed their relation with the bedrock geometry of the basin derived from seismic and gravimetric data.

ESC2021-S15-506

Mapping maximum expected magnitude estimates in the Ibero-Maghreb region

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Maximum expected magnitude Mmax is estimated and mapped for the whole Ibero_Maghreb region using a nonparametric probabilistic approach. For this purpose, an Mw- homogenized earthquake catalog database is compiled from different sources and its magnitude completeness is analyzed. It covers the time period between 1406 and 2019, and includes both instrumental earthquake magnitude records and historical macroseismic intensity data. Several global and local earthquake network databases were used in the catalog compilation, including the International Seismological Centre (ISC), the Instituto Geogràfico National (IGN) and the Centre de Recherche en Astronomie Astrophysique et Geophysique (CRAAG) databases; while the historical database has been compiled using all available peer reviewed published catalog sources. The results are plotted as Mmax maps showing areas expected to host high, medium and low magnitude events as worst earthquake scenarios. In particular, the region corresponding to the largest Mmax estimate has been delimited as including Cheliff basin and its surrounding areas west of Algiers city. The deviation between observed and estimated Mmax values is analyzed and discussed based on a comparative study between the deterministic and the applied nonparametric probabilistic approach. In our case, it is shown that the deterministic approach tends in most cases to overestimate Mmax comparatively to the probabilistic approach.
Keyword: Maximum possible magnitude, ISC catalog, Ibero-Maghreb region.

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Strong ground motion simulation in the near field: An application to the M7.0 Samos 2020 earthquake

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In this work we study the M 7.0, 30 October 2020 earthquake which occurred offshore Samos Island, Greece. Strong ground motions were recorded by accelerometers on the island of Samos and in the city of Izmir in Turkey. We start by considering a rectangular fault in a homogeneous elastic half-space environment. The properties of the model have been determined so that they approximate satisfactorily the actual setting. The propagation problem was mathematically described by the three-dimensional elastic wave equation with appropriate boundary conditions. We address this problem using the three-dimensional discrete wave number method and generate synthetic seismograms at locations that are located in the near-fault region. A variety of slip distribution and slip time functions, that describe alternative source activation mechanisms, are considered. A computer program developed in that context undertakes the generation process of the simulated seismograms. Our future plan is to extend this code to cover more complex environments, more realistic slip time functions and to take into account significant regional properties. A comparison study between synthetic and real recordings from this earthquake is also provided to validate the suitability of the employed methods, under the H2020 financed TURNkey project. A study of the qualitative distribution of near fault motion based on the assumed slip distributions on the fault plane is finally carried out for the region under consideration, especially for sub-areas with unstable structures and buildings.

ESC2021-S15-539

Comparative Probabilistic Seismic Hazard Studies for selected sites in Greece implementing updated Tools and GMP-Models

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The broader region of Aegean has been acknowledged as one of the most seismically active regions in Europe, as almost half of the seismicity in Europe is released in this region. Occurrence of damaging earthquakes in this area is a frequent phenomenon, with the events of Mw7.0 in Samos and Mw6.3 in Larissa, which occurred in 2020 and 2021 respectively, being the most recent examples. Several Probabilistic Seismic Hazard Assessment (PSHA) studies have been performed for many sites in this region in the past, however, updated seismicity models (Vamvakaris et al., 2016), strong motion datasets (Margaris et al., 2021) and Ground Motion Prediction Models (GMPMs) (Boore et al., 2021) have been recently adopted in Greece, and have not yet been fully implemented in such analyses. Herein, in the framework of HELPOS, PSHA in terms of PGA and PGV, is performed for selected sites in Greece for various return periods, incorporating newly-developed calculating tools and seismic sources. PSHA results, which have been derived based on earlier local and global GMPMs (Skarlatoudis et al., 2003; etc) and seismic source models (Papaioannou and Papazachos 2000; Papazachos et al., 2001), as well as, the provisions of the current seismic design code, are also presented and compared in a detail. The logic-tree approach is followed in all the analyses and uncertainties are taken into account regarding the strong motion parameters. Differences of the latest derived results in relation to the previous ones are spotted and discussed among the design code provisions.

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Large scale seismic characterization of Foggia Province (Southern Italy) by means principal component analysis (PCA) of HVSR data

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HVSR (Horizontal to Vertical Spectral Ratio) measurements of ambient vibrations allow a cheap and fast characterization of the study area by identifying the zones potentially affected by ground motion amplification phenomena. In this way, the possible presence of sharp seismic impedance contrasts in the subsoil can be detected by providing general information about their depth and their relevance for engineering purposes. The extensive application of these measurements has also made it possible to investigate large areas (of the order of thousands km2): in this context, automatic procedures aimed at grouping similar HVSR curves can provide a fundamental contribution in identifying regional geological heterogeneities (and therefore the respective seismic characteristics), especially with a dataset consisting of hundreds of measurements.

The purpose of this work is providing a preliminary seismic characterization of the whole territory (about 7000 Km2) of the Foggia Province (Southern Italy) by identifying large-scale geological heterogeneities using the Principal Component Analysis (PCA) on HVSR data. The considered dataset consists of about 400 HVSR measurements carried out during the Seismic Microzonation studies of the 61 municipalities belonging to

this Province. Without any predefined constrain, PCA allowed to group the areas characterized by similar HVSR curves, identifying at the same time the relevant characteristic HVSR patterns. The outcomes of this procedure clearly show different seismic behaviors related to the main geological and morphostructural domains of the study area. Finally, through the use of appropriately calibrated resonance frequency (f0) - resonant interface depth (H) relationships, it was possible to provide a tentative estimate of the seismic amplification effects by following the Italian building code.

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Transfrontier macroseismic intervention group for Pyrenean massif: An INTERREG European project for ground shaking severity estimation

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The Pyrenean massif cross-border (France, Andorra, Spain) experienced major earthquakes in the past, generating local strong intensities (Arette 1967 Io=IX, Bigorre 1660, Io= VIII-IX, Catalonia 1427 & 1428 Io=VIII-IX), i.e. 38 events of intensity equal or greater than VII since 1373.

The instrumental network in this area has undergone unprecedented development in recent decades allowing a more precise characterization of seismic sources and improved knowledge of hazard level.

In parallel, assessment of the macroseismic severity of the earthquake shaking is developing by improving data collection and intensity estimation. Macroseismic intensities allow the characterization of historical earthquakes but also the realization of simulations necessary for crisis management or risk prevention.

Because seismic effects don’t know administrative limits and with the aim of collaborating to improve a common culture of seismic risk on a Pyrenean massif scale, French (CNRS), Spanish (ICGC, IGN) and Andorran (CENMA) institutions have just created, within the framework of the European cross-border POCRISC project, the first Pyrenean Macroseismic Intervention Group (GIM-PYR) for intensity estimation on the field when significant seismic effects occurs (damage to buildings ≥ degree 3 EMS98).

The project is based on the initial organization of the GIM-France (set up in 2011) and steered by the BCSF-RENASS. The GIM-PYR is led by 3 national managers in charge of organizing missions according to the epicenter location. It allows concertation work and collaboration in the field, especially in affected urban zones.
A training of 17 experts took place in the village of Arette in the Pyrenees in October 2019 to acquire and homogenize the collecting information procedures, statistical estimation of effects and intensities estimations, while addressing the logistic and security aspects of the group. The GIM-PYR is currently continuing to set up and organize itself until 2021 through simulation exercises and the creation of coordination tools.

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Space-time analysis of completeness magnitude variation in the Ibero-Maghreb region

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Analysis of space and time variation of completeness magnitude mc is carried out for the whole Ibero_Maghreb region using the Maximum Curvature (MAXC) and the Entire Magnitude Range (EMR) methods applied on a moment magnitude Mw- homogenized earthquake catalog database compiled from different sources. The catalog database which covers the time period between 1406 and 2019, has been compiled based on a set of global and local earthquake network databases, including the International Seismological Centre (ISC), the Instituto Geogràfico National (IGN) and the Centre de Recherche en Astronomie Astrophysique et Geophysique (CRAAG) databases. The results are plotted as a series of mc maps showing space-time variation of mc estimates during different time periods. Observed mc behavior can be explained by the development of the corresponding seismic networks covering the study region. In particular, the observed mc distribution reflects the seismic stations density with low, moderate and high mc values corresponding roughly to dense, less dense and diffuse or poor network coverage, respectively. Especially, mc decrease is observed during the last decade in regions with dense seismic station coverage. On the other hand, reversible local transient raise of mc is observed for about three years after the occurrence of the 2003 Boumerdes earthquake. Our analysis of mc variation in space and time may help network operators to improve earthquake monitoring by using a suitable optimized seismicity coverage
Keyword: Magnitude of completness, ISC catalog, Ibero-Maghreb region

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Low cost microzonation for a high hazard, high risk city: The Beirut case

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Despite a moderate seismicity over the last century, Lebanon experienced several major historical events, resulting in a high long-term risk, especially for its capital city Beirut. The present paper reports the methodology and results obtained within a recent project aimed at delivering a seismic microzonation map to the Beirut municipality. Due to the project constraints (limited budget, short duration) and the pandemic situation, the final propositions are based on pre-existing, readily available information.

The four-zone microzonation map is derived on the basis of a geological map, hundreds of microtremor measurements with a mesh size of ~400 m, and a few Vs measurements with non-invasive techniques in a handful of representative sites. The primary criterion is the value of the fundamental frequency f0HV. A "reference" microzone BR where site effects are considered negligible, is characterized by a H/V curve without any peak below 12 Hz,. The three other BS1, BS2 and BS3 microzones correspond to different f0HV intervals : [6-12[, [3-6[, and below 3 Hz, respectively. The design spectra for each microzone are then derived on the basis of short period (Fa) and intermediate period (Fv) amplification factors combining a linear part (estimated from weak motion recordings at a few sites within each microzone) and a non-linear part (inferred from the non-linear terms of a set of GMPEs considered valid for the Middle-East area, and a rough correspondence between VS30 values and BS microzones: 600, 400 and 250 m/s, for BS1, BS2 and BS3, respectively, from the few available Vs profiles). This approach is applied to different seismic hazard levels of

reference: the present regulatory level for Beirut, and newly calculated hazard levels from a study accounting for the Mount Lebanon thrust fault. The robustness and the limitations of the results are discussed, and directions given for further improvements.

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Influence of low-velocity superficial layer on long-period surface wave propagation in Eastern Osaka Basin

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Earthquake hazard and risk mitigation for large subduction earthquakes with hypocenters at the Nankai trough in Osaka basin concerns mainly low-frequency part of the ground motion spectrum. The effect of such ground motions is crucial primarily on some of the large or dumped structures with low Eigen frequency, excited by the surface waves generated at the edges and propagating through the Osaka basin. The frequency content of the wave field impeding the basin due to the deep events is typically 0.04-0.4 Hz. Because of the sparse data coverage of the several damaging events, the 2D Finite-difference (FD) simulations and the analysis of the surface waves and comparison to data were done at OSA small–aperture array, WOS, MKT, YAE, and ISK stations (Hatayama et al., 1995).

In our study, we analyze 3D FD wave propagation synthetics using updated 3D structural models of Sekiguchi et al. (2013, 2016), and compare these to the respective surface wave data, namely the SL1 surface-wave phase (Hatayama, 1995). Modeling the SL1 phase at the respective stations is very sensitive to the presence of the Vs=260m/s layer in the topmost hundreds of meters of sediments. That appears to be the key factor to model the SL1 phase late arrival times and amplitudes. On the other hand, previous 3D simulation models without such layer or with 400m thick low-velocity layers model SL1 poorer in terms of time and amplitude (Oprsal and Iwata, 2008). Using the semblance analysis we show that the SL1 phase is not generated solely at the eastern edge of the Osaka basin and it is a compound of several waves arriving at the WOS station and OSA array from several directions.

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Seismic risk assessment for the Ionian Islands and cultural heritage vulnerability estimation

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Main scope of the "Telemachus" project is the creation of an innovative seismic risk management system for the Ionian Islands, the most seismically and tectonically active area in Greece and one of the most active worldwide. Seismic risk assessment and vulnerability studies will inform the decision-making system that will operate in GIS environment to support the development of disaster risk reduction activities and management plans. The building stock of Kefallinia, Zakynthos, Ithaki, Lefkada, Corfu and Paxi was mapped at district level, allowing for the typological characterization of structures. A semi-empirical macroseismic method was implemented for the vulnerability characterisation per building and mean vulnerability was attributed per district. Probabilistic seismic hazard assessment (PSHA) was performed using the Cornell-McGuire approach which introduces seismogenic zones. PGA was obtained for a return period of 475 years via the R-CRISIS V20

software. Seismic risk assessment yielded results in terms of structural damage and economic loss estimation. For operational and management purposes, mean qualitative damage per district and loss distribution in monetary terms were mapped. Additionally, a comprehensive database of listed buildings and traditional districts was created. For the estimation of seismic vulnerability of the cultural heritage, a modified approach of the abovementioned methodology was applied, accounting for the peculiarities of the vernacular building stock and the observed seismic performance. Mean vulnerability class was individually estimated per building and vulnerability statistics per district were mapped to provide ex-ante macroscopic awareness of potentially fragile structures that would need preservation, retrofitting and/or rapid intervention.

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Estimating urban seismic damages in Beirut at a fine spatial scale in the context of the lack of comprehensive data

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Beirut, the capital of Lebanon, is a densely urbanized city that holds most of Lebanon’s economic and institutional activities. Historically, Beirut was subject to several destructive earthquakes that have caused thousands of casualties. One of the challenges in estimating the seismic risk in Beirut is the lack of a comprehensive building stock database. The estimation of buildings’ seismic damages in Beirut was covered in Salameh et al. 2017. Based on simple input parameters related to the seismic loading, the soil’s and the building’s resonance frequencies and the building’s typology, buildings damages could be estimated for 1D linear site response. This approach was applied to two zones in Beirut where an exhaustive buildings survey was conducted. We propose to extend these works by considering 1D non-linear site response and performing damage estimations on a 3D buildings model in Beirut, reconstructed using geospatial data and satellite images. The geospatial data on Beirut’s buildings were collected from OpenStreetMap. The height of these buildings were retrieved from the correlation of high-resolution Pleaides satellite images. The existing Beirut buildings’ database was used as a learning dataset to infer additional buildings’ properties based on their heights: number of floors and buildings typology were inferred from a classification tree to predict the building’s construction period from its number of floors and location. Additionally, artificial neural networks were trained on a large dataset of oscillators, soils profiles and accelerograms to estimate buildings damages for 1D non-linear site response. These neural networks were applied to the 3D buildings model to estimate the damages in Beirut at a fine spatial scale for several plausible earthquake scenarios. Finally, the uncertainty in these estimations was evaluated to identify the first-order factors that most control the seismic damages in Beirut.

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Ground-motion simulations for finite-fault earthquake scenarios on the Reykjanes Peninsula, South Iceland

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Since December 2019, an intense period of volcanic and tectonic unrest has been ongoing in the western part of the Reykjanes Peninsula Oblique Rift (RPOR) in Southwest Iceland. This divergent and transcurrent seismic zone is characterized both by SW-NE striking fissure swarms associated with five different volcanic systems along with S-N striking and near-vertical dextral transform faults. The latter are the causative faults of the largest earthquakes in the zone, up to 6.5. Since 24/2/2021, when a 5.7 earthquake took place in Fagradalsfjall in central RPOR, a total of seven earthquakes M≥5 and thousands of smaller earthquakes have occurred associated with a dyke-intrusion that culminated in an eruption in Fagradalsfjall on 19/3/2021. Deformation measurements along the activated part of the plate boundary and around the dyke intrusion itself show considerable displacements. However, in the Centra-Eastern part of the RPOR, effectively no seismic or deformation activity has been observed, exposing a potential seismic gap that has not released much tectonic strain for decades. That along with the redistribution of deformation west of this gap highlights the need for investigating the range of ground motions plausible associated with a strong earthquake on a S-N fault directly south of the capital region of Reykjavik (~7-20 km away).

Thus, we have postulated earthquake rupture scenarios in this region for the maximum considered earthquake magnitude and simulated the corresponding near-fault ground motions, using a kinematic approach based on the finite-difference method to propagate radiated seismic waves through the crustal structure using a 1D velocity model. Simulated peak ground motion parameters at low frequencies (<2.5 Hz) are compared with those predicted by local empirical ground motion models. The results presented as shaking maps show large zones of narrow-band intense near-fault velocity pulses that reach across the city, a phenomenon not generally considered in a seismic design.

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Advances in models, observations and verification towards operational earthquake forecasting

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New GMPE models for Georgia, Caucasus Region

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Georgia is situated in the Caucasus region, which is one of the most seismically active regions in the Alpine-Himalayan collision belt. Analysis of the historical and instrumental seismology of this region shows that it is still of moderate seismicity. The seismicity of the area reflects the general tectonics of the region.

Recently, number of seismic stations and earthquake records in Georgia significantly increased. Thus, we are able to run more detailed studies regarding ground motion prediction.

Ground motion prediction equations (GMPE) relate ground motion intensity measures to variables describing earthquake source, path, and site effects. Estimation of expected ground motion is a fundamental earthquake hazard assessment. The most commonly used parameter for attenuation relation is peak ground acceleration or spectral acceleration because this parameter gives useful information for Seismic Hazard Assessment. In this study ground motion prediction equations are obtained based on new data and new features such as local soil conditions, fault types, etc.. In the study models are obtained for PGAH, PGAV, PGV, SA.

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Combining seismological and GPS data for systematic earthquake prediction

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The results of earthquake prediction largely depend on the quality of data and the methods of their joint processing. Systematic forecast of earthquakes is based on our machine learning technique called the method of minimum area of alarm. The system makes forecast regularly with Δt step. At each time t, it converts all types of input data into uniform spatio-temporal grid fields, trains on all data available of up to time t, and calculates the alarm zone in which the epicenter of the target earthquake is expected in the interval (t, t+Δt). A demo version of the system since 2018 is available at https://distcomp.ru/geo/prognosis/.

At present, for a number of regions, it is possible to use space geodesy data obtained with the help of GPS. The purpose of our study is to evaluate the efficiency of using GPS data as well as combined GPS and seismological data for systematic prediction of earthquakes. Our conclusion is based on the results of forecasting earthquakes with a hypocenter depth of up to 60 km and a magnitude m ≥ 6.0 that occurred in Japan in 2016-2020, and with a magnitude m ≥5.5 that occurred in California in 2013-2020. For each region, we compare the following results: random forecast of earthquakes, forecast obtained with the field of spatial density of earthquake epicenters, forecast obtained with spatio-temporal fields based on GPS data, based on seismological data and based on combined GPS and seismological data. The results confirm the effectiveness of using GPS data and combined GPS and seismological data for the systematic prediction of earthquakes.
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A time-dependent earthquake forecasting

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“Earthquake prediction” has been the goal of unsuccessful empirical research of the past century. Therefore, in the past five decades, efforts have been focused on the implementation of probabilistic earthquake hazard maps often called the Probabilistic Seismic Hazard Assessment (PSHA) approach. In the last two decades, a promising alternative to PSHA was found to be the application of chaotic synchronization theory in seismology. The pioneering studies in this domain were highly theoretical and lacked a direct applicative power. The turning point was achieved in the last years based on (1) advances related to repeating earthquake sequences, (2) developments in the Cosserat theory of faulting and earthquakes, and (3) confirmation of the existence of slow solitary waves called strain or tectonic waves. The Cauchy (classical) continuum fails to solve the problem of earthquake forecasting as it ignores the couple stresses derived within the Cosserat continuum.

Here we present the so-called Quantectum Earthquake Forecasting System (QEFS) that tests the benefits and limitations of earthquake forecasting based on the chaotic synchronizations between earthquake sequences and the time-dependent changes of couple stresses introduced by the Cosserat theory. We present the analysis of many recent moderate to large earthquakes. Based on the results, we conclude that earthquakes can be forecasted with high probabilities and that earthquake forecasting can be achieved, both theoretically and practically.

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Earthquake forecasting and time-dependent hazard scenarios for the Adriatic region

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An operational procedure for time-dependent seismic hazard scenarios has been developed during the last two decades, which integrates fully formalized earthquake forecasting information from pattern recognition analysis (by CN and M8S algorithms), with the realistic modeling of earthquake ground motion by the neo-deterministic approach (NDSHA). The proposed methodology permits to construct, both at regional and local scale, a set of scenarios of ground motion, which refer to the time interval when a strong event is likely to occur within the alerted areas. When dealing with offshore large earthquakes occurrence, this integrated approach can be naturally extended to the definition of time-dependent tsunami scenarios, based on physical models of tsunami waves propagation.

The algorithms CN and M8S permit to deal with multiple sets of seismic precursors, and use detectable inverse cascade of seismic process to allow for a diagnosis of the intervals of time when a strong event is likely to occur inside a specified region. Recent studies (Crespi et al., Pageoph, 2020) demonstrated that CN intermediate-term middle-range forecasts can be improved by properly integrating seismological and geodetic information, so as to achieve intermediate-term narrow-range earthquake predictions. Accordingly,

the extent of the alarmed areas, identified for the strong earthquakes by the algorithms based on seismicity patterns, can be significantly reduced from linear dimensions of a few hundred to a few tens of kilometres. CN and M8S forecasts for the Italian territory and its surroundings, as well as the related time-dependent ground motion scenarios associated with the alarmed areas, are regularly updated since about two decades. We review the results obtained so far by rigorous prospective testing of the developed procedure, including analysis of the statistical significance of issued forecasts; special emphasis will be placed on the recent earthquakes that occurred in the Adriatic region, which support validation of the applied methodologies.

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Gravity measurements as precursor of Earthquake

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Gravity Variations over time are due to different types of changes (abrupt, periodic, approximately periodic, cosmic). The effects on the earth's surface can be local, regional or global. The greater the depth of the source that causes the gravity change, the larger the affected area. Local gravity variations are observed in seismic and volcanic areas when active phases occur. To determine these changes, requires gravity networks that cover a wider area and are measured at regular intervals. Local gravity variations are particularly related to seismic and tectonic processes and pre-seismic or co-seismic phenomena, volcanic processes and fault movements. Seismic activity leads to sudden and brief gravity variations. HMGS at its yearly field campaign performed gravity measurements at gravity stations throughout Greece for the year 2020. The points measured include gravity stations on Samos during the period 5 to 7 August and 9 to 10 August in 5 stations, that is 82 days before the 6.7 magnitude earthquake that occurred north of the island. HMGS performed repeated gravity measurements at the gravity station of Larissa at various times of 2020, on 26 and 30 January 2021 as well as a week after the 6 magnitude earthquake that took place on 03 March 2021. From the study of the above data as well as data from the historical archive of the HMGS, useful conclusions can be derived for the correlation of the temporal gravity variations in an area with its seismic activity. Finally, it is proposed to establish and monitor a network of gravity stations in various areas of the country where historically strong earthquakes are located.

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Declustering algorithms, background seismicity modeling and earthquake clusters analysis

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Declustering of seismic catalogs is required in wide range of earthquake forecasting and seismic hazard studies. However, different declustering methods may discriminate differently between background and clustered events in a given catalog. Hence the need to investigate to what extent the results of a specific study on background or clustered components may depend on the different declustered versions of a catalog. For this purpose we compare the declustered catalogs obtained from two data-driven declustering algorithms: the nearest-neighbor, which classifies the earthquakes on the basis of a nearest-neighbor distance between events in the space-time-energy domain (Zaliapin and Ben-Zion, J Geophys Res, 2013), and the stochastic declustering, which is based on the space-time ETAS point process model (Zhuang et al., J Geophys Res, 2004). Case studies from selected Italian regions are considered.

We first investigate the statistical properties of the obtained background time series (Benali et al., Stoch Environ Res Risk Assess, 2020), statistically checking if they meet the stationary Poissonian assumption. In case the Poissonian hypothesis is rejected, we resort to a model capable of capturing the possible heterogeneity in the background time series. Specifically, we consider the Markov Modulated Poisson Process (MMPP model), which allows the Poisson seismicity rate to change over time according to a finite (unknown) number of states of the system.

We then compare the earthquake clusters extracted by the two declustering algorithms, so as to assess the similarities and differences in their classification and characterization (Varini et al., J Geophys Res, 2020). The connections between events forming a cluster, as defined by the considered declustering method, allow us representing its hierarchical structure by means of a tree graph. The topological structure of the clusters is then investigated by means of centrality measures in the frame of Network analysis.

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Possible locations of earthquakes M5+ in the Bulgarian region

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This study is based on the assumption that strong earthquakes are associated with nodes: specific structures that are formed around the intersections of the fault zones. The block interaction along intersecting faults leads to stress and strain accumulation and secondary faulting near the intersection. This causes the generation of new faults of progressively smaller size, so that ahierarchical mosaic structure of a node is formed around the intersection.

The nodes are delineated by the morphostructural zoning method based on the geomorphologic and tectonic data. The nodes prone to strong earthquakes are identified by the pattern recognition. In this study, the magnitude threshold of M=5 was specified to identify the nodes capable of generating earthquakes with magnitudes equal or greater of 5. We have selected 194 events with magnitude equal or greater than 5 for the period from 29 D.C. to 2020. The data are taken from historical catalogue of the Bulgarian earthquakes as well as from the recent catalogue with instrumental data. Nodes defined by morphostructural zoning host the selected earthquakes M5+. The pattern recognition algorithm Cora-3 identified seismogenic nodes prone to M5+ on the basis of geological-geophysical parameters Most of the recognized seismogenic nodes are located on the borders between the largest tectonic domains. They are boundaries between the Rhodope massif and the Srednogorie, the Stara Planina and the Moesian platform, the Serbo-Macedonian massif and Rhodope massif (Pirin mountain), the Aegean Sea and the North Greece.

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A worldwide foreshock catalogue and statistics

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Foreshock activity is considered as one of the most promising precursory anomalies towards the prediction of the mainshock. Hundreds of foreshock cases have been published in many seismogenic areas of the world but only very few worldwide foreshock lists have been published so far. On the other hand, a variety of foreshock definitions can be found, which usually are not objective but adjusted to the data availability. I compiled more than 450 cases of foreshocks reported in many different seismogenic areas all around the globe and organized a worldwide foreshock catalogue, which is the most updated so far while for each case it includes more parameters than any other in the past. The time period covered is the last century or so although the cases rate increases gradually with time. Due to the variety of definitions in use, each foreshock case has been adopted as it is published by the respective author(s) avoiding to select cases based on my own definition. Therefore, the compilation reflects what the community believes about the foreshock cases. My foreshock criteria have been applied only for Greek foreshocks of the post-1985 time period. The catalogue compiled lists origin time, epicentral coordinates, focal depth and magnitude of the mainshock (M) as well as of the initial (IF) and maximum foreshocks (MF), fault mechanism of M, time and space intervals between M, IF and MF, region/area, and references. In several cases a foreshock quiescence has been reported a few hours or days before M. In such cases the quiescence duration is also included. A global statistics has been performed for the above parameters.

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A comparative study between the Gutenberg-Richter law parameters and radon temporal series for Operational Earthquake Forecasting

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Many previous research studies have observed that the relative size distribution of small events changes in the precursory phase of an impending large event. Thus, the proportion of larger events increase as closer is the moment of the mainshock. This can be described through the changes of the values of the Gutenberg-Richter (GR) law parameters expressed in a logarithm way as: $Log(N)=a-b\cdot M$. Additionally, there are a lot of studies analyzing the distribution of real geophysical and geochemical fields related to the preparatory stages of earthquakes. These studies have been carried out all over the world to meet the desired outcome associated with earthquake predictions and forecasts: stress and strain monitoring, seismic velocities and all possible geophysical and geochemical fields, e.g., the geomagnetic field, electric resistivity, radon and other gases emissions, infrasound, and so on. In this work, the daily seismic activity rate and the radon anomalies are analyzed in the region of Vrancea (Romania) to find the possible relation between them. For that, GR parameter time series is first computed using the seismic catalogue of the area under study.

Additionally, the radon temporal series in the same temporal period on the studied area is obtained and subsequently, the possible connections with the seismic activity, in terms of correlation, are assessed in order to provide a relation between these variables. From the study carried out, a linear relationship between the radon anomalies and the daily seismic activity rate has been found in terms of the magnitude. This relation allows forecasting the seismic activity rate several days in advance from radon measurements only.

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Multi-instrument surveying of atmosphere-ionosphere for pre-earthquake transients features. Case studies for the M8.2/M7.1 Mexico 2017, M7 California 2019, and M7.7 Caribbean 2020 earthquakes

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We present a multi-parameter study of transient phenomena observed in the Earth's atmosphere-ionosphere environment plausibly associated with the latest major seismic activities in Northern America: Tehuantepec and Puebla Mexico, 2017; M6.4/M7.1 of Ridgecrest California, 2019, and the M7 Caribbean earthquake in 2020. We carry out regional monitoring of satellite sensors and the network of observations from ground-based sites to study critical processes in the atmosphere that modify the Earth's plasma environment system under various geophysical conditions, including earthquakes. We are collecting operational data from several instruments that recorded hourly and daily: 1. Very Low Frequency (VLF) modulated signals in the frequency range 10-50 kHz 2. Radon level variations; 3. Outgoing long-wavelength radiation (OLR obtained from NPOESS) on the top of the atmosphere (TOA); 4. Weather Data -Temperature, Atm. Pressure and Relative humidity; 5/ Atmospheric chemical potential (ACP) obtained from NASA assimilation models and 6/ Electron density variations in the ionosphere via GPS Total Electron Content (GPS/TEC). We observed a synergetic abnormal response of satellite OLR data, VLF and GPS/TEC and ACP starting two weeks before the M8 Mexico 2015, M7 California 2019, and M7.7Caribbean 2020 earthquakes. Although the ground sensors were located far from the epicentral areas in Mexico and the Caribbean, integrating search with the ground, satellite, and assimilation models reveals different abnormal patterns inside the Dobrovolsky-Bowman region, therefore estimating the size of earthquake preparation. We show that by combining both the near-space and ground data accordingly to the physical concept of the LAIC model, we were able to identify, on a regional basis, abnormal patterns of pre-earthquake-related features in the atmosphere-ionosphere environment. The implications for studying major earthquake events are discussed.

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Advances in connecting Lithospheric-Atmospheric-Ionospheric precursors of earthquakes: some recent case studies

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After the sudden rupture of a volume of crustal rocks along the involved fault, earthquakes release a huge energy in few seconds. During the preparatory phase of the impending earthquake, the cumulative tectonic stress stores some potential energy in the seismogenic zone, where part of the energy is available to produce some precursory effects. These effects can be usually relevant in the Lithosphere, Atmosphere and Ionosphere (LAI), in the framework of the so-called LAI coupling (or simply LAIC). In this presentation, we will

show some examples of M6+ earthquakes, where a chain of phenomena in the different geolayers develops during the preparation of the imminent earthquake. This chronological synchronicity could point to a possible earthquake forecasting, together with other features we already found in past studies of seismic, atmospheric and ionospheric data analyses.

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3D Stochastic Ground Motion Prediction for an event in the Niigata region

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Ground motion simulation methodologies (GMSM) have been an active research field due to their promising capacity to overcome the inherent limitation of records availability, (Atkinson et al., 2010). Previous studies have demonstrated the capacity of simple stochastic simulation methodologies to provide accurate predictions of ground motion for single events of different magnitude and importance, i.e. Boore and Atkinson (2009), Atkinson et al (2014), Otarola et al (2018), etc. Furthermore, with the aid of campaigns for the statistical characterization of the Fourier Amplitude Spectrum source (FAS) of recorded ground motions, implementation of GMSM for prediction purposes becomes feasible, i.e. modelling the epistemic uncertainty in the GMSM by sampling the distribution of parameters representative of the region of interest.

This study presents the results obtained in the implementation of a stochastic GMSM in the prediction of a ground motion produced by a moderate-to-high magnitude event, occurring at the well characterized seismogenic context of Japan. We simulated a moderate-to-high magnitude event of M6.6 (M_w=6.6), matching an actual recorded event, the 2004 Niigata M6.6 earthquake, considered in this work as a reference for the expected ground motion.

The two simulated sets of ground motions were qualitative and quantitatively compared to the reference ground motions and to predictions from relevant ground motion prediction equations (GMPEs). The obtained results indicate that simulated ground motions have a higher likelihood of representing the spectral content expected of the expected ground motion, for stations closest to the source when compared to the typically considered GMPEs. Specifically for the higher frequency range ($f \geq 1.0$ Hz).

We believe that these results contribute to the literature on the validation of ground motion simulation methodologies, specifically in terms of their use for the analysis of engineered structures matching the performance constraints of the studied GMSM.

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Preliminary application of the NDSHA approach for inland seismogenic sources in the Iberian Peninsula

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The Neo-Deterministic Seismic Hazard Assessment (NDSHA) approach, based on the generation of synthetic seismograms from a set of earthquake sources and layered anelastic structural models, has been applied at regional scale for inland and near offshore sources in the Iberian Peninsula. A working catalogue of significant earthquakes (EMS98 intensity ≥ VII or Mw ≥ 5.0) has been derived for this study, including earthquakes located inland or near offshore in the area between 36ºN and 44ºN and from 10ºW to 4ºE. Earthquake sources were defined by combining two seismogenic models: one consisting of 25 polygonal zones and a second one using 163 seismogenic nodes prone to M ≥ 5.0 earthquakes identified by morphostructural analysis and pattern recognition techniques. A characteristic focal mechanism has been associated to each seismogenic zone and node based on the available fault plane solutions of strongest events and by using most recent compilations of moment tensor solutions. Ten broad regional 1-D crustal models have been defined for application of the NDSHA approach, representing the main structural units in the Iberian Peninsula and their overall characteristics. A number of flat layers, which are described by their thickness, density, P- and S-wave velocities and anelastic attenuation, QP and QS, characterizes each model. NDSHA results provide hazard maps of maximum ground displacement, Dmax, maximum ground velocity, Vmax, and design ground acceleration, DGA. They show largest Dmax values (class 7-15 cm) in central-western Portugal. Similar high Vmax (class 8-15 cm/s) appears both in the west and in the east of the Iberian Peninsula. DGA reaches its highest values (class 0.15-0.30 g) in central-western Portugal, and in eastern Spain (class 0.08-0.15 g).

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Decadal continuous geophysical data observations at MPGO Ghuttu in the Garhwal Himalaya

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Earth science that may hold promise in advancing the short term earthquake prediction is the earthquake precursory studies based on simultaneous and continuous multi-entities geophysical and geochemical observations. In this direction, in the central part of the Himalaya, the state-of-the-art, the Multi Parametric Geophysical Observatory (MPGO) Ghuttu, performs earthquake precursory research in an integrated manner at a single station. The MPGO is located in the inter-plate region of India-Asia colliding plates at a remote site in the Garwal Himalaya. It is within the high seismicity belt of the Himalaya located to the south of the Main Central Thrust. Continuous measurement of different geophysical components for over a decade, starting from 2007, reports a few precursory signatures towards local moderate size and strong Gorkha Nepal earthquake of 2015. The region has recorded a few local moderate magnitude M~5.0 earthquakes with ~300 km distance from the observatory. The Mw 7.8 Gorkha Nepal earthquake of 2015 is the strongest event that occurred at a regional distance of ~640 km. Significant and long duration anomalies during the Gorkha earthquake are prominent of different nature compared to the observation at the time of moderate magnitude earthquakes. The reported earthquake precursory phenomenons include gas emissions, temperature changes, induced electric and magnetic fields along with quiescence and enhanced seismicity patterns. Existing results and future expectations are based on the opening of minor cracks, in-flux of fluids and material strengthening before the occurrence of the strong earthquake through various degrees of stress during phases of the earthquake preparatory cycle. In addition, long continuous time series are utilized to developed techniques for estimating and eliminating non-seismic variations induced by regional and distant geophysical fields. Non-linear and inter-linked non-seismic fluctuations are based on hydrological, meteorological, environmental and terrestrial effects. High quality data is a step forward towards earthquake precursory research and long-term measurement are required for validation.

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Precursory period determination using the data of ionosphere monitoring

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The system of geophysical shells: lithosphere, neutral atmosphere and ionosphere, can be analyzed as open nonlinear system. Internal dissipation within the system together with correlated interaction of its elements, a process of self-organization can occur due to intensive exchange of matter and energy with environment in non-equilibrium conditions. These processes accompanied by the synchronization of geosphere's characteristics could lead the system to the critical state. The synchronization of the geosphere's characteristics can be spatial, temporal or spatio-temporal. The lithosphere-ionosphere synchronization can be identified when the correlated variations of the ionosphere and lithosphere parameters near the future earthquake epicenter is observed. The ionospheric total electron content (TEC) and vertical sounding data synchronization in time with variation of the parameter b in the Gutenberg-Richter ratio for the lithosphere could serve as indicators of the system approaching to the critical state. The specific decrease of the parameter b was observed in the number of the earthquakes sometimes coinciding with the period of the foreshock activity. The b-value decrease was observed synchronously with the specific pattern of electron concentration during unlit hours of the local time and specific traces on the vertical sounding ionograms.
Since the tracking of b-value parameter in real time seems to be a rather difficult task, and in view of the stable synchronization of these variations with ionospheric precursors, the use of the ionospheric precursors only is proposed for indication of the time of start of the final stage of the seismic cycle. According to our results based on 15 years data processing for all earthquakes with magnitude greater than 7 its value lies within the range from 1 to 10 days before the event. Basing on the described analysis, the ionosphere precursors monitoring can be considered as robust and more available method for the strong earthquakes short-term forecast.

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Session 17

Crowdsourcing and macroseismology: reliability, applications and developments

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Merging different country-institution macroseismic data for the Croatian Mw=6.3, Dec 29, 2020 earthquake: a way to compare and attain mutuality between heterogeneous intensity datasets

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Macroseismology has seen an increase in the number of reports, delineated through crowdsourcing. Many institutions collect data of this type but using different macroseismic questionnaires and/or different scales. It is, therefore, necessary to harmonise macroseismic surveys between different countries. This is mainly true for medium to high magnitude earthquakes, where more than one country is involved. However, for events whose effects are confined within a single region, an indirect comparison with events in other countries may also be necessary: for example, to compare different attenuation laws.

We analysed the preliminary intensity data relating to the earthquake occurred in Croatia on December 29, 2020, Mw=6.3. We compared the macroseismic data processed by different research institutes, in which two data sources cover the entire involved territory: USGS-US and EMSC-Europe. Other countries conducted the survey exclusively within their national territory. Our data comparison method is based on the analysis of the attenuation law. After evaluating the differences by both country and differing institution, we based our research on the complete presence of data throughout territories, where we used USGS and EMSC as a term of comparison. We found that macroseismic attenuation is independent per individual country, thus the difference is mainly owed to how institutes collect data and assess intensity. In this way, we were able to define a data "translation" scheme based on the differences of the respective institutes, following the attenuation laws. The final result is the possibility of translating the different intensity macroseismic data, in accordance with the target specific system of the chosen institute. By changing the choice of the target field, we obtain a different adapted macroseismic field. It is also possible to verify the homogeneity of the diverse field versions translated, according to each system, and to compare them highlighting differences.

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The scientific uses of felt reports, geo-located pics and comments

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The EMSC has been collecting felt reports at the global scale for more than 7 years using a set of cartoons representing the different level of the EMS98 macroseismic scale. Intensity values are user-assigned and collected from both its websites and LastQuake smartphone app. Over the last 12-months more than 750k were collected, due notably to the March 2020 Zagreb and Dec. 2020 Petrinja earthquakes in Croatia and their numerous aftershocks. Alongside felt reports, it also crowdsources open comments and geo-located pictures (in case of damaging earthquakes).

The purpose of this talk is to present lessons learnt on the strengths and weaknesses of such an approach: the associated technical challenges, the respective role of the websites and the app during an aftershock sequence, curation processes, their actual use for rapid impact assessment and novel ways to exploit them. Felt reports as well as the initial lack of such reports from damaged areas immediately after an earthquake

(the so-called "doughnut effect") prove indeed effective when in sufficient numbers to rapidly detect the existence of damage. Adaptive grid cell techniques have been explored to automatically cluster and map individual data points. Felt reports are also ingested in ShakeMaps (see Quitoriano's talk in this session) and included for the rapid determination of rupture geometry of large earthquakes, an essential element for predicting the spatial distribution of damage. In our COVID world, a preliminary remote reconnaissance survey of damage in Zagreb was performed by organizing crowdsourced pictures. In addition, linguists analyze comments to understand eyewitnesses' narratives and how they may evolve during an aftershock sequence. We will present the performances of EMSC crowdsourced system and outline these different initiatives to illustrate the benefits of this crowdsourced data and the advances required to optimize their potentials.

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Attenuation differences among transient macroseismic effects

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The crowdsourced service HSIT (Hai Sentito Il Terremoto) provided a huge amount of data about several diagnostic effects that are routinely used to assess macroseismic intensity in the municipalities. Nevertheless, every single effect can provide additional information, as it is the expression of not only the intensity but also the frequency of ground motion. Here we analysed data of several macroseismic transient effects caused by recent Italian earthquakes to study their attenuation model. The differences among the attenuations were highlighted through the magnitude-distance scaling ratio, i.e. the ratio between the two key coefficients of each attenuation model, namely that of the logarithm of the hypocentral distance and that of the magnitude. The comparison with the corresponding values obtained with equations for estimation of response spectral ordinates, reveals a typical frequency of ground motion for each effect. This link explains some experimental observations as, for example, the weak oscillation of hanging objects in case of small earthquakes.

The magnitude-distance scaling ratio method can be applied to cases in which a lot of data is available, but an appropriate modification has made it possible the application to a smaller data set, such as that of observations of those who have or not felt an earthquake while in a parked car. The result, in addition to explaining the statistical findings, showed a good ability in identifying the resonance frequency of the car–observer system. Thus, the data voluntarily sent by citizens show to be of good quality and capable of producing interesting scientific results.

In conclusion, the importance of studying single effects is highlighted so that the definitions of macroseismic scale degrees can be reliable and independent from earthquake magnitude.

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A new method to estimate the depth and the magnitude of Italian earthquakes using crowdsourced and traditional macroseismic data

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We recently developed a new method to infer the depth and magnitude of earthquakes from macroseismic data. The method analyzes the macroseismic field of recent Italian earthquakes to infer their depth and magnitude based on an equation calibrated using well-constrained instrumentally recorded events.

We started our analysis using web-based macroseismic data from INGV's HSIT citizen-science system (http://www.haisentitoilterremoto.it), which collects macroseismic reports for instrumental earthquakes that have occurred in Italy over the past 15 years.

We used a distance binning method that averages the intensity of individual macroseismic data points within 10 km-wide circular moving windows to obtain an attenuation curve. We then calculated the steepness of the line that fits the first 50 km of the attenuation curve of Italian earthquakes, which can be approximated by a bilinear function showing a change in slope between 40 and 50 km. From the analysis of 42 earthquakes we inferred a correlation between their depth and the steepness of the curve, regardless of their magnitude. This relationship holds for the whole Italian territory, as the steepness does not seem to be affected by regional differences.

We then estimated the earthquake magnitude using a multiple regression equation that relates it to the expected epicentral intensity and focal depth.

This methodology was applied to over 350 earthquakes from Italy's CPTI15 catalogue, after excluding events whose macroseismic field is too sparse or too inhomogeneous.

The two-steps calculation allows verifying that the inferred depth is consistent with the presumed earthquake-causative tectonic structures, and is essential to obtain a well-calibrated magnitude value.

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Underestimation of communal intensities in the epicentral zone when deduced from citizen-internet testimonies

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The BCSF-Rénass estimates the communal macroseismic intensity values after each earthquake of magnitude greater or equal to 3.7 (ML) on French territory. The quality and precision of the intensity's estimation increase with time after an earthquake, from the preliminary and rapid ones based on citizens' internet testimonies, to the definitive ones based mainly on statistical forms filled by the municipalities. For places where we observe EMS98 damage level higher than 2, mainly epicentral zone, it is completed by a detailed macroseismic field survey.

We observe that the municipal intensities derived from the citizens' testimonies, whatever the calculation method used, are systematically lower than the intensities precisely determined from field survey. The reasons of this underestimation of EMS98 intensities of VI and more are directly linked to the structure of the EMS98 scale and to the mode of collection of macroseismic information by online forms.

The reasons are numerous and vary according to the degree of intensity. To mention only a few conditions, the low percentages of effects described by the EMS98 on indicators are difficult to access by spontaneous online forms (e.g. degree 2 damage <10% of buildings of vulnerability classes A or B). In the epicentral zone, if the damage is very significant, the electricity supply may be cut off, the internet network inaccessible, or

sometimes the damage in the houses so significant that the occupants have other concerns than filling in a testimony form.

ESC2021-S17-262

Web-based macroseismic intensity study in Turkey – entries on Ekşi Sözlük

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Macroseismic intensity data collection can be carried out via web-based platforms. In this study, we used a Turkish website called Ekşi Sözlük which is a collaborative dictionary for data collection. Instead of predefined questionnaires, we manually labelled users' experiences on 20 earthquakes that occurred in Turkey and its surroundings. We focused on the entries that provide city and district information along with interpretable information related with the experience that users provided. We created shakemaps for the earthquakes by using a ground motion to intensity conversion equation and compare the intensity maps created by using the entries from the website. We find a correlation between the calculated maps and the entries from the website. We also find out the correlation between the local soil conditions and relatively high-intensity measures. Furthermore, we collect the users' magnitude estimations for the earthquakes. The study shows that magnitudes are predicted with ±0.54 misfit. Ekşi Sözlük has a potential to be a reliable source for creating near-real time macroseismic intensity maps for Turkey.

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Comparison of EMSC and USGS Internet-Based Earthquake Reports from Recent Events

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USGS Did You Feel It? (DYFI) has been collecting crowdsourced macroseismic intensity (MI) data from users worldwide for over 20 years. Data from DYFI are used in USGS ShakeMap to create maps of MI spatial distribution by supplementing station data and ground motion prediction models. In Europe, more crowdsourced MI data is available through the European-Mediterranean Seismological Centre (EMSC) LastQuake app. We compare EMSC and DYFI felt reports to evaluate the suitability of supplementing ShakeMaps with EMSC reports. However, ShakeMap requires quantification of the uncertainty of input data. We therefore use a bootstrap method similar to that employed for DYFI in Worden et al. (2012) and apply it to 700,000+ individual felt reports from the EMSC database. We find that higher EMSC intensities (MI>V) exhibit higher uncertainties, which is consistent with damaging intensities needing engineering expertise for proper assignment. We modify the bootstrap method by parameterizing the uncertainty of EMSC intensity estimates as a function of MI. We also update the DYFI uncertainty function to include this heteroskedasticity. To compare the DYFI and EMSC datasets, we use three recent well-reported damaging earthquakes in Europe: M6.4 Croatia (29 December 2020), M7.0 Western Greece (30 October 2020), and M6.4 Albania (25 November 2019). We aggregate 2,515 DYFI reports and 15,869 EMSC reports for the Croatia event into 1-km geocoded cells to create separate ShakeMaps using DYFI alone, EMSC alone, and both datasets combined. We repeat this process with the Greece event (881 DYFI and 3,841 EMSC reports) and the Albania event (1,365 DYFI and 4,036 EMSC reports). We compare these spatial distributions to traditional EMS-98 assignments and MI estimates derived from ground motion instruments. We demonstrate that combining EMSC and DYFI data reduces the uncertainty in important (populated) areas of the resulting ShakeMaps by filling in gaps in coverage of MI reporting.

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Destructive intensity inferred from strong ground motion recordings and its correlation with macroseismic intensity observations for the 2020 Samos Mw7.0, Greece, earthquake

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The 30 October 2020, MW7.0 Samos mainshock occurred offshore, north of Samos Island in eastern Aegean area and caused severe damage across parts of the island and close to the Turkey coast, claiming lives in Vathy (Samos) and mainly in Izmir (Turkey). In this paper we use the strong motion recordings of this event from Greek and Turkish permanent stations to calculate the Destructive Intensity (DI), defined as the logarithm of the absolute value of the inner product of the acceleration vector a (cm/s2) and the velocity vector v (cm/s) (DI=log|a*v|). In addition, we assign EMS98 Macroseismic Intensity through available earthquake testimonies and local media, photographic documentation, in situ observations, etc., at localities in Samos and the opposite Turkish coast. The correlation between Instrumental Intensity (II) and Macroseismic Intensity (MI) is applied and tested for the Samos 2020 earthquake. Localities where macroseismic intensity is assigned are considered phantom strong motion stations and synthetic strong motion recordings are calculated, using a stochastic finite source simulation approach, taking into account local soil conditions and topography. Maps showing the spatial distribution of II and MI are presented and compared.

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Macroseismic observations of micro-earthquakes induced by an enhanced geothermal system

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We report on macroseismic observations related to low-magnitude seismic events obtained with the help of the online questionnaire of the Institute of Seismology, University of Helsinki. Seismic events observed non-instrumentally in Finland in the 2000s include local, regional and global earthquakes, explosions, cryoseisms, and supersonic booms. The online macroseismic data are strongly biased towards positive responses, but they are obtained without any survey launched by seismologists. Combined with the denser seismic networks available today this means that macroseismic observations can be associated with very small events, far below local magnitude ML1, if they are shallow and occur close to population centers. This is attributed to the crystalline bedrock and low attenuation of seismic waves.

New phenomena are micro-earthquakes induced by enhanced geothermal systems (EGS) typically developed close to the customers. We collected around 270 macroseismic reports related to the EGS stimulations in the capital region of Finland in 2018 and 2020. The largest induced event had a magnitude of approximately 1.8 and was observed up to distances of almost 10 km on a Sunday evening. The spatial distribution of the corresponding macroseismic reports is elongated to the northwest and northeast of the EGS site, which is likely governed by the SH-wave radiation pattern of the thrust faulting mechanism. The residents in the neighborhoods located in the direction of the strongest SH radiation were repeatedly disrupted their

nighttime sleep during the 2018 stimulation. The observations are at the threshold of human perception and do not allow intensity assignments.

Reference: Hillers G, Vuorinen TAT, Uski MR, Kortström JT, Mäntyniemi PB, Tiira T, Malin PE, Saarno T (2020) The 2018 geothermal reservoir stimulation in Espoo/Helsinki, southern Finland: Seismic network anatomy and data features. Seismological Research Letters 91(2A):770-786. https://doi.org/10.1785/0220190253

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The complexity of modelling anisotropic intensity attenuation in Belgium

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The traditional methodology of constructing a single intensity attenuation law and intensity prediction equation for large areas is not fit for the complex situation in Belgium. Macroseismic intensity distribution patterns of past Belgian earthquakes do not cohere to the common assumption of an isotropic intensity decrease with increasing epicentral distance. Intensity decrease is strongly influenced by crustal and cover geological features that heavily control and limit seismic wave propagation.

Geological features that have influenced past intensity distribution patterns in NW Europe are:

- The strongly compacted and deformed Lower Palaeozoic Anglo-Brabant Massif, which easily transfers ground motion along its core axis in a WNW-ESE direction.
- The increasing thickness of soft sedimentary Cenozoic strata covering the Anglo-Brabant massif towards the Belgium-The Netherlands border, effectively filtering high-frequency ground motions.
- The Lower Rhine Embayment boundary faults, impeding effective ground motion transfer and serving as seismic mirrors.
- The Midi-Eifel Fault which separates the Ardenne allochton from its foreland and acts as a seismic barrier.
- A band of shallow Carboniferous coal basins with a fast intensity attenuation.

The quantitative effect of these geological regions on macroseismic intensity are best to be modelled separately. But given the small size of both Belgium and these different regions, local earthquakes are prone to hit multiple areas with different attenuation properties at once, urging the necessity of transfer functions from one unit to another. Moreover, anisotropic intensity attenuation laws are very uncommon in literature and adding another dimension, e.g. such as bedrock depth, into an intensity prediction equation complicates the modelling even more. During this presentation, these PhD issues and topics will be discussed by using the extensive traditional and online macroseismic intensity databases of the Royal Observatory of Belgium, which was extended by macroseismic intensity data from neighboring countries.

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Updated method of automatic assessment based on macrosismic data collected online at the Portuguese Seismological Service

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The Portuguese seismological service uses the Internet to collect macroseismic data directly from witnesses, that report their experiences at their geographical locations by filling an online questionnaire, since 2006.

This questionnaire is available to anyone at the webpage of the Instituto Português do Mar e da Atmosfera (IPMA), is called “Did you feel an Earthquake?”. In 2019 an upgrade of the questionnaire was implemented. The questionnaire was designed based on EMS-98 scale and consists on simple questions, most with multiple choice answers. All the questionnaire and the algorithm was revised and more questions and more detail were considered, such as the new group of questions related with damages on buildings. In addition, the questionnaire is now available in Portuguese, Spanish, French and English languages.

ESC2021-S17-391

Preliminary results of new macroseismic data of the 28th February 1969, a 7.9 Ms earthquake at SW of Cape St. Vincent, Portugal

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On the 28th February, 1969, a 7.9 Ms (7.8 Mw) earthquake occurred at 180 km SW of Cape St. Vincent, which was one of the greatest magnitude felt in Europe after the 1755 earthquake, felt with maximum intensity VIII, in the South of Portugal. The Instituto Português do Mar e da Atmosfera (IPMA), since 2010, has an algorithm to process macroseismic data collected from “Did you feel an earthquake?” web-questionnaires that was recently updated. The 50th anniversary of the 1969 earthquake was an ideal pretext to perform a test with real data. New technologies allowed the acquisition of a huge amount of data, which was still in the memory of the population. So, it was launched an international survey in late February, 2019, and published in several languages. A significant collaboration of the population was observed.

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Obtaining macroseismic data through a Facebook group after the 2020 ML5.5 Zagreb earthquake

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On 22 March 2020, at the beginning of COVID-19 pandemic in Croatia, its capital and largest city, Zagreb, was hit by a ML 5.5 earthquake, with the intensity in Zagreb VII EMS-98. Collecting macroseismic data was difficult due to several reasons (small number of personnel, pandemics, etc.). At the same time, numerous photographs and videos of earthquake effects were spreading online, especially on social networks. Thus, Croatian Seismological Survey at the Department of Geophysics, Faculty of Science, University of Zagreb created a Facebook group “Zagrebački potres 2020 – vaše info za seizmologe” (https://www.facebook.com/groups/210791050014517/; English translation: Zagreb earthquake 2020 – your info for seismologists) to complement the existing methods for macroseismic data collection. On its first day, the group gained 2458 members; in the first week after the earthquake the number of members grew to 4500, and plateaued at about 6500 in the following months. Approximately 40 posts were received with members’ contributions in the first month. Most often the posts included dozens of photographs of earthquake damage and an approximate or detailed location (the street or neighborhood). Certain posts contained videos and some only a textual description of the earthquake effects. In the following months, group members provided real-time earthquake information and felt reports for their location, in a way similar

to EMSC Felt earthquakes (Bossu et al., 2008) or USGS Did You Feel It? (Wald et al., 2011). This kind of data collection required constant monitoring and extensive moderation.

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Citizens' awareness of earthquakes, and their concern and fear after the 2020 Zagreb earthquake

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The 22 March 2020 ML 5.5 Zagreb earthquake hit the most populated part of Croatia and affected approximately 1.2 million citizens. In direct communication with the citizens, seismologists were aware thought that fear of earthquakes lingered in the affected area for months. Thus, in July 2020 we conducted an online poll to examine the following:
1) which sources of information citizens mostly use for earthquake data
2) the level of fear present in the population immediately after the main event, and in the subsequent months
3) citizens' awareness and knowledge about earthquakes before the main event and at the time of filling out the survey

The poll was filled out by 1330 people, out of which 98% were located in the City of Zagreb at the time of the mainshock, 76% were female, mostly between 20 and 50 years of age and highly educated. The majority of respondents felt disturbed on the day of the earthquake, and were afraid of another large earthquake occurring. Their safety, as well as the safety of their nearest ones, induced the highest levels of fear, while concern for material goods was lower. Support from their families, information given by Croatian seismologists and the European-Mediterranean Seismological Centre (EMSC) mobile application reduced the stress the most.
When looking for information about aftershocks, the respondents mostly relied on the EMSC app, followed by the Croatian Seismological Survey webpage, and the media. The majority of people did so only after feeling an aftershock, while approximately 40% respondents looked for information on a regular basis. The citizens were asked to assess their knowledge on earthquake-resistance of their homes, what to do during and after an earthquake, and designated emergency areas in the city. Their knowledge in all categories improved in comparison to the period before the earthquake.

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Assessment of the macroseismic field of strong earthquakes using joint information of EMSC testimonies and shakemaps aiming to updated macroseismic intensity attenuation models for the Aegean area

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In this work we present a study of macroseismic data extracted from the EMSC database, to study their spatial variation for recent large earthquakes ($M \geq 6.0$) that occurred in the broader Aegean area since 2010. The main target was to perform a combined interpretation of macroseismic data from EMSC and publicly available shakemaps, to evaluate their usefulness, as well as their compatibility with historical macroseismic

data for earthquakes of the study area. For this reason, we selected several recent large earthquakes for which a large number of macroseismic testimonies was available from EMSC database. We also collected the corresponding strong-motion (PGA, PGV, etc.) information from the shakemaps produced by ITSAK. As a first step, we compared the collected EMSC macroseismic data with the predicted macroseismic intensities from the empirical relation of Papazachos and Papaioannou (1997). In general, the correlation between observed and modeled macroseismic data was satisfactory; however, at very high and very low values of observed macroseismic intensities (as reported from EMSC) a systematic bias was noticed. A Monte Carlo simulation approach and other statistical analysis were applied to test the validity and the reliability of the EMSC testimonies, and to identify the source of the observed dispersion and bias between two types of macroseismic data. The results suggest that EMSC macroseismic information shows a large variability (~1.5 intensity units) with respect to the modeled (theoretical) macroseismic intensity information. Moreover, a correlation compatible with previous strong motion-macroseismic intensity relations was observed for the EMSC macroseismic information and ITSAK shakemap information. The previous analysis allowed us to demonstrate that the available EMSC information can be efficiently employed to reconstruct the main features of the damage distribution and earthquake properties for strong shallow mainshocks in the broader Aegean area, though with relative large uncertainties.

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Regression analysis of macroseismic intensity and ground motion parameters for the Vrancea (Romania) subcrustal earthquakes

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The correlations between macroseismic intensity (MI) and strong ground motion parameters such as Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) for the Vrancea subcrustal earthquakes are compared. The recent Romanian earthquakes, especially Vrancea earthquakes provide valuable data to examine the correlation relationships between these parameters for the entire territory of Romania. The Vrancea region is one of the most active seismic zones in Europe and it is well-known for the strong subcrustal earthquakes. The goal of this study is to develop a new empirical relationships between the strong ground-motion records and the observed intensities for major and moderate earthquakes with Mw ≥ 5.4 and epicentral intensity in the range VI to IX MSK degrees that occurred in the period 1977-2009. For each instrumental record we assigned a macroseismic intensity based on the proximity of the site where reported value are available (no more than 3 km distance around the station). The obtained relations between macroseismic intensity and PGA/PGV will be given both as a mathematical equations, but also as corresponding ground motion intervals. For these correlations we have used the orthogonal distance regression technique which allows for uncertainty on both variables (i.e., MI and PGM), and produces reversible relationships. The most prominent results available in the literature have shown that macroseismic intensity and ground parameters do not always show a one-to-one correspondence, and the errors associated with the intensity estimation from PGA/PGV are sometimes +/-2 MSK degree. These relations can be used as near real-time response regarding ground shaking severity, and potential damages in the areas affected by the Vrancea earthquakes.

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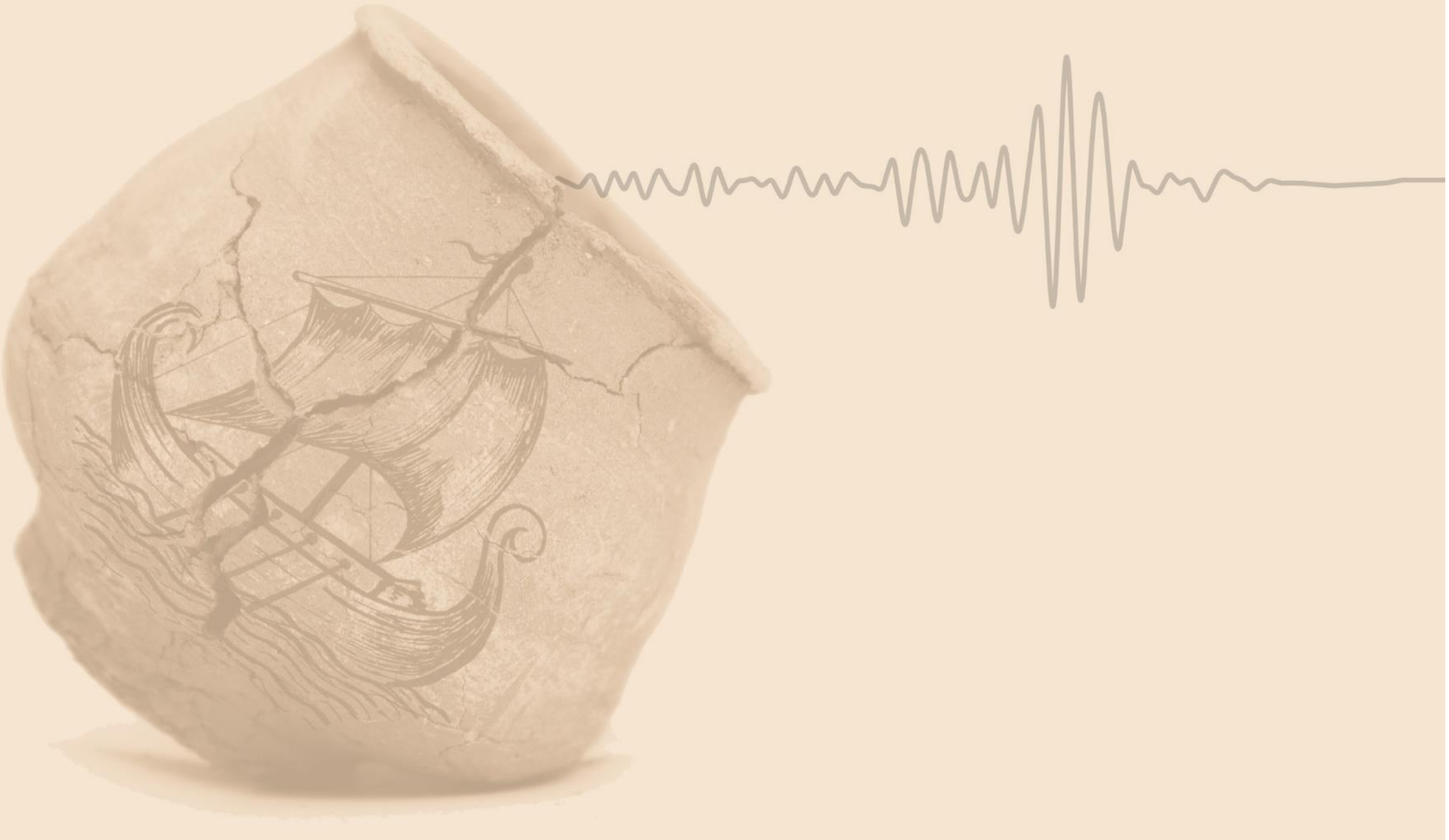
Towards operational forecasting of earthquakes and early warning capacity for more resilient societies



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A cost-benefit analysis approach to explore the feasibility of operational earthquake forecasting in Europe

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Operational Earthquake Forecasting (OEF) is a time-varying probabilistic framework that leads to short/medium/long time-scale notices to target communities before a severe earthquake event to mitigate seismic risk. A flexible and extendable procedure for OEF is being developed for the TURNkey platform, i.e. a European H2020 project entitled: “Towards more earthquake-resilient urban societies through a multi-sensor-based information system enabling earthquake forecasting, early warning and rapid response actions”. This procedure takes into account the short-term changes in the seismic hazard and the uncertainties associated with these changes. As part of a feasibility study, cost-benefit analyses have been performed in order to justify whether OEF is cost-beneficial in different parts of Europe. The benefit-to-cost ratio was estimated based on three principal ingredients: (1) time-varying increases in probabilistic seismic hazard over the base level, (2) cost of an action, and (3) mitigated loss corresponding to this selected action. The action-type and mitigated loss were assessed based on consideration of the testbeds of the TURNkey project and then applied throughout Europe. The results show that areas of high seismic hazard (e.g. Iceland, Italy, Greece and Turkey) would benefit from OEF if there are low-cost, short-term mitigation actions that can be performed even if the increase in the weekly probability of an earthquake is moderate. These triggers would also occur in these areas sufficiently often (every 10 to 50 years) for the local population to have prior experience of what actions to take. Areas of moderate seismic hazard (e.g. Alps, Pyrenees, Rhine graben and south Spain) would only benefit from OEF in the case of substantial increases in weekly probabilities and only if low-cost (or very-low-cost) actions are possible (and the triggers would occur infrequently, i.e. less often than once every 50 years).

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A multi-criteria decision support system to explore the feasibility of actions triggered in a warehouse by operational earthquake forecasting

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Operational Earthquake Forecasting (OEF) is a relatively new concept to encourage an end-user to take risk-mitigation actions during a period of heightened seismicity (e.g. prior to a large mainshock or in the aftershock period). A flexible multi-criteria Decision Support System (DSS) for OEF is being developed within TURNkey (a European H2020 project entitled: "Towards more earthquake-resilient urban societies through a multi-sensor-based information system enabling earthquake forecasting, early warning and rapid response actions") based on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

The first component of this DSS is a framework for short-term time-varying probabilistic seismic hazard assessment, which considers the uncertainties associated with changes in the seismic hazard. The DSS for OEF has been applied to a hypothetical warehouse, which holds stock in the city of Patras (Greece). The DSS is used to assess whether a considered risk-mitigation action would be a reasonable decision during a period of heightened seismic hazard. A set of possible actions were defined in advance: 'moving boxes to storage', 'secure boxes to shelves', 'moving boxes to the floor' and 'take no action'. TOPSIS only compares the available

options, ranking them from best to worst. Therefore, it is not a perfect method as an action may be considered the best out of the set of actions considered, but it may not be the most beneficial of all possible actions or even beneficial at all. Therefore, a complementary cost-benefit analysis is also conducted, and the results compared to those from TOPSIS. This checks whether the best action as indicted by TOPSIS is also cost-beneficial. The results of the DSS are considered versus the ground motion intensity (e.g. peak ground acceleration). Additionally, a sensitivity analysis is performed to study the importance of each input variable on the results.

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Earthquake Early Warning in countries where damaging earthquakes only occur every 100 years – the societal perspective

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The primary aim of Earthquake Early Warning (EEW) systems is to warn the public from impending strong shaking allowing them to take protective actions. EEWs can also trigger automated shutdown procedures such as slowing down trains or act as rapid earthquake information (REI) improving situational awareness. In countries/regions where strong earthquakes occur regularly such as in Japan, Mexico and California (US) such systems are already operational and residents are trained to respond to the alerts. However, what about countries where strong earthquakes only occur rarely. How does the public in such a country assess the potential of EEW?

To answer this question, we conducted 65 interviews with the public in Switzerland, Italy and Iceland to get a first impression of their needs and concerns with respect to EEW. Moreover, we will launch a survey in Switzerland to assess people's general preferences for the implementation of an EEW system (e.g., communication mean, shaking level, information needs). We will compare our results with the findings of the EEW surveys conducted in New Zealand, Japan and the US, which allows us to see whether the preferences for EEW systems differ between countries. In addition to these general preferences, we also designed – based on the insights of our interviews, international best practices as well as feedback from seismologists – various EEW and REI messages which we will test with a between-subject experiment in the survey too.

At the conference, we will present the Swiss public's preferences with respect to EEW and REI. In addition, we will highlight the societal challenges related to a potential rollout being equally important to address as technical or political issues.

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Risk-based Performance Evaluation and Seismic Network Optimization for Earthquake Early Warning in Switzerland

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Earthquake Early Warning (EEW) aims to trigger an alert before the damaging seismic waves of an earthquake arrive. We use warning time as a key performance indicator and develop a multi-level framework to evaluate and optimize the risk-based performance of an EEW system. Our framework is general and has different levels of complexity with regards to seismicity, exposure, and vulnerability. We demonstrate our approach for Switzerland using a 100,000 year long stochastic earthquake catalog derived from the Swiss Hazard Model, which includes almost 168'000 scenario earthquakes ($4.0 \leq M \leq 7.4$). For each scenario, we predict shaking intensities at the largest cities and adopt a representative vulnerability model to relate these intensities to losses (here: fatalities and injuries).

A preliminary analysis suggests that the current Swiss Seismic Network could provide positive warning times at each city for 80% to 90% of very damaging earthquakes with 100 to 1k injured, and for 55% to 75% of earthquakes with 100 to 1k fatalities. Warning times of > 5 s could be achieved for about 40% to 50% of very damaging earthquakes, and > 10 s for about 30%. For around 25% of events with 10 to 100 injured, an EEW system could provide > 15 s of warning in the affected cities. By optimizing the current network with moderate numbers of additional sensors, the warning times can be increased by up to 4 s in single scenarios. However, since the network is already very dense (7 ± 5 km interstation distance), it may be more important to reduce data latencies (currently ~2 s).

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How do people react when they receive an Earthquake Early Warning? A practical case study of Earthquake Network app users in Peru

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So far, Earthquake Early Warning (EEW) research has mainly focused on technical and scientific aspects and these systems started to be put in place by national or local authorities. However, to ensure their true efficiency, these warnings need not only to be delivered to the public, but also, and most importantly, to be understood and trusted. In this respect, it is of prior importance to study the public actual perception and reaction to these messages.

Following a M8 earthquake that hit Peru on May 26th 2019, we led an online quantitative survey (n=2719) towards Earthquake Network (EQN) app users who were in the impacted area. Indeed, EQN is an innovative seismic information app which runs earthquake early warnings triggered by smartphones accelerometers detections. We present here results of the survey that demonstrates that overall, users are very satisfied with the service which meets their needs. We also explore people's reaction when they receive s the warning, showing that most of the respondents didn't adopted a safety behavior but rather tried to warn their relatives or simply to get ready on a psychological point of view. Finally, the survey enables us to understand users' reactions when they got the notification after the shaking or while they didn't feel the earthquake. If this can slightly raise anxiety among some of them, there is a general acceptance for the technical limitations of EEWS and faith in the fact that the system will improve.

This rare survey on citizens' EEW perceptions and reactions allows us to draw conclusion to improve not only EQN system and EEW systems in general in order to increase their efficiency and actively contribute to risk reduction.

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CsLoc: Rapid seismic locations for global earthquakes using crowdsourced detections

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Rapid public earthquake information is essential for both the public and authorities and can contribute to a more efficient earthquake response. In many cases, it takes several minutes after an earthquake to publish online a seismic location with confidence. Via monitoring for specific types of increased website, app, EQN, or Twitter usage, EMSC developed a methodology called CsLoc that uses crowdsourced detections as an initial location to obtain fast and reliable hypocenter parameters for felt earthquakes using arrival time data retrieve by various seedlink and processed by SeisComp. CsLoc methodology has been significantly improved over 3 main aspects. Because the same earthquake can lead to several crowdsourced detections (Twitter, the app, website, and recently EQN, in several countries), we have to determine on the fly that these detections are related to the same earthquake. It is very essential to avoid duplication of event in a fully automatic service. The second improvement concerns the determination of the magnitude and thirdly, detections from an Earthquake Network Application (EQN). CsLoc is a service available on EMSC website since September 2020. We present the performances of CsLoc and show that it can provide rapid and accurate locations, and magnitudes within a minute after the occurrence of a felt earthquake, thus it can provide timely and accurate information on a felt earthquake to the civil protection services and the general public.

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Parameters related to earthquake early warning for specific Balkan Peninsula regions with high seismic activity

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Bulgaria and the Balkans are part of the Alpine-Himalayan seismic belt and are characterized by high earthquake activity. Earthquakes with magnitudes greater than 5 are common and at times cause significant damage and casualties. Since short-term earthquake prediction is still elusive, development of earthquake early warning systems and procedures currently is leading approach to earthquake hazards mitigation. This study aims to assess the possibility for early warning for large Balkan Peninsula earthquakes based on freely available seismic data. Specifically, earthquake early warning scenarios for regions near the stations of the Virtual Seismological Network of Sofia University (VSNSU) are evaluated. Important regional earthquake sources are identified and seismic wave's propagation time for these sources is estimated. Expected seismic intensities are also evaluated. Main characteristics of the seismic records from the VSNSU stations close to the considered earthquake sources are evaluated. These include signal-to-noise ratio, duration, amplitudes and periods of the first trains of P- and S-waves, difference in the arrival time of P- and S-waves, etc. These parameters may be used in the development of regional early warning systems in the near future.

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Earthquake Early Warning System for Structural Drift Prediction using Machine Learning and Linear Regressors

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In this work, we explored the feasibility of predicting the structural drift from the first seconds of P-wave signals for On-site EEW applications. To this purpose, we investigated the performance of both linear least square regression (LSR) and four non-linear machine learning (ML) models: Random Forest, Gradient Boosting, SVM and KNN. Furthermore, we also explore the applicability of the models calibrated for a region to another one.

The LSR and ML models are calibrated and validated using a dataset of ~6000 waveforms recorded within 34 Japanese structures, and a smaller one of data recorded at US buildings (69 buildings, 240 waveforms).

As EEW information, we considered three P-wave parameters (Pd, IV2, ID2) using three time-windows (i.e., 1, 2, and 3 seconds), for a total of nine features to predict the drift ratio as structural response.

The Japanese dataset is used to calibrate all the models and to study their capability to predict the structural drift. We explored different subsets of the Japanese dataset (i.e., one building, one type of construction, the entire dataset). We found that the variability of both ground motion and buildings response can affect the drift predictions robustness. In particular, the predictions accuracy worsens with the complexity of the dataset. Our results show that ML techniques perform better than LSR models, likely due to the complex connections between features. Furthermore, we show that by implementing a residuals analysis, the main sources of drift variability can be identified.

Finally, the models trained on the Japanese dataset are applied the US dataset. We found that the exporting EEW models worsen the prediction variability, but also that including correction terms as function of the magnitude can mitigate such problem. In other words, our results show that the drift for US buildings can be predicted by minor tweaks to models.

ESC2021-S18-236

Communicating Operational Earthquake Forecasts: insights from a co-design study

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Introduction: Operational earthquake forecasting is an emerging science. Just like weather forecasting in the mid-19th century, it holds much potential promise, but is wreathed in uncertainties, low probabilities and ensuing difficulties of communication that must be overcome before that promise can be fulfilled. Whilst seismologists and others refine the tools required to reduce the uncertainties of seismic forecast information, work has to be done in parallel on how best to communicate such information. Here we present the results from a study that has co-designed OEF communications with target audiences in three European countries: Italy, Iceland and Switzerland.

Methods: An iterative series of interviews and focus groups were conducted with different stakeholders in each country, including members of the public, civil protection, media professionals, data producers and seismologists. OEF communication designs were updated based on insights after each round.

Results and Conclusion: The study yielded insights into stakeholders' emotions, impressions and understanding of an evolving series of OEF communication designs, including what they find useful, trustable, actionable and worth receiving and sharing, both in a personal capacity and as part of a group. This led to audience-informed improvements in the OEF communications at each stage. This iterative co-design process ultimately yielded an OEF communication dashboard that makes use of several types of data presentation styles of varying levels of detail, with the individual components of the dashboard as well as the ensemble as a whole having been refined on the basis of the research.

Implications for future design of these communications are discussed.

ESC2021-S18-239

Comparing the performance of regional earthquake early warning algorithms in Europe

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Several earthquake early warning (EEW) algorithms have been developed worldwide for rapidly estimating real-time information (i.e., location, magnitude, ground shaking, and/or potential consequences) about ongoing seismic events. This study quantitatively compares the operational performance of two popular regional EEW algorithms for European conditions of seismicity and network density. We specifically test PRobabilistic and Evolutionary early warning SysTem (PRESTo) and Virtual Seismologist (VS). We conducted two different sets of analyses. The first analysis investigated the operational performance of the PRESTo and SeisComP platforms, the latter considering the implementation of the Virtual Seismologist magnitude component within SeisComP, which we used jointly with the SeisComP scanloc module for locating events. In the specific, we evaluated the timeliness and accuracy of the provided estimates in real-time simulation mode, accounting for the continuous streaming of data and effective processing times.

We also focused on the alert-triggering (decision-making) phase of EEW and investigate both algorithms' ability to yield accurate ground-motion predictions at various temporal instances that provide a range of warning times at target sites. We found that PRESTo produces better rapid estimates of magnitude and ground-motion (i.e., those that facilitate the largest lead times); therefore, we concluded that PRESTo has greater risk-mitigation potential than VS(SC) in general. However, VS(SC) is the optimal choice of EEW algorithm if shorter warning times are permissible. In the second analysis we conducted a conceptual study explicitly focused on the accuracy and associated uncertainties of the PRESTo and Virtual Seismologist (original version) algorithms that highlights the importance of accounting for EEW parameter uncertainties, which are often neglected in studies of EEW performance. Our findings can be used to inform current and future implementations of EEW systems in Europe.

ESC2021-S18-258

Performance of the first public smartphone-based EEW system

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Public EEW systems have the potential to reduce individual risk by warning people of an incoming tremor, but their development is hampered by costly infrastructure.

Since 2013, the Earthquake Network initiative (www.sismo.app) implements a global public smartphone-based EEW system offering an alternative without the need of dedicated infrastructure in the many regions unlikely to be covered by conventional EEW systems in the foreseeable future.

Citizens join the initiative by installing the Earthquake Network app which turns users' smartphones into motion detectors. The app sends information to a central server which is responsible for detecting earthquakes in real time and for sending alerts to the smartphones with the app installed.

Analysing 550 detections made in 15 countries, we show that Earthquake Network already provides an early warning service, including for damaging shaking levels. Detection capability and performance are provided in terms of probability of detection, detection delay, warning time and false alert rate.

We also show that although warnings are understood and appreciated by citizens, notably to get psychologically prepared, only a fraction take protective actions such as "drop, cover and hold".

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Developing easy-to-understand visualisations for ground shaking estimates within TURNkey

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One of the information types to be presented on the TURNkey platform is a visual representation of estimates of ground shaking during all phases of earthquake forecasting (before, during and after). These visualisations should be easy to understand for non-technical end users and include information about uncertainties. In classical shakemaps, uncertainty is often visualised using one map showing the mean shaking (e.g. in terms of peak ground acceleration) and another map showing the standard deviations of this intensity measure. For better understanding, we have combined the information into one map with a slider showing options for low (mean – 2 sigma), best (mean) and high (mean + 2 sigma) estimates of shaking. Moving the slider results in showing the corresponding map to the predefined level of uncertainty. Other aspects that influence how easy it is to understand the visualisations are colour scales, texts (titles, legends), linear or logaritmic scales and graduated or contoured colours. Maps of ground shaking estimates were constructed for all phases of earthquake forecasting. In addition, estimates of ground shaking at a set of predefined points of interest (e.g. hospitals or infrastructure) were designed in the form of graphs with shaded bands representing the uncertainty in the estimate. We tested our visualisations among the Work Package partners during a two-

hour online session including real-time polling using Mentimeter. The feedback from the Project partners is greatly appreciated and will be used to improve the visualisations. During a later stage, the improved visualisations will be assessed by potential end users to verify that they can be correctly understood.

ESC2021-S18-277

Assessing the effectiveness of earthquake early warning in mitigating seismic risk

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Earthquake early warning systems (EEWS) involve the rapid detection of earthquakes and the delivery of warnings of imminent ground shaking to a range of users. The operation of such systems promises a mitigation of earthquake risk by triggering automated system responses and/or prompting individual alert recipients to take swift protective actions. The effectiveness of EEWS hinges on the accuracy and timeliness of alerts, both of which have improved over the years due to significant scientific and technological advancements. Yet, there are physical constraints that limit EEWS speed and accuracy, even for an ideal system. This begs the question of whether an EEWS can be cost-effective, and highlights the need to come up with a quantitative approach to evaluate its performance in terms of fulfilling its end objectives.

In this study, we rely on concepts widely used for regional event-based probabilistic seismic risk assessment, and propose a framework for assessing the effectiveness of EEW in mitigating earthquake risk. Following standard practice in risk assessment, we generate a long stochastic earthquake catalogue and proceed to compute losses for each generated rupture. Earthquake risk is quantified in the form of loss exceedance curves using injuries and fatalities as decision variables. For each earthquake event in the catalogue, we also use the potential event warning time as an indicator to further assess the plausible EEW-related reduction in casualties. This is done by means of a logical framework based on literature-informed assumptions. Risk estimates can then be recomputed under the hypothesis of EEWS operation and contrasted with the initial values. Here our approach is demonstrated using Switzerland as a testbed. The procedure can serve as a stepping stone for a downstream cost-benefit analysis and/or for setting up a decision analysis framework.

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Earthquake Rapid Response System in Austria

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Austria has a moderate level of seismic hazard. Damaging earthquakes are possible anytime, especially in highly industrialised exposed regions and along important infrastructure. Due to the elevated risk and increased safety awareness, fast real-time damage information about earthquake impact is required. As a prototype, we set up three regional rapid response systems using the modular software Antelope-Bighorn by BRTT. It uses real-time continuous response spectra exceedance monitoring to trigger automatic alarms against engineering criteria. These direct measurements support quantitative decisions with low latencies. If the ground movement remains below the design criteria, it also helps to avoid post inspection and therefore downtimes. In the next step, we plan to densify the network at specific infrastructures like tunnels, bridges or factories. In addition, we want to investigate local site amplifications and the optimization of the latencies. In the long run, instant alarms, structural health monitoring and subsequently submitted earthquake information (location, magnitude and impact) will be made available to infrastructure operator.

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Effective uncertainty visualization for aftershock forecast maps

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Seismicity rate estimates and the earthquake forecasts they yield vary spatially and are usually represented as heat maps. While visualization literature suggests that displaying forecast uncertainty can improve how forecast maps are used, research on uncertainty visualization (UV) is missing from earthquake science. We present a pre-registered online experiment to test the effectiveness of three UV techniques for displaying aftershock forecasts. These maps show the expected number of aftershocks at each location for a week following a hypothetical mainshock, and we develop maps of the uncertainty around each location's forecast. Human participants complete experimental tasks using the aftershock forecast displayed with its uncertainty. Three different UVs are produced: (1) forecast and uncertainty maps adjacent to one another; (2) the forecast map depicted in a color scheme, with the uncertainty shown by the transparency of the color; (3) two maps that show the lower and upper bound of the forecast distribution at each location. We compare task performance using UVs and using the forecast map shown without its uncertainty (the current practice). Subjects complete two map-reading tasks that target several dimensions of the readability of the three UVs. They then perform a comparative prediction task. This demonstrates whether a UV is successful in reaching two key communication goals: indicating where an aftershock and no aftershocks are likely ("sure bets'') and where the forecast may be low but the uncertainty is high enough to imply potential risk ("potential surprises''). All UVs perform equally well in the goal of communicating "sure bet'' situations. But the UV with lower and upper bounds is significantly better than the other UVs at communicating "potential surprises." We discuss the implications of these results for communication of forecast uncertainty within and beyond earthquake science.

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TURNkey – An overview

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Among all natural hazards, earthquakes lead to the highest number fatalities and, after severe storms, cause the second highest annual economic losses. From 2006 to 2015, Europe experienced 21 earthquake-related disasters that resulted in 1.049 fatalities, more than 18 billion EUR in economic losses, and affected 284.000 people. In the last years, risk awareness and perception towards seismic threats have increased among the public and policy makers in many European countries.

TURNkey (Towards more Earthquake-resilient Urban Societies through a Multi-sensor-based Information System enabling Earthquake Forecasting, Early Warning and Rapid Response actions, https://earthquake-turnkey.eu/) involves 21 research, business and government partner organisations and has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821046.

The TURNkey project addresses three topics:

• Operational Earthquake Forecasting (OEF), by collecting/analysing earthquake-hazard information for the regions of interest and by monitoring the regions with appropriate instrumentation;
• Earthquake Early Warning (EEW), by distributing reliable information that an earthquake is happening as fast and efficiently as possible to relevant stakeholders; and
• Rapid Response to Earthquakes (RRE), by informing relevant stakeholders about the most probable damage scenarios in near real-time and by estimating losses.

The focus of TURNkey is to close the gap between the theoretical systems and their practical application in Europe and to assist stakeholders in different risk mitigation actions before, during, and after a damaging earthquake in order to reduce future human, social and economic losses.

During the project, a wide range of data sets, tools and models are being developed, which are then integrated into a cloud-based Forecasting–Early Warning–Consequence Prediction–Response (FWCR) platform that will be tested and demonstrated in 6 European testbeds and that is dedicated to public authorities (first responders and civil protection) and private companies (including operators of critical infrastructures).

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Exploring the Variability of ETAS Parameters for Potential Operational Earthquake Forecasting system in Southwestern Iceland

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Over the last decade, earthquake forecasting research has shown that when properly applied, it is becoming increasingly more feasible to forecast the temporal and spatial progression of seismic sequences i.e., aftershocks triggered after a strong earthquake mainshock. This has practical importance because the aftershocks can progressively increase the damage, and an effective post-event response is crucial to reduce losses in the earthquake-stricken regions. In this study, we apply a Bayesian spatio-temporal epidemic-type aftershock sequence (ETAS) clustering model to forecast the progression of the intense aftershock sequence that commenced after the Mw6.4 17 June 2000 earthquake in the South Iceland Seismic Zone (SISZ) in Southwest Iceland. A spatio-temporal model is needed as seismic sequences in the SISZ have been shown to trigger earthquakes over a wide area in its transform fault zone and that of the Reykjanes Peninsula Oblique Rift (RPOR). We apply Bayesian inference of the ETAS parameters to assess their uncertainties robustly through posterior joint probability distributions. The Markov Chain Monte Carlo Simulation (MCMC) is exploited to sample from the posterior probability distribution of the key ETAS parameters. To assess the convergence of the MCMC algorithms, detailed convergence diagnostic analyses are performed, and sample's trace plots and histograms are scrutinized. Adopting fully simulation-based forecasting analyses, the impact of different initial prior information and the number of posterior samplings and Markov Chains in the posterior distribution is explored. In this regard, we delineate the spatial distribution of the increased seismicity rates forecasted across SISZ and RPOR areas in different prescribed short-term forecasting time intervals. The aftershocks following the strong earthquakes are forecasted within the 2-98th /16-84th percentiles of the observations, even in the early aftershock period. We stress the importance of the informative set of ETAS priors to attain reliable forecasts as fast as possible after a strong earthquake.

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Deployment of a multi-sensor system for real-time seismic monitoring of strategic port facilities in Italy

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The port of Gioia Tauro is a strategic hub for container traffic in Europe, connecting the global and regional networks that cross the Mediterranean Sea, which is one of the busiest seas in the world. The Gioia Tauro port is located in the Calabria region, characterized by the highest seismic hazard in Italy. The port plays a crucial role in disaster relief efforts associated with the occurrence of an earthquake. For these reasons, the port of Gioia Tauro was selected as one of the testbeds considered within the European H2020 project, named TURNkey (Towards more earthquake-resilient URban societies through a multi-sensor-based informatioN system enabling earthquaKe Forecasting, early warning and rapid response actions). The project, funded under the European Union's Horizon 2020 research and innovation programme, started in 2019 and will end in 2022.

In the framework of the TURNkey project, a multi-sensor system has been deployed within the port area of Gioia Tauro. Indeed, a unit of 10 low-cost sensors, including 6 RS4D (with 1 velocity and 3 accelerometers channels) and 4 GNSS, were installed for seismic ground motion and structural monitoring. Tools are currently under development for processing the streamed data with the final aim of enabling the effective implementation of an Earthquake Early Warning (EEW) and Rapid Response to Earthquake (RRE) system at the port of Gioia Tauro. Indeed, in parallel, ongoing activities are focusing on the development of algorithms for the estimation of ground-shaking at the port area, the assessment of earthquake-related damage to port facilities, and rapid quantification of induced losses by addressing the multi-component nature of the port system. An effort is underway to address and possibly reduce the uncertainties associated to the various steps. By leveraging on implemented algorithms and tools, a risk-informed Decision Support System (DSS) will be delivered for mitigating earthquake impacts.

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Seismic risk assessment at TURNkey TB4 using a common earthquake scenario: an application to Patras city and Aigion town, central Greece

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The present study focuses on the investigation of earthquake risk in the city of Patras and the town of Aigion (central Greece), under an application within the H2020 financed TURNkey project. The seismic hazard in both urban areas is primarily controlled by the highly extensional tectonics of the Western Corinth Gulf. An impressive expression of this fast opening is the Psathopyrgos fault, which lies between the two studied cities. We examine a scenario earthquake on this fault and assess its impact on the urban environment of Patras and Aigion. The idea is to produce the synthetic ground motion field and apply it as input in an integrated risk assessment system, which could serve as tool for improving earthquake resilience and facilitating rapid response during earthquake disasters. The input ground motion field is computed both from Ground Motion Models applicable in the study area and by the stochastic simulation method for finite faults.

We focus on comparing different representations of the site/soil effect, i.e., through empirical site amplification factors attributed, based on Vs30 maps constructed for both Patras city and Aigion town, as well as using Horizontal-to-Vertical Spectral Ratios of data from an extended strong ground motion array, mainly comprised of low-cost sensors, deployed in public and private buildings within the context of the TURNkey TB4 case. The analysis incorporates soil classification on a block-by-block level for Patras and Aigion and leads to the damage prediction of infrastructures by assessing empirically the structural vulnerability per building block for each target area, after estimating their exposure model. Thus, we assess the resilience of the two urban areas to a strong near-by earthquake source, by incorporating available soil response and structural vulnerability information.

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Rapid time-dependent estimates of earthquake-induced mass-movement likelihoods in Switzerland

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Earthquake-induced mass movements are a substantial threat to mountainous areas in seismically active regions like the Valais, the most seismically hazardous region of Switzerland. This study describes a comprehensive procedure to deliver rapid time dependent predictions of mass-movement likelihoods in the Valais and their impacts on lifelines in near real-time during major earthquake sequences. We rely on the availability of a Swiss-specific empirical model for the prediction of seismically induced mass-movement likelihoods, and combine it with rapid probabilistic earthquake shaking estimates based on short-term seismicity forecasts following a triggering seismic event, and state-of-the-art input models to probabilistic seismic hazard studies in Switzerland. The aftershocks are spatially distributed in proximity to the triggering event, in a volume that can accommodate the largest possible source in the aftershock sequence. The procedure is developed and demonstrated based on the possible repetition of relevant historical and instrumental sequences in the region. The obtained probabilities of mass-movement are spatially associated with exposed assets in the region to estimate the associated risk. We propose a strategy for optimal communication of risks emerging from earthquake induced mass-movement hazards, providing stakeholders with alarm levels and other decision-making tools based on risk-cost-benefit considerations for critical lifelines. Fully automated and largely customisable, the procedure can be easily extended to the greater Swiss region and integrated within the evolutionary earthquake shaking information systems of the Swiss Seismological Service.

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Quadtree based multi-resolution grids for global earthquake forecast experiment

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The Collaboratory for the Study of Earthquake Predictability (CSEP) is an international effort to independently evaluate earthquake forecasting models. CSEP provides the necessary cyber-infrastructure along with a suite of testing methods for earthquake forecasts. CSEP defines a grid-based format for expressing earthquake

forecasts: the expected rate of earthquake occurrence within 0.1° x 0.1° spatial cells. This uniform gridding approach leads to 6.48 million spatial cells. The distribution of earthquakes around the globe is non-homogenous, resulting in 99% of spatial cells containing no earthquake. This leads to an unjustifiably high-resolution grid in low-seismicity regions with an unnecessary computational burden.

In this study, we propose a quadtree-based gridding approach that is capable of providing a multi-resolution spatial grid. The quadtree is a hierarchical tiling strategy for storing and indexing geospatial data. It follows the Mercator projection in which the whole globe is divided into 4 squared tiles and then each tile can be divided into four children tiles, until a final desired grid is acquired. Each tile refers to a unique region on Earth and is identified by a unique identifier called quadkey. To create a multi-resolution grid, subdivision of a tile is driven by a criterion, e.g. maximum number of earthquakes allowed per cell (Nmax). Thus, instead of dividing the whole globe into 0.1° x 0.1° cells, the quadtree approach generates high-resolution (smaller) grid cells in seismically active regions and low-resolution (bigger) grid cells in seismically quiet regions. The proposed multi-resolution gridding approach reduces the total number of cells in the grid from the order of millions to a few thousand cells, thereby reducing the quantity of cells without earthquakes and limiting the computational cost associated with model generation and evaluation. Most importantly, the quadtree offers ease of handling gridding process and compatibility with web mapping services for rendering the data.

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Earthquake Physics imposed limits in Earthquake Early Warning: Application in Greece

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Earthquakes are a continuing threat to Greece, capable of causing significant losses to the built-in environment and suddenly disrupting people's lives in unpredictable ways. While the public often wishes that earthquakes could be predicted in advance, short term earthquake prediction in the near future seems an unattainable goal, making operational early warning systems one of the most important available tools for earthquake damage mitigation.
A fundamental step prior to early warning system's operation, like a potential system for the Greek region, is the assessment of its performance. To that end, we adopt a hypothesized ideal zero-latency system and explore the seismic source physics-imposed limits on its capability to provide timely and meaningful warning information. By examining the delays introduced by the source process, we seek to explore in which cases an alert is physically impossible or arrives too late with no practical usage. Given the seismotectonic context of Greece where shallow and intermediate depth earthquakes are plausible, we examine both cases for target sites where the implementation of such system would be especially meaningful.

Using simple source modeling, our approach involves the implementation of regional applicable ground motion prediction equations through probabilistic concepts, highlighting the balance between false and missed alarms. For realistic earthquake scenarios and past damaging events, considering the varying spatial station density of the national monitoring network and physical constrains, we estimate the theoretical duration of the time window created between the moment an alert arrives and when a user defined strong ground motion threshold is exceeded. Finally, we discuss factors that shape the extent to which such system is operable including source complexity and ground motion modeling uncertainty, through the scope of real well-studied historical and instrumental events.

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Supporting post-earthquake decision-making via probabilistic updating of early recovery forecasts for residential buildings

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The potentially large impact of earthquake-induced damage to the built-environment, and the residential building stock in particular, induces numerous direct and indirect consequences that plague communities for a long time after the event. Adequate post-earthquake decision-making is a crucial enabler of speedy and sustainable recovery from damaging earthquakes. However, intense time pressure, paired with scarce information on the severity and the spatial distribution of earthquake-induced damage, complicates decision-making in the early aftermath of earthquake events. Rapid impact assessments, which are typically produced using regional risk models and instrumental and macro-seismic earthquake intensity data, provide valuable first information to decision-makers. The precision of such damage assessments depends on multiple factors, including the density of seismic network stations, the geological knowledge and applicability of the employed typological building vulnerability functions within the region hit by the earthquake. The first comprehensive building-specific impact data collection is typically done within a rapid safety screening campaign, where engineers visually inspect buildings for a qualitative safety evaluation. However, such inspection-based collection of impact data for all affected buildings might take several weeks. In this study, we leverage the limited data becoming available in the very first days after the event to increase the precision of damage estimates, which serves as the starting point for forecasting the recovery process. A special focus is given to detailed modelling of the different recovery phases that include detailed damage assessments, repair design, construction permitting, contractor mobilization and execution of the planned repairs. Thus, early recovery forecasts enable a prompt identification of potential bottlenecks and planning of countermeasures to reduce recovery delays. In addition, more knowledge on how buildings were affected facilitates the design of targeted repair actions for common building types and damage patterns. The presented methodology is demonstrated using a fictitious earthquake scenario affecting a case-study region in Switzerland.

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Risk-Informed Decision Making for Earthquake Early Warning

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Up to now, the most cutting-edge innovations in the field of earthquake early warning (EEW) - e.g., the use of machine-learning methods for rapid source-parameter characterization - have focused exclusively on the seismological aspects of EEW systems. To maximize the potential of these technologies as credible tools for seismic resilience assessment/promotion however, there is a strong need to develop next-generation EEW decision-support systems (DSSs) that use interpretable probabilistic risk-driven estimates for more informed application-specific stakeholder decision-making on the triggering of alerts.

We contribute to the required effort by developing a state-of-the-art end-user-oriented DSS for real-time earthquake risk management. The proposed DSS involves a novel integration of: (1) EEW seismology-related models; (2) earthquake-engineering-related seismic performance assessment procedures/metrics; and (3) tools for multi-criteria decision-making (MCDM), within an end-to-end probabilistic framework that robustly tracks uncertainties at each calculation stage. The performance-based earthquake engineering component facilitates the computation of end-user focused damage and loss estimates (e.g., monetary costs/casualties), by combining target structure-/infrastructure-specific models of seismic response, fragility, and vulnerability/damage-to-loss with ground-motion shaking predictions of the seismology-focused models in (1), which can be obtained from the scientific entity responsible for EEW/OEF. The incorporated MCDM methodology enables explicit consideration of end-user preferences (importance) towards the predicted consequences, in the context of alert issuance.

We apply the proposed DSS to three European case studies: (1) a school in Patras, Greece; (2) a railway bridge in the Pyrenees, France; and (3) the Port of Gioia Tauro, Italy. We specifically investigate the optimal decision for EEW (i.e., “trigger” or “don’t trigger” an alert) across a range of seismological input parameters and find that the best action for a given estimate of incoming ground motion can change as a function of stakeholder preferences. This work represents an important paradigm shift in current approaches to issuing warnings for short-term seismic activity.

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Could earthquake early warning be effective across Europe?

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This study assesses the potential implementation of earthquake early warning (EEW) across Europe, where there is a clear need for measures that mitigate seismic risk. EEW systems consist of seismic networks and models capable of real-time data telemetry that alert stakeholders, such as civil protection authorities, to the nucleation of an earthquake seconds to before strong shaking occurs at target sites. Examples of important risk-mitigation actions that can be taken in the short warning time provided by EEW systems include: (1) Performing ``drop, cover and hold on'' or moving to a safer location (either within a building or outside), to avoid injuries; (2) slowing down high-speed trains, to reduce accidents; (3) shutting off gas pipelines, to prevent fires; and (4) switching signals to stop vehicles from entering vulnerable infrastructure components (such as bridges), to avoid fatalities.

We specifically investigate probabilistic distributions of EEW lead times available across various parts of the Euro-Mediterranean region, using seismicity models, seismic network density, and a well-established travel-time algorithm for seismic waves. We then determine the potential usefulness of these times for EEW purposes, by defining their spatial relationship with ambient population exposure, seismic hazard and an alert accuracy proxy, using well-established tools for measuring the impacts of earthquakes. The mapped feasibility results demonstrate that, under certain conditions, EEW could be effective for some parts of Europe.

This study offers a unique trans-national perspective on the potential of EEW that is relevant for intergovernmental bodies - such as the International Search and Rescue Advisory Group (INSARAG) of the United Nations - who may be interested in leveraging the technology. It also provides valuable new insights on the possible benefits/limitations of EEW for regions (e.g., Iceland and Georgia) that have not recently experienced large earthquakes, but are likely to do so in the future.

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Robust, an earthquake early warning system in the lower Rhine Embayment, Germany

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The Lower Rhine Embayment in western Germany is one of the most important areas of earthquake recurrence north of the Alps, facing a moderate level of seismic hazard in the European context but a significant level of risk due to a large number of important industrial infrastructures. In this context, the project ROBUST aims at designing a user-oriented hybrid earthquake early warning and rapid response system where regional seismic monitoring is combined with smart, on-site sensors, resulting in the implementation of decentralized early warning procedures.

One of the research areas of this project deals with finding an optimal regional seismic network arrangement. With the optimally compacted network, strong ground movements can be detected quickly and reliably. In this work simulated scenario earthquakes in the area are used with an optimization approach in order to densify the existing sparse network through the installation of additional decentralized measuring stations. Genetic algorithms are used to design efficient EEW networks, computing optimal station locations and trigger thresholds in recorded ground acceleration. By minimizing the cost function, a comparison of the best earthquake early warning system designs is performed as will be presented in the meeting.

ESC2021-S18-461

Retrospective earthquake forecast in Italy using Coulomb based rate-and-state framework

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During 2009-2014, the Collaboratory for the Study of Earthquake Predictability (CSEP) executed a state-wide rate-based forecast in Italy, which provides a platform for the prospective testing of different forecasting hypotheses. Here we implement a retrospective study using the rate-and-state framework and the standard Epidemic Type Aftershock Sequence (ETAS) method to forecast the spatiotemporal variation of targeting earthquakes. We develop the Coulomb-based rate-and-state (CRS) forecast in a pseudo-perspective scenario using static stress transfer with regular updates about earthquake sources, a gradual increase in data input quality and model complexity. The spatial and temporal distribution of forecasted events indicates that adopting the finite slip models, spatially variable receiver faults, and the inclusion of stress rearrangement from secondary triggering could increase the performance of the Italy-wide CRS forecasts. Further testing will consist of evaluating the absolute (N-test and S-test) and relative (T-test) predictive skills of the CRS and standard ETAS models.

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The TURNkey multi-sensor network for rapid-response actions in Bucharest: monitoring setup and preliminary results

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Bucharest is considered one of the most earthquake-endangered capitals in Europe. Given the wide distribution of buildings per various seismic design code periods - in Bucharest, we considered of great interest to instrument and gather strong-motion data from the most representative typologies. In addition to the existing seismic network, in the framework of the TURNkey project, five buildings from Bucharest, representing 3 different generations of earthquake resistant design codes, were instrumented, since August 2020, using Raspberry Shake 4D (RS4D) sensors installed at different building floors and cost-effective double-frequency GNSS equipment. During the monitoring period, a series of earthquakes (crustal and intermediate-depth, with local-magnitudes from 3.7 to 4.5) have occurred mainly in the Vrancea seismic area, which could possibly significantly affect Bucharest. Among these, due to the high-level of the self-noise of RS4D acceleration channels, only the April 9th event presented an acceptable signal to noise ratio and could be analyzed from the perspective of building`s dynamic parameters. Different damage-detection algorithms have been tested in order to provide a rapid and reliable assessment of the seismic response of different building typologies and to assist authorities actions and stakeholders decisions. This paper presents the chosen typologies and the configuration setup for each building. Some preliminary results consisting of dynamic parameters extracted from seismic signals are also presented. This work and the promising results set the premises to integrate them into the more complex TURNkey FWCR (Forecasting – Early Warning – Consequence Prediction – Response) platform, and, correlated with the local ShakeMap for Bucharest, should provide a rapid screening of the damage and losses at the city level, for future strong magnitude events.

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Short-term risk scenario for Hveragerði during the June 2000 South Iceland Seismic Zone earthquake sequence

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The goal of any operational earthquake forecasting (OEF) system is to generate information of a quantifiable reliability that the relevant authorities can use to act upon to increase the effectiveness of any preparatory or response actions to reduce losses in earthquake disasters. The operational aspect of the OEF system implies short-term actions either before or immediately after an earthquake. In this study, we use the results of a Bayesian spatio-temporal epidemic-type aftershock sequence (ETAS) model that has been calibrated to the June 2000 seismic sequence in the South Iceland Seismic Zone (SISZ). After the M6.4 mainshock of 17 June 2000, the ETAS model is applied to generate daily seismicity forecasts of the spatio-temporal progression of the aftershocks in the region. Subsequently, the short-term increase in the seismic hazard is quantified at the city of Hveragerði in Western SISZ. On this basis, the open-source algorithm, SELENA (Molina et al., 2010), is adapted to compute short-term loss curves for Hveragerði during the seismic sequence from 18-24 June 2000. The loss curves are calculated for the residential building stock classified into three main typologies (masonry, timber, and concrete) and the corresponding vulnerability functions (Bessason et al., 2020). The results demonstrate that the building typologies show less damage when compared with similar buildings in Europe. Masonry buildings have the highest vulnerability and timber buildings are the least vulnerable ones. The same observation for the seismic hazard curve can be made: the short-term loss curves are elevated during this seismic sequence and the long-term loss curve represents a lower bound. Finally, a simplified human loss model is defined to estimate injuries and fatalities to the population and a simplified cost-benefit analysis is applied to determine if the mitigation action of evacuation is recommended or not.

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Application of the Foreshock Traffic Light System to the 2019 Ridgecrest sequence

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The relative earthquake size distribution, or b-value of the Gutenberg and Richter relationship, can act as an indirect stress meter in the earth crust, a finding confirmed in numerous laboratory studies but also in diverse natural systems. In 2018, we analysed the average size-distribution of about 60 well-monitored earthquakes sequences showing that, after a mainshock with M>=6, the b-value increases by about 20% respect to the background reference value.

In 2019, based on such result, we hypothesized and demonstrated that it may be possible, under specific circumstances, to discriminate if an ongoing sequence is representing a typically decaying aftershock sequence or rather foreshocks to an upcoming larger event. We proposed a simple traffic light classification to assess in near real-time the level of concern for subsequent larger event, and tested it against 58 sequences, reaching a classification accuracy of 95%.

The Foreshock Traffic Light System (FTLS) has been implemented in a pseudo-prospective test to the 2019 Ridgecrest sequence. Results are fully in line with the hypothesis: in this Ridgecrest case study, after analyzing carefully the magnitude of completeness of the sequences, we find that in the hours after the first Mw6.4 Ridgecrest event, the b-value drops by 23% on average, when compared to the background value, resulting in a red foreshock traffic light. Spatially mapping the changes in b, we identify an area to the north of the rupture plane as the most likely location of a subsequent event. After the second, magnitude-7.1 mainshock, which did occur in the low b-value region, the b-value subsequently increased by 26% over the background value, triggering a green traffic light setting. Here we will report on these findings, discuss additional case studies, criticisms raised and discuss physics-based mechanics that may allow us to understand and model the observations.

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Contamination of frequency magnitude slope (b-value) by quarry blasts: an example for Italy

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Artifacts often affect seismic catalogues: among them, the presence of man-made contaminations such as quarry blasts and explosions is a well-known problem. Using a contaminated dataset reduces the statistical significance of results and can lead to erroneous conclusions, thus the removal of such non-natural events should be the first step for a data analyst. Blasts misclassified as natural earthquakes, indeed, may artificially alter the seismicity rates and then the b-value of the Gutenberg and Richter relationship, an essential ingredient of several forecasting models.

At present, datasets collect several useful information beyond the parameters to locate the quakes in space and time, allowing also the users to discriminate natural and non-natural events. However, selecting them from Web Services queries is neither easy nor clear and part of such supplementary but fundamental information can be lost during downloading. As a consequence, most of statistical seismologists ignore the presence in seismic catalog of explosions and quarry blasts and assume that they were not located by seismic networks or in case they were eliminated.

We here show the example of the Italian Seismological Instrumental and Parametric Database and the impact on the b-value of the Gutenberg and Richter relationship when artificial seismicity is mixed with natural one.

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Is the magnetic field behavior a reliable parameter for an Operational Earthquake Forecast (OEF) of moderate size earthquakes?

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This paper analyzes the opportunity to use geomagnetic data from magnetometers installed inside and outside seismogenic zones for a reliable OEF.
For this purpose, we have studied the relationship between geomagnetic variations inside Vrancea (Romania) seismogenic zone and the occurrence of the intermediate-depth earthquakes in the last decade. During this period, there occurred 10 moderate seismic events with Mw bellow 6.0, at intermediate depths. The geomagnetic data were recorded at Muntele Rosu Observatory (MLR) and at Surlari Geomagnetic Observatory (SUA).

To distinguish possible seismo-electromagnetic anomalies from global magnetic variations, the MLR data were analyzed comparatively with the magnetic data from SUA, located outside the Vrancea seismic zone. Surlari Geomagnetic Observatory included in INTERMAGNET, is located more than 150 Km South-East from the center of Vrancea zone, and was considered as remote station, unaffected by medium size earthquake preparedness processes. In order to separate the variations caused by solar-terrestrial interaction, magnetic data were analyzed together with the geomagnetic indices taken from NOAA/Space Weather Prediction Center.

To highlight the relationship between the geomagnetic anomalies and seismic activity of Vrancea zone, b-value and daily energy release calculations for each anomaly were performed. Statistical nonparametric correlation coefficients and also cross correlation methods were applied on geomagnetic data taken from MLR and SUA and magnetic storms due to solar activity and local seismicity taken from ROMPLUS INCDFP catalogue.

Even if all moderate seismic events occurred during low correlation periods between data from MLR and SUA, the method is affected by bad or missing data on magnetic records and an effective operational forecast is not possible at this moment for the case of moderate events, with moment magnitude less than 6.0.
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Steps forward in rapid earthquake loss estimation for Romania

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The level of seismic hazard in Romania is high on more than half of its territory. Multiple seismic sources contribute to this: both intermediate-depth Vrancea earthquakes and shallow earthquakes occurring in seismic zones such as Banat, Danubius, Crisana-Maramures, Fagaras-Campulung or nearby Shabla. The level of exposure is also significant, along with a highly vulnerable building stock and limited resources for risk reduction. In this context, seismic loss estimates are highly useful for a better understanding of direct and indirect risks, for a prioritisation of investments in risk mitigation strategies and better targeted emergency response. The System for the Rapid Estimation of Seismic Damage in Romania (Seisdaro) became operational in 2011, providing loss estimates at administrative-unit level for all of Romania - starting with version 3 in 2016. New recent projects such as TURNkey (where the capital Bucharest is testbed) or REDACt (with Constanta City as testbed) are providing improved solutions, compared to Seisdaro - allowing the use of new methodologies (for example integration of new design spectra, additional methods for computing damage probability and links toward a system for the rapid evaluation of risk due to road network loss of connectivity) and software (such as new version of SELENA), along with refined exposure and vulnerability models for the aforementioned cities.

Of high importance in these projects is the focus on data standardisation and harmonisation. In our study we present the improvements achieved and also preliminary results which show the impact of higher-resolution data and of the new technological capabilities on reducing uncertainties and enhancing emergency intervention and preparedness. The contribution of low-cost sensors, building monitoring and better consideration of the seismic design code periods is also brought in the discussion. Another aspect we focus on is the way loss estimates are delivered to stakeholders - in accordance with their needs.

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The TURNkey European Testbeds: Towards consistent real-time seismic ground motion and structural monitoring

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The overall objective of the TURNkey project is to contribute to earthquake risk reduction and to mitigate the direct and indirect consequences of earthquakes in Europe. For that purpose, TURNkey develops the TURNkey FWCR (Forecasting, Early Warning, Consequence Prediction, Response) platform, a multi-sensor-based earthquake information cloud-based system. The TURNkey platform is demonstrated and developed in six European earthquake prone Testbeds (TBs) that range in their tectonic setting, levels and types of earthquake hazard, population densities, types of vulnerable infrastructure, and spatial extents. They are TB1, Bucharest, Romania; TB2, Pyrenees, France; TB3, Towns of Hveragerði and Húsavík, Iceland; TB4: City of Patras and Aegion town, Greece; TB5, Ports of Gioia Tauro, Italy; and TB6, Groningen, Netherlands. We present how a total of 132 new TURNkey RS4D accelerometric and seismic sensor units and 26 TURNkey GNSS units have been stratetically deployed in the TBs to address particular weaknesses in existing sensor networks and that demonstrate and secure the real-time streaming of multidisciplinary data (e.g., seismic, deformation, structural response, etc.) in a common data format to both local SeisComP servers and a central cloud based system for archiving and waveform analysis. We show how the deployments serve to optimize earthquake early warning efficiency in some TBs and in others, the increase in spatial resolution of seismic data e.g. for microzonation studies along with structural response data of important building typologies and infrastructure. Cumulatively therefore, the TURNkey approach is demonstrated to be applicable in any European seismic region. Along with earthquake impact reports from affected seismic regions and transient data from TURNkey's mobile early warning system for aftershock, the data from the TURNkey multi-sensor units forms the basis of the development of the TURNkey FWCR platform, to be evaluated by individual stakeholders within the TBs.

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The performance of the new TURNkey network in Iceland during the 2021 Reykjanes Peninsula volcano-tectonic unrest

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The largest and most damaging earthquakes in Iceland take place in two transform zones, the South Iceland Seismic Zone (SISZ) and Reykjanes Peninsula Oblique Rift (RPOR) in the South, and the Tjörnes Fracture Zone (TFZ) in the North. The towns of Hveragerði and Húsavík in the SISZ and TFZ, respectively, are one of six European testbeds (TBs) of the TURNkey H2020 project that contributes towards improved earthquake early warning, rapid response and operational earthquake forecasting in the TBs. We present the results of the intense instrumentation campaign during 2020-2021 of 50 TURNkey multisensor units and 6 GNSS units in the SISZ, RPOR and TFZ that address particular weaknesses in existing sensor networks. On local scale, the Icelandic urban small-aperture strong-motion arrays in Iceland have been further densified, and new ones deployed in the RPOR. Regionally, a dedicated near-fault laboratory has been created with multidisciplinary

instrumentation all along and across the Húsavík-Flatey Fault Zone in the TFZ and along the RPOR and SISZ, respectively. The urban stations use optimal wireless telecommunication (3G/4G/CAT-M/IoT) based on local conditions. All units transmit real-time miniSEED data via Seedlink to a local SeisComP system that forwards it to a central CAPS server at Gempa for cloud- and web-based seismic monitoring and waveform analysis. The system has a proven high monitoring performance during the intense volcano-tectonic unrest that started with a M5.7 earthquake in central RPOR on 24/02/2021 and recorded over 2000 events, including seven earthquakes larger than M5 until the sequence culminated in an Icelandic eruption on 19/02/2021 in Fagradalsfjall, essentially ending the seismic sequence.

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The performance of a new seismic and strong-motion urban array in Grindavík, Iceland, during an intense dyke intrusion event in Reykjanes, Southwest Iceland

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An intense period of volcano-tectonic unrest in Reykjanes Peninsula Oblique Rift (RPOR) zone in Southwest Iceland commenced on 24/02/2021 with a M5.7 earthquake in central RPOR, followed by a drastic increase in seismic activity over the western-central RPOR and clear deformation signals associated with a dyke intrusion. The sequence that saw seven NS-striking earthquakes of M5 or more along the 12 km dyke intrusion culminated in an Icelandic eruption (19/02) in Fagradalsfjall, and effectively ended the seismic sequence. The lateral movement of the magma front repeatedly caused a marked increase in the frequency of phase arrivals, known to affect the reliability of real-time hypocenter location estimates. This had potentially practical implications due to the proximity of the unrest to the capital region of Reykjavik (12 km NE) and the town of Grindavik (6 km SW). Therefore, both the improved seismic monitoring of the advancing magma front was essential as well as mapping the spatial differences in ground motion amplitudes inside the closest town of Grindavik (6 km to the SW). We therefore set up a new seismic and strong-motion array of 6 stations in Grindavik (12/03) and 3 stations in Reykjanesbær (23/03, 15 km NW) that streamed data in real-time to a local SeisComP server. Calibration of the array processing involved tuning gempa's interactive and automatic LAMBDA and AUTOLAMBDA modules applying the PMCC (Progressive Multi Channel Correlation), beam packing and FK-analysis methods. We calculated back-azimuths and slownesses of known earthquakes and compared them to official locations. For most events, the back-azimuth deviates by less than 10° and on average, the distribution of residuals is gaussian. The ground motions in Grindavik itself show resonance at 3 Hz, typical of lava-layers in the region.

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TURNkey Multi-sensor unit and cloud-based FWCR Platform

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TURNkey (Towards more Earthquake-Resilient Urban Societies through a Multi-Sensor-Based Information System enabling Earthquake Forecasting, Early Warning and Rapid Response Actions) is a European project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821046. One of the key product of the project is the development of a multi-sensor unit and the cloud-based FWCR Platform for earthquake forecasting (OEF), real-time earthquake

information for early warning (EEW), rapid consequences prediction and rapid response assistance immediately after an earthquake (RRE).

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Frictional energy patterns related to the temperature increases due to intraplate seismicity, Southern Norway, 2000–2019 catalog

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Low magnitude seismic events (0 ≤ Mw ≤ 3.8) recorded in southern Norway during the period 2000–2019 were used to calculate the sudden co-seismic temperature increases using a simple stress-drop model. The maximum temperature increase associated with an Mw = 3.5 earthquake was ~122°C. Simultaneously, we added 13 historical earthquakes to our study data, which occurred between 1657–1989. Here, the maximum temperature rise was ~560°C for an Mw = 5.6 event. The temperature values were analyzed to derive local thermo-mechanical effects, such as thermal fracturing, frictional drop and the possible formation of cataclasites and pseudotachylites. Using the Kanamori's equations, we estimated the thermal energy released by individual events and in 2D and 3D cumulative patterns. To identify possible correlations between frictional energy, seismicity distribution and regional geology, the results were spatially correlated with a lineament zone located in the south-western coast and a heat flux map. Areas with high thermal energy values seem to be spatially linked with zones that exhibit a high density of lineaments and high heat flux through the whole south-western Norwegian coast.

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Scaling relationships and spatial variability of source parameters in central-southern Europe

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In the framework of the European project URBASIS (https://urbasis-eu.osug.fr/), a spectral decomposition approach is applied to determine the source parameters of earthquakes occurred in central-southern Europe. Using the ISC event catalog (http://www.isc.ac.uk/iscbulletin/), waveforms recorded in the target area since late '90s have been downloaded from the EIDA data archive (https://www.orfeus-eu.org/data/eida/). Fourier amplitude spectra including S-waves have been computed (combination of horizontal components). A non-parametric decomposition approach is applied to isolate the source, propagation and site contributions to ground shaking. About 95,000 Fourier amplitude spectra generated by about 11,000 earthquakes in the moment magnitude range of 2.0-6.5 have been selected for the decomposition. In order to take into account differences in propagation effects, a regionalisation of the attenuation is introduced by defining 4 zones including mainly central Europe, the Alpine region, norther-central Apennines, and the Pyrenees-Iberia region. For each region, a spectral attenuation with hypocentral distance model is determined in a tabular form and used to remove regional specific propagation effects from the spectra of recordings. Once isolated from local site effects, the non-parametric source spectra are fitted to a standard omega-square source model to determine the seismic moment and the corner frequency of each earthquake, which in turn are used to compute the stress drop considering a circular rupture model with uniform stress drop. Results are presented in the form of source parameter distributions, source scaling relationships and maps for presenting the stress drop variability.

ESC2021-S19-129

Stable source spectra from direct-S and coda envelopes: Two perspectives for the determination of source parameters in Central Italy for 2.0<Mw<6.5

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Robustness of source parameter estimation is a fundamental issue in understanding the relationships between small and large events. Indeed, it is difficult to assess how much of the variability of the source parameters can be attributed to the physical source characteristics or to the uncertainties of the methods and data used to estimate the values.

In this study we apply the coda method by Mayeda et al. (2003) using the Coda Calibration Tool (CCT), a freely available Java-based code (https://github.com/LLNL/coda-calibration-tool) to obtain a regional calibration for Central Italy for estimating source parameters. We compare our results using a spectral decomposition analysis (GIT, Generalized Inversion Technique) to validate results and analyze strengths and limitations of both methods.

The Central Italy region is ideal for both approaches as it is characterized by high-quality data including recent well-recorded seismic sequences such as L'Aquila (2009) and Amatrice-Norcia-Visso (2016-2017). This allows us to apply data-driven methods such as GIT, and coda-based methods that require few, but high-quality data. The dataset for GIT analysis includes ~6500 earthquakes and 480 stations, while for CCT we used a small subset of 39 events spanning 3.5<Mw< 6.5 and 15 well-distributed stations.

For the common 39 events, as well as an additional ~250 events not used in either calibration, we find excellent agreement between GIT-derived and CCT-derived source spectra. This confirms the ability of the coda approach to obtain stable source parameters even with few calibration events and stations. Even reducing the coda calibration dataset by 75% we found no appreciable degradation in performance.

This validation of both approaches over a broad range of event size provides the basis for future routine applications of both approaches in this region for events that are too small for waveform modeling.

ESC2021-S19-168

Coda Envelope Moment Magnitudes and Source Scaling along the St. Lawrence Corridor, Canada

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For hazard assessments and other research requiring accurate and consistent magnitudes, direct determination of moment magnitude (Mw) is preferable to relying on conversion relations, which may not have been validated across the complete range of magnitudes in an earthquake catalog. The coda envelope method (Mayeda et al., 2003) has emerged as one of the most promising and stable techniques for direct

determination of Mw for earthquakes too small for Mw to be determined by modeling methods, which generally require long period signals.
The scattered waves that comprise the coda are only minimally effected by source radiation pattern and directivity.

Thus, the method provides stable results even with sparse or azimuthally unequal networks. Recent improvements to the Java-based software through collaboration between AFTAC and LLNL to facilitate the process make it attractive for use as a standard magnitude. The method was successfully applied to the western Quebec region of eastern Canada and we are now turning to the active seismic zones along the St. Lawrence River.

The geology here is more complex as the river marks the boundary between the low attenuation Canadian Shield to the north and the higher attenuation Appalachian region to the south.

This complexity highlights the need for regional path and site calibrations. Using a suite of ground truth reference events, Mw will be determined for as many earthquakes as possible and source scaling relationships developed and compared to western Quebec, where apparent stresses were high compared to other intraplate regions.

The results will also be used to develop improved magnitude conversion relations for earthquakes for which the method cannot be easily applied, such as those for which there is little or no digital data.

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Empirical evidence of frequency-dependent directivity effect for normal fault earthquakes: the case study of Central Italy

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In this study we calibrated a non-ergodic empirical model of the acceleration Fourier Amplitude Spectra in the frequency range from 0.5 to 25 Hz and performed a decomposition of the residuals aimed to investigate the anisotropic distribution of ground motion amplitudes due to fault rupture directivity.

As a case study, we focused on Central Italy, which represents an excellent and almost unique natural laboratory for earthquakes occurring on normal faults. We considered events in the magnitude range between 3.4 and 6.5 on a time frame 2008-2018. Overall, the dataset consists of more than 30’000 high-quality waveforms from 456 earthquakes and 460 stations within 120 km epicentral distance.

We adjusted the median prediction with several corrective terms accounting for source-, site- and path-effects. The remaining residuals are interpreted as source directivity contributions and modelled by the directivity function Cd.

We identified the events with directivity effects by fitting the residuals with the Cd function. About 50% of the events generates directivity-induced amplifications that can occur on a narrow band or persist over the entire frequency band. Generally, events with smaller magnitude (M < 4.0) show directivity amplification at higher frequencies (> 10 Hz), while the largest earthquakes exhibit more significant effects only at intermediate frequencies.

A clear relation is found between the directivity effects and the high-frequency source attenuation parameter, suggesting that the rupture mechanism may be complex also in case of small events. We also observed directivity not only during seismic sequences, but also in background seismicity. This finding could play a key role in understanding which structures can be responsible to trigger the main events in the Central Apennines.

As a future development, we aim to parameterize directivity as a function of magnitude and source parameters, and thus be explicitly implemented in ground motion modelling and scenario predictions.

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A time-domain earthquake full waveform moment tensor inversion system

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In this work, we developed a system to perform joint inversion of an earthquakes full moment tensor, its centroid location and centroid time. Our system is based on a time-domain full waveform inversion methodology. Performing the inversion in the time-domain allows us to utilize several source frequencies at once, unlike frequency-domain inversion. We utilized the levenberg-marquardt algorithm to perform a nonlinear optimization for all of the 10 parameters (6 for the moment tensor, 3 for the spatial locations and 1 for time). Our system outputs the estimated parameters of the earthquake, as well as the gauss-newton approximation of the hessian. The hessian allows our method to converge in only a few iterations, and also allows us to perform uncertainty analysis of the estimated parameters. We based our system in a fast time-domain forward simulation system recently developed in our group. This simulation system was programmed using the GLSL shading language, thus is able to run in the GPU of any relatively modern PC or notebook. Our system does not require saving to disk the forward wavefield, thus saving costly CPU-GPU memory bandwidth. We show the performance and accuracy of our system with an inversion of a well-known earthquake that took place in the Cuban shores in 2017.

ESC2021-S19-266

Earthquake moment magnitudes, apparent stress and spectra from seismic coda

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The scattered and late arriving energy in seismic coda can be used to obtain robust estimates of earthquake source spectra as described in Mayeda and Walter (1996) and Mayeda et al. (2003). Seismic coda provides an azimuthally averaged view of the source, reducing effects of mechanisms and directivity. Utilizing the amplitude of the long coda envelope as a measurement provides a stable average, similar to network averaging. These coda results are fairly insensitive to source and path heterogeneity. The method allows for a consistent measure of Mw over a broad range of event sizes rather than relying on magnitude relationships between Mw derived from waveform modeling and various narrowband magnitudes such as ML, MD, mb. A

challenge to its more widespread usage has been the lack of good software to implement the method. This is changing as we make progress on a Coda Calibration Tool (CCT). The CCT stems from a multi-year collaboration between LLNL and the U.S. National Data Center (NDC) scientists with the goal of developing a fast and easy Java-based, platform-independent, coda envelope calibration and processing tool. We present an overview of the tool and advantages of the method along with several calibration examples, all of which are freely available to the public via GitHub (https://github.com/LLNL/coda-calibration-tool/releases). Once a region is calibrated, the tool can then be used in routine processing to obtain stable source spectra and associated source information (e.g., Mw, radiated seismic energy, apparent stress, corner frequency, source discrimination). We are also exploring the use of envelope ratios to cancel path and site effects in combination with using the low- and high-frequency asymptotic ratio levels which are less sensitive to earthquake model choices as described in Walter et al (2017). We welcome future collaboration, testing and suggestions by the geophysical community using the CCT tools.

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Clustering-based stress inversions in the SE-Carpathians

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The external region of the Southeastern - Carpathians can be characterized by significant seismicity related to the ongoing geodynamic activity. Our research focuses on the examination of the stress relations in the Vrancea-zone and its surrounding area using focal mechanisms' inversion. To carry out stress inversions, we have applied different cluster analysis - methods such as the agglomerative hierarchical method, hierarchical density-based spatial clustering applications with noise (HDBSCAN) and an improved algorithm for the division of the investigated area in smaller subsets. We have taken into account the spatial coordinates and the rake angles selected from the used focal mechanism solutions.

Another important aspect of our work is the analysis of the efficiency of our advanced automated clustering programme and its comparison with the pre-existing declustering methods. Our algorithm has only one optional hyper-parameter which is applicable for the outlier detection.

On the one hand, we can state that our final results are in good agreement with the previously published information about the predominant impact of the compression tectonic style.

On the other hand, it is noteworthy that our clustering method proved to be eligible for the production of compact subareas for these investigations.

ESC2021-S19-395

Four granites in the lab: acoustic emission during the uniaxial loading

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Laboratory loading experiments on rock samples are proxies of earthquakes in nature, and acoustic emission (AE) is an eye into the rock to view its fracturing. Obviously the texture and grain size are the crucial parameters ruling the properties of a rock. We analyzed four different granites in the uniaxial loading to observe the way of their fracturing in terms of (i) the time sequence of the AE initiation and its clustering in time and space, and (ii) of the retrieval of the mode of the fracturing. The shear-tensile crack (STC) source model is advantageously used as a robust inversion tool. Concerning (i), from the seismicity distribution in space and time we evaluated the correlation integrals, and from them the fractal dimensions in space and time. While the temporal fractal dimension seems to be independent of the granite type, the spatial fractal dimension decreases slightly on the line from the fine-grain granite to that one with the largest grain size. It means that in the latter case the AE foci are clustered more than in the former one. Within the study (ii), we performed a detailed analysis of the errors of the retrieved mechanisms in terms of constructing the confidence regions related both to (a) the geometry/orientation of the mechanism and (b) its decomposition into shear vs. non-shear components. In this way we sorted the seismicity into shear events (S), shear-tensile (ST) and tensile events (T) and analyzed their occurrence and orientation changes in the course of the experiment.

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Introducing the SSA2py: Source-Scanning Algorithm in Python

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Back-projection methods constitute nowadays a great way to image the spatiotemporal behavior of the seismic source, especially for the high frequency part of the rupture, that successfully complements the source inversion classic methods. The simplicity of back-projection approach allows fast analysis of the seismic rupture, making possible the near-realtime identification of the rupture plane after a significant event. SSA2py is an emergent python based software that follows the Source-Scanning Algorithm (SSA), a back-projection implementation by Honn Kao and Shao-Ju Shan (2007). Following SSA, the brightness function is calculated for each spatiotemporal grid point near the hypocenter by stacking waveforms around the predicted traveltimes for the corresponding seismic phase and source–receiver paths. SSA2py generates images that depict the radiated energy from the rupture, for a specified time interval during and after the origin time. In order to increase the efficiency of the SSA2py the computation of brightness values in the code has been parallelized and adapted to run in GPU and CPU multiprocessing architectures. Furthermore, the orientation of the software in High Performance Computing and the interconnection with FDSN Compliant Web Services, enables the real-time usage of the methodology. The advantages and limitations of the developing software are explored using synthetic tests and waveform data from well recorded events.

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Resolution of weak earthquake focal mechanisms using a single station: potential and limitations

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The focal mechanism is a parameter of an earthquake which typically demands for observations distributed around the focus. If this is not at hand, only a limited information can be retrieved on the process of rupturing, e.g., its geometry (the orientation of the fault plane and the slip), but not its shear vs. non-shear nature. In the extreme case of monitoring with a single station, the mechanism can be estimated only if more seismic phases are available, in addition to the direct P and S waves. This is however not the case of weak seismic events, for which the station often records direct P and S waves only. Then, the information is limited severely, and the standard synthetics-to-data-matching does not allow unique determination even of the most simple and constrained seismological source model, namely the double-couple, due to an internal ambiguity of the inverse task solution. Nevertheless, we found that at least some important features of the focal mechanism may be retrieved. This happens for particular configurations of the focal mechanism orientation and the source-station direction:

• If the station lies in a direction within the quadrant of compressions, the T axis can be retrieved with a reasonable error, but the P axis remains ambiguous.
• Inversely, if the station lies in a direction within the quadrant of dilatations, there is a reasonable resolution of the P axis, while the T axis remains ambiguous.
• If the data are noisy – apart from extreme cases of a contamination, the chance to estimate the direction of the T/P axis remains; the closer is the source-station direction to the center of the quadrant of compressions/dilatations, the better is the resolution of the T/P axis.

The method was applied to selected weak earthquakes recorded by the 3-component borehole seismic station MDBI, Israel.

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A new method and code for apparent source-time functions based on empirical Green's functions

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Rupture directivity is a key element of earthquake source physics. The directivity can be inferred from apparent source-time functions (ASTF). Inaccuracies of velocity models can be overcome by employing empirical Green's functions (EGF), i.e. the so-called EGF records of small events. Most of the existing ASTF-EGF methods rely on spectral deconvolutions. We present a new, simple but highly reliable alternative technique, fully operating in the time domain. In our approach, the mainshock is represented as a weighted sum of shifted EGF records. The weights are obtained by linear waveform inversion of the mainshock record using the Non-Negative Least Square (NNLS) technique, constrained by a prescribed scalar seismic moment. Finally, assuming a suitable moment-rate time function of the EGF event (e.g. a triangle, whose duration depends on the largest inverted frequency), the summation of shifted triangles with the obtained weights provides the desired ASTF. As such, in the case of quality data, the resulting ASTF is implicitly positive, and the seismic moment is constant across the stations. The Fortran code and Gnuplot graphic package are used to model and visualize the ASTFs. The package can be used in an interactive mode, allowing an easy setup of a few free parameters, checking data quality and waveform fit, checking causality, and determining the duration of ASTF. The application of the method is illustrated on the Samos earthquake (M7) of 30 October 2020, which clearly indicated westward rupture propagation.

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Probabilistic constraints on earthquake moment tensor, source time function and depth

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The Earths seismicity is reported and monitored by a wide range of seismic monitoring agencies which report both worldwide and regional earthquake observations. Comparison of the earthquake hypocentre and moment tensor parameters, often reported by numerous agencies for a single earthquake, highlights the inherent uncertainty in these well understood earthquake parameters. Similarly, there is inherent uncertainty in less commonly constrained earthquake parameters such as the earthquake source time function. Here we present techniques proposed for a new global earthquake catalogue ISC-PPSM (International Seismological Centre – Probabilistic Point Source Model), that aims to constrain the range of earthquake point source models that can describe the body waves (P & SH waveforms) observed from a given moderate magnitude (Mw 5.8 – 7.2) earthquake. ISC-PPSM employs a probabilistic inversion strategy to constrain the earthquake point source (moment tensor, source time function and depth), along with their inherent uncertainties. The resulting ensemble of earthquake point source models allows trade-offs such as the interdependence of STF length and earthquake depth to be considered, adding new depth resolution, particularly to remote, shallow (< 40 km deep) earthquakes of moderate magnitude. Shallow earthquake depths from ISC-PPSM therefore can be used to constrain earthquake depths in the ISC-bulletin that would otherwise be uncertain or fixed to a default depth. As well as informing the ISC-bulletin, these routinely produced probabilistic constraints on source time functions of moderate magnitude earthquakes will provide a new resource for seismic source studies.

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Earthquake faulting complexity documented in the Sea of Marmara

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The Main Marmara Fault, the submerged segment of North Anatolian Fault in the Sea of Marmara, acts as a seismic gap imposing a serious risk to a metropolitan area. The Mw 5.7 Silivri earthquake occurred in 2019 to the north of the Main Marmara Fault, at the eastern tip of the Central Basin. The Silivri earthquake sequence illuminated some peculiarities of this complex, yet enigmatic zone. The moment tensor of the Mw 5.7 mainshock was dominated by a significant negative compensated linear vector dipole (CLVD) component, reflecting the fault complexity of the region. It was resolved as a compact doublet, collocated closely in space and time, both episodes pointing out shear faulting. It nucleated at western edge of the activated zone with a strike-slip faulting in accordance with the dextral Main Marmara Fault, and continued by rupturing a thrust-faulting eastern segment, almost equally partitioning released seismic moment in between these two segments. Due to crustal shortening at the eastern extremity of Central Basin, subsidiary thrust faulting is not unexpected, which was highlighted again by the latter thrust mechanism aftershocks. Nevertheless, this is a striking observation to be taken further into account in seismic and tsunami hazard studies.

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The 2020 Samos (Aegean Sea) M7 earthquake rupture using seismic and GNSS data

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On the 30th of October 2020 (11:51UTC) an earthquake of moment magnitude M7.0 occurred ~9 km offshore the northern coast of Samos Island (Aegen Sea, Greece). It caused severe damage on Samos island but also ~70 km away from the epicenter, in the metropolitan area of Izmir (Turkey). Two fatalities and 19 minor injuries were reported at Samos Island and 116 fatalities and over 1030 injuries in Izmir. Furthermore, the earthquake generated a strong tsunami and caused coseismic uplift of 20 to 35cm of the NW part of Samos Island. Samos northern coastline is controlled by E–W striking normal faults and the marginal fault of the Samos Basin is a structure of ~35 km length and 20-30 km width, inferred from sea topography. This fault named Kaystrios Fault was identified as the causative fault of this sequence. Using picks from regional strong motion and broad-band waveforms we relocated the mainshock and the aftershocks, moreover we used the closest strong-motion recordings to constrain the finite fault slip model. Slip inversion results suggest up-dip and westward propagation of the rupture. The westward rupture propagation is independently confirmed by the apparent source time functions inferred using the empirical Green's function method from near-regional broad-band and strong-motion waveforms. Static displacements measured by GNSS stations constrain near-surface slip of ~1 m, explaining the tsunami and the island uplift. The 2020 Samos event showed that normal faults bounding the basins in the back-arc Aegean region can host M7 earthquakes and when combined with tsunami generation, constitute a constant threat for the nearby coastal areas of both Greece and Turkey

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Earthquake collapse mechanisms and periodic, migrating seismicity during the 2018 summit collapse at Kīlauea caldera, Hawaii

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The 2018 Lower East Rift Zone eruption of Kīlauea volcano was accompanied by a remarkable and periodic succession of collapses in the summit region. Between May-August the eruption and collapse sequence included 54 earthquakes (M~5; M5s) observed worldwide, and over 45,000 intervening earthquakes (M≥0). We estimated seismic full moment tensors for the M5s and analyzed the spatiotemporal evolution of the intervening seismicity. The hypocenters were concentrated.

between 0-3 km depths and reveal arcuate bands that migrated outward by ~300 m (map view) and downward by ~200 m. The temporal evolution reveals almost daily successions of escalating earthquake swarms, followed by an M5, followed by a quiescent period. The moment tensors reveal consistent collapse mechanisms with vertical P-axis orientations. Poisson's ratios estimated from the moment tensors were

variable at first (v = 0.1 − 0.3) and from June 26 onward converged to v ~ 0.28, similar to loading cycles observed in lab experiments. The shallower collapses approximately follow the expanding contour of the crater, while deeper collapses aggregate first to the north of the previous crater and later to the east and south. We interpret that the magma storage complex beneath the summit region comprises a distributed plexus of cracks that progressively evacuated and underwent collapse as magma drained from the summit region to feed the eruption.

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New evidence of interconnection of the intermediate and deep seismicity with the metamorphic transformations in the Earth’s interior

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It is known that at the high pressure and temperature typical of the Earth's interior, the brittle failure fitting the generally accepted Reid's elastic rebound model cannot occur at depths exceeding 20-30 kilometers. Nevertheless, earthquakes occur at depths up to 700 km depth. The paradox is explained by the presence of the deep fluid decreasing the effective friction in rocks and/or by metamorphic processes occurring in the downgoing slabs. It was shown in experiments, that the presence of fluid and the solid-state transformations do mitigate the rock’s strength essentially. However, the experiments could not give unequivocal confirmation of these models because the conditions of deep earthquake occurrence could not be wholly sustained in the laboratory. No convincing geophysical evidence in favor of the models of the intermediate and the deep seismicity were found also. No essential difference was found between source characteristics of the deep and shallow earthquakes.

Here the examples are presented that the evident existence of high stress state and of major tectonic deformations is not a sufficient condition for the occurrence of earthquakes deeper than 30-40 km. It seems that an additional factor, associated with change in pressure and temperature and with the metamorphic transformations is required for the occurrence of these earthquakes. It was shown also that the mean values of a few source parameters of earthquakes (such as the normalized duration of seismic process, the ration of higher and lower frequency components in the earthquake source oscillations, and apparent stress values) change systematically with the depth. These changes can be interpreted as a decrease in an effective friction at depths of 20-30 km and in the interval 40-60 km depth, and as a stable tendency of increase of low-frequency (viscous) characteristics in earthquake sources at greater depths, down to the maximum depth of earthquakes occurrence.

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Session 20

New seismological workflows: from event detection to earthquake forecasting

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The 2016-2017 Central Italy Sequence: A Machine-Learning-Based High-Resolution Catalog of 900,000 Earthquakes

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The 2016-2017 central Italy seismic sequence occurred on an 80-km-long normal-fault system. The sequence initiated with the MW 6.0 Amatrice event on August 24th, 2016, followed by the Visso MW 5.9 event on October 26th and the Norcia MW 6.5 event on October 30th. We analyze continuous data from a dense network of 139 seismic stations to detect and locate earthquakes within this sequence. We use PhaseNet, a deep-neural-network-based picker, to pick P and S arrival times. Using these phase picks, we build a double-difference-relocated catalog of ~900,000 earthquakes spanning a one-year period. Our catalog contains an order of magnitude more events than the catalog routinely produced by the local earthquake monitoring agency. The detection rate of the smallest events shows daily fluctuation, suggesting that the smallest events detected by PhaseNet are close to the background noise level, and that the detection threshold fluctuates with diurnal changes in cultural noise level. We find that none of the largest events were preceded by clear acceleration of seismic activity around their hypocentral regions, and they all initiated at the edge of the aftershock zone of preceding events. These observations support the cascade model, where each earthquake loads its peripheral regions, spawning nucleations that occasionally initiate the rupture of a large magnitude event. Aftershock activity reveals the three-dimensional geometry of complex fault structures and how they were activated during the sequence. Activated faults in the northern and southern regions appear complementary to faults activated during the 1997 Colfiorito and 2009 L'Aquila sequences. Delineated major fault planes are relatively thick compared to estimated earthquake location uncertainties, and a large number of kilometer-long faults and diffuse seismicity were activated during the sequence. The rich details resolvable in this catalog will facilitate continued investigation of this energetic and well-recorded earthquake sequence.

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How do enhanced seismicity catalogs affect aftershock forecasts? A test during the 2016-2017 Central Italy Earthquake Sequence

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Artificial intelligence is transforming seismology with unprecedentedly rich earthquake catalogs. Recent developments in aftershock forecasting show that the performance of Coulomb Rate-and-State (CRS) models is becoming comparable to standard statistical Epidemic-Type Aftershock Sequence (ETAS) models, but only when the data quality is sufficiently detailed to represent sources and receiver mechanisms. In this context, the refined reconstructions of highly clustered seismicity patterns introduced by machine learning-derived seismic catalogs represent a unique opportunity to test to what extent they can be exploited to improve the performance of aftershock forecasts.

We present a retrospective test where we produce CRS and ETAS forecasts employing a recently released high-density catalog of the 2016-2017 Central Italy sequence, which reports ~400,000 events over the first

year. We consider the triggering contributions from 51,400 M1+ events to forecast the spatiotemporal occurrence of the 776 M3+ events recorded from 24 August 2016 to 24 February 2017. We assess the forecasts with likelihood-based tests introduced by the Collaboratory for the Study of Earthquake Predictability and compare their performance to a previous generation of CRS and ETAS models published for the same sequence by Mancini et al. (2019), whose dataset consisted solely of the real-time catalog above M=3.

The comparative evaluation of the two forecast generations shows a slight information loss and no obvious improvements in reproducing the aftershock spatial patterns. We perform sensitivity tests that illustrate how magnitude re-estimations in the enhanced catalog can negatively affect forecasts' likelihoods. Most importantly, we also observe that developing models using a finer spatial discretization reveals improved predictive skills instead.

These results suggest that to capture the highly clustered nature of triggered seismicity and to quantify the benefits that enhanced catalogs potentially bring to aftershock forecasting, their generation should be accompanied by the formulation of higher-resolution model development and testing strategies.

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Session 21

Physics of earthquake preparation process: from laboratory experiments to earthquake forecast

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Identification of precursory swarm pattern and location of future earthquake occurence in Himachal Pradesh, Himalaya

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The present investigation identified a precursory swarm pattern associated with major earthquakes in the Himachal Pradesh, Himalayas in an area bounded by 30.8^{o} N -33.2^{o} N and 77.4^{o} E-79.4^{o} E using seismically data from 1959 - 1991. It has been found that seismicity fluctuate in the order of low-high-low in two characteristic phases from 1959 to 1975 and 1976 to 1991 preceding major earthquakes.

The Kinnaur earthquake of January, 19, 1975 occurred in the eastern Himachal Pradesh have been found to be associated with a well-defined anomalous seismic activity both in space and time during April 12, 1963 to May 31, 1965 some 11 year and 9 months prior to the mainshock. The anomalous seismic activity episode was characterized by considerably high seismicity rate as compared to its preceding background seismicity episode (1959 to April 11, 1963) and following precursory gap episode (June 1, 1965 to January 18, 1975). During the second seismicity phase (1976 to 1991), an extremely well defined anomalous high seismic activity episode has been observed during July 6, 1976 to October 19, 1977 in the same area. This anomalous high seismicity phase has been preceded by an episode of low background seismicity rate (January to July 5, 1976) and is being followed by a long precursory gap period of abnormal low seismicity rate (October 20, 1977 onwards).

It is estimated that a shallow focus ($h \leq 40$ km) potential earthquake in the magnitude range 7-7.4 may be expected in the southern half part of the north- south trending preparatory area bounded by 31.4^{o} N – 32^{o} N and 78.3^{o} E - 78.8^{o} E. The anomalously low precursory quiescence period is still going on, and hence the study envisage the patterns of earthquake swarms may be measured as an important precursor for long-range earthquake hazards forecasting.

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Temporal variations in Gutenberg–Richter law parameter b-value depending on the depth and lateral position in the earth's crust of the Garm Region, Tajikistan

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Spatiotemporal variations in the b-value and in the minimum magnitude of a predicted earthquake (MPE) are studied in depending on the depth and lateral position of the earthquakes data.

The time variations in b-value estimated in the different depth intervals indicate that most of the “strong” events with M ≥ MPE were preceded by the significant time anomalies localized in the vicinity of the source depths of these earthquakes. The maximum amplitudes of these anomalies gravitate to the vicinity of the hypocenters of the strong earthquakes and decay with distance from the hypocenter. The time anomalies in the b-value are not accidental, which is demonstrated by their sufficient statistical representativeness (18 events). Based on the differential approach it is possible to estimate the source depth of a future strong earthquake.

The estimate of earthquake prediction quality on 38 “strong” earthquakes with M ≥ MPE that occurred in seven local regions during a 23-year observation period shows that in 84% of cases, the emergence of b-value anomalies is accompanied by the successful forecasts. The probability estimate of a medium-term forecast of the “strong” earthquakes with false alarms and missed events are taken into account is 71%.

The forecasting quality of the strong earthquakes substantially increases if the b-value time variations are monitored separately in the different depth intervals of the Earth’s crust. The front of the deformation waves emerging on certain time intervals in a number of the local regions of the sample has probably been detected. The deformation waves propagate with the velocities of 40–-50 km/yr with their front moving NE to SE.

The results of the study can be used for medium-term forecasting of the earthquakes with M ≥ MPE, for estimating the depth of the expected earthquake, and for overall seismic hazard assessment in the seismically active regions.

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About determination of the characteristic size of earthquakes focal zone

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Numerous works are devoted to the problem of the relationship between earthquake magnitude and the spatial characteristics of the source. The empirical relationships between source parameters and magnitude make it possible to theoretically understand how those or other model representations of processes in the earthquake source correspond to reality.

This paper presents the results of analysis of the spatial distribution of repeated shocks. Data from the world earthquake catalog of USGS/NEIC from 1973 to 2014 were used. Short time intervals, no more than 10 hours after the main shock, and distances from the epicenter of the main shock, no more than 5°, were considered. The dependence of the number of repeated shocks on the distance from the epicenter was studied. Two properties of the spatial distribution of repeated shocks have been identified.

The first property is that the curve describing spatial distribution has its maximum at a certain distance (approximately from 10 to 120 km) from the epicenter of the main shock. The logarithm of this distance is directly proportional to the magnitude of the main shock. The second property is that the position of the maximum does not depend on time, i.e., it is a stable spatial characteristic of the earthquake source. Based on these properties, a new way to determine the size of the rupture zone was proposed.

We received the regression relation between characteristic size of focal zone and the main shock magnitude lgLkm=0.43M-1.27. It corresponds well with the analogous relation of Yu. Riznichenko (1976) lgLkm=0.44M-1.29 but considerably differs from the relation lgLkm=0.67M-2.9 offered by D. Wells and K. Coppersmith (1994).

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Fracture mechanism surface layer of basalt and tonalite at friction

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The mechanism of fracture of surface layer of basalt and tonalite (granodiorite), with thickness of 1-2 mcm, under friction was investigated by fracto- and photoluminescence, Raman and infrared spectroscopy methods. The samples were taken from borehole drilled in Killari (Latur) earthquake area, Maharashtra, from depth of 209 m (basalt) and 614 m (tonalite). Tonalite consist of quartz and plagioclases (albite and labrador). The crystallographic lattices of these minerals contain many defects: Fe^{3+} ions, oxygen vacancies, electron traps and self-trapped excitons. Concentration of quartz crystals after friction of tonalite decreased by an order of magnitude. Concentration of plagioclase decreased 2-3 times in both rocks. The concentration of the defects increased several times in these minerals. Upon friction, microcracks with several nanometer sizes are formed in the surface layer of basalt and tonalite. Crack growth time is about several nanoseconds. The distribution of cracks by sizes obeys to known in seismology power-law relation (Gutenberg–Richter law) between the numbers of cracks and the energy of their formation. It is assumed that the result indicates the border where the power-law is still observed, because nanometers defects in the crystal lattices of minerals correspond to the dislocation scale.

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Initiation of unstable slips by elastic impulses

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A purpose of our work was to study the transition from metastable to unstable stages during stick-slip events. A series of laboratory experiments have been carried out with a model of two granite blocks under biaxial compression loading. The model was subjected to calibrated mechanical impacts (strokes) which induced elastic impulses. The mechanical stresses, strains, and acoustic emission were recorded. The strokes caused both large slips releasing the stresses down to their initial level and small slips which reduced the stresses by 5-8%. Before the large slips, the stages of speeding-up of the relative motion of the sides of the block contact was observed, similar to those emerging before the natural slips unrelated to the strokes. This feature was not universal: in some cases, the model recovered to the stationary state of the block contact without a large slip. All the slips occurred with a time delay after the stroke. The time delay was shorter when the energy of the blow was higher. With the shorter time delays, the small slip is more likely to occur. The energy of the impacts was by three orders of magnitude lower than the energy accumulated by the model, which points to the triggering mechanism of slip initiation. The series of strokes resulting in the small displacements partially reduced the accumulated energy and prevented the emergence of large motions such as the stick-slip events. If after a series of such blows a large sliding event still occurred, its energy was higher than in the slips unrelated to the impacts. The experiments revealed the difficulties in solving the problem of earthquake hazard reduction by elastic impacts.

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Pseudo-prospective forecasting of large earthquakes in circum-Pacific belt incorporating non-stationary modeling

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The noticeable increase in the occurrence of the great global (M≥8.0) earthquakes since 2004, provoked the interest for investigating the non-stationarity in their occurrence patterns, since a physical mechanism responsible for an apparent change in the seismicity rate remains indistinct. We show that persistent periods of increased seismicity exist, alternating with ones of relative seismic quiescence, and hence non–stationary point processes might be more appropriate than the stationary Poisson process for modeling the global earthquake occurrences. We apply a two-dimensional time-dependent point model, the Markovian Arrival Process (MAP), with intensity function, λt, driven by the current state of a hidden Markov process, Jt and we propose a two-step modeling procedure based on the temporal characteristics of the large earthquakes along the Pacific Rim during January 1918 – December 2020. In our study, the MAP is applied to the complete catalogs since we believe that each earthquake is considered distinct, with its own tectonic context and failure process, comprising equally important threat in terms of hazard. In addition, removing potential aftershocks would reduce the datasets size, decreasing the statistical power of the goodness of fit tests. Finally, we assess the long-term forecasting potential of the model on a 17-year testing period (2004-2020). The forecasting rates of the model are compared with the observed seismicity using a likelihood-based test and its performance is evaluated against renewal models with different interevent times distributions. Our results indicate that a MAP with varying seismicity rates can be significant for earthquake hazard assessment especially against the Poisson assumption.

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The earthquake-volcanic swarm of March 2020 near Tancítaro Volcano, Michoacán

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In 2020, the National Seismological Service (SSN) reported a seismic sequence that lasted from January 5th to February 25th, with 3,695 earthquakes located near Uruapan, Michoacán, Mexico. Eight events of the sequence exceeded an Md of 4.0. After preliminary analysis, it has been determined that it was most likely an outcome of magmatic processes related to the Tancítaro Volcano system in the Michoacán–Guanajuato Volcanic Field (MGVF), a part of the Trans-Mexican Volcanic Belt. Tancítaro has not had any activity during the Holocene, but it remains the most prominent stratovolcano in the region. Another volcanic edifice

nearby, Paricutín, is famous for being one of the few cases in recent times where a cinder cone grows from ground level to its peak height and produces an eruption (1943). Paricutín is widely regarded as monogenetic. The temporal evolution of the b-value of the Gutenberg-Richter relationship indicates that the swarm was a magmatic process, owing to the high values (b > 2.0) achieved during some temporal windows.

As it is a recurrent swarm since previous apparently related episodes had been reported to occur in the area in 1997, 1999, 2000, and during 2006, this sequence may be due to gradual increases in pressure in the ducts, followed by a sudden release of effort when reaching a critical level.

Comparisons are made with what happened during the episode before the East Kilauea Fracture Zone eruption, in Hawaii, during 2018, looking for essential elements for discrimination between an earthquake-volcanic episode that does not lead to an eruption and one that does.

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Large Earthquakes Recurrence Pattern in the Kefalonia Transform Fault Zone, Greece: Results from a physics-based simulator approach

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Large earthquakes (e.g. M≥6.2) recurrence pattern on specific faults or fault segments is one of the key parameters for constructing Earthquake Rupture Forecast (ERF) models. These models return the likelihood of the occurrence of a characteristic event in a specific time span and can be based on either a time-independent or a renewal assumption, representing an elastic rebound behavior.

Kefalonia Transform Fault Zone (KTFZ) is the major active boundary that bounds from the west the area of central Ionian Islands, namely Lefkada and Kefalonia, and it is associated with remarkably high seismic activity. This activity is characterized by frequent large (M≥6.0) earthquakes that have caused severe damage during the last six centuries. KTFZ continuously attracts the research interest and thus a detailed segmentation model is available. Although the number of large earthquakes (both historical and instrumental) is satisfactory enough for regional hazard studies, their number become limited when they are subdivided into subsets that are associated with specific fault segments. Consequently, the robust estimation of the mean recurrence time and discrimination among the appropriate statistical models is difficult to be constrained. The development of earthquake simulators overcomes these limitations, by long lasting earthquake catalogs.

In the current study, a physics-based simulator is applied in the KTFZ, after considering a detailed fault network model. The application is repeatedly implemented and with a wide range of input parameters, aiming at the definition of the most representative simulated catalog in respect to the observed regional seismicity. The most representative simulated catalog is in turn used for investigating the recurrence behavior of the strong earthquakes and assessing the best performance between the renewal model and the Poisson model, after considering both individual and multiple ruptured segments scenarios.

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Comparison of fore- and aftershock activity in the generalized vicinity of large earthquakes, rock bursts and acoustic emission events

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The fore- and aftershock sequences of individual strong earthquakes are very different. The method of examination of a generalized vicinity of a large earthquake (GVLE) was used (Rodkin, 2008; 2012) to average this variability and to reveal a typical regime of fore- and aftershock processes. By GVLE method the features of a power-law foreshock cascade and of the Utsu-Omori law were obtained in more details. Also, a uniform fore- and aftershock change in mean values of a number of parameters of the seismic regime (such as b-value, average magnitude and average depth of earthquakes, degree of consistency of orientation of seismic moments of individual events, and a few others) was revealed. The amplitudes of this anomaly increase in GVLE as a minus of logarithm of time from the generalized main event; we will call this anomaly as MLT anomaly.

The processes of earthquakes' destruction, rock bursts and acoustic emission (AE) are suggested to be similar. The GVLE method here was applied for rock bursts and AE data examination. For AE data, the analysis of fore- and aftershock activity was carried out previously in relation to events of scale of destruction of the whole sample. Here we examine sets of AE pulses around individual strong AE events.

For both the rock bursts and AE pulses the foreshock cascade and the Utsu-Omori law were found. The examples of realization of the MLT anomaly were found also. A significant difference, however, was found in the ratio of the intensities of the foreshock and aftershock cascades. For earthquakes, the intensity of the foreshock cascade is known to be essentially weaker than the aftershock cascade. For rock bursts and AE pulses, the intensity of these cascades was found to be similar. The difference is discussed.

ESC2021-S21-500

Aftershock duration and spatial expansion as a proxy of the coseismic slip: investigating seismic sequences in Greece

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The physics behind aftershock generation remain a critical issue in the scientific community with different underlying mechanisms proposed to interpret the seismological observations. The spatial distribution of aftershocks has been traditionally used to constrain the dimensions of the ruptured fault after the mainshock occurrence, whereas it has been attempted in the literature to identify a link between the aftershock zone dimensions and the mainshock magnitude. The development of advanced earthquake relocation techniques along with the introduction of modern finite-fault slip models have provided the opportunity to better quantify the spatial expansion of aftershocks in relation to the mainshock rupture area, the activation of multiple segments due to stress transfer and the prolongation of aftershock duration due to afterslip. The evolution of aftershocks in space and time is affected by multiple factors e.g. the mainshock magnitude, the

faulting style and stress changes. We attempt to employ a consistent procedure to identify the aftershock patterns in terms of their duration and productivity to assess their relationship with the faulting style and the mainshock rupture area. The relocated aftershock sequences of strong (Mw ≥ 6.0) earthquakes that occurred in Greece during the past few decades are used along with the coseismic rupture area derived from the processing of well-established slip models. The aftershock duration is considered as the first return of seismicity rate to the average background seismicity rate, through a statistically-based approach. The analysis is carried out for both the early aftershock phase and the entire aftershock activity separately, to reveal the possible effects of postseismic mechanisms that may affect the long-term aftershock evolution. The calculated coseismic Coulomb Stress are treated as a triggering mechanism of aftershock activity.

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Unified approach to evaluation of predicting critical events at different scale levels

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The parameters of the concentration of seismogenic faults in the source zone of one of the strong Kamchatka earthquakes and the concentration parameters of microcracks and acoustic signals in laboratory steel specimens before fracture are estimated. The basis for calculating the parameters was the relation proposed in (Zhurkov, Kuksenko, Slutsker, 1969), which relates the number and length of microcracks in laboratory specimens made of polymer materials. The parameter of the concentration of seismogenic faults Ksf, used in seismology to predict strong earthquakes (Zavyalov, 2006), was estimated based on data on the number and energy of seismic events occurring in the rocks. To estimate the parameters of microcracks concentration (Kc) in laboratory specimens and acoustic events (Kae) accompanying the fracture process, we used data from direct observation of microcrack patterns and analysis of acoustic emission events recorded during deformation of metal specimens before fracture (Botvina, Tyutin, Zharkova, 2006). The time dependences of the concentration parameters corresponding to a power-law relation with exponents ≃0.5-0.7 for the dependences Ksf and Kae and ≃2, for the time dependences of Kc, plotted using the patterns of microcracks in metal specimens of two steel, are obtained. The obtained time dependences can be used to analyze and model the fracture process at an early stage of damage development, as well as to predict a critical event - specimen fracture or an earthquake.

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An earthquake clustering model in North Aegean Area (Greece)

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A purely stochastic Epidemic-Type Aftershock Sequence (ETAS) model incorporating short-term earthquake clustering features is fitted to the crustal seismicity of North Aegean area in Greece. The basic assumption of

the model is that each earthquake is dealt as capable to be triggered by previous events and trigger subsequent ones. The application is performed in a catalog of earthquakes with M≥2.6 that occurred between January 2008 until May 2017 and compose the learning period. The aim of the current study is to retrospectively test the predictability efficiency of the ETAS model in the 2017 Lesvos earthquake (Mw6.4) and its aftershock sequence. The evolution of the sequence is tested both temporally and spatially by comparing the expected and observed number of events and by time-dependent seismicity maps, respectively.

The occurrence of one hundred twenty seven target events with M≥3.0 that occurred during June – July 2017 is under examination towards quantitative assessment. The evaluation of the performance of the model is carried out by means of three popular statistical tools: the Relative Operating Characteristic Diagram, the R-score, and the probability gain. The superiority of the ETAS model is testified with respect to a time-invariant Poisson model providing reliable forecasts of the target events.

ESC2021-S21-525

Proxy metrics of energy emission in the stress release model (SRM) applied in the Corinth Gulf (Greece)

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The stress release model (SRM), belonging in the category of self-correcting point processes, combines the gradual increase of the strain energy due to constant tectonic loading and its sudden release at the occurrence time of an earthquake (stick slip model). The seismically released strain energy is measured by the seismic moment of the certain earthquake, which is associated with the shear stress variation on the rupture area. Scaling relations between strain, seismic energy, stress drop, and seismic moment consist the basis for estimating the stress that is released during an earthquake. Supposing that the stress drop is proportional to some power 2η/3 of the energy released, different forms are derived. The comparison is mainly performed through information criteria between Benioff strain, corresponding to η=0.75, the seismic moment, corresponding to η=1.5, and all the values between them. A modeling is attempted for earthquakes with M≥5.2 occurring in the Corinth Gulf (Greece) during the period 1911 -2019, and also for synthetic data generated through a physics-based earthquake simulator applied to the local fault system as well as synthetic data produced through an epidemic model.

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Spatiotemporal regularities of stick-slip along the fault with asperities: Insight from laboratory experiments at the spring-block facility

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We present a study of stick-slip deformation mode of a model extended fault at the spring-block facility, as well as slip triggering by external fluid and electric impacts based on the analysis of acoustic emission (AE). We employed the long movable concrete block of 700 mm length and 125 mm width loaded by shear force from electromechanical drive through the calibrated spring, which slides intermittently on a fixed block. The

gouge layer of 2 mm thickness of quartz sand with grain size of 0.2 to 0.5 mm was placed between the blocks. The length of movable block made it possible to simulate the uneven contact of the movable and fixed blocks (a presence of asperities) and to trace the evolution of active sliding zones over time. For registration of local deformation processes in the gouge layer between the blocks during the preparation and occurrence of dynamic slips an eight-channel AE registration system Amsy-6 Vallen (Germany) was used equipped with broadband miniature M-31 Fujicera sensors (Japan) with a flat amplitude-frequency characteristic in a range of 300-800 kHz. The sensors were mounted on a fixed block symmetrically on both sides along the movable block. As a result of location of AE sources during the slow loading (10 μm/s) of the movable block through the spring up to dynamic fault rupture of the model fault, the formation of zones of clustering of AE sources is demonstrated, and the regularities of their change from slip to slip have been established.

Additionally, the spatial-temporal regularities of AE were investigated during the triggering of slip by injection of water into the gouge and electric current supplied to electrodes located in the central part of the movable block.

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An influence of strong magnetic storms on a recurrent period of repeating earthquakes

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We analyze a possibility of earthquakes (EQ) triggering by strong geomagnetic storms (GMS) generated a burst of geomagnetically-induced currents (GIC) in conductive crust faults. The laboratory experiments at a spring-block model demonstrated the triggering effect of electric current pulse injected into the model crust fault. In the laboratory experiments the electric triggering effect is most effective when the shear stresses in the model fault are 0.98-0.99 of the dynamic fault rupture stress. The mechanism of initiation of EQ by electric current is not yet fully understood. In this regard, it is necessary to continue the search for additional data confirming or rejecting the EQ triggering by strong GMS.

Catalogs of repeating EQs, which are repeated several times in the same place, with the same magnitude and with approximately the same recurrent are ideal databases for verification of an influence of strong GMS on EQ occurrence time. We used a catalog of repeating EQs of Central California to check a probability of changing the EQ recurrent intervals under an impact of strong GMS. The Monte Carlo method was used to compare the observed number of shortened recurrent intervals after geomagnetic disturbances with the distribution of this number estimated for randomized disturbance times.

The results indicate a weak correlation between GMS with geomagnetic index Kp=8-9 and reduced intervals of EQ recurrence. Nevertheless, it should be noted that the obtained correlation coefficient exceeds the analogous value calculated for dynamic impacts from distant EQ for the recurrent period by almost 2 times. Keeping in mind that dynamic EQ triggering is generally recognized, the obtained data may be considered as an additional confirmation of a possibility of EQ triggering by GMS.

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Efficiency of operational, distance prediction of the strong earthquakes for Greece from Azerbaijan - Based on the certified seismic forecasting technologies (only based the year-round monitoring of the seismogeodynamical regime of the fluids)

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In order to prevent the consequences of the seismic hazard in the Aegean Sea, which poses a great threat to the Greece and Turkish population, and the high-pressure gas pipeline "Greece-Italy", we suggest cooperation with the department "Integrated Geochemical Researches" of the RCSS at ANAS. From 2014 to the present (2021), we conduct daily operational assessment of the seismic situation (ml≥3.0) in the Caspian Sea and the territory of Azerbaijan and also operational, distance forecast of strong earthquakes (mb≥5.5) in various seismically active regions of the world, thanks to our certified technologies. Their scientific and practical novelty lies in the fact that for the first time in the world, the issues of operational, distance seismic forecasting for 1÷16 days have been solved. As a result, for the forecasted earthquake are determined "intervals" of the main seismological parameters: the coordinates, depth, magnitude and time of realization only on the basis of the "Database of year-round SFGD monitoring in Azerbaijan" for 1979-2021.

Here is an example. It is known that in 12.06.2017, occurred a strong earthquake in the Aegean Sea (mb=6.3). A timely forecast for this foci it was stated 6 days before its realization (07.06.2017) in the report No.101/02 ("Automated Technology No.1–"Identfire") for 06.06.2017-14.06.2017, also the correct forecast for this earthquake was made 06.06.2017 by "Automated Technology No.2–"Autolog" for 07.06.2017-15.06.2017. The distance from this foci to the objects of observation in Azerbaijan is Δ=1792÷1955 km, but however, the forecast parameters were correct: a) for the coordinates: in "Identfire" is Δ=150 km, and in "Autolog" is Δ=240 km; b) the "magnitude" in both technologies was predicted correctly mb=5.0÷5.9. c) the "realization time" also was determined correctly for 5÷6 days before the earthquake.

Positive statistics have a high level of reliability (80-85%), and our researches continue to the present day.

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Can earthquake simulators improve our understanding of the physics of earthquake preparation process?

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In the last decades, earthquake simulators have gained popularity to produce synthetic (simulated) catalogs of a huge number (even millions) of events, overpassing the limitations of completeness and duration affecting all catalogs of real observations. In this way, statistical analyses of simulated catalogs are by far more robust than those achievable by real ones. Nevertheless, criticism has been expressed against the effective utility of simulated catalogs. For instance, some seismologists have remarked that the algorithms

employed in earthquake simulators are based on oversimplified physical models, and intrinsically contain arbitrary assumptions that constitute serious obstacles for a reliable representation of the real seismicity.
This study is based on the experience collected with the application of earthquake simulators to seismic areas as in Italy, Greece, California and Japan, and the comparisons between the respective simulated and real catalogs, taking into account also the comments expressed by several reviewers of our papers. Here we present an overview of possible advantages and drawbacks in the application of earthquake simulators for the comprehension of earthquake preparation process and pertinent applications to earthquake hazard assessment.

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The 2020 European seismic hazard and risk model: new developments and future directions for seismic hazard and risk assessment in Europe

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Seismic risk maps of the Italian territory including local site effects based on experimental data and numerical simulation

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The last seismic risk maps developed for Italy (Dolce et al. 2020) are still affected by the shortcoming of not including site geological effects, limiting the assessment to the rock type of soil that might lead to unconservative results in the estimated losses. In this work, for the quantification of site effects, we used the results obtained by Mori et al. (2020) and Falcone et al. (under review), based on the Italian Seismic Microzonation studies. A set of 630 input motions was selected according to the reference seismic hazard for a return period of 475 years. About thirty million numerical simulations of seismic site response were performed adopting an equivalent linear approach. The amplification factors, calculated on a regular grid of 50x50 meters, adopting VS30 and input motion as proxies, have been assigned to the chief town of each of the 8092 Italian municipalities, assuming that the building stock is concentrated in that relatively small area. The PGA amplification factor ranges from 0.8 to 2.2 and shows an irregular pattern on the national territory, significantly modifying the hazard map and the prescriptions of the Italian building code. For the seismic risk assessment, we adopted the vulnerability/exposure model described in Rosti et al. (2020). The residential building stock was subdivided into 5 vulnerability classes (3 for masonry and 2 for concrete) derived from the national census data (ISTAT 2011) and further refined based on construction age and building height. The empirical fragility curves originated from damage data collected in the aftermath of Italian earthquakes from 1976 to 2012. As for the hazard assessment, the risk maps are considerably modified respect to the results presented in Dolce et al. (2020) increasing the expected losses (unusable buildings, homeless, casualties, direct economic losses). A municipality ranking, based on a risk index, was also implemented.

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ESRM20, the European Seismic Risk Model 2020

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Over the past 30 years the European scientific community has worked together on many aspects of seismic hazard and risk modelling. The SERA project (2017-2020) provided the first opportunity for the scientific community to integrate this research towards the development of a uniform seismic risk model for Europe. This model has been computed with open source software (OpenQuake-engine) and is now being openly released to the wider scientific community through the risk services of EFEHR, the European Facilities for Earthquake Hazard and Risk (www.efehr.org). Open access, without commercial restrictions, ensures that all aspects of the scientific methods and results are understood, available for critique, compliment, or reuse by all relevant stakeholders working on risk mitigation.

The European Seismic Risk Model (ESRM20) combines a model of the frequency of surface ground shaking due to earthquakes (hazard), with a model of the distribution of buildings (and their occupants) classified according to their physical attributes (exposure) with models that describe the propensity of these buildings to be damaged and suffer losses due earthquakes (vulnerability). The model can be used to estimate a

number of different quantitative risk metrics, including the average annual economic loss, loss of life (number of fatalities), and number of damaged buildings due to earthquakes in 44 European countries. This contribution will describe how the ESHM20 hazard model has been used in ESRM20 (in particular with regards to the modelling of epistemic uncertainties), will summarise the exposure and vulnerability models that have been used, and will provide an insight into the risk results and trends that are emerging from this model.

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Bringing the models to the people: the communication strategy behind the launch of the first seismic risk model for Europe and the next generation seismic hazard model

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Seismic risk information is becoming increasingly available for different regions and countries. Besides manifold challenges in conceptualizing, compiling, and computing seismic risk models there are also various difficulties associated to the dissemination of the results to interested stakeholders and the public. It has already been well documented for seismic hazard that non-experts often struggle to interpret the provided information correctly and to translate it into actionable information. Seismic risk adds a new dimension to this problematic including the difficulty of non-experts to differentiate between hazard and risk. However, by offering information on the actual consequences of earthquakes, seismic risk information also provides opportunities to significantly enhance non-experts' awareness.

In the context of the planning of the joint launch of the first seismic risk model for Europe and the next generation seismic hazard model we have assessed and aimed at addressing such difficulties and opportunities. This presentation will provide firsthand insights into the development process of the dissemination activities related to the launch of the European seismic hazard and risk models. This includes namely the communication strategy, product development, involvement of different stakeholders, and the validation of communication products. It will highlight the importance of each of these process steps to meet the needs of different user groups in the best possible way.

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Updated Historical and Instrumental European Earthquake Catalogues for the 2020 European Seismic Hazard Model (ESHM20)

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A comprehensive and harmonized earthquake catalogue is one of the most critical inputs needed for seismic hazard assessment. Previous initiatives to create such a catalogue for Europe yielded the SHARE European Earthquake Catalogue (SHEEC) and the European-Mediterranean Earthquake Catalogue (EMEC). Together these formed an archive of seismicity in Europe for the period 1000 AD to 2006 AD, proving fundamental for the creation of the 2013 European Seismic Hazard Model (ESHM13). For the ESHM20, both catalogues have been updated to integrate new data and scientific developments, extending the period of coverage closer to the present day.

The 1000 AD - 1899 AD part of the catalogue consists of the European Pre-Instrumental earthquake Catalogue (EPICA), compiled according to the same methodology of SHEEC, which implied the reassessment of earthquake parameters form intensity data with standardized procedures whenever possible, or adopting harmonized magnitudes from regional catalogues otherwise. For each earthquake, input data are selected form the European Archive of Historical Earthquake Data (AHEAD) according to the features of the dataset and independently from any national criteria. Thanks to new and updated datasets in AHEAD, the number of events increased significantly, and half of the over 5000 earthquakes in EPICA have updated parameters.

For the 1900 AD – 2014 AD era, the EMEC catalogue forms the primary information source, compiling data from available bulletins across Europe and defining a set of regionally dependent hierarchies and magnitude conversion relations to select the preferred location and moment magnitude estimate for each event. EMEC has been updated to include earthquakes from 2007 AD – 2014 AD, to reduce the threshold magnitude and to integrate recently compiled national catalogues, including F-CAT (France) and CPTI15 (Italy). The new European catalogue contains over 65,000 events with magnitude 3 and above, more than doubling the number available in the previous ESHM.

ESC2021-S22-150

Development of a Regionalised Ground Motion Model Logic Tree for the 2020 European Seismic Hazard Model

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Ground motion characterisation for seismic hazard analysis at a continental scale has been a key challenge in the construction of the 2020 European Seismic Hazard Model (ESHM20). Differences in the expected ground motion from earthquakes originating in each the diverse tectonic environments in Europe, and their respective epistemic and aleatory uncertainties, need to be appropriately quantified. The comprehensive ESHM20 ground motion model (GMM) logic tree is therefore developed around a data-driven scaled backbone concept. Here, a ground motion model is calibrated for each of the major tectonic region types (active shallow crustal, stable shield and subduction seismicity), and their corresponding epistemics uncertainty quantified using statistical distributions of adjustment factors that account for regional differences in source scaling and attenuation. The European Strong Motion Database provides a wealth of observations that have allowed us to not only calibrate a best fitting "backbone" ground motion model for active shallow and subduction seismicity, but also quantify regional differences within each of these regions. With these regional adjustments we can "tune" the backbone GMM logic tree to capture differences in ground motion within each of the major regions, and to define the maximum region-to-region variability, which used to quantify the epistemic uncertainty in many regions where data. However, the stable cratonic region of northeastern Europe does not provide sufficient data to apply even this data-driven approach, so here the scaled backbone GMM is derived by other means, capitalising on the outcomes of the NGA East project. These new approaches for developing the GMM logic tree create a new framework within which future updates to the seismic hazard model can be integrated. We show how subsequent adjustments can be made to improve the model where new data and other seismological insights emerge.

ESC2021-S22-151

Characterisation of Seismic Site Response on a Continental Scale for the 2020 European Seismic Risk Model

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The 2020 European Seismic Hazard Model (ESHM20) serves multiple purposes: the first to characterize the probability of strong shaking on rock as input into European seismic design codes, and the second to define the ground shaking input for estimation of earthquake losses in the 2020 European Seismic Risk Model (ESRM20). While construction of the ground motion model (GMM) logic tree for design codes concerns the prediction of strong motion only on reference rock (here Eurocode 8 class “A”), calculation of seismic risk requires integration of the local soil amplification. At a regional scale, detailed geophysical parameterisations of the site cannot be determined for each location. Instead, such parameters are inferred from suitable proxies that can be mapped at the scale and resolution needed for the risk calculation, such as Vs_{30} inferred from topographic slope (Wald & Allen, 2007).

For the ESRM20, a harmonised database of surface geology for Europe has been constructed, merging digital geological maps from the ProMine and OneGeologyEurope databases. Together with a 30” seamless topography and bathymetry dataset (GEBCO, 2014), these data sets were combined to define a European reference model of geology, slope and topographically-inferred Vs_{30}. Capitalising on this and recent European Strong Motion (ESM) database, site-specific random effects terms (δS2Ss) for more than 1000 stations across Europe were determined in the regression of the GMM. Using both the measured and inferred site properties for each of the stations, we create a data-driven site amplification model that is conditional on measured or inferred Vs_{30}, or directly on topographic slope and surface geology. This novel approach results in a pan-European site response model at the resolution required for ESRM20. It is both practical and consistent with the GMM of the ESHM20, and its uncertainties are calibrated to reflect those of the underlying site information.

ESC2021-S22-173

Development of a New Seismic Hazard Map of Slovenia (2021) and Interaction with the European Seismic Hazard Model ESHM20

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We conducted a new probabilistic seismic hazard model for Slovenia in accordance with the requirements of the existing and the forthcoming seismic design standards (CEN EC8), to replace the official 20-year-old design ground acceleration map. The new seismogenic source model includes smoothed seismicity, area

sources, and fault sources for the first time. Over the past seven years, ARSO and GeoZS have worked together to estimate the source parameters and their uncertainties, using all available seismological, geological, and seismotectonic data. To improve the fault source model in influential areas outside of Slovenia, we relied on the European Database of Seismogenic Faults (https://www.seismofaults.eu/).

We analysed the sensitivity of the main parameters and modeled them through a logic tree consisted of 1377 end-branches. Mean and fractile hazard maps of PGA and ten spectral accelerations, as well as hazard curves and spectra for selected locations, were calculated using OpenQuake software (Pagani et al, 2014). The mean PGA for the 475-year return period ranges from 0.10 to 0.35 g.

In parallel to the Slovenian PSHA, the 2020 update of the ESHM (Danciu et al, 2019) has been in course. Although a continental scale of the European model is too large to deal with details on a national level, its full documentation provides a very beneficial source of knowledge, and many methodological details have been discussed in the project's regional meetings. The new European ground motion model (Weatherill et al, 2020) is regionally parameterized, which allows its use in the Slovenian PSHA. On the other hand, Slovenian earthquake catalogue, fault, and area source models have been provided to the ESHM20, which empowers harmonization in bordering areas and allows more accurate regional calculations.

The main features and results of the new Slovenian seismic hazard model are shown, underlining the mutual knowledge and data flow with ESHM20.

ESC2021-S22-280

Overview of the Seismogenic Source Model for the 2020 European Seismic Hazard Model (ESHM20)

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Seismogenic sources depicting the spatial and temporal variability of the earthquake rate forecast are a critical component of the 2020 European Seismic Hazard Model (ESHM20). The model building process begins with compilation and cross border harmonization of multidisciplinary datasets (seismicity, geology, and tectonics), spatial delineation of seismogenic sources, and the description of methods and parameters of earthquake recurrence models, all representing the current state of knowledge and practice in seismic hazard assessment.

We present an overview of the seismogenic source model with a focus on their main properties and individual source characterizations, as well as giving an overall view of the uncertainties. The ESHM20 seismogenic source model consists of two main seismic source models that are fully cross-border-harmonized: an area source model and a model of seismically active faults combined with background-smoothed seismicity. Earthquake catalogues (both historical and instrumental) provide the input to estimate the earthquake rates and their uncertainties of area sources, while geologic slip-rates are used to characterize fault-specific earthquake recurrences. A power low adaptive kernel has been used for smoothing the background seismicity and two alternative magnitude frequency distributions are considered: a double-truncated

Gutenberg-Richter distributionand a Pareto distribution. Maximum magnitude models have been also updated in light of the updated datasets and the newly proposed seismotectonic zonation (Basili et al 2020).

We further summarize the testing framework to evaluate the statistical consistency of the estimated earthquake rate models with the observed rates of past and future earthquakes. Finally, we conclude with a description of the main logic tree, as used to evaluate the ground shaking hazard across the Pan-European region. All input datasets, seismogenic layers and input files are made available through the web-portal of the European Facilities for Earthquake Hazard and Risk (www.efehr.org).

ESC2021-S22-336

ESHM20: Unified catalog, declustering, magnitude of completeness, and sensitivity analyses

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We first present the features and summary statistics of the updated unified earthquake catalog, which is used as input for activity rate estimation for the European Seismic Hazard Model 2020 (ESHM20). We further compare this updated ESHM20 catalog to its ESHM13 version highlighting regions with the largest changes. We then present a suite of declustering methods that aim to divide earthquake catalogs into independent and clusters of triggered events. We demonstrate that the choice of declustering method and the corresponding parameters have a huge influence on the extent to which the catalogs are declustered or thinned out. For this, we make a comparison between three popular (window-based, Reasenberg's, and Zalliapin's) declustering methods. Within each declustering method themselves, we explore the sensitivity of the choice of different declustering parameters.

Finally, we present the improvement we made over the widely used temporal course of earthquake frequency (TCEF) method by incorporating standard statistical tests and combination with the maximum curvature method. This improved method, which allows for automatic detection of completeness time steps, is applied to the updated ESHM20 earthquake catalog enclosed within the 48 completeness superzones regions defined using expert elicitation. We find that completeness time steps identified using the proposed algorithm lead to more self-consistent frequency magnitude distributions compared to those resulting from the expert-driven magnitude of completeness time steps. This self-consistency is measured in terms of KS distance and shown to be significantly smaller than the expert-driven completeness time steps. Finally, we present the sensitivity of the method of the choices of different hyper-parameters such as choice of the declustering methods and their effect of the resulting frequency magnitude distribution within each completeness superzone.

ESC2021-S22-337

Smooth seismicity component of the seismogenic source model of ESHM20

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One of the three components of the ensemble seismogenic source model underlying the European Seismic Hazard Model 2020 is a seismicity rate forecast based on smoothing the location of declustered earthquakes (ESHM20). Making forecasts based on smoothed seismicity approach involves several choices. Some of the main decisions include (1) choice of the smoothing kernel (gaussian or power-law), (2) choice of adaptiveness of the bandwidth of the kernel, (3) choice of smoothing parameters, (4) choice of the declustering algorithm, and (5) choice of the declustering parameters. Training and validation sets are typically required to obtain the best possible combination of options. The training set is used to generate the smoothed seismicity model for a given combination of the options mentioned above, while the validation set is used to rank the options in terms of mutual information gain. We first propose a penalized-maximum-likelihood system that allows us to find optimal smoothing parameters using only the training set without invoking the need for a validation set. We then set up a pseudo-prospective test bench to validate the different combinations of choices we make to obtain the smoothed seismicity forecasts. In this test bench, we use all the data until the end of 2006 to train a series of smoothed seismicity models and compare their forecasting ability using the earthquakes between January 1, 2007, and December 31, 2015. Finally, we perform a long-term retrospective validation of different smoothed seismicity modeling against the large shocks (M>6) in the catalog. Based on these two validations, we recommend the hyper-parameter choices for obtaining the final smoothed seismicity model for ESHM20.

ESC2021-S22-366

The 2020 European Seismic Hazard Model (ESHM20) – Overview and results

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The 2020 updates of the European Seismic Hazard Model (ESHM20), was completed within the framework of Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (SERA) Project (Giardini et al 2019, www.sera-eu.org). The ESHM20 provides an advanced model built upon the most recent and up-to-date earthquake catalogues, compilation of crustal and subduction fault sources, development of new ground motion models, improvement of methods for data analysis, as well as development of the seismogenic source models to capture the intrinsic uncertainties.

In this contribution, we summarise the efforts towards developing the cross-border homogeneous seismic hazard model of Europe with focus on its main components, the computational model and results. The computational model combines various seismogenic source models and a backbone ground motion characteristic models for assessing the earthquake ground shaking at the pan-European scale. A wide range of results are available, ground shaking hazard maps, uniform hazard spectra and hazard curves for the entire region, for various statistical descriptors, median quantiles and weighted mean for a full range of response spectra ordinates (0.05s to 5s). All datasets, components and results are made available through the web-portal of the European Facilities for Earthquake Hazard and Risk (www.efehr.org). Direct comparison with previous model (i.e. ESHM13, Wössner et al 2015) and the national hazard models is given.

The new results are basis for further update and revision of the Eurocode 8 provisions and provide a homogeneous baseline input for the correct seismic safety assessment for critical industry, such as the energy infrastructures. Last but not least, the ESHM20 provides the input to the development of the first European Seismic Risk Model (ESRM20, Crowley et al 2020).

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Towards open, reproducible and transparent European seismic hazard and risk models. EFEHR vision and data policy

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It is our belief that the European seismic hazard and risk models ESHM and ESRM should be intended for use by the widest possible audience. This includes the possibility to reproduce the construction of the model, to use some or all of its datasets for the purpose of constructing new models, and to utilise the outputs of the model to the broadest possible set of applications including commercial usage.

In order to support this vision, the EFEHR (European Facilities for Earthquake Hazard and Risk) community has discussed and voted in its first general assembly the key principles which are driving the development and dissemination of the models: Reproducibility, Transparency, FAIR (Findable, Accessible, Interoperable and Reusable) outputs, respect of the intellectual property and clear scientific ownership.

The presentation will explain these founding principles and discuss their practical implications in terms of model development and integration of data or models developed by the seismological community. Examples will be given to illustrate the present complexity of developing such transparent and open hazard and risk models. In particular, we will describes the datasets which are compiled by the EFEHR Parties for the purposes of the model construction and full reproducibility: the compiled EMEC catalogue, the parametric historical catalogue, the final active fault database, the OpenQuake input files (source model, site model, Ground Motion Models, exposure and vulnerability input files).

Using these datasets as examples, we will illustrate the importance of data licences choices and the difficulties associated to unclear licence attributions. We will show that the application of the reproducibility and transparency principles implies that the data providers clearly state the license associated to their contribution and use preferably a CC-BY license or similarly compatible open data license.

ESC2021-S22-423

Testing PSHA estimations against observations: example in mainland France with the European Seismic Hazard Model ESHM20

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This study aims at comparing the hazard predictions from the European Seismic Hazard Model 2020 (Danciu et al. 2021) with the observations available in France. The observations considered are strong motion recordings at a set of instrumented sites (French network RAP-RESIF, lifetimes up to 20 years, Traversa et al. 2020), as well as synthetic accelerations predicted over ~250 years from an earthquake catalog coupled with the Kotha et al. (2020) ground-motion model at the same set of sites. Predictions and observations are compared at the level of the site (hazard curve) as well as at the level of the whole network (number of sites with exceedance over the total lifetime). The sites are selected depending on the distance between stations, and distributed throughout France. The comparison at the level of the whole network implies that the sites must be independent (no correlated ground motion).Two earthquake catalogs are used to predict the synthetic acceleration history at the sites, the EMEC catalog (Weatherill et al. 2021) and the catalog built for ESHM20. The results show that : 1) considering the RAP-RESIF recordings (total time window ~300 years considering 23 stations), the observed number of sites with exceedance falls within the predicted range for accelerations larger or equal to 0.07g; for lower levels the observation is in agreement with the predictions only if the Mmin of hazard calculations is lowered to Mw3.5; 2) considering the synthetic accelerations (total time window ~6000 years), the comparison of hazard curves at the site level shows that predicted rates can be equal, higher or lower than "observed" rates, nonetheless at the scale of the network "observations" are within predicted ranges. These results show that testing at the scale of a network can have a very low resolution power if the area sampled is too large.

ESC2021-S22-429

ESHM20 Main Datasets: crustal faults and subduction systems of the European Fault-Source Model 2020 (EFSM20)

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The probabilistic framework established for the 2020 European Seismic Hazard Model (ESHM20) requires a continent-wide seismogenic model based on input from earthquake catalogs, tectonic information, and active faulting. The development of the European Fault-Source Model (EFSM20) fulfills the requirements related to active faulting.

EFSM20 has two main categories of seismogenic faults: crustal faults and subduction systems. Crustal faults are meant to provide the hazard model with the spatial distribution and earthquake rate forecasts in a variety of tectonic settings, including onshore and offshore active plate margins and plate interiors. Subduction systems are meant to provide the hazard model with the spatial distribution and earthquake rate forecasts, both for slab interface and intraslab seismicity. The model covers an area that encompasses a buffer of 300 km around all target European countries (except for Overseas Countries and Territories, OTCs) and a maximum of 300 km depth for slabs.

The compilation of EFSM20 relies heavily on publicly available datasets, some voluntarily contributed datasets spanning large regions, and solicited local contributions in specific areas of interest. Currently, the EFSM20 compilation includes over 1,200 records of crustal faults for a total length of about 100,000 km and four subduction systems, namely the Gibraltar Arc, the Calabrian Arc, the Hellenic Arc, and the Cyprus Arc.
In this contribution, we present the curation of the main datasets and their associated information, the criteria for the prioritization and harmonization across the region, and the main strategy for transferring the earthquake fault-source input to the hazard modelers.

The final version of EFSM20, adopting FAIR data principles, will be made available through standard OGC web services published in the EFEHR (http://www.efehr.org) and SEISMOFAULTS.EU (https://www.seismofaults.eu) platforms, by which will later join the EPOS ICS-C portal (https://www.ics-c.epos-eu.org/).

ESC2021-S22-474

Evaluation of ground motion models for Vrancea inslab events

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Romania is an earthquake prone country, with earthquakes of moderate to high moment magnitude frequently occurring each century due to the deep seismogenic source in the Vrancea Region. The impact of such large magnitude earthquakes nucleating at large hypocentre depth (60 to 150km) transcends the national borders with significant damage being reported in neighboring countries (e.g. observed intensities of VII-VIII at more than 250 km epicentral distances during 7.7Mw 1940 event).

In this contribution, an exploratory analysis was conducted to evaluate the use of ground motion prediction models proposed for subduction zones in the context of the Vrancea deep seismogenic source. Residual analysis and statistical ranking (Scherbaum et al., 2004, 2009) were performed to evaluate selected models ((Sokolov et al., 2008; Skarlatoudis et al., 2013; Vacareanu et al., 2015; Abrahamson et al., 2015) with the latest ground motion recordings in the region. The dataset used in this analysis contains over 5000 geometric means of the horizontal components from 170 VRI events with Mw within 4 to 7.4. The strong motion data were recorded by 130 seismological stations of the Romanian National Seismic Network, since 1977.

In summary, the residual analysis indicates that four ground motion models are robust in depicting recorded data within the magnitude range (i.e. Mw > 5), however these models overestimate the ground shaking for lower magnitudes. The latter is of key importance, as the ground shaking predictability is relevant for the ShakeMap implementation in Romania. All the equations with the exception of Abrahamson et al., 2015 gave the highest capability to predict the PGA and SA at different periods. For peak ground velocity (PGV), Skarlatoudis et al.(2013) has high capability to predict while the others have lowest scores, thus this model might be a potential candidate of the ShakeMap system.

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Ground Motion Models for Vrancea Intermediate-Depth Earthquakes

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A newly compiled high-quality ground-shaking dataset of 207 intermediate-depth earthquakes recorded in Vrancea region of the south-eastern Carpathians - Romania was used to develop region-specific empirical predictive equations for various intensity measures, as peak ground acceleration, peak ground velocity and 5%-damped pseudo-spectral acceleration up to 10s. Beside common predictor variables (e.g. moment magnitude, depth, hypocentral distance and site conditions), additional distance scaling parameters were added to describe the specific attenuation pattern observed at the stations located not only on the back- and fore- but also along the Carpathian arc. In this model, we introduce a proxy measure for the site as the fundamental frequency of resonance to characterize the site response at each recording seismic station beside the soil classes. To additionally reduce the site-to-site variability, a non-ergodic methodology was considered, resulting in a lower standard deviation of about 25%.

Statistical evaluation of the newly proposed ground-motion models indicates robust performance compared to regional observations. The model shows significant improvements in describing the spatial variability (at different spectral ordinates), particularly for the fore-arc area of the Carpathians where a deep sedimentary basin is located. Furthermore, the model presented herein improves estimates of ground shaking at longer spectral ordinates (>1s) in agreement with the observations. The proposed ground-motion models are valid for hypocentral distances less than 500 km, depths over 70 km and within the moment magnitude range 4.0 to 7.4.

ESC2021-S22-538

Application of One Factor analysis in Probabilistic Seismic Hazard Assessment (PSHA): An example from the broader Aegean area

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A quantification of the main factors controlling Probabilistic Seismic Hazard Assessment (PSHA) for the broader Aegean area has not been made yet, even though several PSHA studies have been published for this area. To study the effect that each input factor (seismic source model, Ground Motion Prediction Equations – GMPEs, etc.) has on the PSHA analysis, a One Factor at A Time (OFAT) analysis has been performed, focusing on PGA and PGV for a mean return period of 50 years. For the study area we have considered 2 main controlling factors: a) Different areal seismicity source models, as well as the uncertainties related to these sources (seismicity rate uncertainty, fault plane solution variability, minimum and maximum magnitude considered for each source, etc.) and, b) Several GMPEs published either for the study area or for similar seismotectonic environments (together with the corresponding uncertainties).

The analysis has been performed for 40 sites distributed throughout the broader Aegean area and appropriate Tornado diagrams were generated for all sites. The spatial distribution of the PSHA sensitivity analysis, as recovered from the Tornado diagrams for each controlling factor, revealed several interesting features. For example, the recovered PGA values show a significant increase of variability for low seismicity areas, while a similar effect was not observed for PGV. Moreover, uncertainties in the maximum magnitude assessment are more than 200% larger for low seismicity areas in the Aegean (central-west Cyclades, Thrace), in comparison to high-seismicity regions (e.g. Hellenic Arc, North Aegean Trough).

Overall, the results indicate that the input parameters that mostly affect the PSHA variability in the study area are the selected GMPE and the uncertainties in the assigned G-R parameters (b and a) for the considered area sources, while other factors (source model, fault plane solutions, maximum Magnitude for each source, etc.) are less critical.

Probabilistic seismic hazard assessment of Sweden

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Sweden finds itself in a region with low-seismicity and sees very few damaging earthquakes. In terms of geology, most of the country lies on Precambrian crystalline rocks which are part of the 1 billion year old Fennoscandian shield. The seismicity in Sweden, on the other hand, is primarily driven by plate tectonics through the continental-scale ridge-push from the mid-Atlantic ridge, which is located a fair distance away towards the west. The post-glacial isostatic rebound is another driver of seismicity in Sweden and has been attributed to the genesis of the post-glacial faults that caused large earthquakes (~M8.0).

The modern-day seismicity in Sweden, however, is relatively benign, with only four M4+ events in last 20 years, and is mostly observed in the south-west around Lake Vänern, along the north-east coast near Skellefteå, and in the Norrbotten region. The rest of the country is relatively inactive. Seismicity is also limited by the span of instrumental observations, oldest of which have been recorded back in 1375. The seismic catalogs, however, have been more complete in the recent years with the magnitude completeness being about M0.5 for earthquakes between 2000 and 2020. In this study, we have decided to focus on the recent seismicity (2000-present) and have excluded older and paleoseismic observations.

We will present the challenges we faced when performing the PSHA study of Sweden, a stable continental region, using OpenQuake. We will discuss challenges pertaining to demarcating seismic source areas, estimating the Gutenberg–Richter (GR) a- and b-values, the maximum earthquake magnitude (Mmax), choosing appropriate ground motion models, building and assigning reasonable weights to the logic tree etc., and our approach to overcoming them. We will also present the results for peak ground acceleration (PGA) values, in the form of a hazard map, and other intensity measure types.

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Swarm-like and earthquake sequences driven by local transients in tectonic and volcanic areas

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A comparison among the 1992, 1999, and 2015 volcano-tectonic earthquake swarms at Deception Island volcano, Antarctica

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Deception Island volcano (South Shetland Islands, Antarctica) has undergone three episodes of seismic unrest since the last sequence of eruptions in 1967-1970. They happened in 1992, 1999, and 2015, and were characterized by intense swarms of volcano-tectonic earthquakes. These episodes have been interpreted as consequences of magmatic intrusions within the volcano plumbing system. However, the seismicity displays significant differences in terms of earthquake energy, temporal evolution, and spatial distribution, that lead us to think that the processes initiating the series are not exactly the same. The 1999 series comprised mostly small-magnitude earthquakes, produced regularly during 1.5 months. They were located at shallow depths (<4 km) within the caldera, mostly along a WSW-ENE trend that parallels the Bransfield rift. There was no precursory seismic activity, and a few months after the series onset the seismicity was back to normal levels. The 2015 series included earthquakes with larger magnitudes, occurring during 5 months in temporal clusters separated by aseismic periods. They were located at deeper levels (<10 km) with epicenters distributed all around Deception Island, at distances up to 30 km. Additionally, distal volcano-tectonic seismicity was reported SE of Livingston Island months before the 2015 series onset, and the seismicity at Deception Island remained anomalously high during a few years after the volcano-tectonic swarm. Taking also into account the limited data available for the 1992 unrest, we conclude that the 1992 and 1999 series were produced by shallow, short-lived, small-volume (~4·10^4 m3) magma intrusions that affected the shallowest part of the volcanic edifice. On the contrary, the 2015 series was consequence of a deep, long-lasting intrusion that involved a larger volume of ~5·10^6 m3 and modified the stress field of the whole volcanic edifice.

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Imaging complex faulting using a waveform-based clustering toolbox

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Clusty is an open-source seismicity clustering toolbox for the identification and characterization of active faults and fault networks. Applications range from seismic sequences in complex tectonic regions to studies of acoustic emissions. The toolbox includes several techniques to compute network similarities based on cross-correlations of waveforms recorded across a network of seismic stations. The density-based clustering approach allows the identification of events belonging to a common fault even over long segments. The clustering procedure is transparent, flexible and easy to tune with several graphical outputs visualizing the cluster properties, e.g. the homogeneity within each cluster or the differences between distinct clusters. We present results of two case-studies covering different magnitude scales: (1) The aftershock sequence of the Mw 6.9 2018 Zakynthos (Greece) Earthquake. Our clustering analysis reveals simultaneous slip on multiple faults of various geometries and kinematics within a complex tectonic setting at the western termination of the Hellenic Subduction System. Based on our results we are able to identify the causative fault planes of representative focal mechanisms and assign them to individual active faults. (2) A decameter-scale injection experiment conducted at Äspö Hard Rock Laboratory, Sweden. We apply the clustering toolbox to acoustic emissions detected during high-pressure water injections into granitic rock to gain insight into the growth of hydraulic fractures. The waveform-based clustering allows the identification of event clusters that cannot be

discriminated based on locations or origin times alone. By capitalizing on waveform similarities, even closely located active faults can be identified and characterized.

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Unraveling physical mechanisms driving spatio-temporal clustering of seismicity in the Armutlu peninsula (NW Turkey)

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A sub-branch of the North Anatolian Fault located below the Sea of Marmara, west of the 1999 M 7.4 Izmit earthquake rupture, crosses the northern part of the Armutlu peninsula in a region that hosts intense hydrothermal activity. In addition to likely hosting a M 6.3 normal faulting event in 1963 (the second largest recorded in the Marmara region), recent work has also documented cases of aseismic slip episodes. Here we use up to 30 synchronous seismic stations, including the SMARTnet seismic network, deployed in the northern part of the Armutlu peninsula from 25-01-2019 to 10-02-2020, and KOERI stations, to generate an enhanced seismicity catalog. We use matched-filter techniques that enable lowering the initial STA/LTA catalog magnitude of completeness from Mw~1.5 to 0.8. The aim of this work is to illuminate seismicity with unprecedented detail and identify the physical mechanisms driving it. Very intense seismicity occurs within a small area (latitude ~40.5-40.6, longitude ~28.9-29.0) south of Esenkoy, and forms distinct NW-SE aligned structures with hypocentral depths ranging from 5 to 13 km. The northeastern edge of the area with intense seismicity ruptured in a Mw 4.5 earthquake on 20-12-2018, prior to the SMARTnet installation. The temporal distribution of seismicity shows month-long periods with less than 10-20 events per day, alternating in week-long sequences where the daily event counts exceed 100-200 and can reach counts of up to ~450-500 events, such as the period in November 2019. We will present results on earthquake interaction and spatio-temporal clustering by applying both waveform-based and nearest-neighbor clustering approaches to investigate the mechanisms driving earthquake interactions and the primary deformation mechanisms (i.e. seismic vs aseismic slip). We will also present the results in the context of the regional seismotectonic setting and the implications for seismic hazard assessment.

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Earthquake swarms and migration patterns during the 2020-2021 seismic crisis in the western Corinth Gulf, Greece

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On December 23, 2020 a seismic crisis initiated in the western Corinth Gulf offshore Marathias, lasted several months, and generated thousands of small magnitude earthquakes. The area is well known for earthquake swarm occurrence and short-lived burst-like earthquake sequences, mostly triggered by crustal fluids. Here, we perform a detailed seismic analysis aiming to identifying earthquake swarms within the seismic crisis and define the characteristics (location, duration, etc.). Thanks to the dense seismic station coverage in the area, operated by the Hellenic Unified Seismological Network and Corinth Rift Laboratory, we relocate shallow seismicity and compile a high-resolution earthquake catalog containing ~1400 earthquakes spanning the first two months of the seismic crisis. We identify earthquake clusters by applying spatio-temporal criteria and

define the geometry (strike and dip) using principal component analysis. Our results are consistent with moment tensor solutions computed for the largest earthquake in each cluster. A striking feature of the seismic activity is the west-towards-east migration with a notable change in Vp/Vs values for each cluster. Furthermore, we looked for repeating earthquakes, i.e. highly similar earthquakes, and classify those into multiplets of repeating earthquakes. We find that each cluster contains burst-like, short interevent time, multiplets of repeating earthquakes, which could be related to aseismic slip or fluid migration. Overall, we show that the 2020-2021 seismic crisis consists of several earthquake clusters that bifurcate between swarm-like and mainshock-aftershock-like sequences. Reporting cases of complex earthquakes sequences, like this study, is of great importance in order to understand the underlying mechanism of earthquake swarms in tectonic environments.

ESC2021-S23-122

Non-DC earthquakes in 2017 swarm in Reykjanes Peninsula, SW Iceland: Sensitive indicator of volcano-tectonic movements at slow-spreading rift

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The analysis of the 2017 earthquake swarm along the obliquely divergent Reykjanes Peninsula plate boundary revealed the most frequent focal mechanisms corresponding to main activated fault, which relates to transform faulting of the North Atlantic Rift in Iceland. Detailed double-difference locations, focal mechanisms and non double-couple (non-DC) volumetric components of seismic moment tensors indicate an activation of three fault segments suggesting continuous interactions between tectonic and magmatic processes. They are related to inflation/deflation of a vertical magmatic dike and comprise: (1) shearing at strike-slip transform fault with left lateral motion; (2) collapses at normal faulting with negative volumetric components due to magma/fluid escape, and (3) shear tensile opening at oblique strike-slip faulting with positive volumetric components connected to flow of trapped over pressurized fluids. The identification of three regimes of complex volcano-tectonic evolution in divergent plate movement proves an enormous capability of the non DC volumetric components to map tectonic processes in such settings.

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Are spatiotemporal patterns of earthquake swarms at depth – repeating, lineaments, and migration, suggest fluid-driven mechanism?

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There were earthquake swarms during 2007–2011 in Berne, New York. Each swarm started with a small event (ML ~2) followed by a dozen shocks of ML 1.5–3.1. Those earthquakes showed no connection to the seismicity in Adirondacks to the north and in Lower Hudson Valley to the south. These shocks occurred at depths 15–20 km, hence they were in the lower crust or close to the upper- and lower-crust boundary where high temperature and pressure might not allow brittle failure. Shocks in each swarm occurred as a cluster and appeared as repeating earthquakes. High precision relocation of those shocks revealed that each swarm events align on a lineament but not connected to the previous swarms.

An earthquake swarm occurred in Haenam area in southwestern tip of Korean peninsula, a tectonically stable region. During April-May 2020, over 225 small earthquakes (ML < 3.1) have occurred in Haenam area. Accurate relocation of these shocks showed hypocenters on lineament that defined the fault plane at a depth of ~20 km. The hypocenters progressed toward up and east along the strike until the largest event occurred at shallower part of the fault plane where the migration was headed. This observation suggests a spreading of fluid flow that could induce the migratory behavior of the earthquake sequence. The idea of a fluid-driven earthquake swarm is supported by the presence of a seismic migration front, comparable to a hydraulic diffusivity of 0.012 m^2/s along the inherited structures showing a fault-fracture mesh geometry.

We compare these earthquake swarms at two different continental regions with similar tectonic setting to assess if these swarms can be interpreted as being driven by fluid. Our analysis of spatiotemporal patterns of the 2020 Haenam and 2007-2011 Berne earthquake sequences may be valuable to understand the earthquake swarms in intraplate stress fields.

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Slow-slip triggers the 2018 Mw 6.9 Zakynthos Earthquake at the NW termination of the Hellenic Subduction System

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Slow-slip events (SSEs) have been recorded at numerous subduction margins to precede large-magnitude earthquakes and potentially may be used as precursor indicators. Here, we combine geodetic, mechanical and Coulomb failure-stress models to explore the causal relationship between two SSEs and the 2018 Mw 6.9 Zakynthos Earthquake within the Hellenic Subduction System (HSS). We find that both SSEs, which occurred on the subduction plate-interface, were intimately linked to the Zakynthos mainshock and triggered long-range earthquake interactions that gradually destabilized the faults in the overriding plate. Coulomb wedge models further show that the forearc where the western Hellenic subduction terminates is in a mechanically fragile state, with stresses fluctuating around a near-neutral state between deviatoric compression and tension.

ESC2021-S23-298

Seismicity and earthquake swarms at ridge-transform fault systems in north Iceland

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Ridge-transform faults (RTFs) accommodate differential motion of the adjacent mid-ocean ridge segments at divergent plate boundaries where tectonic strain is released via large-magnitude earthquakes, swarm-like activity, creeping and, slow-slip transients. High temperature gradients and abundant fluid circulation produce frictional segmentation of RTFs that promotes aseismic and seismic slip release. Detailed observations of seismicity can help deducing the rheological fault characteristics of RTFs. The Tjörnes Fracture Zone (TFZ) in North Iceland is a RTF zone primarily consisting of two large structures, the Húsavík-

Flatey Fault (HFF) and the Grímsey Oblique Rift (GOR). The HFF is a right-lateral 100 km long strike-slip fault, while GOR includes multiple en-echelon faults that accommodate strain via both normal and strike-slip motion. Both structures have hosted earthquakes with magnitude 6-7. We analyzed the 1995-2021 seismicity using a relocated catalog. Seismicity is dominated by swarms on both two-faults system. The most energetic earthquake activity in the TFZ in over 40 years started on 20 June 2020 with Mw5.4 and 5.7 strike-slip earthquakes near the western end of the HFF that were followed next day by a Mw6 normal faulting event and intensive seismic activity in the following weeks. In general, seismic swarms on HFF and GOR start with break-out phase confined to a small patch of a fault that eventually migrates outward at speed of km/d. These spatial and temporal migrations are not compatible with simple high pore pressure diffusion processes. They rather indicate a more complex pressurization of the fault plane with reduction of effective normal stress likely promoted by transient increase of permeability. Under these conditions, a combination of seismic and aseismic slip release is possible and may suggests hidden aseismic slip underlying seismic swarms. However, no clear evidence has yet been found in GPS measurements of large transient slow-slip events along these two structures.

ESC2021-S23-312

Seismic and volcanic unrest at Svartsengi and Fagradalsfjall, Reykjanes Peninsula, Iceland: interaction of magmatic, tectonic and hydrothermal processes

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In January 2020, a rapid, large-scale uplift (14 km x 12 km) began at the Svartsengi geothermal field near Mt. Thorbjörn, on the plate boundary of the Reykjanes Peninsula, preceded by an intense earthquake swarm in the lower crust about 10 km east of the uplift centre, where one year later a volcanic fissure eruption built-up at Mt. Fagradalsfjall. We used a dense network of seismic data to detect and locate ~39.000 earthquakes over a period of 8 months. During this period, three uplift cycles occurred at Mt. Thorbjörn, each lasting several weeks and followed by periods of relatively rapid subsidence with clear trends in their duration and recurrence time. While the centre of the uplift remained stationary, the accompanying earthquake swarms at shallow depth indicated bilateral migrations from the centre along the N70°E striking plate boundary. The density of shallow earthquakes correlates in general with isolines of uplift, but is enhanced in belts with similar strike as pre-existing volcanic fissures. Other types of seismicity indicates the influx of magma at larger depth. We study the correlations between seismic swarms and unrest and the interaction between tectonic rifting, deep magmatic influx and the pressurization of hydrothermal aquifers at the brittle-ductile transition at 4 km depth.

ESC2021-S23-342

Analysis of the microseismicity of the submarine volcano Orca using data from the BRAVOSEIS network

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Orca seamount is located in the Bransfield Basin, between the South Shetland Islands and the Antarctic Peninsula. The volcano developed on an extensional rift produced by a combination of slab rollback at the South Shetland trench and transtensional motions between the Scotia and Antarctic plates. Between 2018 and 2020, the BRAVOSEIS project deployed a dense amphibious seismic network in the Bransfield region, comprising both land and ocean bottom seismometers (OBS), as well as moored hydrophones. In this work, we perform an analysis of the microseismicity recorded in the area of Orca volcano. The network used for this study is a subgroup of the BRAVOSEIS network, and consists of 15 OBS placed around Orca seamount and its SW rift, covering a region of about 20 km x 10 km, with inter-station distances of ~4 km. OBS data are organized, visualized and analyzed using the SEISAN software package. The identification of the microearthquakes is based on the observation of waveform, amplitude, duration, and spectral content of the signals. In this way we are able to discriminate local earthquakes from other types of signals produced by distant quakes, whales, icebergs, etc. Subsequently, the arrival times of the P and S waves are identified, in order to obtain the source locations using a suitable velocity model. The epicentral distribution and source depths may help us determine if these earthquakes are originated by the internal dynamics of Orca volcano, or else are related to the accommodation of tectonic stresses in the Bransfield rift. Additionally, we analyze their temporal evolution to understand if there are any changes that could be considered as precursors of the intense seismic swarm that started in September 2020 in the Orca volcano region.

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Pre-eruption March 2021 seismic activity on Reykjanes Peninsula, SW Iceland

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Iceland is situated on the onshore continuation of the Mid Atlantic Ridge, which separates the North American and the Eurasian plates and represents the only section of the Mid-Atlantic Ridge exposed above sea level. The Reykjanes Peninsula in SW Iceland forms an active oblique spreading segment of the Mid-Atlantic Ridge in the place where the rift bends to a landward continuation and connects the Mid-Atlantic Ridge to the Western Volcanic Zone. Such setting produces transtensional tectonics characterized by high seismicity, recent volcanism and high-temperature geothermal fields. The main tectonic features are a large number of NE-SW trending volcanic fissures forming crater rows, tindars and normal faults forming shallow grabens. The fissures and normal faults form a series of fissure swarms arranged in a right-stepping en-echelon pattern. In addition there are several N-S striking faults from large earthquakes.

The Fagradalsfjall volcanic system in the southern part of the Reykjanes Peninsula erupted during the last glaciation in Pleistocene and comprised eruptive fissures, cones and lava fields. At recent time, a strong seismic activity started near Fagradalsfjall in late February 2021 and was interpreted as an intrusion of magma at shallow depths based on surface deformation data. This activity led to the first present volcanic eruption in this area on 19 March 2021. We use seismic data recorded by local REYKJANET seismic network to reveal the geometry and migration patterns of the pre-eruption seismic activity. More than 30,000 earthquakes with ML magnitudes in the range from 0 to 5.7 (24th February 2021) were located. The hypocentres at depths 2-6 km form several bands of earthquake clusters exhibiting anomalous trends compared to previous activities. Detailed double-difference locations show distinct migration in space and time. They indicate the activation of several fault segments revealing interactions between tectonic and magmatic processes.

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A common model to explain similarities between injection-induced and natural earthquake swarms

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Fluid injections at depth can trigger seismic swarms and aseismic deformations. Similarly, some natural sequences of seismicity occur clustered in time and space, without a distinguishable mainshock. They are usually interpreted as driven by fluid and/or aseismic processes. Those seismic swarms, natural or injection-induced, present similarities in their behavior, such as a seismic front migration. However, the physical processes that drive both types of swarms, and that can explain such similarities are still poorly understood. The effective stress drop, defined as a ratio between seismic moment and cluster size, is weak for all swarms, when compared to usual earthquakes values, suggesting an aseismic moment release. We observe that the migration velocity of the swarms behaves like the rupture velocity of an aseismic slip. To explain those observations, we propose a mechanical model in which the fluid primarily induces an aseismic slip, which then triggers and drives seismicity within and on the edges of the active zone. This model is validated using a global and precise dataset of 18 swarms, from natural or induced origins, in different geological contexts. Consequently, our measurements of the migration velocity of the seismicity front, and of the effective stress drop for our swarms can be related to the ratio of seismic-to-aseismic moment. This sheds new light on the swarms driving process.

ESC2021-S23-457

Recent seismic swarm activity in the Lower Rhine Graben (Germany, The Netherlands)

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In 2021, three tectonic seismic swarms occurred in Lower Rhine Graben (LRG). The Rott low-magnitude seismic swarm (North Eifel, DE) started on 1 January 2021 close to the German-Belgian border near the western rim of the LRG. The two largest events occurred in January 2021 with local magnitudes of ML = 2.6 and were felt up to Aachen (~25 km radius). The sequence lasted for months and more than 100 seismic events were measured. During the Rott sequence, also in Voerendaal (NL) and Eschweiler (DE), in the middle of the LRG, swarm activity occurred. In this contribution we discuss swarm catalogue and statistics, waveform cross-correlation and relocation, focal mechanism and crustal stress pattern, intensity distribution of the largest events, and potential swarm causality and its link with LRG faults.

The magnitude-frequency distribution of the Rott sequence indicates a completeness magnitude between ML=0.2 and ML=0.7, with corresponding estimated Gutenberg-Richter b-values of ~0.7 and ~1.0, respectively. These low b-values are typical of swarms with a tectonic origin. Focal depths are mostly between 8 and 11 km (1-sigma location uncertainty). Epicenters are located 2 - 4 km east of the Laurensberg fault, a secondary LRG fault parallel to the main graben faults with documented throw of Cretaceous strata and present-day morphology to the west. However, the dip direction and dip angle are not well known, and it is possible that the observed throw reflects Late Cretaceous inversion. In that case, the Laurensberg fault,

which should currently have extensional kinematics similar to the other faults in the LRG, may well dip eastward and could potentially be related to the Rott sequence. If not, the causative structure remains unknown. Seismotectonic analysis of low-magnitude tectonic swarms helps in locating and understanding seismogenic faults in stable continental regions in NW Europe.

ESC2021-S23-489

Characterization of the microseismicity produced during the 2020 seismic series at Orca volcano, Antarctica

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Orca volcano is a submarine seamount located in the Bransfield Rift, Antarctica, between the South Shetland Islands and the Antarctic Peninsula. At the end of August 2020 there was a strong increase in seismic activity in this region, that has been continuing for several months. Between September 2020 and April 2021, the global catalogs report about 200 earthquakes near Orca volcano, with magnitudes larger than 4. Due to the scarcity of seismic stations in the area, the seismic series is obviously incomplete below magnitude 4. In the present work we use data from the permanent station JUBA (ASAIN network) located at the Carlini Base (ARG) on King George Island, just ~25 km northwest of Orca volcano, to complete this catalog. We initially select the period from August to December 2020. During the most intense part of the seismic series, many hundreds of earthquakes were recorded every day. Some of them have large magnitudes above 5, but most part are microearthquakes with very small magnitudes. In order to optimize the earthquake identification process, we use a semi-automated method based on a simple STA/LTA trigger algorithm. We expect that the number of microearthquakes may amount to many thousands. We characterize these seismic events by determining the P and S phase arrivals, S-P delays, maximum amplitudes, durations, and magnitudes. The analysis of their temporal distribution, hypocentral distance, and b-parameter of the frequency-magnitude relationship may shed some light on the possible relationship between the seismic series and the dynamics of Orca volcano and the Bransfield Rift.

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Comparative analysis of two low magnitude earthquake swarms in Calabria (Italy)

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We studied two seismic swarms occurred recently in Calabria, in the Mesima valley and near Albi. We located all earthquakes of each swarm, then we computed focal mechanism for as many events as possible considering the P and S wave polarity. For very small events an estimation of the focal mechanism was done also by comparison of wave polarity with those of larger events. A swarm of more than 150 small earthquakes occurred in the Mesima valley during May-June 2019, started with a mainshock of magnitude M3.6. The hypocenter distribution ranges from 16 km to 19 km depth, and it is elongated for about 2 km in the NE-SW direction. Albi seismic swarm occurred from January to March 2020, started with a M3.8 earthquake followed by more than 120 events in a month and many others later. Here we found a hypocenter distribution much more spread if compared with the Mesima valley swarm, with depth in the 6-12 km range and a broader epicenter area. We also performed relative location for the most of events of each swarm, and the results allowed to evaluate the seismogenetic volume, obtaining 12 km³ for Mesima valley swarm and 30-40 km³ for

Albi swarm. The predominant focal mechanism is normal for both swarms, but at Albi we observe broader ranges of strike, dip and rake angles. The aim of this comparative observation is the investigation of the seismogenetic volumes that produce low magnitude seismic swarms. Our results show that for Mesima valley the most of events fit well a fault, or a small fault system, characterized by NE strike and SE dipping. On the contrary, hypocenter distribution and focal mechanisms of Albi swarm suggest many small faults with different kinematics distributed in a larger volume. In both cases the active stress field is normal.

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Spatio-temporal evolution of the 2018 seismic sequences in São Miguel island (Azores)

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The Azores Archipelago is located on a privileged setting to study seismogenic process. Its location, on the triple junction between the Eurasia, African and North American plates and above a low-velocity (possibly hot) anomalous mantle, results in a high rate of both tectonic and fluid related seismic activity. The island of São Miguel is one of the most seismically active regions of the Azores archipelago. Here the seismicity is characterized by the occurrence of seismic swarms. In this work, we will focus on understanding the detailed spatio-temporal evolution of two different seismic sequences that occurred in the island of São Miguel in the year of 2018: 1) the February 2018 seismic sequence, and 2) a second seismic sequence that occurred between June and early July of 2018. Based on the local catalog, the first sequence has 342 events all above 10 km depth and with magnitudes lower that 3.5. The second sequence is characterized by 95 events, between 10 and 30 km depth with a maximum magnitude of 2.3. Inspection of the seismic data shows that the waveforms of the February 2018 have approximately half the duration of the waveform of the June/early July 2018 crisis. We carry out automatic scanning of continuous seismic data and detection of new seismic events using Lassie, an open-source python-based software for automatic earthquake detection. Lassie implements a delay-and-stack approach based on characteristic functions, where the hypocentral location is mapped by assessing the coherence of arrival time times at different stations. Based on waveform similarity, we run a clustering analysis on order to identify families of identical seismic events. The detailed spatio-temporal evolution of the sequences is presented.

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Deformation monitoring in South-Aegean volcanic areas from GNSS data analysis

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Monitoring volcanic surface deformation is a useful method to gain knowledge on the state of a volcano. Among various geodetic techniques applicable to volcano studies, the Global Navigation Satellite System (GNSS) is one of the most popular methods due to its clear advantages in continuity and high accuracy.

Dionysos Satellite Observatory (DSO) of the National Technical University of Athens (NTUA) in Greece has developed an automated processing scheme to accommodate the daily analysis of all available continuous GNSS stations in Greece. This daily analysis process is implemented for several years now, yielding results which enhance the understanding of the complicated tectonic setting of Greece.

This paper describes and discusses analysis results obtained from a subnetwork of continuous GPS/GNSS stations, located mainly in the Aegean, in the vicinity of the Hellenic South Aegean Volcanic Arc. Coordinate time series are presented, including sites installed on Santorini island during the well-known inflation episode which took place in 2011-2012.This effort constitutes a first approach on designing a Volcanic Arc monitoring platform. Processing strategies, implemented algorithms, instrumentation considerations and in-house designed software tools are discussed and evaluated. Future steps will be also discussed on the prospect of coupling and combining GPS/GNSS data with data collected from other sensors located nearby.

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Atmospheric and hydrological modulation of seismic sequences in the Azores

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This work investigates the connection between atmospheric and hydrological loads and crustal deformation in the Azores region, looking in particular for seasonal and inter-annual modulations of the earthquake occurrence rate caused by atmospheric pressure and rainfall variations. The work involves the manipulation and declustering of the Azores seismic catalogue, from 2008 to 2018. The New Madrid Seismic Zone (NMSZ), where a connection between enhanced seismicity and low rainfall rate in late summer had already been recognized, is used as a benchmark study site. Assuming a Gutenberg-Richter magnitude-frequency distribution the Azores catalogue is complete, down to, and including M1.9. Just as for the NMSZ, the seismicity rates in the Azores are higher during Summer/fall (JASO) and lower during Winter/Spring (JFMA), with a ratio JFMA/JASO significantly lower than 1. Monte Carlo simulations, used to check if the seasonal and inter-annual variations found in the seismicity pattern are statistically significant and not observed by chance, show that the probability of observing such a seasonality by chance is less than 1% for magnitude bands 1.9-2.7 and 3.8-5. The influence of extreme climatic events is investigated using a Jack-knife approach. The results demonstrate that the seasonal modulation of the seismicity rate is present at each calendar year and is not the consequence of single extreme climatic deviations.

The origin of the seasonal modulation will be investigated using methods of decomposition and reconstruction of geophysical time series (SSA and wavelet transform) to identify synchronous modes of oscillation, as well as correlation analysis to recognize common patterns in seismicity and atmospheric/water loads. The results provide a first assessment of cyclic variations in seismicity and its relationship with atmospheric disturbances in the Azores region.

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Improving the detection capability of the West Bohemian network by template matching approach

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During the West-Bohemia/Vogtland earthquake swarms thousands of events are detected within short periods of few days, whose preliminary location is provided by an automated procedure. The manually verified high quality catalog is provided with some delay and is usually less complete than the automatic one.

We developed a template matching procedure combined with differential time measurement and double difference location whose application in real time will allow to provide precise hypocentre locations for much larger data set than provided by the manual processing. Among others, the template matching approach includes flexible setting of the time difference between P and S waves which allows for event detection in a wider distance to the template's hypocentre. This makes the size of the template dataset small enough to allow for efficient detection process.

Our application of the template matching approach is aimed at identifying repeated activation of some patches during the swarms and weak background activity in the intermediate periods. Detecting and analyzing the repeating earthquakes will help revealing the continuing background activity and identifying fault areas that are active permanently. This will point to the possible sources of fluids or aseismic creep that are supposed to play significant role in swarm generation.

ESC2021-S23-565

Analysis of earthquake swarm dynamics using a 3D seismic array at the ICDP Eger Rift site in Landwüst (Vogtland, German-Czech border region)

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The ICDP project "Drilling the Eger Rift" focuses on the study of earthquake swarms in the German-Czech border region (Vogtland/ West Bohemia) . These swarms consist of small magnitude earthquakes (Ml<4) which are supposed to be related to the migration of mantle fluids within the crust. Within the project, we aim to improve the seismological observations of these events and related processes, especially for the high frequency content above 50 Hz. For this purpose, a seismic 3D array was recently installed in Landwüst (Vogtland) about 10 km West of the main earthquake swarm activity area in Novy Kostel (CZ). This 3D array consists of a surface array with 12 geophones and an aperture of 400 m and a borehole chain with 8 3-component geophones up to a depth of 400 m. The seismic traces are recorded with sampling rates between 400 Hz and 1000 Hz to ensure a high temporal resolution of the high frequency content of the swarm quakes. After the completion of the installation in November/ December 2020, several earthquake swarms have been recorded at the 3D array.

In this study, we present first results for the analysis of these earthquake swarms using the 3D array.

Besides a classical 2D frequency-wavenumber-analysis (fk-analysis) at a surface array, the combination with a borehole chain offers the possibility to estimate the full 3D slowness vector of an incoming wave front. Based on the obtained results with the 3D array, we analyse the temporal evolution of the earthquake swarms. Furthermore we investigate the implications for the spatial event distribution based on the parameters estimated using the 3D array such as backazimuth and incidence angle. Analysing the spatio-temporal behaviour of the small magnitude earthquakes will give indications for the dynamics of the underlying processes and their relation to fluid migration within the crust.

ESC2021-S23-603

Seismic activity in the Tetovo-Gostivar Epicentral Area in the period between November 2020 - March 2021

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The epicentral area Tetovo-Gostivar, located in the northern part of the Western Macedonian seismogenic zone, according to its geological structure and seismic activity, is one of the most clearly differentiated seismogenic zones, with a concentration of earthquakes throughout the zone.

The seismic activity of this epicentral area is characterized with rare occurrence of moderate earthquakes, magnitudes ML=5.6, to frequent weak earthquakes.

Tetovo-Gostivar epicentral area showed increased seismic activity in the period of November 2020 till March 2021with two moderate earthquakes, magnitudes of ML5.0 and epicentral intensity Io=V-VI EMS-1998 and four earthquakes, magnitudes ML4.0 and epicentral intensity Io=IV-V EMS-1998. They are result of tension between the marginal faults separating horst and depressions, under lateral pressures of the Sharsko-Pelister orogenic arc, originating from preneotectonic processes that continue today.

The solutions of the mechanisms of the two moderate earthquakes compared with the tectonic data of the active faults belonging to this epicenter area, indicate the activity of a normal fault, whose identification of the fault plane has the direction of extension WSW.

The results obtained from the performed seismic research are expected to be a solid basis in the research of the modern and the expected seismicity in the epicenter area.

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Physical and statistical models and pattern recognition techniques applied to foreshocks, aftershocks and multiplets at different scales, from laboratory experiments to real-scale observations

ESC2021-S24-149

NESTORE: A machine learning approach to strong following earthquake forecasting

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Strong earthquakes that occur after major events are extremely dangerous because they strike already damaged structures. Because in real time it is unclear whether a strong earthquake is the mainshock or if a stronger earthquake will follow, determining the likelihood of a strong following earthquake has clear civil protection implications.

We define an o-mainshock (operative mainshock) as the first event in a cluster with magnitude Mm greater than a given threshold, and we are interested in clusters with at least one subsequent earthquake with magnitude Ma≥Mm-1; we refer to these clusters as "type A," while to the others as "type B." NESTORE (NExt STrOng Related Earthquake) analyzes seismicity in the hours/days following the o-mainshock to extract features based on earthquake occurrences, frequency, and spatial and temporal distribution of earthquakes. From a few hours after the o-mainshock, it uses machine learning based on decision trees to estimate the probability to have an A cluster. The classification is repeated after a predetermined number of time intervals to see if it changes as more information becomes available. This enables the forecasting of potential danger in the region, even months before the next large earthquake.

For seismicity in southern California, the algorithm has an 80% hit rate and a 15% false alarm rate.
It correctly classifies well-known clusters such as Sierra Madre, Ridgecrest, and Whittier Narrows; for clusters with Mm≥5.8, we will show the classification over time in detail.
In addition, we developed a noise-resistant new version of the classifier, which we successfully applied to eight clusters in Northern California and Nevada.

ESC2021-S24-178

Analysis of recent seismic sequences in the Catalan Pyrenees (NE Iberian Peninsula)

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In the Pyrenees, around a thousand earthquakes of magnitude greater than or equal to 1.5 are registered each year, 90% of which have their epicenter in a strip of about 50 km around the Franco-Spanish-Andorran border. For this reason, collaboration between institutions on both sides of the border is essential for the study of seismicity in this area. The POCRISC project is an example of the cross-border collaboration that has been going on for decades, involving agencies from all three states. The project, which began in 2018 and is scheduled to last 4 years, is part of Axis 2 of the European POCTEFA program, whose objective is to promote adaptation to climate change and risk prevention and management.

Within the framework of the aforementioned project, we are carrying out an analysis of the most significant seismic sequences that occurred in our study area. We intend to identify certain patterns or trends that characterize these areas, detect anomalies, improve the understanding of the regional seismotectonics and generate valuable information for the improvement of seismic hazard studies.

The result of this work is aimed at the various actors involved in the management of the seismic crisis: authorities, civil protection and scientific community, as well as at the general population.

From each one of the seismic sequences, we are analyzing and comparing their patterns: its type, its space-time evolution, the geometry of the fault involved and the relationship between the number of large and small earthquakes. This preliminary work shows the results obtained for the seismic sequences of the Selva and Alt Urgell areas, both located in the Catalan Pyrenees, between 2016 and 2020.

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Physics-based simulation of sequences with foreshocks, aftershocks and multiplets in Italy

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We apply a newly developed version of physics-based earthquake simulator upon a seismogenic model of the Italian seismicity derived from version 3.2.1 of the Database of Individual Seismogenic Sources (DISS; http://diss.rm.ingv.it/diss/), selecting, and modifying where appropriate, all the fault systems that are recognized in the study area. In this way we can obtain synthetic catalogs spanning hundreds of thousands years, without the limitations that real catalogues suffer in terms of completeness, homogeneity and time duration. The resulting synthetic seismic catalogues exhibit typical magnitude, space and time features, which are comparable to those obtained by real observations. These features include, besides the frequency-magnitude distribution, also short- and medium-term earthquake clustering. A typical aspect of the observed seismicity in Italy, as well as elsewhere, is the occurrence of earthquake sequences characterized by multiple main shocks of similar magnitude. These sequences are different from the usual earthquake clusters and aftershock sequences, since they have at least two main shocks of similar magnitude. Therefore, special attention was devoted to verifying whether the simulated catalogue includes this notable aspect. For this purpose, a computer code was developed especially for this work to analyze the statistical relation between some physical parameters of the simulation algorithm and the productivity of seismic clusters and multiplets in the simulated catalogues. We found that the phenomenon of Coulomb stress transfer from causative to receiving source patches during an earthquake rupture has a critical role on the behavior of seismicity patterns in the simulated catalogues.

ESC2021-S24-311

Assessment of the seismic situation in the eastern coast of the Greece Aegean Sea prior to the earthquake of ML = 6.7 (30.10.2020)

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Detailed studies of the seismicity temporal variations have been carried out in the zone of the eastern coast of the Aegean Sea of Greece, where in the vicinity of the Samos island the earthquake with M = 6.7 (30.10. 2020) occurred. To describe the seismicity was the use of the Gutenberg-Richter law parameter b, the value of the released seismic energy lgE 2/3, and parameter seismic activity logN.

The results showed that, in the 15 years period prior to the event, bay-shaped forms of seismic parameters anomalies can be confidently identified. Moreover the past 50 years, in the same region, similar on forms anomalies duration of about 4-6 years have been observed for 5 more earthquakes M≥ 5.5.

It is shown that the amplitudes of temporal anomalies increase as the sample of data earthquakes approaches the depths of the sources of strong events preparation. It is concluded that the amplitude dependence of the temporal variations of seismic parameters on depth can be used to assess the depth of the future strong events.

In addition, studies of temporal variations in seismicity, in the vicinity of the islands Lesvos, Samos, and Kos, show that prior to occurred three earthquakes with a magnitude M ≥ 6.1, anomalous precursors of the studied parameters were observed in the period of about 10 years (2010-2020).

The spatiotemporal sequence of the occurrence of these events is explained on the basis of the formation concept of a seismic gap in this region. It is concluded that in the region between island Lesvos and Kos, the occurrence of earthquakes with M≥6.1 over the next 10-15 years is unlikely. At the same time, it is assumed that to the south of island Kos, in the island Rhodes area, a strong earthquake with M≥6.0 in the next 2-3 years is possible.

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Simulating the statistical properties of Earthquake Cycles by using a new version of the TREMOL Code

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Seismic cycle refers to the observation that earthquakes repeatedly rupture a given section of a fault. However, this "cycle", not being constant, is rather unpredictable. The cumulative motion along a fault patch through many seismic cycles is responsible for the often significant displacements that can be observed in a fault scarp. The fact that regional seismicity follows the Gutenberg-Richter power-law relation between the number of events and magnitude suggests that the crust is in a state of self-organized criticality SOC (Sammis and Smith, 1999). Laboratory experiments suggest that the b-value along a seismic cycle is inversely correlated with the regional stress conditions, where b-value continuously decreases with time as failure approaches (Riviere et al., 2018).

From a statistical point of view, the study of these hypotheses in real seismicity implies observing a large number of seismic cycles which is difficult due to our short recording time. However, the use of analogous numerical models with statistical patterns similar to those observed at Earth's scale becomes a useful tool to search for insight into the physical process behind the seismic cycles and the state of SOC.

Our objective is to couple a loading stage to the rupture stage into the model based on the sTochastic Rupture Earthquake MOdeL (TREMOL) to simulate the statistical properties in earthquake cycles. In particular, we focus on the magnitude characteristics and their correlation to the b-value along the process. The tectonic load is simulated using an Equal Load Sharing rule, where all the cells in the domain are equally assigned a value. A co-seismic rupture load is modelled using the Local Load Sharing rule including static stress transfer considerations. We aim to identify the parameters in the model that give statistical patterns similar to those expected/observed by theoretical and experimental approaches.

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Spatial and temporal variations of the earthquake clustering factor in Kamchatka region

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Mechanisms of stress transfer and probabilistic models have been widely investigated to explain earthquake clustering features. However, these approaches are still far from being able to link individual events and to determine the number of earthquakes caused by a single event. An alternative approach based on proximity functions allows to generate hierarchical clustering trees and to identify pairs of nearest-neighbours between consecutive levels of hierarchy. Then, the productivity of an earthquake is the number of events of the next level to which it is linked. To account for scale invariance in the triggering process we use a relative magnitude threshold DM. Recently it was shown that the relative productivity attached to each event is a random variable that follows an exponential distribution. The exponential rate of this distribution, called a clustering factor, does not depend on the magnitude of triggering events and systematically decreases with depth. Here we study spatial and temporal variations of the clustering factor in Kamchatka region. Preliminary analysis shows that large earthquakes usually occur in zones of higher clustering factor and they are preceded by a rise of the clustering factor. The study was partially by Ministry of Science and Higher Education, Project no. 14. W03.31.0033

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A Non-Extensive Statistical Physics view to the temporal properties of aftershocks related to major subduction zone earthquakes worldwide

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Large subduction zone earthquakes generate aftershock sequences which last over an extended period of time and affect wide spatial areas. Modeling aftershock sequences of large subduction zone earthquakes is of considerable importance for seismic-hazard assessments and earthquake risk mitigation.

In this work, we analyze the statistical properties of the temporal evolution of aftershock sequences that followed recent large subduction zone earthquakes worldwide from 1976 to 2020. We analyzed 77 aftershock sequences generated by mainshocks of M 7.0 and above and with focal depths less than 70km. To model their temporal behavior, we estimate the parameters of the modified Omori law. Their temporal scaling properties are further studied by looking into the probability distribution of the interevent times between the successive aftershocks, in terms of Non-Extensive Statistical Physics (NESP), a generalized statistical mechanics framework that characterizes complex systems with finite degrees of freedom, long-range interactions and self-organized criticality. We demonstrate the applicability of NESP in the cumulative distribution functions of interevent times and the presence of a crossover behavior from power-law ($q \neq 1$) to exponential ($q=1$) scaling for greater interevent times. Furthermore, most of the estimated q-values that

characterize the observed distributions are close to 1.65, suggesting a system with one degree of freedom. A discussion of the observed crossover behavior in terms of superstatistics is further provided.

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ESC2021-S24-420

A Non-Extensive Statistical Physics view to the temporal properties of the recent aftershock sequences of strong earthquakes in Greece

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Greece represents one of the most seismically active region in Europe. Over the last five years seismic activity in Greece presents a series of strong earthquakes, with magnitudes that reach up to Mw=7.0. Our analysis is focused on the recent strong events, as that of the Mw6.0 Elassona (03/03/2021), the Mw7.0 Samos (30/10/2020), the Mw5.1 Parnitha (19/07/2019), the Mw6.6 Zakynthos (25/10/2018), the Mw6.6 Kos (20/07/2017) and the Mw6.1 Mytilene(12/06/2017) earthquakes. In this work we study the temporal evolution of the aftershock sequences that were triggered by the mainshocks, based on the probability distributions of interevent times between the successive events. We approximate the observed distributions with a statistical mechanics model derived in the framework of Non-Extensive Statistical Physics (NESP). NESP provides an essential generalization of the Boltzmann-Gibbs statistical mechanics for complex systems in which memory effects, (multi)fractal geometries and long-range interactions, among other properties, are important. We show the applicability of NESP in the temporal evolution of the recent aftershock sequences in Greece and demonstrate the existence of a crossover behavior from power-law ($q\neq1$) to exponential ($q=1$) scaling for greater interevent times. We further discuss the observed crossover behavior in terms of superstatistics.

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Fault rupture evolution during the Emilia 2012 earthquake sequence (Northern Italy) by multiplets analysis

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This work has the aim to clarify the origin of the two Emilia mainshocks, occurred on 20 and 29 May 2012, respectively, by means of multiplets detection. Starting more than 5.300 relocated hypocenters, a cross correlation analysis was performed to search for waveforms similarity considering 44 permanent and temporary INGV seismic stations.

After a preliminary analysis on background seismic noise, performed in order to choice window signal characterized by a high signal to noise ratio, we select 12 reference stations, some of them in the epicentral area and others installed in far field. The cross correlation matrix were calculated considering the vertical component of each analyzed waveform, previously filtered between 2 and 10 Hz and considering a portion of windows ranging between 4 s and 6 s, in order to capture both P and S phases.

The calculated matrix allow us to obtain more than 1 million pair of events with an associated cross correlation coefficient. In order to group the pairs of analyzed events in multiplets, a minimum threshold of waveforms similarity has to be a priori imposed. The cross-correlation threshold is usually chosen trying to assure the highest number of multiplets and, in average, the highest number of components per multiplets. The analyses allows us to group 1.232 events in 209 multiplets, each of them related to a particular asperity, allow us to build a detailed history of the 2012 Emilia sequence. The relocated multiplets allow us to depict two sector of the fault plane, the shallower of which (from 5 km to 11 km) with a dip angle around 85° and the deeper (from 11 km to 15 km) with a dip angle around 40°.

ESC2021-S24-573

The concepts of complex network advance understanding of earthquake science II

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Recently, we have proposed the complex-network representation of seismicity (31st ESC2008). The seismic data are mapped to growing random networks. Vertices and edges of such networks correspond to coarse-grained events and event-event correlations, respectively. Yet unknown microscopic dynamics governing event-event correlations and fault-fault interactions is replaced by these edges. Global physical properties of seismicity can then be explored by examining its geometric (e.g., topological etc.), statistical and dynamical properties.

In this presentation, we discuss the dynamical evolution of the structure of earthquake network. In particular, we focus our attention on the evolution of the community structure, that is, how the whole network is partitioned into sub-networks, in which member vertices are densely interconnected with each other. Since main shocks play the role of hubs, they give an impact on the global structure of the network. In turn, it is expected that the community structure may characterize main shocks in a peculiar manner. We monitor the maximum value of the modularity measure, Q_{max}, of the earthquake networks constructed from the seismic data taken from California and Japan. We report the discovery of a universal behavior in the evolution of Q_{max} around main shocks. Q_{max} stays at a large value before a main shock, suddenly drops to a small value at the main shock, and then slowly increases to a large value again relatively slowly. This result implies that a main shock absorbs and merges communities to create a larger community. Thus, main shocks are characterized within the network approach in a peculiar manner. We also make a comment on this result in connection with the clustering structure of the earthquake networks.

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Research on array seismology and earthquake mechanisms at seismic experimental sites

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Seismic tremor monitoring using small-aperture arrays: application in Greece

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Seismic tremors, associated with slow slip, have been observed at several subduction zones and detachment faults worldwide. They are the result of superposition of a large number of microearthquakes and appear as emergent, noise-like but coherent signals, mainly within the 2-8 Hz frequency band. Their source is expected to be sustained at the same fault patch for several minutes to hours, days or even weeks, gradually migrating over time. In this work, we present a variety of array processing tools that were applied on partially overlapping sliding windows for the detection of tremor events, using the NORSAR proprietary software "Event Processor" (EP). The implemented techniques include: Classic FK analysis on each available component; Average correlation coefficient between traces aligned at the maximum FK-power time-delays; Time-domain delay-and-sum beamforming; Cross-correlation beamforming. We evaluate their efficiency with a "training dataset" from the SOOKE array in Cascadia, where tectonic tremors have been recorded at a known range of azimuths and slownesses. Candidate signals require a high degree of correlation and sustained measurements of similar azimuth and slowness for at least several minutes. We examine the sensitivity of each method at different bands and window lengths and apply the most promising methods to continuous recordings from two arrays in Greece: one located in Pylos, S. Peloponnese, close to the subduction interface of the Hellenic Arc, and another in Magoula, at the Western Corinth Gulf, a region of intense microseismic activity and a growing detachment. Preliminary results of candidate signals and their characterization are presented from both sites. The detection and location of such events may provide information on aseismic slip that could possibly accelerate the occurrence of significant earthquakes in the area of study. Acknowledgements: This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730900.

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Segmentation characteristics of the Longmenshan fault: Constrained from dense focal mechanism data

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In this paper, we determined 1495 focal mechanism solutions (FMS) in the nearly 10 years following Wenchuan earthquake (WCEQ) by the full waveform inversion, and proposed a "sliding window" scanning method to study the variation curves of numbers of different earthquake types along the Longmenshan fault (LMSF). Dense focal areas were finally divided into 9 segments and named S1~S9 from SW to NE. In addition, the damped linear inversion technique was employed to invert the regional stress field. Our results show: (1) Proportions of thrust, strike-slip and normal faulting are the highest in S1, S8 and S9, respectively. In the late stage of Wenchuan aftershocks, stress supplements and adjustments occurred generally along the LMSF. In

addition, post-seismic adjustment processes near WCEQ and in the far end of aftershock zone (AZ) are longer than that in the middle section, and the far end of AZ is related to the more complicated and intensive post-seismic adjustment processes. (2) Fault plane structures reveal the buried faults near WCEQ and in the far end of AZ as well as the south end of Huya fault (HYF) participated in the post-seismic activities. Dip angles range of 50°~70° in the areas with obvious thrust components and are generally larger than 60° in the areas with obvious strike-slip components. The increase of dip angles is coincided with narrowing of the width of AZ. (3) Segmentation differences of σ1 directions are deduced to cause the crustal tearing and mantle material upwelling in the seismic gap between WCEQ and LSEQ, buried faults near WCEQ and in the far end of AZ as well as abundant thrust earthquakes in the south end of HYF. Combined regional stress filed with previous geodetic surveys, we infer the uplift of Longmenshan may be mainly caused by the shortening and thickening of upper crust.

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Weak Off-fault Structures Revealed by Micro-seismicity along Xiaojiang Fault Zone (China) and Their Implications for Seismic Hazard Assessment

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The Xiaojiang Fault (XJF) Zone is located in the southeastern margin of the Tibetan Plateau and defines the boundary between the South China and Sichuan-Yunnan blocks. Seismic hazard assessment for XJF is of great scientific and public importance due to the frequent occurrence of large earthquakes. In this study, we utilized broadband seismic records to unravel the microseismic activities, in purpose of investigating the regional fault structures and slip behaviors. We detected and relocated more than 13,000 micro-seismic event, which reveals widespread off-fault structures showing conjugate geometry with the XJF. The majority area of the main fault is locked with a low level of seismicity. We conduct b-value calculation, cluster analysis, and repeating earthquake detections to unveil the spatial and temporal behavior of regional seismic activities. The area to the NE side of the Xiaojiang fault presents intensive off-fault seismicity, which is characterized by shallow earthquake depths, high b-value, and active repeaters. Regional clustering of micro-seismicity indicates the seismic activity of this area may be attributed to shallow slow-slip events that occurred on shallow off-fault structures. Combining with other seismological and hydrological evidence, we suggest this area is characterized by weak crustal strength and subject to distributed shear loading, which may produce "partially locked" stress status on XJF, thus works as a stress barrier. The along-strike variation of seismicity depth on XJF reveals a shallow creeping segment on the southern XJF between 25.25°N to 25.75°N. Results show that the events on the XJF are characterized by a low level of activity and low b-value in contrast to the high level of activity and high b-value on off-fault structures. The stress status on XJF is consistent with the previous estimation of a high moment deficit. We infer XJF has a high potential for a large earthquake in the near future.

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Bayesian algorithm for magnitude determination by merging multiple seismic networks

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The earthquake magnitude determined by a mobile seismic network usually differs from that given by a fixed network due to several factors, including the site response, the determination method, and the operation mode. This problem cannot be solved even by correcting the gauge function in the magnitude determination formula for the mobile network. A large number of small earthquakes recorded only by mobile networks that cannot be directly added to the standard catalogs. This paper aims to provide a novel fast calculation algorithm for solving this problem. Assuming that an observed magnitude follows the Gaussian distribution, with a mean of its unknown true value if it is determined by the fixed network, or with a mean as a linear function of its true value if it is given by a mobile network, we derive formulas for the posterior probability density function of the magnitude given its observation values by different networks, based on the Bayesian theorem. The parameters in these formulas can be estimated by use the maximum likelihood method from observations, and then can be used to calculate the posterior estimate of the earthquake magnitude, namely the 'revised magnitude'. This algorithm is applied to earthquake catalogs recorded by the Xichang (XC) mobile seismic network and by the China (CN) seismic network. We find that the 'revised magnitude' approximately follows a linear relationship against its observed value given by the CN seismic network, generally larger than its value measured by the XC seismic network. The proposed Bayesian method provides a fast algorithm for correcting the unprecise magnitudes determined by mobile networks, and simultaneously, improves the stability and accuracy of the magnitudes estimated by the fixed network by taking account of the consistency of the magnitudes measured by the mobile network.

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Velocity contrast along Anninghe-Zemuhe Fault, China determined from fault zone head waves

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We detected fault zone head waves (FZHWs) along Anninghe-Zemuhe fault (AZF) zone, and determined the cross-fault velocity contrast along AZF. FZHW is the seismic phase produced by bi-material interface, the moveout values between FZHW and direct-P wave arrivals reflect the average P-wave velocity contrast. The seismic velocity contrast indicates the inhomogeneity of elastic properties, which determine the rupture dynamics of faults and further influence its seismic hazard. AZF is part of eastern boundary of Sichuan-Yunnan block in China, which is located in the southeast of Tibet Plateau. There were 17 M>6~7 and 5 M7~8 earthquakes occurred historically in AZF since 1500s. In this study, we utilized 38 broad-band stations densely distributed along AZF from 2013-2018, and a catalog containing more than 12,000 events. FZHW is detected with a combination of automatic algorithm and manual inspection. The automatic detection is realized with two steps: (1) STA/LTA and kurtosis to capture the amplitude change between P and FZHW, and (2) principal component analysis (PCA) to measure the particle motion. There are 1169 candidate phases with potential FZHW passed the algorithm, which is further refined by manual inspections, considering inter-station features. Finally, we picked 689 FZHWs at 12 stations near the fault. The velocity contrasts range from ~3% along Northern AZF (29.0°-29.7°N) to ~8% along Southern AZF (26.7°-27.1°N), where the northeast side having faster P wave. However, we did not observe FZHW in the middle segment of AZF, suggesting small velocity difference. These observations provide evidence for the existence of a continuous bi-material interface on AZF with sharp velocity contrasts, which is also the key property to refine the seismic hazard in this area.

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Rayleigh wave tomography based on ambient noise in Xiaojiang fault zone

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Sichuan and Yunnan provinces are located on the east side of the collision zone between the Indian plate and the Eurasian plate. It is one of the most seismically active regions in continental China.

We collected nearly 9 years (from 2012 to 2020) of continuous vertical-component seismic recordings from several dense arrays covering the eastern boundary of Sichuan-Yunnan Block to investigate variation in local crustal velocity. These arrays were deployed at different times. We analyzed group velocity dispersion from 2s to 30s through cross-correlations of all the station pairs and extracted the Rayleigh wave Empirical Green Functions (EGFs). Preliminary results show that the phase velocity structure presents a significant difference between the east and west side of the fault zone, besides, in some major terrain regions, there are also noticeable anomaly in speed. By analyzing the time differences between the coda of EGFs, we can also investigate temporal changes of seismic velocity in the crust including seasonal variations and occurrence of nearby large earthquakes.

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Seismic hazard maps based on Neo-deterministic Seismic Hazard Assessment for China Seismic Experimental Site and adjacent areas

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Many devastating earthquakes claimed numerous casualties and severe property losses in the seismically active China Seismic Experimental Site area (CSES: 97.5°~105.5°E, 21°~32°N). A first-order seismic zoning based on Neo-deterministic Seismic Hazard Assessment (NDSHA) has been performed in CSES. The seismic hazard is expressed by maps of peak ground displacement (PGD), peak ground velocity (PGV) and design ground acceleration (DGA) values, extracted from synthetic seismograms computed at a regional scale. The values are mapped on a regular grid of 0.2° × 0.2° over the study area, grouped with a step consistent with effective information content of the used data. For the computation of synthetic seismograms, we considered all the available geophysical-geological-tectonic information as the input datasets, including historical and instrumental earthquake catalogues, seismogenic zones, seismogenic nodes, focal mechanisms, and geophysical structural models. The performance of our modelled ground motion was validated by available strong ground motion data (i.e., the 2008, May 12th Ms=8.0, Wenchuan and the 2013, April 20th Ms=7.0, Lushan earthquakes). Moreover, we tested and demonstrated the negligible influence of two large events (i.e., the 1920, December 16th Ms=8.5, Haiyuan and 1927, May 23th Ms=8.0, Gulang earthquakes) occurred 200~300km to the north boundary of the study area.

The obtained results indicate that the high seismic hazard of the region, with a particular attention to the areas (where DGA>0.6g), distributes around the main fault zones, e.g., the Longmenshan, Anninghe and Zemuhe Fault Zones. This first-order zoning of NDSHA scenarios may serve as a knowledge basis to support preparedness actions at large- to middle-scale in space (i.e., the whole mainland China and North China) and in time (i.e., from the Two Centenary Goals[1] to the 14th Five-Year Plan[2]).

1 http://www.china.org.cn/china/china_key_words/2014-11/18/content_34158771.htm. Last accessed on May 3, 2021.
http://en.qstheory.cn/The14thFiveYearPlan.html. Last accessed on May 3, 2021.

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Geospatial vulnerability mapping of multi-geohazard using the combination of historical inventory and CWS models in Qiaojia seismic zones, Yunnan Province

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Seismically affected areas with frequent geohazards covering the regional population and infrastructures always suffered severe post-disaster losses. The Qiaojia earthquake zone in Yunnan Province, as a part of the China Seismic Experimental Site (CSES), lies in the transition zone from the Wumeng Shan to the Zhaotong Basin with strong neotectonics and modern tectonic movements, which have induced multiple secondary hazard effects. The vulnerability assessment of geohazards has proved to be one of the most effective interventions for disaster mitigation, especially in a seismic setting, making it more necessary to evaluate the vulnerability for secondary geohazards.
In this work, the Contribution Weighting Superposition (CWS) model and 102 historical earthquake-induced landslides (Hongshiyan, Ganjiazhai, and Wangjiapo landslides occurred on August 3, 2014, e.g.,) were utilized to quantitatively assessing vulnerability in the Qiaojia areas. In general, the input of the model contains three dimensions: exposure, response, and resilience. At the same time, ten computational variables (Buildings, roads, and economic densities, e.g.,) related to infrastructure, population, economic and social development of the area were involved, covering a total area of 16,455.25 km2. Moreover, such databases were divided into 0.5 km × 0.5 km grids and superimposed with their weights depending on the disaster frequency. Finally, using the natural breaks method to delineate the vulnerable levels within the earthquake area.
The results revealed that the overall vulnerability grades of earthquake-induced geohazards in the region are moderate to very high, accounting for 53.69% of the total evaluation areas. Among them, the distribution is most concentrated in, Yanjin and Daguan counties. We also found a significant correlation between population, economic, infrastructure density, and vulnerability class, mainly dominating the impacts on the spatial distribution patterns of vulnerability ranking. The above characteristics may be regarded as references and guidelines for earthquake-induced geohazard policy formulation, construction planning, and prevention engineering projects.

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Seismicity and geodynamics in Corinth Gulf and other Near Fault Observatories

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A 10-year-long earthquake catalogue of area monitored by The Altotiberina Near Fault Observatory (Northern Apennines, Italy)

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We present a new earthquake catalogue 10-year-long (2010–2020) related to the activity of the Altotiberina (ATF) low-angle normal fault system (Northern Apennines of Italy). The analyzed seismicity has been recorded by the seismic network of The Altotiberina Near Fault Observatory (TABOO, Chiaraluce et al., 2014).

TABOO seismic network is a dense array of broad band and short period seismographs covering an area of 120×120 km2, including three vertical arrays deployed within shallow (250m deep) boreholes. Such a network configuration allows a very low detection threshold of seismic events, resulting in a catalogue composed by high-resolution locations of almost 100,000 events with a completeness magnitude ≈0.5 ML.

Up to May 2013, the earthquakes composing the revised catalogue were manually treated (Cattaneo et al., 2017; Cattaneo et al., 2019a, Cattaneo et al. 2019b), and since June 2013 an automatic procedure was adopted to detect phase arrival times (Spallarossa et al. 2014), where pick identification is checked and refined iteratively, based on the computation of earthquake locations using the Hypoellipse code (Lahr 1999). Arrival times were manually revised whenever the automatic procedure fails to reach a satisfying result. As of November 2016, an updated version of the automatic detection-location system has been adopted, Including an enhanced picking scheme (Scafidi et al., 2018) and NonLinLoc earthquake location code (Lomax et al., 2001).

Based on these starting locations and arrival times, we have been firstly working on the construction of a consistent MySQL-database. Then we worked on the improvement and homogenization of earthquake locations and magnitudes calculation for the new locations. Earthquake locations have been computed with the NonLinLoc, including newly estimated static station corrections.

The novel and comprehensive catalogue will be compared to the existing ones in terms of both earthquake locations and fault system geometries, in order to test its consistency and quality.

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The intense 2020 – 2021 earthquake swarm in Corinth gulf: faulting architecture and stress direction from high resolution microseismicity and focal mechanisms

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The recently activated faults and associated stress field acting in Corinth Gulf is investigated through an ongoing seismic crisis of several hundreds of small earthquakes (maximum magnitude M=5.4 on 17 February 2021). The study area is frequently visited by moderate earthquakes and triggered seismicity either in the form of main shock – aftershock sequence or earthquake swarms. The regional seismological network, which is adequately dense in the study area, provides high quality recordings that can be used to significantly improve the accuracy in location, focal mechanisms, and stress field estimation. We use a microearthquake data set that occurred from December 2020 to April 2021 by integrating data recorded by ~25 seismic stations of the regional seismological network at a maximum distance of 100 km. We obtained high–precision locations and focal mechanisms using the double–difference method and waveform inversion, respectively. The highly accurate seismicity locations and focal mechanisms illustrate the fine scale fault geometry of an ~10–km–long activated structure, east west striking and north dipping, and extensional kinematics. The seismicity does not occur on a single fault but rather on subparallel predominantly normal fault segments, and even smaller minor faults with slightly different strike and sense of slip. Previous works have established the prevalence of normal faulting in Corinth Gulf on east west trending normal faults consistent with the north–south extension. This new data set contributes additional analyses that highlight the features of the seismic swarm and support additional interpretation of the study area, and their relationship with major faults can be quantitatively assessed. These multiple minor normal fault segments are rooted into the more regional shallow–dipping detachment.

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Potential near fault observatory site in Slovenia: Overview of the area south of Postojna

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The area south from Postojna is composed mostly of karstified Mesozoic carbonate rocks and partly of non-karstified Eocene flysch. The landscape has numerous karst features as caves, poljes, dolines, uvalas, karst springs, ponors, karst periodical lakes etc. with typical karst groundwater drainage. Postojna flysch basin represents the hydrological divide between Adriatic and Black Sea watershed, which is connected with regional active tectonics. The study area holds several karst springs used for water supply and a military training area, altogether resulting in highly impact environmental protection issues.

The seismicity of the research area is moderate, where three known tectonic active faults in the Dinaric direction (NW-SE) intersect the region - Idrija, Predjama and Raša faults. However, the earthquake locations are not so reliable that they could be attributed with certainty to any known fault in the potential NFO area. To improve the accuracy of the locations and other earthquake parameters, the seismic network in the area was recently densified. In addition to four existing seismic stations of the national network, seven new ones were installed in 2020, all within an area of 26 km x 30 km. Thus, moderate earthquakes and seismic swarms can be continuously recorded, which makes possible to investigate the kinematics and dynamics of active faults in the area and consequently contributes to a more accurate development of the seismic hazard map. Moreover, one of seismic stations (owed by University of Trieste - Italy) is installed in Postojna Cave about 100 m below the surface since 2010. This increases the dimensions of the complex measurements in a cave where more years-long data sets of climatic (T, carbon dioxide, methane, radon, humidity, ventilation etc.) and micro-displacement monitoring are provided.

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Combined analysis of GNSS, gravity and historic surveying data at the Alkyonides fault

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Greece is located on the collision boundary of two tectonic plates (Eurasia and Africa-Nubia) and in combination with a dense network of active faults in its Earth's crust, becomes the most tectonically active country in Europe. The need to monitor and detect geodynamic changes is constant, especially near known faults that cause disastrous earthquakes over time. One of the most seismic areas which exhibits a long record of historical seismicity is the Corinth Gulf, where catastrophic earthquakes occurred in early 1981 with three successive destructive events originated from the Alkyonides fault. The deformation of the area is distributed along several E-W trending active normal faults and there is therefore, great need to understand the deformation mechanisms over time. The HMGS retains historic geodetic data from 1967 and 1981 surveying campaigns on specific triangulation points in the wider area of the Alkyonides fault. Similarly, SRSE had performed in 1992, a GPS campaign on selected triangulation pillars in the area. In 2020 HMGS has remeasured the same network following a GNSS survey campaign alongside with gravity measurements. The aim of this work is to evaluate the contribution of the campaign data to the monitoring of the ground deformation in the area. Specifically, use of all the above available geodetic data, i.e. surveying (1967, 1981), GPS/GNSS campaigns (1992, 2000) and gravity data are analyzed to derive displacement information over time. The paper describes the analysis using all the above available data and presents displacement results which in combination with other data may be used as a long-term earthquake prediction system for the area. Finally, for the first time, a network of trigonometric stations is set up by HMGS, which is proposed to be measured annually or at denser periods, for the monitoring of the displacements and the early warning of the fault activation.

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The recent 2020-2021 seismic crisis in the CRL area (Western Gulf of Corinth, Greece)

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In the past 20 years, the Corinth Rift Laboratory (CRL) network has been closely monitoring the Western Gulf of Corinth (WGoC), the area being the main focus of the Corinth Rift Near Fault Observatory.

The local seismological and geodetic network permitted the detection and location of microseismicity in high resolution, revealing complex sequences of seismic swarms exhibiting spatiotemporal migration related both to fluid diffusion and aseismic creep, which can trigger short and long-term repeating earthquakes. Herein, we investigate a seismic crisis that occurred in the WGoC between December 2020 and February 2021. An Mw=4.6 event initiated the sequence on 23 December 2020 at the northern shore, north of Aigion, while on 12 January 2021, an Mw=5.0 event activated structures further east, towards Trizonia Island. Finally, on 17 February 2021, an Mw=5.3 offshore event occurred ~4 km southwest of the previous clusters and ~3 km northeast of the Psathopyrgos fault, with aftershocks gradually migrating westwards, triggering another cluster on 25 – 28 February west of the fault, near its junction with the Rion-Patras fault zone. Moment tensor inversion revealed mainly normal faulting, while strike-slip mechanisms also appear, composing a complex tectonic regime in a region dominated by E-W normal faulting. We also retrieve information of past seismicity recorded by CRL to explore long-term seismogenic processes. We employ observations of co-seismic and transient deformation via geodesy to constrain the geometry and kinematics of the structures that hosted the major events of the sequence. Possible triggering mechanisms that have led to the second and third stages of the sequence are examined, including fluid migration or aseismic creep, along with Coulomb Stress transfer due to the Mw=5.3 event and its potential implications to the seismic hazard of the region.

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Real time earthquake analysis from strong motion data

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The seismicity of Romania is significantly affected by earthquakes produced by the Vrancea seismic source with intermediate depth events (3 shocks/century with magnitude Mw greater than 7.0). The seismic activity on the Romanian territory consists of both shallow and intermediate-depth earthquakes. The crustal seismicity is moderate and more scattered in comparison with the intermediate-depth one. The recent upgrade of the seismic network in Romania with high dynamic range accelerometers (114 real time seismic stations equipped with episensors) allows recording of moderate to large magnitude earthquakes at very close epicentral distances (less than 10-20 km). Strong motion data of high quality are also of help in increasing the effective preparation against seismic disasters, and the response during seismic emergencies. The consequent increased ability of a community to quickly recover from the damages of an earthquake thus contributes to lower the seismic risk, usually measured in term of casualties and economic losses.

During 2016 in this seismic area were recorded two moderate events with 5.7 magnitude in September respectively December. The purpose of this work consists mainly in the estimation of moment magnitude Mw using the strong motion network of the NIEP. A stable and automatic method was developed by Gallo et al.,2014, has been implemented in the real time data acquisition and processing system (ANTELOPE) to estimate in real time the seismic moment, the moment magnitude and the corner frequency of events recorded by accelerometers, using Andrews (1986) method applied to S waves. The main goals are the independent estimation of seismic moment and the common characterization for all events recorded by the strong motion network.

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The development of the Eger Near Fault observatory

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The Eger NFO is based on the achievements of the ICDP-Eger drilling project, which aims to build a comprehensive laboratory at depth for the study of the interrelations between the flow of mantle-derived magmatic fluids through the crust and their degassing at the surface, the occurrence and characteristic of crustal earthquake swarms, and the relation to the geo-biosphere.

The western Eger Rift in the Czech-German border region and the Cheb basin provides an ideal natural laboratory for such a purpose. It is characterized by frequent earthquake swarms and CO2 degassing that, according to the observations, correlates with the seismic activity. At present, continuing swarm activity has been observed since December 2020.

Two existing monitoring wells are being complemented by five new, distributed, shallow (<400 m) drill holes. A multi-level gas monitoring system isbeing bulit at the Hartoušov mofette field. Fluids from three adjacent boreholes F1, F2 and F3 - 30 m, 70 m, and 230 m deep - will be continuously monitored at high sampling rates for their fluid-geochemical properties and stable isotopes.

Drillings S1-S4 are prepared for seismological monitoring to reach a new level of high-frequency, near source observations of earthquake swarms and related phenomena, like seismic noise and tremors generated by fluid movements. Drilling of site S1 (Landwust), which is the only site located on German territory, was completed in August 2019 to a depth of 402 m and is equipped by 3D seismic array. Site S2 (Tisova/Kraslice) was drilled in November 2017 with depth 450 m. Site S3 (Studenec) was completed in December 2018 to a depth of 408. The drilling of S4 is planned in 2020 at one of the recently discovered Maars at the Czech German border region.

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The evaluation of tectonic stress within Vrancea slab (Romania) based on focal mechanism inversions

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The Vrancea seismic zone, located in the bend region of the South-Eastern Carpathians is an unique area with both crustal and intermediate-depth seismic activity and known as one of the most active seismic area in Europe. Moderate crustal seismicity is recorded all over the Carpathian region, but the far more intense activity occurs in a small subcrustal seismogenic volume beneath the SE-bend of the Carpathian arc with about 20×50 km lateral and 110 km vertical extent (70–180 km depth).

A unique slab geometry, likely preserved until the present, causes stress localization due to the slab bending and subsequent stress release resulting in large mantle earthquakes in the region.

The main focus of this study is to determine the focal mechanisms for events with a magnitude larger than 3, in the period 2005-2020 and evaluate the current stress field along the Vrancea subcrustal region, from the solutions obtained.

The main style of faulting for Vrancea subcrustal events presents a predominant reverse one, with two main earthquakes categories: the first one with the nodal planes oriented NE-SW parallel with the Carpathian Arc and the second one with the nodal planes oriented NW-SE perpendicular on the Carpathian Arc.

The results of stress inversion indicate a dominant reverse faulting style, with an average stress regime index of 2.9. The stress pattern shows similar partitioning with vertical extension in the slab and no preferred orientation in the overlying crust, showing a transition regime from the extensional regime in the Moesian Platform to the compressional regime in the Vrancea subcrustal zone.

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The Corinth Rift Laboratory (CRL) near fault observatory: History, infrastructure and research

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The Near Fault Observatories (NFO) are one of the European Plate Observing System (EPOS) thematic core services. According to EPOS definition, NFOs are long-term research infrastructures that intend to provide near-fault, multidisciplinary, high-resolution data, and high-level scientific products. NFOs are built for advancing scientific knowledge on seismogenesis, related processes and associated hazards. The Corinth Rift Laboratory (CRL) is one of EPOS's near-fault observatories, located at the western end of Corinth Gulf (Greece) which is one of the most active continental rift systems on Earth. This major research infrastructure started in the late '90s and was developed in the '00s, mainly based on funding from European projects. Monitoring arrays include seismic and GNSS networks, vertical and horizontal arrays, tiltmeters, strainmeters, dilatometers, tide-gauges, geochemical stations, etc. Significant seismic events have occurred within the CRL's research area in the past, causing extensive damage, the latest being the Aigion 1995 earthquake. Long-term microseismic monitoring in the area reveals that the earthquakes are clustered between depths of 5 and 10 km and define an active seismic layer that is dipping to the north. The major normal faults of the rift, which are mapped both onshore and offshore, are rooted in this layer. A huge number of earthquakes are continually recorded in the CRL area, of the order of some thousands per year. Quite often, microseismicity is expressed with earthquake swarms that are possibly connected with fluid migration. Fault creeping is also observed either by GNSS or strainmeters. Although CRL enters its third decade of existence, it has just started to reveal the Corinth Gulf fault mechanics. In the following years a lot of effort must be devoted to maintaining the infrastructure, processing of data, and advancing the research in the area.

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Focal mechanisms characterization for Vrancea crustal earthquakes during 2010-2020

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Vrancea region, has one of the most dynamic and complex seismic activity in Europe, with both crustal and intermediate depth earthquakes.

The main focus of this study is to determine and analyze focal mechanisms, for earthquakes recorded in Vrancea zone with crustal depths (<60km), although seismic activity is observed to be concentrated in the first 40 km, the seismic gap between 40 and 80 km might be explained by the opening between crust and mantle owing to ongoing delamination.

Shallow earthquakes are related to a series of fault systems and fractures located in the earth's crust in the area adjacent to the Carpathian Arc, faults activated by the tensions resulting from the movement of converging sub-plates in Vrancea region.

For this study we determined 82 focal mechanisms, using P wave polarities (FOCMEC code), from crustal depth earthquakes, occurred during 2010-2020. The retrieved fault plane solutions of the weaker earthquakes point both normal and reverse faulting with strike-slip components, the stress field is complex in the study area, showing a transition regime from the extensional regime in the Moesian Platform to the compressional regime in the Vrancea subcrustal zone.

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Anisotropic properties of the upper crust and spatiotemporal patterns of seismicity in the Western Gulf of Corinth (Greece)

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The Western Gulf of Corinth (WGoC), Central Greece, is one of the fastest expanding continental rifts in the world and a closely monitored site of high geophysical interest. In this work, we employ data from the Corinth Rift Laboratory network and the Hellenic Unified Seismological Network to investigate the anisotropic properties of the upper crust in the WGoC and the characteristics of microseismicity during the years 2013-2014. We combine the Eigenvalues and Cluster Analysis methods to perform automatic measurements of shear-wave splitting parameters in over 20 local stations in the WGoC. The mean fast split shear-wave (Sfast) polarisation directions (φ) are consistent with the orientation of local structures and the maximum horizontal component of regional stress. We also present a high-resolution relocated catalogue of earthquakes and explore its features in terms of clustering and distribution of hypocenters, highlighting the activated structures at depth, the spatiotemporal characteristics of seismicity, the geometrical features of major spatial groups, and focusing on migration patterns related to the diffusion of fluids or aseismic creep. The evolution of seismicity presented various patterns, including signs of fluid diffusion through the fracture network along the main axis of the gulf, accompanied by the occurrence of swarms or short-lived aftershock sequences with mainshocks of moderate magnitude. Changes of the normalised time-delays between the Sfast and Sslow split-shear waves, examined in conjunction with the observed seismicity, presented weak correlations of decreasing tn before the occurrence of moderate events or swarms.

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Present-day state of the late-interseismic central Alpine Fault, New Zealand: findings from the Deep Fault Drilling Project (DFDP) and surrounding geophysical networks

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The central Alpine Fault in the South Island of New Zealand is late in its <300-year typical interseismic period, having last ruptured in 1717 AD, and the conditional probability of a large (Mw~8) earthquake in the coming 50 years is estimated to be 75% (Howarth et al., Nature Geoscience, 2021). Since 2011, two phases of scientific drilling have been undertaken as part of the Deep Fault Drilling Project (DFDP), investigating both the long-term evolution of the fault and the much shorter-term mechanical, thermal, and hydrological processes associated with repeated large earthquakes. Instrumentation installed in the DFDP boreholes before, during and after drilling has included conventional seismic sensors, distributed acoustic sensing using a 900 m-long optical fibre, and multi-level temperature and pressure sensors. The borehole observatories are surrounded and augmented by the Southern Alps Microseismicity Borehole Array (SAMBA) and other regional seismic networks deployed near the central Alpine Fault, and at larger scales by the national geohazard monitoring network (GeoNet). Here, we review what these complementary datasets imply regarding the thermal and hydrogeological structure of the Alpine Fault, the late-interseismic distribution of microseismicity, and coseismic slip in future large earthquakes. We focus on the very high thermal gradient (c. 125^{o}C/km) revealed by DFDP drilling, the scale of the hydrogeologically active fault zone, and the thermal controls on present-day seismogenic cutoff depths — and thus the presumed distribution of coseismic slip in future large earthquakes — arising from ongoing rapid (1–8 mm/yr) exhumation of the Southern Alps.

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Data and services from the EPOS Near Fault Observatory community to face challenges in the understanding of faulting and earthquake processes

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Near Fault Observatories (NFO) in Europe are long-term, innovative infrastructures whose main goal is to understand the mechanical processes related to faulting and earthquake preparation and generation. They are based on very dense networks of multi-parametric (seismic, geodetic, geochemical and other geophysical sensors) that continuously monitor the underlying instability processes over a broad time scale in the near-source domain of active faults where large earthquakes (M>6) are expected in the future. Today, the NFO community represents six NFOs operating on different tectonic regimes in Europe, with deformation rates ranging from mm/yr to cm/yr. They include the plate boundary systems of Marmara Sea (MARMARA) and Corinth (CRL) rift; the Alto Tiberina (TABOO) and Irpinia (INFO) faults in the Apenninic area, the Valais (VALAIS) region in the Alps, and the Vrancea (VRANCEA) fault in the Carpathian Mountains.
In those regions, NFOs are targeted to track the evolution of fault systems and the earthquakes preparatory phase, through accurate location and characterization of micro-seismic and aseismic transients, the mapping

of the forcing mechanisms possibly influencing rupture development, and the characterization of the fluids involved in diffusive processes and rock interaction.
To face the challenge of understanding how faults slip, NFOs provide the scientific community with a broad variety of multidisciplinary data. Those data can be discovered and downloaded through the EPOS ICS web interface and the community dedicated portal FRIDGE, where available visualization and pre-processing tools can enable data discovery and availability. Case studies and best practices at NFOs based on those data and related services will be presented. Also, the community has developed the testing facility CREW to provide a framework for testing and comparison of the performances of Earthquake Early Warning software, enabling the setup of decision modules tailored for specific applications.

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Micro-seismicity, seismic-wave velocity model and earthquake clustering in the Akarnanian region (western Greece)

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Characterized for the first time in 2013, the Island Akarnanian Block (IAB) is a micro-plate located in the western Greece. This micro-plate accommodates the deformation in between larger scale tectonic structures as the Gulf of Corinth (South-East), the Hellenic subduction (South) and the Apulian collision (West).

We started a micro-seismic survey (MADAM) at the end of 2015 with a dense seismological network over the area, between the Gulf of Patras and the Gulf of Amvrakikos. In order to obtain precise locations of the recorded events, we better constrained the local velocity model. In fact, several velocity models (local or regional) have been proposed for this area. However, the velocity model generally used by the scientific community remains the Hasslinger 98 velocity model. This model, nevertheless, is only constrain for the North part of the region and raises some questions about its physical meaning, mainly due to a low velocity layer between 4 and 7 km-depth.

Thanks to our seismological network and permanent networks of the Corinth Rift Laboratory and the Hellenic Unified Seismic Network, we collected and analysed a huge quantity of data acquired between October 2015 and December 2017. Those analyses of more than 10,000 events allowed us to develop a new and robust local velocity model, which is consistent with the seismic data and the geophysical observations.

The observed seismic activity is characterized by the presence of numerous clusters. The clusters are analysed in detail by relative relocations in order to appraise their physical processes and their possible implications in the faults activity to finally have a better understanding of the deformation mode(s) of the IAB micro-plate.

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Networks and open data in seismology the example of HELPOS: Hellenic plate observing system

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Geodynamics and Seismic Hazard in the Lasithi Region (East Crete, Greece)

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Lasithi is the easternmost regional unit on Crete Island (Greece), south of which lies the Hellenic Arc. The broader offshore study area is dominated by reverse and strike-slip faulting, while active normal faults are mapped on land. Detailed research of the latter suggests that the northern and central parts of Lasithi are affected by arc-parallel extension, whereas the southern part by arc-normal extension. The NNE-SSW striking faults are more frequent and form horst and graben or half-graben macro-structures. These faults usually consist of two or more segments accompanied by post-glacial scarps and clear evidence of recent reactivations. The E-W to ESE-WNW striking faults are scarcer and mainly observed along the southern coastal zone or offshore. Compared to the NNE-SSW striking faults, they present fewer active traces. Significant events in the study area include the 8th August 1303 (M≈8.0) earthquake and the 1st July 2009 (Mw=6.4) earthquake that occurred south of Crete, triggering a small tsunami. A probabilistic seismic hazard assessment is performed for Lasithi. The maximum expected ground motion parameters (PGA, PGV and PGD) for mean return periods of 475 and 950 years are determined using the SHARE 2013 zones and seismicity model. Greek GMPEs that consider type of faulting and soil type were applied. Optimum results are obtained through a logic-tree approach, which considers all GMPEs. The Uniform Hazard Spectrum for Agios Nikolaos, Sitia and Ierapetra are presented and compared with the elastic design spectra proposed by the Greek National Building Code and Eurocode 8.

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The HeLPOS Fault Database: a new contribution to seismic hazard assessment in Greece

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In seismically-active regions such as Greece, the mapping of active faults is a key step to assess seismic hazards and evaluate deterministic ground motion scenarios for infrastructure works, pipeline designs and other constructions of critical importance. Here, we present a comprehensive database of active onshore and offshore faults in Greece based on existing studies and GIS geospatial mapping using geological, geophysical, seismological and geomorphological criteria. The design and population of the database follows

the NOAFaults concept http://doi.org/10.5281/zenodo.3483136 and development in ARCGIS environment. The HELPOS database includes over 550 faults with simplified (linear) traces and lengths between 8 – 108 km (onshore part) together with their corresponding 2D rupture planes. Additional information includes parametric data such as maximum expected magnitude, slip rate, length, width, strike, dip angle, last seismic event, rupture depth (to top-fault) and fault kinematics. A particular aim of the HELPOS Fault database has been an update of the seismic sources model for the seismic hazard assessment of Greece considering shallow earthquakes, which involves modeling surface fault traces in terms of seismic sources at depth.

The fault database is a major contribution to HELPOS with applications among others in volcano-tectonic settings, urban planning, paleoseismology, landscape processes, and in the study of active tectonics, deformation and interactions between overriding plate (Aegean) faults and the Hellenic subduction.

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An application for real-time PGA and PGR online vector maps in Greece

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Real-time ShakeMap and PAGER applications are among the most useful tools for rapid and accurate estimation of seismic ground motion and damage assessment based on the combination of recorded timeseries and Ground Motion Prediction Equations (GMPEs). An application depicting in real-time Peak Ground Acceleration (PGA) and Peak Ground Rotations (PGR) has been initiated since 2018, providing PGA information based on GMPEs calibrated for Greece, considering the epicentral distance, earthquake magnitude, soil and focal mechanism types. The application underwent a major update, focusing on: (a) the capability to incorporate data from seismological and accelerometric stations, (b) an enhanced capability of web PGA and PGR maps in vector format, with the form of grid as well as contours of PGA, (c) a more user friendly layout and improved guidance on interpreting results, (d) the capability of presenting the PGA or PGR value of a grid point, (e) the capability of reading more than one earthquakes and consequently reading specific updates and (f) the capability of email notification to specific users. Past related bugs are eliminated and corrected. When recorded data are available, the best fitted GMPE per earthquake and respective residuals are also indicated. More features will be added, such as macroseismic intensity and affected population. Besides the PGR maps, which are a worldwide innovation, the vector format maps with the selection of layers and PGA-contours are also unique, making the map easily readable.

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The Mw=5.1 19 July 2019 event and its relation to the aftershock zone of the 1999 Mw=6.0 earthquake in Athens, Greece

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On 19 July 2019, an Mw=5.1 event struck the region south of Mt Parnitha, ~20 km NW of Athens, the capital of Greece. This event is the largest in nearly 20 years since the Mw=6.0 earthquake of 7 September 1999, at roughly the same epicentral region and with similar normal fault kinematics. Herein, we investigate the relation between the 2019 sequence and the 1999 aftershock zone through a high-resolution dataset obtained by double-difference relocation. This is achieved by employing catalogue and waveform cross-correlation data from recordings of local networks that were installed in the area in both cases. The results indicate that the 2019 sequence partially overlaps with the western half of the 1999 aftershock zone, while some activity was also detected towards the eastern group, in the vicinity of the 1999 main rupture. The planar geometry of the hypocenters also suggests activation of the same structure, with both sequences being distributed on a plane striking N113°-118°E and dipping 48°-55° towards SSW. Its updip extension is traced at the top of Mt Parnitha, to the west of the mapped Fili fault segments. A waveform comparison of events that occurred in 1999 with those of the 2019 sequence at co-located stations was also performed. Adequate waveform similarity was found for several multiplets to further support re-activation. The 2019 sequence occurred in a region where Coulomb stress-transfer by the 1999 mainshock indicates stress-load, likely rendering the 2019 event a delayed major aftershock.

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The response of the Macedonia University instrumented building to the 03-03-2021 M6.3 and the 04-03-2021 M6.1 Thessaly earthquakes

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The study presents the response of the instrumented Building D of the University of Macedonia in Thessaloniki, Greece, during the 03-03-2021 and the 04-03-2021 far-field earthquakes of magnitude 6.3 and 6.1 that occurred in the region of Thessaly, Greece. The instrumented building is an irregular, nine-storey, pilotis-type, reinforced concrete (R.C.) building that together with another 9 buildings form the building complex of the University of Macedonia, in the center of Thessaloniki, Greece. The building was constructed in the late 1980's, having dimensions of 32.00 m × 23.70 m and a total height of 32.90 m. Building D has a structural system consisting of R.C. columns and Zoellner slabs of B300 and St III concrete and steel grade, respectively (fcm = 25 MPa and fyk=400 MPa). In the framework of the HELPOS project Building D has been equipped with a TRITON - LUNITEK special array that is fully operational since March 2020. The array consists of one free field and three more accelerometers distributed at the bottom, at mid-height and at the roof of the building. Each accelerometer records the response in the two horizontal and in the vertical directions at a 24-bit resolution rate, all four stations are synchronized through GPS antennas, whereas, their response is recorded through a JUPITER – LUNITEC software platform. In this paper the acceleration time histories that were recorded at all stations of the instrumented Building D of the University of Macedonia during the 03-03-2021 M6.3 and the 04-03-2021 M6.1 Thessaly earthquakes are presented. Also presented are the results deriving from Power Spectra Density analyses of the same records, from which the dynamic characteristics of Building D in terms of modal periods of vibration that were activated during the two far-field events are identified.

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Shakemaps development in Greece: Advances in the past decade and perspectives

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Ground shaking maps are of great importance in providing rapid assessment of potential damage and societal losses in the broader affected area after a strong earthquake. In addition, a priori seismic risk scenarios for built environment have recently become an attractive tool in the hands of decision makers and local authorities towards risk mitigation. Such services can be provided by the Shakemaps (SM)software, developed by USGS. The backbone of Shakemaps is a real time continuous recording nationwide network of accelerometers or/and velocimeters, representative ground motion predictive models (GMPMs) and as much as possible detailed distribution of shear wave velocity of the uppermost 30m geologic layers (Vs30). For almost a decade, the generation of Shakemaps for events with M≥4.0 in Greece and broader Aegean area, as well as their near real time web-based dissemination (< 10 minutes after an earthquake occurs), utilized an older version (v3.5) of SM.

The deployment of ~200 broadband high resolution accelerographs in Greece during the last 10 years, and the development of new generation GMPMs for the area of Greece led to recent advances in engineering seismology. In addition, geologic and topographic proxy based on Vs30 along with measured values in Greece have been elaborated, facilitating reliable estimation of amplification, based on a recent version of USGS Shakemaps (v4.0).

In this work, the new SMv4.0 was tested and validated for the 1978 earthquake scenario of Thessaloniki (M6.5) using advance knowledge in engineering seismology and geo-information. A comparison of results from SMv3.5 and SMv4.0 was also attempted showing improved accuracy of the latter. The new SM configuration render it a reliable tool in near-real time Shakemaps assessment in Greece and may effectively serve decision makers and civil protection a few minutes after the occurrence of a strong earthquake with damage potential in urban and natural environment.

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A Revised moment tensor catalog for Western Greece

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The University of Patras Seismological Laboratory (UPSL) is operating since 1990 and on 2005 it became member of the Hellenic Unified Seismic Network (HUSN), operating a permanent seismic network (HP) at Western Greece and Peloponnese. During the last four years the HELPOS project, following the EU -EPOS initiative, offered the funds f to upgrade the stations and revise data processing procedures. Moment Tensor solutions (MTs) provide important information for seismotectonic, stress distribution and source studies. It is also important as a real time or near real time information in shakemaps, tsunami warning, and stress transfer. Therefore a reliable and rapid MT computation is a routine task for modern seismic networks with broadband sensors and real-time digital telemetry. UPSL is using the seismic data from broad band and strong motion stations and the ISOLA moment tensor inversion software to derive the moment tensor of events with M>4 in western Greece. Herein we present the revised database of Moment Tensor solutions computed

during the last ten years in western Greece by the UPSL.The moment tensor database includes solutions for events in the magnitude range 3.0 - 6.8 and provides a unique insight into the faulting characteristics of Western Greece. Moreover it paves the way for detailed studies of stress tensor and stress transfer. The weak events' moment tensors included in UPSL's database are important for the comprehension of local seismotectonics and reveal the role of minor faults, which may be critical in seismic hazard estimation.

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Seismic vulnerability categorization of the Paliki, Kefallinia building stock

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The essential goal of vulnerability assessment of buildings, critical facilities, lifelines etc. to ground shaking is to estimate their expected performance to ground motion. Seismic vulnerability is thus defined as the likelihood of damage from future earthquakes. Vulnerability (V) is an integral component of seismic risk (i.e. probabilistic estimation of economic loss, life loss or injury, downtime and business interruption). Relationships determining V are classified into empirical, analytical or hybrid, according to the type of data and method used. A successful attempt to categorize the country's building stock in vulnerability classes per municipality was performed during the research project "Greco-Risks".

In the framework of the HELPOS project, the National and Kapodistrian University of Athens carries out vulnerability assessment using, after homogenization, the most recent data of the Greek building stock, derived from the February 2011 Building Census. The data are categorized in periods of construction, height classes (number of floors) and construction material classes. The analytical final results of the aforementioned methodology will present the most recent categorization of the Greek building stock and the percentage of vulnerability classes at municipality and prefecture level.

An example of this implementation is presented for the Municipality of Paliki, Kefallinia. Due to its high seismicity levels, the Paliki buildings express, in general, low vulnerability. However, during 2014, the area experienced two strong earthquakes, which damaged a number of buildings and led to repair and reinforce of many, according to the revised Greek seismic design code.

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An overview of significant activity of moderate events in Greece (2018-2021)

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In the present study, we mainly focus on significant seismic activity that occurred during 2018-2021 time period, developing local velocity models upon selected datasets of these sequences and constructing a new seismic catalogue that can reveal distinct spatial clusters, aiming that way the seismotectonic analysis for the broader area of Greece.

During the last three years (2018-2021), more than 50,000 events have been recorded by stations of both the Hellenic Unified Seismological (HUSN) and the Hellenic Strong Motion (HSMN) networks. Among the moderate-size events that marked this period we focus on a) the Trizonia (Western Corinth Gulf) sequence in December 2020 – January 2021 b) the activation of shallow structures along the central and eastern portion of the Hellenic Volcanic Arc, in Santorini and Nisyros respectively.

More specifically, on 23 December 2020, a significant swarm was initiated within the Western Corinth Gulf, an area covered by the seismic stations of the Corinth Rift Laboratory (CRL) network. Further to the south, in the central and eastern part of the HVA, a series of moderate earthquakes occurred during the first semester of 2021. The main events of Nisyros sequence (Mw 4.9 and 5.2) were located along the NE-SW trending Fault System bounding the Southern Nisyros Basin. On the other hand, the Santorini swarm was located about 15 km NE of Thira, near the Columbo volcanic centre, and the strongest event was determined with Mw=4.5. In both cases, spectral and spectrogram analysis revealed the tectonic origin of this sequence.

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Site characterization of accelerometer stations in urban environment based on ambient noise and non-invasive geophysical methods

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In this study, inversion of HVSR curves was applied at six accelerometer sites of the Hellenic Accelerometric Network, in combination with non-invasive geophysical methods, to obtain shear wave velocity profiles and propose a self-restrained methodology in estimating reliable Vs30 values. Properties of the very surficial layers (thicknesses , Vsz velocities) were estimated by electrical resistivity tomography (ERT) and multichannel analysis of surface waves (MASW), respectively, in order to be used as a priori information, improving the HVSR inversion procedure for greater depths. The HVSR inversion procedure includes tests with initial models that did not use any a priori information, leading to ambiguous results affected by the non-uniqueness of the HVSR inversion. Tests with only thickness values constraints and tests with both thickness and Vs velocity values were also implemented and led to the conclusion that the utilization of a priori information is pivotal to tackle, to some extent, the non-uniqueness issue of the HVSR inversion. The Vsz profiles produced by the HVSR inversion are consistent and agree with data from other geophysical methods or boreholes. Comparison of the HVSR transfer functions based on ambient noise are generally in agreement with the corresponding ones based on earthquake recordings at the examined accelerograph stations. Finally, modeling of ambient noise sources around the accelerograph stations were implemented calculating the media response to ground motion via Green’s functions (Hisada 1994). For this purpose, the theoretical 1-D transfer functions derived from the Vs profiles estimated in this study, are compared with the HVSR transfer functions from ambient noise measurements at the accelerograph sites, showing satisfactory

agreement. The aforementioned methodology for site characterization was implemented and validated for a variety of geological conditions in the city of Thessaloniki and led to encouraging results.

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Structure of the Hellenic Lithosphere deduced from regional body and teleseismic Rayleigh wave tomography

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Thousands of regional and teleseismic earthquake recordings were employed towards obtaining constraints on the deeper part of the Hellenic lithosphere. The data used were waveforms of more than 5000 regional and 1000 teleseismic events recorded by the stations of the HUSN and KOERI between 2010 and 2018. Additional recordings were acquired from CRL, GEOFON and MEDNET networks. Regional body wave traveltimes and teleseismic Rayleigh wave phase velocity inversion were performed using LOTOS and a novel two-station cross-correlation technique, respectively. For both datasets, the 3-D velocity model was obtained down to the depth of 140 km. The most prevalent features in both the shear and body-wave velocity perturbation maps are the Hellenic Subduction Zone (HSZ) and the North Anatolia Trench (NAT), manifested by high and low velocities, respectively. Moreover, a high velocity anomaly extends below the Greek mainland and the Hellenic Volcanic Arc (HVA), consistently with other tomographic studies. Low velocities found at depths <50 km beneath the island and the back-arc are explained by convection from a shallow asthenosphere since they are interrelated with recent/remnant volcanism in the Aegean and W. Anatolia. Both the 3-D body-wave and shear velocity models support an N–S vertical slab tear beneath SW Anatolia that justifies deepening, increase of dip and change of dip direction of the Wadati-Benioff Zone.

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HELPOS-Risk, a platform for rapid seismic risk mapping in Greece

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Rapid Seismic Risk assessment methods are considered nowadays state of art towards the earthquake threat. With the aim to whelm civil protection authorities and other stakeholders with a tool that yields valid and fast scientific and also perceptive seismic risk assessment, we developed a GIS-based platform in the frame of HELPOS project that allows for the deterministic seismic risk assessment of the urban environment, given the hazard level and structural vulnerability of the latter. The platform receives georeferenced information on the distribution of ground motion parameters, yielded by a stochastic ground motion simulation procedure. The obtained Seismic Intensity Measures are combined with the exposure layer of the built environment, provided in the spatial resolution of building block level or higher. The structural vulnerability model incorporated in the platform follows a macroseismic semi-empirical method (Giovinazzi &

Lagomarsino, 2004), based on the EMS-98 vulnerability indices taking additionally into account several typological characteristics of the buildings. The HELPOS-Risk pertinent algorithm assesses the probability of damage of the input building stock for a provided seismic scenario which includes a finite seismic source, source-site GMPEs and site response on ground motion. Risk assessment mean output is given in both qualitative and quantitative terms, combining all probable damage estimates, in order to facilitate its utilization for operational purposes. Case studies for three Greek cities have been implemented up to now and are presented in this work: Aigion, Cephalonia and Lefkada, for which previous studies were considered for validation of the platform’s performance.

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Characteristics of the Hellenic National Accelerometric Network: Implications of Soil-Structure interaction housing effects and preliminary corrections

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The Hellenic National Accelerometric Network (HNAN), run by the Institute of Engineering Seismology and Earthquake Engineering (ITSAK), the Institute of Geodynamics of the National Observatory of Athens (NOA-IG) and University of Patras (UPAN), comprises of up to 333 accelerographic stations, which have contributed records to the most recent strong motion dataset for Greece (Margaris et al., 2021). This dataset has been the base for regional calibration and development of the most recent Ground Motion Prediction Model (GMPM) for Greece (Boore et al., 2021). A significant percentage of the stations is installed at the lowest level (basement or ground floor) of multi-storey buildings, essentially recording the response of the building’s base, instead of the free-field ground motion (Margaris et al.,2021). This fact introduces additional epistemic uncertainty to the dataset, due to possible soil-structure interaction effects (Sotiriadis et al., 2019, 2020). As a matter of fact, soil-structure interaction housing effects have been recognized by Boore et al. (2021) as one of the reasons why global GMPMs overestimate the ground motion in comparison with the strong motion data in Greece and, thus, introduced a bias parameter to overcome this uncertainty. Herein, within the framework of HELPOS, the features of HNAN stations are presented in terms of geology, site conditions and type of housing, by adjusting an existing 3-letter classification scheme (GEOMATRIX classification, Chiou et al., 2008). Based on housing characteristics of stations and on a recent work quantifying the ratio between intensity measures of strong motion recorded at the basement of buildings and free-field ones (Sotiriadis et al., 2020), correction of PGA values reported in the strong motion flatfile of Margaris et al. (2021) is attempted and correlated to earthquake magnitude, source-to-site distance and local site conditions.

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A review of seismic crises in volcanic centres of the Hellenic Volcanic Arc (HVA)

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Volcanic crises are usually anticipated to occur due to a loading process triggered by an overall upward magma migration, inducing gas release and stress build up within the feeding system. There are common patterns of behavior, gleaned from analyzing the seismic data from many volcanic eruptions. The recent crises in Nisyros (1995-1997), Santorini (2011-2012) and Poros (2016-2017) urge the concept of volcanic monitoring in Greece, mainly due to the vicinity of local volcanic centers to major urban areas.

The state of Santorini volcano during the 2011–2012 seismic crisis was evaluated by employing several methods, such as hypocenter relocation, earthquake tomography and shear-wave splitting parameters measurement, showing that the critical state wasn't reached. On the other hand, the tomographic study that was conducted in Poros in order to identify the source of 2016-2017 seismic swarm, led to the identification of hydrothermal fluid circulation which may be released from old intrusive magmatic rocks to the NNE of the island.

The study of the latest swarms that occurred during the first semester of 2021, in the central and eastern tip of the HVA, revealed the tectonic origin of these earthquakes through extensive analysis of the waveform shape and frequency content of the recorded events, showing that the state of these volcanoes is not considered to be critical. On the contrary the results from volcanic centers abroad (e.g. Hawaii, Piton de la Fournaise, Redoubt) had clear indications of precursory signals of an upcoming volcanic eruption.

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Permanent GNSS network monitoring in Southern Greece

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Geodetic measurements based on satellite data has improved the ability of continuous monitoring crustal deformation processes. Continuous Global Navigation Satellite System (GNSS) networks are widely used to estimate tectonic movements. Accuracy, availability and continuity are the main advantages of the GNSS.

Higher Geodesy Laboratory of the National Technical University of Athens (NTUA) in Greece has established a permanent GNSS network since 2002 which covers an area extending from Northern Peloponnese to South Crete and Gavdos island including Santorini and Milos islands. Automated processing scheme has been developed providing daily analysis not only from the established network but also of all available continuous

GNSS stations in Greece. Results of the daily data analysis have improved our understanding of complicated tectonic processes in one of the most active area of Greece.

In this paper, analysis results obtained from the network of continuous GPS/GNSS stations of the South Greece are described and discussed. Processing technics and algorithms, designed software tools, along with coordinate time series are presented, including all available results are also evaluated. Furthermore, we discuss the advantages of the contribution of the Hellenic Plate Observation System in terms of unification of all available geodetic data in Greece and future steps are presented.

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Integration of the Gravity and Magnetic Anomaly fields of Greece into the respective anomaly maps of Southeastern Europe and comments on their relation to contemporary tectonics and seismicity

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We present an update and upgrade of the Gravity and Magnetic Anomaly maps of Greece and derivative maps (e.g. isostatic anomaly, Moho depth and RTP magnetic anomaly). They are presented, in their original form as well as integrated with regional data from Southeastern Europe, obtained by satellite gravity and magnetic observations. We further discuss their association with the geodynamic and seismicity regimes at large and regional scales.

The gravity signatures of the subduction systems encountered in the area stand out very clearly. The gravity low in the foreland basins is such that inner crustal loads (buried thrusts) are needed in order to be explained. The “thickened” part of the crust at the subduction fronts coincides with the distribution of seismicity and, in their most seismically active parts the still non compensated overriding loads are clearly observed in the isostatic anomaly map. In the inner parts of the system there is a remarkable correlation between contemporary active tectonics and undulations of the Moho, possibly indicating a two-way interaction in the evolution of both.

The RTP magnetic anomalies exhibit remarkable correlation with past and present geodynamics and tectonics. Considering that the majority of land magnetic anomalies are related to ophiolites, the magnetic anomaly map clearly outlines their presence. The main geotectonic units can be identified with provinces of magnetic anomalies of similar character and clearly defined boundaries. Moreover, magnetic anomalies are clearly correlated with active tectonic structures, with particular reference to the Greece, Aegean and Turkey; this clearly indicates the influence of the latter in the configuration and shape of the former.

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Tsunamis and fast seismo-geodetic rupture inversion in Europe and worldwide: Observations, theory and numerical analyses for hazard and risk assessment

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Preliminary study on the semi-empirical equation for initial tsunami amplitudes generated by underwater landslides

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In the recent past, tsunamis generated by underwater landslide appear to be one of the major coastal hazards. In this respect, predicting the initial wave amplitude is essential for coastal impact assessment of tsunami waves generated by underwater landslides. Several studies in recent years addressed the initial wave amplitudes resulting from underwater landslides via different approaches such as numerical modelling and laboratory works. In general, numerical models for estimating underwater landslide waves require both landslide geometry and nonlinear interaction between landslide motion and surface wave field. Alternatively, semi-empirical equations from laboratory studies can provide an estimation of initial wave amplitude given minimal information about the failing underwater mass. Here, we derive a new predictive equation taking advantage of existing experimental data combined with limited laboratory works conducted in this research. In our lab works, the effect of slope angle on initial landslide wave amplitude is examined with three different angles, i.e. 20°, 30° and 45°, and two different slide volumes, i.e. V=1.4906e-13 and 1.1925e-12 km^3. The new equation is applied on some real landslide tsunami case studies such as the 1998 Papua New Guinea tsunami and the 2018 Palu (Indonesia) dual earthquake-landslide tsunami. We show that our predictive equation can provide rapid estimates of initial landslide-generated tsunami amplitude given limited information about the underwater sliding mass.

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A new method to perform fast high-resolution S-PTHA along the Western Mediterranean Sea coastlines. Application to the Bay of Cannes.

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Probabilistic Tsunami Hazard Assessment (PTHA) is a fundamental tool for producing time independent forecasts of tsunami hazards at the coast, taking into account local to distant tsunamigenic earthquake sources. If high resolution bathymetry and topography data at the shoreline are available, local tsunami inundation models can be computed to identify the highest risk areas and derive evidence-based evacuation plans to improve community safety. We propose a fast high-resolution Seismic-PTHA approach to estimate the tsunami hazard at a coastal level using the Bay of Cannes as test site. The S-PTHA process is firstly fastened by performing seismic and tsunami hazards separately to allow for quick updates, either from seismic hazard by adding new earthquakes, or from tsunami hazard by adding new scenarios of tsunamis. Furthermore, significant tsunamis are selected on the base of the extrapolation of tsunami amplitude collected offshore from low-resolution simulations to an a priori amplitude nearshore using Green's law. This allows a saving in computation time on high-resolution simulations of almost 85 %.The S-PTHA performed in the Bay of Cannes exhibits maximum expected tsunami waves that do not exceed 1 m in a 2500-year period, except in some particular places such as the Old Port of Cannes. However, the probability to experience wave heights of 30 cm in this same period exceeds 50 % along the main beach of Cannes and is to be seriously considered given the high touristic attraction of the area, especially in summer times.

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EWRICA project: first results for real-time GNSS in the Mediterranean Sea

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In this contribution, we are committed to develop a real-time GNSS precise positioning system for earthquake monitoring. Currently the function of real-time PPP and PPP-AR (Ambiguity Resolution) is available. Multi-GNSS joint processing (GPS + GLONASS + Galileo + BeiDou) is used to provide even more precise and robust solutions. About 80 stations from the RING network are employed to evaluate the performance of real-time kinematic PPP and PPP-AR using real-time precise satellite orbit and clock products generated by GFZ or other providers in the RTCM format. The evaluation of the results is carried out by estimating an average accuracy computed at a daily scale and a short-term accuracy computed in a minutes-scale sliding window. In the first case, we show that the daily averaged accuracy is 0.031 m, 0.037m for PPP and 0.016 m, 0.025 m for PPP-AR in horizontal and vertical directions, respectively. In the second case, we observe that more than 95% of short-term accuracies show values within 0.005 m and 0.010 m for the horizontal and vertical components, respectively. The first test of GNSS and seismic loose combination has also been implemented using the data in 2010 El Mayor-Cucapah (Mexico) earthquakes.

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Multiple, earthquake-triggered, submarine landslides generated the July 1956 devastating tsunami(s) in the South Aegean Sea, Greece

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The largest tsunami in the 20th century in the Mediterranean Sea occurred after the July 9th, 1956, M:7.8 Amorgos earthquake in the South Aegean Sea. Maximum run-up values between 10 m and 30 m were reported on the coasts of Amorgos and Astypalea Islands. Tsunami modeling indicate that it was generated by earthquake-triggered submarine landslides, which however remained unidentified. In this paper we present results from the analysis of data sets (multibeam, airgun profiles, side scan sonar, deep-towed chirp profiles, sediment coring and analyses) obtained during three cruises on board R/V AEGAEO in 2016 (Eurofleets2 LGT-AMORGOS-56), 2017 (SE AEGEAN GEODYNAMICS) and 2019 (OTE-2019).

The seismic and bathymetric data indicate active tectonic movements along NE-SW faults, creation of steep slopes, basin inversion, enhanced subsidence and development of multiple subbasins. The infill of the subbasins is largely composed of mass transport deposits.

Multibeam and side scan sonar data show multiple slope failures and associated MTD lobes scattered in the area between Amorgos, Astypalea and Anaphi Islands. Deep-towed chirp profiles revealed multiple chaotic layers in the shallow sub-seafloor, with the last one forming the present seafloor. More than 20 sediment cores were retrieved from the multiple subbasins, targeting the MTD features. They contain an MTD layer,

which varies in character between structureless silt or sand and coarse/fine grain turbidites and in thickness between a few tens of cm and over one meter. The MTD layer is draped by a thin layer of silt and overlays an oxidized layer, interpreted as the previous seafloor that was abruptly covered by the landslide.
Laboratory analyses and dating are in progress and expected to confirm that the observed MTDs are associated with the 1956 earthquake. That will verify the hypothesis that multiple submarine landslides were triggered by the 1956 Amorgos earthquake and may have generated multiple tsunamis.

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Real-time Characterization of Finite-Fault Rupture on Existing and Planned Networks in Sichuan-Yunnan Region of China

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A multi-dimensional characterization of the source model to represent the complexities of a large earthquake is necessary to improve earthquake early warning (EEW) and post-earthquake damage assessment. The Finite-Fault Rupture Detector (FinDer) is an efficient algorithm to compute a line-source model of an ongoing earthquake fault rupture from real-time high-frequency seismic data using template matching. In this study, we test the performance of FinDer in the Sichuan-Yunnan region (98.5°E-106.0°E, 22.0°N-34.0°N) of China for two datasets: the first consists of seismic broadband and strong-motion records of 58 earthquakes with 5.0 ≤ Ms ≤ 8.0; the second comprises additional waveform simulations at sites where new stations will be deployed in the near future. We utilize observed waveforms to optimize the simulation approach to generate ground-motion time series. Overall, the FinDer estimated line-source models agree well with the catalog source parameters and focal mechanisms, but they can be computed faster compared to traditional approaches. Based on these outputs, we determine a theoretical relation that can predict for which magnitudes and station densities FinDer is expected to trigger, assuming that at least 3 neighboring stations must have recorded accelerations of 4.6 cm/s² or more. We find that FinDer likely triggers and sends out a report, if Depi ≤ (50 Mw-228) for Mw ≥ 4.8, where Depi is the average distance between the epicenter and the three closest stations. If the data used in this study had been available in real-time, 40%-70% of sites experiencing seismic intensities of V-VIII (on both Chinese and MMI scales) and 20% experiencing IX-X could have been issued a warning 5-10 s before the S-wave arrives. Our offline tests provide a useful reference for the planned future installation of FinDer in the nationwide EEW system of Chinese mainland.

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Automated Earthquake Line-Source Models from Felt-Reports

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Rapid information on fault rupture geometry is critical to assess damage in large earthquakes and is urgently needed in order to coordinate rescue efforts if necessary. However, many countries around the world cannot afford to operate the dense seismic networks required to quickly determine fault rupture geometry. In a recent feasibility study (Böse et al., 2021) we applied the Finite-Fault Rupture Detector (FinDer) algorithm to felt intensity reports collected by the European Mediterranean Seismological Centre (EMSC) for 36 global earthquakes (6.0 ≤ M ≤ 7.3). We found that the resulting FinDer line-source models generally agree with the spatial intensity patterns described by the felt-reports and, for many earthquakes, achieve good agreement

with the finite-source models published in the literature: for 50% of events the difference in strike is less than 30 deg, and for 75% less than 55 deg. We have now started to automatically calculate FinDer line-source models for global earthquakes (M ≥ 6) within 10 to 120 minutes of their occurrence, provided a sufficient number of felt-reports is available. Our prototype system adopts the httpMsgBus (HMB) messaging system developed by the GeoForschungsZentrum (GFZ) Potsdam. The Swiss Seismological Service (SED) at ETH Zurich runs a listener that connects to the EMSC server and triggers a python script for data preprocessing and calling FinDer when new felt-reports are on the bus. The FinDer line-source models are currently shared internally with the SED and EMSC groups for evaluation and process optimization.

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The 30th October 2020 Samos tsunami: Comparison between numerical modeling and observations

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Samos Island and the surroundings in the eastern part of the Aegean Sea were struck by powerful Mw7.0 earthquake on October, 30th 2020. The earthquake and the induced tsunami are the largest since 1956. Tsunami waves propagated toward the mainland Turkey and the nearest Greek islands. Several far-field tide gauges from the network of the Aegean Sea registered the tsunami. The fault plane solution of the main shock showed a normal fault rupture on an E-W direction, dipping to the north. In our study we analyzed several focal mechanisms and performed numerical simulations of tsunami using the code UBO-TSUFD. The results from the modeling are compared to the data from the mareograph network. In addition, collected data (measurements, eyewitness accounts and video records) from post-tsunami filed surveys made by researchers from Greece and Turkey are used to estimate correctly the tsunami inundation line in some points in the northern part of Samos Island and in western Turkey localities. The results of the tsunami modeling are summarized in several maps showing the maximum wave elevations, the tsunami propagation fields, the tsunami time travel and the expected water column on the coast.

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Tsunami waves in the Southeastern European region (review)

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Huge tsunami waves are caused due to strong earthquakes, underwater landslides and volcanic eruptions. These phenomena are quite often events in the Pacific, especially near the countries around the Ring of Fire, nevertheless the coasts of the Mediterranean and its connected seas experienced such destructive waves since the ancient times. Our study examined the strongest earthquakes that generated tsunami waves in the regional basins: the Adriatic Sea, the Ionian Sea, the Aegean Sea, the Marmara Sea, the Black Sea and the most eastern part of the Mediterranean Sea. We divided the area in subdomains since the geodynamic characteristics are essentially different. Historical data for seismicity and tsunamis are taken from several open access catalogues supplemented with data from scientific publications and compiled into unified database published online in the project`s website and available upon request. For each sea we built a composite map containing historical earthquakes, the faults system in the region, and geographic location of past tsunamis. For the strongest offshore earthquakes we analyzed also the focal mechanisms proposed by different data centers and we calculated the geometry of the seismic sources in order to build an input for tsunami simulations. We constructed hypothetical seismic sources for recently registered local tsunami

waves in the Southeastern European region changing the length, the width and the slip over the fault and varying the focal mechanism parameters. The results are summarized in detailed table.

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Seismotectonics of tsunamigenic earthquakes in the Mediterranean Sea and connected seas

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In the Mediterranean and the connected seas (Marmara Sea, Gulf of Cadiz) several tsunamis have been reported from the antiquity up to the present. Various tsunami generation mechanisms have been recognized but earthquake activity is the main cause of tsunamis. Understanding the seismic and tectonic characteristics of the tsunamigenic earthquakes is progressively improving with the improvement of the instrumental record of earthquakes and of tsunamis by seismograph and tide-gauge networks, respectively. Nearly complete record of strong earthquakes is available since the beginning of the 20th century. However, tide-gauge networks in the Mediterranean region expanded only in about the last decade. Although the instrumental tsunami record is quite limited, yet it is highly valuable since some recent small tsunamis would escape recognition without the instrumental record.

In this study we considered the submarine and coastal seismicity for the time period from AD 1900 up to 2020 and compiled data sets regarding source parameters and fault-plane solutions, when available, for both the tsunamigenic (TE) and non-tsunamigenic (NTE) earthquakes in the study region. We determined the minimum magnitude and the maximum focal depth of the tsunamigenic earthquakes as well as the variation of the ratio TE/NTE. From a set of published fault-plane solutions and tectonic studies we investigated the main faulting types associated with both the TE and NTE. Our results are examined in the prospect of not only better understanding the process of tsunami generation but also of the possible operational utilization in the frame of early tsunami warning.

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Low frequency full waveform ground motion modeling via Neural Networks for rapid impact assessment

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The assessment of the impact after a significant earthquake is mostly based on maps visualizing the predicted strong ground motion in the area (shakemap). Shaking levels are usually derived via empirical ground motion prediction equations (GMPEs). They allow for a rather quick ground motion prediction but are limited by their simple source description and restricted to the currently accepted ground motion parameters of interest (PGA, PGV, SA).

Accounting for finite rupture orientation allows producing ground motions based on physics of wave propagation and therefore enabling effects like rupture directivity. Here, we propose the use of a full waveform modeling approach to predict ground motions in the vicinity of intermediate to large earthquakes.

We use finite fault source models combined with 2 Hz Green's-Functions for a standard 1D velocity model to generate synthetic waveforms. This allows the extraction of ground motion parameters of interest, independent to standard quantities, for any desired location within the area of expected impact.

Results from low-frequent ground motion parameter simulations (e.g. PGD) are in good agreement with those extracted from a number of well studied larger earthquakes (observations). Especially, the desired rupture directivity is clearly visible in contrast to GMPE results.

Waveform calculation and subsequent ground motion parameter extraction is computationally expensive when compared to GMPE estimates. We propose to directly learn a Neural Network model from a large set of 100.000 different synthetic finite fault models and their corresponding spatial ground motion distribution. Given any set of source parameters, we obtain prediction errors smaller than 0.1 log units and a computational speed up of up to 1000 times compared to the full waveform modeling.

In order to account for the uncertainties in the ground motion parameters, the new model can therefore be run quickly with variations of a source model reflecting its uncertainties.

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Automatic schemes of extended seismic source inversions for tsunami early warning

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Fast and robust seismic source estimates are crucial in the frame of tsunami early warning (TEW). Extended rupture models imaging the slip distributions and main asperities can enhance the performance of tsunami forecasts. As only little data is available shortly after an earthquake, the use of a priori information can increase the reliability of fast extend source inversions.

Here we develop an approach which uses location specific a priori information on seismicity and seismic faults combined with scaling laws to estimate both the orientation and possible extends of a rupture plane. The information is fed into two recently developed source models: the kinematic Iterative and Deconvolution (IDS) and the semi-dynamic Eikonal source model.

We test the resolution of the models to different possible synthetic scenarios regarding the location of main asperity location comparing synthetic and modelled waveforms for different station setups and within different waveform domains. In order to get hold of directivity effects, we test both models for a set of evenly distributed potential hypocenters.

We present results from the different scenarios and compare them to results from Bayesian full waveform inversions. We discuss the potential use of the testes models within automatized TEW.

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Slip distribution of the 2021 MW 8.1 Raoul Island Earthquake from DART buoy and Tide-gauge data inversion

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We estimate the tsunami source of the MW8.1 2021 Raoul Island earthquake - Kermadec subduction zone - by inverting the tsunami waveforms from DART stations and tide-gauges. We followed a Green's functions approach by parameterizing a 3D fault geometry with variable strike and dip and tessellated with 162 quadrilateral subfaults. Tsunami Green's functions were computed through the HySEA code that solves the nonlinear shallow water equations on a telescopic nested grids system (resolution of 1 arc-min in open ocean, 15 arc-sec around the tide-gauges); the tsunami initial condition for each subfault was computed by taking into account the contribution of the horizontal seafloor deformation and the filter of the water column. The inverse problem was solved by using the Simulated annealing algorithm, minimizing a misfit function that takes into account any time mismatch between observed and predicted tsunami signal due to dispersive, water column gravity, and water density gradients effects potentially affecting the DART station modeling, or the inaccuracy of the bathymetry that might affect the tide-gauge waveform modeling.

The estimated coseismic earthquake rupture shows a unilateral northeastward propagation from the hypocenter, featuring a maximum slip value of about 5 m; the rake angle is consistent with the convergence between Australian and Pacific plates. The results indicate that the coseismic rupture is compatible with both the aftershock distribution and back-projection analysis. The tsunami ensuing the Raoul Island earthquake is comparable with other tsunamigenic earthquakes that occurred in the same area in the past.

This event is important because is the first great tsunamigenic event captured by the new New Zealand DART network installed in the South-West Pacific; these instruments confirmed to be valuable to estimate a robust image of the tsunami source and in addition they contribute to enhancing the effectiveness tsunami warning system in the region.

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Recent tsunamigenic earthquakes in the Mediterranean modelled in a tsunami early warning perspective

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In the early warning context for earthquake-generated tsunamis impacting near-field coastlines, one of the biggest open challenges consists in complementing the localization and magnitude information obtained from seismic networks with reliable, near-real-time estimates for the complete fault rupture features, including the geometry, the relative position of the hypocenter and of the fault, the focal mechanism, the on-fault slip distribution. These characteristics are essential in determining the efficiency of the generation process and the distribution of the maximum run-up and inundation along the nearby coasts.

Opposed to other tsunamigenic provinces such as the oceanic subduction zones, where rather rich databases of finite-fault models exist, the Mediterranean Sea counts only few examples of moderate-magnitude tsunamigenic earthquakes for which complete geometry and slip distribution is available.

Taking into account the most recent earthquakes occurred in the eastern Mediterranean basin (2nd May 2020 offshore southern Crete, Mw = 6.6); 30th October 2020 in the Aegean Sea, Mw = 7.0), we discuss the applicability of a methodology that can be summarized in the following steps: 1) fault geometry and on-fault slip distribution are computed through available regression laws against the magnitude provided by seismic networks; 2) the position of the hypocenter, and consequently of the maximum of the slip distribution, is varied by sampling probability density functions derived from the analysis of global finite-fault databases; 3) average values with associated uncertainty are assigned to strike, dip and rake angles based on the zone where the hypocenter falls into. We run tsunami numerical simulations for each scenario resulting from the previous methodology. Finally, we quantify in probabilistic terms the water elevation time series in selected offshore/coastal tide-gauges, the flow depth and run-up, and compare the results with the available observations.

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Optimization of fault plane and coseismic slip from tide-gauges data for the 2nd May 2020 Crete earthquake (Mw 6.6)

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We present a tsunami source solution for the 2nd May 2020 Mw 6.6 earthquake that occurred about 80 km offshore south of Crete on the shallow portion of the Hellenic Arc Subduction Zone (HASZ).

Using the tide gauges data of Ierapetra and Kasos harbours we constrain the geometry and orientation of the causative fault, and of the rupture mechanism and slip amount. We first modelled an ensemble of synthetic tsunami waveforms at the tide-gauge locations, produced for a range of earthquake parameters values constrained by some of the available moment tensor solutions. We allow for both a splay and a back-thrust fault, corresponding to the conjugate fault planes between which the moment tensor solutions cannot discriminate. Our results identify a shallow highly-dipping back-thrust fault as the source of this earthquake producing the lowest misfit evaluated between the synthetic and the observed marigrams for each realization of the source parameter set. However, a rupture on a lower angle fault, possibly a splay fault of the subduction interface, with a sinistral component due to the oblique convergence on this segment of the HASZ, cannot be ruled out. This earthquake reminds that the uncertainty regarding potential earthquake mechanisms at a specific location remains quite significant. In this case, for example, it is not possible to anticipate if the next event will be one occurring on the subduction interface, a splay fault, or a back-thrust which seems the most likely for the event under investigation. This circumstance bears important consequences because, as well as splay faulting, back-thrust faulting might enhance the tsunamigenic potential where the subduction itself may be less tsunamigenic due to their flatter dip. Then, these results are relevant both in the framework of the long-term tsunami hazard assessment and of the tsunami early warning systems.

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Wet demo SMART cable at Western Ionian Sea

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Western Ionian Sea is one of EMSO (European Multidisciplinary Seafloor and water column Observatory) Regional Facilities and it is located at about 25 km off the Eastern Sicily coasts at 2100 m w.d. An underwater electro-optical cable runs on the seafloor from Catania harbor and splits in two branches that host geophysical and environmental seafloor platforms, managed by Istituto Nazionale di Geofisica e Vulcanologia (INGV) and Istituto Nazionale di Fisica Nucleare (INFN).

The observation area is prone to numerous natural hazards due to the high seismicity and the region experienced large historical earthquakes some of which caused also very destructive tsunami wave such as the 1908 Messina earthquake.

In 2019 the InSEA project, funded by the Italian Ministry of Research, started to enhance the Western Ionian Sea infrastructure capabilities. One of the main goal of InSEA is to realize the first wet demonstrator SMART (Science Monitoring and Reliable Telecommunications) cable designed by a Joint Task Force (JTF) across the International Telecommunication Union, World Meteorological Organization, the UNESCO Intergovernmental Oceanographic Commission. The goal of the JTF for SMART cables is monitor Earth and the oceans trough sensor-enabled submarine telecommunications cables on a global scale, to support climate, sea level monitoring, tsunami and earthquake early warning and disaster risk reduction.

The Western Ionian Sea wet demo SMART cable will consist of a cable with sensors integrated into the housing of three commercial standard repeaters. The housings will include a temperature sensor, an absolute pressure gauge, a force balance accelerometer and a broadband seismometer.

In situ pressure and seismic measurements are needed to generate reliable tsunami height forecasts in Ionian Sea and data coming from SMART cable could improve tsunami warnings based on land seismic data.

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The EWRICA Project on early-warning and rapid impact assessment with real-time GNSS in the Mediterranean

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High-precision real-time applications of the Global Navigation Satellite System (GNSS) have recently expanded to monitoring and early detection of natural hazards. German national research project EWRICA (Early-Warning and Rapid ImpaCt Assessment with real-time GNSS in the Mediterranean) funded by the national Ministry for Education and Research (BMBF) aims for the prototype implementation of the GNSS-based seismic source inversion and triggered physical impact assessment in the seismically active region of Central Mediterranean. The project exigently benefits from the close cooperation with partners from Italy (INGV) and Greece (NOA) operating real-time high-rate GNSS networks RING and NOANET, respectively.

An overarching goal of the project is to create robust local ground motion models shortly after an earthquake to assess secondary effects such as tsunamis and landslides as well as to identify areas of possible building damage and collapse. This should be achieved by firstly improving the accuracy of real-time GNSS processing (RTPPP+RA: precise point positioning PPP with regional augmentation) to a cm-level. The processing can optionally include collocated accelerometers, and real-time displacements will be distributed in SEED-format via SeedLink for later processing with standard seismological analysis software (e.g., SeisComP). The joint inversion of near-field seismo-geodetic data will not only improve the assessment of seismic moment, hypocentre and rupture kinematics, but also will significantly speed-up source parameter derivation in comparison to usual processing based on far-field data. The improved source assessment will allow more reliable prediction of ground motion which, in turn, will improve forecasting of secondary effects like landsliding and tsunami generation. The prototype will deliver probabilistic estimates for medium- and short-period ground shaking parameters and potential slope instabilities as soon as few minutes after an earthquake. Additionally, integration to the CAT system is planned.

In this presentation we will report about the project progress to it's midterm.

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GNSS/InSAR inputs for geodynamic modeling, tectonic strain and seismic hazard in the Mediterranean

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TEC variation over Europe during the intense tectonic activity in the area of Groatia on December of 2020.

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In a series of papers we investigate the Lower ionospheric variation on the occasion of intense tectonic activity.In the present paper, we investigate the TEC variations during the intense seismic activity in Croatia on December 2020 over Europe. The Total Electron Content (TEC) data are been provided by the Hermes GNSS Network managed by GNSS_QC, AUTH Greece, the HxGN/SmartNet-Greece of Metrica S.A, and the EUREF Network. These data were analysed using Discrete Fourier Analysis in order to investigate the TEC turbulence. The results of this investigation indicate that the High-Frequency limit fo of the ionospheric turbulence content, increases as aproaching the occurrence time of the earthquake, pointing to the earthquake epicenter, in accordane to our previous investigations. We conclude that the Lithosphere Atmosphere Ionosphere Coupling, LAIC, mechanism through acoustic or gravity waves could explain this phenomenology.

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A novel GNSS-based velocity field for the Iberian Peninsula

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To study the crustal deformation pattern over the Iberian peninsula, we analysed an extensive GNSS dataset which, covering 21 years of observations (from 1999.00 up to 2020.00), includes more than 400 continuous GNSS sites available at the EUREF Permanent Network, at the Crustal Dynamics Data Information System and from various networks deployed and managed on the study area by local institutions and agencies mainly for engineering and cadastral purposes. In addition, we also included data from 25 episodic GNSS sites located in Morocco with surveys spanning the 1999.8 - 2006.7 period, whose raw observations are available through the UNAVCO archive. The GNSS phase observations were processed by using the GAMIT/GLOBK 10.7 software in order to obtain a consistent set of positions and velocities in the ITRF2014 reference frame. To improve the detail of the geodetic velocity field over the studied area, we perform a rigorous integration of our solutions with those reported in recent literature.

The spatially dense crustal velocity field allowed us to provide new insights into the crustal tectonic processes currently occurring in the western Mediterranean Sea. Moreover, it also allowed to detect significant vertical motions mainly related to overexploitation of shallow aquifers.

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The March 2021 seismic sequence in Northern Thessaly (central Greece), its seismotectonic characteristics and geodynamic effects

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On March 3, 2021 10:16 UTC a Mw=6.3 shallow earthquake occurred in northern Thessaly, near Damasi, about 20 km to the northwest of Larisa. The epicentral area is characterised by low seismicity and low strain rates unlike southern Thessaly that hosted several M6+ events during the 20th century. A Mw=6.0 shallow earthquake occurred on March 4, 2021 18:38 UTC beneath the sedimentary basin of the Titarisios river. On March 12, 2021 12:57 UTC a third event of Mw=5.6 occurred near the NW edge of the Titarisios basin. We present a preliminary analysis of seismological, geological and geodetic data that constrain the location and geometry of the activated faults. We resolve the source mechanism and rupture process (slip distribution) of the 3rd March 2021 shock, obtained from kinematic joint inversion of teleseismic P– and SH– body-waves and near-field strong-motion waveform analysis. Moreover, we relocated hundreds of aftershocks and computed the focal mechanisms for events with M≥4.0. Due to the shallow depth of the earthquakes, it was possible to map the surface deformation using InSAR. The interferograms show three main lobes of subsidence, partially overlapping with a NW-SE orientation. We also processed GNSS data from seven permanent stations located at distances 15 to 40 km. The displacement data were inverted to model the dislocation sources assuming homogeneous elastic half space. The inversion modelling indicates the activation of three normal faults, previously unknown. The earthquakes generated numerous secondary phenomena with vast areas of alluvial deposits exhibiting spectacular liquefaction features. No tectonic ruptures were found in the field, in agreement with the modelled faults. However, several NW-SE surface breaks were observed north of village Zarko, aligned with the vanishing gradient of the interferometric phase of the 1st event. We interpret those as tensional cracks related to the dilatational strain of the rupture.

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Study of Tectonic Deformation in NW Peloponnese: preliminary results on crustal coupling from GNSS and seismology

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The tectonics of western Peloponnese have been studied widely since the advent of space geodesy (1990s) using both campaign and continuous GNSS data. The active tectonics are mainly dominated by strike-slip and

reverse faulting. In particular, the active tectonics of NW Peloponnese, is dominated by the NE-SW Movri Fault Zone, that is a crustal-scale right-lateral structure continuing towards Patras. At the south margin of this region (near Pyrgos), geological data indicate the existence of E-W striking normal faults. New seismological data (onshore and offshore) also indicate the activation of a series of 5-10 km long strike-slip faults that are arranged in NW-SE and NE-SW directions. The GNSS data is crucial to investigate how elastic strain is accumulating in this complex region. We use the new GNSS velocities published by Briole et al. (2021) to model the present-day deformation by means of a continuous strain and rotation rate field. We used the STRAINTOOL EPOS Software to calculate the strain tensor parameters. We map extension across the Gulf of Patras which is nicely correlated with geological data showing offshore active normal faults. At most part of NW Peloponnese and its offshore extension (close to Zakynthos), the overriding plate of the western Hellenic Arc is under strong compression in the ENE-WSW direction, that decreases from north towards south. Moreover, we map 6-7°of clockwise rotation of the crust. We also analysed seismological data and obtained relocated seismicity maps and moment tensors for tens of shallow events. The P-T axes orientation agree with the orientations of the principal axes of strain. Our results suggest strong kinematic coupling between the upper and lower crust of the overriding (Aegean) plate.

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Active crustal deformation and rotations in the southwestern Balkans from continuous GPS measurements

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The western limb of the Hellenic Arc defines the boundary of a large intracontinental active extensional domain covering the Aegean and the southwestern part of the Balkan peninsula. Along this boundary a transition from collision in the north to subduction in the south is associated with post-Miocene

clockwise rotations. We present a new GPS velocity field that, with new permanent station velocities in Albania, Bulgaria, Kosovo, Montenegro, and Northern Macedonia, provides insights into previously unresolved aspects on the large-scale dynamics of continental lithosphere and on the relation between long and short-term kinematics. In particular we address (1) the kinematic description of the collision/subduction transition, (2) the relation between long-term finite rotations with geodetically- measured instantaneous rotations, (3) the forces maintaining and resisting the deformation of the extensional domain and (4) the extent of its northern boundary.

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Impact of seasonality and GIA on the behavior of permanent GNSS sites vertical position time series in Romania

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We describe a comprehensive analysis of permanent Romanian Global Navigation Satellite System (GNSS) sites' on vertical position time series. The GNSS observations were computed using Gipsy X software and the final estimates to obtain the seasonal signal and station velocity was analyzed using Maximum Likelihood Estimation (MLE) and MIDAS trend estimator. We aimed to establish an uplift dome, an approximate latitude GIA influence threshold, and we may eventually be able to determine the area of the Eurasia tectonic plate where GIA is of significant importance. In particular, we focus on the known national GPS observation level model areas in Romania to advance geodetic observation precision/accuracy toward 0.1 mm/year and therefore further constrain models of GIA and subsequent present-day ice mass change estimates at 45° latitudes. Additionally, our investigation results will be applied to the revised analysis strategies of vertical deformations over the Romanian region. Moreover, a comparison between the GPS-derived rates, seasonalities amplitudes and impact, and the present-day motion predicted by the newest Glacial Isostatic Adjustment (GIA) model is provided.

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ESHM20 source model versus strain rate map: comparison of moment rate estimates

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Most national and international seismic regulations require quantifying seismic hazard based on probabilistic seismic hazard assessment (PSHA) methods. The probabilities of exceeding ground-motion levels at sites of interest over a future time window are determined by combining a source model and a ground-motion model. This research work aims at understanding how the measurement of strain rates by geodesy can provide constraints on the source model.

Earthquake catalogs, merging instrumental and historical data, are usually used to establish earthquake recurrence models. Although these catalogs extend over several centuries, the observation time windows are often short with respect to the recurrence times of moderate-to-large events and in some regions the recurrence models can be weakly constrained.

Strain rates maps were calculated for Europe using a combined velocity field (Piña Valdes et al. 2021). These strain rates are compared to the source model of the new European seismic hazard model (ESHM20, Danciu et al. 2021). More precisely, the moment rates estimated from the earthquake recurrence models are compared to the geodetically-derived moment rates. The first results show that a correlation exists between the seismically and geodetically derived moment rates, but the regression coefficient is not one. In areas characterized by high activity, such as Betics or Apennines for example, the moment rates derived by both methods are comparable. In areas of lower activity, such as at the interior of plates, the error associated with geodetic measurements is of the same order of magnitude as the measured strain, and the relation between catalog-based and strain-based moment is not straightforward. In this work we explore the different uncertainties in both data sets to understand better how both observables are related, and to assess under what conditions geodetic observations could be used in PSHA studies.

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Constraints on the Northern Apennines-Adria shortening from continuous offshore GNSS stations

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We analyze the position time-series of a GNSS dataset including 22 continuous stations located on offshore platforms of the Italian ENI company. The offshore data have been analyzed together with data from several hundred onshore continuous GNSS stations in the peri-Adriatic region. The displacement time-series of the offshore stations reveal clear deviations from linearity, other than peculiar seasonal displacements, conceivably due the anthropogenic activity. We present and discuss ground displacements in a local tectonically-stable reference frame (Adria-fixed) to characterize the linear trend of the time series and their deviations. We use a trend-filtering approach to analyze each position components independently, for each station, separating the seasonal terms from piecewise linear trends. The trends, and estimated trend change points, have been compared with data from monthly hydrocarbon production. We found for several stations that deviations from linearity in the horizontal components are temporally correlated with changes in the rates of gas volume extractions. Moreover, the linear long-term trends, even without any deviation, can be influenced by the local deformation due to the constant reservoir depletion. We defined a criterion to discriminate whether the horizontal linear rates of the offshore GNSS stations are representative of the occurring tectonic deformation or not. Horizontal velocities of onshore and selected offshore stations allow to provide some new constraints on the kinematics of the active, mainly offshore, outer thrust front of the Northern Apennine chain in the central and northern Adriatic region. We use a kinematic elastic block model to provide new insights into the fault slip-rates and the spatial heterogeneity of the interseismic coupling of the offshore thrust front. The obtained results provide new hints on the use of offshore, industrial, GNSS stations on resolving interseismic fault coupling, showing to be useful data to seismic hazard assessment in the central and northern Adriatic region.

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Evidence of fault-valve behaviors in a continental collision area from deformation data

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We evidenced a coherent transient signal at the Adria-Eurasia plate boundary by applying the data-driven empirical mode decomposition (EMD) technique to the recordings of four tiltmeter sites of the NE-Italy subsurface tilt and strainmeter network. The transient produced a tilt propagating along the main fractures in the 1984–1990 period. Borrowing from classical seismology techniques, we used the uprise times to locate the transient signal source. The propagation velocity is compatible with a fluid diffusion process that starts from a source located close to the hypocenter of the February 10, 1983, Uccea earthquake, MD = 4.2 at the Italy-Slovenia border. Previous, independent analyses on the seismic velocities time variations and tidal admittance evidenced vp/vs and elastic parameters changes compatible with our observations and the pore-pressure time changes. These results add to the previous observations from navigation satellite system

(GNSS) stations in 2006–2009, ascribed to a transient fluid diffusion from below the Bovec basin (Slovenia) at about 6 km from July 12, 2004, Bovec–Krn earthquake, Mw = 5.1. These data strongly suggest that the area is subject through time to fault valve behavior episodes that release fluids trapped at depth to the surrounding region as pore-pressure variations. The convergence between Alpine and External Dinarides structures in this area puts highly permeable dolomitic limestones in contact with low-permeable fine-grained limestones and flysch formations. Therefore, the conditions for overpressure generation can be created, in the interseismic period, whereas fault movements, from time to time, in close relation with seismic events, can enable fluid diffusion in the surroundings. We also estimate the possible fluid influx needed to maintain overpressure and possible discharge across the faults involved in both episodes: the one here reported for 1984-1990, and the other inferred from GNSS measurements in 2006-2009.

ESC2021-S29-517

Crustal deformation in western Greece from GNSS measurements stress field, with focus in Aitolo-Akarnania prefecture

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Since 2013 crustal deformation at the Aitolo-Akarnania prefecture (Greece), is monitored by a dense GPS network. The GNSS Network PPGNet consists of five stations in Aitolo-Akarnania, equipped with Leica and Septentrio receivers. Large active faults have been mapped in the area and the most significant include the Katouna sinistral strike-slip fault and the Trichonis Lake normal fault system. This work is based on the GNSS measurements from the 2015 – 2019 year period, using data from the PPGNet and GNSS stations around, and covering the area of southwestern Greece (from the Aitolo-Akarnania area in the north to the western part of the Peloponnese peninsula in the south). The daily network solutions in Bernese 5.2 software were used, which were loosely connected to the EUREF Permanent Network (EPN) stations in the south-eastern part of Europe. Based on the analysis of coordinate changes time series, both vertical velocities and displacement vectors in horizontal directions were derived. By applying the theory of small displacements, from the continuum mechanics, to the displacement vectors, the field of deformations was calculated in the considered area. The advantage of calculating the deformation field is that it is independent of the fixed station against which the displacement vectors were computed. Two areas related to the Katouna fault and the western part of the Corinth Rift are interesting, where they show significant deformations, especially around the Trichonis lake. Deformations can also be observed along the Kefalonia Fault further west. The results, which still must be considered preliminary can be used as an input in seismic hazard studies and seismotectonic modeling of the region.

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Robust estimation of intraplate strain rate and vertical land motion in intraplate Europe: Correlations with seismicity, volcanism, and mantle plumes

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We analyzed the horizontal strain rate field and vertical land motion (VLM) of intraplate Europe using ~2400 velocities derived from continuous GPS stations. These velocities were derived from time-series after common-mode components (CMC) were removed using a novel approach. This noise reduction directly translate to a similar reduction in velocity uncertainty, and spatial resolution in the strain rate model.

We used updated robust estimation algorithms to estimate VLM and strain rate. After GIA correction, we found significant surface uplift rates up to ~1.0 mm/yr roughly centered on the Eifel Volcanic Field, and above the putative mantle plume seismically imaged underneath. The same area that uplifts also undergoes significant N-S-oriented extension of ~3 nanostrain/yr. For another area of Quaternary volcanism and with a possible mantle plume underneath, the Massif Central, we find evidence of localized extension, but no evidence for uplift.

For the Eifel area, the remarkable superimposition of uplift, horizontal extension, and volcanism strongly suggests a causal relationship with the underlying mantle plume. We model the plume buoyancy as a half-space vertical force applied to a bi-modal Gaussian areal distribution exerted on a plane at 50 km depth and find a good regional fit to the long-wavelength aspects of the surface deformation.

Tectonic uplift of ~150–250 m as occurred near the Eifel since 800 ka, when recent volcanism, faulting, and uplift reactivated, which would imply an average VLM of 0.1–0.3 mm/yr since that time. Our VLM results suggest that the uplift may have accelerated since 800 ka. We also note that the highest extension rates are centered on the Lower Rhine Embayment (LRE), where intraplate seismicity rates are high, and where paleoseismic events increased since 800 ka. We suggest that the surface uplift imposed by the Eifel plume explains the relatively high activity rate of the LRE.

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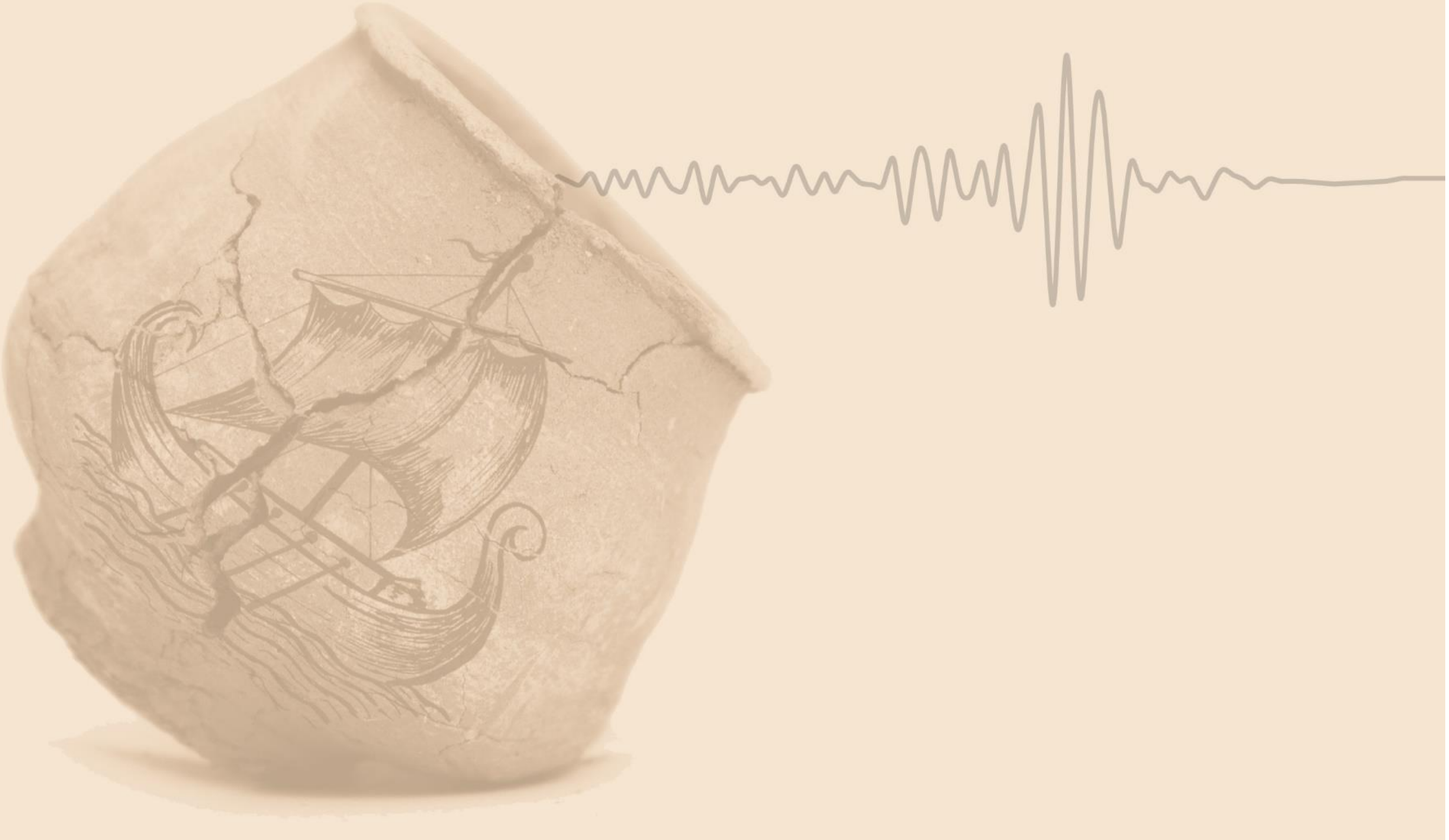
New challenges for urban engineering seismology



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Application of the real earthquake recordings from buildings to explore the sources of epistemic uncertainty and the efficiency and sufficiency of ground motion intensity measures in building response prediction.

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Performance-based earthquake engineering is a probabilistic decision-making framework aimed to mitigate seismic risk, based on a comprehensive scientific foundation. In this framework, the ground motion intensity measures (IM) is linked to the threshold damage parameters (EDP) to measure the expected damage of the structures. Two natures of IM are defined: (1) an efficient IM defined as providing the smallest variability in EDP given IM relation, and (2) sufficient IM defined as providing EDP conditionally independent on earthquake magnitude and distance. Often, numerical methods are used to model the building response for given IM. We know that experimental data from the full-scale observations are much more representative of the complex physical process than even the most sophisticated laboratory or numerical experiments, integrating them into our modes helps to identify the sources of epistemic uncertainty.

In this study, we considered a number of spectral and ordinary ground motion IMs for use in structural performance assessment. Real strong motion values recorded at the top and the bottom of US, Japanese and Romanian buildings are analyzed in order to identify the source of uncertainties in the prediction of EDP (i.e. structural drift) for given IMs (i.e. σEDP|IM). The efficiency and sufficiency of each IM from a large set of building and earthquake motion data are tested for different criteria characterizing the seismic source (magnitude and source-to-site distance), and considering several building classes and a specific single-building analysis including aging due to cumulative earthquake damage over time.

The spectral values at co-seismic resonance frequencies are found to be the most efficient IMs for the range of buildings and earthquakes investigated, particularly for velocity with a reduction of approximately 50% of the σEDP|IM value. Conversely, most IMs are relatively insufficient.

ESC2021-S30-088

Earthquake ground motions in Thessaloniki urban area based on 3D physics-based Numerical Modeling

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A reliable description of earthquake ground motion and of its spatial variability is crucial for seismic hazard and risk analysis of spatially distributed portfolios in urban areas. Ground Motion Prediction Equations (GMPEs) are widely used to predict earthquake ground within both probabilistic and deterministic seismic hazard assessment studies, but they have some intrinsic drawbacks because of the limited number of recordings in special conditions, such as in near-source region of large earthquakes. An advanced 3D physics-based numerical approach has emerged as a powerful alternative to provide realistic details on earthquake ground shaking and its spatial variability, considering explicit 3D models of seismic source, propagation path in heterogeneous media, and local geological site conditions. This research focused on the case study of Thessaloniki (Northern Greece) and aimed at providing an enhanced characterization of earthquake ground motion in this area using 3D physics-based numerical simulations. A dataset of broadband earthquake ground

motion from different rupture realizations of given earthquakes originating from different seismic faults around the city of Thessaloniki is generated and analyzed. After comparing the results with those from the traditional GMPEs method, selected applications of simulated ground motions are shown to highlight their potential benefits for earthquake engineering.

Key words: 3D physics-based simulations; broadband ground motions

ESC2021-S30-103

Exploring the impact of spatial correlations in the catastrophe modelling process

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Catastrophe models are very important tools to provide proper assessment and financial management of earthquake related emergencies that still create the largest protection gap across all other perils. Earthquake catastrophe models include three main components, namely: (1) the earthquake hazard model, (2) the exposure model and, (3) the vulnerability model. Simulating spatially distributed ground-motion fields within either the deterministic or probabilistic seismic hazard assessment practice poses a major challenge when site related financial protection products are required. Several authors have demonstrated that the spatial correlation of earthquake ground-motion is period-, regionally- and scenario-dependent, so that the implementation of a unique correlation model may represent an oversimplification.

In this framework, we have established a joint research project between the University of Strathclyde and Impact Forecasting, Aon's catastrophe model development centre of excellence, in order to advance the understanding of spatial correlations within the catastrophe modelling process. We performed a deterministic scenario calculation, taking the Mw 6.5 Norcia (Central Italy) earthquake as reference. In particular, we developed ad hoc correlation models for different Italian regions (e.g. Northern and Central Italy) using both ad hoc ground-motion models (GMMs) and existing GMMs calibrated on different databases for purposes of probabilistic seismic risk analysis in Italy. We employed the OpenQuake-engine for our calculation, which is an open-source tool suitable for accounting for the spatial correlation of earthquake ground-motion residuals.

The main goals are: (1) illustrating the impact of spatially dependency modelling on the resulting earthquake shaking losses of building portfolios or spatially distributed infrastructures and, (2) investigating the effects on-per-event loss estimates and in-location loss estimates for underwriting purposes. The results of this project will have implications for (re)insurance companies evaluating the risk to high-value civil engineering infrastructures.

ESC2021-S30-176

Empirical amplification model for the city of Lucerne, Switzerland

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The earthquake-induced damage can be significantly increased in densely populated urban areas due to the ground-motion amplification at sediment sites. Hence, detailed site effects evaluation is essential for cities located in soft sedimentary basins. The aim of the study is the evaluation of the site response variability in the city of Lucerne in Switzerland, situated on unconsolidated deposits and struck by several strong historical earthquakes (i.e. Mw5.9 in 1601). We would like also to highlight the specifics and challenges of site response evaluation in an urban environment. This work is in the framework of the Horizon 2020 ITN funded project URBASIS-EU focusing on urban seismology.

Firstly, we estimated the relative amplification factors at selected urban sites using Standard Spectral Ratio (SSR - Borcherdt, 1970) and Empirical Spectral Modelling (ESM - Edwards et al., 2013) methods. We took advantage of the weak motion observations from earthquakes recorded by 10 velocimeters installed for several months and by 3 accelerometers of the permanent Swiss Strong Motion Network (SSMNet). Then, we inferred the spatial variability of the soil response in the city center and surrounding areas using the Hybrid Standard Spectral Ratio method (SSRh - Perron et al., 2018) combining earthquake recordings at few sites and about 100 densely distributed single-station noise measurements. Moreover, the ambient vibration data supplemented by more than 200 recordings performed in Lucerne in the past was processed employing the RayDec approach (Hobiger et al., 2009) to calculate the Rayleigh wave ellipticity function and map the fundamental resonance frequency.

The resulting empirical linear amplification model indicates a strong increase of amplitude and duration of ground-motion in some parts of the city, even up to 10 times for frequencies between 0.8 and 2Hz. We observe a good consistency between our model and geological information concerning the thickness of unconsolidated deposits.

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Mode-selective focusing of Rayleigh waves to study scattering due to shallow buried structures

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An effort is made towards better understanding the physics of Rayleigh wave scattering and the nature of metamaterial bandgaps in the presence of periodic pile-like inclusions clamped to an elastic half-plane and buried in the shallow elastic soil layer. The study of surface wave scattering due to regular and periodic heterogeneities buried near the surface is important in the understanding of seismic wavefields in dense urban areas. Large-scale seismic metamaterials like periodic soil inclusions are known to introduce frequency bandgaps which have traditionally been attributed to Bragg scattering mechanism. However, individual or collective resonance effects can be possible when these inclusions are clamped to a stiffer bottom layer. To investigate this effect, we choose to perform time-domain spectral element simulations in a P-SV domain using SPECFEM2D, a spectral-element code. We devise a methodology to filter the fundamental or first higher mode from the incident field propagating in the layer over half-space medium. A horizontal source array is employed to insonify the scatterer after the modes are decoupled using a spatial-temporal time-reversal filter. A scattering matrix is constructed to quantify the contribution from forward-scattered and back-scattered modes. This study can help in better identifying the contribution of Mie scattering to the bandgap generation mechanism.

ESC2021-S30-223

Microzonation of the Durres city (Albania) using ambient noise

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In high seismicity areas seismic microzonation in urban environment is of high importance towards seismic risk mitigation and resilience of the society. For this purpose preventive measures must be based on detailed knowledge of spatial distribution of seismic shaking for any given earthquake scenario. However, it is difficult and sometimes prohibitive to characterize sites in urban environment using classical active methods (boreholes, heavy blows for active geophysical prospecting etc.). In addition, such an approach can be proved time consuming and expensive. An alternative approach widely used during the past 3 decades, utilizes ambient noise either of single station or array measurements, providing either the fundamental frequency of the site and its corresponding amplification or shear wave velocity profile.

In this study, after the disastrous earthquake (M6.4) of Nov. 26, 2019 close to Durres city, single station ambient noise measurements were performed at 80 sites evenly distributed down-town in the city. The well known Horizontal to Vertical Spectral Ratio (HVSR) technique was performed following the SESAME guidelines and fundamental or/and dominant frequencies as well as the entire HVSR curve were determined for each site. All available for the city geological and geophysical data were compiled and used in combination with HVSR results for site characterization. In selected sites where borehole and geophysical data was available, a theoretical 1D approach (1D Hishada method) was performed to assess and document a Vsz profile till the seismic bedrock beneath the city. The experimental HVSRs curves were grouped in four categories sharing similar spectral shape and comparable amplitudes. The classification methodology adopted in this study, can facilitate 1D response analyses for the Durres city and consequently estimate realistically expected ground motion of any future seismic shaking scenario in the city of Durres as well as in other urban environments of similar geological characteristics.

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Urban-Scale vulnerability assessment of buildings including soil foundation structure interaction

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Urban scale vulnerability assessment is commonly addressed considering fixed-base structures, i.e., neglecting the interaction between soil, foundation, and structure (SFSI). The state-of-the-art literature proves that neglecting SFSI effects may lead to inaccurate fragility or loss estimates by a substantial margin. Including these effects on the city-scale fragility, analysis is considered a challenging task due to the high exposure concentration and the high level of complexity of the whole interacting urban system. An alternative to reduce the computational effort required by the urban-scale assessment is to consider secondary factors, which increase or decrease the seismic vulnerability. To this aim, this study proposes predictive regressions of secondary factors (hereafter Fragility Modifiers) to modify the existing fixed-base fragility curves to account also for SFSI. In particular, for each damage state, the fixed/base fragility median value can be multiplied by an appropriate value depending on the relative soil-to-structure stiffness

parameter. These Fragility Modifiers regressions were evaluated performing dynamic analyses on multi degree of freedom systems where the compliance of foundation soil is considered. The great advantage of the proposed regressions led to performing an urban risk assessment including nonlinear SFSI effects without the need to run individual building-to-building analyses. The applicability of the proposed approach is based on globally available data regarding the soil parameters, the foundation, and the building taxonomy, all necessary to define the fragility modifier regressions. The main findings reported herein demonstrate that, especially in soft soil formations, the conventional way of calculating fragility curves, i.e., fixed-base structures subjected to free-field motion, may lead to an incorrect evaluation of the seismic risk.

ESC2021-S30-335

Concurrent seismic events identification and uncertainty quantification via Bayesian convolutional neural networks

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In recent years, a significant increase in the volume and variety of seismological data has been observed. While the prospect of harnessing such a good amount of data to provide insights or improved models is tempting, caution is needed as data problems (sparse, limited, incomplete, corrupted, etc.) might be implicit in many automatic processing procedures. Recently a concurrent-seismic-events problem is identified in dealing with segments from the continuous stream via automatic downloading and pre-processing procedures. 'Multi-event' records might appear when a station simultaneously records a near event as well as other events (i.e. teleseismic events or aftershocks), thus contaminating the main earthquake recording of interest. In this research, we approach this automated multi-event identification challenge as an image classification problem and consider the uncertainties using the scheme of Bayesian convolutional neural network (CNN). Based on time-frequency representation, a CNN is constructed. More importantly, under the Bayesian scheme, uncertainties with respect to the parameters of the neural network are introduced by putting a prior distribution on each weight. During training, the posteriors are learnt through variational inference approach. A dataset that contains six thousand manually inspected and labelled seismic waveforms, sourced from strong motion or broad-band stations at stable and active tectonic areas across Europe, are adopted to train our model. Since an end-to-end CNN model can directly work on data (even on raw data) without hand-crafted feature design, this efficient yet accurate pipeline thereby making a great match with our goal of automatic data processing. In addition, we programmed the proposed approach in Python environment (more specifically, Tensorflow) so that it could be further integrated into existing preprocessing programs, such as Stream2segment, to streamline workflow.

ESC2021-S30-339

Seismic vulnerability and risk assessment of critical city infrastructure: A systemic approach

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Assessment of vulnerability and losses of critical infrastructure exposed to natural hazards is an important step toward safeguarding resiliency of our society. City infrastructure, on the other hand, is composed by various systems and infrastructures like the utility systems, which are interdependent to each other and the

interdependencies are more prominent during and after the adverse conditions like the occurrence of earthquakes. Identification and modelling of interdependencies in the context of a systemic vulnerability analysis is a rather young and complex area of study which has gained importance the last few years. It is now imperative for understanding the impact of dependencies to the overall vulnerability and risk of the city infrastructure. To achieve efficient risk mitigation planning, it is important to know the impact of the systemic vulnerability in the performance of the city infrastructure under different hazard consideration and to identify in a probabilistic or/and scenario based approach the most adverse conditions. To this respect SYNER-G approach proposes a holistic effort toward integrating the hazard input, the vulnerability of individual components and sub-systems, and finally the impact of the interdependencies between the systems to the global vulnerability, considering also the associated uncertainties. To this end the paper presents a comprehensive study for different seismic scenarios of the impact to the global vulnerability and loss assessment, of inter and intra-dependencies among sub-systems and systems composing the water system and other interacting infrastructures in the city of Thessaloniki. Also, while considering different hazard scenario, variation in the site effects which is one of the most essential aspect has been scrutinized. The performance of the infrastructure is mainly checked through connectivity loss between electric power network and water supply system. The outcome of this study aims at providing meaningful risk metrics to city stakeholders and infrastructure owners.

ESC2021-S30-357

Towards better understanding of soil-structure interaction effects using ambient vibration measurements – a case study in Ferrara, Italy

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In order to mitigate the impact of earthquakes on buildings and reduce human losses, the urban planning should be improved based on a better understanding of the variability of ground shaking over short distances during earthquakes. These variations can be due to site effects, but also to interactions between buildings and soil, and among buildings through soil. Buildings may act as secondary sources of waves during earthquake shaking, and thus contribute to the damage pattern. We focus on soil-structure interaction effects which have until now been studied mainly by 2D and 3D numerical simulations, that are always simplified representations. To improve our knowledge about soil-structure interaction, in particular about wave propagation from buildings to the soil, we tackle the topic both by analyzing real data sets and by carrying out numerical simulations. In this study, we present the outcome of the real data analysis of a particular 3D ambient vibration experiment in Ferrara (Italy) based on an extensive installation of sensors (139 vertical geophones) on an athletic field and nine 3-component sensors in two nearby buildings located close and parallel to the athletic field. These buildings are of the same construction type and height, and similar ground plans. Moreover, different methods of geophysical exploration, including SH-wave seismic reflection, were applied to obtain additional information about the soil properties, in particular S wave velocity profiles. The buildings' dynamic behavior, including fundamental frequencies and wave propagation velocities, has been estimated using ambient vibration measurements at different points of the buildings. Finally, analyses of the wave propagation through the buildings and soil layers have been carried out using a deconvolution approach considering different configurations, making it possible to extract the wavefield contribution radiated back from the buildings.

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Evaluation of Soil-Building Resonance Effect in the Urban Area of the City of Matera (Italy)

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Studying the characteristics of urban soils together with the built environment means adopting a holistic vision for the seismic risk of our cities and taking a step forward compared to the current microzonation approach. In the framework of the CLARA project (CLoud plAtform and smart underground imaging for natural Risk Assessment), funded by the Italian Ministry of University and Research, the interaction effect between near surface geology and all overlying buildings has been evaluated in the city of Matera (Southern Italy). Single-station seismic ambient noise measurements (213) performed on the main lytologies (117) and on the principal building typologies (96) allowed estimating the fundamental frequency of urban soils and the first vibrational frequency of buildings. The 488 georeferenced and downloadable surveys (geological, geotechnical, geophysical, and engineering data) have been digitally archived in CLARA WebGIS available at this link: https://smartcities-matera-clara.imaa.cnr.it/). CLARA WebGIS is a useful tool to share the principal outputs derived by crossing all geophysical and engineering data available in the database: (1) the estimation of fundamental resonance frequency for all urban soils; (2) the main vibrational frequencies for 4043 buildings located in the urban area, which have been estimated knowing the height of each building and using the experimental period-height (T-H) relationship derived for 96 buildings of Matera; (3) the resonance effect of each building with respect to the relative foundation soil in the linear elastic domain, evaluated by means of matching the vibrational frequencies of the 4043 buildings with the interpolated frequencies map of the underlying soil; (4) a DSM map, and 5) a building height map obtained from the DSM. Matera represents an important case study because the first vibration frequency for most of the buildings is quite close to those of the foundation soils.

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Soil-structure interaction assessment: First outcomes from seismic measurements in Matera experiment

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Soil-structure interaction (SSI) can be described as the process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil. The importance of SSI is recognized, and studies of this subject, primarily based on numerical modelling and lab tests, showed that it does not necessarily have a beneficial role on the seismic response. To understand better this phenomenon, our study is focused on SSI assessment from the perspective of wave propagation analysis.

In October 2019, for the need of the SSI experiment, we installed a dense array of sensors in a building and on a nearby athletic field at the selected test side in Matera (Italy). During three consecutive days of the experiment, ambient vibration and one M4.6 earthquake (epicenter ~145 km from Matera) were recorded. To better understand the composition of the wavefield recorded on the athletic field and to identify its sources (including those due to possible SSI effects), the first step of the analysis was the estimation of the structure's dynamic behavior and, in particular, the identification of the resonance frequencies of the structure. Second, after localization of the seismic noise source, by checking the back azimuth of the noise filtered around the resonance frequencies of the nearby building, we performed the deconvolution of the wavefield and applied the polarization filter to classify the detected signal. In fact, signals with high energy content at these frequencies in the wavefield recorded on the athletic field might originate from the building itself.

The study shows the preliminary results of the data analysis with the aim to better understand wave propagation and its polarization aspects at the test site.

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Evaluation of source and basin-induced surface waves on seismic performance of large scale structures

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In the case of large structures overlying soil sediments, the ground motion rotational components may affect the same magnitude as the translational components commonly applied in soil-structure interaction studies. These complex components appear in the form of surface waves and are a combination of source effects, path effects and basin effects. The latter are created by multiple diffraction and refraction of the seismic wave propagating through different soil layers in a three-dimensional medium. In this paper, the domain reduction method (DRM) is used to simulate a complete 3D numerical model of wave propagation from source to structure. We evaluate the influence of source type, basin geometry and building position inside the basin. Using an 1D MDOF building model with a rigid foundation, the study compares the generally used SH-wave input motion against a point source, and two canonical basin geometries against an horizontal stratified medium without the presence of the basin. It was observed that the combination of point source and basin effects amplifies the torsional components, transferred to the buildings generating larger roof displacements. Simplification of all parts of the model allowed quantifying the effects that create rotational motions separately and could give insight into the parameters that govern the soil-structure dynamic response including complex effects.

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An integrated geophysical approach for structural behavior characterization of the Gravina Bridge (Matera, Southern Italy)

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In the framework of non-destructive structural health monitoring, we have developed an integrated geophysical approach by using non-invasive, non-destructive and cost-effective seismic and electromagnetic techniques. It is aimed at evaluating the structural properties of the infrastructure (i.e. eigenfrequencies, equivalent viscous damping factors and related modal shapes) and its interactions with foundation soils both in static and dynamic conditions. We have applied and validated this approach on the Gravina bridge, a bow-string bridge located on outcropping calcarenites in the city of Matera (Southern Italy) that extends over 144 m along a single-span steel-concrete deck. The diverse sensors used have been fine-tuned for multi-sensing monitoring at multi-scale and multi-depth levels (i.e. with different degrees of spatial resolution and different soil subsurface depths). The foundation soil characteristics have been evaluated by means of three high-resolution geo-electrical tomographic surveys, one bi-dimensional seismic array data processed using Extended Spatial Auto Correlation (ESAC) and two single station seismic noise measurements analyzed by means of Horizontal to Vertical Noise Spectral Ratio (HVNSR). The main structural behavior of the bridge has been evaluated both overall and in its five distinct key points through permanent and on-demand monitoring by seismic and electromagnetic sensors. The former consisted of accelerometers and velocimeters installed in different geometrical arrangements for permanent earthquake and on-demand ambient vibration recordings, the latter used a microwave radar interferometer placed below the deck. The agreement of the results obtained by different techniques and independent data sets constitutes a validation procedure of the presented approach and sets up the zero-time reference point of the bridge dynamic parameters.

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A testing framework for non-linear site amplification models

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Site effects caused by variations in the near surface have a strong impact on earthquake ground motions. In ground-motion models (GMMs) and seismic hazard assessments this effect is taken into account using site proxies, the most common being the average shear-wave velocity in the top 30m of a soil column; VS30. For strong ground motions and soft-soil sites, non-linear site amplification is expected although observations are rare. Non-linear site amplification is therefore often modeled using numerical simulations. In this study a testing framework to test non-linear amplification models is developed. The amplification models are tested against observed site amplification at high recording stations in Japan. The observed site amplification is derived from the residuals between observations and the predictions of a GMM derived using only distance and magnitude. The test show that for most of the selected sites, a linear amplification model scores better than non-linear models. Moreover, the site response has a large variation between sites, even within similar site proxies. These results suggest that VS30 does not sufficiently capture non-linear site effects and that for the range of ground-motions considered (peak ground acceleration < 0.2 g), including non-linear site amplification in GMMs and building codes may not be recommended. The testing procedure presented in this study is reproducible and can be used to test site proxies as well as site amplification models.

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Influence of hypocentral distance on induced seismicity ground-motion predictions

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Ground motion models (GMMs) associate ground motion intensity measures to various parameters, including magnitude, distance, depth and fault mechanism. Each of these parameters has a different effect on the developed GMM. GMMs are generated from datasets that include specific, typically truncated, ranges of magnitude and hypocentral distance. Hence, even within the model space for which data are available, we cannot eliminate the probability that GMMs are biased (under or overprediction), particularly toward the edge of the data distribution, such as in the near-field. This is particularly important in the case of induced seismicity, due to the small magnitude events and small aperture monitoring networks typically deployed. This study investigates the impact of hypocentral distance truncation on three separate induced seismicity GMMs constructed using independent datasets – the Geysers geothermal field (North California), the Groningen gas field, and the Preston New Road shale gas site. We use linear mixed-effects regression techniques on these datasets to develop separate models for truncated ranges of hypocentral distance. The comparisons show that in using different datasets and models, systematic differences are apparent. Equations derived from the near-source (< 7km) data alone typically underpredict far-field ground motions. On the other hand, models based on data from greater distances provide robust prediction results (with respect to the complete dataset) but typically underpredict in the near-field. We created a synthetic dataset to verify the independency of results and investigate the underlying cause. The results suggest that the application of GMMs with simple attenuation models (e.g. depending on distance and log-distance), developed from datasets with different ranges of hypocentral distances to those of interest, is questionable. The consideration and modelling of near-source data for the development of induced seismicity ground-motion models must be handled carefully to reduce the potential for biased predictions and reduce uncertainties in seismic hazard analysis.

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Improving the configuration of seismic networks in urban areas in order to better understand local site effects and building vulnerability - Bucharest case study

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In this study we present a GIS-embedded methodology for the analysis of seismic network configuration, capable of evaluating which areas should be better monitored by seismic stations, in order to: i) contribute to the understanding of site effects (with impact on microzonation studies); ii) contribute to refined rapid loss estimates (with impact on better targeted emergency response) and iii) provide relevant input for the analysis of building damage (with impact on future seismic design codes and risk analysis). As input data for this methodology we use station locations, characterization of the quality of seismic records, ground-motion models and the analysis of their uncertainties also in relation with local site condition, loss estimates (in terms of affected buildings and casualties), building stock distribution and urban noise levels. By using multi-criteria decision analysis, the importance of specific locations (both existing and proposed) can be assessed and new locations of importance for research and risk reduction activities can be determined. For our case study area (Bucharest), we initially evaluate the performance of available sensors located free-field and in buildings (both professional and low-cost seismometers and accelerometers) - also accounting for aspects of seismic noise revealed by the COVID-19 lock-down period. Most recordings are for earthquakes originating in the Vrancea Zone (which poses the great threat for Romania's capital city). This evaluation helps in determining whether specific equipment or site conditions are suitable - given also noise levels and magnitude thresholds. The input of the recently improved Seisdaro system for rapid loss estimation is used, also with ground-motion estimates from new models for Vrancea earthquakes.

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Stochastic Simulations for the Development of a Ground Motion Prediction Equation for Induced Seismicity, Case Study: Preston New Road, UK

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Directly adapting and implementing pre-existing tectonic ground motion prediction equations (GMPEs) for induced seismicity often produces unsuitable results. Examples include biased predictions, model form incompatibility or high variability (sigma). This emphasizes the importance of developing a specific GMPE compatible with induced seismicity applications. Abundant ground-motion recordings representing a range of magnitude-distance combinations that cover relevant earthquake scenarios are the key factors for regression analysis in deriving empirical GMPEs. In the case of induced seismicity, the earthquake of interest has lower magnitude than used in the development of tectonic models. Extending empirical equations far below the range covered by the underlying data involves great uncertainty and needs to be avoided. On the other hand, empirical data may be sparse, particularly prior to the onset of induced seismicity, and certainly noisy. For this reason, a stochastic approach may be preferable to generate GMPEs (Boore, 2003), effectively treating the earthquake ground acceleration as a random process, with frequency content and duration controlled by a small number of parameters with physical basis.
In this study, we present a GMPE for the Preston New Road (PNR) shale gas site, Blackpool, United Kingdom. The GMPE is developed using a stochastic point-source model calibrated with parameters such as seismic moment (M0), stress drop (Δσ), the path effects (related to Q and geometrical attenuation), and the site-specific exponential decay, κ. These parameters were derived from inversion of the Fourier amplitude spectra (FAS) of induced seismicity records with magnitude lower than 3 (ML<3) recorded in 2018-2019 at hypocentral distances less than 25 km. Local attenuation models were estimated using spectral fitting and coda envelope decay methods resulting in low Q corresponding to more rapid attenuation in the near field than the regional Q. These local Q models then adopted in the stochastic simulations.

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Exploring epistemic uncertainties of probabilistic building exposure models in scenario-based earthquake loss models

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In conventional seismic risk assessment for large-scale building portfolios, the inferred composition of the exposure model is made up of a predefined set of building classes with fixed proportions. Typically this is done through top-down approaches, such as disaggregating population counts of remote sensing data products relying on a fixed number of inhabitants per building class. This practice neglects the presence of epistemic uncertainties in the exposure model. However, since these proportions are inferred from expert elicitation, we propose to view them as informative prior distributions within a Bayesian framework, rather than as definitive compositions. Complementarily, likelihood terms can be obtained by addressing the degree of compatibility between sets of predefined building classes and their attached observable attributes (comprised in a faceted taxonomy). Increased data collection for these attributes will ultimately drive the configuration of conjugate posterior distributions, which in turn will become progressively similar to the

actual composition of building stocks. We exemplify this method for a single subduction earthquake scenario generating uncorrelated and correlated ground motion fields that affects the residential building stock of Valparaíso (Chile) that is classified into two different schemes (i.e., HAZUS and SARA). The disaggregation of their enclosed building classes into building attributes is not only used to assign the actual building classes (surveyed by Chilean structural engineers) in a transparent manner, but also to exemplify a novel probabilistic inter-scheme compatibility mapping. The probabilistic exposure modelling framework is applied to customise synthetic buildings portfolios that recognize the degree of confidence in the exposure (i.e. ranging from divergent to convergent compositions). We show how these epistemic uncertainties differentially impact expected building counts and propagates up to risk estimates (i.e. financial losses). We invite the inclusion of epistemic uncertainty in probabilistically constructed exposure models, while including the collection of standardized data.

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Seismic hazard assessment using time-dependent models for an induced seismicity case in the UK

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The probabilistic seismic hazard assessment (PSHA) is a well-known procedure that follows a Poisson process, in other words, a memory-less process is carried out where the occurrence rate of events is constant in space and time. To this end, foreshocks and aftershocks are removed from the earthquake catalogue of past seismicity by a process known as declustering and then with a proper magnitude of completeness periods, magnitude frequency distributions are estimated describing the rate of earthquakes per year at the site or region of study. However, although this practice is reasonable enough for most of the cases, it will represent the seismicity of the mainshock events, and for some particular cases, such as regions affected by aftershock sequences or induced seismicity, this would not represent accurately the seismicity of the site, leading an underestimation of the computed seismic hazard levels. Herein, we study the seismicity for a hydraulic fracturing shale gas site in the UK with different methodologies such as the epidemic-type aftershock sequence (ETAS) model and the seismogenic index model and then we estimate the contribution of this type of induced seismicity to the seismic hazard at the site and compare the results with the conventional PSHA outcomes for seismic risk assessment purposes.

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When science meets industry: Advances in engineering seismology stemming from practice

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Evaluating the minimum number of earthquakes in empirical site response assessment: input for new requirements for microzonation in the Swiss building codes

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Site-specific hazard analyses and microzonation are important products for densely populated areas and for facilities of special risk. The empirical amplification function is classically estimated using the Standard Spectral Ratio approach (SSR - Borcherdt, 1970). The SSR simply consists in comparing earthquake recordings on soil sites with the recording of the same earthquake on a close-by rock reference. Recording a statistically significant number of earthquakes can be however difficult, especially in low seismicity areas. Among others, the appendix SIA 261/1 to actions on structures of the 2020 Swiss building code provides specifications on how to perform site-specific hazard analysis. In this frame, we were tasked to define recommendations regarding the minimum number of earthquake recordings to be used in empirical site effect assessment.

We carefully compute empirical amplification functions at 60 KiKnet sites in Japan from several hundred earthquakes and at 3 Swiss sites from several tens of earthquakes. We performed statistical analysis on the amplification functions to estimate the geometric mean and standard deviation, and more importantly to determine the distribution law of the amplification factor as function of the number of recordings. Independently to the site and to the frequency, we find that the log-normal distribution is a very good approximation for the site response. Based on that we develop a strategy to estimate the minimum number of earthquakes from the confidence interval definition. We found that a minimum of 10 samples are necessary to have a good statistical significance of the results. As a general rule, 10 uncorrelated earthquakes is the minimum number of earthquakes to be considered, but the higher the number of earthquakes the lower the uncertainty on the geometric mean of the site amplification function. Moreover, the linear site response is observed to be independent to the intensity of the ground motion level.

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Investigating the site-term of strong motion duration from a systematic analysis of the KIK-NET waveform database

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Ground motion duration is a key parameter in the description of ground shaking caused by earthquakes. Duration has been correlated to earthquake-induced phenomena (e.g. liquefaction), the response of buildings and site amplification functions; it depends primarily on the seismic source properties and path-related mechanisms, but site-specific conditions have also a proven significant effect. We have carried out a study focusing on the role of site conditions, part of the project "Earthquake research for Swiss nuclear facilities" commissioned by the Swiss Federal Nuclear Safety Inspectorate (ENSI). We systematically evaluated the duration of earthquakes' ground motions from the KiK-net waveform database.

The obtained duration measures were clustered by magnitude bins, and we defined a median duration versus distance curve for each interval. The deviation from the median observed at each station has been identified as the site-term of duration. With this approach, we determined the relative factors of local

prolongation/shortening for ~110 KiK-net stations. We then collated these factors with a database of site proxies (e.g. VS30, extracted from the KiK-net site condition metadata) and multi-scale topographical parameters (slope, curvature). Our main results are:

- site effects on duration are not negligible (generally within +/-30%);
- site effects are primarily related to 1D resonance phenomena (moderate correlation for M > 4.5 with proxies referring to 1D resonance);
- it is difficult to decouple 1D and 2D resonance phenomena; the latter are second-order contributions affecting sites with moderate negative topographical curvature (edges of basins, valleys).

Our ongoing work is dedicated to the comparison of the results obtained for the Japanese sites with other waveform datasets (e.g. Engineering Strong-Motion database). In this perspective, the completeness, reliability and compatibility of event and site metadata among the various databases play a key role.
Keywords: ground motion, duration, KiK-net, site response, site metadata.

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How Well Can We Predict Site Amplifications So Far?

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It is known that sediments within a few hundred meters from the ground surface can significantly modify the earthquake-induced ground motions. To evaluate the amplification, we currently have a few options: (a) use pre-defined parametric amplification prediction models which are functions of site characterization parameters, e.g., shear-wave velocity in the top 30 m, sediments thickness, and site resonant frequency; (b) conduct ground response analyses (GRA) which simulate the propagation of vertically-incident seismic waves through a one-dimensional (1D) ground model; (c) correct the horizontal-to-vertical spectral ratio when a few earthquake recordings are available at the target site, and (d) use machine learning techniques.

Input information of the above methods varies from topographic proxies available on a regional or even global scale, to simple site parameters from in-situ measurements, to detailed 1D velocity profiles, and to on-site earthquake recordings. To estimate the site response at a target site, it is logical to choose a model/method that capitalizes on all available information at the site. In this study, we first establish a toolbox of site amplification models which directly utilize site data with different levels of complexity/accessibility. We then evaluate and compare their performance in predicting observed site responses. This is achieved by using 1725 K-NET and KiK-net stations at which site metadata is collected from an open-source database compiled by Zhu et al. (2021). Observed site-response data was derived by Nakano et al. (2015) from recordings in the Fourier domain with reference to outcrop bedrock (Vs=3.45 km/s).

Our results show that the proxy-based site-response models using a combination of a few site parameters can achieve a similar or even better performance than GRA. The deliverables of this study could help improve the precision of site correction in real-time or rapid assessments of the spatial distribution of ground-motion intensity.

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Multi-period shake maps for earthquake response and engineering forensics

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ShakeMap, a tool widely used for earthquake analysis and response, has new functionality that will be of interest for critical facility and other earthquake engineering evaluations: the ability to provide multiperiod spectral accelerations (SA) in addition to its traditional peak acceleration and velocity, intensity, and three standard (0.3, 1.0, and 3 sec) SA periods. The latter IMs were needed for FEMA's Hazus loss estimates, for industry, and in the PAGER system. The new multiperiod implementation of ShakeMap, introduced by Worden et al. (2018), overcomes prior limitations by implementing an interpolation scheme based on the conditional multivariate normal distribution (MVN).

The MVN accommodates the interpolation of ground motion fields correlated spatially, across spectral periods, and more generally across any IM for which a correlation model has been developed. The method simultaneously conditions on observed IMs and provides the conditional IM mean and standard deviation at all prediction sites. The additional 20 periods can provide a more complete, interpolated spectrum for any location, facilitating more sophisticated loss calculations, post-event structural forensics, and building-code based Disproportionate Damage Triggers which mandate inspection and retrofitting. For such engineering applications, we have released the ShakeMap Sampling Tool (SST) to return IM values—along with their estimated uncertainties—at user-specified locations by sampling the closest ShakeMap grid value. We are implementing an on-demand solution for custom shaking estimates at exact locations by running a cloud-based instance of the ShakeMap code specifically for those sites. Loss models can similarly use this tool for portfolio analyses, in conjunction with structural or infrastructural fragilities, though that functionality (along with automatic alerting) is the basis for the USGS ShakeCast system. All these advancements were motivated by interactions among seismologists, civil engineers, and critical utility and lifeline operators.

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The SIGMA-2 program: industry-funded research to enhance the reliability of seismic hazard assessment

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SIGMA-2 is a research program on Seismic Hazard Assessment (SHA). It coordinates efforts at the international level to improve the reliability and the accuracy of seismic hazard studies for industrial critical facilities. This program is funded by a consortium of 7 industrial partners involved in the nuclear energy sector (EDF, CEA, PG&E, SWISSNUCLEAR, ORANO, CEZ & CRIEPI). It supports more than 50 research actions conducted by academic and private scientific partners.

Current safety regulations require that critical infrastructures, such as nuclear power plants, prove their resilience to very-low-probability seismic hazard levels. For this purpose, a particular effort has been made by seismologists and seismic engineers to develop sound seismic source models and sophisticated approaches which account for a representative range of epistemic uncertainties. In addition, the crucial importance of safety and financial stakes associated with nuclear facilities require a special attention to local site conditions. Engineers have to adapt practices in order to properly account for such effects. This definitely creates a need for more site-specific, non-ergodic (probabilistic) hazard models, devoid of over-conservatism. We here present an overview of SIGMA-2 scope and research results in the field of seismic hazard assessment. Research encompasses various fields such as seismotectonics, seismology and earthquake engineering, with a particular focus on low-seismcity regions. For example, we present new methods and data to improve earthquake locations and magnitudes. We introduce new ground-motion models for reference rock (i.e. unamplified) conditions, and present advances towards fully non-ergodic GMPEs. We summarize advances in site-response characterization and simulation techniques. Finally, we discuss methods and current applications of the Bayesian framework, for the calibration of models parameters (occurrence rates, maximum magnitude…) or for the objective evaluation of PSHA input models and results with respect to observations.

Data, models and results are in open-access, and available at www.sigma-2net.

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Assessing the epistemic uncertainty captured in a ground-motion model for a UK site-specific seismic hazard assessment

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One of the key tasks when developing a ground-motion model (GMM) is to demonstrate that it captures an appropriate level of epistemic uncertainty. This is true whether multiple ground motion prediction equations (GMPEs) are used as logic-tree branches or whether a backbone approach is followed.

As part of a seismic hazard assessment conducted for the site of a proposed UK new-build nuclear power plant, we undertook a detailed assessment of the epistemic uncertainty captured in our GMM, which was developed using multiple GMPEs adjusted for site-specific shear-wave velocity and kappa. This assessment consisted of the following complementary approaches. Firstly, shaded trellis plots showing the various fractiles of the GMM were examined for relevant magnitudes, distances and structural periods, specifically to search for evidence of “pinching”, where the fractiles narrow excessively. Secondly, Sammon’s maps for each structural period were examined, including GMPEs that had been excluded from the logic tree, to check the spread of the GMPEs for all relevant magnitudes and distances in a single plot. Thirdly, contour plots of the standard deviation of the logarithms of predicted ground motions from each branch of the logic tree (so called sigma_ln mu) were drawn and compared with plots drawn for other relevant hazard studies. Fourthly, uncertainties implied by a GMM derived using the backbone approach and Campbell (2003)’s hybrid stochastic-empirical method were compared to those of the proposed multi-GMPE GMM.

Finally, the spread of the fractiles of hazard curves resulting from implementing the GMM were examined for different return periods to check whether any “bands of lower uncertainty” in ground-motion space resulted in “bands of lower uncertainty” in hazard space. The conclusion of this assessment was that an appropriate level of uncertainty was being captured by the proposed multiple GMPE logic tree.

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Assessing the value of information for site-response analyses

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Seismic hazard assessments are key to the safe design of buildings and critical infrastructure such as power plants. Outcomes from these assessments inform design parameters to ensure infrastructure resilience to earthquakes, and, as such, the safety of the local population.

In seismic hazard assessments the importance of knowing different input parameters accurately depends on their weights within the hazard model, which comprises of seismic-source, ground-motion and site-response components. Many aspects of the assessment require inputs based on knowledge and data from experts. When it comes to decisions about data collection, infrastructure developers and owners and seismic hazard analysts need to estimate the possible added value brought by the data along with the budget and time available for its collection. In other words, they need to answer the question “Is it worth paying to obtain this information?”

Assessing the value of information (VoI) before data collection should lead to optimising the time and money that one is willing to invest. VoI is computed as the difference between the prior and posterior outcomes. In this study, we propose a method that combines available data and expert elicitation to facilitate the decision-making process within seismic hazard assessment, specifically within the site-response component. The approach combines Bayesian networks and influence diagrams to translate the causal-relationships between the input parameters in site-response analysis (e.g., shear-wave velocities) and Bayesian inference to update the model when new evidence is considered. Here, we assess VoI for a specific hypothetical site. Consideration of the VoI should enable a prioritisation of which information to collect first and to estimate the potential benefits of collecting one type of data over another. In other words, it should determine “Which data gives us more bang for our buck?”

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Identification of reference rock sites in Italy: methodology, results and seismic regulations fallouts

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The identification of reference rock sites, i.e., rock sites without seismic amplifications, is very important for several engineering applications. The common practice in seismic norms is to identify sites where the time-averaged shear-wave velocity in the uppermost 30m (VS,30) exceeds a given value, such as 800 m/s. However, several studies have been showing local amplifications with resonance peaks at intermediate and high frequencies at sites having VS,30 > 800 m/s.

In this work, we present a multi-proxies method for the identification of the reference rock sites in regions with medium to high seismic activity, i.e. areas where there is a fairly wide availability of seismic records. The methodology (RRIM, Lanzano et al. 2020) is applied to the set of 1600 recording stations, available in the ITalian ACcelerometric Archive (ITACA; D’Amico et al., 2020), with different levels of site characterization. Given the large number of sites, the pre-selection of candidates is performed via residual analysis, and, later, RRIM is applied allowing the identification of 116 reference rock stations in Italy, ordered on the basis of a ranking.

Additional results of this study are corrective factors for ITA18 (Lanzano et al., 2019) generic-rock predictions to obtain the corresponding FAS (Fourier Amplitude Spectra) and SA (Spectral Acceleration) values at reference rock sites. The correction has a significant effect at high frequencies, reducing the ground-motion by up to a factor 1.7 at f = 10Hz. We also develop a tentative model, parametrized in terms of $V_{S,30}$ and κ_0 , i.e. the high-frequency decay parameter (Anderson and Hough, 1984), from 3Hz onwards; this model is able to fit the averaged reference rock spectra with κ_0 = 0.01s and $V_{S,30}$ = 900m/s. This work is carried out in the framework of the SIGMA2 project.

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Earthquake multi-cycle modeling for realistic heterogeneous rupture parameters

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In order to reduce uncertainties in strong ground motion predictions, it is necessary to use a deterministic approach that employs detailed information on the target fault and site. The recipe for predicting strong ground motions developed by Irikura and Miyake (2001, 2011) has been well validated by past and real-time earthquakes and is used successfully in practice. Further improvements in the Recipe require understanding and revision of basic physical assumptions on earthquake rupture embodied in the Recipe. However, some critical rupture parameters, e.g., stress drop, rupture velocity and slip rate function, are poorly resolved by methods based on the kinematic approach.

In this project supported by the Secretariat of Nuclear Regulation Authority (NRA), Japan, we generate sets of hundreds of spontaneous physically self-consistent rupture models using multi-cycle simulations under the rate-and-state friction law on a heterogeneous fault. Applying this methodology to 1992 Landers earthquake (Galvez et al, 2019), we generate rupture models that reproduce the observed slip, rupture velocity and ground motions. Models are validated by comparison with: (1) source scaling relations obtained from seismic source inversions, (2) ground motion prediction models, and (3) observed fault displacements.

From the heterogeneous rupture models, we studied one-point correlations between parameters and two-point cross-correlations considering the possible spatial offset between slip, peak slip rate PSR, stress drop $\Delta\sigma$, rupture velocity Vr, parameters of the source time function STF, as well as the rate-and-state critical distance Dc, the only initial heterogeneity parameter in the multicycle modeling. Dynamic STFs are well approximated by the regularized Yoffe function. The main findings are: (1) Positive correlations are confirmed between Slip, $\Delta\sigma$, PSR, Vr, and STF; and (2) In models having strong rupture directivity, high PSR areas are located on the outer edge of the large slip areas. Other parameters have no spatial offset.

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High frequency ground motion patterns at reference rock sites in mainland France

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The objective of this work is to characterize the high frequency behavior of reference rock ground motion in a weak-to-moderate seismicity region as mainland France. First, reference rock sites in France are identified, using the approach proposed by Lanzano et al. (2020) based on different proxies. Then, high frequency kappa parameter is estimated at identified reference rock sites.

We observe that rock sites exempt from any amplification effect are very rare in France. Indeed high frequency amplifications related to the presence of a thin sediment layer, or weathered rock, above stiffer rocks are often identified at French seismic stations. Moreover, sensor installation conditions can also have a significant impact on the high frequency content of the recorded ground motion. As a consequence, these pieces of information must be carefully taken into account when dealing with high frequency behavior of ground motion and kappa parameter estimation. Epistemic uncertainties in kappa estimates stemming from different estimation approaches (i.e. kappaAS and kappaTF) are evaluated and discussed in relation to the factors with potential impact on high frequency ground motion previously identified. Finally, reference rock sites in France did not show significant correlation with average shear wave velocity in the top 30 m (Vs30).

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InSAR techniques as a tool for assessing the vulnerability of cultural heritage sites - The SCIENCE Project

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SCIENCE is a large bilateral project between Greece and China introducing advanced engineering research to the service of monument protection. In particular, SCIENCE develops a new approach to estimate the vulnerability of cultural heritage monuments through the innovative technique of multitemporal Synthetic Aperture Radar Interferometry (MT-InSAR), which detects the ground deformation in time and space. In the framework of this project are used: a) open access ERS-1 & 2 and Envisat SAR datasets, Copernicus SAR datasets (Sentinel-1) and third part mission high resolution SAR datasets (TerraSAR-X and Cosmo-SkyMed) and b) the commercial optical datasets of Pleiades 1A and Pleiades 1B (with spatial resolution up to 0.5m). The four case studies under investigation are: a) the Acropolis of Athens and b) the Heraklion City Walls in Crete (Greece) and c) the Ming Dynasty City Walls in Nanjing and d) Great Wall in Hebei and Beijing (China). Spaceborne SAR interferometry has proven to be a powerful remote sensing tool for detecting and measuring ground deformation (including major seismic events and induced seismicity) and studying the deformation's impact on man-made structure with a millimetric accuracy. Considering the limitations of conventional MT-InSAR techniques, such as Persistent Scatterers Interferometry (PSI), a two-step Tomography-based Persistent Scatterers (PS) Interferometry (Tomo-PSInSAR) approach is proposed for monitoring ground

deformation and structural instabilities. The high-resolution optical data is used for the identification of the persistent scatterers. Furthermore, the validation of the results is taking place through in-situ measurements (geological, geothechnical e.t.c) and data for the cultural heritage sites' structural health. In conclusion, SCIENCE project aims to introduce a risk assessment analysis of the cultural heritage monuments and their surrounding areas to benefit institutions, organizations, stakeholders and private agencies in the cultural heritage domain through the creation of a validated pre-operation non-invasive system and service.

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When science meets standardization: the case of the national seismic hazard assessment for Germany

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Probabilistic seismic hazard assessments (PSHA) represent the most well established means to calculate seismic load parameters for seismic building codes or other anti-seismic design provisions. This talk will present the lessons learned from the development of the seismic load parameters for the upcoming German national design regulation (DIN EN 1998-1/NA) and related interactions with the engineering community. This PSHA project was developed for about seven years on behalf of the Deutsches Institut für Bautechnik (DIBt; German Institute for Civil Engineering) and was launched by the respective national committee on standardization of the DIN. We will describe this new version of the national seismic hazard assessment (Grünthal et al., 2018) and present the key questions which have emerged from the use of this new model by the engineering community. We will first discuss the key issue of uncertainties evaluation, visualisation and communication, which highlight how modern methods used to capture epistemic uncertainties (e.g. logic trees) are generating probability distributions which are difficult to handle for many practical applications. We show how to visualize these uncertainties and identify their controlling factors. We will also discuss the critical issue of the choice of the mean or fractiles (e.g. median) of the resulting probability distribution to represent the seismic action used in the building code, and its potential implications for seismic safety. In a second step, we will show that new methods are needed to evaluate the consistencies of this new generation of models with other logic-tree based PSHA studies obtained in neighbouring countries (France, Switzerland) or at the European level (ESHM20). Finally, recent developments (e.g. testing strategies) that have been initiated by the interactions with the civil engineering community and influence the way the model is updated to take into new needs (e.g. seismic zonation for Nuclear waste disposal projects) will be presented.

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Towards a bridge between observational and engineering seismology through the use of simulated ground motions in engineering applications

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Traditionally, ground motion simulations (GMsim) of past events have been predominantly dealt with by observational seismologists. Since its advent, we note that simulated ground motions have been increasingly used to augment existing strong ground motion databases on the global scale. We also find that simulated ground motions have the potential to become standard practice in earthquake engineering due to ever-increasing computational capabilities and advances taking place in earthquake source modeling and site characterization techniques. The use of simulated motions could help explore seismic resilience of urban regions and distributed infrastructure while taking into account near-surface nonlinearity phenomena and other site effects, including those from the influences of basins, surface topography, and soil stratigraphy. Additionally, simulated ground motions have the potential to provide site-specific ground motion datasets engineers seek while covering a wide range of parameters related to event magnitude, source-to-site distance, and directivity. However, accurate and reliable ground motion simulations of past and scenario events rely on well-defined earthquake sources, path, and robust site models. In this talk, we present a review on the state-of -knowledge and ongoing research on the use of simulated ground motions in earthquake engineering analyses. We discuss findings from recent studies that feature the use of the simulated datasets in seismic hazard, loss and damage estimations, nonlinear response analyses of single- and multi-degree-of-freedom structural models, city-soil interactions, and dynamic modeling of critical infrastructure. We also address alternative GMsim approaches and delineate their modeling assumptions and frequency resolution in relation to the input site models.

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On the performance of low-cost seismic sensors for Structural Monitoring: a case study in Magurele, Romania

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Monitoring the dynamic parameters of buildings before, during and after an earthquake has proven to be a useful tool to track the integrity of the structures affected by strong earthquakes and, consequently, to understand their level of safety in case of such hazards.

The large Vrancea intermediate-depth earthquakes pose a real threat to buildings in the Bucharest (Romania) metropolitan area. In view of a strong local earthquake, many efforts have been made recently to improve structural monitoring systems in buildings. Two such examples are the PREVENT project, recently funded by The Executive Agency for Higher Education, Research, Development and Innovation Funding, Romania (UEFISCDI) and the EU TURNkey project - Towards more earthquake-resilient urban societies through a multisensor-based information system enabling earthquake forecasting, early warning and rapid response actions, in which the seismic monitoring system of the building of the Institute of Atomic Physics (IFA) in Magurele - a city close to Bucharest - was upgraded by installing new low-cost seismic sensors. Currently, the IFA building monitoring system consists of 3 professional accelerometers (Metrozet TSA-100S) located in the basement of the building, on the 6th floor and at the top, on the 10th floor and 7 RaspberryShake (RS) stations. Of the latter, five are RS4D type and two are RS3D type. Three RS stations are co-located with the professional stations and the rest are installed on the first, third and seventh floors of the building. In this paper, we present the results of a detailed comparative analysis performed in both spectral and time domains on the seismic and ambient noise recordings obtained from the professional and low-cost sensors installed in the building. We discuss the results in terms of noise variations, peak ground values and dynamic characteristics of the building.

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Modeling constraints in ground-motion development

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Nonlinear response history analysis has become an increasingly important tool in the design process of critical facilities and performance-based design projects in regions with high seismic hazard. In response to the growth in these types of projects, engineering seismologists have become responsible for developing design earthquake time series for a variety of seismic settings, site conditions, and project specifications. Coordinated research projects like the PEER NGA programs have provided the engineering community with robust libraries of recorded and uniformly processed earthquake time series, but formal guidance on seed selection and modification is generally limited and irrespective of the type of infrastructure, even though the relationships between various earthquake intensity measures (IMs) and engineering demand parameters are well-studied for many structures. For example, the dynamic response of tall buildings in near-field settings can be heavily influenced by PGV and pulse characteristics in the design ground motions, whereas embankment dam response is generally more sensitive to significant duration and Arias Intensity. Developing an unbiased sample of design ground motions that capture an appropriate range of the IMs of interest for the design hazard level is necessary to produce meaningful results in the structural analysis. We provide examples herein from real projects where we have bridged the gap between academia and professional practice to select and modify earthquake time series, considering conditional IMs, showcasing many of the newly developed models and their potential applications. Regulatory and peer review acceptance of design ground motions also commonly requires the verification of target IMs and an evaluation of the extent of variability reflected in the sample, after modification. These topics are explored in detail to provide recommendations for practicing engineering seismologists tasked with providing the appropriate level of earthquake demand for critical infrastructure projects.

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Source scaling relations of interface subduction earthquakes for strong ground motion and tsunami simulation

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The recording on high-resolution, broadband seismic networks of several great interface subduction earthquakes during the last decade provides an excellent opportunity to extend source scaling relations to very large magnitudes and to place constraints on the potential range of source parameters for these events. At present, there is a wide range of uncertainty in the median rupture areas predicted for a given seismic moment by current relationships for subduction interface earthquakes. In the majority of these studies the relationship between the two variables for each equation are estimated by linear regression independently in an effort to find the best fit that would describe the specific dataset. This common approach results in optimum results for each individual scaling relation however, the final set of equations is not usually tested for self-consistency in the sense that they do not enable moment or moment magnitude, rupture length, width, area, and slip to be estimated from each other.

We develop an updated set of earthquake source scaling relations that will reduce epistemic uncertainty and improve the accuracy of seismic hazard analysis and the prediction of strong motion characteristics and tsunamis of future subduction earthquakes. We compile a database of slip models of interface earthquakes

that occurred worldwide with moment magnitudes ranging from M 6.75 to M 9.1. We characterize the seismic sources based on well-established criteria to estimate the asperity areas and the average slip on the faults and we use these parameters to compute an updated set of magnitude scaling relations of the various characteristics of the fault. Additionally, we follow an alternative approach to quantifying slip models for use in developing characteristic slip models of future earthquakes. This involved analyzing the 2D Fourier transforms of the slip functions of the compiled database and deriving a wavenumber spectral model of the slip distribution.

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In search of hard-rock attenuation in Central-Eastern North America

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The attenuation parameter κ is the principal site parameter controlling high frequencies at short distances, and its large uncertainty in hard-rock affects seismic risk for critical infrastructure. Considering classical reference rock κ values from literature, analytical studies suggest large increases in ground motion above 10-20 Hz for hard-rock sites in Central-Eastern North America (CENA) compared to soft-rock sites in the West. Yet observed ground motions from CENA do not show this large increase.

In the past few years, through an industry-academia collaboration, we have sought to better understand hard-rock attenuation in CENA. We first revisited the original data used in the 1990s to perform an 'anatomy' of how the first κ values were derived. We coupled the original broadband estimation methods with other current band-limited approaches, introducing a tool to assess frequency dependence. One of the main findings was the possible trade-off between site attenuation and site amplification. We then performed new analyses at recently characterised hard-rock CENA stations to further understand the attenuation-amplification coupling on rock.

Several studies to date have rejected negative κ values as non-physical. We find that high-frequency resonances from shallow impedance contrasts can yield highly variable, non-positive apparent κ values. Such low values, reflecting the net effect of damping and amplification, may eventually control ground motion scaling if used to derive rock correction factors. Since the interpretation of κ0 as solely damping is not consistent with observations, it is recommended that it be reevaluated.

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Benefits and implementation challenges of non-ergodic site response in seismic hazard analyses: Case studies

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Partially non-ergodic seismic-hazard analyses (SHA) that utilize site-specific site response in the ground motion model (GMM) have been employed for critical structures such as nuclear facilities for many years. Recently, non-ergodic SHA has been utilized for other types of projects ranging from low- to high-rise structures. We present recent case studies of non-ergodic SHA for various types of structures. We highlight the benefits and discuss implementation challenges and how they were addressed.

Ergodic GMMs generally estimate site response based on site parameters such as the time-averaged shear-wave velocity in the upper 30 meters (VS30) and/or basin depth terms (e.g., Z1.0 and Z2.5). Global average conditions for a given VS30 generally show gradual increases in shear-wave velocity with depth; consequently, GMM-based site-response estimates are not well suited for sites with conditions that deviate appreciably from the average condition, such as sites with large impedance contrasts. In theory, ground-response analyses (GRA) can be used to develop more accurate site-response estimates, which can be incorporated into the SHA. However, modeling uncertainties significantly impact the reliability of such analyses in many cases. Moreover, uncertainties in material type and the associated dynamic properties generally increase with depth. Therefore, the consideration of local ground-motion records in addition to GRA can be especially important for tall structures on deep soil sites. We present a case history for a high-rise wherein the pseudo-spectral acceleration (PSa) would have been under-predicted at the site period and over-estimated at shorter periods if ergodic SHA and GRA alone were performed. Additionally, we present two case studies that highlight implementation challenges associated with non-ergodic SHA, including the consideration of hard-rock reference conditions and ground-motion records that were influenced by kinematic soil-structure interaction. These examples illustrate that non-ergodic SHA can produce reductions in PSa across certain period ranges, while also capturing site resonances.

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Advancing time-dependent seismic hazard and risk modeling

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Catastrophe (CAT) risk models are commonly used tools in the insurance and reinsurance industries for estimating potential losses due to natural hazards. The current state-of-practice in earthquake risk modeling involves a number of significant modeling assumptions, which mainly neglect (1) the interaction between adjacent faults; (2) the long-term elastic-rebound behavior of faults; (3) the short-term hazard increase associated with aftershocks; and (4) damage accumulation of building assets resulting from the occurrence of multiple earthquakes in a short time window. Several recent earthquake events (e.g., 2010 Canterbury earthquakes, New Zealand; 2016 Central Italy earthquakes; 2019 Ridgecrest earthquakes, USA) have emphasized the need to re-evaluate these assumptions and investigate alternative methodologies to account for the short- and long-term time-dependent characteristics of earthquake risk. Our ongoing research addresses this challenge, leveraging the insights of scientists at Willis Re (through the award-winning Willis Research Network). Our work specifically centers on the development of an end-to-end approach for more realistic time-dependent earthquake risk modeling in three stages. The first stage focuses on fault-based hazard assessments, unifying state-of-the-art advances in this field within a single harmonized framework. The framework specifically incorporates the elastic-rebound motivated methodologies of the latest Uniform California Earthquake Rupture Forecast (UCERF3) and explicitly accounts for fault-interaction triggering between major known faults. The second stage of the research investigates the use of the Epidemic-Type Aftershock Sequence (ETAS) model in earthquake risk assessments, which has not yet been explored in the literature. The third stage of the research aims at developing damage-dependent vulnerability curves accounting for the accumulation of damage in building assets over successive earthquakes. Our holistic approach to time-dependent risk modeling will provide valuable industrial guidance on related issues, including the effectiveness of hourly and reinstatement clauses that are commonly implemented in CAT insurance and reinsurance contracts/products.

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Shaping research from challenging discussions with industry: a few examples related to site effects

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This presentation will report a few examples related to site effects, showing how some challenging - and sometimes frustrating - exchanges between seismological and civil engineering communities resulted, in the long run, in fruitful research projects for the benefits of both parts. One of the incentives of the SESAME project two decades ago was the impossibility to propose a simple alternative to the VS30-based site classification considered in EC8. The success of this project contributed not only to shape the minds for modifying site classification criteria in the ongoing EC8 revision, but also to introduce alternative, non-invasive site survey tools. Despite some initial reluctance, further investigations carried on within various collaborative projects (PEGASOS, SIGMA, SINAPS@, INTERPACIFIC) with the nuclear industry, including careful benchmarking studies, ended up two decades later with practical guidelines for the broad use of non-invasive techniques (and a lot of methodological developments and software tools).

Similarly, the initial unwillingness of most important energy operators to support the deployment of the French accelerometric network in the early nineties, was replaced after three decades by their proactive contributions, and sometimes leadership, in the building of ground motion databases with rich site metadata, and the deployment of sensitive instruments.

Finally, complex amplification effects linked with subsurface geometry or rheology, though known for a long time, could never be properly introduced in building codes or microzonation studies. However, the needs of the nuclear industry for some specific sites led to several research projects or advanced site-specific hazard studies (CASHIMA, E2VP, PRENOLIN), that allowed, through careful international benchmarks, to assess the prediction capability of numerical simulation tools, which in turn paved the way for the building up of metamodels affordable enough to be used in microzonation studies.

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Numerical modelling of rupture dynamics constrained by past seismicity for ground motion prediction

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Predicting ground motion by physics-based modelling, particularly at magnitudes and distances that lack empirical data, has been an attractive avenue for seismic hazard assessment studies. In the proximity of a fault, both source- and site-related complexities control the final ground motion; understanding the impact of these complexities on ground motion, therefore, matter to reason and constrain the associated variability of ground motion. Initial stress heterogeneity is one of the acknowledged source-related complexities to account for, and we hypothesize that it results from the superposition of residual stresses left by past seismicity. Here we develop a new method to generate initial stress heterogeneity that is governed by the regional statistics of past seismicity, including the Gutenberg-Richter frequency-magnitude distribution and the hypocentral depth distribution. Our modelling conforms with fracture mechanics theory and applies scale-dependent fracture energy, and we calibrate rupture models to satisfy empirical earthquake scaling laws and ground motion prediction equations. We validated our method through Mw 7 earthquake models suitable for California and investigated the impact of background seismicity on rupture dynamics and near-field ground motion. Our results, with 1 Hz resolution, suggest a notable spatial variation of ground motion metrics close to faults due to background stress heterogeneity. The ongoing work comprises the verification of preliminary results on different cases of rupture stochasticity, and increasing model resolution to 3 Hz. The outputs of our study promises to disentangle source and site effects on near-field ground motion with the use of regional statistical data.

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Induced seismicity: observations, modelling, monitoring, discrimination and risk management strategies

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Injection-driven seismic hazard and loss modeling using the Seismogenic Index

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In the past decade, several parts of the United States, including Oklahoma, have experienced unprecedented seismicity rates that have been attributed to wastewater disposal activities carried out by the oil and gas industry. In this study, we perform a probabilistic assessment of the time-dependent seismic hazard in Oklahoma and incorporate these results into an integrated seismic risk model to assess the evolution of the state-wide economic losses, including a conservative forecast through 2030.

Our risk model employs an injection-driven earthquake rate model based on the Seismogenic Index (Shapiro et al. 2010; 10.1190/1.3353727), a region-specific ground motion model, a recent Vs30 map, HAZUS exposure data and updated vulnerability curves for both structural and non-structural elements, and contents. The calculations are performed using a stochastic Monte Carlo based approach implemented in the OpenQuake software engine. The resulting one-year seismic hazard maps illustrate the incompatibility of the regional seismic provisions with the recent seismicity. During the peak of seismicity in 2015, the seismic risk was 275 times higher than the background level, with the vast majority of losses originating from damages to non-structural elements (66%) and contents (20%). We believe that our seismic risk model is a significant upgrade to previous efforts, with our loss estimates being in reasonable agreement with the paid insurance claims. Even though our risk estimates are fairly stable overall, they show significant sensitivity to the Ground Motion Model selection. Our risk model can be adopted in an ongoing manner, helping stakeholders to quantify the benefits of various risk mitigation measures and to define acceptable production levels. Finally, this framework is generic enough to be applicable to any region and scale and can also tackle hydraulic fracturing.

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Integrated seismic and ground surface deformation monitoring of the Cornegliano Laudense (Northern Italy) gas storage

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A new underground gas storage facility has recently been built by Ital Gas Storage S.p.A. exploiting a depleted natural gas reservoir near Cornegliano Laudense (Lodi) in Northern Italy, about 30 km south of Milan. The Company has commissioned on a voluntary basis an integrated seismic and geodetic monitoring in accordance with the Italian Guidelines for the monitoring of underground activities. The design and management of the monitoring system has been entrusted to two Italian public research institutes, namely OGS and CNR-IREA, which have associated themselves.

The local seismic network (Rete Sismica di Cornegliano Laudense – RSCL) is managed by OGS. It consists of 9 stations, each one equipped with a borehole broadband seismometer deployed at a depth of about 75m and an accelerometer at surface. A GNSS permanent station was also deployed within the storage area. The RSCL

integrates as well off-line data recorded by other stations located in the surroundings and belonging to the National or Regional Seismic Networks. The RSCL monitoring system is fully operating since 1/1/2017.

Surface ground deformation monitoring is carried out by CNR-IREA by exploiting satellite Synthetic Aperture Radar (SAR) data that are processed through Differential SAR Interferometry (DInSAR) techniques. At present, SENTINEL-1 data with 6-days sampling are used. Interferometric analysis is constrained with data from 4 other surrounding GNSS stations that are within a few tens of km of the local GNSS station.

As recommended by the ministry guidelines, the natural seismic activity and surface ground displacement have been analysed before the start of storage operations on December 2018, in order to define the baseline. In this presentation, we will describe the integrated monitoring infrastructure and show the results of the analysis of both the seismic and geodetic baseline, as well as some results obtained during the first period of gas-storage activity.

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Correction for local site amplification on dwelling mound structures

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During recent years a sophisticated seismic hazard and risk analysis has been performed for the Groningen region, the Netherlands. The motivation for the analysis is the induced seismicity due to the gas extraction from the Groningen onshore field. The Ground Motion Model (GMM) is one of the components of the seismic hazard analysis. So far, dwelling mounds were not included in the GMM. Dwelling mounds were constructed several centuries ago to raise building foundations as a defence against flooding. Several older and potentially vulnerable buildings are located on dwelling mounds. There are approximately 900 of these dwelling mounds in the study area. Eight representative dwelling mounds were selected to study the potential effect of these mounds on the seismic hazard and risk.

Local shear-wave velocity (VS) profiles were determined using Multispectral Analysis of Surface waves. Together with local soil descriptions from hand augers the VS profiles formed the input for 1D equivalent linear site response analysis. The calculations show that the spectral amplification factors derived from local soil columns at dwelling mounds are different from the reference GMM amplification factors. The soil-structure interaction for buildings on dwelling mounds, however, is not significanlty differerent from the reference situation for the relevant building typologies present on the dwelling mounds. Therefore, no separate fragility functions for building on dwelling mounds are required. We propose a frequency-dependent Penalty Factor to be applied to the spectral amplification factors for building situated on dwelling mounds. The Penalty Factor is the result of a multidisciplinary approach, combining information from archeology and geopgraphy (dwelling mound occurence), field work (descriptive drillings and in situ shear-wave velocity), geology (subsurface structure), geo-engineering (subsurface properties) and earthquake engineering (site response and soil-structure interaction).

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On the Dynamics of the Seasonal Components of Induced Seismicity in the Koyna–Warna Region, Western India

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The spatial and time dynamics are analyzed for the seasonal components of induced seismicity in the Koyna–Warna region of Western India. The peculiarities of the variations in these components are compared to the changes in the local tectonic regime inferred from the focal mechanism data of the earthquakes. Based on this, the hypotheses about the probable nature of the dynamics in the seasonal components of seismicity are suggested. It is noted that the variations in the seasonal seismic activity after the impoundment of the Koyna reservoir in the north are caused by the spatial migration of the induced seismicity and activation of the normal faults in the south. It is hypothesized that the process of fracture migration from the north to the south at this stage advanced the diffusion of the fluid from the Koyna reservoir, and as the water front reached the southern zone of normal faulting, this caused reactivation of the seasonal seismicity. Results of the laboratory simulation of the water induced failure migration support this hypothesis qualitatively. An explanation is suggested for the stronger response of the seasonal activity in the region of Warna reservoir compared to the Koyna area: in contrast to Koyna, filling the Warna reservoir was geographically close to the area of activated seismicity. It is shown that the localization and sizes of the areas of the instantaneous and delayed components in the seasonal activity of the induced seismicity are determined by the localization and sizes of the areas of high stresses created by the increase in the pore pressure in highly permeable fault zones.

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Rupture directivity in 3D inferred from acoustic emissions events in a mine-scale hydraulic fracturing experiment

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Rupture directivity, implying a predominant earthquake rupture propagation direction, is typically inferred upon the identification of 2D azimuthal patterns of seismic observations for weak to large earthquakes using surface-monitoring networks. However, the recent increase of 3D monitoring networks deployed in the shallow subsurface and underground laboratories towards the monitoring of microseismicity allows to extend the directivity analysis to 3D modelling, beyond the usual range of magnitudes. The high-quality full waveforms recorded for the largest, decimetre-scale acoustic emission (AE) events during a meter-scale hydraulic fracturing experiment in granites at ~410 m depth allow us to resolve the apparent durations observed at each AE sensor to analyse 3D-directivity effects. Unilateral and (asymmetric) bilateral ruptures are then characterized by the introduction of a parameter κ, representing the angle between the directivity vector and the station vector. While the cloud of AE activity indicates the planes of the hydrofractures, the

resolved directivity vectors show off-plane orientations, indicating that rupture planes of microfractures on a scale of centimetres have different geometries. Our results reveal a general alignment of the rupture directivity with the orientation of the minimum horizontal stress, implying that not only the slip direction but also the fracture growth produced by the fluid injections is controlled by the local stress conditions.

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First developments of a seismicity laboratory for the study of induced and low-magnitude events. Stage I: Implementation and research

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In 2021 we began the implementation of the first seismicity laboratory in Chile whose main objective is the study and analysis of induced and low-magnitude seismicity. The laboratory is located at the Department of Metallurgy and Materials Engineering which belongs to the Universidad Técnica Federico Santa María, a university located in Santiago, Chile. The laboratory is planned to perform academic research, as well as to be used for undergraduate students which might be interested into develop a scientific career. Currently, we count with four acoustic emission detection sensors model W500/1, with frequency range between 100 - 1000 kHz and resonant frequency of 500KHz. We are now in the first implementation stage, which includes the calibration process and testing of the different equipment configurations. So far, we are using the laboratory to develop a few studies which involve finite element numerical modeling of a fractured rock specimen and co-seismic frictional energy generation. In the near future, we will acquire more acoustic emission sensors and a Hoek cell to perform acoustic emission studies during triaxial compression tests and, we will perform out explicit dynamic modeling for micro-seismic events. We hope to link our laboratory with academic institutions and industries related to the areas of geology, geophysics, and mining, with the objective to create a collaboration network between different countries.

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Improving the detection of fluid injection induced seismicity in the High Agri Valley by a single-station template matching algorithm

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Improving the capability of a seismic network to detect weak seismic events is one of the timeless challenges in seismology: the greater is the number of detected and locatable seismic events, the greater insight on the mechanisms responsible for seismic activation may be gained.

Here we present a work about the analysis of the 2016-2018 fluid-injection induced seismicity located close to the Costa Molina 2 (CM2) injection well in the High Agri Valley, Southern Italy. The area hosts the largest productive on-shore oil field in West Europe, and the wastewater produced during the oil and gas field exploitation is managed by pumping the disposal fluids back into the subsurface through the CM2 injection well.

We implemented a single-station template matching algorithm to improve the detection of weak induced events belonging to the seismicity cluster in the period of study. The nearest station to the analyzed seismicity cluster (INS1 station) of the INSIEME seismic network (https://doi.org/10.7914/SN/3F_2016) was used for detection. We provide a seismic catalogue consisting of 192 located and 32 detected earthquakes. Located events are in the magnitude range -1.2 ≤ Ml ≤ 1.2, with a completeness magnitude Mc=-0.5 ± 0.1 and a b-value of 1.36 ± 0.05. We compared the seismicity with operational injection parameters, discovering through a statistical investigation that most of the fluid-induced events occur when acidification operations are applied and for injection rates greater than 1900 m^3/day. We also computed the dip of critically stressed fractures with a pore pressure increase of 6 MPa (the maximum bottom-hole injection pressure applied during the period of investigation), obtaining a dip range from ~45° to ~75°.

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Microseismic cluster localization with DAS for monitoring Enhanced Geothermal Systems

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We present a workflow towards efficient localization of clustered (micro-)seismicity with a combination of Distributed Acoustic Sensing (DAS) and seismometers. Microseismic monitoring is a key part of Enhanced Geothermal Systems (EGS) throughout their operational lifetime. DAS is gaining interest as a (micro-)seismic monitoring tool, as its easy deployment and dense array of sensors can provide high-resolution information about the wavefield in a cost-effective way. Challenges in DAS monitoring are the amount of data collected and the single-component nature of the measurements along the fiber.

We investigate the potentials of microseismic localization using DAS and a combination of single or multiple surface stations at the FORGE geothermal test site in Utah, USA. We use the software package HADES[1] that computes relative distances between clustered seismic events using the difference between S- and P-wave arrival times. Subsequently, the absolute location and orientation of the cluster is found with the use of master events: events with a priori known locations. Only a few master events are needed to find the locations of all events in the cluster. HADES was designed for single- or two-station measurements and is now adapted to work for the multitude of channels that DAS offers, in combination with one or more surface seismic stations.

Both synthetic arrival times and arrival times picked from the FORGE test site are used to showcase the method. With a vertically deployed DAS fiber and several surface stations to choose from, we show how different configurations of seismometers, master events and velocity models will influence the accuracy of the shape and orientation of the seismic cluster.

[1] HADES: https://github.com/wulwife/HADES

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Stochastic modelling and diffusion rate variations of fluid-induced seismicity

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The presence and circulation of pressurized fluids in the Earth's crust can induce earthquakes. Such phenomena, related either to natural processes or to man-made activities, have recently drawn intense scientific attention due to the increased number of the globally reported events. A characteristic of fluid-induced seismicity is its spatial migration with time, associated with pore-fluid pressure diffusion, poro-elastic effects and/or aseismic creep transients. Understanding the diffusion properties of fluid-induced seismicity represents a major challenge. To account for the wide range of spatial and temporal scales that might be present in earthquake diffusion and to overcome any assumptions and uncertainties related to the in-situ conditions in the seismogenic crust, we develop a stochastic model to map the spatiotemporal evolution of fluid-induced seismicity. The model is based on the well-established Continuous Time Random Walk (CTRW) theory that has widely been applied to nonlinear fluid flow phenomena in complex heterogeneous media. Within this context, we describe the spatiotemporal evolution of fluid-induced seismicity with an appropriate master equation and the time-fractional diffusion equation. We apply the model to fluid-induced seismic sequences, either associated with fluid-injections in the subsurface, or with tectonic seismic swarms associated with fluid flow in the crust. The results demonstrate that earthquake diffusion deviates from the linear (Fickian) diffusion equation and presents all the intrinsic characteristics of anomalous diffusion. Within this context, the CTRW model can successfully capture the main features of earthquake progression in time and space. In addition, we show that fluid-induced seismicity presents higher diffusion rates compared to tectonic earthquakes and mainshock/aftershock sequences, a result that may provide novel constraints on the discrimination between fluid-induced and tectonic earthquakes.

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Induced seismicity at Enguri Dam, Georgia (Sakartvelo) based on old catalogs and on-going monitoring

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Enguri Dam, Georgia, is one of the tallest high-rise dams currently operating. The operation of hydropower reservoirs can trigger induced seismicity, posing a significant hazard to the population living nearby. We aim to study the current seismicity around the dam and update the old earthquake catalog with modern methods. Thereby, we expect to improve our knowledge of the active structures near the dam and to investigate the relationship between seismicity and dam operations.

Installation of a seismic network around Enguri dam began in 1972 before its operation in 1978. The first induced earthquake (4.3 Ms) occurred in 1979, when the dam reservoirs filled for the first time. About 80 aftershocks were observed over several months. In 1992, the local seismic network stopped operating. In 2010, National Seismic Network of Georgia recorded another earthquake (4.3 Ms) close to the dam, unfortunately, the aftershocks were not recorded.

The waveforms of the events before 2006 are not available for re-processing; however, an analog catalog exists including phase arrival times, amplitudes and polarities, and locations of 288 events, that enables us to update events locations and fault plane solutions.

In the frame of the DAMAST (German-Georgian cooperation) project, we plan to install a local network around the dam, including 4 surface stations, 3 stations in 20-m shallow boreholes and 1 station at 250 m depth. Since October 2020, 4 stations are continuously running. The network will be fully operational in July 2021. So far, more than 60 local events are identified in ~10 km around the dam. While 3 events are of magnitude greater than 1.2 Ml, magnitudes of the others are between 0. and 1.0 Ml. Given the relatively high sensitivity of the new network, we expect to reach our goals and better understand the relationship between local seismic activity and dam operations.

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Advances in single station and array methods for subsurface characterization onshore and offshore

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Analysis of the local site effects of the Međimurje region (North Croatia) and its consequences following the 1738 M5.1 Međimurje, 2020 M5.5 Zagreb and M6.2 Petrinja 2020 earthquakes

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On 30 March 1738 the Međimurje region was struck by an earthquake with macroseismic intensity estimated in epicentre of 7.9 °MCS and magnitude of 5.1. Historical archives reported heavy earthquake damage for the entire region, especially of brick wall and wooden structures, churches and chapels. The famous Church of St. Jerome located in Štrigova was rebuilt in 1749 following the earthquake demolition as the original 15th-century-built chapel. Old Gothic architecture of the Zrinski Old Town Castle in Čakovec city was damaged. On 22 March 2020, the M5.5 earthquake struck the capital city of Zagreb and small damages to older churches were reported also in Međimurje (approx. 80 km from epicentre). However, moderate damages to churches and older buildings in the whole Međimurje region (approx. 100 km from epicentre) were reported following the destructive M6.2 Petrinja earthquake, which occurred on 29 December 2020.

The Međimurje region is entirely a part of Tertiary basin that is distinguished by three major subbasins - Mura, Čakovec and Kotoriba, with relatively thick sedimentary sequences. Its elevations range between 120 and 344 meters, the latter being the elevation of the highest hill, Mohokos in the Međimurske Gorice, structure which is morphologically and topographically most pronounced in the Upper Međimurje.

The aim of this analysis is to understand the local site effects of Međimurje region and damage after 1738 and 2020 earthquakes. We used Horizontal-to-Vertical Spectral Ratio (HVSR) method to estimate the local site parameters; resonance frequency, sediment thickness, Vs30 and HVSR amplitude as an indication of the local site amplification. There is a reasonable indication that the analyzed earthquakes involved three local site effects; strong amplification and probably potential nonlinearity due to hypothetically strong shaking or highly nonlinear soil behavior on soft soils, as well directional ground motion effects at sites with strong topographic features.

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Site characterization in Lake Lucerne using ocean bottom seismometer recordings

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Submerged slope failures can generate tsunamis that affect the surrounding infrastructure and population. Although less frequent, this phenomenon can also occur in lakes. For example, tsunamis occurred in 1601 and 1687 in Lake Lucerne (Central Switzerland), caused by earthquake-triggered mass movements and the spontaneous Muota river delta collapse, respectively. The maximum wave height in both cases reached 5 m.

Nowadays, such a tsunami would cause significant damage and casualties. To assess the hazard related to tsunamis, a slope stability assessment based on site characterization measurements is necessary.

On land, passive seismic array and single-station measurements are routinely used for site characterization. The application of array techniques offshore faces additional challenges during the data pre-processing: the unknown instrument position and orientation due to the free-fall deployment, and imprecise timing due to the absence of connection to the GPS. Additional tools and techniques are needed to tackle these issues.
We conducted ocean bottom seismometer (OBS) surveys for site characterization in Lake Lucerne as one of the steps towards slope stability assessment. Between 2018 and 2020, we deployed OBS as arrays and single stations in the lake to assess the seismic response, the fundamental frequency of resonance and the shear-wave velocity profile at different sites. The target locations were the slopes which are potentially prone to failure.

The recorded data were analyzed to derive the single-station horizontal-to-vertical spectral ratio (H/V), the Scholte wave ellipticity, the fundamental frequency of resonance and surface wave phase velocity dispersion curves. Single-station data indicate very large H/V amplitude at the peak frequency and, for some sites, noticeable heterogeneities in sediment cover thickness and/or physical properties. The array data were inverted for the shear-wave velocity profiles using a transdimensional Bayesian inversion. Overall, we observed a significant difference in the properties of lake sediments in comparison to onshore sediments.

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Inversion of the Rayleigh wave ellipticity at the InSight landing site for the shallow Martian structure

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The InSight lander successfully touched down in Elysium Planitia on Mars on 26 November 2018. It deployed a broadband seismometer, which continuously operates to record marsquakes and ambient seismic vibrations. In windy times, lander-induced vibrations dominate the ambient seismic wavefield. Based on quiet time windows, we analyze ambient seismic vibrations to assess the ellipticity of Rayleigh waves. The ellipticity is low over a wide frequency range and shows a prominent trough at around 2.4 Hz.

Using additional assumptions on the structure of the shallow Martian subsurface at the landing site, we invert the retrieved Rayleigh wave ellipticity curve between 1.5 and 8.0 Hz by a trans-dimensional Bayesian inversion to constrain the shear-wave velocity profile down to about 200 m depth.

The resulting velocity profile is consistent with a local structure composed of a thin regolith layer above stacks of lava flows. A low-velocity zone in a depth of about 30 to 75 m can be interpreted as a sedimentary layer sandwiched between older and younger basaltic layers.

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Ambient noise H/V analysis using OBS data at the Fukushima forearc region for deeper investigation below the seafloor

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In the offshore Fukushima forearc region the oceanic Pacific plate subducts beneath the continental Okhotsk Plate along the Japan Trench. Shallow S-wave (VS) information below the seafloor of this region is poorly known. Therefore, this study aims at estimating the VS profile along several thousand meters below the ocean floor at sundry offshore locations in Fukushima region. A total of 16 short-period ocean bottom seismometers (OBSs) were used in this research. At first, H/V curves within the frequency range from 0.1 to 10 Hz were computed for each station. Afterwards, they were inverted for the VS profile below the seafloor. This H/V inversion and forward modelling, based on diffuse field theory of noise wavefield (Sánchez-Sesma et al., 2011), was performed utilizing the code by Lontsi et al. (2015, 2019) that accounts for a water layer effect atop the OBS sensor. A layer parametrization reflecting the VP profile allows to reduce the non-uniqueness of the solution while searching for the best model. This study successfully revealed the seismic structure up to around 8,000 m below the seabed in the study area. The newly retrieved VS profiles detected subsurface features that are already found, i.e., an unconformity at a depth of around 2,400 m, and a major stratification within island arc crust at about 5,800 m depth (e.g., Tsuru et al., 2002; Miura et al., 2003). Moreover, synthetic H/V analysis exhibited a shift of the fundamental frequency peak of almost 2 Hz towards lower frequencies regarding the water layer effect, whereas a previous study (Lontsi et al. 2019) exhibited a water layer effect only on the H/V curve amplitude around higher frequency peaks and with minor shift in fundamental frequency. This observation is perhaps related to the complexity of the structure below the water layer that needs further study.

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Simulating the spectral structure of seismic ambient vibrations as an effect of a distribution of random surface sources of finite dimensions

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In the frame of the well-established theories describing the seismic ambient-vibration ground-motion as effect of a distribution of aleatory forces located uniformly on the Earth surface (Distributed Surface Sources, DSS), a model is here presented able to describe some aspects linked to the finite extension of the sources. Precisely, the ground motion and its generating forces are described as 3-dimensional and 3-variate random wavefields, established on the surface of a flat weakly-dissipative Earth, which are stationary and homogeneous, with zero-mean and finite variance, and can be characterized by their power spectral density functions. A frequency-dependent spatial correlation of the force random field is introduced to represent the different scales of dimension of the sources. The parameters of this correlation can be partially constrained

by assuming the sea-wave dynamics as mainly responsible for seismic ambient vibrations observed in the frequency range of possible engineering interest (0.1 to 10 Hz). Differently from other models, this one allows a realistic description, both in shape and amplitude, of the power spectral density function of the ambient vibrations observed worldwide at reference soil conditions, which gives us another constrain on the parametrization. Effectiveness of the model is tested by reproducing observed average Horizontal-to-Vertical Spectral Ratios and dispersion curves obtained from ambient vibration measurements at a well documented site in Northern Italy.

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Novel Bayesian inversion of dispersion and ellipticity curves intended for subsurface characterization

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Properties of subsurface structure determine principal effects of local ground motion. Attributes of primary importance, i.e. S- and P-wave velocity profiles, can be inferred from Rayleigh and Love wave dispersion and ellipticity curves as retrieved from the single-station and array measurements. However, the measured data are subject to uncertainty and the solution exhibits significant inherent non-uniqueness as different velocity models provide a similar fit to observed data. This highlights the importance of rigorous treatment of uncertainty. Standard non-linear optimization inversion techniques chasing velocity models that provide a minimal data misfit; then a set of tested models might not be representative in terms of solution uncertainty. This can be overcome by an inversion formulation in the Bayesian (probabilistic) framework, where the uncertainty of the measured data is rigorously propagated to results.

This research is focused on the development and application of a novel Bayesian inversion method intended for local subsurface characterization. Our inversion method is formulated in the transdimensional Bayesian parameter space, where 1-D velocity models may have a varying number of layers. The number of layers is treated as the model complexity that is governed by the data-driven law of parsimony. This parameter space is explored by a reversible-jump Markov chain Monte Carlo algorithm that produces an ensemble of models representative in terms of solution uncertainty. To suppress a possible dependency on an initial model, we use multiple parallel Markov chains with independent and random initial models (parallel tempering technique). We introduce also a multizonal formulation of the prior, allowing to include additional information to the inversion (from geological profiles, etc.). In this contribution, we present a validation of the inversion method using a synthetic test and application to a selected Swiss site. Our method is suitable for sites with low-velocity zones and it provides reliable estimates of solution uncertainty.

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Single station particle motion in combination to consecutive short-time windows procedures for the location of moving seismic sources (snow avalanches)

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The use of the seismic signals for the characterization of snow avalanches is a common methodology in mountain areas. The UB-RISKNAT group study the ground vibrations produced by snow avalanches using 3-axis short-period and broad-band seismic sensors placed along the snow avalanche path to characterize their behaviour.

In this case, we focus on the first vibrations generated when the snow mass is still accelerating and far from the sensor. We aim to deduce with the use of a single seismic station the origin of these vibrations to identify the avalanche release area. We use a Geospace Mini-seismonitor sensor (2Hz, 500/6 Vs/m) plugged to a Spider data-logger (Worldsenisng Co.). The seismic station is located 2,250 m.a.s.l at the experimental site of Vallée de la Sionne (Valais, Switzerland, SLF) in the position closest to the avalanches release areas (<750m). At this location, the signal-to-noise ratio is good for recording the start of avalanches.

Because snow avalanches are moving seismic sources the seismic signal contains multiple wave fronts mixed. We process the seismic signal in consecutive short-time windows (1s, 50% overlap) to highlight information of the most longitudinal seismic wave fronts. For each window we perform polarization studies using the method defined by Vidale (1968) and Jurkevics (1988) to obtain the back-azimuth. The evolution of back-azimuth values throughout the seismic signal generated by the start of the avalanche gives us information about the approximate area from where it has been released.

We performed an automatic execution over 157 case studies. Of the 37 avalanches studied with clear identified release area, we obtain a 78% of success rate and a precision of ±7º. We consider that the method is capable of tracking seismic moving sources like avalanches given the proximity source-sensor.
Spanish MINEICO project PROMONTEC (CGL2017-R AEI/FEDER, UE) supported this study.

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Modal analysis of an unstable rock compartment overlooking the A8 highway (Peille, Southern French Alps)

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Following the collapse of a large rock compartment located in calcareous cliff area, overlooking the A8 highway (near Monaco Monte-Carlo in the Southern French Alps), a seismic monitoring campaign has been set-up for stability assessment. The upper part of the compartment, with a volume close to 450 m^3, has remained in place and its level of stability appears unchanged following the event, but the rockfall hazard remains high to very high. The compartment is part of a limestone massif (late Jurassian) crossed by vertical fractures with East-West azimuth, progressively opened by weathering effects which tend to individualize large rock columns along the cliff.

Seismic instrumentation was set-up in two one-day campaigns (July 2019 and March 2020) in order to: 1) characterize the dynamic behavior of the actual rock compartment, and 2) investigate the feasibility of long-term monitoring based on ambient vibrations. The instrumentation consisted of two measurement networks of four Lennartz velocimeters (Le3D 5 sec). The measurement points covered the maximum of the exposed and accessible surface of the block, as well as on the intact rock massif. Data analysis in the frequency domain identified several resonance peaks as well as their preferred azimuths. The analysis of the two networks using modal identification technique by FDD (Frequency Domain Decomposition) highlighted the main modes of vibration of the compartment, including torsion and tilting modes from 4 Hz up to 10 Hz. First results of numerical modeling of the compartment help to constraint the time evolution of the identified modes, as they are sensitive to boundary conditions of the studied rock compartment.

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Advances in real-time monitoring for detection, identification and characterization of rockfalls and landslides with continuous seismic data along with other monitoring techniques (LiDAR, photogrammetry and video recordings)

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The UB-RISKNAT group studies various geological hazards with multidisciplinary vision, including observations and modeling of seismic signals generated by rockfalls, landslides and snow avalanches. In this contribution we present the use of the signal of single seismic stations, as well as small arrays to two different studies.

In the first study, a natural landslide at La Riba was identified at a seismic station of the Spanish permanent network located at 10 km distance. The performed seismic analysis allowed its location and characterization that otherwise would not have been obtained. The subsequent clearing blasting works were also recorded by two seismic stations installed ad hoc few meters from the site. Seismic signals along with video, LiDAR and photogrammetry data provided relevant information about the dynamics of the artificial landslide.

In the second study, we investigate frequent rockfalls on a scarp of an historical landslide that we use as an experimental site (Puigcercós, Catalonia). Our objective here is to characterize the seismic signals generated by rockfalls, considering that the signal is strongly dependent on the structure and geotechnical properties of the terrain. We have conducted an experiment, where small rockfalls (<0.001 m3) were released artificially to characterize possible precursors of the larger events, important step for developing a monitoring and early-warning system based on seismic records. In a second phase, larger natural rockfalls were identified with LiDAR and photographic monitoring, providing time windows of months, days, or hours to identify events in the continuous seismic data . We adjust STA/LTA techniques for automatic seismic detection and the events are selected/discarded, based on the results of the experiments. Incorporating these new natural events of higher volumes, makes the system increasingly intelligent until achieving a fully automatic detection based on seismic data.

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3D seismic velocity model of Tehran basin

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Located on a sedimentary basin including faults and folds, Tehran city is prone to large site effects. Past seismological studies have indeed revealed a large amplification of seismic ground motion over a broad frequency range (from 0.4 Hz to 4 Hz).

Despite important site effects, there is no detailed knowledge related to Tehran's basin geometry and mechanical properties yet to be used for seismic strong ground motion simulations. In order to build a three-dimensional velocity model of Tehran's basin, we carried out an extensive geophysical survey including more than 400 single station measurements and 33 ambient vibrations arrays.

As already shown in Tehran, single-station seismic noise H/V measurements often failed to provide reliable H/V peak frequencies at low resonance frequency of the basin (< 1 Hz). We obtained only 25% H/V peaks at measurement sites in our study.

As an alternative, we extracted the Rayleigh wave ellipticity from the early coda waves of regional earthquakes recorded by 13 seismological stations installed in the Tehran's basin in 2002, located closeby some of the noise array measurements.

Shear-wave velocity (Vs) structure from the surface down to seismic bedrock was obtained at all array sites by joint inversion of dispersion curves at high frequency (> 1 Hz) and Rayleigh wave ellipticity (when available) obtained at arrays at low frequency. Inverted shear-wave velocity profiles, together with available geotechnical and geological information and H/V peak frequencies from seismic noise or earthquake recordings, have allowed us to build the first 3D model of Tehran's basin. This 3D model exhibits a deep trough in the plain zone on the southern part of the basin with a seismological bedrock depth at about 900 m. The basin comprises two main layers with Vs. ranging from 600 m/s at the surface to 1300 m/s at depth.

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Seismic Imaging Using Cross- and Auto-correlation of seismic noise in the Quito (Ecuador) basin

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Temporary seismic networks installed in urban areas provide a powerful tool for investigating shallow geological structures and assessing the seismic hazard using passive seismic methods, including auto- and cross-correlation of seismic noise. To examine the feasibility of the methods to image the uppermost geological structures in a urban area, 20 broad- and mid-band seismological stations were deployed progressively throughout Quito in an irregular array to record ambient seismic noise between May 2016 and July 2018. Quito, the capital of Ecuador, is located in a high seismic zone, 180 km from the Pacific subduction zone and surrounded by crustal-faults prone to generate significant earthquakes. The city is built on a sedimentary basin, located on the hanging wall of a system of active reverse faults. The high population density (around 2.5 million inhabitants) and the lack of planning of most of its buildings, make Quito a metropolis exposed to high seismic risk.In Quito, the basin's filling has been described as volcano-sedimentary sequences consisting of lavas, lahars, lacustrine,and pyroclastic deposits (Alvarado et al., 2014). However, the thickness of the in-fill material, its spatial arrangement, and the basin's deep structure remain poorly known.This study presents the results of ambient noise auto- and cross-correlation of simultaneous operating seismic stations to retrieve: 1)zero-offset high frequency body-wave crustal reflections,and 2) inter-station, surface-wave Green's functions in the frequency band 0.1 - 2 Hz.Auto-correlation of seismic

noise indicated at least one reflection within the first 2.5 s from the surface.Careful analyses of day-night variations in noise spectral power were carried out to select optimal time windows for the cross-correlation. Additionally, Rayleigh and Love phase-velocity dispersion curves were inverted to obtain shear wave velocity profiles throughout the city. Love wave trainstraveling in the longitudinal direction of the basin (NNE-SSW) are much clearer than Rayleigh wavetrains.

ESC2021-S33-579

Extracting Scholte and Love waves phase-velocity from small aperture Ocean Bottom Seismometer arrays in Lake Lucerne (Switzerland)

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The phase-velocity dispersion curve (DC) is an important characteristic of the propagation of surface waves in sedimentary environments. Although the procedure for DC estimation in onshore environments using ambient vibration recordings is well established, the DC estimation in offshore environments using arrays of Ocean Bottom Seismometers (OBS) presents three main challenges. These are the localization, the orientation of the OBS horizontal components, and the clock error. Here, we concentrate on the workflow for a robust estimation of the phase-velocity dispersion curves from small aperture OBS array measurements in Lake Lucerne (Switzerland). OBS array campaigns were performed between 2018 and 2020 using arrays with a maximum aperture of 679 m at a maximum water depth of 81 m. The challenges related to the OBS location on the lake floor were addressed by combining the multibeam bathymetry map and the backscatter image for the investigated site with the differential GPS coordinates of the OBS at recovery. The OBS measurements were complemented by airgun surveys. Airgun data were first used to estimate the misorientation of the horizontal components of the OBS and second to estimate the clock error. Finally, we use two array processing methods, namely the three-component high-resolution frequency-wavenumber and the interferometric multichannel analysis of surface waves, to estimate the dispersion characteristics of the propagating surface waves for one of the array sites. We clearly observe the phase-velocity dispersion curve branches for Scholte and Love waves in the frequency range between 1.2 and 3.2 Hz for both array processing techniques.

ESC2021-S33-580

Vs profiles onshore and offshore from full microtremor horizontal-to-vertical (H/V) spectral ratio inversion

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Recent theoretical developments in horizontal-to-vertical (H/V) spectral ratio modeling are used to invert the microtremor H/V spectral ratio curves for the shear wave velocity profile at one onshore and one offshore sedimentary site in Switzerland. The full H/V forward model uses the seismic interferometry principles under the diffuse field assumption to estimate the imaginary part of the Green's function for co-located source and

receiver. At the onshore site at Buochs, the H/V spectral ratio curves are obtained from a strong motion borehole station with three sensors located at surface, 26, and 100 m depth. At Lake Lucerne (offshore Weggis), the H/V curve is estimated from an ocean bottom seismometer station located on the lake floor at 38.1 m water depth. The inversion of real offshore H/V curves is preceded by a synthetic modeling and inversion where a water layer is considered on top of the best model candidate from H/V inversion at Buochs.

ESC2021-S33-606

Site-characterization of permanent stations using industrial purpose, three-component, short-period sensors

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The use of independent low-cost sensors is highly beneficial in site-characterization studies based on the non-invasive analysis of the ambient seismic wavefields. Recent improvements of seismic sensors with an initial industrial user base bring their usability closer to comparable well-approved seismological recording systems.

As a novelty, we present the results of array seismological surveys based on ambient seismic waveforms using 24 SmartSolo three-component instruments. These low-cost instruments in an autarkic casing, that includes GPS, digitizer and internal storage and thus enabling unconditionally arbitrary array geometries, surpass conventional sensors in reduced weight and size. This appearance notably advances their installation speed with reduced labor force for short-term installations, allowing to experiment with various array geometries on single sites or the investigation of more sites in a projects lifetime. In addition, the low cost state of industrial sensors permit the purchase of more instruments that leads to finer sampling of the apparent wavefield and lowering the chances of spatial aliasing.

In parallel to the EPOS-BE upgrading of the Belgian permanent seismic network into broad-band sensors, we perform a site characterisation of some key Belgian stations using these three component, cost-effective, autonomous geophone sensors. To invert shallow subsurface 1D seismic velocity models for these sites, we apply a variety of well established array processing techniques (e.g., frequency-wavenumber, H/V ratio, MSPAC) from which we further extract site-characterization parameters (e.g., vs30, f0, bedrock depth). To ensure the robustness of these ambiguous methods based on these non-standardized sensors, special attention is given to the overall recording quality and issues that arose and became evident in the post-processing by event-based calibration with respect to broad-band data of the permanent network.

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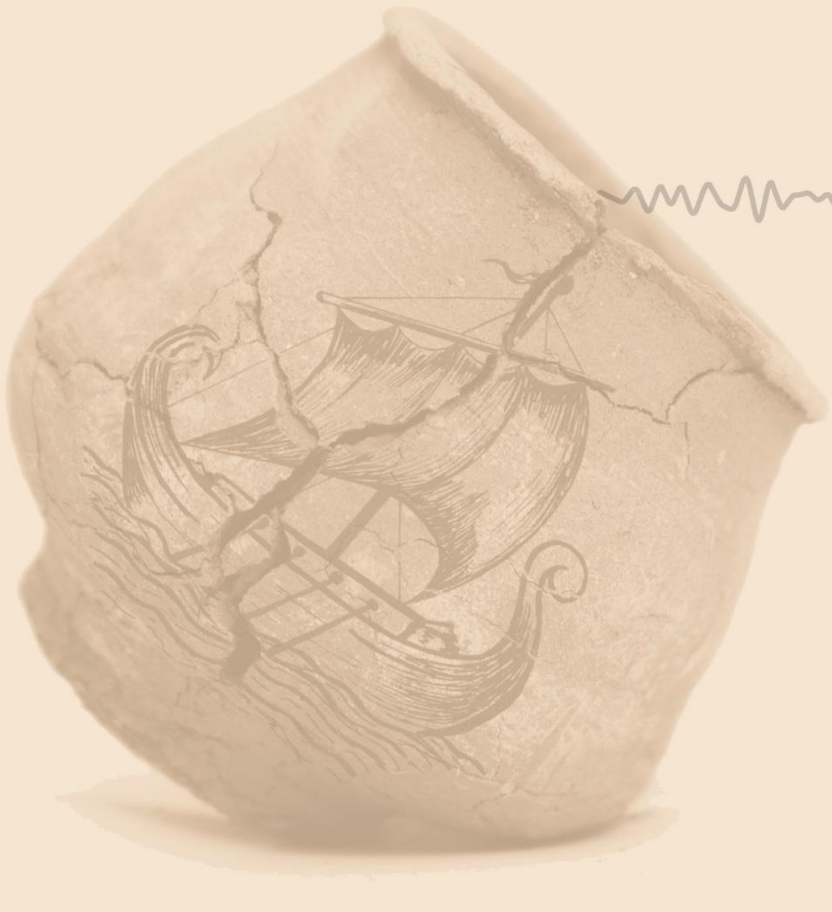
Earthquake Induced Landslides: from triggering to stabilization, methods and techniques of monitoring



ESC2021-S34-136

Artificial intelligence for landslide documentation from Tweets

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Contrary to felt earthquakes, which can generate large numbers of tweets, landslides do not produce the same volume and dynamic of publication on social media, probably because they are only perceived visually and during daylight. Often, researchers are left to manually harvest landslide information from social media, a time-consuming process to document landslides.

In order to improve this situation, a two-step method was developed and is being tested. Our objectives are first, to help photographically document landslides globally by ultimately offering an open service for researchers. Secondly, we aim at testing whether such a tool could help in the rapid detection and localization of earthquake-triggered landslides. This is essential for efficient response as landslides can significantly hamper rescue operations by blocking roads.

The method retrieves tweets in real time with pictures that are possibly related to landslides through multi-lingual keyword analysis. Then an AI identifies those pictures representing landslides. The use of AI is indispensable as post-training it disregards more than 99% of the collected pictures. A significant proportion of the work so far has been to train this AI, by testing the system on sets pictures that include images of landslides and visually checking the results.

We will present the method and its performance and how interested parties could possibly make use of it at a later stage.

ESC2021-S34-157

The role of seismic illumination in the estimation of the near-field topographic site effects

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After an earthquake in a mountainous area, we usually observe near the seismic source high levels of heterogeneities in the damage distribution. On a decametric scale, we can see that some areas are more affected than others, both in terms of damage to buildings and in the triggering of coseismic landslides. One of the factors controlling this variability is the topography of the surface.

A previous study made it possible to predict the average topographic amplification of the seismic waves by simply considering the frequency and the topographic curvature at the site of interest (Maufroy et al., 2015). However, this estimator doesn't account for the role of the seismic source in the near field and still presents high levels of uncertainties.

In order to reduce these uncertainties and to better understand how the topography-source interaction affects the damage distribution, we use the same numerical simulation data of seismic wave propagation that was used in the previous study, together with artificial intelligence methods (neural networks), to identify the key parameters controlling this variability. We suggest a quantitative definition of the seismic illumination phenomenon mentioned in the literature: amplification is generally greater on slopes oppositely

facing the incident wave field. We also suggest a method to calculate this parameter and quantify its contribution by including it into a new estimator of the topographic site effect. Compared to the initial estimator, the addition of this parameter can reduce the uncertainties by a factor exceeding 2.

In order to study the relationship between the seismic motion amplifications predicted by the new estimator and the spatial distribution of earthquake-induced effects, we are carrying out a statistical study on the Nepal landslide inventory triggered by the 2015 Mw 7.8 Gorkha earthquake. This step will require extending the capabilities of the new estimator for an extended source.

ESC2021-S34-203

What is the potential for earthquake-induced landsides in Norway?

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It is well established that the most important triggers of landslides in most places are precipitation and earthquake ground shaking. In Norway, which is a stable continental region of low to moderate seismicity, precipitation has traditionally been considered as the sole triggering mechanism, whereas the potential for earthquake-induced landslides has received more attention in recent years. However, there are still no systematic studies evaluating this potential based on Norwegian data. Written reports on Norwegian earthquakes of M>4.5 during the last two centuries are systematically analysed and compared to meteorological data to reveal at least six landslide-triggering earthquakes in the magnitude range 4.6-5.9. Triggered events include rockfalls, rockslides, clay slides and a debris slide. The events are distributed throughout the country, and triggering occurs up to ~200 km distance from the epicenter for the largest events. This indicates a fairly large potential for earthquake-induced landslides in Norway, which may have severe consequences, especially in cases where a landslide runs into a body of water to trigger a tsunami.

ESC2021-S34-472

Application of the Acoustic Emissions Technique to the physical modelling of earthquakes-induced landslides

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The triggering of landslides in unstable slopes by strong earthquakes is frequently observed worldwide, causing in many cases considerable loss in human lives and infrastructure damage. In the present work, the physical modelling of earthquakes-induced landslides is achieved through the development of an experimental apparatus suitable for performing laboratory scale experiments. Real-time monitoring of the phenomenon is carried out by means of the powerful Acoustic Emissions Technique (AET). Although AET has recently been applied successfully to real-scale landslide monitoring surveys (Dixon et al., Landslides, 2015, 12:549-560), the smaller-scale study in the laboratory under controlled conditions presents many problems and is still very limited.

In our study, a plexiglass container (35x40x75 cm) was filled with fine-grained sand mixed with different amounts of water in order to control the soil moisture content. Mechanical vibrations were applied in different directions along the slope to simulate the ground motion, while acceleration was recorded simultaneously. The utilization of suitable passive acoustic emission (AE) sensors adapted to innovative waveguides inserted into the slope significantly increases the sensitivity of AE detection. This setting allows for more effective real time monitoring of the different stages and processes of the observed vibration-induced landslides.

Factors such as the slope geometry, the soil moisture content, the duration of the mechanical vibrations and the maximum induced acceleration of the slope in the horizontal and vertical direction were examined and related to the recorded hit- and frequency-based AE parameters.

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Estimating earthquake mechanisms from major landslides in Alaska, Greenland and Switzerland and dense seismic arrays

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We computed earthquake focal mechanisms (full moment tensors) with their uncertainties from major landslides (M~5) in Alaska, Greenland and Switzerland, and observed at seismic stations worldwide. The mechanisms were computed with seismic waveform data obtained from all possible seismic stations in the broader landslide region, including from dense seismic array deployments in the Alps (AlpArray) and Alaska (USArray), in total over 400 seismic stations at up to 2000-km distances. To compute the mechanisms we applied an efficient methodology that has proven successful in earthquake source characterization for various events on Earth. The methodology searches the full space of moment tensors (over 40 million solutions per estimate) to find a mechanism that best fits the observed waveforms (frequency range 0.02-0.1 Hz), and estimate uncertainties from the ensemble of moment tensor solutions appraised during the search. In this methodology, the observed and synthetic waveforms are compared using a misfit function, and the synthetic seismograms are computed with a velocity model for the region of the seismic event. To estimate uncertainties, the methodology computes statistical distributions in the space of earthquake solutions (a source-type diagram). Our results reveal remarkably consistent collapse mechanisms despite their different geographical settings and local topography (Greenland fjords, Swiss Alps, Lamplugh Glacier in Alaska), the different material mobilised, and the different durations of the seismic source (up to 20 seconds). We further characterize each of the earthquake source mechanisms, their orientations, and uncertainty tradeoffs with other mechanisms.

ESC2021-S34-492

A new database of historical earthquake-induced landslides in Italy

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We present a new database of historical earthquake-induced landslides (HEILs) prepared within the project "Multi-scale, integrated approach for the definition of earthquake-induced landslide hazard in Italy" funded by the Italian Ministry for the Environment. The goal of this project is to develop a multidisciplinary approach for assessing the earthquake-induced landslide hazard, at national, regional and local scales, and integrating existing databases with previous projects and research activities results.

The CFTI database (https://doi.org/10.1038/s41597-019-0091-9) holds a central role, because it was compiled at the national scale and also because its latest version (CFTI5Med https://doi.org/10.6092/ingv.it-cfti5) documents about 600 landslides associated with strong historical earthquakes.

We review and integrate data relating to HEILs, already included in the CFTI database, by means of:

1)the identification of new landslides on the basis of the review of historical sources, newly found or already archived in the CFTI database;

2)the analysis of recent scientific articles and technical reports and on the comparison with other digital archives such as the CEDIT (https://doi.org/10.4408/IJEGE.2012-02.O-05) and the EEE catalogues (http://eeecatalogue.isprambiente.it/);

3)a more accurate localization and definition of the slope movement types of the HEILs, when the descriptions of historical sources allowed it, through the geographical comparison with data of different origin, such as aerial photographs, geomorphological and instability maps, associating them, where possible, to the individual landslides registered in the IFFI database (https://www.progettoiffi.isprambiente.it/).

The final result is a dataset with about 1,000 landslides divided into 3 classes of location accuracy (A, B, C). The dataset is addressed to a large audience of potential users: researchers and scholars, administrators and technicians of local institutions and civil protection authorities.

The results will be collected in a new independent database, connected to the CFTI5Med, that will be publicly accessible online through a dedicated geographic interface, designed to be interoperable with both INGV and external databases.

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Earthquake-induced landslides and seismological parameters of historical and instrumental Italian events

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We present new preliminary empirical relationships relating to seismological parameters and the distribution of historical and instrumental earthquake-induced landslides for the central Apennines. The study is developed within the project "Multi-scale, integrated approach for the definition of earthquake-induced landslide hazard in Italy" funded by the Italian Ministry for the Environment, aimed at developing at the national, regional, and local scales a multidisciplinary approach for assessing the earthquake-induced landslide hazard, integrating existing databases with results from previous projects and research activities.

A new database of historical earthquake-induced landslides (HEILs) was derived from:

1) the information included in the CFTI database (https://doi.org/10.1038/s41597-019-0091-9), which was compiled at the national scale and in its latest version (CFTI5Med https://doi.org/10.6092/ingv.it-cfti5) documents about 600 landslides associated with strong earthquakes of the past, and

2) the review of historical sources, recent scientific articles, and technical reports, together with the analysis of other digital archives.

The final database contains accurately located and characterized HEILs, divided into three classes of location accuracy.

Using the landslides included in this database, classified by type and divided by their occurrence in different lithological macro-areas, and comparing them with an integrated historical and instrumental dataset of earthquakes that occurred in the region, we studied the empirical relationships relating landslides and the earthquakes main seismological parameters (i.e. magnitude, epicentral location and distance, faulting mechanism, and at the individual landslide sites, macroseismic intensity and level of shaking).

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Functionality of seismometer and accelerometer in ground-moBon recording

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The interdependent quality control procedure for collocated seismometers or collocated seismometer and accelerometer

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The interdependent quality control (IQC) is a procedure that offers a very precise control of the operation of two collocated seismological systems in a simple way.

The number of seismic stations where seismometer and accelerometer are installed side by side is growing, therefore the number of quality control activities should increase. Yet, with the IQC, the collocated seismometer and the accelerometer are controlled by the single procedure. There are not that many locations where two seismometers are placed together. This is usually due to the testing of one of the seismometers. With the IQC, this task can be performed easier.

When two measuring systems are placed next to each other at the same seismic pier, both detect the same spatial seismic ground movement, and the outputs from the both systems should give the same information (e.g., estimated ground motion). Due to various reasons, outputs can differ but can be equalized numerically by using proper 3D transformation matrix, which transforms spatial detection of a seismic signal of one seismological system to the space of detection of another seismological system. The following three main causes of unequal detection are the differences related to the accuracy of calibration data, the errors resulting from misalignment of two collocated systems, and the errors resulting from the defects in a particular system. These sources can be identified by IQC, whose basis is a transformation matrix, whose calculation is based on the minimization of uncorrelated signals in the frequency space.

IQC of seismometers can be performed at any time, as the secondary microseism is significantly larger than the self-noise of modern seismometers. Since the self-noise of the accelerometer is usually higher than of the seismometer, moderate ground shaking (stronger regional earthquakes, local earthquakes) is required to perform the IQC on the seismometer-accelerometer pair.

ESC2021-S36-540

Enabling a higher level of seismic array performance by the use of boreholes (> 10 meters depth) at new and upgraded permanent stations

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Most seismic networks utilize shallow (< 3 meters) vaults, piers or shallow cased holes (or direct burial for temporary or logistically challenging deployments). Quiet low-frequency vertical noise performance can be achieved using shallower deployment techniques, but the horizontal channels will have higher noise, especially on sediment sites, with local environmental and cultural noise affecting frequency bands important to both research and monitoring. There is a better way for permanent stations with suitable infrastructure, and it's proven through many examples in practice and in experimental comparisons - boreholes! While commonly viewed as the best solution but expensive, recent installations of 10 to 30 meter cased holes have provided better performance for a relatively inexpensive investment. The life span of a properly constructed borehole is long, so the initial construction cost ends up being a small part of the overall cost of running the station over its lifetime. The borehole depth can be selected based on site characteristics and the purpose of the array, but it should be a minimum of 10 meters for a broadband seismometer. Creating better signal to noise for the advancement of AI and ML will enable important new discoveries by researchers working on hazard reduction. Most seismic networks around the world are multi-purposed: local monitoring, regional monitoring, hazard monitoring and, now, early earthquake warning. All benefit from the improved stability of borehole emplacements, which can also host more than one instrument. Using dry cased boreholes is a simple and cost effective way to upgrade networks and working with local water well drillers can make it as cost-effective as vault construction.

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Historical earthquake data in seismology practice

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A new method to re-assess historical earthquake focal parameters by the Austrian Intensity Prediction Equation

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Equations that predict ground-shaking distribution (Ground Motion Prediction Equations - GMPs, and Intensity Prediction Equations - IPEs) as a function of magnitude, focal depth, distance, and site correction, are a key for hazard and risk assessment allow building structures to be earthquake-resistant designed.

Macroseismic historical research is paramount for reliable input parameters for Probabilistic Seismic Hazard Analysis (PSHA), e.g. magnitude activity rates computations and magnitude estimates because it is the only source of information available before the advent of instrumental seismicity. Therefore, good assessments of epicentral and local intensities are vital for locating and estimating magnitudes and focal depths of historical events.

Difficulties with gathering sufficient information, such as tracing testimonies or identifying other evidences, can be overcome by applying Intensity Prediction Equations (IPEs) in historical Earthquakes Research. Therefore, this work aims to use the Austrian IPE for a re-assessment of magnitudes and depths of historical earthquakes with epicenters in Austria. The method is based on the minimization of the IPE residuals (Root Mean Square Error – RMSE) and the application of a grid search algorithm to determine the optimal set of values (epicentral intensity, local intensity, magnitude, and depth) for the given IPE. To apply this method, earthquakes with a large number of Intensity Data Point (IDP), such as the earthquakes of Wiener Neustadt (1768 – with I0=VII), and Schwadorf (1927 – with I0=VIII), are reviewed.

ESC2021-S37-026

California Historical Intensity Mapping Project (CHIMP): A consistently reinterpreted dataset of seismic intensities for the past 162 years and implications for seismic hazard maps

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Because major earthquakes and resulting strong shaking are rare events in any one area, seismologists know little about how well earthquake hazard maps describe actual shaking that occurs. Shaking data recorded since probabilistic seismic hazard assessment began span a short time period, hence, rarely include data from the moderate and large earthquakes that control hazard. We have previously used retrospective assessments, comparing hazard maps to compilations of historical shaking data spanning hundreds of years for Japan and Italy, to explore this problem. We have now compiled a shaking dataset for California termed CHIMP (California Historical Intensity Mapping Project) showing maximum shaking at points within the region over the past 160 years. The dataset provides a long, consistently interpreted intensity record. It includes USGS "Did You Feel It" data for recent earthquakes, intensities reinterpreted from felt reports collected by the U.S. Coast and Geodetic Survey, and intensities inferred from historical and oral accounts. CHIMP is a publicly available resource for investigators conducting various studies and can be updated using data from future earthquakes or additional historical earthquake data.

We compare CHIMP to USGS seismic hazard maps to explore aspects of map performance and possible approaches to improving them. Initial comparisons show that the fraction of sites at which shaking exceeds the mapped value is lower than expected. This overprediction, which also appears for Italy and Japan, could occur due to chance, downward biases of the dataset, or upward biases of the map. Data smoothing has been explored to account for biases of the dataset and appears to reduce overprediction. Since hazard maps are developed using ground motion models, we explore how well current ground motion models fit CHIMP data and if they could cause the map's apparent overprediction. Later goals include providing data for non-ergodic models that describe specific source-receiver pairs.

ESC2021-S37-038

Testing the Environmental Seismic Intensity scale on data derived from the earthquakes of 1626, 1759, 1819, and 1904 in Fennoscandia, northern Europe

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The Fennoscandian Peninsula in northern Europe is an intraplate domain where instrumental data must be extended back in time to improve knowledge of earthquake consequences. We opted to search for hitherto disregarded earthquake environmental earthquake effects (EEEs) for the important earthquakes of 1626, 1759, 1819, and 1904, and analyze their geographical distribution. We mainly investigated EEEs using contemporary newspaper accounts.

The compiled data sets are most probably incomplete, but testify to such EEEs as rockfalls and turbulent waters. In 1759, turbulent waters were reported from distances up to approximately 380 km. In 1904, they caused trouble to sailors on many lakes. Numerous rockfalls and landslides were reported in 1819 and 1904. In the 1904 rockfalls, boulders fell onto a roadway and into a river, causing flooding that reached rye crops.
We assessed the EEEs for the localities of interest using the Environmental Seismic Intensity scale ESI-07. A challenge in using slope failures for intensity assignment is that the triggering of landslides is highly dependent on the level of water saturation in the slope prior to the earthquake. This precipitation effect poses an extra uncertainty in the assignment of ESI-07, which is especially pronounced in areas of high precipitation, such as western Norway. EEEs are also affected by temperature: the winter earthquake of 1759 cracked ice on many lakes.

The overall agreement between ESI-07 values and EMS-98 intensities is good, but many assigned ESI-07 intensities remain uncertain due to the character of the textual information and brevity of the documentation. However, the ESI-07 scale also has practical importance for regions with infrequent EEEs.

Reference: Mäntyniemi P, Sørensen MB, Tatevossian RE (2021) Testing the Environmental Seismic Intensity scale on data derived from the earthquakes of 1626, 1759, 1819, and 1904 in Fennoscandia, northern Europe. Geosciences 11, 14. https://doi.org/10.3390/geosciences11010014

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On the promise and limitations of historical intensity data

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Recent studies have demonstrated a high degree of consistency between instrumental ground motion parameters and intensity values from on-line systems such as "Did You Feel It?" But do historically observed intensities also provide reliable indications of ground motions for very large earthquakes? We consider whether the intensity distributions of two of California's largest historical earthquakes – 1872 Owens Valley and 1906 San Francisco -- are consistent with predicted intensities from a modern ground motion model and ground motion-intensity conversion equation. For the 1906 earthquake, applying this approach to an extensive intensity data determined by Boatwright & Bundock (2008) set yields an optimal intensity magnitude of 7.9, the same value estimated previously from instrumental seismic and geodetic data (Song et al., 2008). For the 1872 earthquake, however, the intensity-based magnitude is higher than the moment magnitude estimated from geologic observations, providing evidence that it was a high stress drop event, with high slip relative to rupture area. This in turn suggests a moment towards the upper end of the range implied by scaling relations, given the estimated surface rupture length. We note that, for historical earthquakes especially but also for recent earthquakes, intensity data provide an integrated measure of shaking at relatively high frequencies, i.e., a few Hz to 10 Hz. Given the strong dependence of high frequency shaking on stress drop and its relatively weak dependence on seismic moment, simple relations predict that an intensity-based magnitude can be a full unit higher or lower than the moment magnitude. In the absence of constraints on rupture dimension, this uncertainty is likely irreducible. We further note, however, that the "failure" of intensity data to reflect moment magnitude could be viewed as a failure of moment magnitude to reflect ground motions at frequencies of engineering concern.

ESC2021-S37-094

On the use of data mining to improve the knowledge of historical earthquakes

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In regions that undergo low deformation rates, as is the case in mainland France, the use of historical seismicity, in addition to instrumental data, is necessary when dealing with seismic hazard assessment.

For about 40 years, started in support of the development of the nuclear industry in France, efforts have been jointly made by BRGM (Bureau de Recherche Géologique et Minière), EDF (Électricité de France) and IRSN (Institut de Radioprotection et Sûreté Nucléaire) to collect, compile, and distribute information related to historical events through a common database known as SISFRANCE. The SISFRANCE macroseismic database contains about 100,000 macroseismic observations (MSK intensity scale—Medvedev et al. (1967)) associated with about 6000 earthquakes (AD463-2007).

Some past earthquakes are better known than others and the reliability of earthquake-parameters depends on both the number and the quality of archive documents coming from different geographical locations where the earthquakes were felt. Indeed, having a maximum of information on past earthquakes is crucial to estimate robust epicentral intensity (and magnitude) and location.

With the emergence of big data technology, the expansion of specific online communities, innovative approaches to find new historical documents on past earthquakes are now possible. This work presents the development of a methodology based on data and text mining techniques to extract new information, especially about past earthquakes suffering from a lack of data.

This work led through particular websites of digital historical archives to the finding of more than 2000 documents dealing with earthquakes felt in mainland France. More than 60% of them are not listed in the SisFrance database.
This methodology aims at facilitating source findings and delivering new sources but it is not destined to replace historian expertise on documents themselves. Expert assessment, by analyzing and interpreting sources, and putting them into the historical context is crucial.

ESC2021-S37-102

Refining the parameters of historical earthquakes with the nonseismological information in Yunnan province, China

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The earthquake catalog from instrumental records covers about one hundred years, too short a period to catch the recurrence interval of large earthquakes. Historical earthquake catalog from macroseismic intensity data have significantly expanded backwards in time our knowledge of the seismic behaviour of many areas in the world. For the catalog of historical earthquakes, the problem is that the errors of parameters are larger generally. If abundant macroseismic data are available, the estimation of historical earthquake parameters is with little error relatively. The actual situation, however, is usually unsatisfactory. Seismologists often have to deal with a historical earthquake with only limited historical records.

Many reasons may cause the limited historical records. Yunnan Province, in southwestern China, is very famous for its mountain terrain. The land suitable for human survival is very limited, so that the sites with historical recordings were not balance in spatial distribution. In this case, the estimation of epicenter might be with larger uncertainty. In order to reduce the error, we collect information of local geography, hydrology, population distribution through field trips. As example, a historical earthquake occurred in 1500 was analyzed. With the nonseismological information, right site of the IDP was determined and the uncertainty of epicenter was reduced. In this process, we emphasize the important of understanding historical records in the historical time period and local scenario.

ESC2021-S37-172

A probabilistic approach for the integration of macroseismic intensity distributions: an application to Italian data

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The knowledge of the effects of past earthquakes at different places quantified in terms of macroseismic intensities is a basic tool for several purposes (e.g., source characterization of pre-instrumental events and

risk analysis). The geographical distribution of these effects as inferred from historical documentation may present spatial gaps with respect to all the places that are likely to have been affected. To reduce these gaps, we present a probabilistic approach aimed at integrating the incomplete macroseismic intensity distributions of historical earthquakes. The proposed procedure better constrains the intensity values estimated at a given site by an Intensity Prediction Equation (IPE) using the macroseismic intensity data documented at nearby localities for the considered earthquake. As a key element, this method takes into account the uncertainties related to the nature of intensity data (discrete and ordinal) and the outcomes of in-depth analysis of the spatial variability of intensity data collected in the Italian Macroseismic Database DBMI15. The proposed procedure was tested at 28 localities with long and rich seismic histories homogeneously distributed over the Italian territory. In addition, a comparison test for a set of Italian earthquakes was carried out in order to verify the capability of this procedure in predicting intensity values with respect to using an IPE alone. We present an application of this procedure for the integration of macroseismic intensity distributions of earthquakes with incomplete and scattered intensity data.

ESC2021-S37-213

Reducing differences in earthquake activity rate estimates across borders in Europe

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Earthquake activity rates estimated in cross-border regions can differ between countries. For example, considering the FCAT or CPTI15 catalogues in the Italian and French Alps, earthquake activity rates can differ from 20 to 80% depending on the magnitude bin. This study aims at answering the following question: how much of the difference in the annual seismicity rates in the Alps cross-border region is due to different methodologies used to compute historical earthquake magnitudes? To answer this question, we built two new historical (pre-1980) parametric earthquake catalogues for this region considering a common post-1980 earthquake catalogue based on the CPTI15. To focus on methodological differences, it was necessary to first build a common macroseismic and instrumental magnitude dataset to calibrate the two methodologies considered, namely Boxer and QUake-MD. We then applied the two methodologies to the same macroseismic dataset to build the two new historical (pre-1980) parametric earthquake catalogues. Finally, we computed earthquake rates for the two catalogues and found them to be statistically similar. This exercise underlines that reducing existing differences in seismic activity rate estimates across border regions will necessarily require a common definition of instrumental magnitudes and a common macroseismic dataset.

ESC2021-S37-226

On the importance of uncertainty definition in earthquake catalogues and their impact on SHA: a case study in the French-Italian Alps

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Earthquake catalogues constitute the main input data for probabilistic seismic hazard (PSH) models. As discussed in the abstract by Provost et al. (ESC 2021), defining the historical catalogues from macroseismic

data requires the implementation of the methodology to compute historical earthquake magnitudes and depths. These methodologies may impact earthquake parameters and uncertainty estimates.

Moreover, for PSH purposes, pre-processing has to be conducted on the earthquake catalogues, namely: declustering, estimation of the completeness periods, and computation of the magnitude-frequency distribution. Each of this step is affected by uncertainties as well. We developed tools to propagate these uncertainties in PSHA, from the catalog to the estimate of the activity rates. We illustrate the propagation of such uncertainties and their impact on PSHA using the two catalogs of Provost et al. (2021) for the French-Italian Alps

ESC2021-S37-247

Ten years of the European Archive of Historical Earthquake Data AHEAD

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Ten years have passed since the appearance among European seismological databases of the European Archive of Historical Earthquake Data AHEAD, an achievement of the networking activities of the EU-FP6 NERIES Project. AHEAD was publicly released in 2013, and its content contributed to the definition of the 1000-1899 catalogue for the European Seismic Hazard Model 2013. Later on, AHEAD consolidated as a distributed archive relying on the eight independent regional nodes for Italy, France, Switzerland, Spain, Catalunya, Belgium, and Greece, whose data are complemented with those from the most recent scientific literature. In the last few years, web services have been developed to provide direct access to the data and to make AHEAD the official provider of historical seismological data within EPOS.

The content of AHEAD recently underwent a major update, incorporating the most recent version of the contributing regional databases, e.g. SisFrance and the Italian Archive of Historical Earthquake Data ASMI, and all the most recent scientific literature. As a whole, 77 new sources of data are included in AHEAD, dealing with over 6700 earthquakes. In addition, AHEAD integrated records from some old sources of data partially or not yet archived. As a result, the earthquakes dealt with in AHEAD increased by more than one thousands. AHEAD also presents information related to over 400 fake earthquakes included in seismic catalogues. The new and revised data provided the input for the new version of the 1000-1899 catalogue for the European Seismic Hazard Model 2020.

The presentation will detail the update of AHEAD and its impact on the overall picture of the European pre-instrumental seismicity, as well as some hints on the future developments of the archive.

ESC2021-S37-292

A new intensity attenuation model using 19th-20th century shallow seismicity in the Hainaut coal area in Belgium

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The 19th to 20th century shallow seismicity in the coal area of the Hainaut province in Belgium is the second largest source of seismic hazard in NW Europe. In this sequence, five seismic events (Mw~4.0) locally caused moderate damage to buildings to maximum intensity VII on the EMS-98 scale. For decades, the natural causality of this seismicity and its potential link with coal extraction is disputed. To provide a complete catalog to tackle this discussion in the near future, we reviewed a century of intensity data collected by official macroseismic surveys, press reports, and contemporary scientific studies. In this contribution, we present methodological advances on how we updated the magnitude, epicentral intensity and location, and depth of 123 Hainaut seismic events only using macroseismic data.

The damage related to these events was mainly induced by the shallow source (< ~6km) of the events. Inside the Carboniferous coal basin (that extends from Mons to Liège) intensity attenuates much faster than in the surrounding Paleozoic basements. Using the improved intensity dataset, we therefore modelled a new intensity attenuation law, only applicable for this coal basin, that needs to be considered in future seismic hazard modelling. The new attenuation model is moreover useful to evaluate the potential impact of current and future, e.g. geothermal energy, projects in the Hainaut area and other regions with a similar geological configuration.

ESC2021-S37-427

Macroseismic source parameters of seismic sequences: study of the 2016-2017 and 1703 Central Italy

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Recent studies have addressed the issue of the assessment of macroseismic intensities related to seismic sequences, suggesting that the contribution of the individual earthquakes to the intensity assessment is not separable. Consequently, the estimation of the cumulative damage is unavoidable, although it may lead to an overestimation of the intensities.

Nowadays the quantitative assessment of earthquake parameters, such as location, magnitude and even length and orientation of the seismogenic fault, from intensity data with robust and repeatable tools provides a straightforward comparison between recent and historical earthquakes. However, the experience of the 2016-2017 seismic sequence in Central Italy has shown how intensity data related to multiple shocks could bias the parametrization of intensity data and the subsequent seismological interpretations.

This problem triggered a warning about the parametrization of historical sequences, lacking a comparison with instrumental data. In historical earthquakes' sequences, the uncertainty due to the cumulative effects caused by the aftershocks, adds to the uncertainty about the interpretation of the sources. Unfortunately, these uncertainties are difficult to be considered by the parameterization procedures, often driving misleading results.

The aim of this work is to highlight how critical is the parametrization of a seismic sequence. We first tested different approaches to deal with effects of the cumulative intensities on the macroseismic parameters of the 2016-2017 Central Italy earthquakes. The very same approach was then applied to a new dataset for the 1703 seismic sequence in the same area. The results demonstrate that the interpretation of the macroseismic parameters can strongly bias the subsequent inferences about the seismic sources. A careful macroseismic evaluation of historical facts may help to define a range of probable solutions, rather than to provide certain solutions on the seismotectonic interpretation of seismic sequences.

ESC2021-S37-513

A new earthquake catalogue for Tyrol/Austria

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Tyrol is one of the provinces with the highest seismicity in Austria. Most of the stronger historical earthquakes occurred around Innsbruck and Hall in Tirol (1572, 1670, 1689).

The project "Historical and recent earthquake activity in Tyrol - sources, data, seismological analysis" (2014-2020) mainly dealt with historical earthquakes in Tyrol up to 1900 but also in detail with damaging earthquakes in Tyrol in the 20th century. The project's purpose was to create a new earthquake catalogue for Tyrol, which for the first time also includes Macroseismic/Intensity Data Points (M/IDPs).

An essential aspect of this study is the detailed documentation of the contemporary sources and the literature used for all Tyrolean earthquakes up to the year 1900 and for selected damaging earthquakes of the 20th century. Numerous Tyrolean archives, such as the Tyrolean Provincial Archives, and the City Archives of Hall in Tyrol, were searched for contemporary earthquake sources. Likewise, the seismic archive of the Austrian Seismological Service at ZAMG contains a wealth of valuable recent information, such as the questionnaires on earthquakes of the entire 20th century.

To (re-)evaluate the focal parameters for historical and recent earthquakes in Tyrol for the first time the (Austrian) intensity prediction equations (IPE) with the Grid Search (GS) technique was applied.

A total of 1750 M/IDPs for 35 damaging earthquakes from the Austrian Earthquake Catalogue (AEC2020) could be determined based on the historical sources. Likewise, 726 new M/IDPs from a total of 154 non-damaging earthquakes not yet included in the AEC2020 were determined. For 38 of them, it was possible to calculate new sets of focal parameters.

The project was funded by TIWAG-Tiroler Wasserkraft AG, ASFINAG Alpenstraße GmbH, Fachgruppe der Seilbahnen Tirol, Verbund Hydro Power GmbH, Amt der Tiroler Landesregierung - Abteilung Allgemeine Bauangelegenheiten, Landesgeologie, ÖBB Infrastruktur AG and ZAMG.

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Quadratic reversible ground motion-to-intensity conversion equations for Italy, based on a novel benchmark data set (INGe)

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Introduction: Macroseismic intensity reveals an essential parameter in the engineering, seismological and loss modelling fields. Nowadays, with the availability of abundant strong motion data, macroseismic intensities still play an important role in:

1. Reconstructing shaking distributions, location and magnitude of historical events;
2. Development of macroseismic intensity attenuation relationships;
3. Calibrating regression relations between the peak ground motion parameters (PGM) and the reported intensities;
4. Seismic loss estimation and modeling;

5. Post-earthquake damage assessments in near-real-time.
In general, macroseismic intensities have been found to facilitate the exchange of earthquake impact information from seismologists to the population and vice-versa.

Methods: We have assembled an updated and homogeneous earthquake data set for Italy (named INGe) compiled by joining the Italian Macroseismic Database DBMI15 and the Engineering Strong-Motion (ESM) accelerometric data bank. An extensive review of the data available, with the extraction of the localities reporting intensity values located within 3 km from the accelerograph stations, resulted in a data set consisting of 519 records from 65 earthquakes, 227 stations and 338 localities in the time 1972-2016 (doi:10.13127/inge.2).

Based on this data set, we derived new reversible relationships between macroseismic intensity and peak ground acceleration (PGA), peak ground velocity (PGV) and the spectral acceleration (SA) at 0.3, 1.0 and 3.0 s (SA(0.3), SA(1.0) and SA(3.0)) for Italy, by adopting orthogonal distance regression to fit a quadratic function.

Results: Tests performed to assess the robustness of the results demonstrate that quadratic relationships for the regression are valid and accurate equations to model the data. Furthermore, compared with the relations already available in the literature for Italy, the proposed equations show an overall improvement in terms of statistics.

Conclusion: These regressions can be valuable for inferring the strong ground motion of historical events and the calculation of shakemaps and seismic hazard maps in Italy.

ESC2021-S37-590

Historical earthquakes in Samos, Greece in the period 1800-1899

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Sources containing descriptive information on earthquake effects in Samos from the period 1800-1899 are analysed and EMS-98 macroseismic intensities are assigned. Many of the events occurred in this period are presented in the Hellenic Macroseismic database (http://macroseismology.geol.uoa.gr). Access to the Greek newspaper “Amaltheia”, published in Izmir, allowed for systematic reading of its issues in the period of study. The final product is an increased number of re-assigned EMS-98 intensities and Macroseismic Data Points, leading to updating the seismic history of the island and macroseismic parameters determination, using MEEP package. The analysis showed that two earthquakes, probably similar to the 30 October 2020 Samos event, occurred in the 19th century.

ESC2021-S37-591

Earthquake-related damages at two archaeological sites east of the Dead Sea Transform: an archaeoseismological study (Beit-Ras and Umm el-Jimal, Jordan)

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The Levant is a desirable region for historical earthquake studies because of its abundant archaeological sites that is still standing in the vicinity of the Dead Sea Transform Fault (DSTF). The DTSF, which forms a left-lateral strike-slip fault and defines the NW plate boundary between Arabia and Africa plates, is the most active tectonic structure in the Middle East region. The region can be considered as an ideal laboratory for applying archaeoseismological investigations.

Accurate reading of many historical earthquake catalogues and primary sources of historical earthquake data of the region have indicated that many of the reported ancient sites that have experienced substantial earthquake damages are located to the west of the Dead Sea Rift in comparison to those located to the east. This seemed quite alerting considering the many archaeological sites located in Jordan, which are not included in these reports. Several isoseismal maps of macroseismic damages have been constructed for the major historical earthquakes. It is concluded that most of the reported events require further and detailed investigations because of the scarcity of data about earthquake effects within the eastern part of DSTF, uncertainties associated within the exact date of the major event or its associated sequence of events, and the accuracy of the reported location of many archaeological sites that hold identical historical names.
This study reports the archaeoseismic features observed at two archaeological sites of Jordan, Beit Ras and Umm el-Jimal, located east of the DSTF, aiming to show how such these studies can enhance the accuracy of these maps of already known and potentially identified historical earthquakes not mentioned in existing catalogues.

The study represents the necessity of conducting a comprehensive historical earthquake investigation approach, integrating archaeoseismic, macroseismic, and archaeologic results, to enhance the accuracy of historical earthquake demand for an accurate seismic hazard assessment.

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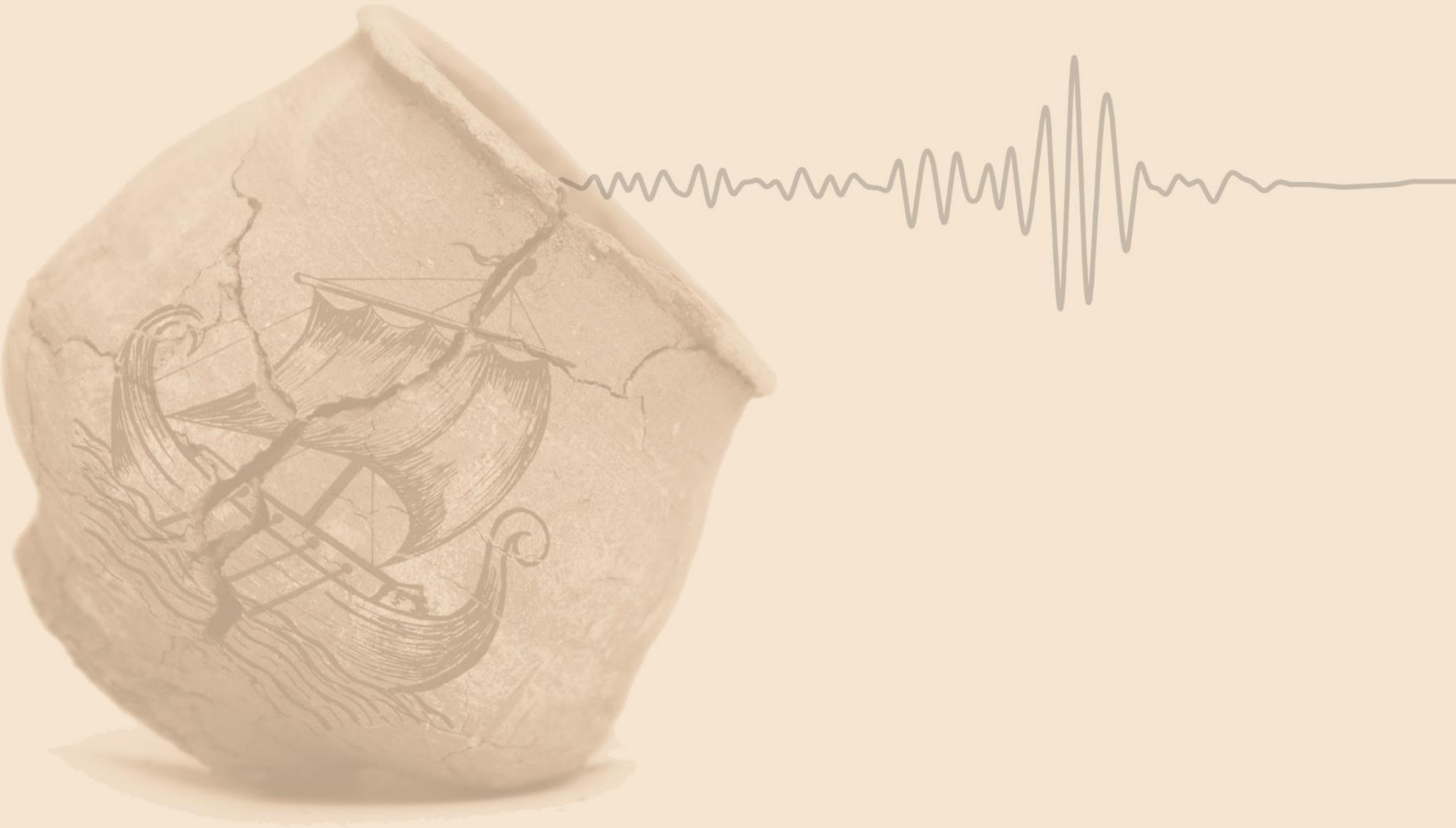

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Study on the relative behaviour of time in P waves propagation

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This paper presents experimental evidence showing the relative behaviour of time for a compression wave (P wave) generated at different frequencies by the impact of a battering ram, as well as a theoretical model that explains the experimental observations in two reference frames. The problem is solved using the two postulates of relativity i.e. the wave velocity is the same for all observers and the two reference frames are inertial. Research shows that the arrival time of the wave is dependent on the wave's frequency generated and the distance separating the source from the receiver. Results show that serious mistakes could be made in the material velocities calculations and, therefore, in their elastic modulus when using distance over the wave's arrival time to calculate the material's velocity. The problems related to these errors have not yet become in technical norms, such as those that have been published in ASTM D4428/D4428M-14 for geophysical explorations of this type.

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Characteristics of the frequency content of strong ground motions from intermediate-depth earthquakes of Vrancea region (Romania)

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The Vrancea region, Romania, is one of the most active intracontinental earthquake-prone areas in Europe. According to the existing historical catalogues, during 100 years the intermediate-depth seismic source may produce one-to-six strong earthquakes (Mw 7 and above), with significant damaging effects over large areas. The frequency content of earthquake ground motions affects substantially the dynamic response of structural systems subjected to shaking. This study is focused on two engineering characteristic parameters, based on the Fourier amplitude spectra of acceleration time histories: the dominant frequency – defined as the frequency corresponding to the maximum value of the smoothed average horizontal spectra, and the mean period (Tm) – calculated by averaging the periods (over a specified period range) weighted by the squared Fourier amplitudes.

The study data are horizontal acceleration records from 18 earthquakes with moment magnitude ≥ 4.5. For 14 moderate-size events (magnitudes in the range 4.5-6.0) which occurred in the period 2004-2020 digital records are available. Data from 4 strong events (moment magnitudes between 6.4 and 7.4) recorded with analog instruments in the period 1977-1990 are also considered.

We investigate the dependence of the frequency content of strong ground motions on source, path and local conditions by analyzing the effects of magnitude, hypocentral distance, site soil classification on the two spectral parameters.

ESC2021-S38-076

Seismotectonic implications of the 2020 Samos, Greece, Mw7.0 mainshock based on high–resolution aftershock relocation and source slip model

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The 30 October 2020 Mw7.0 Samos main shock took place in the offshore north of Samos Island in eastern Aegean area. The investigation of the aftershock seismicity evolution and the properties of the activated fault network was accomplished with aftershock relocation performed with the double–difference and cross–correlation techniques. The improved relocated aftershocks span a depth range 5–15 km and mostly between 10–15 km, with an average depth of ~12 km. This pattern suggests that the mainshock ruptured a strongly locked patch located down dip and then the coseismic slip was propagated up dip. Focal mechanisms for the larger magnitude aftershocks are determined by full waveform moment tensor inversion and are used along with the ones published by other Institutions to determine the geometries of the main rupture and the activated secondary ones, indicating mostly normal faulting with an average T–axis ~185o.

Teleseismic and strong motion waveform modeling revealed a N–dipping fault plane with slip mainly concentrated in a single asperity implying a rupture mode of asperities breaking in isolated earthquakes rather than to cooperate to produce a larger rupture. The main patch is located down dip of the main rupture offshore, without extending to the shallow part, but with a westward relatively small displacement. Our preferred model with the largest concentration of slip near the coastline and downdip under a submarine environment is in good agreement with the timing and magnitude of the observed tsunami and geological investigation for the observed displacement.

Coulomb stress calculations were performed with the variable fault slip model and their spatial distribution were compared with the epicentral distribution of the aftershocks. The increased positive static stress changes values are found at the locations of ~75% of the aftershocks and the positions of the activated minor fault segments.

ESC2021-S38-121

Contact of the Samoan plume with the Tonga subduction from intermediate and deep-focus earthquakes

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The Tonga subduction zone in the southwest Pacific is the fastest convergent plate boundary in the world with the most active mantle seismicity. This zone shows unique tectonic features including Samoan volcanic lineament of plume-driven origin near the northern rim of the Tonga subducting slab. The proximity of the Samoa hotspot to the slab is enigmatic and invokes debates on interactions between the Samoa plume and the Tonga subduction. Based on long-term observations of intermediate and deep-focus Tonga earthquakes reported in the Global CMT catalog, we provide novel detailed imaging of this region. Accurate travel time residua of the P and S waves recorded at two nearby seismic stations are inverted for the P- and S-wave velocities and their ratio, and reveal pronounced lateral variations. In particular, they differ for the southern and northern parts of the Tonga subduction region. While no distinct anomalies are detected in the southern

Tonga segment, striking low-velocity anomalies associated with high Vp/Vs ratio are observed in the northern Tonga segment close to the Samoa plume. These anomalies spread through the whole upper mantle down to depths of ~600 km. Together with a fast extension of the northern back-arc Lau Basin, slab deformation and geochemical enrichment in the northern Tonga region, they trace deep-seated magmatic processes and evidence an interaction of the Tonga subduction with the Samoa plume.

ESC2021-S38-123

Modeling of non-linear site response during earthquakes sequence on March 2021 in Central Thessaly, Greece

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On the 3rd and 4th of March 2021, a sequence of strong earthquakes with M6.0 and M5.9 (according to the catalogue of the National Observatory of Athens) occurred on previously unknown normal faults in Thessaly, central Greece. These events caused extensive liquefaction in several sites within the struck region, with more than 400 reported cases of sand blows, craters, fissures and lateral-spreading cracks and ruptures along the Pinios and Titarisios river banks, as well as in several local villages.

In the present study we model the non-linear response of the sites located in the vicinity of the areas with reported liquefaction, based on the results of several geophysical surveys that were conducted in the roader region, as well as geological information, which were incorporated to the numerical model. In the framework of our analysis, the built-in effective stress, cyclic degradation of material properties with hydraulic interaction between layers, i.e., dynamic response plus pore-water pressure generation plus pore-water pressure dissipation and redistribution were calculated for all tested sites.

The analysis of obtained excess pore water pressured distribution with depth, as well as time allows us to simulate the development of the liquefaction phenomenon and to better understand which seismic event was responsible for it.

ESC2021-S38-206

The 2020 October 30 Mw 7.0 Samos earthquake

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The October 30, 2020 (Mw 7.0) Samos earthquake is the largest well-recorded modern earthquake in the Aegean, a tectonically complex region that accommodates active extension and strike-slip deformation. The Samos earthquake caused severe damage, particularly in Western Turkey, killing ~118 and injuring ~1100 others. Utilizing a variety of tools from seismology and satellite geodesy, we study the source parameters, rupture characteristics, and aftershock distribution of this earthquake, as well as its relationship with

previous instrumental seismicity and regional tectonics. We further integrate the determined fault model in the tsunami numerical modeling and compare our results with data obtained from post tsunamis field surveys.

The mainshock nucleated at a depth of 13 km, rupturing upwards and unilaterally to the west. Although teleseismic and regional waveform modeling indicates rupture on an N-dipping E-W trending structure aligned with the known N-dipping Samos fault, geodetic (InSAR and GPS) and kinematic fault modeling suggest a multi-segment rupture with significant along-strike variations in the fault geometry. Calibrated aftershock locations are confined to depths of 6 – 21 km. We identify three spatially distinct groups: (1) a denser group of events to the east of the mainshock with dominantly E-W trending normal mechanisms, (2) a ~20 km long area to the west of the mainshock with very few aftershocks, and (3) a smaller group of aftershocks to the west of this sparse seismicity, with mostly strike-slip mechanisms. Our calibrated locations of previous seismicity (180 events, M > 4) from the last two decades provide further valuable insights into the seismotectonics of this region.

ESC2021-S38-214

Seismotectonic implications of the March 2021 Damasi-Elassona (Central Greece) earthquake sequence based on high-resolution aftershock relocation and focal mechanisms

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In early March 2021, three shallow earthquakes, two mainshocks with M6.3 and M6.0 and one major aftershock with M5.6 impacted the mountainous Damasi-Elassona region and a Plio-Quaternary basin formed by Titarisios River in Central Greece. Each major event was followed by rich aftershock activity. The broader Elassona region is known for active crustal extension but with low strain-rate, and it is considered key-point for the Aegean geodynamics, since it hosts structures formed during two main phases of tectonism: one during Pliocene-Early Pleistocene representing NE-SW direction of extension, and the modern one exhibiting N-S extension thereafter. We present results of a comprehensive analysis of this sequence, from its initiation on 28/2/2021, with several foreshocks, until 31/3/2021. We investigate the properties of the activated fault zone using a high-resolution earthquake catalogue and focal mechanisms computed by moment-tensor inversion and P-wave first motion polarities. Over 2000 events were manually located with an optimal velocity model and relocated with a double-difference method. First results indicate that the aftershocks form a zone that spans ~42km NW-SE, with focal depths between 5 and 15 km. More than 400 focal mechanisms were computed for events with M≥2.5, mainly implying normal faulting in NNW-SSE direction, whereas NE-SW and N-S normal faulting is also evidenced. Strike-slip faulting is present as well, demonstrating that a complex stress/strain regime dominates the region. Analysis of Coulomb stress transfer after the three major events reveals that stress-loaded areas include most of aftershocks in neighboring crustal sections that were activated during the course of the aftershock sequence. The Damasi-Elassona earthquakes could have potential implications to the seismic hazard of the broader area, as stress was transferred to a major NW-SE active normal fault heading towards Larisa city, constituting a possible candidate source for a significant future earthquake.

ESC2021-S38-220

Integrated Seismic Program (ISP): A new Python GUI based software for earthquake seismology and seismic signal processing

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Integrated Seismic Program (ISP) is a software equipped with a Graphical User Interface (GUI) specially designed to facilitate and provide a user-friendly framework for performing diverse common and advanced tasks in seismological research. ISP is composed of five main modules tasked with earthquake location, time-frequency analysis and advanced signal processing, implementation of array techniques to estimate the slowness vector, seismic moment tensor inversion and receiver function computation and analysis. Additionally, several support tools are available, allowing the user to create an event database, inspect the background seismic noise, download data from FDSN services and compute synthetic seismograms. The bulk of ISP is written in Python3, supported by several open-source and/or publicly available tools, and its modular design will allow for new features to be added in a collaborative development environment.

ESC2021-S38-222

Toward a new seismic hazard model for Guadeloupe: Model development and sensitivity analysis

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The official probabilistic seismic hazard model made for the purpose of the EC8 enforcement in France dates back to about 20 years ago. Based on that model the French ministry established the French seismic zonation which classifies the territory in 5 zones where the highest seismic zone is assigned to the French Antilles. Since then, relevant progresses have been made in the acquisition of new data and in the development of new models and methods to be used in probabilistic seismic hazard assessment (PSHA). Moreover, PSHA practice evolved significantly particularly in terms of treatment and consideration of uncertainties.

In this contribution we present the development of a new seismic hazard model for Guadeloupe consistent with the current state-of-the-art PSHA. We will focus in particular on the development of a homogenized earthquake catalogue, the integration of new available studies to develop seismic source models for both subduction and crustal sources and the consideration of new ground motion models and their comparison with records collected at RAP stations in Guadeloupe.

A sensitivity analysis will show the impact of alternative model hypotheses on the resulting hazard at several return periods. Preliminary results will be compared to the official French zonation at selected location at 475 years return period.

ESC2021-S38-273

Holocene activity of the Opak Fault (Central Java, Indonesia): Characterization of an active fault in a tropical environment

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Numerous shallow crustal faults situated near densely populated areas on the island of Java accommodate the tectonic strain caused by the subduction of the Indo-Australian Plate beneath the Sunda Plate. Identification and characterization of faults in Java are often challenging: its tropical environment hastens landscape degradation that erodes and buries faults and their associative geomorphology leading to poor surface expression of faulting. We use detailed geomorphological and structural mapping of Quaternary deposits and paleoseismic features, combining field data with remote sensing observations, to map and characterize the geometry, kinematics, and relative activity of the Opak Fault and other faults in the province of Yogyakarta (southern central Java). We provide data supporting the Opak Fault as an active SW-NE transtensional left-lateral strike-slip reactivated normal fault consisting of several parallel fault strands. Although geomorphological expression of neotectonics is subtle and diffuse, we found several pieces of field evidence of active tectonics such as tilted Quaternary fluvial terrace risers, triangular facets, linear valleys and ridges, migration of meanders, wind gaps, peculiar drainage patterns, and knickpoints that allow us to provide evidence of the Holocene activity of the Opak Fault. Our results highlight the importance of improving seismic hazard assessment with regional studies to characterize active faults, especially in densely populated areas like Yogyakarta and where faults can be underestimated because of subtle geomorphological expression.

ESC2021-S38-318

The 2021 Tyrnavos (central Greece) doublet (Mw6.3 and Mw6.0): Aftershock relocation, faulting details, coseismic slip and deformation

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The aftershock sequence of the Tyrnavos doublet is notable both for its remarkable productivity and for its geometrical complexity. The aftershocks clearly define the fault planes of the two main shocks, consistent with the NW–striking and NE–dipping planes implied by the moment tensor solutions, along with multiple secondary structures. We investigate the sequence by relocating the aftershock catalog using waveform cross–correlation arrival times and double–difference techniques and determining focal mechanisms for individual events and event clusters. The high–accuracy locations reveal that the aftershock activity occurred in the upper 15 km of the crust, in the eastern depression of Thessalia basin. Moment tensor solutions for the largest aftershocks show prevalent normal faulting.

To obtain a detailed picture of the coseismic slip and deformation, we combine seismic waveforms with Global Positioning System static offsets and Interferometric Synthetic Aperture Radar observations. The main ruptures are found to be simple in terms of coseismic slip.

The remarkably high productivity of the 2021 Tyrnavos sequence and consecutive failure of secondary fault segments unveil significant details of the local fault network and the normal faulting mechanics.

ESC2021-S38-330

The Malta Seismic Network: From earthquake monitoring to seismic imaging of groundwater

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Following the setting up of the Malta Seismic Network, new opportunities for research arise which go beyond the conventional monitoring of earthquakes. The new data is used to carry out site response studies as well as high-resolution sub-surface studies such as velocity profiles and groundwater imaging of the aquifers. These studies have significant importance for Malta, particularly because it is a small island country 15 km wide by 30 km long in the centre of the Mediterranean Sea (~100 km south of Sicily, Italy).

The network operated by the Seismic Monitoring and Research Group at the University of Malta is being exploited to maximize its full potential aiding the local Department of Civil Protection with earthquake monitoring and tsunami modelling and now the Energy and Water Agency with groundwater monitoring.

We present the recent developments of the seismic network, examples of local earthquake recordings, earthquake catalogue and site response studies. In addition, we present SIGMA (Seismic Imaging of Groundwater for Maltese Aquifers), a new project aimed at imaging the spatial and temporal characteristics of aquifers across Malta–a first to cover a whole country that is completely surrounded by sea.

The data set is derived from a combination of 13 stations, including those of the Malta Seismic Network and other temporary instruments spanning across the whole archipelago. We use auto/cross-correlation of noise recorded on the stations to extract information about the subsurface and track temporal and spatial changes in water content at different scales. These changes are compared to in situ borehole readings and meteorological parameters.

Funding for stations was provided by Interreg Italia-Malta projects (SIMIT and SIMIT-THARSY, Codes B1-2.19/11 and C1-3.2-57) and by Transport Malta. Project SIGMA is financed by the Energy and Water Agency under the National Strategy for Research and Innovation in Energy and Water (2021-2030) https://seismic.research.um.edu.mt/sigma/.

ESC2021-S38-383

Seismotectonic implications of the 30 October Mw=6.9 Samos Earthquake

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A large offshore earthquake (Mw=6.9) occurred on 30 October north of Samos Island (Eastern Greece), also triggering a small tsunami, mainly at the Turkish coasts. This event caused two fatalities in Samos and 115 in Western Turkey. The focal mechanism of the mainshock, obtained by regional body-wave modeling revealed normal faulting in an approximately E-W direction.

The north-dipping plane is selected as the causative one, taking into account the observed uplift at western Samos and the subsidence at the northernmost edge of the central part of the island. The majority of aftershocks occurred east of the mainshock's epicenter, in a region where intense clustering is identified. A smaller number of aftershocks is also located to the west, with a gap between the two regions. Coulomb stress transfer indicated loading of the western and eastern margins triggering aftershock activity. The possibility of activation of multiple structures is investigated, given the complexity of the source time function of the main event. Only minor damage was reported to the building stock of the Samos Island, whereas severe damage was observed at Izmir, mainly at high-rise building,

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DEUNET: The real time seismic monitoring in Izmir and its surroundings, Western Turkey

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Dokuz Eylül University Seismological Observation Network (DEUNET) is a local network that observes the earthquake activity which occurs in the Izmir and its surroundings. Izmir is the third largest city in Turkey and has the distinction of being the most crowded city of Western Anatolia and Aegean region. Izmir and Aegean region exists an important set of faulting systems and complex geological structure. This network is operated by seismology laboratory of Dokuz Eylül University Engineering Faculty and at the present time consists of 5 stations. The aim of the study is determining the earthquakes nearby the network area and especially to analyse the micro earthquakes that not recorded or overlooked by national networks. Earthquake data that recorded between 2019-2021 were analyzed with the Seisan software.

The rms of analyzed earthquakes is less than 0.4, their magnitude ranges are $1 \leq ML \leq 6.6$ and the seismicity up to 30 km has been identified. We determined that most of the seismicity in the region tends to concentrate near the normal faults. In addition to these faulting systems, we identified strike-slip faults and small amount of reverse-slip fault mechanism too. We also made focal mechanism solutions by adding the data of other stations in the region. During the 2 year observation process we identified more than 1400 earthquakes and 575 of them was micro-earthquake. DEUNET is important for the region as it enables more precise hypocentral locations and to assign zones of active tectonics. One of the purposes of the DEUNET network is to support education and make analyzes with students.

ESC2021-S38-463

A grid-based b-value approximation through Southern and Northern Norway: preliminary results

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The Gutenberg–Richter's b–value is commonly used to analyze the frequency–magnitude distribution of earthquakes, describing the proportion of small and large seismic events as the first estimation of seismic hazard. Additionally, the b–value has been used as a stress meter, giving some insights into the stress regime in different regions around the world. In this research, a grid–based spatial distribution for the b–value was estimated in two different areas of Norway: northern (74°–81°N / 12°–26°E) and southern (57°–64°N / 3°–12°E). For this, we used a complete catalog from the years 2000 to 2019, which was obtained from the Norwegian National Seismic Network online database. The magnitude of completeness was estimated separately for each zone both in time and space. Our results show a regional variation of the mean b-value for northern (b_north = 0.79) and southern (b_south = 1.03) Norway, which can be interpreted in terms of the predominant stress regime in the different zones: Shallow compression in northern Norway and deep compression in southwestern and southeastern areas. Further analysis will be carried out using the ZMAP software.

So far, a few calculations regarding the b–value were previously done in Norway to analyze local intraplate sequences. Then, according to our knowledge, this research corresponds to the first estimation of a regional spatial variation of the b–value in the country.

ESC2021-S38-515

Analysis of signals from two temporary small aperture seismic arrays in southern Portugal

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The installation of two small aperture arrays aims to investigate the detection and localization capabilities of a future array in Portugal. We installed ten three component stations in an irregular grid with interstation distances between 125 m and 2000 m during a three week long campaign. The pool of sensors and digitizers is homogeneous; the natural frequency of the sensors is 2 Hz, and the seismic data were continuously recorded with a digitizing rate of 100 Hz. Each station is coupled to GPS for correct timing. The topography of the selected sites is smooth, avoiding the application of corrections to compensate travel-time effects due to large altitude differences.

In this study, we investigate the inter-sensor coherence of the seismic noise field for both small aperture arrays using both a classic approach as well as a dynamic approach which accounts for possible slowness characteristics of the noise field. Additionally, we analyzed seismic signals from local and regional earthquakes observed by the two test arrays. For this we applied the well-known array methods beamforming and f-k analysis to both P- and S-wave signals.

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ESC2021-S38-566

Redefining the rupture geometry of Mw 7.8 Kangra 1905 earthquake based on shear wave velocity structure and recent seismicity

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Devastating and only large instrumental recorded earthquake of the northwest Himalaya is Mw 7.8 event of 1905. This is the most studied earthquake of the region where the rupture geometry of the Kangra earthquake is still poorly resolved due to limited information on sub-surface structure and seismogenesis High resolution shear wave velocity structure reduced from the ambient noise tomography using present day modern continuous broadband seismic data redefine the rupture geometry. It is coupled with the past and recent seismicity, focal mechanism and topography relief to properly infer the source geometry of the Kangra 1905 earthquake. High-resolution 3-D shear wave velocity of upper crust in the Kangra region reveals double ramp geometry on the Main Himalayan Thrust (MHT) based on ambient noise cross-correlation. It images low-velocity channel with ~9% decrease in shear wave velocity compared to adjacent parts in the uppermost and deep crust beneath the High Himalaya. Inferred low velocity may correspond to mineral anisotropy or the presence of aqueous fluid due to hydration along MHT.

Drawing analogy with the recent Mw 7.8 Gorkha earthquake of 2015, it is surmised that the double ramp along the down-dip and up-dip direction of MHT beneath High Himalaya played a significant role in the rupture geometry and rupture extent during occurrence of the Kangra earthquake. The redefined co-seismic deformation geometry of the 1905 Kangra earthquake, formulated and supported with different entities is partly towards north from the previous assumed rupture zones. These results are supported with the present day micro and moderate cruatal scale seismicity of the region. These findings can play crucial roles to understand fault segmentation and extents of ruptures of future earthquakes in the thrust and subduction zones. We presents the results with multiple entities of recent and past data sets to infer complex geodynamic processes.

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Seismicity of the Terceira Island (Azores) recorded by a temporary seismic network

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Terceira Island comprises four central polygenetic active volcanoes, Santa Bárbara, Pico Alto, Cinco Picos-Serra do Cume, Caldeira Guilherme Moniz, and a Basaltic Fissural zone. The former two are explosive volcanoes. The last eruption in the Azores archipelago occurred in 1998-2000 and took place offshore, broadly 10 km WNW of Terceira.

To study the seismicity at Terceira Island, we installed a dense seismic network with an average inter-station distance of 5 km. The total number of instruments in use were 31: 12 short-period (2 Hz) and five very short period (4.5 Hz), both from Institute Dom Luiz (IDL), eight broadband (30s) from the University of Evora (UEv). The temporary network was completed with the permanent stations operated by the Instituto Português do Mar e da Atmosfera (IPMA), namely two broadband (120s), two short period (5s) and two accelerometers. The seismic network operated at full capacity for 11 months, and later with instruments from UEv and IPMA until now. The very short period instruments were installed around the Pico Alto geothermal power plant to improve the detectability of the micro-seismicity of the zone.

The earthquake detection relies on the visual inspection of daily spectrograms for a set of stations; Seismograms were stored in a database for later processing.

This work presents the preliminary results obtained with the seismic network from August 2019 until December 2019. In this period, we detect some volcano-tectonic earthquakes, mostly related to the Santa Bárbara Volcano. Behind the regular seismicity around the island, we observe an abnormal number of earthquakes in the stations installed in Pico Alto and central part regions of the island.

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Detection and analysis of a microearthquake sequence through a semi-automated approach: The Castelsaraceno (Southern Italy) case study

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The study of micro-seismic sequences allows gaining insights on fault geometries and properties and it is especially important in high seismic hazard areas. To this purpose, an accurate detection and analysis of seismic data data is required.

In this work we investigate the low-magnitude earthquake sequence occurred on August 2020 close to the municipality of Castelsaraceno, in a sector of Southern Apennines (Southern Italy) capable of generating up to M=7 earthquakes. The sequence was characterized by a 2.5 Ml mainshock which took place on 7 August. Seismic data, mainly recorded by eight broadband stations of the High Agri Valley geophysical Observatory (HAVO) and located at a maximum epicentral distance of ~20 km from the seismicity cluster, allowed investigating the main properties of this seismic sequence. First, we manually detected 56 microearthquakes in the period between 7 and 10 August, when most of the seismicity occurred. Then, we applied a single-station template matching technique for the two nearest stations to the cluster. Using six different master templates we obtained a seismic catalogue, spanning from July to October, consisting of ~150 microearthquakes. We found about the 75% of the total number of events occurring between 7 and 10 August, thus revealing the typical behavior of a mainshock-aftershock sequence. The P- and S-wave arrival times were automatically picked by a deep-neural-network (PhaseNet). We thus provided absolute and relative locations of the most of detected events and the focal mechanisms solution of the 2.5 Ml mainshock. These analyses revealed the alignment of the seismic sequence at an average hypocentral depth of about 10 km, along a normal fault with a strike-slip component. Finally, the mainshock seismic data were inverted for

source parameters estimation, aiming to extend these analyses to the largest quality events of the sequence as well.

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Strong ground motion recordings for the Thessaly, March 2021 doublet earthquakes: Spatial distribution of parameters and preliminary results

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On March 3, 2020 a sequence of doublet earthquakes, in the region of Thessaly (Central Greece), initiated with a Mw6.3 event followed 32 hours later by a Mw6.0 event. The earthquake aftershock sequence defined a rupture zone striking NW-SE, in accordance with the computed fault plane solutions. The seismogenic fault is not related to any previously mapped known faults. The area affected belongs to the zone II in the Greek earthquake design code, corresponding to an effective acceleration, ag=0.24g. The most serious damages caused by the both earthquakes were observed at villages located about 25 km NW of the city of Larissa, with maximum reported and observed intensity MMI=VIII. No significant damages were reported for the reinforced concrete buildings. However, partial collapses were observed for poor construction quality masonry structures. Geotechnical failures, mainly close to river banks (liquefaction) were extensively observed. No accelerograph was installed within the meizoseismal area prior to the events. The nearest accelerograph sites located at Larissa city within epicentral distances of 20-28km. For the first March 3, strongest event, the highest PGA values vary 80-140 cm/sec2 and the PSA exceeded 200cm/sec2 for a wide range of periods. For the March 4, second event, the values were lower, as the size was smaller and the distances were longer in comparison to the first event. The study of toppled objects after field work following the two events, resulted to minimum PGA values of 35-40%g. The pattern of the geographical distribution of the instrumental strong ground motion parameters, based on standard USGS ShakeMap application, is in good agreement with the strike of the fault zone revealed by the aftershock sequence.

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The 30 October 2020 Mw 7.0 Samos-Izmir earthquake and tsunami: multi-stage source characterization from teleseismic, strong motion, HR and static GPS, InSAR, and tsunami data

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We study the source of the 30 October 2020 Mw 7.0 Samos-Izmir earthquake and tsunami that occurred in the eastern Aegean Sea just north of the Samos Island, Greece. Starting from the first available moment

tensor solutions and considering the aftershock distribution, we identify an initial range for the parameters describing the approximate location and geometry of a planar fault hosting a normal earthquake, on a north-dipping plane. This is also fairly consistent with the polarities of the tsunami first arrivals on the Greek and Turkish coasts according to the comparison of numerical models to observations. We then perform a nonlinear inversion for the fault plane parameters from GPS and InSAR data. As a second step, we use this fault in two different inversions for the rupture kinematics on a planar fault: a teleseismic inversion and a nonlinear joint inversion of strong motion, high-rate and static GPS, and InSAR data, using the simulated annealing technique and a layered velocity model. The solutions from the two approaches consistently provide dominantly shallow slip up-dip of the hypocenter. However, while the teleseismic solution is robust but weakly sensitive to the fault orientation, the residuals of the joint inversion fit to the near-field data indicate the need for further refining the source model and/or the modelling approach. As a third step, we then extract a subset of solutions, characterized by a good misfit, from those explored in the joint inversion. We apply on them a cluster analysis, to identify similarities and representative source models, in order to minimize the number of subsequent forward models to the seismic and geodetic data that we perform with SPECFEM3D. We finally analyze the misfit of this new ensemble to address the importance of the 3D fault model and of realistic bathymetry and topography.

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Characterization of small-scale absoprtion and scattering properties from seismic ambient noise and consequences earthquake ground motions

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In this work we study the absorption and scattering properties of seismic waves on randomly heterogeneous media. We present some preliminary results which are mainly focused on the understanding of scattering properties by using the coherent wavefield which was obtained from the numerical modelling of 2D SH wave propagation with the spectral element method. In this way, we explore the information that can be retrieved from the coherent wavefield such as mean free path, scattering quality factor, phase velocity and energy envelope fluctuations. The coherent wavefield was computed as the ensemble average over 60 realizations on five random media having different perturbation levels, but with the same background velocity and correlation length. The source term is represented as an impulse plane wave propagating vertically from the bottom to the top of the domain. Some comparisons between the synthetic results and analytical solutions are also done in order to verify how properly these parameters are being estimated. A second stage of this work corresponds to the understanding of absorption attenuation and the sensitivity of coda waves to local perturbations either on scattering or absorption. Since attenuation is still the most poorly understood factor among the physical processes that control the amplitude of seismic waves, we aim to be able to constrain separately these two mechanisms (absorption and scattering) from seismic ambient noise, and analyze its effects on the estimation of earthquake ground motion at the scale of a sedimentary basin.

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