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The Near Fault Observatory community in Europe: a new resource for faulting and hazard studies

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Abstract

The Near Fault Observatories (NFOs) community is one of the European Plate Observing System (EPOS, http://www.epos-eu.org) Thematic Communities, today consisting of six research infrastructures that operate in regions characterised by high seismic hazard originating from different tectonic regimes.

Earthquakes respond to complex natural systems whose mechanical properties evolve over time. Thus, in order to understand the multi-scale, physical/chemical processes responsible for the faulting that earthquakes occur on, it is required to consider phenomena that intersect different research fields, i.e., to put in place multidisciplinary monitoring. Hence, NFOs are grounded on modern and multidisciplinary infrastructures, collecting near fault high resolution raw data that allows generation of innovative scientific products.

The NFOs usually complement regional backbone networks with a higher density distribution of seismic, geodetic, geochemical and other geophysical sensors, at surface and sometimes below grade. These dense and modern networks of multi-parametric sensors are sited at and around active faults, where moderate to large earthquakes have occurred in the past and are expected in the future. They continuously monitor the underlying Earth instability processes over a broad time interval.

Data collected at each NFO results in an exceptionally high degree of knowledge of the geometry and parameters characterizing the local geological faults and their deformation pattern. The novel data produced by the NFO community is aggregated in EPOS and is made available to a diverse set of stakeholders through the NFO Federated Specific Data Gateway (FRIDGE). In the broader domain of the Solid Earth sciences, NFOs meet the growing expectations of the learning and communication sectors by hosting a large variety of scientific information about earthquakes as a natural phenomenon and

a societal issue. It represents the EPOS concept and objective of aggregating and harmonising the European research infrastructures capabilities to facilitate broader scientific opportunity.
The NFOs are at the cutting edge of network monitoring. They conduct multidisciplinary experiments for testing multi-sensor stations, as well as realise robust and ultra-low latency, transmission systems that can routinely accommodate temporary monitoring densification. The effort to continuously upgrade the technological efficiency of monitoring systems positions the NFO at the centre of marketing opportunities for the European enterprises devoted to new sensor technology.
The NFOs constitute ideal test beds for generating expertise on data integration, creating tools for the next generation of multidisciplinary research, routine data analysis and data visualization. In particular focus is often on near-real time tools and triggering alarms at different levels are tested and implemented, strengthening the cooperation with the Agencies for risk management. NFOs have developed innovative operational actions such as the Testing Centre for Earthquake Early Warning and Source Characterisation (CREW) and detailed fast ground shaking and damage characterization.
Complementing the recent growth of modern laboratory and computational models, the NFOs can provide interdisciplinary observations of comparable high resolution to describe the behaviour of fault slip over a vast range of spatial and temporal scales and aiding to provide more accurate earthquake hazard characterizations.

Keywords: Near Fault Observatories; Research infrastructures; Active faults; Multidisciplinary approach; High resolution data products

1. Introduction

1.1 Mission

The Near Fault Observatories in Europe target understanding the physics of faulting including the transition between stable and unstable fault slip behaviour and the near-surface response to earthquake shaking. Also crucial is the estimation of the seismic hazard and ultimately the mitigation of risk for exposed populations and infrastructures.

The idea of performing and implementing interdisciplinary investigations and alert systems, targeting crustal faults, requires consideration of the geological structures as complex natural systems whose physical and chemical properties evolve over time. Thus, the inference of the multi-scale processes associated with earthquakes and faulting requires considering phenomena studied in different research fields: this is the road of integration that has led to the birth and development of the NFO community in Europe. NFOs were identified as required infrastructures by EPOS, the European Plate Observing System. NFOs are innovative, advanced research infrastructures based on dense, state-of-the-art networks, that continuously monitor instability processes developing on underlying faults, over a broad time scale, from seconds to years. NFOs collect multi-parametric near-fault data and provide advanced scientific products to the earth science community and other stakeholders through EPOS-related services. Some NFOs that provide mono-thematic data, with specific, fault-related scientific objectives, have a plan to integrate multi-disciplinary data in the infrastructure in the near future.

NFOs complement the existing regional geophysical monitoring networks. Generally, these independent backbone networks are characterised by relatively coarse station spacing with similar sensor types (in most cases several tens of kilometres) that are not coordinated. In contrast, as multi-disciplinary densifications, NFOs can be considered as on-field laboratories that illuminate underlying active faults by recording and analysing multi-disciplinary signals related to the processes that occur beneath our feet, down to very small scales. NFOs aim to trace the evolution of fault systems, through accurate detection [Ross et al., 2019], location [Waldhouser and Ellsworth, 2000; Chiaraluce et al., 2011] and characterization of micro-seismicity [Abercrombie, 2015; Supino et al., 2019], to intercept the aseismic forcing mechanisms, such as creeping, that may influence future rupture development [Bouchon et al., 2021] and to identify the diffusive processes associated with fluid migration and fluid-rock interaction [Miller, 2013]. Owing to the long-time scales related to a full single seismic cycle for a large (e.g., tens of kilometres long) fault, NFOs focus on high resolution deformation episodes occurring along small patches of the main faults or along minor faults that pertain to the major system. In this framework, more frequent small events (with M ~3) can be considered as local mainshocks, considerably shortening the seismic cycle. This provides scientists the opportunity to test models and hypotheses on a more robust statistical basis and to follow the pre-, co- and post-seismic phases of an active fault, even if small (e.g., from hundreds of meters to a few kilometres), with all the related scaling problems. At the same time, the collected information on the geometry and deformation style of the major faults can be used to develop ground shaking scenarios that account for diverse slip distributions and rupture directivity models [Evangelista et al., 2017].

1.2 The NFO community in EPOS

The NFO community in Europe originated under the FP7 European project NERA – Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation (2010-2014), when a networking initiative started to coordinate efforts of different institutions owning dense observatories on faults, culminating in sharing of technology know-how and data analysis best-practice. The success of the initiative led to the NFO community becoming a Thematic Working Group of the EPOS-PP – Preparatory Phase (EU project funded under the FP7 programme – 2010-2014). In the EPOS-IP project (EPOS Implementation Phase, funded under the Horizon 2020 programme – 2015-2019) the NFO community was officially recognized as one of the Thematic Core Service (TCS). During EPOS-IP, the current foundations for our community were built, through the definition of a Consortium Agreement that comprised a Legal, Governance and Financial framework. Further, services dedicated to NFOs we developed to make data, data products and software interoperable and accessible through the EPOS data distribution platform, the Integrated Core Service Central Hub system (ICS-C; https://www.ics-c.epos-eu.org/). During the EPOS-IP project, the community successfully negotiated the validation phase that required reaching technical, financial and governance targets. The community also received concurrent support from the SERA project – Seismology and Earthquake Engineering Research Infrastructure for Europe – (EU project funded under the INFRAIA

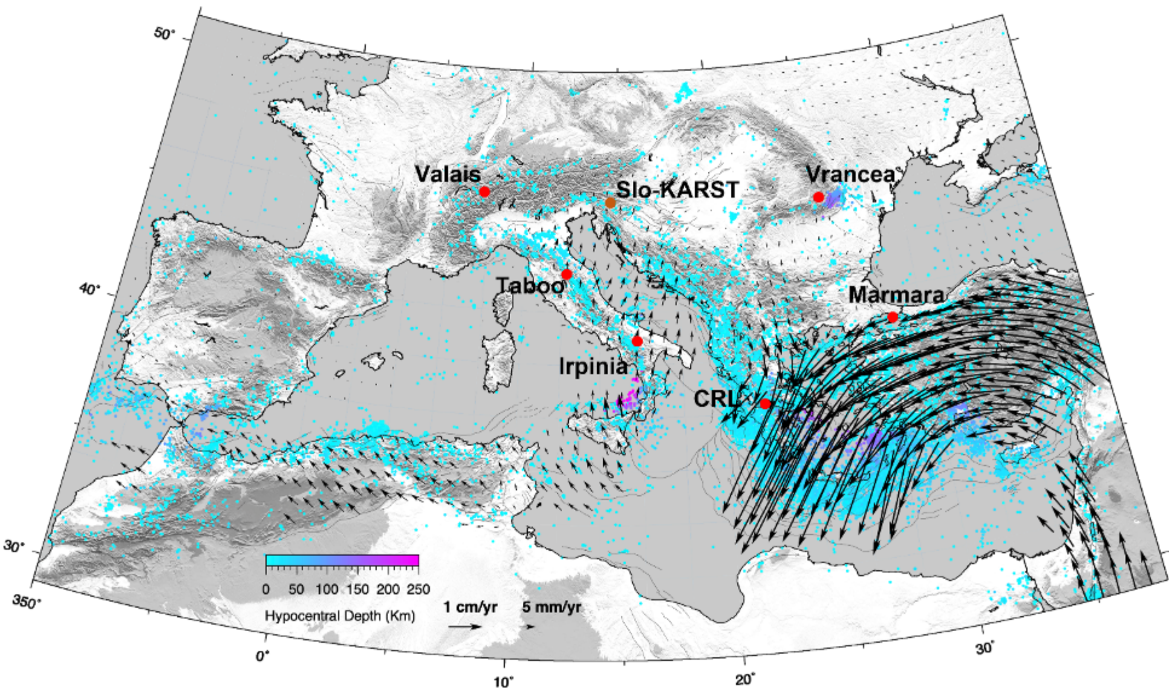

Figure 1. Location of Near Fault Observatories in Europe. The map also shows the time derivative of the deformation vectors with arrows, whose length is associated with the amplitude of the strain rate (Serpelloni p.c.). Seismicity is also superimposed on the map, with colours associated with event depth. The NFOs are in regions with different strain rate and kinematics, featuring shallow and medium depth seismicity.

Horizon 2020 programme, 2017-2020) to develop and apply advanced strategies and techniques of data analysis for microseismicity.

Today, the NFO community is a TCS of the EPOS delivery framework. The NFOs comprise six members and one observer. They span different tectonic regimes, different areas and different space scales over Europe (Figure 1), all of them at sites of elevated seismic hazard. They include plate boundary systems at the Marmara Sea and the Corinth rift. In mountain settings, NFOs monitor the Alto Tiberina and Irpinia faults in the Apennine Mountain range, the Vrancea fault in the Carpathian Mountains, the Valais in the Alps and the Slovenian Karst region in the Dinarides. They look at diverse faulting mechanisms (strike-slip, normal and thrust), high to low angle, shallow to deep faults, as well as regions with fast and slow strain rate accumulation. Each fault zone can generate large earthquakes ($M > 6$) that pose substantial seismic hazard. Two of the zones, Marmara Sea and Corinth, include offshore seismic sources that pose an additional, even though low, tsunami hazard. The focus of the observatories varies, ranging from small- to large-scale seismicity and includes the role of different parameters, such as fluids in fault initiation, the geometrical and mechanical structure of fault systems, site effects and secondary phenomena, such as landslides and tsunamis. In response to their specific objectives, the NFOs operate a diverse set of instrumentation to monitor the surface and sub-surface using seismic, deformation, strain, geochemical and electromagnetic equipment.

1.3 The TCS Delivery Framework

The mission of the TCS NFO is to provide a sustainable platform for coordination between each European observatory, sharing data and products promoting best practice that ultimately will foster breakthrough research on faulting and earthquakes. his effort is regulated through the Consortium Agreement (CA), representing the NFO reference framework, specifying the relationship between Parties, their rights and obligations, as well as providing organisational, managerial and financial guidelines.

The TCS portfolio comprises data access, visualization and processing tools, testing facilities and transnational access. Data access from NFOs follow existing EPOS TCS services where they exist for seismic and GNSS datasets (raw data and high-level products) and provide new NFO-specific access services otherwise such as for Vp/Vs time series, high resolution earthquake catalogues and geochemical data. To process multi-disciplinary time series and intersect information appearing in different records, NFOs have developed tools that will help in providing improved models of transient processes in/around fault zones and in building advanced databases and catalogues of such processes. These tools will be in the future included in the Virtual Laboratory service. Also, the NFO community has developed a testing facility, built on real-time and offline high-resolution data, to foster the development of next generation methodologies and software for real-time monitoring of faulting processes. For physical access, NFOs will open their on-field laboratories to design new experiments, to test new instruments, to validate methodologies and real-time software, approaching breakthrough scientific questions.

Data and products delivered by the TCS are intended to provide the Earth Sciences scientific community with a fundamental dataset that can accelerate to advancement in understanding fault system behaviour. Data and high-resolution data products will provide clues to understand the forcing mechanisms associated to earthquakes (fluid migration, creeping), the preparation phase of large earthquakes, the partition of the slip in seismic and aseismic contributions, as well as markers for changes in the mechanical properties of the faults. The NFOs represent ideal testbeds for generating expertise on data integration, for creating tools for the next generation of multidisciplinary research, advanced routine data analysis, also grounded on machine learning and artificial intelligence, and data visualization, for developing new experiments and survey through transnational access. These integrated datasets alongside provision of virtual and physical access to NFOs is expected to create positive feedback to solve the puzzle of faulting and associated deformation. The NFO delivery framework also facilitates technological and knowledge transfer for scientific and technical training, as well as public outreach, at different levels: general education of public on natural hazards and seismo-tectonic processes, higher education (summer schools, masters and postgraduate research) on advanced instrumentation techniques, multi-parameter analysis of crustal processes. Bringing together multidisciplinary data and expertise at a single site to be processed and integrated, will put important pieces in the puzzle of earthquake mechanics. Finally, besides the monitoring of the faults before the occurrence of main events, the dense NFO networks can also improve operational actions conducted in the aftermath of a large earthquake, such as Earthquake Early Warning (EEW) and detailed, fast ground shaking and damage characterization during the on-going rupture on the fault.

2. The Near Fault Observatories in Europe

In the following, we introduce the six NFOs that have formally signed the CA. The six NFO infrastructures are indicated in Figure 2. NFOs are usually operated by a single National organisation but can also be represented by multiple National and European organisations. The complexity beyond National Research Infrastructures (NRIs) is managed at the NFO level. NFOs, in line with other TCS service providers, fully adopt the EPOS data policy and permit open and free distribution of their own data and products through the EPOS services, on behalf of the data owners (Suppliers), and in compliance with FAIR principles.

In future, new NFOs can be expected to join the community. Recently the Slovenian Karst NFO has joined the Consortium as an Observer; a status formally recognised by the community, allowing potentially new NFOs to participate in the CA board meetings and initiatives. This is an initial step prior to becoming a full member in the future.

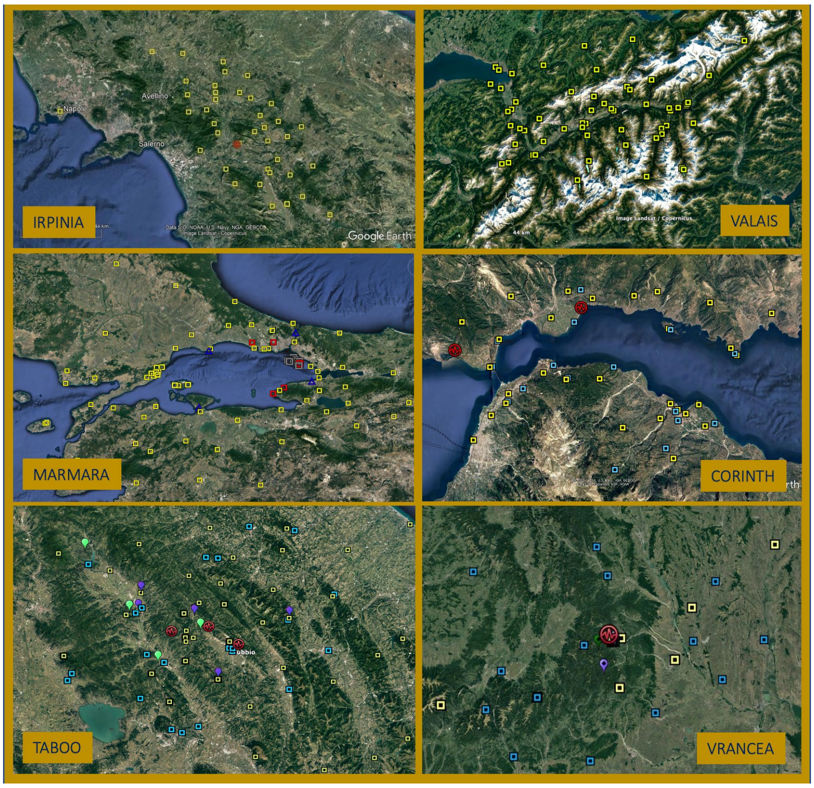

Figure 2. Maps of the six European Near Fault Observatories showing details of each infrastructure. The symbols indicate: yellow squares for seismic stations, blue squares for GNSS stations, purple drops for radon stations, green drops for CO_2 stations. A red circle with a seismogram inside indicates multi sensor sites; in TABOO they stand for co-located seismometer, strainmeter, pore pressure gauge and optic fiber cable within boreholes, in Irpinia for fibre cable and seismometer, for Vrancea infrasound array and seismometer and for Corinth strainmeter, borehole water-level, tide gauge and meteorological sensors.

2.1 The Corinth Rift Laboratory (CRL)

The Western Gulf of Corinth (WGoC) is a 110-km-long rift dominated by active, ~E-W-trending normal faults, located in Central Greece. An extension rate of 15 mm/yr in a N9°W direction has been determined [Briole et al., 2021]. It is characterized by significant seismic activity, with the occurrence of destructive earthquakes [Makropoulos et al., 2012]. In 1995 the Ms = 6.2 Aigion earthquake occurred, caused by an offshore low-angle fault [Bernard et al., 1997]. In the beginning of the 21st century, the Corinth Rift Laboratory network (CRL) was established (http://crlab.eu/), covering an area of ~30 × 30 km^2, centred between Patras to the west and Aigion to the east [Cornet et al., 2004], with main scientific goal to investigate in detail the intense and continuous microseismic activity and deformation. Currently, CRL is the only multinational NFO. The European Institutions that form CRL are the Centre National de la Recherche Scientifique (CNRS, France), the National and Kapodistrian University of Athens (NKUA, Greece), the University of Patras (UPATRAS, Greece) the National Observatory of Athens (NOA, Greece) and Charles University (CUP, Czech Republic).

CRL is a dense network of 29 permanent seismological operated by CRL (CL network, DOI: 10.15778/RESIF.CL), NKUA (HA network, DOI: 10.7914/SN/HA), UPATRAS (HP network, DOI: 10.7914/SN/HP) and NOA (HL network, DOI:10.7914/SN/HL). HA, HP and HL networks also belong to the Hellenic Unified Seismological Network [HUSN; Evangelidis et al., 2021]. CRL is equipped with 16 GNSS stations installed by CRL and NOA [Ganas et al., 2008; Chousianitis et al., 2021]. Furthermore, two multiparameter sites are operated in CRL (see Figure 2). The first is RIZA which is equipped with borehole three-component strainmeter, rainmeter, borehole water-level and atmospheric pressure sensors. The second site is MOKI, where the multparameter instruments are borehole three-component strainmeter, tide gauge, borehole water-level and atmospheric pressure sensors. Seismological data are available through the European Integrated Data Archive (EIDA) nodes at RESIF and NOA [Evangelidis et al., 2021]. EIDA has declared the virtual network identifier _NFOCRL for all seismic stations within the CRL perimeter.

CRL also distributes scientific products, such as phase and focal mechanism data NKUA, NOA and UPAT. GNSS data and positioning solutions are now available at the CRL portal (https://crlab.eu) and will migrate to the EPOS data portal.

The use of the freely available CRL data highlighted that most seismicity is clustered, with the frequent occurrence of swarms, as the 2001 Agios Ioannis [Pacchiani and Lyon-Caen, 2010], the 2013 Helike [Kapetanidis et al., 2015, 2021; Kaviris et al., 2017] and the 2015 Malamata [De Barros et al., 2020] ones. Geodetic studies, from permanent and campaign GNSS network measurements and InSAR, identified the deformation sources of the Aigion [1995] and Efpalio [2010] earthquakes, as well as slow aseismic shallow slip [Elias and Briole, 2018]. The recent 2020-2021 seismic crisis was studied by the CRL research group [Kaviris et al., 2021]. In the latter case, the analysis of the CRL multiparametric data significantly contributed to understand the seismogenic process. Combined seismological and geodetic data were considered in order to constrain the geometry and kinematics of the structures that hosted the major events of the 2020-2021 seismic crisis. In addition, the significant role of CRL tide-gauge data, analyzed along with seismological and GNSS recordings, is proven in ongoing research that aims to identify the rupture process of the largest event of the sequence that occurred on 17 February 2021.

The wealth of the multiparametric CRL data led to the in-depth knowledge of the seismogenesis in the Western Gulf of Corinth. The dual behaviour of certain fault segments, subject to transient creep and to pore pressure diffusion, has been identified in the WGoC. The detailed analysis of multiparametric CRL data also led to the identification of a brittle, highly fractured layer in depths between 6 km and 9 km, where the major normal faults of the CRL area are rooting [Lambotte et al., 2014; Duverger et al., 2018]. It is obvious that the free provision of CRL data, scientific products and services to the whole community will significantly contribute to the detailed knowledge of the mechanics and kinematics of the area, with a high scientific impact, as it will be possible to apply similar procedures in other regions worldwide.

2.2 The Irpinia Near Fault Observatory (INFO)

The Irpinia Near Fault Observatory -INFO – (http://isnet.unina.it) is a natural laboratory (see Figure 2) that monitors the underlying fault system along the Campania-Lucania Apennine chain (Southern Italy), a normal fault environment, frequently struck by destructive earthquakes, with a recurrence period of events with $M > 5.5$ of about 30 years [Cinti et al., 2004], and the last major event in the area being the $M = 6.9$, 1980 Irpinia earthquake. This area undergoes an extensional rate of ~3 mm/yr, as inferred from geodetic measurements [D'Agostino et al., 2010]. Present-day low-magnitude seismicity ($M < 3.5$) occurs in the shallow portion of the crust, is organized in seismic sequences [Festa et al., 2021] and appears spread into a large, fractured volume confined in the graben responsible for the 1980 earthquake. Beyond the large seismic hazard of the area, the main scientific questions targeted by this infrastructure is to understand the role of fluid-rock interaction and fluid diffusion - water and carbon dioxide [Amoruso et al., 2014], in the production of the earthquakes, and the contribution of the charging process of shallow aquifers in affecting the stress of rocks at seismogenic depths [D'Agostino et al., 2018]. INFO is ultimately aimed to catch and track the preparatory phase of large events in the area, through the fine characterization and modelling of the seismicity and the deformation.

INFO is managed by the University of Napoli Federico II and operates the Irpinia Seismic Network (ISNet), a dense, high-dynamic range seismic network of 31 stations, covering an area of about 120×90 km^2, deployed within two concentric ellipses, with the major axis parallel to the Apennine chain [Iannaccone et al., 2010]. The average inter-station distance within the inner part of the infrastructure is less than 10 km. All stations are equipped with a strong-motion accelerometer and a weak motion sensor, the latter being a short-period, a broadband velocimeter or an accelerometer with lower full-scale to record both strong and weak motions associated with earthquakes and ambient noise. ISNet provides real-time data with a controlled delay, allowing the infrastructure to be the Italian backbone for testing EEW systems [Satriano et al., 2011]. The seismic network is complemented with 9 additional broadband stations from the national network, 15 GNSS stations, managed by INGV, and two seismic arrays of 5 six-component stations at the centre of the network. Recently, a 1.1 km fibre optic cable (FibIR) has been installed near the emergence of the main fault that generated the 1980 earthquake, and it is now sensed by a DAS, in the frame of the IrpiDAS survey. In the near future, the area will be also covered with additional GNSS and geochemical stations, to better constrain the ground deformation and monitor geochemical fluids.

2.3 The Marmara Sea Observatory

The North Anatolian Fault Zone (NAFZ) is one of the largest plate-bounding transform faults that separate the Anatolia and Eurasian plates and extends for 1600 km between Eastern Anatolian and the Northern Aegean. The Anatolian block is moving westward with respect to the collision zone between the Eurasian and Arabian Plates, at a rate of ~25 mm yr-1 east of the Sea of Marmara, activating major strike-slip and N-S extensional normal faulting earthquakes south of the Marmara region [Armijo et al., 2002]. Along the NAFZ a series of large earthquakes occurred since 1939, starting from Erzincan in the eastern Anatolia and propagating westward toward Istanbul and Marmara region located, where the devasting Izmit earthquake occurred in 1999. West of the Izmit rupture a ~100 km long seismic gap exists along the fault portion placed below the Sea of Marmara connecting the Ganos [1912, Mw7.3] and Izmit [1999, Mw7.4] ruptures; such a segment can generate an earthquake with magnitude ~7.1 [Ergintav et al., 2014]. The 30-year probability for an event $M \geq 7$ below the Sea of Marmara is estimated at 35- 70% [Parsons, 2014].

There are many multidisciplinary geophysical networks monitoring the heterogenous pattern of interseismic loading of the area, showing both creeping and locked segments [Ergintav et al., 2014; Schmitbull et al., 2015; Klein et al., 2017; Lange et al., 2019; Yamamot et al., 2019]. The backbone of the monitoring systems has been built by local Universities like Boğaziçi University (BU-KOERI, Istanbul University) and governmental organizations like AFAD, TUBITAK and General Directorate of Mapping (GCM). BU-KOERI's National Earthquake Monitoring Center (NEMC) is a 24/7 operational centre comprising 136 broad-band (BB) and 107 strong motion (SM) sensors at the national level. About 200 digital strong motion accelerometers are operated by KOERI as dense urban network in and around Istanbul (Rapid Response and Early Warning System). KOERI also operates 5 sea-floor multi-instrument observation systems in the Sea of Marmara, actually deserving renovation, and acts as the National Tsunami Warning Centre for Turkey under the ICG/NEAMTWS initiative. AFAD's Earthquake Data Center System of Turkey (TDVMS) is a system which pairs up all the earthquake data obtained from seismic stations all around Turkey and shares these data via its web portal. It also operates like BU-KOERI and run more than 1000 BB and SM stations. GCM controls more than 150 Continuous GNSS stations, including other geodesic networks (e.g. gravity, sea-level monitoring).

At the same time, many international efforts have been posed to better define the earthquake hazard pattern of the region. For example, to monitor the offshore microseismic activity in the NAFZ nearby Istanbul, below the Çinarcik Basin (ÇB), a permanent seismic array [PIRES; Bohnhoff et al., 2013] was installed on the Prince Islands in 2006, at a very close proximity to the main fault. Jointly operated by German Research Centre for Geosciences Potsdam (GFZ) and BU-KOERI, PIRES allows to constrain the spatiotemporal character of the microseismicity based on well-constrained hypocenters is performed to understand the interaction between fault segments of the NAFZ along the ÇB [Bohnhoff et al., 2013]. To extend this study, in 2013 the GONAF project [Geophysical borehole Observatory at the North Anatolian Fault; Raub et al., 2016] started under a joint research venture between German GFZ and Turkish Disaster and Emergency Presidency (AFAD), Turkey. The aim of this project is to monitor earthquake activity at low magnitude-detection threshold in the Istanbul and eastern Sea of Marmara region where a major ($M > 7$) earthquake is pending. In this context, also borehole strainmeters have been installed together with US agency UNAVCO [Bohnhoff et al., 2010 and Martinez-Garzon et al., 2019].

However, in 2014, the Marmara region has been designated a "Permanent Supersite" by the CEOS (Committee on Earth Observation Satellites) under GEO Geohazard and Natural Laboratories Initiative (GSNL). This initiative provided the opportunity to measure the surface displacements, in terms of mean deformation velocity maps and corresponding time-series, affecting the Marmara Region via the exploitation of SAR data acquired by the different satellite systems investigate. The achieved results can be fruitfully compared with the available independent in-situ measurements (e.g., GPS data, Strainmeter) providing additional constrains and details [Diao et al., 2016; de Michele et al., 2017; Aslan et al., 2018; Martínez-Garzón, 2021]. In this framework, a core study group has been established in the consortium of the European Commission funded MarSite (New Directions in Seismic Hazard Assessment through Focused Earth Observation in the Marmara Supersite) project (2012-2016). MarSite organized as the demonstrator for integrating satellite and in-situ observations and for providing integrated access to data until the end of the project.

From the end of the MarSite project, most of the activities and related data and scientific products, were reorganized and harmonised within the Marmara Near Fault Observatory, coordinated under EPOS support. Permanent and temporary sets of data have been standardised following communal open access sharing rules and new web services have been implemented in the EPOS framework. Not all the existing infrastructures have been already harmonised; this is a long process deserving time to be pursued. For sure NFO community represents an optimal opportunity to create a common scientific environment primarily finalised to gain valuable information about the off-shore unbroken segments of the region to be shared with decision-makers to improve the hazard maps of the Marmara (specially Istanbul) and their risk-plans. At the same time, NFO novel platforms for data exposure and sharing will represent an occasion as well to provide to every kind of users with all the available data and scientific products generated by such an important suite of multidisciplinary monitoring and research infrastructures.

2.4 The Alto Tiberina Near Fault Observatory (TABOO)

The Alto Tiberina fault (ATF), located along an extending sector, at a rate of about 3 mm/yr [Serpelloni et al., 2006], of the Northern Apennines (Central Italy) is a 60 km long very low-angle normal fault (mean dip 20°) that is the target of TABOO (The Alto Tiberina Near Fault Observatory), a permanent monitoring infrastructure managed by the Istituto Nazionale di Geofisica e Vulcanologia [INGV; Chiaraluce et al., 2014].

Taboo is a state-of-the-art dense network (see Figure 2) with mean inter-distance of about 5 km between multidisciplinary sensors, deployed both at surface and within shallow boreholes (< 250 m). Stations record and transmit in real time via dedicated Wi-Fi technology; then data is stored in standard formats on open access thematic portals and distributed via web services.

While seismic data from TABOO reveal release of microseismicity, at a consistently high rate on the ATF fault plane, including repeating earthquakes (RE), no historical earthquake can be unambiguously associated with the activation of the whole ATF [Chiaraluce et al., 2007 and references therein]. REs [Valoroso et al., 2017] together with a steep gradient in crustal velocities [Vadacca et al., 2016], measured by GNSS, and transient surface motion, lasting for few months and coinciding with seismic swarms [Gualandi et al., 2017 and Vuan et al., 2020], support the hypothesis that portions of the ATF are creeping aseismically. Recent studies document that any given patch of a fault can creep, nucleate slow earthquakes, and also host large earthquakes [e.g., Iquique earthquake, Ruiz et al., 2014; Tohoku earthquake, Kato et al., 2012 and Parkfield, Veedu and Barbot, 2016]. Why a fault patch would switch from one mode of slip to another one runs contrary to the standard theory. Thus, these observations are forcing a revolution in our way of thinking about how faults accommodate slip. However, the interaction between creep, slow and regular earthquakes is still poorly documented by observation. TABOO is currently collecting unique data needed to address such questions; by illuminating the physics that allows for both seismic and aseismic slip on a single fault patch, will have important implications for seismic hazard and risk assessment globally.

2.5 The Valais Observatory

The NFO VALAIS is a particularly dense multidisciplinary component of the monitoring infrastructure in Switzerland, operated by the Swiss Seismological Service at ETH Zurich. It is centred around the Canton of Valais in the SE corner of the country and in the high Alps. Although damaging earthquakes are rare in Switzerland when compared to more seismically active regions, such events have occurred and will continue to do so. Over the past 700 years, a total of 28 events of magnitude Mw ≥ 5.5 are known, twelve of which caused severe damage (Intensity of VIII or higher). The Valais region is the area of greatest seismic hazard in Switzerland and has experienced a magnitude 6 or larger event every 100 years (1524, 1584, 1685, 1755, 1855, 1946), with the last magnitude 6.1 earthquake in 1946 close to Sion and Sierre [Fritsche and Fah, 2009]. This area and in particular the region of Visp holds special interest: on average, the Visp region has been struck by damaging earthquakes every 40 years, with the last in 1960 reaching a macroseismic intensity of VIII. The Visp event of 1855 is the largest in Switzerland in the last 300 years. In addition to elevated seismic activity, the extreme topography, with steep unstable slopes and deep soft soil valleys, and extreme climate, with large glaciers and deep snow cover, add to the total hazard level in the Valais. The area has experienced great damage from earthquake ground motion and different secondary phenomena, such as liquefaction in the Rhone plain, landslides and rock fall [Fritsche et al, 2012]. The human impact of the last centuries has further raised the hazard. River regulations, advances in engineering methods and population growth have meant settlements and industries are now sited in seismically vulnerable areas.

The particular densification of the seismic monitoring in the Valais, as well as the introduction of complementary multidisciplinary instrumentation, including those with the potential to provide precursory information, began during the COGEAR project [Fäh et al, 2012] and continues today. NFO Valais comprises 16 co-located broadband and strong motion stations and 37 strong motion stations (see Figure 2) that are openly available and also integrated in the backbone national network (Swiss Seismological Service (SED) at ETH Zurich; 1983). NFO Valais stations, like all the NFO ones, are updated under EIDA virtual network code (e.g., _NFOVALAIS). Multiple additional temporary stations are also routinely available. GNSS and magnetotelluric sensors complement this network. The network features 2 boreholes at Visp and Collombey that include multiple downhole accelerometers and a string of pore-water pressure sensors. The seismic network is densest along the Rhine valley, with multiple strong motion stations located in the towns of Visp and Sion that demonstrate the strong and variable site amplifications that can be observed across the heavily populated deep alluvial basin. The network allows the detection and location of microseismicity in high resolution, since in this area swarms are common. The SED/ETH team has focused on the real-time double difference relocations and a weekly updated multi-event re-located catalogue, allowing high precision solutions for any sequence. Another key feature of this network is the longevity of the stations - many of the broadband stations date back over 20 years. The available waveform archive also includes all digitised triggered earthquake records from short period stations dating back as early as 1976, and strong motion stations dating back to 1992. Today, the NFO Valais seismic stations are all optimised for extreme low-latency data and contribute to the the emerging early warning infrastructure in Switzerland [Massin et al, 2021].

2.6 The Vrancea Observatory

Vrancea area, located within the bend region of the Carpathian orogen and characterised by compressional tectonic, is one of the most active seismic zones with intermediate depth earthquakes in Europe. Vrancea seismic zone consists of both intermediate and crustal depth earthquakes (30-180 km) with the shallower ones (depth <50 km) usually generating moderate events ($M_W \leq 5.5$), while the deepest (70-180 km) reaching M_W 7.0.

Vrancea is an observatory composed by state of art networks of multidisciplinary sensors whose backbone consists of seismic stations together with both infrasound and seismic arrays. All seismic stations are equipped with both short period/broadband and strong motion sensors and are located at the surface or within shallow boreholes. While the infrasound arrays are of course located at surface. Then, GNSS antennas, radon monitoring system, meteorological stations, electromagnetic stations and atmospheric ionization monitoring systems complement the infrastructure [Mărmureanu et al., 2021; Toader et al., 2021]

Such a high-resolution multidisciplinary monitoring and research infrastructure consents the availability of a large variety of data to better understand the possible extension at depth of the signature of active tectonic processes.

However, although deep, the major seismic events occurring in Vrancea are not only felt in a very large area but generate massive damage [earthquake intensities up to IX recorded in Bucharest for 1977 Mw 7.4 event, Mărmureanu et al., 2011]. And it is for this reason that starting from 2012 National Institute for Earth Physics designed the NFO seismic network in Vrancea area to be fully operational for an efficient Early Warning System

(EWS). The seismic infrastructure is (spatially and technically) tailored to detect and locate strong and intermediate depth earthquakes.

EWS main target it is represented by Bucharest capital city hosting almost 2 millions of people. Until now the existing EWS issued more than 50 successful alerts, all with a leading time larger than 25 seconds, to ~450 legal authorities going from emergency response agencies, via SMS gateway. 16 additional dedicated EWS receivers are located in between Romania and Bulgaria at various governmental agencies, including a nuclear-powered research institute in Bucharest and Vidraru Dam. The alerts are also sent to nuclear power plants "Kozloduy" in Bulgaria and Cernavoda [Mărmureanu et al., 2021]. Having the NFO community the leadership in EWS services, furnishes the great opportunity to continuously test and update innovative schemes and benchmarking systems such as the communication freely to users through social platforms, currently counting in Romani ~14000 users.

3. FRIDGE: the NFO Federated Data Gateway

NFOs contribute to the EPOS enterprise by delivering (long) time-series of multidisciplinary and high-resolution raw data collected near active faults and derived cutting-edge scientific products (named high level data products in the EPOS taxonomy).

For raw data (and station information) repository and distribution, the community benefits as much as possible of the existing services. This is the case of the seismological and geodetic community already possessing format and metadata recognised as standard by the community. Thus, these data are delivered and distributed through the existing European nodes organised and managed by the respective thematic communities.

In the last years, all NFO seismological (velocimetric and accelerometric) data from both permanent and temporary (during experiment) stations, have been converted into the standards decided by the seismological community and together with the stations (and metadata) information have been moved to the closest European Integrated Data Archive (EIDA) node ready to be distributed [Strollo et al., 2021]. In order to facilitate the NFO data identification, discovery and download, together with the Seismology TCS, we created the NFO Virtual Networks (VN), allowing the user an easier and more comprehensive way to discover and download the data. Now, all the 6 NFOs have a VN code identifying the infrastructure.

The same concept is being developed for the geodetic data, working in close collaboration with the GNSS TCS. The community is currently inserting/uploading the NFO GNSS station information (and metadata) into the nodes of the newly implemented GLASS open-source platform.

Since the NFO also provide additional data and products that are not provided by other TCS, these NFO Specific Data, defined as raw data and high-level data products originally not having a standard (e.g., format, unit of measurements, metadata), the NFO community built a dedicated portal named FRIDGE, standing for Federated Specific Data Gateway (http://fridge.ingv.it).

NFO Specific Data are the continuous raw geochemical data (e.g., radon counts, CO_2 flux time series), with associated meteorological parameters. High level data products cover diverse disciplines characterizing the NFOs, such as seismology (e.g., vp/vs time series, various generation and typology of earthquake catalogues, velocity and attenuation models, historical earthquakes), geodesy (e.g., strain-rate time series) and geology (e.g., fault inventories, geological maps). Thus, the process of distributing NFO specific data and products included not only planning FRIDGE from the computer science perspective but also the identification of new standards. An example of this activity comes from the work we carried out and/or currently undergoing, together with the volcanological and seismological communities (always within the specific harmonization groups), in order to standardise geochemical data and seismological data products, respectively.

FRIDGE is then a unique and coordinated access for NFO Specific Data pointed by both the EPOS-ICS-C platform and services as well as by the indigenous users. From a technical point of view, FRIDGE has been thought as a federator exposing HTTP API for discovering and querying all the available NFO datasets and combining replies for the user (ICS-C or anybody) as well as for hosting a Virtual Laboratory, an engagement and knowledge sharing instrument (see Figure 3). The federator is implemented in a modular way through Tornado Framework, a python web server composed by a main module and different plugins for each web service implemented by the single NFOs. This allows an easy development of new future services while reducing its maintenance. The federator exposes a set of APIs, through which it is possible to query the web services asking for the data provided by the NFOs. When a user performs a request based on geographical coordinates, the federator addresses and

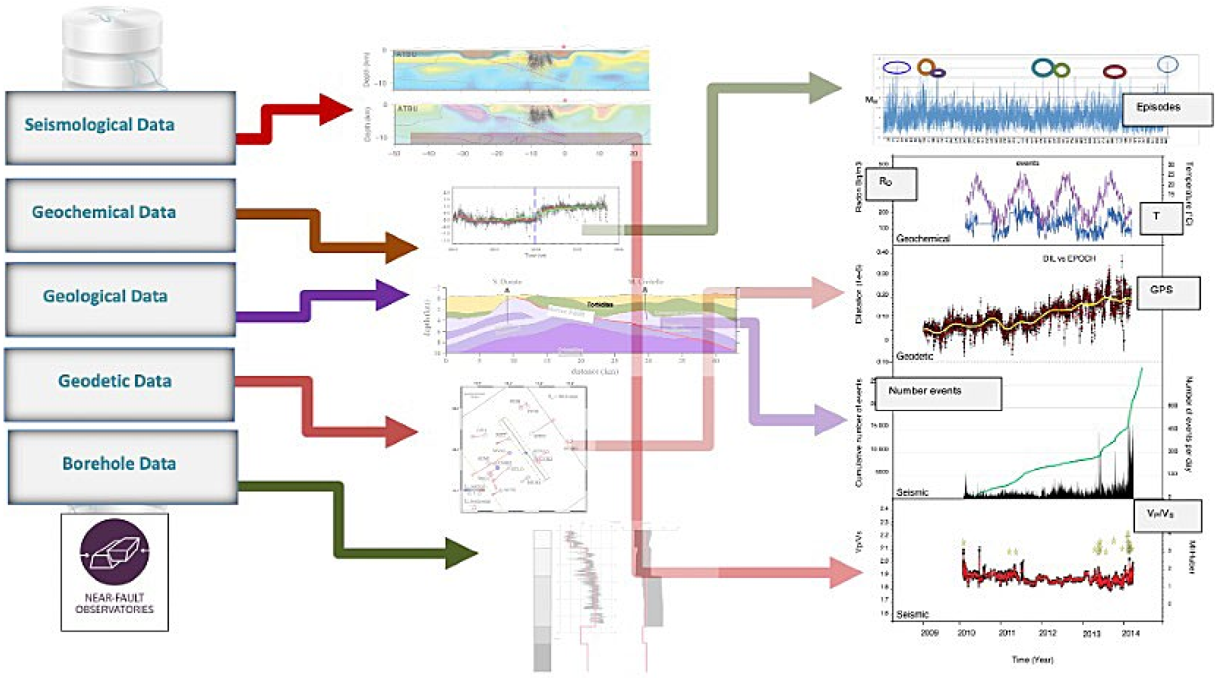

Figure 3. Design of the Virtual Laboratory in FRIDGE aimed at visualization and combination of multidisciplinary data and products, which are available at the FRIDGE portal.

redirects it to the corresponding NFO. The federator exposes their APIs also to the Fridge web portal that offers an alternative graphical user interface (GUI) to search and download data and data products, and view time series and graphical maps.

The availability of such a diverse kind of time series gives to the scientific stakeholders the novel opportunity to start looking together at interdisciplinary data and derived scientific products collected in the same area and at the same time. These actions, opening to the possibility of connecting different observations to the same phenomena, can also give the rise to a new generation of scientists capable right from the beginning to consider multidisciplinary data.

4. CREW

Consisting of dense, modern and low-latency infrastructures, the NFOs are also ideal sites to process real-time data, making them test-beds for experimenting Earthquake Early Warning (EEW) systems. EEW systems can be used to activate security actions and mitigate the seismic risk during an occurring earthquake. In this context, the community has developed the platform CREW - EU Testing Centre Early Warning & Source Characterization - to test state-of-the-art systems, software and platforms, to provide a fair comparison of methodologies, based on community-based performance criteria, providing a complete report of the results.

From a technical point of view, CREW (Figure 4) is structured in virtual machines, such that each system can be fully configured and customized according to its architecture by the relevant experts during the initial set-up and tuning phase that precedes the formal testing. This includes the installation and tuning of the Operating System and the installation of support tools that might be needed to achieve its full potential.

Today, CREW compares the EEW software PRESTo [Satriano et al., 2011] and VS - Virtual Seismologist [Behr et al., 2016], on the real time data streaming from ISNet [Festa et al., 2021]. Each virtual guest has been assigned the same amount of (virtual) hardware resources, so that its final performances will only depend on the EEW software algorithms and configuration, given the availability of the same set of recorded waveform data in a timely fashion.

Inputs and outputs to each EEW system are provided in a standardized and widely accessible format. Each EEW systems, receive data in an identical manner from the SeedLink server and produce real-time alarm messages in case of earthquake detection. A new alarm is issued every time the estimate of a relevant earthquake source

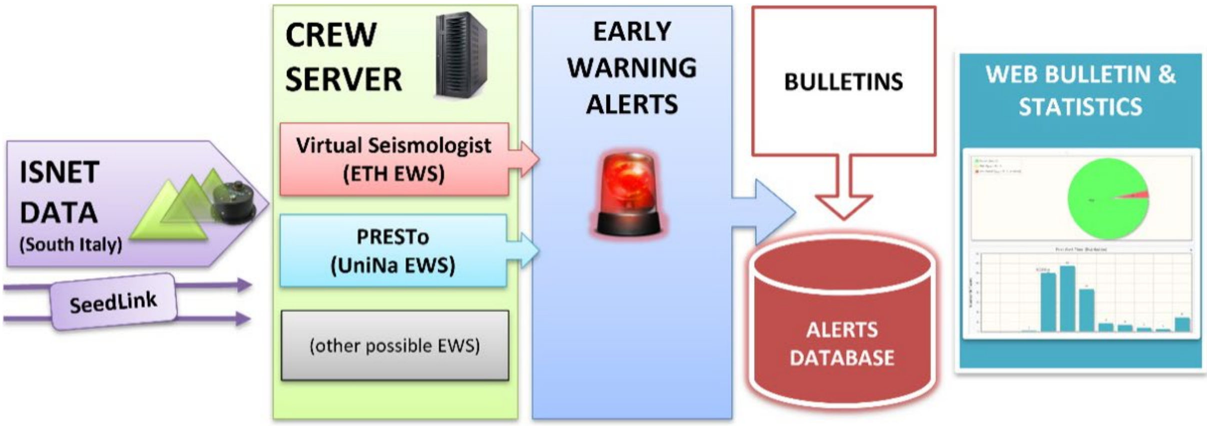

Figure 4. The CREW workflow and infrastructure. Real-time data flow in the server where software runs on different virtual machines to define alerts, that will be compared with authoritative bulletins.

parameter produced by the system is changed (e.g., earthquake location, magnitude) or when a new data input is included in the evaluation (a new P- or S-wave arrival time). The Testing Centre server hosts the QFeed2 software from ETH (written in Java), which retrieves the seismic bulletins for the Irpinia region, namely the authoritative one from INGV (http://terremoti.ingv.it/) and the bulletin published by INFO (http://isnet-bulletin.fisica.unina.it/cgi-bin/isnet-events/isnet.cgi). The latter might be more complete in terms of lower magnitudes for events well located within the network. The earthquake information from the bulletins is parsed and inserted in a PostgreSQL database, which forms the authoritative source of real earthquakes and source parameters. This event database is also updated when the external agencies revise some of their published information.

Finally, a GUI (http://lccepos.fisica.unina.it) has been implemented that consists of a web application that can list the alarm messages from each system as compared to reference seismic bulletins, plot them on a map and provide statistics about the quality and speed of the outputs of each system.

Scientists can access to CREW for testing new EEW software or some parts, to compare against state-of-the-art software, through the direct plugin of their modules and the control of parametrization. Also, a user can evaluate the performance of existing, state-of-the-art software on their own data, finely tune the system parameters and design tailored decision modules. Access to CREW may be granted as Transnational Access [TNA; Wessels et al., 2022].

Beyond scientists, additional stakeholders can be public agencies representatives, and private companies. Within testing EEW in CREW, stakeholders can design and evaluate the performances of software to be interfaced with actuators for end-to-end EEW applications: this will include target-oriented software and output combination and a direct connection of this output to appropriate decision modules, for risk mitigation actions specific to the site to protect. The CREW will also act as a flywheel for the NFO, EEW and earthquake source communities, allowing to share know-how and high-quality data with a broad population of researchers, favouring indeed their enlargement and interaction, and to promote leading-edge science and technology. Finally, the CREW may become a proof-of-concept of testing facilities that can be exported to other scientific environments and topics.

5. Future perspectives of the European NFOs

The understanding of the slow and fast deformation within the Earth crust associated with fault slip is one of the major challenges in Earth sciences. The European NFOs plan to integrate state-of-art field observations with novel instruments, such as borehole seismometers and strain meters, fibre optic cables, dense geodetic and geochemical networks, monitoring several parameters. The resulting data, distributed to the scientific community, will be complemented with geologic studies of fault zone structure, analytical methods and laboratory experiments, to illuminate the geophysical processes at very different scales.

The NFO challenge is the achievement of a new expertise able to process and integrate multidisciplinary data and place them in the puzzle of earthquake mechanics, based on state-of-the-art tools (e.g., Artificial Intelligence).

This opening is a great opportunity to train a new generation of scientists with the know-how of modelling and interpreting long time series of high-resolution multidisciplinary observations attributable to the same underlying natural phenomena.

NFOs are also ideal sites for meeting the growing expectations of the learning and communication sectors by hosting a large variety of scientific information about earthquakes as a natural phenomenon and a societal issue. At the same time, by working on the improvement of predictive models for future large earthquakes, based on multi-parameter monitoring of diverse types of transients, NFOs contribute to better configure the next generation of the monitoring systems and to provide interpretation and communication models for the authorities and public both before and during the occurrence of a large event. Within this context, disaster managers and related scientific disseminators are among the main stakeholders. Improved monitoring of active faults posing high hazard to society, as well as progress in the knowledge of seismic faulting, including inspection of different signals, will enhance our common capabilities to face and assess seismic hazard at different spatial and temporal scales. In this perspective, a new generation of near-real time tools and triggering alarms at different levels can be tested and developed, strengthening the cooperation with the Agencies for risk management. A series of various actions like meetings of experts, simulated operations, including educational experiences for the population, can also be tested.

However, the processing of continuous and large data flow is expected to progress with time, in particular for the multi-sensor correlation analysis. These tools will evolve with the improved models of transient processes in/around fault zones. NFO can provide the finest context to exploit this expertise and testing. The NFOs are expected to become ideal sites for hosting state-of-the-art experiments for testing in situ both new scientific ideas/models and new geophysical instruments or arrays. A NFO would provide the proper environment in terms of reference instrumentation, data and infrastructures facilities. The accessibility of NFOs databases allows for rapidly evaluating and selecting the most appropriate site for the instrument or software testing and/or new scientific hypotheses validation. This will achieve synergies in research, monitoring and tools (e.g., automatic analysis) by sharing technological best practice for implementation (e.g., boreholes instrumentation for multi-sensor stations) and technological issues regarding instrumentation and software.

The NFOs are also the natural sites for scientific drilling experiments, as testified by the fact that several sites have already been declared of interest for ICDP and IODP.

ICDP and IODP have been already involved in drilling the rift of Corinth. The AIG10 borehole of about 1000 m provided cores of the Aigion fault, an active normal fault placed at the centre of CRL-NFO, within the Deep Geodynamic Laboratory (DG-LAB project; Cornet and Vardoulakis, ICDP proposal 2003). The objective of the project was a better understanding of the physics of faulting in an extensional tectonic regime, with special attention to interactions between fluids and faulting.

The Gulf of Corinth was also the site of an IODP project dedicated to the seismic sounding and deep sediment coring in the central part of the gulf [McNeill et al., 2018].

ICDP is instead currently involved in (e.g. STAR, standing for A Strainmeter Array Along the Alto Tiberina Fault System, Central Italy project in TABOO-NFO area; https://www.icdp-online.org/projects/world/europe/northern-apennines-italy/). STAR is an ongoing project led by INGV in collaboration with UNAVCO US agency, finalised to the instrumentation with strain- and seismometers of six 80-160 m deep vertical boreholes surrounding the creeping portion of the ATF. Each station, named "*small observatory*", is also equipped with surface GPS, meteorological instruments, and fibre optic cables (see Figure 5).

The suite of instruments will enable the collection and calibration of strain records with exquisitely high precision, allowing for a quantitative characterization of ATF creep (~1 mm over <1 km^2), enhanced monitoring of microseismicity (below Mc 0.5), and allowing correlation between degassing (CO_2, Rn) measurements and subsurface strain. Importantly, the spatiotemporal characteristics of creep on the ATF bear directly on the relationship between seismic and aseismic processes, including possible stress triggering of large earthquakes by transient creep events, an issue of global importance in the seismic hazards' community.

This TCS will experience for the first time the technological integration of multidisciplinary observing systems in diverse tectonic environments. Shared technical basis, as well as strengthened cooperation between institutions, will foster exchange of scientific analysis techniques (both strategies and implementations) and will help to lower costs of new scientific achievements. The need for a continuous upgrade in the technological quality and density of multi-parameter monitoring systems clearly represents a big opportunity of growing market for the European industrial sector for new technologies. At the NFOs a new generation of multidisciplinary experiments

Figure 5. TSM2 *observatory site*: a single site hosting strain- and seismo-meters within a 160 m deep borehole, roundtrip fibre optic cable and pore pressure gouge within a pipe installed within the same hole. At the well head, covered by the small brick cottage (on the left), is visible the GNSS antenna, while in the centre of the picture there is the aluminium cover to protect the sensor pocket installed on the surface. On the right, the wood hose hosting the acquisition and satellite transmission system with Meteo antennas on the roof. The power system composed by a set of solar panels are placed in the front of the house.

can be established, testing multi-sensor stations, as well as fast and light transmission systems for temporary densification of monitoring instruments. This environment will allow the NFO community to develop strong synergies also with small medium enterprises able to construct state of art sensor prototypes that can be tested in a controlled environment with a large number of external constraints deriving from dense permanent networks.

Thus, NFOs are entirely qualified as a network for transnational Education and Training. Common portals with a large choice of training possibilities may highlight the large variety of the instrumental, scientific and natural contexts offered by the NFOs. The NFO community will provide many opportunities for scientific and technical training as well as public outreach, at different levels: general education of public on hazard and natural seismic and tectonic processes, higher education (summer schools, masters and postgraduate research) on advanced instrumentation techniques and multi-parameter analysis of crustal processes.

For these reasons, we expect the implementation of many Near Fault infrastructures in the coming years, focused on the physics of tectonic faulting and able to generate data and scientific products interrogating a broad spectrum of fault slip behaviour [Peng and Gomberg, 2010]; key ingredient for the next generation of scientists finally able to embrace a real multidisciplinary investigating approach.

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