DESTRESS

Demonstration of soft stimulation treatments
of geothermal reservoirs

Deliverable D6.4: Environmental performance monitoring for validation and control

WP6 Intelligent tools controlling performance and environment

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Summary

This report entitled "***Best practices in environmental monitoring operations***", describes a set of practices and rules to follow during the environmental monitoring operations in order the safely exploit geothermal energy resources, with particular focus on Enhanced Geothermal Systems (EGS). In this document we first introduce the induced seismicity problem, which is the main concern of the local population living close to geothermal projects. We then elaborate in more detail different environmental monitoring strategies to ensure the safety of such industrial operations. It is important to note that the multidisciplinary aspect of this problem requires the study of a wide range of environmental parameters, including seismicity, ground-deformation and pore-pressure to cite a few. This technical report corresponds to the Deliverable 6.4 of the European ***Destress*** project and was developed within the framework of the WP6, "***Intelligent Tools controlling performance and environment***". The main contributors of this report are ETH (Switzerland), TNO (Netherlands) and ESG (ES-Geothermie).

Introduction

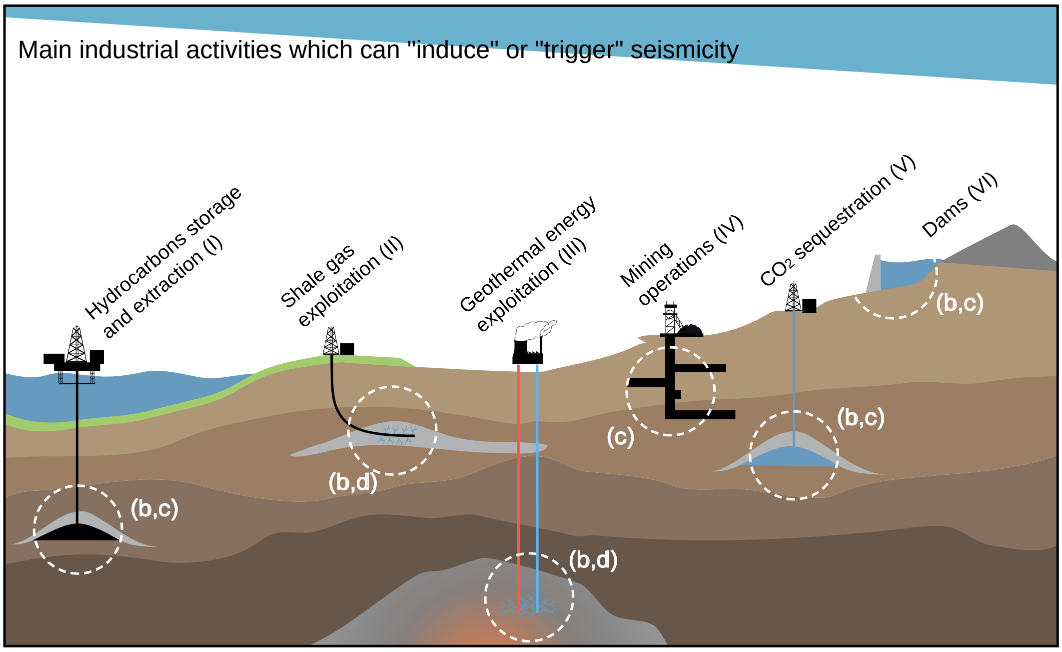
The rise of energy demand started in the recent past has led to a constant increase of underground industrial operations in densely populated regions. As a consequence, the amount of felt earthquakes linked to these activities also raised significantly [*Ellsworth* 2013]. The term "induced seismicity" generally refers to the earthquakes directly or indirectly generated by these human activities. Over the last decade this controversial topic has become more and more important and has opened strong debates at a scientific, political and societal level, especially owing to the concern that underground related industrial activities could cause damaging earthquakes [*Ellsworth* 2013]. As schematically represented in the box figure, Induced seismicity can be linked to different industrial operations, including: conventional and non-conventional hydrocarbon production, geothermal energy exploitation, mining, water impoundment, CO2 sequestration and natural gas storage operations [*Suckale* 2009, *McGarr et al.*, 2010, *Ellsworth* 2013, *Grigoli et al.,* 2017]. These activities can alter the stress field of the shallow Earth's crust by pore pressure changes, or volume and/or mass changes inducing or triggering seismicity [*Ellsworth* 2013], a nuisance or even danger to the local population that can strongly undermine societal acceptance of a project [*Trutnevyete and Wiemer*, 2017, *Grigoli et al.,* 2017, *Hirschberg et al.*, 2015. Induced earthquakes are globally distributed and in many reported cases they reached a significant magnitude (figure 1), damaged private and public buildings and, most important, put in danger the population. The last notable case is the Mw 5.5 November 2017 South Korea earthquake which severely injured about 70 people and caused extensive damage (~ 52 million US$) in and around the city of Pohang [*Grigoli et al.* 2018]. To date, this is the most devastating earthquake ever occurred in the Korean Peninsula since the last century, compounded by the fact that it was probably triggered by geothermal energy exploitation operations carried close to the epicentral area [*Grigoli et al.* 2018]. Also in Europe most of the geoengineering projects, including the exploitation new forms of renewable clean energy based on deep geothermal resources, are located (or planned) in urbanized areas, thus induced seismicity not only put in danger the local population living close to these industrial sites, but also strongly undermine the societal acceptance of these projects [Trutnevyete and Wiemer, 2017, Grigoli et al. 2017]. Large magnitude induced seismic events are a risk for the population and structures, as well as an obstacle for the development of new techniques for the exploitation of underground georesources. The problem of induced seismicity is particularly important for the future development of geothermal energy in Europe, in fact deep geothermal energy exploitation projects such as Basel (2006) [*Haering et al.*, 2009], St Gallen (2013) [*Diehl et al.,* 2017] and Pohang (2019) [*Grigoli et al* 2018*, Kim et al* 2018*, Lee et al* 2019] have been aborted due to the felt induced earthquakes they created and the increasing risk aversion of the general population. It is important to recall that, especially in the context of geothermal energy production, induced seismicity is, at the same time, an unwanted product of such industrial operations, but also the tool that makes these technologies possible since it is the required mechanism to increase the permeability of underground geological structures, enhancing reservoir performances. Furthermore, the analysis of induced microseismicity allows imaging of the spatial distribution of fractures within the reservoir, which is needed, not only to identify active faults that may trigger large induced seismic events, but also to identify regions with higher permeability, optimizing hydraulic stimulation operations and enhancing energy production [Fehler 2001; Zoback 2010]. Among the different parameters to monitor during geothermal energy exploitation activities seismicity, ground deformation and pore pressure are probably the most important ones, and the analysis of their spatio-temporal evolution is extremely important for ensure the safety and the efficiency of such operations.

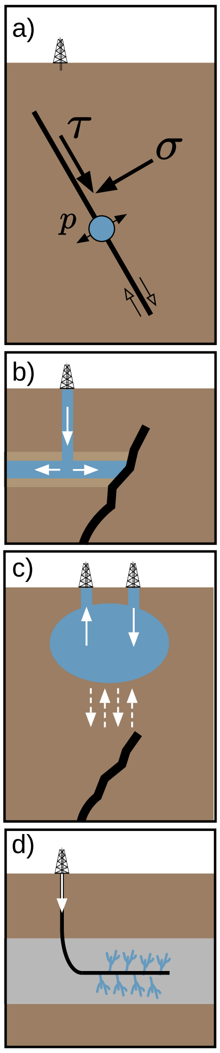
Seismicity monitoring operations aim to detect and locate earthquakes within a volume surrounding the industrial site, also with the purpose to discriminate natural seismicity from the induced one. The monitoring must allow to track the evolution of seismicity in the space-time-magnitude domain with the scope to modulate or interrupt the fluid injection/extraction operation to reduce the probability of occurrence of felt seismic events.

Ground deformation monitoring operations aim to identify possible surface deformation phenomena linked to subsurface fluid injection/extraction. Synthetic Radar Interferometry (InSAR) in combination with GPS measurements allow to measure and analyze the spatio-temporal evolution of the ground deformation which compared to the background conditions can be used to estimate the volume perturbed by the underground industrial operations.

Pore-pressure monitoring operations aim to measure the bottom hole pressure at the stimulation and production wells to verify the fluid-dynamic model of that part of subsurface interested by human activities and to quantify the enhancement of permeability during the stimulation operations.

BOX: Induced seismicity: Industrial activities and physical mechanisms





Induced and triggered seismicity has been observed in conjunction with several industrial activities such as: Hydrocarbon extraction and natural Gas storage operations (I), Shale Gas exploitation through the extensive use of hydrofracking techniques (II), Geothermal energy exploitaion (III), Mining operations (IV), CO2 sequestration (V) and Water impoundment (VI). All these industrial activities may alter the stress field of the shallow Earth's crust inducing or triggering earthquakes. This generally occurs when, according to Coulomb criterion, the shear stress acting on a fault plane exceeds a value τ defined as: $\tau=\tau_0+\mu(\sigma-p)$ (where τ_0 is the cohesion, μ the friction coefficient, σ the normal stress and p the pore pressure). Subfigure (a) illustrates the shear stress τ, the normal stress σ and the pore pressure p acting on a fault plane. Thus, when the shear stress acting on a fault increases or the strength of the fault is reduced by a decrease of the normal stress or an increase of pore pressure, failure can occur.

Earthquakes triggered by fluid injection operations (e.g. I, II, III, V) may be observed in presence of porous and permeable layers in contact with active faults (subfigure b). The pore pressure increase due to fluid injection reduces the effective normal stress acting on the pre-existing fault causing its failure. This process requires a high permeability pathway between the injection well and the fault.

In other cases industrial operation involving mass/volume changes (e.g. I, IV, V, VI) may alter the shear and/or normal stress acting on a fault facilitating (or inhibiting) the failure (subfigure c). In this case no hydrologic connection is required (Ellsworth 2013). Finally during hydraulic fracturing processes (subfigure d) induced seismicity is generated by the tensile cracks related to high pressure fluid injection in impermeable shale layers. The whole rupture process is in this case driven by the fluid injection and starts when the fluid pressure exceeds the minimum principal stress of the in situ stress field.

***Box**: Industrial activities which can "induce" or "trigger" seismicity (Grigoli et al. 2017)*

Monitoring of seismicity

Microseismic monitoring plays a key role in better understanding the physical mechanisms governing induced seismicity, but it is also the fundamental tool used by decision makers to decide whether to stop, decrease, or continue the industrial operations being monitored. High-density microseismic monitoring networks allow the detection of weak events (generally below magnitude 0), even in the presence of strong noise contamination. A consequence of the improved detection performance is a decrease in the magnitude of completeness and the generation of extremely large, sometimes massive, microseismic catalogs. For this reason, a high-quality monitoring network should be combined with noise robust, real-time and fully automated data analysis procedures, which are required to handle such large data sets and thus provide reliable results for interpretation [*Cesca and Grigoli*, 2015].

Well-designed microseismic monitoring networks are fundamental to improve the detection performance of weak seismic signals, to obtain accurate locations, magnitudes, and source parameters, both for natural and induced microseismicity. However, hypocentral locations, magnitude estimation, and source parameters based on national, regional, and microseismic networks using different processing tools often provide different results. Such discrepancies may cause severe concern in areas hosting industrial activities potentially inducing earthquakes. In several cases, the availability of multiple results from different institutes or applying different methods, the lack of information on the location and magnitude accuracy, or even the communication of mislocated events may lead to severe interpretation and communication problems. In this framework, the monitoring network setup and the performance of its processing system make an important difference, also toward the public communication of results. An illustrative example about this problem is given by the natural seismic sequence that occurred in Valdobbiadene (Northern Italy) on 12–15 May 2015, with two *M* 3.6–3.7 events and about 100 aftershocks.

The epicentral area of these earthquakes is very close to the natural gas storage reservoir of Collalto, which is being monitored by a dedicated microseismic network [*Priolo et al.*, 2015]. While the national network located only six events with uncertainties of few kilometers (http://iside.rm.ingv.it), the NE Italy regional network managed by the Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS) located about 90 events with uncertainties generally below 1 km. However, three earthquakes with *Ml* of about 1.0 were mislocated within the gas reservoir (Figure 1a). These three events were included in the regional seismicity bulletin available online (http://rts.crs.inogs.it). The use of the dedicated microseismic network allowed correct location of these three earthquakes to the sequence cluster at distances larger than 10 km from the reservoir (Figure 1b). This example shows that mislocated seismicity can lead to critical public communication problems. These challenges may arise in seismically active areas, where, in addition to the other problems associated with induced seismicity, the discrimination between natural and induced seismicity needs to be addressed. The lack of a good network raises several issues related to the interpretation of results, especially concerning the possibility to discriminate between induced and natural seismicity.

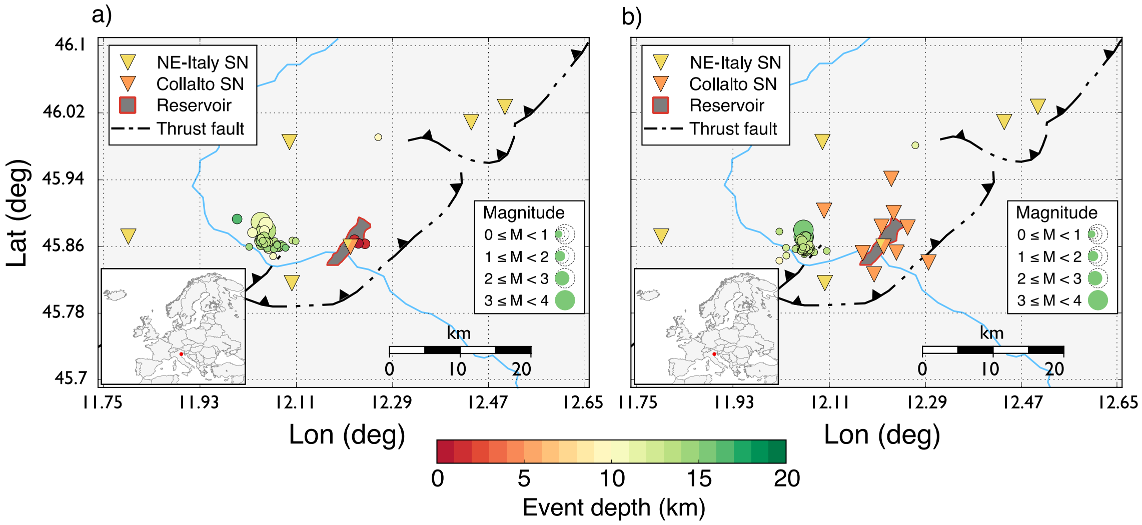


***Figure 1**: Seismic sequence occurred in Valdobbiadene (Veneto Region, Italy) on 12–15 May 2015. The sequence consists of two M3.6–3.7 events and about 100 of aftershocks which have been located (a) with regional network managed by OGS (in this case three events were mislocated within the reservoir and at compatible depth) and (b) with a dedicated microseismic network. (figure from Grigoli et al. 2017)*

A well-designed and dedicated microseismic monitoring network, on the other hand, solves this problem and also provides a lower magnitude of completeness to support the management of the industrial activity and the related decisional protocols to prevent the occurrence of critical situations (e.g., the so-called traffic light system). Unfortunately, most of industrial activities are often inadequately monitored. Although this situation seems quite common in the U.S. [*Hornbach et al.*, 2015], where most of the industrial sites do not have a dedicated microseismic network, monitoring conditions in Europe are often poor. Except few cases worth of note, like Groningen (Netherlands, see the previous sections), Collalto (Italy [*Priolo et al.*, 2015]), Basel (Switzerland [*Kraft and Deichmann*, 2014]), and St. Gallen ((Switzerland [*Edwards et al.*, 2015]), where the presence of dedicated networks, equipped with different instrument types including broadband seismic stations, borehole sensors, and accelerometers, guarantee optimal monitoring conditions, many industrial sites still lack appropriate monitoring infrastructure. For instance, Blackpool (UK [*Clarke et al.*, 2014]) and Castor (Spain [*Cesca et al.*, 2014; *Gaite et al.*, 2016]) seismicity cases are among the most scrutinized induced seismicity cases in Europe, where the lack of an adequate monitoring network did not allow a quick and accurate analysis of the microseismicity. After the crises both industrial activities were definitively interrupted. However, it is not clear whether the presence of better monitoring networks, in combination with more advanced data analysis procedures and decision protocols, would have led to the prompt suspension of the industrial operations, avoiding the occurrence of the critical events. Poor monitoring conditions without adopting appropriate data analysis tools can lead to results that are difficult to interpret and may delay timely decisions. This is well illustrated by the Castor sequence (Figure 2a). A successive analysis of the seismic sequence with more sophisticated waveform-based location methods (Figure 2b) revealed a clear spatial clustering and correlation between seismicity and injection operations, relocating the seismic events approximately at the same depth of the reservoir [*Cesca et al.*, 2014]. It remains an open question, whether the quick interruption of the injection at the Castor platform might have had an impact on the occurrence of largest magnitude events, which took place after the injection stop (Figure 2c). It is important to mention that seismic monitoring of offshore industrial operations is a complex, expensive, and technological challenging task. Monitoring the Castor injection site would have, of course benefited from a network of ocean bottom seismometers (OBSs), which are economically expensive and technologically difficult to manage. A possible alternative, cheaper solution, when the operations occur at a close distance from the coastline, could be the deployment of multiple onshore small-scale seismic arrays (instead of using single stations like in this case). The use of seismic array techniques allows to increase the signal-to-noise ratio and the number of detected events and location quality [*Gibbons and Ringdal*, 2006].

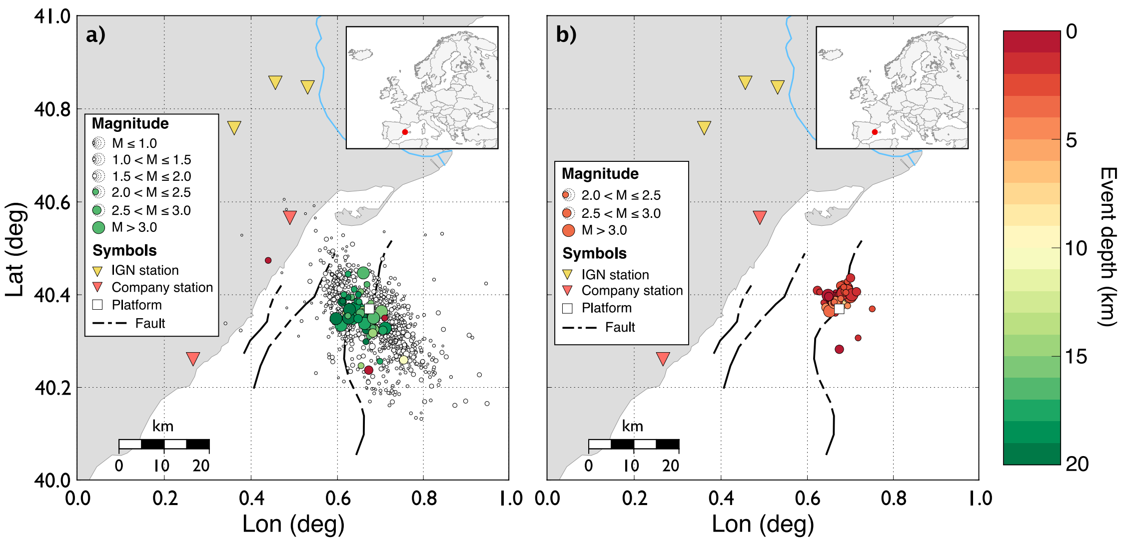


***Figure 2**: (a) Seismicity located by Ebro Observatory, all the events with magnitude ML > 2 are denoted by colored circles. (b) The relocation of seismic events with ML > 2. The white square the gas injection platform and the seismic stations are denoted by reverse triangles. [after Cesca et al., 2014].*

To ensure an optimal monitoring of induced seismicity, two main conditions should be satisfied: (1) the design and deployment of a dense microseismic monitoring network and (2) the use of sophisticated near real-time data analysis procedures.

Technical specifications of a microseismic network to ensure desired monitoring conditions are still debated and not standardized. In the last years different network design and optimization methods for microseismic monitoring applications have been proposed, though their use is not yet a standard practice. The performance of a seismic network depends on many factors, including sensor type, number of stations, network geometry, instrumental, and ambient noise level. It is well known, for instance, that the spatial distribution of the detection performance for different target magnitudes strongly depends on the network geometry and source properties [*Schorlemmer and Woessner*, 2008; *Plenkers et al.*, 2011; *Kwiatek and Ben-Zion*, 2016]. In most cases seismic network optimization is often managed following simple empirical rules based on the analysis of ambient noise level at each site [*Kraft et al.*, 2013]. Although ambient noise level estimation at each station site is important, network design and optimization processes should also include an assessment of the performance in terms of detection, location, and magnitude estimation. Furthermore, they should be always performed before the deployment of a new network or the extension of an existing one. The event magnitude, the hypocentral distance to stations, the dynamic range and the frequency of the sensor, the acquisition system, and the site noise are the main factors limiting the detectability and the ability to analyze source properties of a seismic event [*Kwiatek and Ben-Zion*, 2016]. For these reasons the use of synthetic data (simulating different source locations, mechanisms, and magnitudes) with realistic noise conditions (for instance, real noise extracted from the available stations in the target area) is an important tool for the optimal design of a microseismic network [*Kraft et al.*, 2013; *Stabile et al.*, 2013; *Kwiatek and Ben-Zion*, 2016]. *Kraft et al.* [2013] developed a network design tool based on global optimization methods to find the geometry and size of the network satisfying certain requirements (mainly magnitude of completeness and location accuracy). *Mahani et al.* [2016] used a simulation-based method (Seismic Network Evaluation through Simulation [*D'Alessandro et al.*, 2011]) to assess the detection and location performance of a seismic network designed for monitoring induced seismicity related to oil and gas operations in the British Columbia (Canada). An important aspect, which is often not considered during the network performance assessment, is the effect of poor knowledge of the velocity model on location accuracy, especially concerning event depth. Especially in microseismic monitoring application, the lack of a detailed velocity model of the study area is generally the largest source of error in the seismic event location process. An interesting example of modeling the effect of erroneous velocity model assumptions in the velocity model in the location performance assessment procedure is provided by *Kinnaert et al.* [2016]. This work was applied to the microseismic monitoring network of the Rittershoffen Geothermal field (Alsace, France). In general, we suggest that modeling the effect of wrong assumptions associated with the velocity model should also be included in the location performance assessment procedures, especially when detailed 3-D velocity models are not available in the target area. The desired performance on detection and location of an induced seismicity monitoring infrastructure is strongly dependent on the type of application [*Trutnevyte and Wiemer*, 2017] and should be designed in synergy with a risk assessment and site characterization phase, for the cost-benefit optimization. The detection capability of the network, which is related to the magnitude of completeness *Mc*, is application dependent and should be carefully chosen taking in consideration the seismic hazard, background seismicity, and the *Mc* of the national/regional seismic network in the area. The accuracy of the location performance is important to understand ongoing seismic processes (e.g., to map the spatiotemporal evolution of the seismicity which could reflect fluid migrations) [*Ogwari et al.*, 2016] and also is a fundamental information to discriminate between natural and induced seismicity [*Dahm et al.*, 2015]. However, also in this case, the desirable location uncertainty remains intrinsically linked to the type of operations and potential hazard, for instance, more precise locations could be needed to ensure the integrity of reservoirs or an accurate mapping of fracturing and enhanced permeability regions [*Maxwell et al.*, 2010]. Since the location performance is controlled not only by the geometry and technology of the monitoring infrastructure but also on the adopted methodology for location and on the available velocity model, tests with synthetic simulation and real data remain the best practice to assess the location performance of the network [*Kinnaert et al.*, 2016]. Location uncertainties can be reduced by using dense networks with at least one station (better if deployed in a borehole) directly above or within few kilometers from the potential source of seismicity (e.g., injection well). Finally, it is worth noting that some traffic light system requires, among different input parameters, the Peak Ground Acceleration (PGA). In these cases the presence of strong motion sensors within the microseismic monitoring infrastructure is extremely important.

In order to obtain optimal results, well-designed microseismic monitoring networks should be combined with advanced data analysis methods. Microseismic monitoring is a basic tool for reservoir characterization [*Fehler et al.*, 2001] and to better understand the geomechanical processes governing induced seismicity. To achieve these goals, the adoption of an optimal monitoring infrastructure is not sufficient, we need efficient real-time earthquake detectors, high-precision locations, and reliable source parameters (e.g., magnitude and, if possible, source mechanisms) for a statistically significative number of microseismic events [*Zoback*, 2010]. Furthermore, the reliability of these results, in case of occurrence of critical events, is a necessary condition to correctly assess the decision protocol or, in other words, to evaluate whether to stop, alter, or continue the ongoing industrial operations. The locations and source mechanisms of microseismic events allow the extraction of useful information about the distribution and geometry of active faults close to the industrial site and to estimate the seismic response in consequence to stress perturbations associated with human operations. Since microseismic events are often characterized by low signal-to-noise ratio, obtaining reliable source parameters is still challenging [*Guilhem et al.*, 2014]. In addition, microseismic networks generally record a large number of weak earthquakes (magnitude completeness of these networks is commonly $Mc \geq 0.0$), and quick analysis of such huge data sets is hardly achieved through manual data analysis procedures. Thus, robust automated data analysis procedures should be established.

Modern full-waveform methods can be used as robust and fully automated procedures for microseismic data analysis, which can lead to more reliable results than standard approaches based on phase picking. An overview of the full waveform methods currently used in microseismic monitoring applications is given by *Kwiatek et al.* [2013] and *Cesca and Grigoli* [2015]. The adoption of full waveform-based methods to automatically detect, locate, and characterize microseismicity led to recent promising results. Among these approaches, detection methods based on waveform template matching have been extensively applied to induced seismicity data sets [*Barrett and Beroza*, 2014; *Yoon et al.*, 2015; *Skoumal et al.*, 2015; *Goebel et al.*, 2016; *Caffagni et al.*, 2016]. *Huang and Beroza* [2015] applied a single-station template matching to the Guy-Greenbier (Arkansas, USA) seismicity sequence induced by wastewater injection operations. They found over 100 times more earthquakes than those detected by the Advanced National Seismic System. *Kim* [2013] used a waveform correlation detector to the Youngstown (Ohio, USA) induced seismic sequence (Ohio, USA), finding about 97 seismic events undetected by the regional network, which only detected 12 events greater than *Mw* 1.8[*Kim*,2013].Finally, *Bao and Eaton*[2016] shown a space-time correlation between seismicity and industrial operations near hydraulic fracturing sites in western Canada, combining a template-based seismic catalogue with injection data. Waveform template matching allows successful detection of a large number of hidden events which often are buried by noise and lead to a dramatic increase of the catalog completeness, highlighting more detailed relationships in the space-time-magnitude domain between the seismicity and industrial activities [*Skoumal et al.*, 2015; *Goebel et al.*, 2016; *Bao and Eaton*, 2016]. Another important family of methods specifically developed for microseismic monitoring purposes are the waveform stacking methods used for simultaneous detection and location of seismic events. Such approaches, in conjunction with dedicated microseismic networks, allow the detection and location of weak events (often with magnitude below 0.), even when strongly noise contaminated, reducing the magnitude of completeness and producing larger catalogs [*Cesca and Grigoli*, 2015]. A significant limitation of standard detection and location methods is, in fact, that automated phase picking is performed on each individual station, without using the coherency information between stations [*Poiata et al.*, 2016]. Microseismicity data sets are often characterized by event bursts, with multiple or overlapping events; in this case, the processes of phase identification and event association are critical tasks, often leading to missed detections and/or reduced location resolution. Waveform stacking methods do not require phase picking and association and directly exploit the wavefield coherence information simultaneously using data of the whole seismic network. The sketch in Figure 8 shows, without loss of generality, a schematic representation on how these methods work. In the last years waveform- based methods has been used to analyze induced seismicity associated with different industrial activities such as mining operations [*Gharti et al.*, 2010; *Grigoli et al.*, 2013], geothermal energy exploitation [*Sick and Joswig*, 2016; *Folesky et al.*, 2015], natural gas storage [*Cesca et al.*, 2014], and oil and gas operations (including hydrofracturing) [*Zeng et al.*, 2014; *Pesicek et al.*, 2014; *Stanek et al.*, 2015]. In presence of strong noise contamination these methods have the potential to offer more stable and reliable results than standard location methods based on automated picking procedures. However, an extensive comparison with more sophisticated pick-based detection and location methods is still lacking, therefore, further investigations are required to better evaluate the pros and cons of the aforementioned methods. It is important to point out that the performance of absolute location methods strongly depends on the quality of the available velocity model. When dealing with poor velocity models, location accuracy can be strongly reduced, affecting the output of further geological and geophysical analysis (e.g., estimation of source mechanism, and event magnitude) [*Grigoli et al.*, 2016]. To reduce the dependence on the velocity model and obtain more accurate results, relative location methods are thus required. Most of these methods rely on differential travel times for pairs of earthquakes observed at common stations [*Waldhauser and Ellsworth*, 2000], which can be computed automatically using cross-correlation [*Schaff and Waldhauser*, 2005]. Differential times can be now computed in a fast and efficient way, allowing to obtain double difference locations in real time [*Waldhauser and Schaff*, 2008]. The Real-Time Double-Difference analysis has been successfully applied to the northern California seismicity, including the induced seismicity recorded at the Geyser Geothermal Field [*Waldhauser*, 2009] (http://ddrt.ldeo.columbia.edu). Another new relative location method is the Master-event Waveform Stacking [*Grigoli et al.*, 2016], which combines the waveform-based location approaches previously introduced with the master event location method [*Deichmann and Giardini*, 2009]. This approach inherits the advantages of the waveform location methods but, at the same time, is less dependent on the knowledge of the velocity model (the velocity model is only used to estimate travel time within the source volume, and not along the entire source- sensor path). The location accuracy is improved because it accounts for phase delays due to local site effects (e.g., surface topography or variable sediment thickness). This method has been applied to natural seismicity associated with fluid migration in North-West Bohemia (Czech Republic Figure 3a). In this application about 115 earthquakes with local magnitude between 1.0 and 2.5 were located using both the standard and master-event waveform stacking method [*Grigoli et al.*, 2016]. This study shows that the Master-Event waveform stacking location is less dependent on the velocity model and performs better than the standard waveform stacking method (see Figures 3b and 3c). A comparison between the locations obtained using the Double Difference method [*Waldhauser and Ellsworth*, 2000] (Figure 3d), the classical waveform stacking (Figure 3e), and the Master-event waveform stacking locations (Figure 3f), shows that the results obtained using the latter method have comparable resolution of the Double Difference methods. On the other hand, due to the lack of a detailed 3-D velocity model, the locations obtained using the classical waveform stacking approach have a lower resolution than the Double Difference and the Master-Event waveform stacking locations. Although waveform-based methods (such as the real-time double difference and Master Event waveform stacking) are not yet extensively used in induced seismicity-monitoring applications, their results are promising and should be considered to include them in the routine processing.

The earthquake magnitude is a sensitive parameter for induced seismicity, because it is a concept that can easily reach the public, and the first one which the nonscientific community will look at, when judging the impact of an induced earthquake. Robust magnitude estimation is important and should be performed in any induced seismicity monitoring operation. The quality of the magnitude estimation, as for the location, will not depend only on the monitoring setup, but can be improved by using waveform-based techniques. In this perspective, the presence of one or more broadband seismometer remains fundamental to cover low-frequency (i.e., less than 1 Hz) spectra and to better constrain the magnitude of larger events, which can, in combination with a short-period seismic network, be used to calibrate magnitudes of smaller earthquakes. Given the multiple magnitude types and estimation techniques, transparent procedures to estimate the magnitude should be provided. The magnitude determination is not a trivial process, and important differences have been detected among different catalogs related to induced seismicity [*Edwards and*

Douglas, 2014]. Moreover, induced seismicity often occurs in low-seismicity region, where robust attenuation curves cannot be easily calibrated. Weak-induced events (i.e., generally with magnitude less than 1) may be recorded only locally, and the adoption of regional attenuation laws may bias the magnitude estimation. The problem has been recently illustrated for the Blackpool (UK) induced seismicity case by *Butcher et al.* [2017], who depicted large, critical discrepancies between magnitudes calculated using local-distance stations (*Ml* 2.3) and those based on records from the regional network (*Ml* 1.2). This has obvious significant implications for the regulation of the risk of induced seismicity, which is often managed on the base of traffic light schemes, depending on the estimated magnitude. The radiation pattern of earthquakes can affect magnitudes, e.g., if the monitoring network has large azimuthal gaps. Therefore, full waveform modeling techniques to characterize the seismic source processes are useful to investigate the geometry of active faults, to detect tensile failures or to investigate stress drops. These techniques also benefit from the availability of broadband records, possibly covering the source radiation patterns from different azimuths.

Finally, it is worth to highlight that a good microseismic network is a necessary, but not sufficient condition to successfully monitor induced seismicity. Although several advanced and reliable analysis methods are currently available, in routine monitoring operations most of the processing is done using standard approaches which often do not lead to reliable results when dealing with noisy data or when the velocity model is poorly known. In many cases, in fact, routinely monitoring operations are performed by using techniques not specifically designed for this type of applications, thus they may not fully exploit the performance of the monitoring infrastructure. At the Groningen gas field, for instance, the densification of the network (Figure 4a) enabled the use of a local detailed 3-D velocity model and new analysis methods [*Spetzler and Dost*, 2017]. It should be always a good practice to use location procedures allowing to manage 3-D velocity model, when available. However, introduction of new methods and models into routine operations requires extensive testing, which is currently being carried out for Groningen. Concerning the Collalto case, the adopted seismic data analysis procedures are, at the moment, not specifically designed for such kind of applications. For instance, the semi-automated detection procedure is mainly based on the visual inspection of recorded waveform, while the location procedure is based on the iterative inversion of *P* and *S* arrival times retrieved by manual picking operations. These procedures require a huge amount of work carried out by an expert seismologist which, in case of crisis, would not be able to process and analyze very large data sets (i.e., hundreds or thousands of microseismic events per day) in short time frames. For this reason the data analysis routines to monitor the gas storage operations at the Collalto reservoir would need an update. Finally, in almost all cases, more sophisticated or specialized seismic data analysis methods are generally applied only after the occurrence of critical events and mainly for scientific purposes.

Monitoring of ground deformation

The underground industrial activities involving fluid injection/extraction in the subsurface can be linked to ground deformation processes at the surface. Ground deformation has a rather slow dynamics and it is spatially extended and these processes can give important information on the subsurface response to fluid injection/extraction. The advent of space-based geodesy and remote-sensing over the last 2 decades has provided new tools space such as the space-borne Synthetic Aperture Radar (SAR) interferometry which, in complement to seismology, allows monitoring surface displacement associated with fluid injection and/or extraction operations [*Massonet and Feigl* 1998, *Shirzaei et al.,* 2016, *Rucci et al.,* 2010, *Verdon et al.,* 2013, *Xuejun et al.,* 2018]. Measurement accuracies are in the order of centimeters [*Massonet and Feigl* 1998], furthermore, the advent of new satellites constellation, such as the ESA Sentinel-1, opens new horizons in monitoring industrial sites. In particular, the 12-day (6-day in Europe) revisit time ensured by these satellites allow to better image the temporal evolution of ground displacement processes, in several cases overcoming the limitations of previous SAR satellite missions. Space borne DInSAR [*Massonet and Feigl* 1998] technique is thus extremely powerful and it has already demonstrated to be very useful to track the ground uplift or subsidence due to fluid injection/extraction operations [*Rucci et al.,* 2010, , *Xuejun et al.,* 2018, *Yang et al.,* 2015, *Barnhart et al.*, 2018]. The DInSAR is also a powerful tool for induced seismicity discrimination studies, and it was has already successfully applied in this context [*Grigoli et al.* 2018], allowing to identify the seismogenic structure associated with the Mw 5.5 Pohang (South Korea) earthquake showing a clear spatial correlation between the activated fault and the injection wells used for geothermal energy production operations (figure 4 and 5). In this case the InSAR analysis provided an independent constrain on the fault geometry and depth of the largest event, which was extremely close to the injection well, further supporting the hypothesis of the anthropogenic origin of the Pohang earthquake. By applying Multi-temporal InSAR processing techniques to a series of radar images over the same region, it is possible to detect the ground displacements in the millimeter range, and therefore, better quantify the effect of fluid injections/extraction operations in term of ground deformation and its temporal evolution [*Sansosti et al.*, 2010, , *Shirzaei et al.,* 2016]. The results of InSAR processing are represented by the temporal series of ground deformation, whose values are referred to a reference area, which is typically selected in a non-deforming area. The achieved deformation time series is relevant to the component projected along the radar Line Of Sight (LOS) of detected surface deformation during the considered time interval. However, the principal limitations of the InSAR technique are: i) the limited temporal resolution, related to the revisiting time of satellites (which is in the order of days/weeks), and ii) it measures only one component of the 3-D terrain displacement (along the radar Line Of Sight, LOS). This means that DInSAR measurements along a single LOS do not allow to derive the 3D surface displacement and iii) the DInSAR measurement contains information on both terrain displacement and temporal changes of atmospheric phase delay, thus geodetic and atmospheric signals need to be separated. On the other hand, GPS systems have a much higher temporal resolution and provide a 3D ground displacement with higher accuracy, but with very limited spatial resolution. The integration of DInSAR and GPS data should provide information on ground deformations by taking advantage of the positive features of both these techniques (i.e., the high spatial resolution of the InSAR and the high temporal resolution and sub-centimeter accuracy level of the GPS), allowing to obtain high-resolution 3D displacement maps that can be used to better quantify the subsurface response to fluid injection/extraction operations.

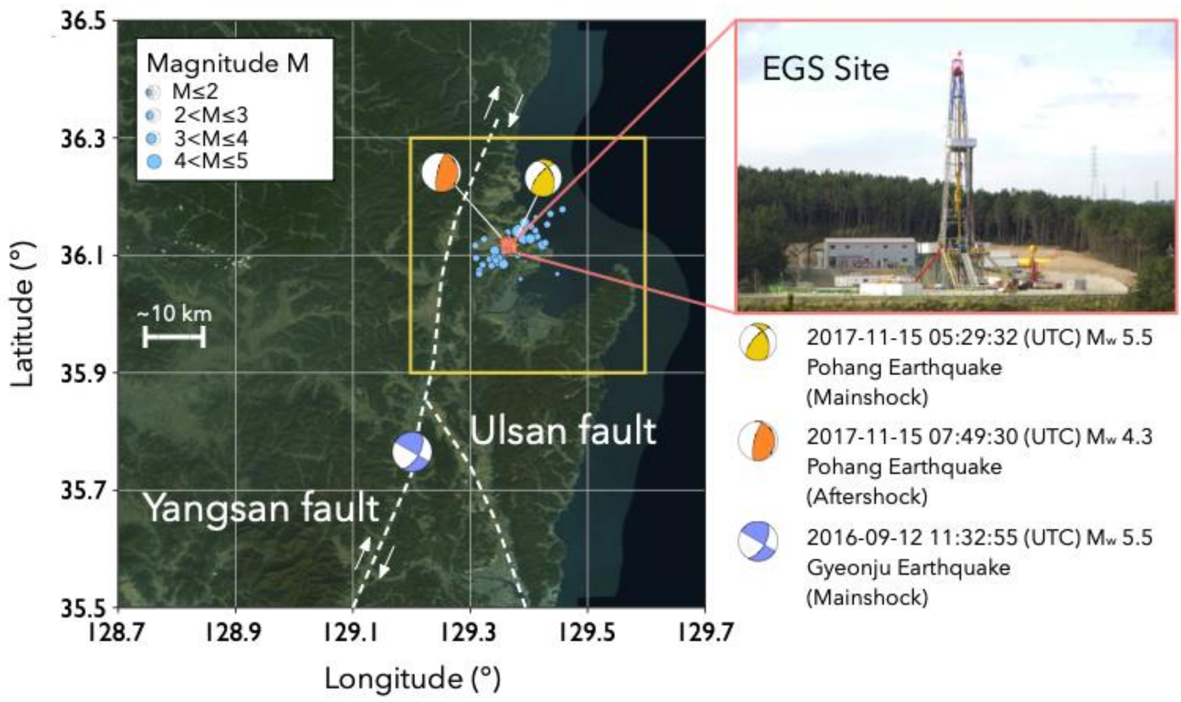


Figure 3*: Map of the Pohang, showing the main faults, the distribution of seismicity with respect to the EGS site, and the mechanisms of the largest events. (figure from Grigoli et al. 2018)*

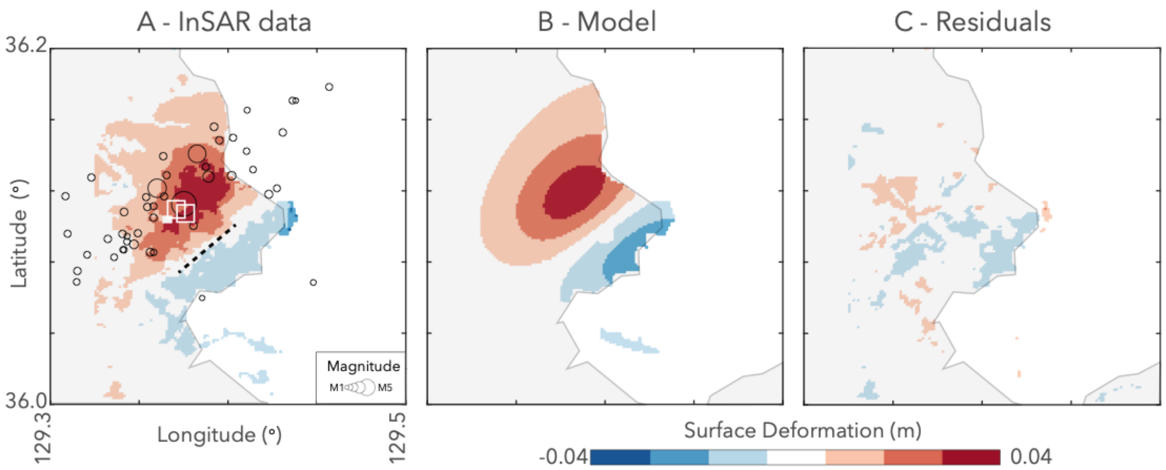


Figure 4*:(A) Surface deformation (satellite line-of-sight displacements) obtained with InSAR. Seismicity and the extrapolated fault trace are indicated by black circles and a dashed line, respectively. (B) Modeled surface deformation using a rectangular fault plane with the following parameters: latitude = 36.100° ± 0.005°, longitude = 129.383° ± 0.003° (center of the rectangular fault), depth = 4.3 ± 0.3 km (upper edge of the fault), strike (from north) = 225° ± 12°, dip (from horizon) = 75°±11°,length=5.0±0.7km,width=1.6±0.4km,slip=1±0.22m,and rake = 123° ± 35°. (C) Difference between InSAR data and model. The standard deviation is <0.5 cm, which is below the accuracy threshold of the measurements. (figure from Grigoli et al. 2018)*

Such a monitoring system aims at providing information both on the temporal trend of ground deformations (more precisely of the upper ground layer) during the observed period, and on their spatial distribution over the analyzed area, highlighting possible variations with respect to the background deformation scenario. According to different regulations [e.g. MISE]**,** an optimal geodetic monitoring of the industrial site should have the following features:

- for a particular industrial site, surface deformations detected by using InSAR measurements carried out with accuracies of 5-10 mm (for what attains the single InSAR measurement in LOS) and of about 1-2 mm/year for the mean deformation velocity values.
- the InSAR measurements should be based on the use of SAR data acquired from both ascending and descending orbits, in order to reconstruct the vertical and horizontal (E-W) components of the detected ground deformations.
- the ground deformation values inferred by InSAR measurements need to be integrated with the data of continuous GPS stations at the industrial site, already existing or installed at least 1 year prior the start of the injection/extraction opration. The integration of data from GPS stations make the InSAR measurements independent from the "reference zone" selected for their analysis and representation and allow to detect (and correct) possible artifacts that can be present in InSAR measurements, perform 3D modeling of the detected deformation field.
- For each GPS station, deformation time series have to be provided, relevant to the three daily N-S (latitude), E-W (longitude) and vertical displacement components, and their corresponding velocity values.

Monitoring of pore pressure and other environmental parameters

According to the guidelines of the Italian Government [MISE], monitoring the pore pressure in proximity of injection wells is useful to update and verify reservoir models for storages and reinjections. The choice of the wells to be monitored will be based by considering the geological setting of the area. The pore pressure should be measured in continuous at bottom well level through dedicated tools that will provide real time measurements. For some of the existing wells, memory gauges, temporarily placed at the bottom well, will be used for remote recording of pressure at pre-defined intervals [MISE]. Moreover, campaigns for measuring pore-pressure of the field need to be periodically carried out. A further way to acquire pressure values is to use non-productive wells, also located outside the reservoir in its proximity. The pressure values in the volume surrounding the wells should be evaluated carrying out correlations with other monitoring wells and with the help of hydro-geomechanical models. Reports on measured or estimated pressure rates should be produced every 6 months at least [MISE].

The prevention against environmental impacts, pollution and nuisances is the main principle, together with safety at work, on which are based the drilling and exploitation authorizations. The definition of well-established procedures and measures aiming at minimizing the environmental impacts is also a way to increase the acceptability of the population. Indeed, the environmental effects and nuisances are usually the main concerns of the population living in the surroundings of a geothermal plant or project (e.g., Chavot et al., 2018). Several topics are addressed that are presented below. Exploitation and drilling works must be performed so as to minimize noise emissions and mechanical vibrations, which could disturb the surrounding population or have an impact on the close environment. Day- and night-time noise measurements must be performed before the start of exploitation/drilling near the closest houses to determine the level of background noise. Those measurements must be repeated several times during exploitation/drilling, to check if noise emissions exceed the regulatory levels of emergence (that is, above the determined background noise). In that case, it is mandatory for the operating company to take measures or establish procedures to decrease the level of generated noise. In particular, during the drilling phase, any loud operation is forbidden during the night-time (22h – 7h). Figure 4 presents the locations where noise measurements are regularly performed around the Soultz-sous-Forêts power plant.The general principle states that the operating company must take all possible measures or apply specific procedures in order to guarantee the protection of surface and underground water and minimize the risk of accidental pollution. Some specific concerns are related to:

- management of rainwater: the company must make sure that the rainwater drained on platform is not polluted;
- any discharge of any type of water/fluid into the environment can be strictly forbidden. If not, the discharged water/fluid must respect maximal concentration values for specific parameters;
- discharge of geothermal fluid into the environment is strictly forbidden. It must be stored in dedicated ponds;
- management of accidental pollution;
- protection of underground water: boreholes' completion must guarantee the protection of potential permeable layers. Moreover, the exploitation authorization defines a program of regular inspection of wells' integrity (control of casing and cement quality). Inspections shall be performed every 6 years for production wells and every 3 years for injection wells;
- presence of groundwater table: in this case, the operating company must install a network of piezometer into shallow observation wells. At least, one piezometer must be installed upstream from the facilities and 2 piezometers downstream of the facilities. Regular measurements of the groundwater table's level, conductivity, temperature, pH, reduction potential. In addition, water samples are monthly taken and analysed. The concentration in main anions, cations, metallic species, pollutants and the radiological activity of main natural radionuclides are then characterized. All these measurements aim at detecting any pollution of the groundwater table by geothermal fluid.

In the case of geothermal plants exploiting a reservoir containing natural radionuclides, the probability exists that some of the radionuclides could be washed out by circulation of geothermal fluid and then trapped during the formation of scales in the plant's surface equipment. This type of slightly radioactive scales is called "NORM" (Naturally Occurring

Radioactive Material). Typically, the geothermal plants developed in the Rhine Graben have to face this issue: indeed, they exploit a geothermal fluid circulating in granite, a rock containing small amounts of radionuclides, for instance Uranium 238, Thorium 232, Potassium 40 and the products of their decay chain. On surface, enhanced concentration of Radium 226, Radium 228 and Lead 210 can be found in sulfates and sulfides scales, as shown on Figure 6 (Cuenot et al., 2013, 2015; Scheiber et al., 2012; Eggeling et al., 2013; Mouchot et al., 2018). cross-section of a scaling layer showing sulfide and sulfate scaling (Scheiber et al., 2012). Radioactivity is one of the main environmental concerns among the population. Thus, the drilling and exploitation authorizations require that the operating company at least performs measurements to check the level of radiation on the facilities and to monitor its evolution. Last year, the French Mining Code was modified to take into account the problem of NORM: a new chapter was added, mainly dedicated to the protection of environment and population. It defines the measurements that are mandatory for the operating company. Radiological characterization is asked for all kinds of solid, liquid and gaseous effluents, to be sure that no radioactive material could be spread into the environment and could be harmful for the surrounding population. In addition, in France, the regulation regarding radioactivity is defined in the Labour Code and the Public Health Regulation, which defines the measures and procedures that must be followed by employers for the protection of workers. The basic principle of radiation protection states that every exposure to radiation, even the lowest, could have potential, harmful effects on human's health. Thus, the regulation imposes that at least, the level of radiation has to be measured and the potential exposure of workers should be calculated. Depending on the results, radiation protection measures have to be implemented, in order to respect the following principal law: the maximal cumulative dose that can be received by workers and population over 12 consecutive months is 1 mSv (one milli-Sievert). As an example, are listed some of the monitoring measures that are applied on the geothermal plants of Soultz-sous-Forêts and Rittershoffen:

- Quarterly measurement survey: every three months, ambient and contact dose rate measurements are performed on several tens of locations over the plants' surface equipment. This allows to accurately monitor the evolution of radioactivity, which has to be reported to the Mining Authorities.
- Characterization: regular sampling of geothermal fluid and scaling is performed. Samples are then fully analysed in terms of geochemical content and radiological characterization. This is explicitly asked by the regulation, at least once per year.
- Aerial emission: quantification of Radon emission on the plant, but also, in the environment around the plant (typically, near the closest habpohangitations) is mandatory, as well as radiological measurements on the dusts that can be emitted on the plant. It has to be done once per year and reported to the Mining Authorities
- Effluents: sampling and radiological analysis of liquid and solid effluents that can be released into the environment or stored on site (for example, rainwater, mud, …) must be performed once per year. In addition, if some effluents are released in the

environment, soils, flora and fauna located near the discharge place must also be sampled and analysed to check for the presence of radionuclides.

In case radiations have been measured on site:

- Appointment of a radiation protection expert: the expert will be in charge of the monitoring described above, but also to all actions related to radiation protection
- Estimate of individual exposure: from the list of all possible works that employees are likely to perform on the plant, duration of each work and dose rate measurements on facilities, a calculation of the possible received dose for each worker has to be made and compared to the maximal permitted dose over 12 consecutive months (1 mSv).
- Workers' dosimetry: each worker must wear a passive dosimeter during its working time if he works on the plant's facilities. The dosimeters are analysed every three months to check the value of the cumulative dose.
- Installation zoning: if the measured ambient dose rates exceed given thresholds, it is required to proceed to a zoning of the installation, according to the procedure defined in the regulation. It has to be noticed that, as soon as an area is determined and reported, workers must compulsorily wear their passive dosimeter when entering the zone. It is applicable even for the first zone defined in the regulation ("blue" or "supervised" area).
- Work procedures and authorization: specific work procedures have to be defined for the work in supervised or controlled area (including the access authorization), or for work where the risk of exposure is higher (for example, when opening a contaminated equipment implying a risk of contact with radioactive material). A particular attention should be paid to the collective and individual protective equipment that is required regarding the type of operation.
- Employee's training: each employee who is likely to be exposed to radiations must be trained, or at least informed, about radioactivity in general, but especially about all related issues in its framework.

Conclusions

We have shown that induced seismicity monitoring of underground industrial operations is an important tool which strongly help the decisional protocols in case of crises; however, many of these industrial sites are lacking an adequate monitoring network which allows the detection of microseismic events (generally with $ML < 0.0$). Despite its societal impact, the management of induced seismicity is still an open problem and many European countries do not have yet regulations requiring adequate seismic monitoring of the industrial activities which may generate induced seismicity. One of the major issues in Europe is the presence of several small countries whose industrial sites are often located at border with other countries, like Basel (Switzerland) or St. Gallen (Switzerland), to cite a few. In these cases the problems of different regulations, guidelines, and overlapping responsibility (for instance, what would happen if an induced earthquake occur in one country but has also damaging effects in another country?) could be solved only with a unified framework for the induced seismicity regulation. This suggests the need for more effective guidelines or regulations, possibly within a European framework, defining which requirements an efficient microseismic monitoring infrastructure should have. Furthermore, even in the presence of an adequate monitoring network, often, standard automated data analysis procedures are not sufficiently sophisticated to produce reliable results in real time. Since more advanced data analysis procedures are now available, standard methods used within the routinely monitoring operations should be replaced with modern and more reliable approaches. An optimal micro-seismic monitoring network combined with sophisticated data analysis procedures allows the recognition of the occurrence and migration of the induced seismicity very early [*Ogwari et al.*, 2016]. Therefore, early characterization of microseismicity and its spatiotemporal evolution [*Keranen et al.*, 2014; *Ogwari et al.*, 2016] might be used to track fluid migration and identify potential interactions with known pre-existing faults, ensuring safer operations. We thus believe that robust and automated waveform data analysis procedures to detect, locate, and characterize microseismicity should extensively be used in routinely monitoring operations. Within this framework, standardized protocols to monitor induced seismicity might help to make results more reproducible among different research groups and should bring more control on quality of the results. Combining seismological, geophysical, geological, and hydrogeological data and with the aid of geomechanical modeling, induced earthquakes may be better understood, modeled, and forecast than natural earthquakes, and eventually perhaps managed [*Juanes et al.*, 2016]. In support of decisional protocols, the management of industrial operations (e.g., control of injection/extraction volumes and flow rate) should rely on modeling methods to forecast seismicity, in order to estimate the probability of event exceeding a certain magnitude in space and time. Furthermore, data should be promptly made available and suitable processing methods should be applied right afterward.

We further suggest that setting up seismic monitoring, especially in addition to the existing national monitoring network, is the responsibility of the project operator together with the operator of the national network. Furthermore, we believe that data (at least the monitoring data) should be openly accessible to the public research institutes in an Open Data context. By definition Open Data is the process of defining how scientific data may be accessed, used, and published without any barrier. Geophysics was the first scientific field to promote open data access with the creation of the first World Data Centre, aimed to archive and distribute data collected during the 1957 – 1958 International Geophysical Year [*Hough*, 2008]. Although Open Data is nowadays strongly promoted by different countries and scientific societies, several critical problems still remain, especially when dealing with industrial data. One of these critical aspects concerns the public availability of data related to underground industrial activities. In Europe induced seismicity monitoring data generally belong to private companies, usually the same company carrying the industrial operations to be monitored, and their access is often restricted, even when public research institutes are involved (Collalto and

Groeningen are two exceptions, since their data are open and publicly accessible through their respective web sites).

This situation of course creates several scientific and sociological problems. The first one is related to reproducibility of results: restricting data access to other research institutions does not allow to verify the reliability of monitoring results. Furthermore, additional industrial data (e.g., production data), generally restricted, are often needed to correctly discriminate whether the observed seismicity correlate or not with industrial operations.

The second problem concerns the distribution of data products to the general public and might have a strong impact on both industry and society. In this context two main questions remain unanswered: Which kind of data product should be distributed to the general public (raw data, processed data, technical reports)? How to avoid potential misuse of the data that could negatively impact industrial activities?

These questions highlight the importance of correct communication campaigns, which should be addressed not only to a technical audience but also to the general public. In the social media era the misinformation and the diffusion of conspiracy-like information is becoming a problem. In fact, The World Economic Forum labeled massive digital misinformation as one of the main threats for our society [*Bessi et al.*, 2015; *Zollo et al.*, 2015]. Induced seismicity is one of the topics where misinformation has a negative socio-economic impact [*Rubinstein and Mahani*, 2015]. Thus, the importance of correct and well-designed communication campaigns are strongly necessary. A clear example on how misinformation can alter the perception of the general public is given by the 2012 Emilia earthquake, when the term fracking started to be searched on Google in Italy. This was mainly due to the systematic misuse of the term by the media and has lost its technical meaning, becoming a catch phrase for all operations associated with unconventional (or for the Emilia case, conventional) hydrocarbon production. In light of this, exhaustive communication campaigns should be carried out in advance, before the initiation of any activity potentially responsible of induced seismicity and not after the occurrence of crises. Finally, we strongly believe that Open Data policy, if adequately managed, would give valuable help not only to improve the scientific knowledge about the physical processes governing induced seismicity but also to increase the social acceptance of the related industrial activities.

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