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D23.4 Testbed validation of tools and resulting high level products: software toolbox, validation methodologies, demonstration report

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Introduction

The objective of the WP23 was to develop and test new methodologies and tools for better resolving the mechanical processes at work underlying the dynamics of the seismicity and the preparation of large earthquakes. The project also aimed at providing automatic, real-time processing softwares to track these processes in real-time, usable by seismic agencies and geo-industries.

Several test beds have been selected, for providing high quality data from dense, multiparameter networks, for natural seismic crisis, episodes of induced seismicity, and controlled experiments in deep underground laboratories.

The present deliverable D23.4 presents a short summary of the work achieved on these test-beds for the validation of tools and methodologies. It is built on the tools presented in deliverable D23.1 and D23.2, and on new approaches as illustrated in deliverable D23.3. The work involved all partners of WP23: INGV, GFZ, CNRS, ETH, IGPAS, and UNINA.

The main test-beds are the following:

Natural seismicity:

- The Alto-Tiberina Near Fault Observatory (TABOO), Italy
- The Central Appenines seismic sequence of 2016-2017, Italy
- North Anatolian fault system, Western Turkey
- The Corinth Rift Near Fault Observatory (CRL), Greece
- The northern Chile IPOC observatory
- The Nankai subduction, Japan

Underground deep laboratory:

- The Grimsel test site, Switzerland

Induced seismicity

- The Geysers geothermal field, USA
- The Garpenberg deep mine, Sweden
- The Rudna mine, Poland
- The hydrofacturation field Wysen, Poland

Several tools have been applied to the high quality near-faut seismic data sets from these test beds, among which those listed in D23.1&2:

- Back-Track BB (CNRS), an automated back projection method for detection and location of events, applied to the seismicity for the Alto Tiberina fault, the Chilean subduction, and to the Garpenberg Mine test beds

- PyMPa (INGV) , an automated software for template matching and construction of families of similar events, applied to the Alto Tiberina fault, the central Appenine sequence, the Rudna mine, and the Wysen experiment.

- SPAR (UNINA), a spectral inversion software for getting the basic earthquake source parameters, applied on the Alto Tiberina fault, the Central Appenines, and the Nankai subduction.

- Statistical tools boxes (IGPAS) for an analysis of advanced forms of clustering and of magnitude complexities, applied to several induced seismicity test beds, including the Rudna mine.

- MSATSI/Hybrid-MT (GFZ), softwares for inversion of moment tensor of sources and tectonics stresses of seismic zones, applied to the Geysers and the Marmara region.

In addition, advanced methodologies have been tested and further developed on the seismic data from some of these test-beds, for a better inference and understanding of the hidden physical processes forcing the seismicity and controlling its dynamics. Each of the basic transient forcing processes, namely: **pore pressure changes and diffusion, slow slip events, earthquake cascade,** and **blasts and caving (in mines),** have been found in one or several test beds, allowing for a more comprehensive analysis of the dynamic process and the related seismic hazard.

The main test beds, the studied triggering processes and related triggered seismicity, and the new tools, are summarized in the Table 1.

TEST BEDS	Transient forcing by				Triggering of		
Naturalseismicity	**pore pressure**	**slow slip**	**EQ cascade**	**blasts & caving**	**seismic swarm**	**Main- -shock**	**New Tools**
Alto Tiberina Fault		■	■		■		PyMPa, SPAR,BTBB
Central Appenines			■		■	■	PyMPa, SPAR
Corinth rift	■	■	■		■		
Marmara NAFault		■	■		■	■	MSATSI
Chili subduction		■	■		■	■	BTBB
Japan subduction	■	■					BTBB, SPAR
Undeground Experiment							
Grimsel/Bedretto	■	■			■	■	
Induced seismicity							
Garpenberg mine		■		■	■		BTBB
Rudna mine			■	■		■	PyMPa, BTBB
Hydrofrac Wysin	■				■		PyMPa
Geysers	■				■		MSATSI

New tools and methodologies :

- **source detection : template matching - PyMPa**
- **source spectra : bayesian spectral inversion - SPAR**
- **source location : real time back-projection - BTBB**
- **moment tensor and stresses inversion: MSATSI/HybridMT**
- **statistics of seismicity : Magnitude complexity, Clustering,TE2D transforms, ...**

Table 1

Natural seismicity:

The Alto-Tiberina Near Fault Observatory (TABOO), Italy (INGV)

The Alto-Tiberina Near Fault Observatory (TABOO) is a research infrastructure monitoring with cutting edge multidisciplinary networks an active normal fault system located in the Northern Apennines. In the past five years TABOO seismic network collected more than 50,000 small magnitude earthquakes, now available to investigate slow-fast deformation processes.

The Altotiberina fault (ATF) is an extensional low-angle dipping fault (15-20°) that accommodates crustal extension. The ATF mechanical behaviour and seismogenic potential are still enigmatic. Within SERA, a template matching technique (PyMPA) has been developped by INGV to augment the available catalogue along the ATF between 2010 and 2014. Detections are increased by a factor 5 diminishing by about 1 degree the completeness magnitude. This greater detail allows to better highlight creeping at variable intermittent rates and interactions with shallow, moderate seismic sequences in the ATF hanging wall. A better characterization of seismic sequences in terms of clusters (swarm-like or typical mainshock-aftershock) allows to define aseismic-seismic transients and an active role of ATF in loading the faults at shallower depths (Brondi et al., 2019; Chiaraluce et al., 2019).

The fault parameters of the sources in the hanging wall, above the ATF; were investigated with the probabilistic spectral inversion code SPAR developed by UNINA in order to evaluate the value and variability of the stress drops, and of the related source dimensions through the determination of the corner frequency. The preliminary result points to an unusual corner frequency scaling with seismic moment, it being almost constant around 10 Hz. It is believed that this might be a bias from the initial assumption of a too simple attenuation model with a constant quality factor Q. A strong, frequency dependent anelastic attenuation might explain this anomaly, keeping valid the constant stress drop scaling. This additional parametrization is presently been implemented in the inversion code.

The Central Appenines seismic sequence 2016-2017, Italy (UNINA)

The destructive seismic sequences of 2016-2017 in the Central Appenines provided a large number of high quality records of moderate earthquakes, with tens of events above magnitude 4. This provided the opportunity to test and apply the spectral inversion code SPAR in order to evaluate the value and variability of stress drops, and the of the related source dimensions through the corner frequency (Supino et al., 2019). The results points to a rather classical and regular scaling, with a constant stress drop independent of magnitude. The average stress drop is $\Delta\sigma$=2.7 ± 0.4 MPa. The largest events show a stress drop on the high value side, with $\Delta\sigma$ = 7 ± 3 MPa for the main event.

Strain transients and precursory seismicity in western Turkey (GFZ)

Precursory sesmicity of the 2019 M=5.8 earthquake on the North Anatolian Fault, Marmara

The spatio-temporal evolution of seismicity is analyzed during a sequence of moderate (a Mw4.7 foreshock and Mw5.8 mainshock) earthquakes occurring in September 2019, at the transition between a creeping and a locked segment of the North Anatolian Fault in the central Sea of Marmara, NW Turkey (Durand et al., submitted) . To investigate in detail the seismicity evolution, a matched-filter technique is applied to continuous waveforms, thus reducing the magnitude threshold for detection. Sequences of foreshocks preceding the two largest events are clearly seen, exhibiting two different behaviors: a long-term activation of the seismicity along the entire fault segment and a short-term concentration around the epicenters of the large events. This suggests a two-scale preparation phase, with aseismic slip preparing the mainshock final rupture a few days before, and a cascade mechanism leading to the nucleation of the mainshock. Thus this study shows a combination of seismic and aseismic slip during the foreshock sequence changing the strength of the fault, bringing it closer to failure.

A large Slow Slip Event detected on a Borehole Strainmeter Offshore Istanbul

The GONAF borehole straimeter is installed close to the Armutlu fault, 40 km SSE from Istanbul. In 2016, it has recorded clear differential and engineering strain signals, lasting for 50 days (Martínez-Garzón, P. et al., 2019). These signals have an amplitude of several microstrain (amongst the largest ever recorded). They correlate in time with the larger (M>3.5) local earthquakes and reflects a 20° rotation of the horizontal strain tensor. Before and after a 16 months back-rotation, the orientation of maximum horizontal strain is sub-parallel with the local trend of SHMAX. The strain signal is of tectonic origin, and likely originates from aseismic deformation in direct vicinity of the strainmeter, probably along the Armutlu fault somewhere within the seismogenic layer or at its lower base.

The Corinth Rift Near Fault Observatory (CRL), Greece (CNRS)

The Near Fault Observatory (NFO) of Corinth is operational since 2000, focused on the normal fault systems of the western part of the rift (Corinth Rift Laboratory, CRL, www.crlab.eu). It presents the highest microseismicity and strain rate of the euro-mediterranean area, with a rift opening rate of 1.5 cm/year, and several M6-6.5 earthquakes per century. The double-difference relocation of 205,000 events and the construction of a catalogue of earthquake multiplets has brought a refined image of the fault geometries, and revealed the space-time evolution of the microseismicity, which allows to infer the forcing mechanisms, as already detailed in deliverable D23.3 (Duverger et al., 2018)

Regular multiplets, identified as repeaters, are located at the root of the low dip normal faults, providing evidence for steady creep loading the fault system. Irregular multiplets, identified as interacting asperities, are located at the root of the outcropping, high dip angle normal faults. At these depths, one observes migration of seismicity during many of the frequent seismic swarms, with two different velocities, implying two different forcing mechanical processes: fast migration, above 1 km/day, associated to diffusion of creep on fault surfaces; and slow migration, 1 to 100 m/day, due to pore pressure diffusion. Evidence for sequential activation of the same fault with slow then fast migration reveals and strong coupling between both processes. This coupling is likely to be based on the same hydromechanics principle as what is the basis of hydroshear experiments, as done in geothermal production.

Finally, the structure and dynamics revealed by these various seismic analysis led to the identification of the main, large locked fault segments of the western rift of Corinth, some located on outcropping high dip normal faults, others on blind, low dip normal faults. These locked segments are mainly identified as fault areas with low microseismicity, surrounded by clusters with high seismicity. The seismic potential of these asperities is estimated to be with earthquake magnitudes 6 to 6.5.

The northern Chile IPOC observatory

(CNRS)

The 2014 Iquique seismic crisis in Chile has culminated with a Mw 8.1 earthquake on April 1st, showing a complex unlocking process of the North Chile subduction interface (Aden-Antoniow et al., in revision). During the year preceding this event, at least three clusters of seismic activity were observed: in July 2013 and January and March 2014. Recent studies have proposed large-scale slab deformation as a potential trigger for the megathrust earthquake, and these clusters would have indicated aseismic slip transients accompanying the progressive destabilization of the interplate contact. However, no evidence of gradual unlocking of the interface or transient deformation has yet been found in the rate. To address this question, a dense earthquake catalog is constructed for the fifteen months preceding the mainshock, running the Back-TrackBB detection and location code on the continuous waveforms from the Integrated Plate Boundary Observatory Chile (IPOC) and the Iquique Local Network (ILN) networks. After declustering the seismicity, a space-time statistical analysis highlights a large-scale acceleration of the seismicity along the interface accompanied by a deceleration of intermediate-depth earthquakes. We also provide evidence for the existence of a seismic quiescence down-dip of the mainshock rupture before the July 2013 cluster. This seismic sequence may be related to fluid circulation and/or to aseismic motion along the main fault(s).

The Nankai subduction, Japan

(UNINA)

A catalogue of more that 10,000 Low Frequency earthquakes (LFE), detected and located by the BTBB code in the Nankai subduction zone (Japan) (period 2012-2016), has been used for investigating the mode of rupture of these yet poorly know seismic sources, and for inferring the mechanical conditions prevailing at their hypocenters, on the interplate contact, or close to it.

The spectral inversion code SPAR has been applied to the LFE waveforms, which allowed to provide evidence for a simple corner frequency scaling with constant stress drop (Supino et al., 2020). The latter however present a very low value, possibly 10 to 100 kPa, considering the additional information from the observed tidal modulation of their distribution, which leads to very slow rupture velocities, 5 to 20% of the S velocity. This low stress drop is classically interpreted as due to nearly lithostatic pore pressure.

SPAR also provided the decay exponent of the high frequency power law of the spectra: instead of a value of 2 as for the standard w-square earthquake source, its value is close to 3, thus showing a much stronger decay of energy radiated at high frequency. This new result suggests very smooth rupture dynamics and arrest, which would result from specific friction laws prevailing at the transition zone between brittle and ductile environment on the subduction interface.

Underground deep laboratory :

The Grimsel and Bedretto test site, Switzerland

(ETH)

The fault stimulation experiment conducted in the Deep Underground Laboratory in the Grimsel Test Site (GTS operated by NAGRA, experiment lead ETH) is the largest (30m scale) and best monitored (hundreds of multi-parameter sensors embedded in the rock volume) stimulation experiment so far, conducted at 500m depth in hot rock on three intersecting faults. The few hydroshear and hydrofracturation experiments have led to the location of more than 5000 microearthquakes, with magnitude ranging from -6 to -2.5, in a distance range up to 50 m from the boreholes. (Amman et al., 2018; Gischig et al., 2020; Gischig et al., 2018; Hertrich et al., 2019; Krietsch et al., in review, 2020; Jalali et al., 2018; Villiger et al., 2019)

The hydroshear experiments have produced seismicity generally constrained to the target shear zones, with more seismic events in shear zones with higher transmissivity. Depending on the stimulation, the seismicity may appear clustered, or, to the contrary, evenly distributed.

The hydrofracturing experiments induce a seismicity which preferentially propagates downwards, with an initial fracture orientation at the wellbore according to stress field orientation, and later evolving according to its interaction with the preexisting geological structures.

Induced seismicity :

The Garpenberg deep mine, Sweden

(CNRS)

The BTBB code was adapted for an improved detection and location of microseismic events in the context of mining, using continuous seismic records from an underground, in mine seismic network. The challenge was to locate and characterize the seismic sources under the constraints of high sampling rate, variable source types (micro-earthquakes, collapses/rock bursts), and large anthropic noise, through a near-real-time monitoring scheme.

The method consists of two steps: (1), event extraction from amplitude criteria (STA/LTA or Kurtosis) at several stations, and preliminary location based on amplitude ratio between stations; and (2), event relocation using the BTBB back-projection code. The event extraction, based on multiband signal characterization implemented in the first step, allows to overcome the challenge of high sampling rate data (8 kHz), reducing the volume of transferred data and providing an energy-based signal classification scheme. This allows to remove a significant number of machinery noise sources. The technique is developed and tested with INERIS on the case study in the Garpenberg mine of Boliden (Sweden), monitored by a local seismic network maintained by INERIS (Palgunadi et al., 2019). This leads to an improvement in event detection capacity by a factor of 50, compared with the standard triggered-based monitoring schemes. This increased number of detected microseismic events allows to investigate the migration pattern of induced microseismicity that is generated in response to production blast. In particular, in addition to the immediate vicinity of the blasted rock volume, a secondary activation zone has been identifid, at the edge of the present mine works. It reveals a the existence of a weak zone of soft rocks and/or unstable faults, which may present transient creep as suggested by the identification of seismic repeaters.

The Rudna mine and the hydrofacturation field of Wysen, Poland (IGPAS, CNRS)

The induced seismicity through the mining activities in the deep Rudna copper mine, SW Poland, was investigated. The mine is known for the occurrence of intermediate magnitude events of up to M4 causing considerable damages and even fatalities. The matching phase algorithm PyMPA has been applied to the triggered records of the Lumineos surface array., which allowed to retrieve new events. When applied to the records of the Wysen array (hydrofacturations experiments), PyMPA showed a good efficiency but no new event s were recorded.

The BTBB detection and location code was used to analyse the waveforms from 5 days of major mine collapses occurrences. Up to 10,000 events per day were detected. These events resulted from mining activity and machinery noise, blasting activity, and induced and triggered seismicity. The spatial distribution of additionally detected and located events line out the major features of the mine like the main production area, large galleries, vertical structures which are suggested to reflect shafts or faults. Daily histograms show a major influence of blasting activity on the number of events, and large mine collapses influence the maximum number of events, with aftershock-type sequences.

Tool-Boxes

- Statistical Toolboxes (IGPAS) , with codes, sample data, and documentation, can be found at: https://git.plgrid.pl/ projects/EA/repos/sera-applications/browse

- The **BackTrackBB (CNRS)** code for full-waveform detection and location software used in the analysis is available from Git-Hub :

http://backtrackbb.github.io on open-sourcebasis

- PyMPA (INGV) code is freely available at https://github.com/avuan/PyMPA37

- SPAR (UNINA) code is still at the status of a beta version. Some work is needed on the structure for an open version which should be available on git hub repository after summer 2020.

- HybridMT (GFZ) software can be downloaded at the project website:

https://www.induced.pl/software/hybridmt. The documentation is at the link:

https://www.induced.pl/download/hybridmt-manual?wpdmdl=2769&refresh=5caaecbf1ed0a1554705599

Discussion and Conclusions

The tools and methodologies developed in WP23 have been successfully tested and qualified in various tests bed, dealing with natural seismicity in various tectonic contexts, as well as with induced seismicity in mines, in geothermal fields, and in a large underground experiment. They provide fast – and for some, real-time - determination of earthquake parameters and of the dynamics of seismicity. These tools are open-source, and thus should help to significantly improve the monitoring of natural and induced seismic activity in other contexts.

In this perspective, they could be integrated in a future generation of "early" warning systems which would include information of transient deformation processes, like earthquake swarms or slow slip events. The latter indeed increase the probability of nucleation of the large earthquakes (being the main triggering factor, or a simple - but significant- detectable side-effect), so that warning or pre-alerts may be issued to the researchers for fast deployment of new instruments, refined studies of the records, integration of multiparametric data, and also possibly issued to the authorities for preparedness-related actions.

However, although these tools and methods provide accurate and quantitative estimate of earthquake and seismicity parameters, the knowledge of the latter do not allow yet to provide quantitative estimates on stress and pore pressure changes, nor on the strengths of fault systems, and hence prevents from any reliable prediction, in a probabilistic sense, of the evolution on the system. This was clearly illustrated with the well documented large-scale preparation phases of the Iquique 2014, M=8 earthquake, and of the 2017 Marmara, M=5.8 earthquake, which at the time intrigued seismologists and raised concerns on their possible significance for a large earthquake on the way or to be triggered.

What is presently missing, and could not be tackled in the WP23, is the quantification of these forcing processes in terms of stress change, to be integrated in a probabilistic forecast scheme like it is done for seismicity alone, with time-space-magnitude influence kernels and earthquake cascade processes. But the more systematic use of these tools, their further refinement and automatization, the future increase of number of observations of strain transients in many different contexts, and the development of realistic and site dependent hydro-mechanical models of fault systems, will allow to develop these probabilistic approaches for a transient increase of triggering capabilities, and to bridge the gap between the present rather fundamental observational studies of earthquake initiation, and more applied research for seismic hazard assessment and risk mitigation.

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