ANNALS OF GEOPHYSICS, 65, 2, DM213, 2022, doi:10.4401/ag-8767
OPEN ACCESS

Coordinated and Interoperable Seismological Data and Product Services in Europe: the EPOS Thematic Core Service for Seismology

Florian Haslinger[*,1], Roberto Basili[2], Rémy Bossu[3a,b], Carlo Cauzzi[4], Fabrice Cotton[5], Helen Crowley[6], Susana Custódio[7], Laurentiu Danciu[1], Mario Locati[8], Alberto Michelini[2], Irene Molinari[9], Lars Ottemöller[10], Stefano Parolai[11]

(1) Swiss Seismological Service (SED) at ETH Zürich, Switzerland
(2) Istituto nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy
(3a) European-Mediterranean Seismological Centre (EMSC), Arpajon, France
(3b) CEA, DAM, DIF, F-91297 Arpajon, France
(4) ORFEUS and Swiss Seismological Service (SED) at ETH Zürich, Switzerland
(5) GFZ German Research Centre for Geosciences , Potsdam, Germany
(6) EUCENTRE, Pavia, Italy
(7) Instituto Dom Luiz (IDL), Faculty of Sciences of the University of Lisbon (FCUL), Portugal
(8) Istituto nazionale di Geofisica e Vulcanologia (INGV), Milan, Italy
(9) Istituto nazionale di Geofisica e Vulcanologia (INGV), Bologna, Italy
(10) Department of Earth Science, University of Bergen (UiB), Norway
(11) Istituto Nazionale di Oceanografia e di Geofisica Sperimentale - OGS, Sgonico, Italy

Article history: received November 26, 2021; accepted February 21, 2022

Abstract

In this article we describe EPOS Seismology, the Thematic Core Service consortium for the seismology domain within the European Plate Observing System infrastructure. EPOS Seismology was developed alongside the build-up of EPOS during the last decade, in close collaboration between the existing pan-European seismological initiatives ORFEUS (Observatories and Research Facilities for European Seismology), EMSC (Euro-Mediterranean Seismological Center) and EFEHR (European Facilities for Earthquake Hazard and Risk) and their respective communities. It provides on one hand a governance framework that allows a well-coordinated interaction of the seismological community services with EPOS and its bodies, and on the other hand it strengthens the coordination among the already existing seismological initiatives with regard to data, products and service provisioning and further development. Within the EPOS Delivery Framework, ORFEUS, EMSC and EFEHR provide a wide range of services that allow open access to a vast amount of seismological data and products, following and implementing the FAIR principles and supporting open science. Services include access to raw seismic waveforms of thousands of stations together with relevant station and data quality information, parametric earthquake information of recent and historical earthquakes together with advanced event-specific products like moment tensors or source models and further ancillary services, and comprehensive seismic hazard and risk information, covering latest European scale models and their underlying data. The services continue to be available on the well-established domain-specific platforms and websites, and are also consecutively integrated with the interoperable central EPOS data infrastructure.

EPOS Seismology and its participating organizations provide a consistent framework for the future development of these services and their operation as EPOS services, closely coordinated also with other international seismological initiatives, and is well set to represent the European seismological research infrastructures and their stakeholders within EPOS.

Keywords: Interoperable seismological data; Product services; EPOS Seismology

1. Introduction

Theoretical, observational, computational, applied, engineering, exploration, citizen-based, environmental, planetary: this is only a short, incomplete selection of terms often associated with "seismology". In essence, a remarkably diverse, complex and interdisciplinary domain, where researchers and research infrastructures have always been at the forefront in the development of science, instrumentation and services for scientists. In the greater European region three international and inter-institutional organizations have been established by the seismological research community to support the operation of pan-European data and products services as well as overall coordination, namely the Euro-Mediterranean Seismological Center (EMSC), the Observatories and Research Facilities for European Seismology (ORFEUS), and the European Facilities for Earthquake Hazard and Risk (EFEHR): these initiatives are briefly introduced in the following paragraphs and described in greater detail in the next Sections.

Realizing the benefits arising from rapid collection and dissemination of information about the occurrence of earthquakes, and that this requires setting up a dedicated organization, the EMSC was established under the auspices of the European Seismological Commission (ESC) in 1982 as an international, non-governmental organization with a membership of national academic and governmental institutions that have a role in earthquake monitoring in the countries of the European-Mediterranean region. Today EMSC has more than 80 member institutions from 56 countries across Europe and the world, provides openly accessible services for various earthquake-related information products that are rapidly available for both scientists and the general public, and operates one of the world's most popular earthquake information apps, LastQuake. Information about historical earthquakes is provided through AHEAD, the European Archive of Historical Earthquake Data, represented within EMSC by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) where AHEAD is hosted.

In the mid-1980s, ORFEUS became the next pan-European seismological community infrastructure [Nolet et al., 1986]. ORFEUS too is an international non-profit organization, set up to coordinate and promote waveform seismology, in particular the collection and exchange of digital seismological waveform data, at a time when these data became available in large amounts, together with information technologies for exchange and access. At its start ORFEUS was closely linked to national broadband seismology initiatives in Europe like NARS [Network of Autonomously Recording Seismographs, Nolet and Vlaar, 1982, Utrecht University, 1983], GEOSCOPE (Institut de physique du globe de Paris and Ecole et Observatoire des Sciences de la Terre de Strasbourg, 1982), or the Gräfenberg array [Harjes and Seidl, 1978; Buttkus, 1986; Federal Institute for Geosciences and Natural Resources, 1976]. With the inception of the European Integrated waveform Data Archive EIDA in 2013, the originally centralized ORFEUS Data Center [ODC, van Eck et al., 2004] became part of a federated service that comprises more than a dozen collaborating institutions across Europe and the Middle East. ORFEUS today provides free and open access to data from more than 16,000 permanent and temporary seismic stations, contributed by more than 60 institutions from over 30 countries. In addition to waveform data and related metadata and station information, ORFEUS provides services for waveform-derived products like strong-motion information and peak-motion parameters.

In 2019, the EFEHR consortium was founded to provide a project-independent framework for coordination and collaboration in the domain of seismic hazard and risk, following a decade-long development supported by a number of EU funded projects that were targeted towards the harmonized development of state-of-the-art, transparent and reproducible, earthquake hazard and risk models for Europe. EFEHR is open for all academic and governmental institutions with a role in providing seismic hazard and/or risk information, and currently has more than 25 members from more than 15 countries. In addition to providing access to the harmonized European seismic hazard and

risk models and the ability to host national models if desired, EFEHR services provide access to many underlying data relevant for hazard and risk estimation and ensure the reproducibility of the derived models.

The coordinated development of products and services of EMSC, ORFEUS and EFEHR was significantly sponsored by a number of EU projects of the FP6, FP7, and Horizon 2020 programs, which also greatly helped the build-up of a European community of contributors. The success of these community-driven initiatives and the experience gained in their development and operation contributed significantly to the inception of EPOS during the first decade of the third millennium.

While many European seismological institutions are today at the same time members of EMSC and ORFEUS, and a growing number of institutions are joining EFEHR, the areas of interest and responsibility of each community are sufficiently different so that a relatively clear separation of the content of the three initiatives can be maintained. Nevertheless, coordination mechanisms between them have since the beginning been part of the governance structures of the three initiatives. At the same time, each initiative has specific connections with the global seismological community, e.g.,: EMSC with the National Earthquake Information Center NEIC of the United States Geological Survey USGS (www.usgs.gov/natural-hazards/earthquake-hazards/national-earthquake-information-center-neic) or the International Seismological Center ISC (www.isc.ac.uk); ORFEUS with the International Federation of Digital Seismograph Networks FDSN (www.fdsn.org), the Incorporated Research Institutions for Seismology IRIS (https://www.iris.edu/hq/) and the Consortium of Organizations for Strong Motion Observation Systems COSMOS (https://www.strongmotion.org/); EFEHR with the Global Earthquake Model GEM (www.globalquakemodel.org). In particular the development of standards and standardized formats, products and services are to a large extent governed by these international collaborations. In this context, the International Association of Seismology and Physics of the Earth's Interior IASPEI (www.iaspei.org), together with its regional European Seismological Commission (ESC), also plays an important role as de-facto 'standards body' for seismology. Having this active European and global coordination in place is a key element in the promotion of FAIR [Wilkinson et al., 2016] data and open science in seismology. It, however, may at times present challenges in the cross-domain coordination within EPOS, where global standards or established best practices within seismology should be harmonized with other Earth science disciplines of EPOS.

2. EPOS Seismology Services

2.1 Community governance and coordination

During the initial phase of EPOS [EU FP7; EPOS Preparatory Phase project, 2010-2014], the seismological community started organizing itself as a domain component of the emerging EPOS infrastructure. In the early years mainly anchored in ORFEUS, it expanded to cover all the existing organized sub-domains and the 'pillar' concept was developed in 2013 (Figure 1). Initially it included the four *pillars* 'Waveform Data', 'Earthquake Products', 'Hazard and Risk', and 'Computational Seismology', corresponding to the three existing seismological community initiatives above and – at that time – an expected fourth one for computational seismology.

During the EPOS Implementation Phase (EU FP7 project, 2015-2019) the requirements for harmonization across the different solid Earth science domains represented in EPOS, together with the realization that computational seismology still needed more time to reach a mature 'community service provisioning' level, led to the formation of a seismological EPOS Thematic Core Service (TCS) 'Seismology' (Figure 2). It covers the seismology sub-domains 'waveform services' (represented by ORFEUS, where computational seismology topics are expected to be integrated), 'seismological products services' (represented by EMSC), and 'earthquake hazard and risk services' (represented by EFEHR).

The EPOS Seismology Consortium was then formally established in October 2019 with the three organizations as consortium members (Parties). Within EPOS Seismology the responsibility for the various activities and in particular for the coordination, management and operation of specific services, remains within the respective pillar and sub-domain. Also the interaction with the data provider as well as the data and service user communities continues to rest with the established pillar organizations. The EPOS Seismology Consortium as the governing body of EPOS Seismology is set up as a lightweight and slim 'integration and coordination layer', also to avoid duplication of efforts and consumption of resources. The main tasks of the EPOS Seismology Consortium are the coordination of activities between the pillars, the coordination of the activities and contributions of EPOS Seismology to EPOS,

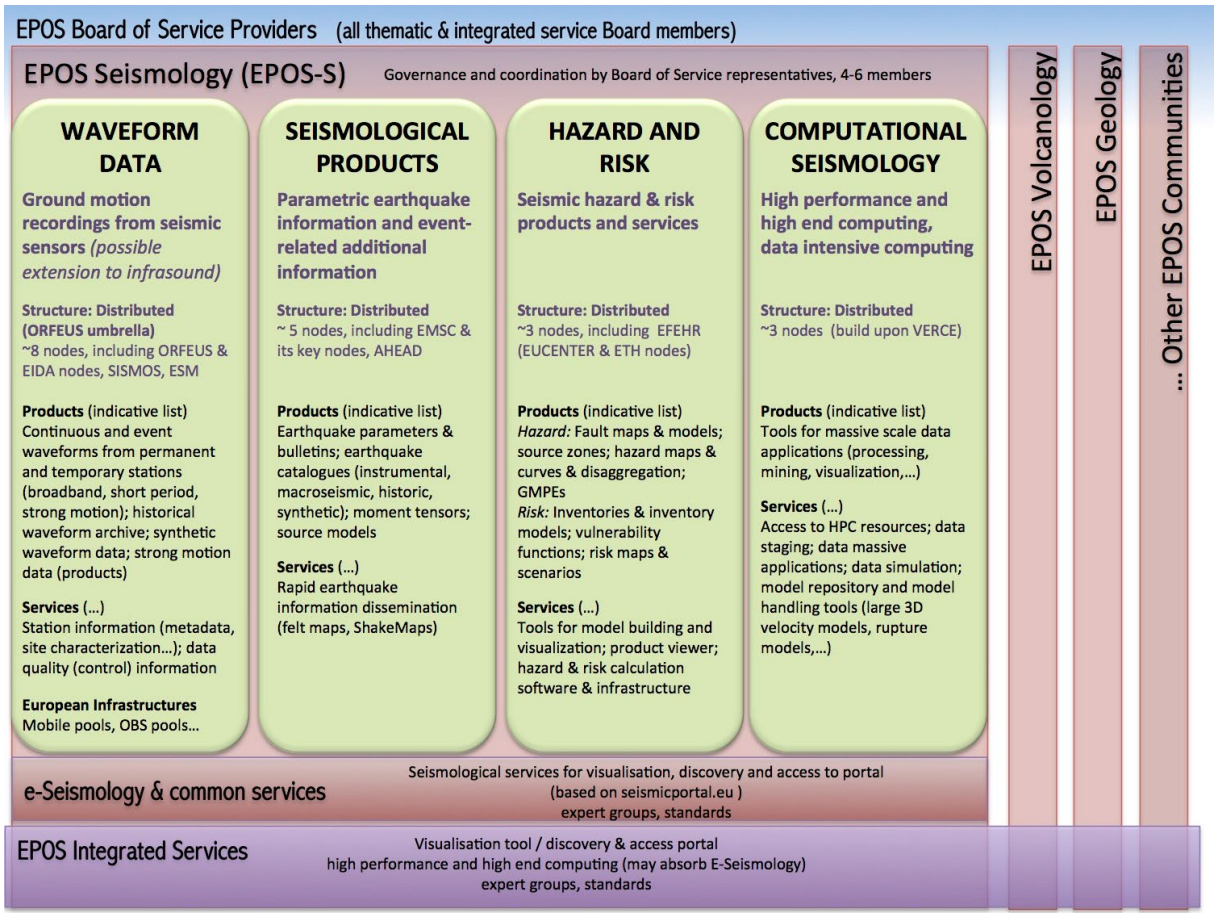

Figure 1. The original 2013 pillar design of seismology within EPOS.

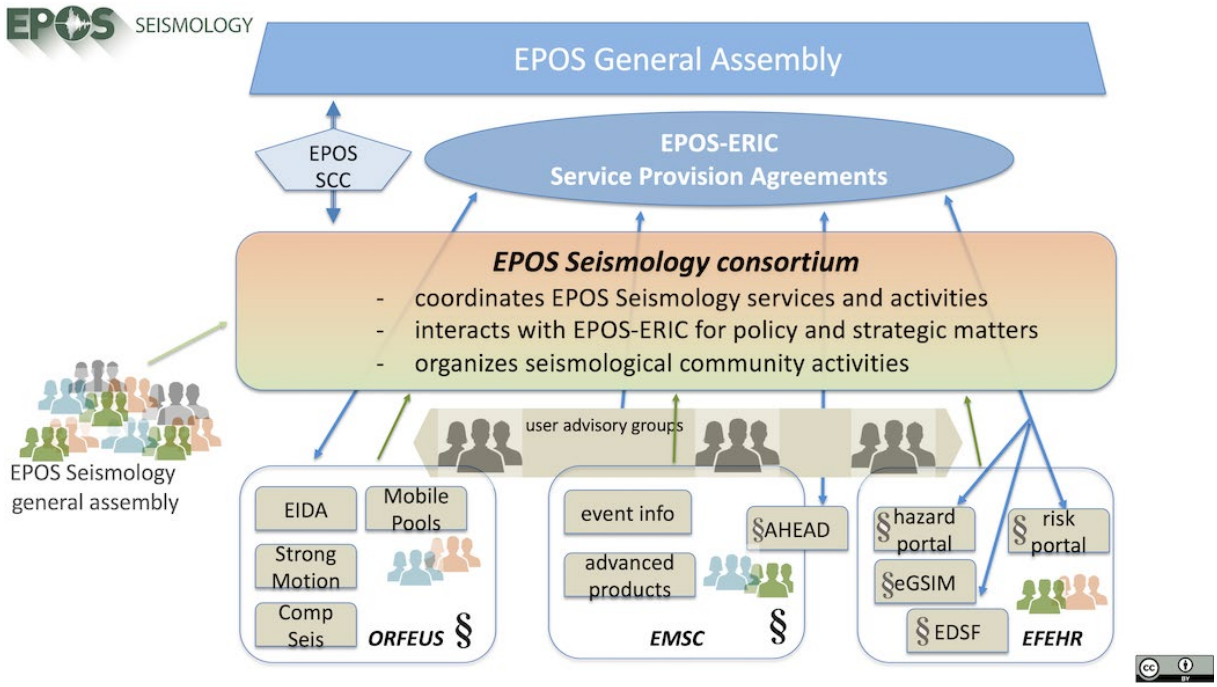

Figure 2. The EPOS Seismology governance structure at a glance.

to represent the seismological community within the EPOS governance, and to interact with EPOS (ERIC) bodies on behalf of EPOS Seismology. The working body of the EPOS Seismology Consortium is the Consortium Assembly, where each party has up to three representatives. The Assembly elects the Consortium Chair from among these representatives. Up to three 'community representatives' are invited to the Assembly as voting members, and further individuals or institutions may be invited as observers. Currently the European Seismological Commission (ESC) participates as Observer to the Assembly.

In addition to administratively supporting the integration of seismological services with EPOS, EPOS Seismology also promotes community engagement, namely by organizing specific community interactions, e.g., the joint EPOS Seismology / ORFEUS workshops in 2017 and 2019, or specific side events at ESC General Assemblies or other scientific conferences.

2.2 ORFEUS: Access to waveform data and related products

ORFEUS (Observatories and Research Facilities for European Seismology, http://orfeus-eu.org/, founded in 1986) is a non-profit foundation that promotes 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 (see https://orfeus-eu.org/organization/corporate_founders/ and https://orfeus-eu.org/organization/participation/) in the greater European region. They are further developed, integrated, standardized, homogenized and promoted through ORFEUS. ORFEUS data and services are open, *FAIR*, and accompanied by licencing information. Among the goals of ORFEUS are: (a) the development and coordination of waveform data products; (b) the coordination of a European data distribution system, and the support for seismic networks in archiving and exchanging digital seismic waveform data; (c) the encouragement of the adoption of best practices for seismic network operation, data quality control and data management; (d) the promotion of open access to seismic waveform data, products and services for the broader Earth science community. ORFEUS also supports the coordination and implementation of large scale community initiatives and experiments: among the recent examples are AlpArray [Hetényi et al., 2018] and the planned AdriaArray.

These goals are achieved through the development and maintenance of data services targeted to a broad community of seismological data users, ranging from earth scientists to earthquake engineering practitioners. Two Service Management Committees (SMCs) are consolidated within ORFEUS, devoted to managing, operating and developing (with the support of one or more Infrastructure Development Groups): (i) the European Integrated waveform 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/). A new Service Management Committee is being formed to represent the community of European mobile instrument pools. Products and services for computational seismologists are also considered for integration in the ORFEUS domain.

EIDA [Strollo et al., 2021] is the distributed infrastructure in ORFEUS that provides access to raw seismic waveform data archives and associated station metadata collected and curated by European seismic networks. Established in 2013, EIDA presently provides seamless access to 12 data archives – the EIDA nodes – by means of standard services (FDSN and EIDA-specific services), exposing data on behalf of hundreds of network operators and research organizations. EIDA currently comprises ~ 14,000 seismic stations and approximately 600 TB of seismic data [Strollo et al., 2021; their Figure 2]. The seismic networks integrated in EIDA include weak-motion, strong-motion, pressure, rotation and other sensor types. EIDA typically serves 5000+ unique users / year. The EIDA system is designed to scale up to add new services, data types, and nodes. Leveraging on EC funding opportunities, EIDA is currently active in developing suitable data management approaches for new emerging technologies (e.g., Distributed Acoustic Sensing systems DAS, dense nodal and MEMS-based instrumentation) and challenges related to big and novel datasets.

The European strong-motion systems [Lanzano et al., 2021] coordinated by ORFEUS are the Rapid Raw Strong Motion [RRSM; https://orfeus-eu.org/rrsm/; Cauzzi et al., 2016], the Engineering Strong Motion [ESM; https://orfeus-eu.org/esm/; Luzi et al., 2016] databases, and the associated web interfaces and web services. The RRSM and ESM platforms are unique examples of data access in the domain of strong-motion seismology. The RRSM is a totally automatic system for rapid dissemination of earthquake data, while the ESM provides quality-checked, manually processed waveforms and reviewed earthquake information. The RRSM and ESM operate as complemen-

tary services on two different time scales: the RRSM provides automatic information within the first few hours or days after the earthquake occurrence; after manual processing, the ESM becomes the authoritative source of information. The RRSM is a downstream product of EIDA and uses only data integrated in EIDA (including on-scale velocity data), while the ESM also includes offline data from other data sources. The ESM includes advanced interactive software tools, e.g., allowing users to process strong-motion data or to select ground-motion waveform sets for engineering studies. The ESM is presently the reference database for harmonised seismic hazard and risk studies in Europe.

Overall, ORFEUS services currently provide access to the waveforms acquired by ~ 16,000 stations, including dense temporary experiments, with strong emphasis on open, high-quality data (Figure 3). 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 ensured through state-of-the-art information and communication technologies, with strong emphasis on web services that considerably enhance user access to data gathered and/or distributed by the various ORFEUS institutions (see https://orfeus-eu.org/data/eida/webservices/ and https://esm-db.eu/#/data_and_services/web_services).

Web services also facilitate the automation of downstream products. Particular attention is paid to adopting clear policies and licenses, and acknowledging the crucial role played by data providers, who are part of the ORFEUS community. Note that ORFEUS strongly encourages the use of international network codes, seismic network digital object identifiers [Evans et al., 2015], and full network citations (generated using the web interface of the FDSN, "networks - generate citations for network data") in journal papers using data provided by seismic networks [details are given in Cauzzi et al., 2021]. All ORFEUS services are developed in coordination with EPOS and are largely integrated in the EPOS Data Access Portal (https://www.ics-c.epos-eu.org/). Documentation on ORFEUS data and services is provided on the ORFEUS website and is complemented by a large archive of ORFEUS community workshops and webinars (typically attended by more than 100 participants on average, and with maximum attendance exceeding 200 people for virtual events) organized in the last few years (https://orfeus-eu.org/other/workshops/). ORFEUS data and services are assessed and improved with the help of technical and scientific feedback from a User Advisory Group (UAG), which comprises European Earth scientists with expertise on a broad range of seismology domains. ORFEUS actively participates in EC-funded projects (see Acknowledgments) and collaborates with global and international organizations with similar scope, as mentioned in the Introduction. Recent examples of coordinated actions include: guidelines for seismic network DOIs; the establishment of the registry of data centres at the FSDN and the integration of routing information; the StationXML documentation project.

2.3 EMSC: Access to earthquake and other seismological information products

The European Mediterranean Seismological Centre (EMSC, https://www.emsc-csem.org/), founded 1982 in Strasbourg (France), is a not for profit organization that federates seismological observatories in the European-Mediterranean region that promotes scientific collaborations and data exchanges and provides rapid earthquake information on earthquakes and their effects. It is governed by its currently 81 member institutes from 56 countries and has a structure comprising a central infrastructure and five nodal members, institutions who provide specific support to EMSC or its operations. LDG (France) is a nodal member as a host of the EMSC and its central infrastructure since 1994, IGN (Spain) for operating a back-up website, INGV (Italy) for offering the AHEAD [European Archive of Historical EArthquake Data; Albini et al., 2013; Locati et al., 2014; Rovida et al., 2015] service on historical European seismicity (INGV Milan) and for expertise in earthquake location (INGV Rome), and GFZ Potsdam (Germany) for providing rapid earthquake locations. Since 1998 EMSC also produced a comprehensive reviewed earthquake bulletin for the European-Mediterranean region from all the data it received [Godey et al., 2006]. In order to avoid duplicate efforts with the ISC, and also due to shortage of resources, the decision to discontinue the EMSC bulletin was taken in 2015. That bulletin covers the period 1998-2012, contains 550'000 events and 10 million seismic phases. Specific European earthquake catalog requirements are today re-discussed in particular with regard to the needs of the earthquake hazard community.

The EMSC data and products service infrastructure is based on a comprehensive IT architecture comprising data collection, processing, archival and dissemination that has continuously evolved over the last decades (Figure 4). Parametric seismic data are collected from seismological observatories around the globe and collated at EMSC, while eyewitness observations (felt reports and geo-located pictures) are crowdsourced through the LastQuake

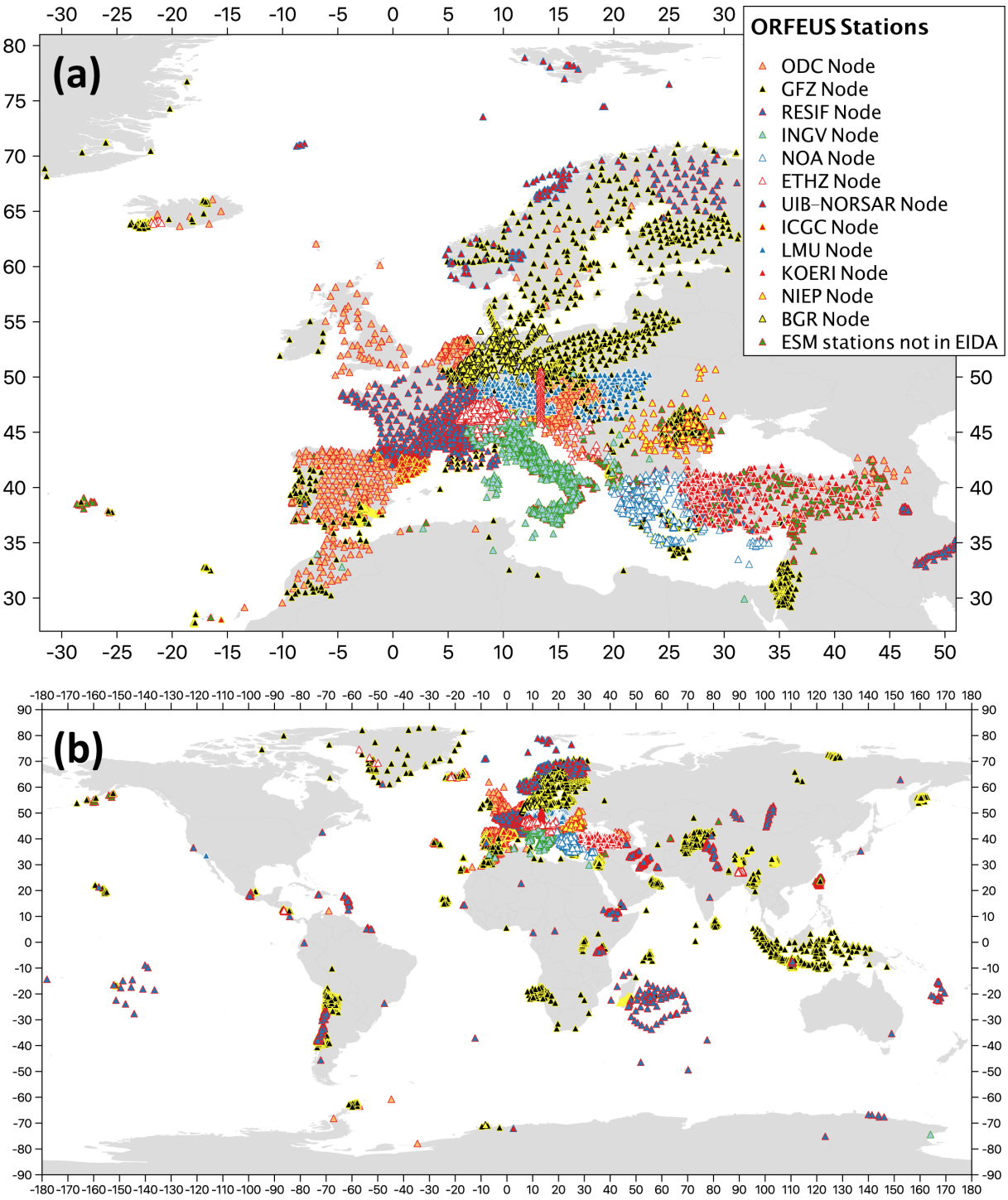

Figure 3. Map of the stations contributing to the ORFEUS-coordinated data services EIDA and ESM (the RRSM uses all EIDA stations). (a) Focus on the greater European region: stations are shown as triangles, colored according to the EIDA node in charge of data archival and distribution; the acronyms of the EIDA nodes are listed in the legend; the picture also shows the ESM stations non included in EIDA. (b) Global overview: note that some EIDA nodes provide access to stations pertaining to global networks and to temporary experiments worldwide.

[Bossu et al., 2018] mobile app and websites. Seismic information is then disseminated through social media, websites and apps as well as dedicated mechanisms [web services, http message bus HMB; Heinloo, 2016] for the scientific community. The "Seismic Portal" (www.seismicportal.eu), initially developed within the EU FP6 NERIES project, provides a common entry point for EMSC services and the link to EPOS data portal.

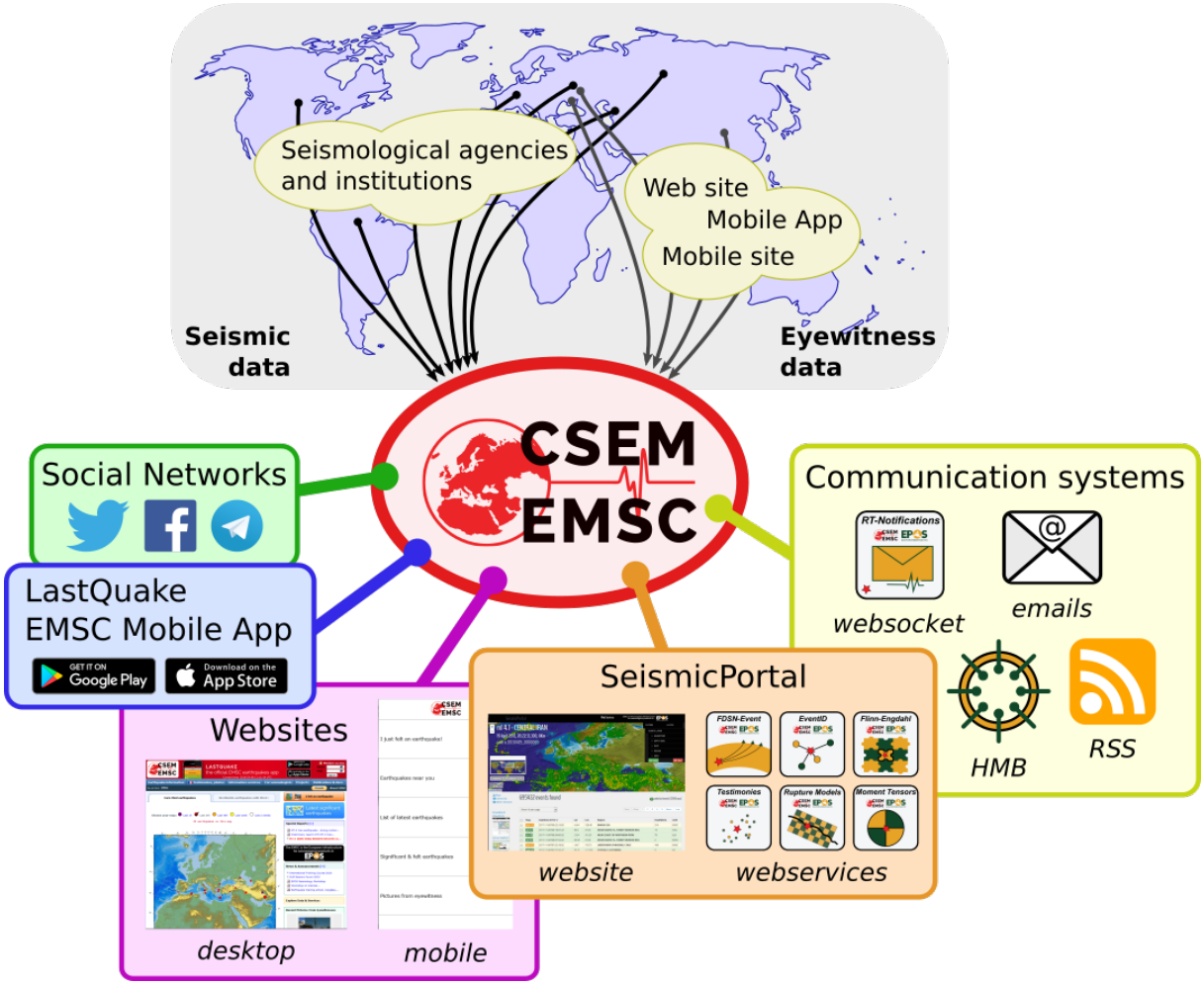

Figure 4. Schematic view on EMSC data collation and distribution mechanisms. Parametric earthquake information as well as eyewitness reports are collected globally and collated at EMSC, feeding a wide variety of products that are disseminated then through various services and communication systems.

Rapid earthquake information products are based on the collation of parametric data from about 100 institutes and more than 7,000 stations worldwide, leading to about 50,000 to 70,000 earthquake locations per year published by EMSC. There are 3 types of EMSC locations (i.e. earthquake source parameters time, location, magnitude): *Reported locations* are locations – generally of small magnitude earthquakes – reported by a single network and falling geographically within the reporting network. An *authoritative location* is a reliable and accurate location (generally from the institute responsible for the region) as described by Bossu and Mazet-Roux [2012] that is published by EMSC as received, although the earthquake is reported by several other agencies. Finally, when none of the several locations available for the same earthquake fit the authoritative criteria, a location is recomputed by EMSC based on part or all the received phase arrival information, depending on station coverage at short epicentral distances [see Bossu and Mazet-Roux, 2012]. These only represent 10 to 15% of all the disseminated locations. Alongside earthquake locations, focal mechanisms and moment tensors are also collected and made available.

Earthquake effects are mainly derived from crowdsourced data (felt reports, geo-located pictures) by LastQuake, a citizen seismology initiative comprising websites, a smartphone app and an eponym Twitter quakebot [Bossu et al., 2020]. Felt reports (750,000 collected over the last 12 month period) are exploited to generate rapid automatic macroseismic maps and intensity vs distance curves. They contribute to ARISTOTLE, a rapid multihazard impact evaluation service for the European Civil Protection Unit [Michelini et al., 2020], and a methodology is being finalized to ingest them in ShakeMap [Quitoriano and Wald, 2020; Quitoriano et al., 2021]. A real-time exchange mechanism for felt reports is being tested and will allow any institute to exploit them.

AHEAD is conceived as a pan-European, common, and open platform to support the research on historical earthquake data, by tracing back, retrieving, preserving, inventorying, and eventually granting access to the sources of earthquake data (such as papers, reports, macroseismic intensity data, and catalogues), by suggesting relationships among earthquake data of different provenance, to foster new insights and promote cross-border cooperation. AHEAD is the successful result of previous attempts (sponsored by EU framework programmes 1, 3 and 6) to establish a coordination framework and common data archive among European organizations collecting information about earthquakes that occurred in the pre-instrumental era, thus mostly described by means of macroseismic intensity data. AHEAD covers the years from 1000 to 1899 and the continental European region in space. Macroseismic data come from the collection of published research activities that investigate and interpret historical documents in seismological terms (Figure 5). AHEAD is governed by the Board of AHEAD Members that is composed of 12 organizations operating under a Memorandum of Understanding and INGV acts as the executive body taking care of the data archive. Data archived in AHEAD is of fundamental importance for the compilation of long-term, continent-wise, and homogeneous earthquake catalogues [Stucchi et al. 2012; Rovida and Antonucci, 2021], an essential component for seismic hazard assessment [Woessner et al., 2015].

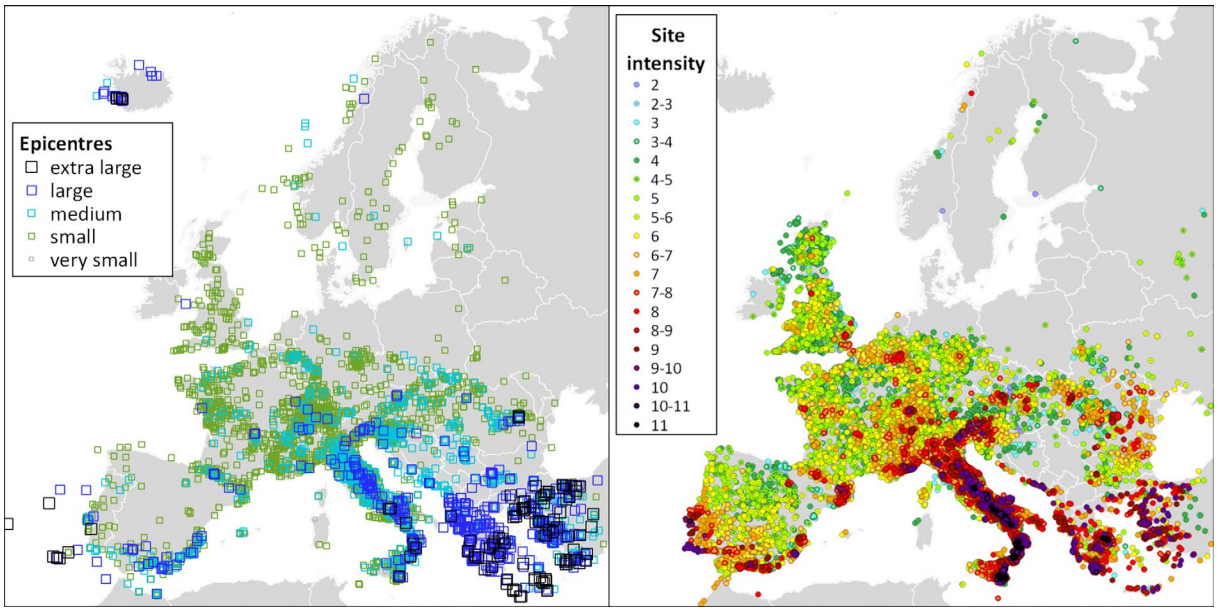

Figure 5. Map of the epicentres (left) and maximum macroseismic intensity data points (right) contributing to the European Archive of Historical Earthquake Data (AHEAD). Epicentre size (left) is on purpose given in 5 broad categories to indicate that there is no direct correspondence to a precise magnitude range. Site intensity (right) data point values come from multiple macroseismic intensity scales of the original data.

The data and products offered by EMSC, including those from AHEAD, are accessible in various ways: through web services, where applicable following international standards, in particular those developed within FDSN and by the Open Geospatial Consortium OGC (www.opengeospatial.org), some dedicated services (e.g. the Flinn-Engdahl region lookup, the event ID mapping service and the AHEAD macroseismic data service), and also by means of interactive GUI-based websites. All web services are compliant with the EPOS guidelines on data interoperability, therefore are fully integrated in the EPOS ICS-C data access portal. A major effort has been initiated, thanks to dedicated financial support, to improve EMSC services, covering data collection and dissemination, websites, standardization and harmonization, with first effective results expected by the end of 2022. These developments are an opportunity to improve *FAIR*ness of EMSC products and services by adding relevant identifiers and enhancing the visibility of data contributors without affecting user experience and remaining coordinated at global level for formats and standards.

2.4 EFEHR: Access to seismic hazard and risk products

EFEHR is a non-profit network of organizations and community resources aimed at advancing earthquake hazard and risk assessment in the European-Mediterranean area. In October 2019, 11 institutions signed the EFEHR consortium agreement and became founding members of the EFEHR consortium, and a total of 26 institutions are now members of the EFEHR General Assembly. The EFEHR Consortium also benefits from the participation of a number of observers, including the GEM Foundation, the European Association of Earthquake Engineers (EAEE), and participation of the European Seismological Commission (ESC) is under discussion.

The key objectives of EFEHR are to: (1) coordinate seismic hazard and risk assessment on a European level, including the coordination and harmonization of data, methods and scientific approaches, as well as development of guidelines and best practices; (2) maintain and make available the European Seismic Hazard and Risk Models (ESHM and ESRM), including the planning and coordination of further updates; (3) promote coordinated activities e.g. with the European Committee for Standardization sub-committee CEN/TC250/SC8 related to the development of reference seismic hazard maps for Eurocode 8 'Design of Structures for Earthquake Resistance'; (4) organize and provide oversight for European level services for seismic hazard and risk as part of EPOS Seismology; (5) support scientific discussions and training of EFEHR participants as well as the wider community to improve key elements of the seismic hazard and risk assessment, supported by tools, peer-review, performance benchmarking, training events and workshops; (6) coordinate interaction with other relevant international bodies in prevention, preparedness, and Disaster Risk Reduction (e.g. the Sendai Framework).

The currently active services of EFEHR that are fully integrated within EPOS, and which can be accessed via http://www.efehr.org, include: the European Databases of Seismogenic Faults (coordinated by INGV Italy), a web service designed to facilitate the exploration of ground motion models and their comparison against observational strong motions from European data sets (coordinated by GFZ Potsdam), a European seismic hazard platform (coordinated by ETH Zurich) and a European seismic risk platform (coordinated by EUCENTRE, Pavia).

The services related to the European Databases of Seismogenic Faults (EDSF), are made available through the www.seismofaults.eu/ platform, which provides access to the European database released in 2013 as part of the European SHARE project [EDSF13; Basili et al. 2013], the Italian DISS database [all versions since 2001; DISS Working Group, 2021] and the recent European Fault-Source Model 2020 [EFSM20; Basili et al., 2020], which has been used in the development of the European Seismic Hazard Model 2020 [ESHM20, Danciu et al., 2021]. The geologic fault information is organized into crustal faults and subduction systems, which are both meant to provide the necessary elements to estimate seismicity rates in a variety of tectonic contexts, including onshore and offshore active plate margins and the plate interiors. The EDSF platform is designed to distribute other regional datasets, provided that appropriate agreements with various data distributors are established. Presently, all datasets are identified by a DOI and distributed under a CC-BY or CC-BY-SA license. The data and products offered by EDSF are accessible through web services that follow OGC standards (WFS and WMS), and the metadata follows the EPOS-DCAT-AP standard which has allowed the EDSF13 data to be accessible through the EPOS ICS-C platform.

The European Ground-Shaking Intensity Models (GSIMs) service (https://egsim.gfz-potsdam.de/home) is a web application programming interface (API), implemented recently along the lines of popular seismological web services (e.g., FDSN): the user can query the toolkit via configurable URLs in order to retrieve model predictions of ground motions from either observed or hypothetical earthquake scenarios. These can be used to develop model-to-model comparisons of the expected shaking, but also to provide fields of expected ground motions and their uncertainties at user-defined locations. Web services are designed to facilitate the exploration of ground motion models and their comparison against observational strong motions from European data sets.

The European seismic hazard platform (http://hazard.efehr.org) provides access to specialized hazard datasets, input models, results, documentation and information. In terms of available hazard models, the EFEHR web-portal distributes the seismic hazard models for: the 2013 European Seismic Hazard Model [ESHM13, Wössner et al., 2015], the 2014 Earthquake Model of the Middle East [EMME14, Giardini, 2018], the 2015 Swiss Hazard Model [SuiHaz15, Wiemer et al., 2015], the 1999 Global Hazard Map of the Global Seismic Hazard Assessment Program [GSHAP, Giardini, 1999] and the 2020 European Seismic Hazard Model [ESHM20, Danciu et al., 2021, a recent output of the European project SERA, www.sera-eu.org]. The hazard platform consists of three stand-alone web applications for interactively discovering and retrieving hazard curves, hazard spectra and hazard maps. Viewers can retrieve hazard data (as well as metadata on available models and parameters) using a RESTful web service

API. The API is public and can be used directly by researchers to programmatically retrieve data. A WADL (Web Application Description Language) definition allows automatic generation of web service clients for several modern programming languages. For hazard maps, parameter discovery is implemented using EFEHR's REST API; maps themselves are shipped via custom services (ASCII data), file download (compressed ESRI shapefiles), and OGC WMS standards (projected map images). These web services, together with the EPOS-DCAT-AP metadata, have allowed the hazard maps to be made available through the EPOS ICS-C platform (Figure 6).

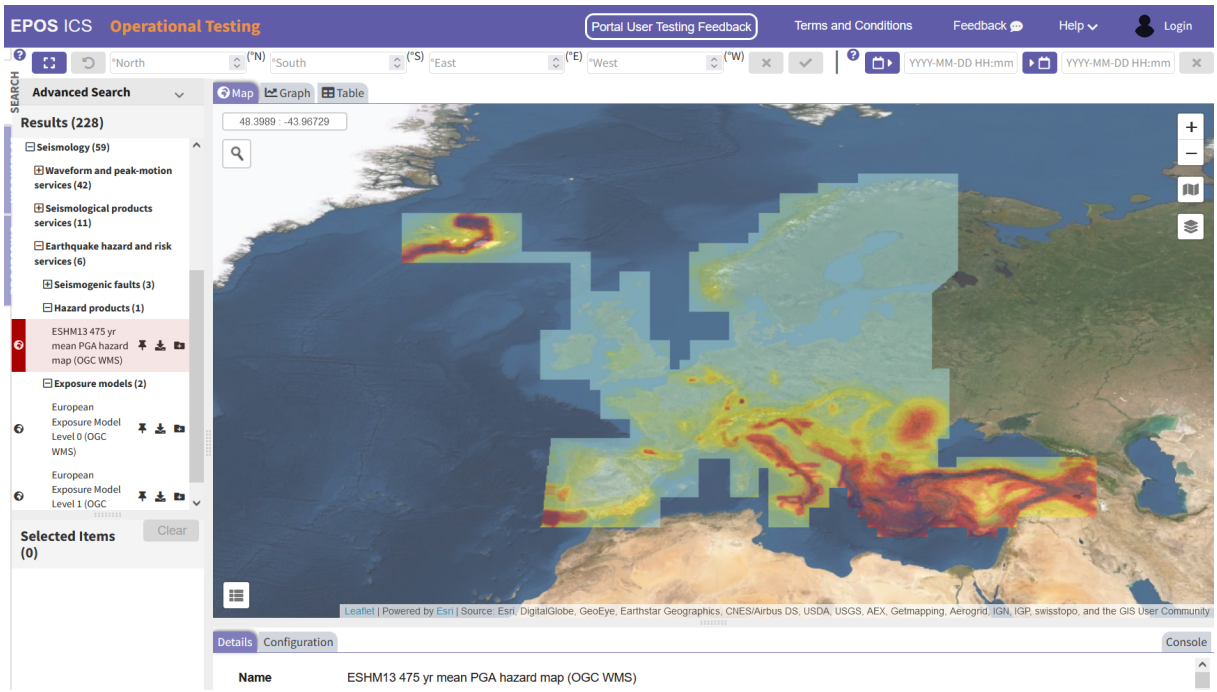

Figure 6. EFEHR's European Seismic Hazard Map (ESHM13) integrated into the EPOS ICS-C platform (https://www.ics-c.epos-eu.org/data/search).

The European seismic risk platform (http://risk.efehr.org) provides interactive access to: i) exposure data and models for European residential, commercial and industrial buildings and their occupants; ii) fragility and vulnerability models for classes of European buildings; iii) site response data and models at European scale; iv) earthquake scenario models; v) the newly released European Seismic Risk Model [ESRM20, Crowley et al., 2021]; vi) documentation and scientific support on all of the datasets and models; vii) web services for automated access to the data and models. All products are released under a CC-BY license, and are associated with DOIs and clear instructions related to how to use and cite the work. Two main categories of web services are currently available for the various seismic risk data and models released by EFEHR: 1) web services to access the data available in the interactive map viewers that follow the OGC and Open Source Geospatial Foundation (OSGeo) standards; 2) web services to access the data, models and files stored in various GitLab repositories that can be found at https://gitlab.seismo.ethz.ch/efehr, making use of the GitLab API. As with the other services of EFEHR described above, the exposure maps have been made available through the EPOS ICS-C platform.

3. Ongoing efforts in service improvements to support future research challenges

Regarding the future, one may have questions as: What is the intended role of the EPOS Seismology framework in the coming years? How will seismologists and seismological agencies benefit from the existence of EPOS Seismology? How will EPOS Seismology establish and maintain an active link with its participating communities? Answering these questions is crucial to further develop and consolidate the EPOS Seismology initiative in the com-

ing years, as well as to fully benefit from its existence, by increasing its impact and outreach in the seismological community in Europe and beyond.

The need for multi-disciplinary science for the development of resilient societies implies that joining forces and competences is crucial to address future challenges. EPOS candidates as the framework to integrate all geoscience services in the greater European region. EPOS Seismology is committed to support this vision as the coordination layer of data services for seismological research. With this background, we envisage a key supporting role of the EPOS Seismology initiative in international multi-disciplinary activities that require data, products, services and facilities from the waveform, catalogue and hazard & risk domains.

One recent example is the collaboration framework being promoted on the harmonization of ShakeMaps across Europe. This project is motivated by the rather high heterogeneity of ShakeMap strategies in Europe - different magnitudes, locations, ground-motion models, input data, software and mapping tools are generally used by different agencies to compile shaking information for the same earthquake – and the need to promote cross-border homogenization and best practices in this domain. The project started as a spontaneous initiative of selected European data centers [Cauzzi et al., 2018] active in the global ShakeMap community (namely SED at ETH Zurich and INGV, with support from the ORFEUS Data Center). They leveraged on existing standard seismological web services provided by ORFEUS, EMSC and EFEHR to demonstrate that a harmonized European ShakeMap system could be achieved and serve as a technical and scientific collaboration platform among the many ShakeMap operators in Europe. The demonstration system presently runs at INGV based on ShakeMap v4 [Worden et al., 2020] and a web interface specifically developed for this project: https://shakemapeu.ingv.it/ within the framework of the EC funded project RISE (Real-time earthquake rIsk reduction for a reSilient Europe, http://www.rise-eu.org/home/).

The system is not meant to replace any authoritative national ShakeMap services, but rather to amplify their relevance and outreach through integration into a coordinated European framework with the expectation, in turn, of leveraging on the Shakemap services at national level. The initiative provides ShakeMap capacity in regions where it is presently lacking and could be a backup solution for existing authoritative installations. The system currently integrates the ShakeMap approaches adopted in Switzerland and Italy, and other national systems are being added, starting from Greece. This collaboration framework is envisaged to continue and to enlarge in the coming years towards the establishment of a lively discussion forum of European ShakeMap operators and the consolidation of a consensual European set of ShakeMap services in close cooperation with EPOS Seismology.

Among the multidisciplinary research activities is also citizen seismology, that thanks to its capacity to massively and rapidly crowdsource information on earthquakes at global scale, is likely to play a growing role for the rapid impact assessment of global earthquakes, including finite earthquake source characterization [Böse et al., 2021]. The power of rapid collection of citizen information was demonstrated in a recent study [Bossu et al., 2021], showing that a smartphone application – EQN, developed by the University of Bergamo [Finazzi, 2020] - offers the first smartphone based earthquake early warning system. Efforts are under way to combine citizen seismology and instrumental data on the fly to further improve impact assessment products, coordinated within EPOS Seismology and also with other international players like USGS and its NEIC.

Multidisciplinary activities are also increasingly being carried out within the EPOS Seismology subdomains. For example, the ORFEUS Annual Observatory Meeting and Workshop 2021 was devoted to “New Data Types and Communities”, and aimed at discussing the challenges posed by integration of special datasets (e.g. large-N deployments, seismic data acquired by Distributed Acoustic Sensing systems, portable instrumentation including Ocean Bottom Seismometers, processed GNSS time-series, rotational data, gravimetry data and infrasound data) into existing seismological archives and workflows, i.e., a task that also requires coordination with other communities in EPOS.

Another multidisciplinary example is the cross-domain service utilisation in ongoing initiatives such as the candidate TCS Tsunami in EPOS [Babeyko et al., 2022, this volume] with its highly interdisciplinary community. EPOS seismology products, such as earthquake catalogs and fault databases, have already been used to inform the earthquake-generated tsunami hazard model NEAMTHM18 [Basili et al., 2021]. Harmonizing the hazard and risk data and products across the various facets expressed by different EPOS TCSs is of enormous societal value and one of the inevitable steps toward the build-up of multi-hazard risk analyses as envisioned by the Sendai Framework for disaster risk reduction 2015-2030 [UNISDR, 2015].

Integrated accessibility to geoscience data remains the central task of the EPOS Integrated Core Service (ICS) infrastructure and its associated data portal (https://www.ics-c.epos-eu.org/), where EPOS Seismology presently contributes with about 60 data services that allow cross-domain and multidisciplinary data discovery. EPOS Seis-

mology supports the consolidation of the ICS data portal as the main access point and showcase of all data services integrated in EPOS, and recommends its future developments be centered on scientific user feedback. It is important to acknowledge that web portals and graphic user interfaces are meant to be mainly used for data discovery and / or occasional download of datasets of small-to-moderate size. Frequent users, as well as users that need access to large or massive datasets, typically do not rely on web interfaces and rather access data directly through automated queries to web services [e.g., Quinteros et al., 2021]. With this background, supporting the consolidation and improvement of data services provided by the various communities contributing to EPOS is a crucial issue to be addressed by EPOS.

In order to increase the accessibility of seismological data to a wider audience, we are also developing new tools that take advantage of already available web services compliant with EPOS guidelines. A novel example in this respect is QQuake [Locati et al., 2021], a plugin for QGIS that enables any GIS user to retrieve seismological data using FDSN compliant event and station web services, intensity data related to historical earthquakes provided by AHEAD, and any kind of seismological data provided via OGC (Open Geospatial Consortium) WFS and WMS web services. The tool comes pre-configured with a series of built-in web services carefully selected among those validated by EPOS, providing the user with high quality and reliable data. QQuake allows the user to easily add new, custom web services compliant with any of the supported web service standards, and is fully open sourced on GitHub so that anyone could contribute to its further development in collaboration with INGV developers.

The long-term sustainability and development of EPOS Seismology also requires enhancing its overall awareness within our community at large, with special attention to early career scientists. Our current strategy mainly relies on the organization of joint workshops, conference sessions, dedicated information meetings, and editorial initiatives. In the coming years, we plan to integrate these efforts with training events on multidisciplinary data access and processing, and software / travel grants. We hope that all these actions will significantly contribute to community building and to a deeper engagement of the next generation of geoscientists with EPOS and EPOS Seismology, to the benefit of Seismology, Earth Sciences and Society at large.

4. Conclusion and outlook

Two years after its formal establishment, and ten years since the community started to work towards it, EPOS Seismology is now firmly established as TCS within the EPOS Delivery Framework. Implementing EPOS Seismology has further strengthened the interaction and collaboration between existing sub-domain community initiatives of European seismology: EMSC, ORFEUS and EFEHR. Together, these three engage in their membership a large fraction of the academic and governmental institutions in and around Europe that deal with seismological observations, monitoring of seismic activity and assessment of seismic hazard and risk. EPOS Seismology thus is well positioned to adequately represent the European seismological community in the EPOS infrastructure. EPOS Seismology provides a wide variety of data and product services that are highly relevant to support cutting-edge science and that make seismological information accessible to a wide range of stakeholders, including the private sector, government actors, disaster risk managers and the general public. In addition to tackling the continuous challenge of maintaining the existing services at the scientific and technical state-of-the-art and securing their stable operation, coordinated efforts in EPOS Seismology will further advance the implementation of the principles of FAIR and open science for seismological data, products and services. Significant challenges and opportunities lay ahead, related to the increasing use and usefulness of machine learning and artificial intelligence based methods, to the advent of new data types of massive volumes, to bringing data and computational power closer together, and to further improving attribution and provenance-tracking through the whole data lifecycle and for all products and services. Addressing these issues efficiently requires both global coordination within seismology and related fields, as well as cross-domain interaction and coordination across a wide range of scientific disciplines. The close internal coordination together with the full integration with the EPOS infrastructure will facilitate the contribution of the seismological community to further developments as well as the uptake and adaptation of progress made elsewhere.

Acknowledgments. In EPOS Seismology as well as in each of the community infrastructures EMSC, ORFEUS and EFEHR, the success in building and maintaining them, and in keeping them properly rooted in the community, depends largely on the engagement and quality of individuals. While the contribution of every person engaged in the

governance and operation of our services and infrastructures is essential and highly appreciated, a few stand out: Torild van Eck, Secretary of ORFEUS for almost 20 years, who passed away sadly too soon in 2014, Domenico Giardini, champion of European integration in various fields of seismology and in particular in seismic hazard and risk, and together with Torild leader and motor of numerous projects and initiatives, and Massimo Cocco, the unstoppable force behind moving EPOS forward from the very beginning, were all crucial to bring us to where we are today.
Other colleagues who significantly contributed and are still contributing to the EPOS Seismology initiative are: Andrea Rovida, Angelo Strollo, Antonio Correia, Celine Beauval, Chiara Felicetta, Emiliano Russo, Erdal Safak, Eser Cakti, Evi Riga, Graeme Weatherill, Helle Pedersen, Jan Michalek, Javier Quinteros, John Clinton, Jordi Diaz, Luca Trani, Lucia Luzi, Maria D'Amico, Matthieu Landes, Olga-Joan Ktenidou, Päivi Mäntyniemi, Philipp Kästli, Reinoud Sleeman, Roberto Vallone, Wayne Crawford.
Developments over the last two decades were supported by various European projects: MEREDIAN (FP5 EVR1-CT-2000-40007), NERIES (FP6 26130), NERA (FP7 262330), SERA (H2020 730900), EPOS Preparatory Phase (FP7 262229), EPOS Implementation Phase (H2020 676564), RISE (H2020 821115), TURNkey (H2020 821046).
Work on this paper was partially supported by the current EU Horizon 2020 project EPOS Sustainability Phase, Grant Agreement 871121, and by the 2021 Work Program of the 2021-2023 Multi-Year Collaboration Agreement between EPOS ERIC and EPOS Seismology.
The seismic networks contributing to ORFEUS coordinated services are listed at https://orfeus-eu.org/data/eida/networks/ and at https://esm-db.eu/#/about/who/contributing_networks. ORFEUS is thankful to all members of its governance bodies and service management committees (listed on the ORFEUS website at https://orfeus-eu.org/organization/structure/), and to its Core Participants (https://orfeus-eu.org/organization/corporate_founders/) and Participants (https://orfeus-eu.org/organization/participation/).
The development of AHEAD, EDSF and QQuake benefited from the financial support of the Italian Ministry for University and Research funding to the Joint Research Unit EPOS-Italy, programme of activities 2021-2024.
With sincere thanks EMSC acknowledges the contributions by its member institutions that are listed at https://www.emsc-csem.org/about/?d=1#members.
EFEHR benefits from the continued support and guidance of its Consortium Members and Observers, as well as its Executive Committee (all listed here: http://www.efehr.org/efehr/governance). The support of the GEM Foundation in maintaining the software used to compute these models and their role in co-developing the risk services is also gratefully acknowledged.
We thank Johannes Schweitzer and an anonymous reviewer for their valuable comments that helped to improve the manuscript.

References

Albini P., M. Locati, A. Rovida, M. Stucchi (2013). European Archive of Historical EArthquake Data (AHEAD). Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.6092/ingv.it-ahead

Babeyko, A., S. Lorito, F. Hernandez, J. Lauterjung, F. Løvholt, A. Rudloff, M. Sørensen, A. Androsov, I. Aniel-Quiroga, A. Armigliato, M. A. Baptista, E. Baglione, R. Basili, J. Behrens, B. Brizuela, S. Bruni, M. D. Cambaz, J. Cantavella-Nadal, F. Carrilho, I. Chandler, D. Chang-Seng, M. Charalampakis, L. Cugliari, C. Denamiel, G. G. Dogan, G. Festa, D. Fuhrman, A.-A. Gabriel, P. Galea, S. J. Gibbons, M. Gonzalez, L. Graziani, M.-A. Gutscher, S. Harig, H. Hebert, C. Ionescu, F. Jalayer, N. Kalligeris, U. Kânoğlu, P. Lanucara, J. Macías, S. Murphy, Ö. Necmioğlu, R. Omira, G. A. Papadopoulos, R. Paris, F. Romano, T. Rossetto, J. Selva, A. Scala, R. Tonini, K. Trevlopoulos, I. Triantafyllou, R. Urgeles, R. Vallone, I. Vilibić, M. Volpe, A. C. Yalciner (2022). Towards the new Thematic Core Service Tsunami within the EPOS Research Infrastructure, Ann. Geophys., this Volume.

Basili, R., V. Kastelic, M.B. Demircioglu, D. Garcia Moreno, E.S. Nemser, P. Petricca, S. P. Sboras, G. M. Besana-Ostman, J. Cabral, T. Camelbeeck, R. Caputo, L. Danciu, H. Domaç, J. F. Fonseca, J. García-Mayordomo, D. Giardini, B. Glavatovic, L. Gulen, Y. Ince, S. Pavlides, K. Sesetyan, G. Tarabusi, M. Tiberti, M. Utkucu, G. Valensise, K. Vanneste, S. Vilanova, J. Wössner (2013). European Database of Seismogenic Faults (EDSF). Istituto Nazionale di Geofisica e Vulcanologia (INGV), https://doi.org/10.6092/ingv.it-share-edsf

Basili, R., L. Danciu, M. M. C. Carafa, V. Kastelic, F. E. Maesano, M. M. Tiberti, R. Vallone, E. Gracia, K. Sesetyan, J. Atanackov, B. Sket-Motnikar, P. Zupančič, K. Vanneste, S. Vilanova (2020). Insights on the European Fault-Source Model (EFSM20) as input to the 2020 update of the European Seismic Hazard Model (ESHM20),

EGU General Assembly 2020, Online, 4-8 May 2020, EGU2020-7008, https://doi.org/10.5194/egusphere-egu2020-7008

Basili, R., B. Brizuela, A. Herrero, S. Iqbal, S. Lorito, F. E. Maesano, S. Murphy, P. Perfetti, F. Romano, A. Scala, J. Selva, M. Taroni, H. K. Thio, M. M. Tiberti, R. Tonini, M. Volpe, S. Glimsdal, C. B. Harbitz, F. Løvholt, M. A. Baptista, F. Carrilho, L. M. Matias, R. Omira, A. Babeyko, A. Hoechner, M. Gurbuz, O. Pekcan, A. Yalçıner, M. Canals, G. Lastras, A. Agalos, G. Papadopoulos, I. Triantafyllou, S. Benchekroun, K. Agrebi Jaouadi, S. Ben Abdallah, A. Bouallegue, H. Hamdi, F. Oueslati, A. Amato, A. Armigliato, J. Behrens, G. Davies, D. Di Bucci, M. Dolce, E. Geist, J. M. Gonzalez Vida, M. González, J. Macías Sánchez, C. Meletti, C. Ozer Sozdinler, M. Pagani, T. Parsons, J. Polet, W. Power, M. B. Sørensen, A. Zaytsev (2021). The making of the NEAM Tsunami Hazard Model 2018 (NEAMTHM18), Front. Earth Sci., 8, 616594, https://doi.org/10.3389/feart.2020.616594.

Böse, M., S. Julien-Laferrière, R. Bossu, F. Massin (2021). Near Real-Time Earthquake Line-Source Models Derived from Felt Reports, Seismol. Res. Lett., 92, 3, 1961-1978, https://doi.org/10.1785/0220200244.

Bossu, R., and G. Mazet-Roux (2012). An operational authoritative location scheme. In Bormann, P. (Ed.) (2012). New Manual of Seismological Observatory Practice (NMSOP-2), IASPEI, GFZ German Research Centre for Geosciences, Potsdam, https://doi.org/10.2312/GFZ.NMSOP-2.

Bossu, R., F. Roussel, L. Fallou, M. Landès, R. Steed, G. Mazet-Roux, A. Dupont, L. Frobert, L. Petersen (2018). LastQuake: From rapid information to global seismic risk reduction. International journal of disaster risk reduction, 28, 32-42, https://doi.org/10.1016/j.ijdrr.2018.02.024.

Bossu, R., L. Fallou, M. Landès, F. Roussel, S. Julien-Laferrière, J. Roch, R. Steed (2020). Rapid public information and situational awareness after the November 26, 2019, Albania earthquake: Lessons learned from the LastQuake system, Front. Earth Sci., 8, 235, https://doi.org/10.3389/feart.2020.00235.

Bossu, R., F. Finazzi, R. Steed, L. Fallou, I. Bondár (2021). "Shaking in 5 Seconds!"—Performance and User Appreciation Assessment of the Earthquake Network Smartphone-Based Public Earthquake Early Warning System, Seismol. Res. Lett., 93, 1, 137-148, https://doi.org/10.1785/0220210180

Buttkus, B. (Editor) (1986). Ten Years of the Graefenberg Array, Geologisches Jahrbuch Reihe E, Heft 35, 135.

Cauzzi, C., R. Sleeman, J. Clinton, J. D. Ballesta, O. Galanis, P. Kästli (2016). Introducing the European Rapid Raw Strong-Motion Database, Seismol. Res. Lett., 35, 9, 1671-1690, https://doi.org/10.1785/0220150271

Cauzzi C., J. Clinton, L. Faenza, S. Heimers, M. Koymans, V. Lauciani, L. Luzi, A. Michelini, R. Puglia, E. Russo, R. Sleeman, D. Jozinović (2018). Introducing a European Integrated ShakeMap System, Seismol. Res. Lett., 89, 2b, 717-966, https://doi.org/10.1785/0220180082.

Cauzzi, C., S. Custódio, C. P. Evangelidis, G. Lanzano, L. Luzi, L. Ottemöller, H. Pedersen, R. Sleeman (2021). Preface to the Focus Section on European Seismic Networks and Associated Services and Products, Seismol. Res. Lett. 92, 3, 1483-1490, https://doi.org/10.1785/0220210055.

Crowley, H., J. Dabbeek, V. Despotaki, D. Rodrigues, L. Martins, V. Silva, X. Romão, N. Pereira, G. Weatherill, L. Danciu (2021). European Seismic Risk Model (ESRM20). EFEHR Technical Report 002, V1.0.0. https://doi.org/10.7414/EUC-EFEHR-TR002-ESRM20.

Danciu L., S. Nandan, C. Reyes, R. Basili, G. Weatherill, C. Beauval, A. Rovida, S. Vilanova, K. Sesetyan, P.-Y. Bard, F. Cotton, S. Wiemer, D. Giardini (2021). The 2020 update of the European Seismic Hazard Model: Model Overview, EFEHR Technical Report, 001, v1.0.0, https://doi.org/10.12686/a15.

DISS Working Group (2021). Database of Individual Seismogenic Sources (DISS), Version 3.3.0: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas, Istituto Nazionale di Geofisica e Vulcanologia (INGV), https://doi.org/10.13127/diss3.3.0.

Godey, S., R. Bossu, J. Guilbert, G. Mazet-Roux (2006). The Euro-Mediterranean Bulletin: A comprehensive seismological Bulletin at regional scale, Seismol. Res. Lett., 77, 4, 460-474.

Harjes, H.-P., and D. Seidl (1978). Digital recording and analysis of broadband seismic data of the Gräfenberg (GRF) array, J. Geophys. 44, 511-523.

Hetényi, G., I. Molinari, J. Clinton, G. Bokelmann, I. Bondár, W. C. Crawford, J.-X. Dessa, C. Doubre, W. Friederich, F. Fuchs, et al. (2018). The AlpArray Seismic Network: A Large-Scale European Experiment to Image the Alpine Orogen, Surv. Geophys., 39, 5, 1009-1033, https://doi.org/10.1007/s10712-018-9472-4.

Evans, P. L., A. Strollo, A. Clark, T. Ahern, R. Newman, J. F. Clinton, H. Pedersen, and C. Pequegnat (2015). Why seismic networks need digital object identifiers, Eos, 96, https://doi.org/10.1029/2015EO036971.

Federal Institute for Geosciences and Natural Resources. (1976). German Regional Seismic Network (GRSN). Bundesanstalt für Geowissenschaften und Rohstoffe, https://doi.org/10.25928/mbx6-hr74.

Finazzi F. (2020). The earthquake network project: A platform for earthquake early warning, rapid impact assessment, and search and rescue, Front. Earth Sci., 8, 243, https://doi.org/10.3389/feart.2020.00243.

Heinloo, A. (2016). The httpmsgbus general-purpose HTTP-based message bus. GFZ Data Services, https://doi.org/10.5880/GFZ.2.4.2016.001.

Institut de physique du globe de Paris (IPGP) and Ecole et Observatoire des Sciences de la Terre de Strasbourg (EOST) (1982). GEOSCOPE, French global network of broad band seismic stations. Institut de physique du globe de Paris (IPGP), Université de Paris, https://doi.org/10.18715/GEOSCOPE.G.

Lanzano, G., L. Luzi, C. Cauzzi, J. Bienkowski, D. Bindi, J. Clinton, M. Cocco, M. D Amico, J. Douglas, L. Faenza, C. Felicetta, F. Gallovic, D. Giardini, O.-J. Ktenidou, V. Lauciani, M. Manakou, A. Marmureanu, E. Maufroy, A. Michelini, H. Özener, R. Puglia, R. Rupakhety, E. Russo, M. Shahvar, R. Sleeman, N. Theodoulidis (2021). Accessing European Strong-Motion Data: An update on ORFEUS coordinated services, Seismol. Res. Lett. 92 (3), 1642-1658, https://doi.org/10.1785/0220200398.

Locati, M., A. Rovida, P. Albini and M. Stucchi (2014). The AHEAD Portal: A Gateway to European Historical Earthquake Data, Seismol. Res. Lett. 85 (3), 727-734, https://doi.org/10.1785/0220130113

Locati, M., R. Vallone, M. Ghetta and N. Dawson (2021). QQuake, a QGIS Plugin for Loading Seismological Data From Web Services, Frontiers in Earth Science, 9:614663, https://doi.org/10.3389/feart.2021.614663.

Luzi, L., R. Puglia, E. Russo, M. D'Amico, C. Felicetta, F. Pacor, G. Lanzano, U. Çeken, J. Clinton, G. Costa, L. Duni, E. Farzanegan, Ph. Gueguen, C. Ionescu, I. Kalogeras, H. Özener, D. Pesaresi, R. Sleeman, A. Strollo, M. Zare (2016). The engineering strong-motion database: A platform to access pan-European accelerometric data, Seismol. Res. Lett. 87 (4), 987-997, https://doi.org/10.1785/0220150278.

Michelini, A., G. Iley, Ö. Necmioğlu, G. Wotawa, D. Arnold-Arias and G. Forlenza (2020). ARISTOTLE (All Risk Integrated System TOwards The hoListic Early-warning)-European Natural Hazard Scientific Partnership, EGU General Assembly 2020 Conference Abstracts, 20016, https://doi.org/10.5194/egusphere-egu2020-20016.

Nolet, G., B. Romanowicz, R. Kind and E. Wielandt (1986). ORFEUS Science Plan, Reidel, Dordrecht, 45.

Nolet, G. and N.J. Vlaar (1982). The NARS project: probing the Earth's interior with a large seismic antenna, Terra Cognita 2, 17-25.

Quinteros, J., J. A. Carter, J. Schaeffer, C. Trabant, H. A. Pedersen (2021). Exploring Approaches for Large Data in Seismology: User and Data Repository Perspectives, Seismol. Res. Lett., 92, 3, 1531-1540, https://doi.org/10.1785/0220200390.

Quitoriano, V. and D. Wald (2020). USGS "Did You Feel It?"—Science and Lessons From 20 Years of Citizen Science-Based Macroseismology, Frontiers in Earth Science, 8, 120. https://doi.org/10.3389/feart.2020.00120

Quitoriano, V., R. Bossu, M. Landès, D. Wald (2021). Comparison of EMSC and USGS Internet-Based Earthquake Reports from Recent Events , ESC 2021

Rovida A. and A. Antonucci (2021). EPICA - European PreInstrumental Earthquake CAtalogue, version 1.1. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/epica.1.1

Rovida, A. and M. Locati (2015). Archive of Historical Earthquake Data for the European-Mediterranean Area, Perspectives on European Earthquake Engineering and Seismology, 359-369, Springer International Publishing. https://doi.org/10.1007/978-3-319-16964-4_14

Strollo, A., D. Cambaz, J. Clinton, P. Danecek, C. P. Evangelidis, A. Marmureanu, L. Ottemöller, H. Pedersen, R. Sleeman, K. Stammler, D. Armbruster, J. Bienkowski, K. Boukouras, P. Evans, M. Fares, C. Neagoe, S. Heimers, A. Heinloo, M. Hoffmann, Ph. Kaestli, V. Lauciani, J. Michalek, E. Odon Muhire, M. Ozer, L. Palangeanu, C. Pardo, J. Quinteros, M. Quintiliani, J. A. Jara-Salvador, J. Schaeffer, A. Schloemer, N. Triantafyllis (2021). EIDA: The European Integrated Data Archive and Service Infrastructure within ORFEUS, Seismol. Res. Lett., 92, 3, 1788-1795, https://doi.org/10.1785/0220200413.

Stucchi, M., A. Rovida, A. A. Gomez Capera, P. Alexandre, T. Camelbeeck, M. B. Demircioglu, P. Gasperini, V. Kouskouna, R.M. W. Musson, M. Radulian, K. Sesetyan, S. Vilanova, D. Baumont, H. Bungum, D. Fäh, W. Lenhardt, K. Makropoulos, J. M. Martinez Solares, O. Scotti, M. Živčić, P. Albini, J. Batllo, C. Papaioannou, R. Tatevossian, M. Locati, C. Meletti, D. Viganò and D. Giardini (2012). The SHARE European Earthquake Catalogue (SHEEC) 1000-1899. In J. Seismol., 17, 2, 523-544, Springer Science and Business Media LLC, https://doi.org/10.1007/s10950-012-9335-2.

UNISDR (United Nations International Strategy for Disaster Reduction) (2015). Sendai framework for disaster risk reduction 2015-2030, http://www.wcdrr.org/uploads/Sendai_Framework_for_Disaster_Risk_Reduction_2015-2030.pdf (last accessed February 2022).

Utrecht University (UU Netherlands) (1983). NARS [Data set]. International Federation of Digital Seismograph Networks, https://doi.org/10.7914/SN/NR.

van Eck, T., C. Trabant, B. Dost, W. Hanka, and D. Giardini (2004). Setting Up A Virtual Broadband Seismograph Network Across Europe, EOS Transactions, 85, 13, 125-132, https://doi.org/10.1029/2004EO130001.

Wilkinson, M. D., M. Dumontier, I. J. Aalbersberg, G. Appleton, M. Axton, A. Baak, N. Blomberg, J. W. Boiten, L. B. da Silva Santos, P. E. Bourne, et al. (2016). The FAIR guiding principles for scientific data management and stewardship, Sci. Data 3, https://doi.org/10.1038/sdata.2016.18.

Woessner, J., L. Danciu, D. Giardini, H. Crowley, F. Cotton, G. Grünthal, G. Valensise, R. Arvidsson, R. Basili, M. B. Demircioglu, S. Hiemer, C. Meletti, R. W. Musson, A. Rovida, K. Sesetyan, M. Stucchi (2015). The 2013 European Seismic Hazard Model: key components and results, Bulletin of Earthquake Engineering 13 (12), 3553-3596. Springer Science and Business Media LLC, https://doi.org/10.1007/s10518-015-9795-1.

Worden, C.B., E.M. Thompson, M. Hearne, D. J. Wald (2020). ShakeMap Manual Online: technical manual, user's guide, and software guide, U. S. Geological Survey, http://usgs.github.io/shakemap/. https://doi.org/10.5066/F7D21VPQ.

***CORRESPONDING AUTHOR: Florian HASLINGER**,
Swiss Seismological Service at ETH Zurich,
8092 Zurich, Switzerland,
email: florian.haslinger@sed.ethz.ch