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Key Points:
- We provide a unified and concise summary about the still open questions on monitoring, discrimination, and management of induced seismicity
- We review critical cases of induced seismicity in Europe which led to the suspension of the related industrial activities
- This study outlines the scientific and societal challenges posed by the induced seismicity in a European perspective

Supporting Information:
- Supporting Information S1
- Table S1

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Current challenges in monitoring, discrimination, and management of induced seismicity related to underground industrial activities: A European perspective

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Abstract Due to the deep socioeconomic implications, induced seismicity is a timely and increasingly relevant topic of interest for the general public. Cases of induced seismicity have a global distribution and involve a large number of industrial operations, with many documented cases from as far back to the beginning of the twentieth century. However, the sparse and fragmented documentation available makes it difficult to have a clear picture on our understanding of the physical phenomenon and consequently in our ability to mitigate the risk associated with induced seismicity. This review presents a unified and concise summary of the still open questions related to monitoring, discrimination, and management of induced seismicity in the European context and, when possible, provides potential answers. We further discuss selected critical European cases of induced seismicity, which led to the suspension or reduction of the related industrial activities.

1. Introduction

In recent years, seismicity induced by industrial operations has become an important topic of interest to the general public. In many cases, earthquakes occurring in the vicinity of industrial facilities carrying underground operations were felt by the population, caused damages to private buildings, and increased the public concern about the development of these industrial activities. The increasing number of reported cases of such "man-made" earthquakes and their strong socioeconomic impact has raised intense public debates and the interest of the nonscientific community on this topic. Although seismic events close to certain industrial facilities often raise concerns among the local communities, attributing the cause of an earthquake to an existing human activity and discriminating between anthropogenic and natural seismicity is not trivial; the Emilia, Italy, 2012 earthquake sequence is an illuminating example. In this case, a few months after the occurrence of the earthquake sequence that culminated with a magnitude 5.9 (M_l) event on 20 May 2012 and a magnitude 5.8 (M_l) event 9 days later, there was an intense public discussion concerning the possible relationship between these earthquakes and the hydrocarbon production operations in the epicentral area. The public concerns prompted the Italian government to charge an international expert panel to investigate the relationship between hydrocarbon extraction operations in Emilia and the 2012 earthquake sequence [*Juanes et al.*, 2016]. In numerous other cases, the possible relationship between reported earthquakes and human operations remained debated for years, even at scientific level. One of these cases is the May 2011 M_l 5.5 Lorca (Spain) earthquake, which has been linked to groundwater exploitation by some authors [*Gonzalez et al.*, 2012] while it was considered natural by others [*Martinez-Diaz et al.*, 2012].

Due to the steady growth of various underground industrial operations in highly populated regions, in the recent years the amount of felt earthquakes suspected (or considered) to be related with human activities has increased. Such activities include water impoundment, mining, fluid subsurface resulting from operations related to hydrocarbon extraction, hydraulic fracturing for shale gas exploitation, wastewater injection, hydrocarbon storage operations, CO_2 geological sequestration, and hydraulic stimulation of geothermal fields. The number of reported induced earthquakes also has apparently increased because many countries have now developed seismic monitoring infrastructures covering wider regions; it is easier to discover seismic events potentially associated to industrial activities. However, it is worth noting that the current list of documented induced seismicity cases [e.g., *Davies et al.*, 2013] remains partially incomplete because they generally only include earthquake sequences felt by the population, therefore they have occurred nearby to residential areas [*Wendel*, 2016]. For instance, induced earthquakes occurring in remote areas are generally not felt by population and might not be detected by the regional seismic monitoring networks (if not dense enough), thus such events are not be reported.

An overview of various case studies from across the world can be found in *McGarr et al.* [2002]. There are a number of mechanisms that can produce induced seismicity. The stress perturbations produced by underground industrial activities, when proximal to seismogenic structures, might generate earthquakes. Fluid injection and consequent pore pressure alteration may also create new fractures and/or alter the frictional condition on existing faults, triggering new failures. In recent years the impact of such mechanisms on seismicity has been largely studied from a physical point of view, and several models have been proposed [*Shapiro*, 2015]. However anthropogenic seismicity remains difficult to forecast and manage [*Petersen et al.*, 2016]. The term "induced seismicity" generally refers to anthropogenic seismic events in a wide sense; however, several studies [e.g., *McGarr and Simpson*, 1997; *Shapiro et al.*, 2013; *Dahm et al.*, 2015] tend to make a clear distinction between "pure" induced and triggered seismicity. In the first case, induced seismic events are entirely controlled by stress changes caused by human operations and the whole rupture process, including its size, is driven by this stress [*Dahm et al.*, 2013]. In triggered seismicity the tectonic stress plays a primary role, while the human activity contributes only for a small fraction of the stress change. However, when close to tectonic faults, such (even small) stress changes can cause a loaded fault to fail. In this case, human operations are the trigger for an earthquake that would have occurred naturally in any case, but likely at a later time [*Dahm et al.*, 2013]. Furthermore, since these operations act only to accelerate the process of tectonic stress release, the magnitudes of such earthquakes can be large, depending on the amount of elastic strain energy accumulated on the fault due to tectonic loading and the fault dimensions. In this sense, a large earthquake could be triggered by minor induced stress changes, if the fault is prone to rupture. Despite this difference, in this paper we will refer to both cases using the term induced seismicity. The box figure shows a sketch representing industrial activities which might induce or trigger seismicity and describes the related physical mechanisms.

Anthropogenic seismicity is globally distributed and it is known since the beginning of the twentieth century, with several reported cases mostly related to mining operations [*McGarr et al.*, 2002]. Figure 1 provides an overview on the geographical distribution of induced seismicity, classified by magnitude and industrial activity. Induced seismicity associated with oil and gas operations has been observed since the 1920s [*Pratt and Johnson*, 1926; *Hough and Page*, 2015]. Around the same period, underground fluid injection techniques started to be used to increase production from existing oil and gas fields and, in later years, to dispose industrial wastewater. This technique is generally used when oil wells start to produce more water than oil (like in Oklahoma). Since wastewater (generally brine) cannot be used for any other application, it is recycled back in the producing formation to maintain the reservoir pressure and enhance oil production [*Langenbruch and Zoback*, 2016]. Although subsurface fluid injection techniques started to be used in the 1930s, the first, scientifically documented, relevant case of fluid injection-induced seismicity is probably the Denver (Colorado, USA) 1960s episode, a consequence of a massive wastewater injection experiment at Rocky Mountain Arsenal [*Healy et al.*, 1968]. Injection operations started on March 1962 and continued, with some interruption, until February 1966, when fluid injection was stopped because of the connection with the seismicity in the area and the increased public attention and concern [*Healy et al.*, 1968; *Nicholson and Wesson*, 1990]. Between April 1962 and August 1967 the Denver area experienced an increase in seismicity rate, with more than 1500 seismic events recorded in about 5 years. In 1967 three earthquakes with magnitude between 4.5 and 4.8 [*Herrmann et al.*, 1981] caused damage to several buildings [*Nicholson and Wesson*, 1990]. Before this case, the seismic hazard associated with deep well injection was not fully appreciated [*Nicholson and Wesson*, 1992]. Since the 1960s, many other cases of anthropogenic seismicity occurred worldwide and a broad, while not complete, list of major events can be found in different review papers [*Suckale*, 2009; *Davies et al.*, 2013; *Ellsworth*, 2013; *McGarr et al.*, 2015] and governmental reports [*National Research Council (NRC)*, 2013; *International Commission on Hydrocarbon Exploration and Seismicity in the Emilia region (ICHESE)*, 2014].

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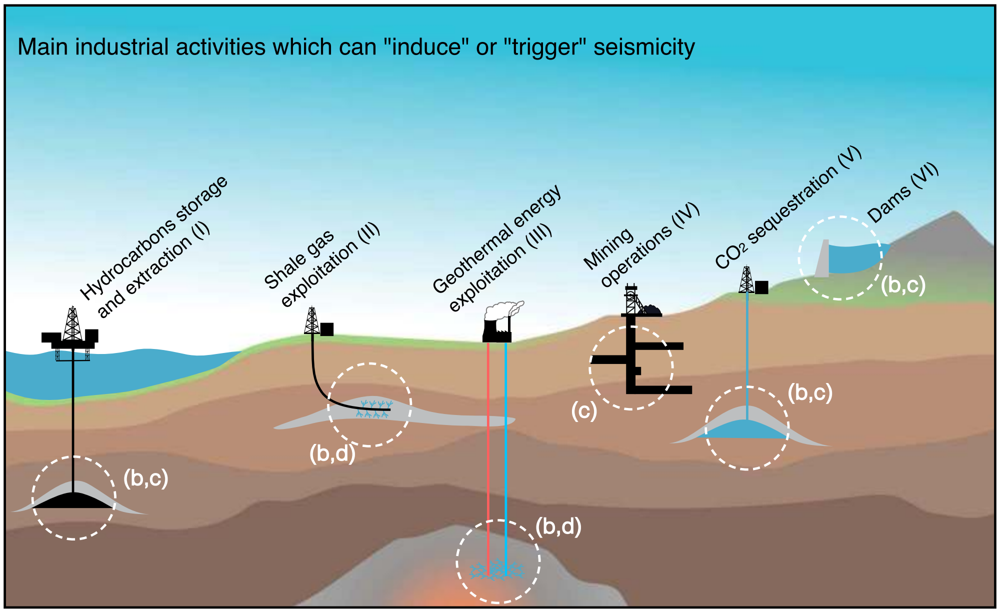
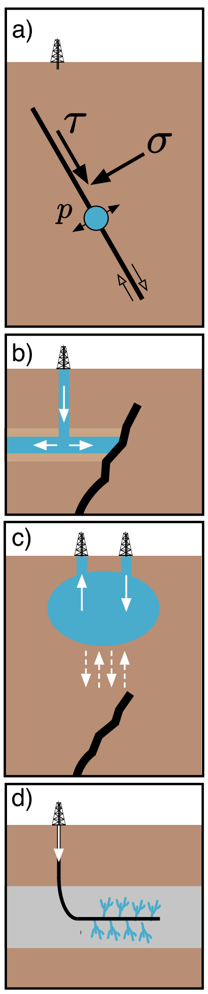
BOX: Induced seismicity: Industrial activities and physical mechanisms





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.

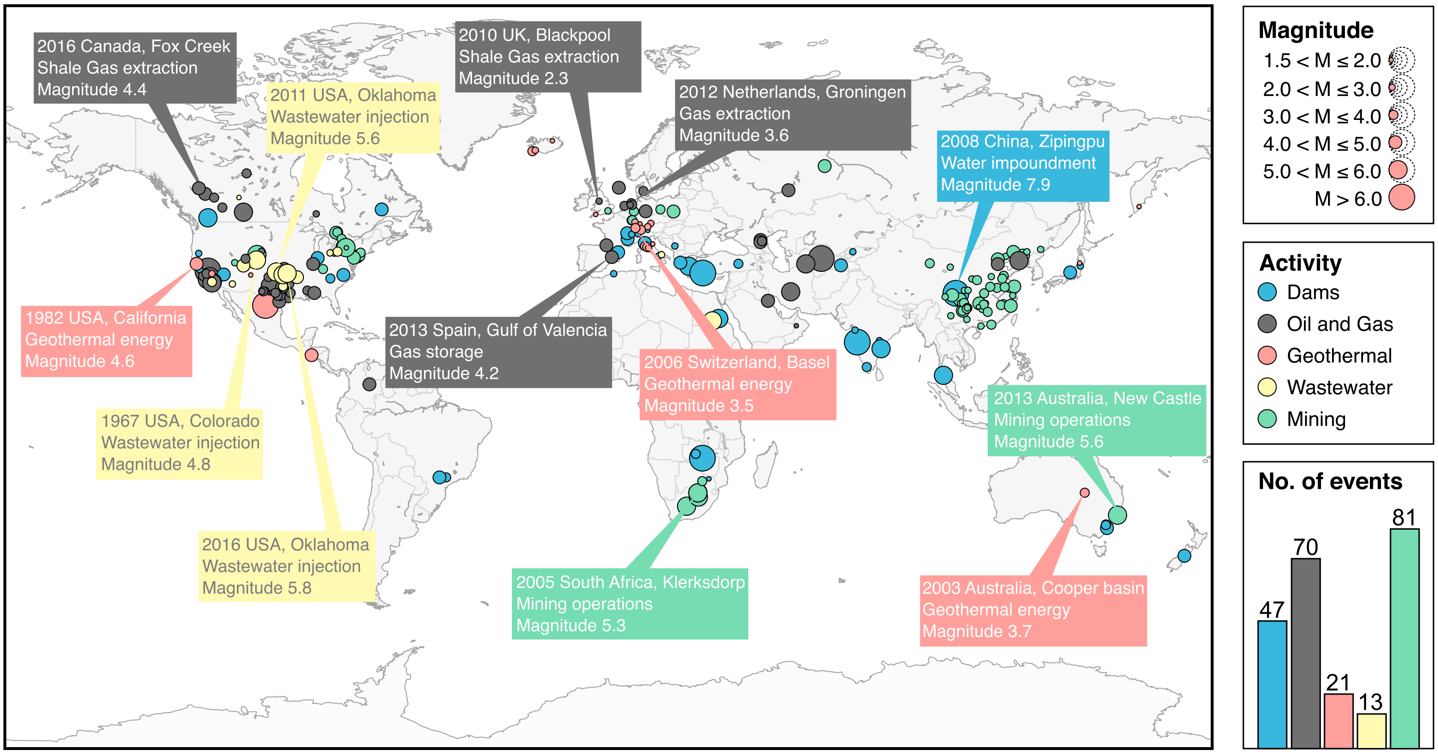


Figure 1. Induced and triggered seismicity has been observed worldwide in conjunction with several industrial activities. This figure shows the global distribution of anthropogenic seismicity and the maximum magnitude reported at each site. The catalogue (source: *Davies et al.* [2013]), updated until August 2016, shows the scientifically documented seismic events associated to different industrial operations (each type of industrial activity is represented by a particular color). The seismic sequences are declustered and only its maximum magnitude of the sequence (if $M_L > 1.5$) is reported. The highest number of induced seismic events are related to mining and hydrocarbon industrial activities, while those related to wastewater injection operations, although significant in terms of magnitude, are the fewest (plot on the bottom right corner). The label "Oil and Gas" includes hydrofracking, secondary recovery, oil and gas extraction, and natural gas storage.

Recent cases of induced seismicity related to different industrial operations had a negative impact on the surrounding communities living close to these industrial sites and have opened (aided by new communication media) strong public debates. As a result seismicity from the industrial activities under question may reduce their public acceptance and raise concerns about the risk associated with them. The growing scientific interest toward this topic during the last years is depicted in Figure 2, which shows the yearly number of scientific papers indexed with the keyword induced seismicity. This analysis has been performed using the Scopus database (website: www.scopus.com). The trend in Figure 2 shows a significant increase after November 2011, when the M_l 5.6 Oklahoma earthquake was induced by wastewater injection [*Keranen et al.*, 2013] (see Figure 1). In a similar way, the interest of the general public in this topic can be seen by analyzing the (global) web queries containing the nontechnical term "fracking earthquakes" (Figure 3a) which dramatically increased after November 2011. This analysis has been performed using Google trends, which does not report the absolute number of queries for a given search terms, but a query index. The query index starts with the query share (the total query volume) for a given search term in a given region and at a given time. The query share numbers are then normalized so that they start at zero on 1 January 2004. Values at later time indicate the deviation (normalized to 1) from the query share at the reference date [*Choi and Varian*, 2012]. In light of this analysis, one could argue that the November 2011 induced earthquake in Oklahoma "triggered" the interest of both the scientific and nonscientific community on this topic.

The seismicity rate in Central United States dramatically increased since 2009 [*Ellsworth*, 2013]. In 2015 Oklahoma experienced more than 900 $M_L > 3$ felt earthquakes, while before 2009 the average rate of $M_L > 3$ earthquakes was about one event per year [*Langenbruch and Zoback*, 2016]. Among the many different reported sequences of fluid injection-induced seismicity in the world, the activity in this region is probably the most significant example. In response to the constant increase of seismicity rate associated with wastewater injection [*Ellsworth*, 2013], the state regulator (the Oklahoma Corporations Commission) called (at the end of 2015) for a 40% reduction of such industrial operations [*Langenbruch and Zoback*, 2016]. The very elevated

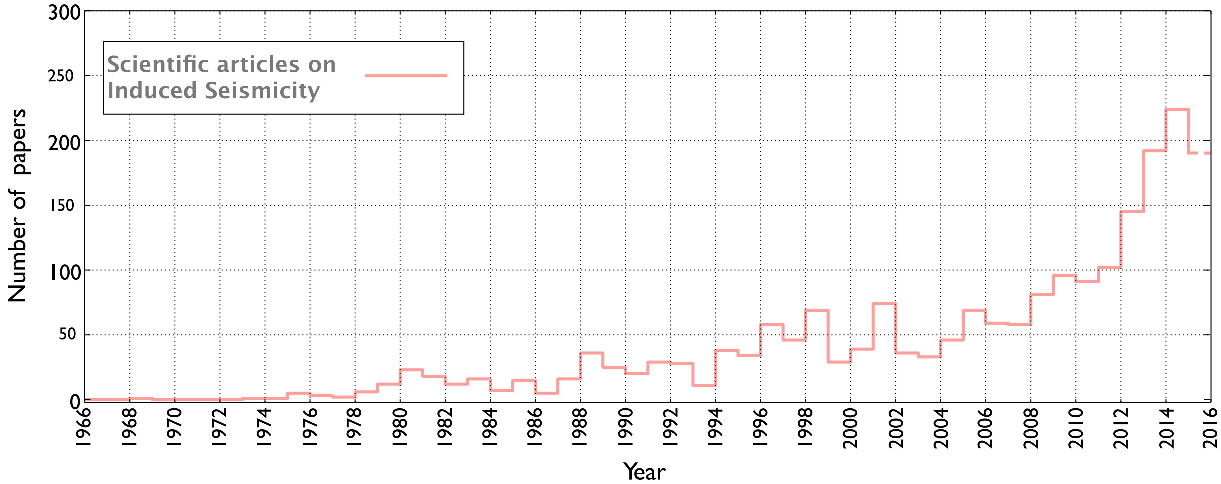


Figure 2. Yearly number of scientific papers on topic of induced seismicity (Scopus Database).

public interest on the issue of wastewater injection operations resumed following the recent induced earthquakes in Oklahoma, such as the M_w 5.1 Fairview event [*Yeck et al.*, 2016] in February 2016 and the M_w 5.8 Pawnee event in September 2016. This one is so far the largest induced earthquake related to wastewater injection operations and, at the same time, the largest instrumental earthquake ever recorded in Oklahoma [*Manga et al.*, 2016; *Langenbruch and Zoback*, 2016].

The United States is not the only North American country currently dealing with the issues of anthropogenic seismicity. Recent seismic activity in Alberta (Canada) has been associated with hydrofracking operations [*Atkinson et al.*, 2016]. In this case the Alberta Energy Regulator introduced a three-stage traffic light protocol (see section 5), in an attempt to prevent the occurrence of felt induced seismicity [*Schultz et al.*, 2017]. Despite these regulations, on 12 January 2016, a M_w 4.1 earthquake struck Fox Creek in Alberta, Canada, to date the largest seismic event ever caused by hydraulic fracturing [*Schultz et al.*, 2017]. Since the magnitude of this event was higher than the threshold for the red light level of the traffic light system (which was set to M_l 4.0), hydraulic fracturing operations were halted.

In Europe there have also been recent induced seismic events associated with underground exploitation activities felt by the population. In most cases the consequence was the reduction or cessation of the related industrial operations. Key examples are as follows: Basel, Switzerland (2006 [*Haering et al.*, 2008]), Blackpool, UK (2010 [*Clarke et al.*, 2014]), Castor, Spain (2013 [*Cesca et al.*, 2014]), and the long-lasting seismicity at Groningen, Netherlands [*van Thienen-Visser and Breunese*, 2015]. All these cases highlight the fact that induced seismicity is not an issue easy to manage which has an important socioeconomic impact. This study aims to introduce the scientific and societal challenges posed by the induced seismicity from a European perspective, focusing on the still open questions on its monitoring, discrimination, and management. We further review in detail key cases of induced seismicity in Europe, which have led to the suspension or reduction of the related industrial activities.

2. The Problem of Fluid-Induced Seismicity in Europe

The increasing public attention and concern on induced seismicity has led governmental agencies from different countries to address this problem by releasing new regulations or updating existing ones. In the United States, for instance, USGS included the hazard for induced seismicity in the National Seismic Hazard Model [*Petersen et al.*, 2016], while in several European countries (e.g., Italy, Netherlands, and Switzerland), governments require exploitation companies to arrange appropriate microseismic monitoring infrastructures. It is important to note that different geographic and social factors exist between parts of the United States such as Colorado or Oklahoma, and many European countries, such as Germany, France, Netherlands, United Kingdom, and Italy, that have a population density almost 10 times larger. Another important difference between the European countries and the U.S. concerns the ownership of the subsurface natural resources. In Europe, on the one hand, the owner of subsurface natural resources (oil, gas, gold, coal, and other resources) is the state and the exploitation of natural resources is managed directly by the government, releasing licenses

Figure 3. (a) Normalized number of searches on Google for the word "fracking earthquakes." (b) Normalized number of searches on Google from Italy for the words "drilling," "gas extraction/storage," and "fracking" (the Emilia earthquake occurred within the time frame highlighted in yellow). (c) Normalized number of searches on Google from Spain for the words "Project Castor," "gas injection," and "fracking" (the Castor earthquake sequence occurred within the time frame highlighted in yellow).

to companies. In the United States, on the other hand, the owner of the surface land have also the rights to exploit natural resources underneath, in this case companies directly contact the land owners to secure exploitation rights. In Europe, the government is a main actor during the entire exploitation process of natural resources (from the exploration to the production phase), in the United States it has a marginal role. Demographics, lifestyle, culture, and vulnerability of historical and artistic heritage are key factors influencing the impact of the induced seismicity problem [*Hays et al.*, 2015]. This means that in order to address this issue, potential solutions applicable to the United States might not be feasible in Europe. High population density and the relative vicinity of many industrial sites to residential areas mean that any attempt to satisfactorily address the induced seismicity issue in Europe must involve an adequate monitoring of industrial activities and more sophisticated monitoring techniques that include real-time seismicity analysis coupled with clear, transparent decision protocols. The ultimate goal is to stop or reduce industrial operations before the occurrence of potential damaging earthquakes. It is also important to note that the public perception of induced seismicity also depends on the geographical region where it occurs. On the one hand, in tectonically active regions induced seismicity is better tolerated, even when it can be distinguished from natural seismicity, as the population regularly experience small earthquakes and buildings are generally designed taking into account the seismic hazard of the area. On the other hand, people living in relative stable tectonic regions with low seismicity rates may never have felt an earthquake before, and their reaction to felt induced seismicity is relatively larger. Thus, seismic events that may cause minor, nonstructural damage can place industry on notice or halt its operations altogether. From this perspective, the societal impact of induced seismicity consists of a low risk of injury or loss to those exposed to an unfamiliar hazard, while industry faces a high risk of business loss due to what might be considered only minor, nuisance ground shaking in a tectonically active region.

In this section we focus on few critical cases (mainly related with fluid injection or extraction operations) in Europe where seismicity close to industrial sites has led to strong public debate and consequently to a reduction or cessation of the related industrial activities. We will further focus on the data analysis procedures and decision protocols that followed during these crises.

2.1. Groningen (the Netherlands), Natural Gas Production

Seismicity observed at the Groningen field, in the Netherlands, is probably the most widely known and important case of recent induced seismicity in Europe. The Groningen field is the largest European gas production field, and it is one of the main supplier of natural gas in northern Europe. This field was discovered in 1959, gas production started in 1963, and as of today about the 75% of gas initially in place has been extracted [*van Thienen-Visser and Breunese*, 2015] (Figure 4a). There is no evidence of historical earthquakes in the Northern Netherlands, thus the region is considered tectonically stable. Seismicity induced by gas extraction operations started to be observed in the Northern Netherlands in 1986, while the first event within the Groningen field was recorded in 1991 [*Dost and Haak*, 2007]. Between 1991 and 2002, the increased seismic activity (Figure 4b) raised public concern and led the Dutch government to release a new mining law which requires, for each exploitation license, a hazard and risk analysis and microseismic monitoring of the industrial operations [*Dost et al.*, 2012]. The seismic activity continued to increase after 2002 and reached a maximum in 2013 (Figure 4b). The largest recorded event, the M_w 3.6 Huizinge earthquake (Figure 1), occurred on 16 August 2012. This episode reactivated the interest of the population toward the issue of induced seismicity, pushing the government and the company to build a large microseismic network composed of more than 60 borehole stations (each station contains four three-component seismic sensors equally spaced between 0 and 200 m depth). Figure 4a shows the spatial distribution of the induced seismicity and the evolution of the microseismic monitoring network of the northern Netherlands. Most of the seismicity is confined within the Groningen field and it is accompanied by ground surface subsidence caused by the massive exploitation of the gas reservoir. In order to mitigate both the effect of subsidence and induced seismicity and to increase the societal acceptances of these industrial activities, the Dutch government decided to move the gas production from the central part of the main field toward the less compacted peripheral parts of the Groningen field and to further reduce the overall production [*van Thienen-Visser and Breunese*, 2015] (Figure 4c).

2.2. Basel (Switzerland), Geothermal Energy Exploitation

Another important European case of induced seismicity was related to an Enhanced Geothermal Systems (EGS) project in Basel (Switzerland). EGS technologies, unlike the conventional geothermal systems, exploit geothermal resources in Hot Dry Rocks (HDR) through hydraulic stimulation. The aim of a hydraulic stimulation process is to enhance the reservoir permeability through shearing and opening of preexisting fractures (hydroshearing) or creating new ones (hydrofracturing). The stimulation occurs by pumping high-pressure

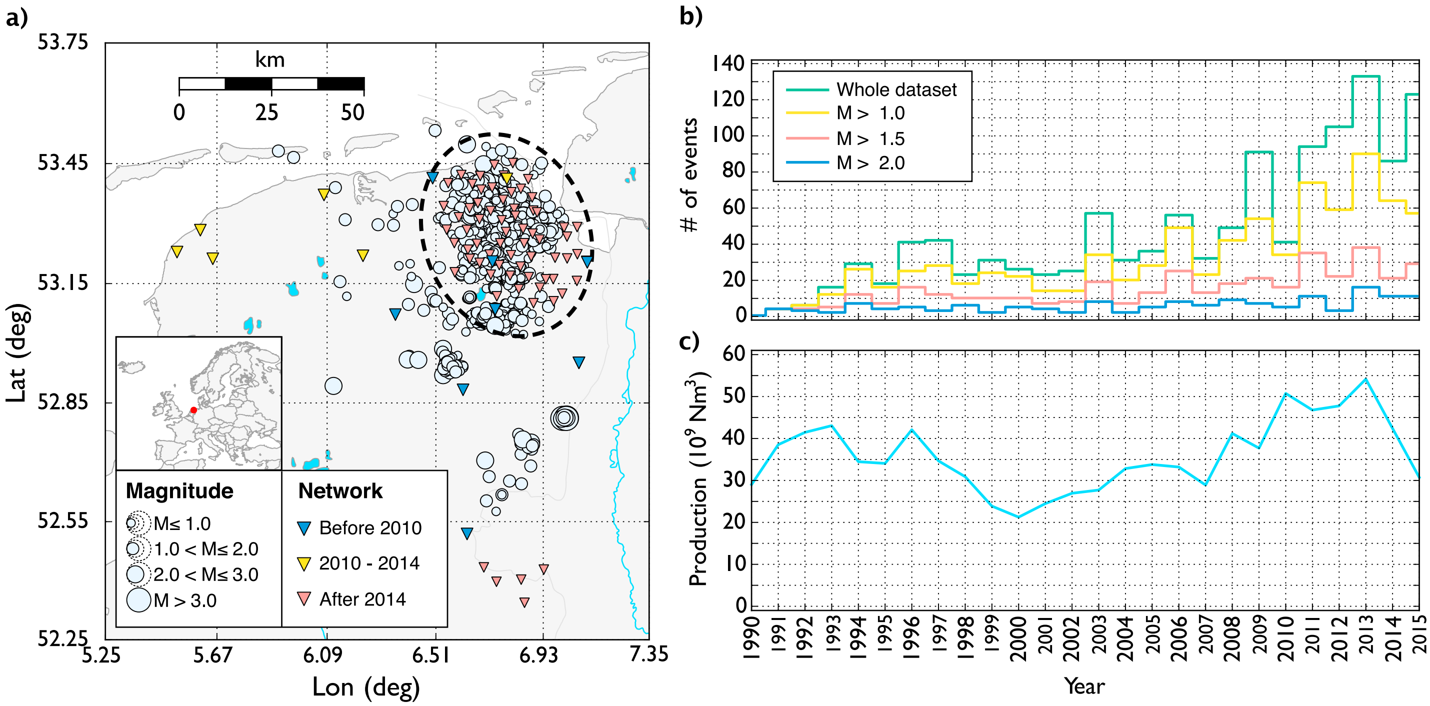


Figure 4. (a) Temporal evolution of the seismic monitoring network in the northern Netherland. Inverted triangles represent seismic stations, while each color is related to a different time period. The circles in the map (Figure 4a) represents the induced seismic events (depth of the events is fixed by default at 3 km), while the region within the dashed line corresponds with the Groningen gas field. (b) Number of seismic events per year sorted per magnitude range. (c) Yearly gas production expressed in normal cubic meters Nm^3. Seismicity and production data from KNMI (www.knmi.nl) and NLOG (www.nlog.nl).

cold water into the HDR formation at few kilometer depth, allowing generation of efficient subsurface heat exchanges. The aim of the Basel project, starting in 1996, was to develop a geothermal power plant from an EGS in the city of Basel (Switzerland). After several feasibility studies and tests, the stimulation experiments in the Basel EGS site started on 2 December 2006 by injecting approximately 11,500 m^3 of water at high pressure into a 5 km deep well [*Haering et al.*, 2008]. During the injection phase, an intense seismic activity consisting of thousands of induced earthquakes was recorded by a local borehole array (installed by the company) and by the regional network of the Swiss Seismological Service (SED). At the peak of the injection (wellhead pressure of about 30 MPa) a seismic event of magnitude M_l 2.6 occurred. This earthquake surpassed the safety threshold of a four-level "traffic light" system established for halting operations in order to prevent potentially damaging induced seismic events. For this reason it was decided to stop the injection process. However, after well shut-in, a M_l 3.4 earthquake occurred during preparations for bleeding off the well to hydrostatic conditions [*Haering et al.*, 2008]. After this event several concerns and damage claims arose from local residents of the Basel area. At the end of the crisis the damage claims associated with the M_l 3.4 earthquake amounted to more than \$9 million [*Giardini*, 2009]. While for a natural earthquake, the damage would have been covered by the homeowners, in this case the whole cost was picked up by the company's liability insurance [*Giardini*, 2009].The induced seismicity in Basel led to the suspension of its EGS project, prompted a strong public debate, and raised the general interest on the topic of induced seismicity in Switzerland. One consequence was the definitive suspension of the project in 2009.

2.3. Emilia (Italy), Natural Seismicity

In some cases, natural earthquakes occurring close to industrial sites can be associated to human operations, raising strong public concern and causing huge financial losses to several industrial activities. The May 2012 Emilia (Italy) earthquake sequence is a perfect example of such kind of cases. This sequence occurred in the Po plain, a seismically active region between the Alps and Apennine mountains chain (Figure 5), which experienced several significant (with an estimates magnitude $M_e < 5.5$) historical earthquakes [*Vannoli et al.*, 2015]. The largest and most relevant historical earthquake in the area, before the May 2012 sequence, was the 1570 Ferrara earthquake with an estimated magnitude M_e 5.5 [*Vannoli et al.*, 2015], with a seismic sequence that started on 17 November 1570 and caused severe structural damage and partial collapses in the city of Ferrara

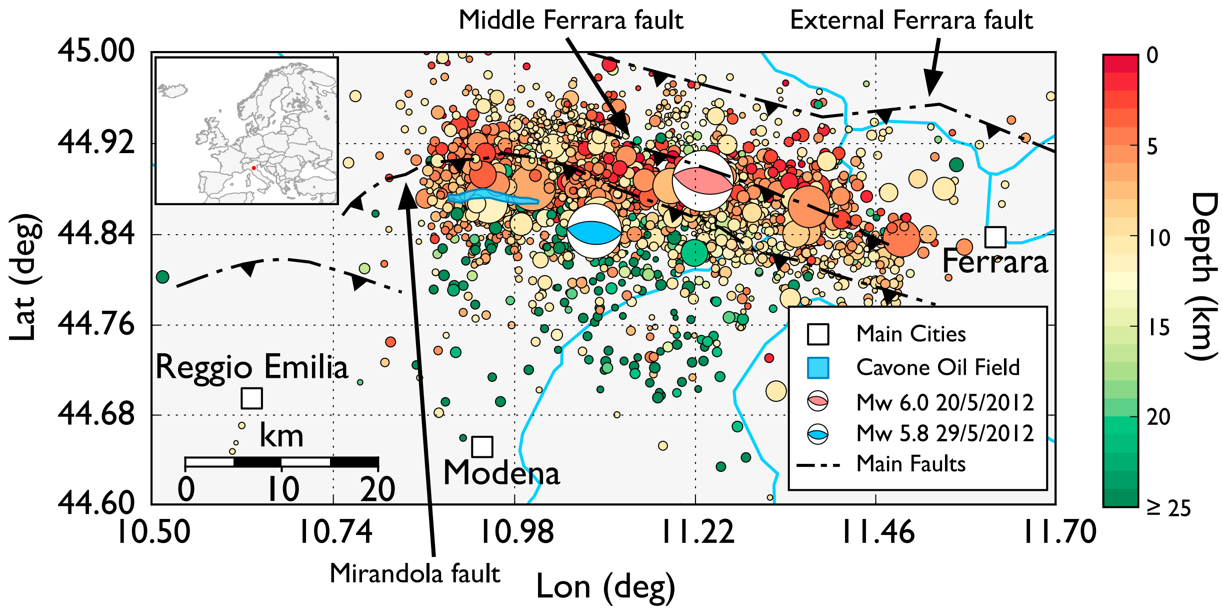


Figure 5. Map showing the seismicity in the Cavone area (from the INGV earthquake catalog, time period between January 2011 and February 2013), the focal mechanisms of the two largest 2012 Emilia-Romagna earthquakes, the Cavone oil field (light blue area), and main faults in the area (black lines).

and its surroundings. On 20 May 2012 a M_w 6.0 earthquake occurred in the Emilia Romagna region (northern Italy), with a shallow focal depth of 6.3 km [*Cesca et al.*, 2013a]. This event started a long seismic sequence, culminating in a second M_w 5.8 strong shock on 29 May 2012 followed by several aftershocks. The two strongest events of the sequence caused structural and nonstructural damage to residential, industrial, and public buildings as well as 27 fatalities [*Masi et al.*, 2014]. The 20 May earthquake occurred on the western segment of the Middle Ferrara fault, while the 29 May earthquake nucleated about 10 km to the southwest of the 20 May event epicenter and occurred on the Mirandola fault, which bounds the Cavone oil field from the north [*Juanes et al.*, 2016] (see Figure 5). The proximity of the sequence to this industrial site encouraged speculation on the possibility that earthquakes have been affected by anthropogenic factors. Public concern is reflected in the dramatic increase of web queries from Italy for the words “drilling,” “gas extraction/storage,” and “fracking” following the beginning of this seismic sequence (Figure 3b). Also, in this case, the analysis has been performed using Google trends. It is interesting to note that, although hydrofracturing operations are not allowed in Italy, the web queries of the keyword fracking reached the maximum peak immediately after the Emilia earthquake sequence (Figure 3b). We interpret this as an effect of a miscommunication campaign which opened a hot debate on the anthropogenic origin of the Emilia earthquakes. In December 2012, the Italian government encharged an international group of experts, the ICHESE (International Commission on Hydrocarbon Exploration and Seismicity in the Emilia region) commission, to investigate the possible relationship between the sequence and the industrial operations carried out in the vicinity of the epicentral region. In its final report, the commission did not exclude a link between the regional seismicity and the oil extraction operations performed in the Cavone oil field (Figure 5) [*ICHESE*, 2014], although there was no clear link with the May 2012 earthquake sequence. These results have raised political discussions and strong debates in Italy and worldwide [*Cartlidge*, 2014]. On April 2014 the company managing the exploitation of the Cavone field funded a research activity to be carried out by another group of experts, which demonstrated that there was no physical reason to suspect that pressure changes associated to the exploitation of the Cavone oil field triggered the earthquakes that occurred in the Emilia Romagna region in 2012 [*Astiz et al.*, 2014; *Juanes et al.*, 2016]. Furthermore, a quantitative probabilistic approach proposed by *Dahm et al.* [2015] to discriminate induced, triggered, and natural earthquakes was applied to this seismic sequence. The authors concluded that the proposed discrimination scheme clearly indicates that the 2012 Emilia earthquake was neither triggered nor induced by field depletion; therefore, it is very likely of tectonic origin. Despite these scientific findings, the anthropogenic origin of the Emilia earthquakes still remains a topic of public debate. This case highlights the difficult issue of discriminating between natural and anthropogenic seismic events. Considering the strong socioeconomic impact of induced seismicity on both companies and local communities, correct discrimination of induced seismicity is a very important task in currently active topic of research.

2.4. Castor Project (Spain), Natural Gas Storage

Another recent case, which focused the attention of the general public on the issue of induced seismicity, was linked to an underground gas storage (UGS) facility in Spain, named the Castor project. This UGS plant was considered the most suitable solution in balancing supply and demand of natural gas in Spain, as well as serving as a main strategic reserve, and it was considered a strategic priority for the Spanish government. This project was the first of this kind in the Mediterranean coast [*Barat*, 2011; *Watercraft Capital*, 2013]. The Castor Project expected to reuse the depleted Amposta oil field, located 21 km off the coast of the Valencia Gulf (Spain) (see Figure 1). This offshore geological structure, in operation between 1973 and 1988, and with unique reservoir characteristics (including a high withdrawal capacity, a low requirement of cushion gas, and the possibility of injecting the full cushion gas and working gas volumes in the first year), provides an estimated total of 1900 million Nm^3 (Normal cubic meters, i.e., the gas volumes at standard conditions of pressure and temperature) of gas storage capacity. The offshore injection platforms are linked to an onshore plant by an approximately 30 km long, high-pressure pipeline. With an estimated cost of about $2 billion, the Castor Project was one of the few European Projects of Common Interest selected in July 2013 to be financed under the pilot phase of the Europe 2020 Project Bond Initiative, launched in 2012 by the European Commission and the European Investment Bank [*EIB*, 2012; *Watercraft Capital*, 2013; *Counter Balance*, 2014; *Dhondt et al.*, 2014]. Preliminary injection tests were performed in June 2013, with no evident seismic activity observed. In September 2013 the first injection phase started, and it was followed by a sudden increase of seismicity. More than 1000 events with magnitudes between M_l 0.7 and 4.3 and located close to the injection platform were recorded in about 40 days (see Figure 6a). This seismic activity was unusual if compared to the instrumental and historical seismicity of the area. Several events were felt in localities at the shoreline, triggering significant concern among the local population. The public concerns arising from seismic activity made the Spanish Government shut down the activity. However, the seismic sequence continued for weeks after the shut down operations (on 16 September 2013) and culminated with a M_w 4.3 on 4 October 2013, the largest earthquake ever associated with gas storage operations [*Cesca et al.*, 2014; *Gaite et al.*, 2016]. At the end of 2014, the Spanish government definitively terminated the concession of the UGS plant. Since January 2015 about 20 people who took part in the transaction and approval of the Castor Project have been indicted. The interest of the general public in this event can be clearly seen in Figure 3c, which shows the web queries in Spain for the words “Project Castor” and “gas injection.” Unlike the Italian case, we observe no correlation with the keyword fracking, which may denote a better information campaign concerning the industrial operations related with the project and a better perception on induced seismicity. Also, in this case, web queries analysis was carried using Google trends [*Choi and Varian*, 2012].

These cases highlight that there are issues with induced seismicity that are far from being fully addressed. The potential of induced seismicity is sometimes strongly underestimated by companies, and once it occurs can easily become a matter of intense public discussion. Further recent relevant examples of seismicity related to underground exploitation operations in Europe, not discussed in detail here, include St. Gallen (Switzerland [*Edwards et al.*, 2015]), Val D’Agri (Italy [*Stabile et al.*, 2014; *Improta et al.*, 2015]), and Blackpool (UK [*Clarke et al.*, 2014]). The ambitious aim of reducing and preventing potentially damaging induced earthquakes can be reached only overcoming the current scientific and technical challenges, described in the following sections.

3. Challenges in Monitoring Induced Seismicity

Microseismic monitoring plays a key role in better understanding the physical mechanisms governing induced seismicity. 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].

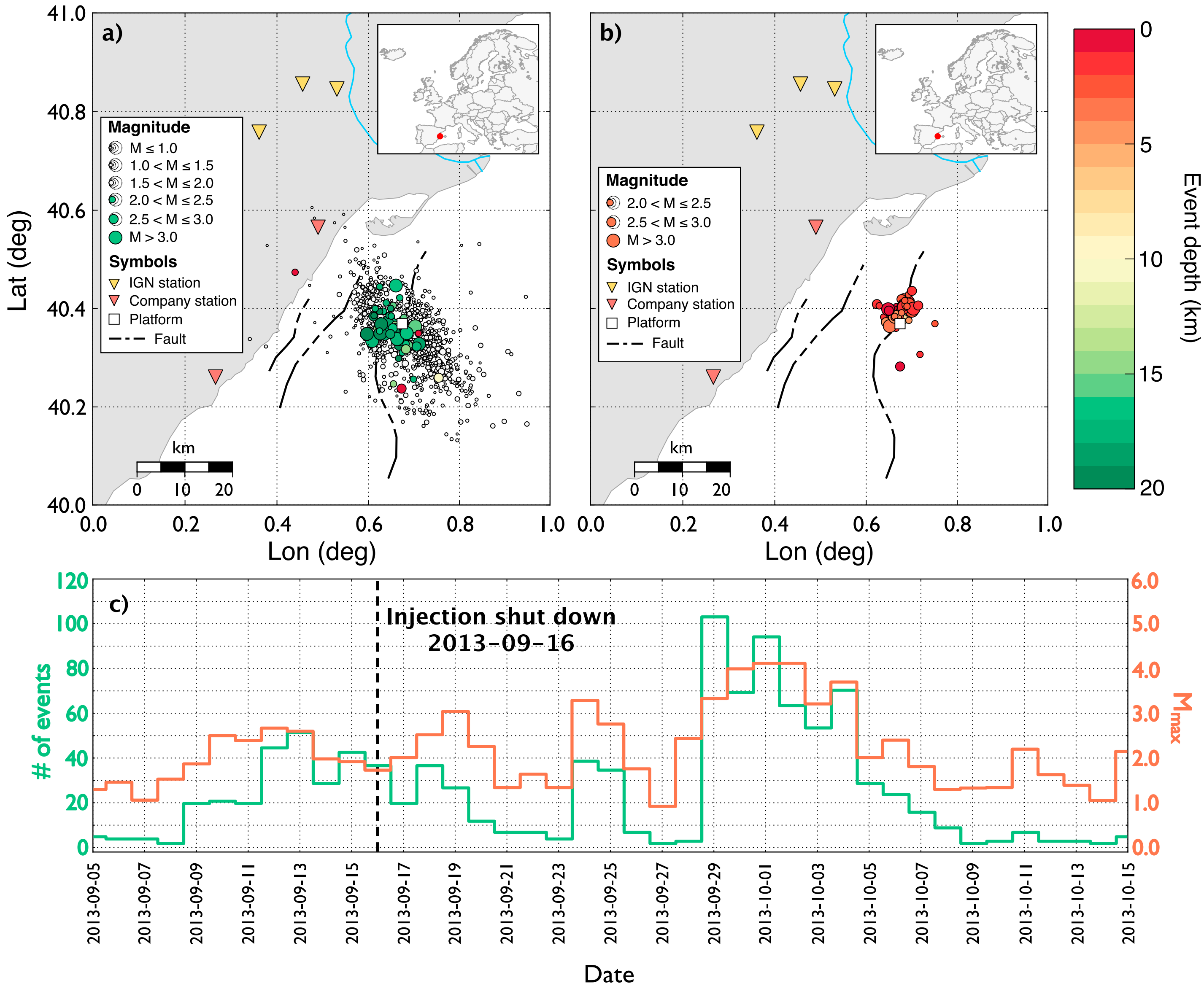


Figure 6. (a) Distribution of seismicity according to the catalog of the Ebro Observatory, all the events with magnitude $M_L > 2$ are denoted by colored circles. (b) The relocation of seismic events with $M_L > 2$ by using a waveform stacking location method [*Cesca et al.*, 2014]. For both panels (Figures 6a and 6b), the event depth is represented in color scale (from red to green); the white square is the location of the gas injection platform and the seismic stations are denoted by reverse triangles. (c) The temporal evolution of the seismic sequence in terms of the daily number of events (green line) and maximum daily magnitude (red line) [after *Cesca et al.*, 2014].

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 (see, for instance, the Castor case [*Cesca et al.*, 2014]). 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.

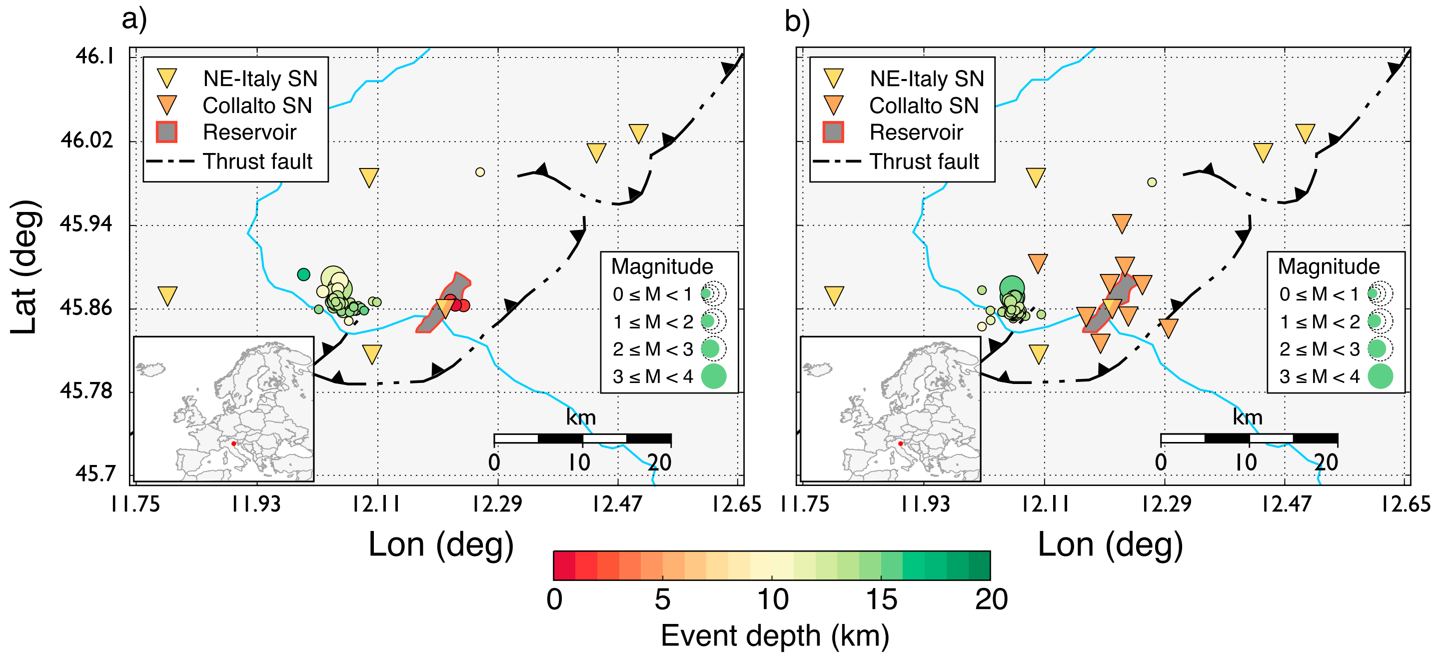


Figure 7. Seismic sequence occurred in Valdobbiadene (Veneto Region, Italy) on 12–15 May 2015. The sequence consists of two *M*3.6–3.7 events and about 100 of aftershocks which have been located (a) with regional network managed by OGS (in this case three events were mislocated within the reservoir and at compatible depth) and (b) with a dedicated microseismic network. In this case (Figure 7b) the events were relocated within the sequence cluster at distance larger than 10 km from the reservoir. Depth is represented in the color scale.

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 M_l of about 1.0 were mislocated close to the gas reservoir, and at approximately the same depth (Figure 7a). 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 7b). 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. 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 6a). A successive analysis of the seismic sequence with more sophisticated waveform-based location methods (Figure 6b) revealed a more 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 6c). 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].

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 proprieties [*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 M_c, is application dependent and should be carefully chosen taking in consideration the seismic hazard, background seismicity, and the M_c 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 (see section 5) 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 $M_c \geq 0.0$), 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 M_w 1.8 [*Kim*, 2013]. Finally, *Bao and Eaton* [2016] showed 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

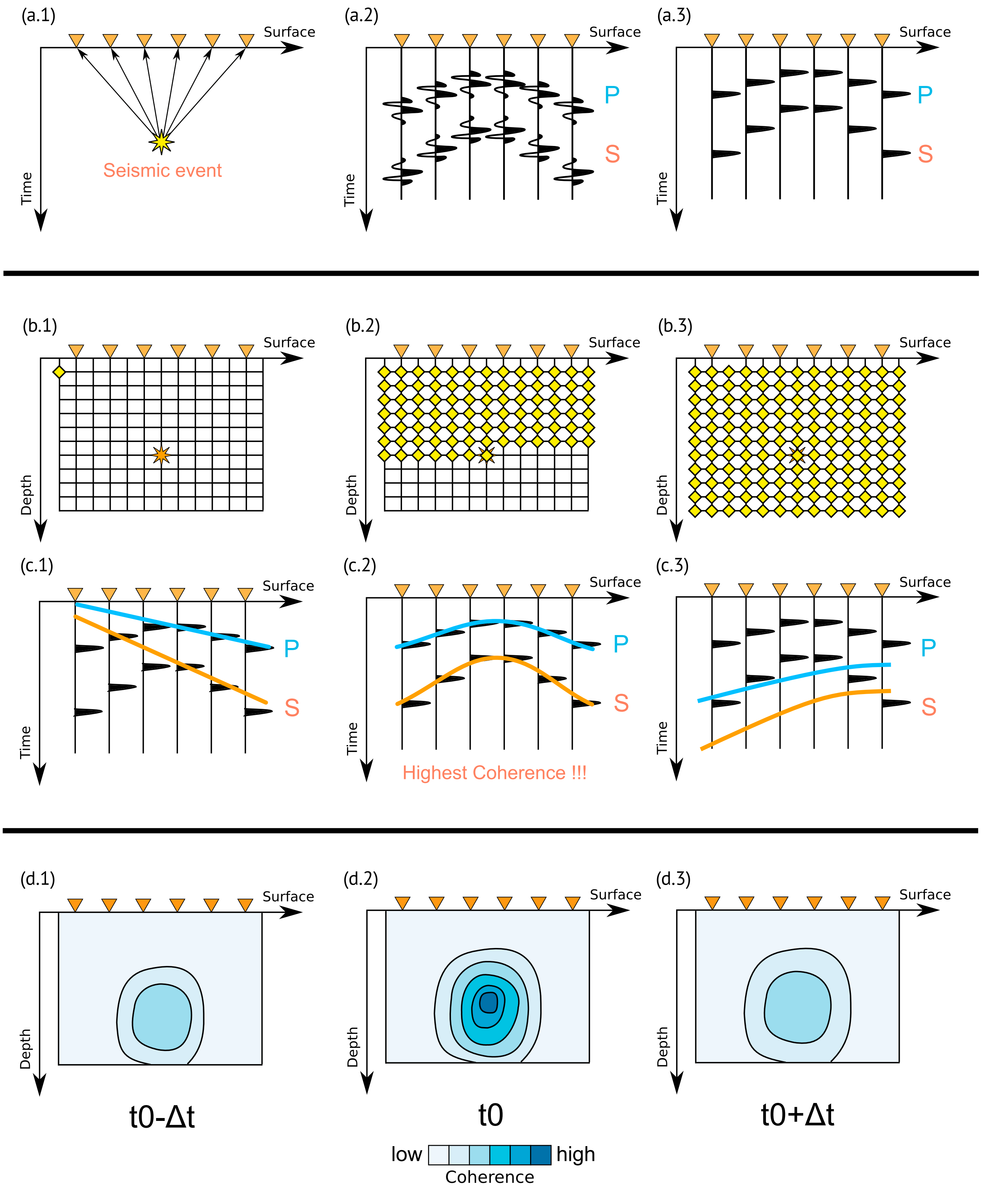


Figure 8. Seismic event recorded by a line of receiver deployed on the (a.1) surface, (a.2) raw, and (a.3) processed traces. Waveform stacking is performed by scanning different (b.1–b.3) source locations and (c.1–c.3) origin times. The e output of the location process is (d.1–d.3) a multidimensional coherence matrix whose maximum corresponds with the hypocenter and the origin time *t*0 of the seismic event (Figure 8d.2). [After *Grigoli et al.*, 2016].

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 9a). 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 9b and 9c). A comparison between the locations obtained using the Double Difference method [*Waldhauser and Ellsworth*, 2000] (Figure 9d), the classical waveform stacking (Figure 9e), and the Master-event waveform stacking locations (Figure 9f), 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

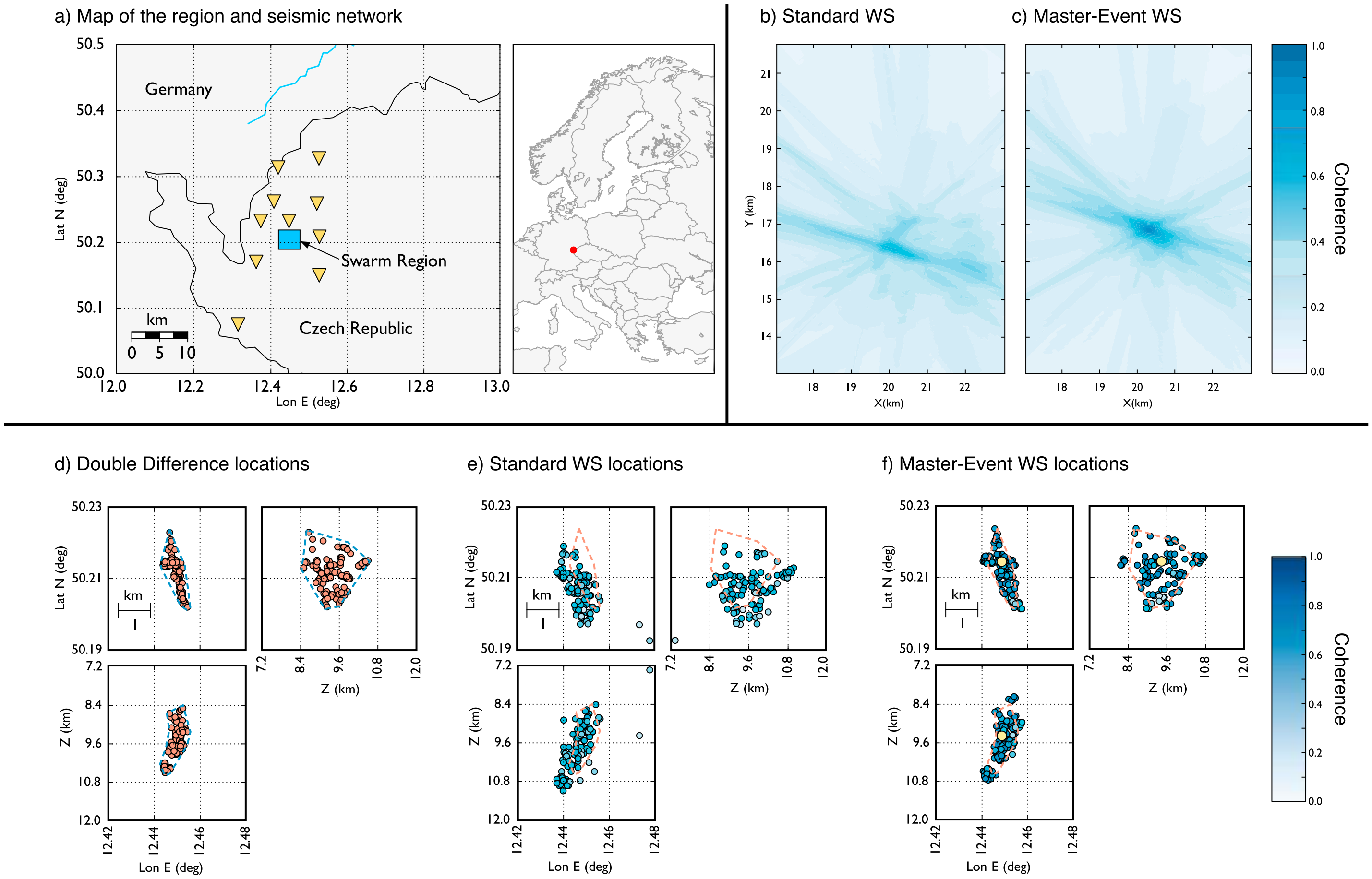


Figure 9. (a) North-West Bohemia (Czech Republic) region and seismic network. Coherence matrices (epicentral projections only) of a sample event obtained using the (b) standard WS and the (c) master-event WS location method. Location results using (d) double-difference, (e) standard WS, and (f) master-event WS location methods. [After *Grigoli et al.*, 2016].

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 (M_l 2.3) and those based on records from the regional network (M_l 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 semiautomated 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.

4. Challenges in Discriminating Induced/Triggered From Natural Seismicity

How to discriminate between natural and induced seismicity? The problem is not yet solved and represents a big challenge for future studies. Before discussing the current methods to differentiate natural and anthropogenic earthquakes, it is worth here to mention the difference between triggered and induced seismicity. Purely induced earthquakes have been recognized in the literature on the base of spatial and temporal correlation to human operations, in some cases considering deviations from background seismicity and/or anomalous seismic source parameters (e.g., shallow depth, detection of tensile source components). For triggered seismicity cases, recent works suggest that human operations control the rupture nucleation, the tectonic stress controls the rupture process, then magnitude and aftershock distribution [e.g., *van der Elst et al.*, 2016]. Hence, for triggered seismicity the discrimination problem is extremely challenging and may only be considered within a probabilistic framework [*Dahm et al.*, 2015]. In several cases different scientific studies on the anthropogenic origin of a particular seismic events do not converge to the same conclusion. One of these, still debated, cases is the M_l 5.5 Lorca earthquake which has been associated to groundwater exploitation by some authors [*Gonzalez et al.*, 2012], while it was considered natural by others [*Martinez-Diaz et al.*, 2012].

Intuitively, the spatial and temporal correlation between human activity and event occurrence may represent a key parameter to discriminate between natural and anthropogenic seismicity, but unfortunately this is not always the case. Indeed, many industrial operations involving subsurface fluid injection (e.g., wastewater disposal) can transmit pore pressure changes at large distance, causing earthquakes several kilometers away from the industrial site. In these conditions, and specially in tectonically active regions, the discrimination problem is very challenging [*Goebel et al.*, 2015]. In addition, an induced event may occur months or years after the related industrial operations has been stopped or reached the maximum peak [*Mulargia and Bizzarri*, 2014; *Keranen et al.*, 2013]. Furthermore, in many cases anthropogenic seismicity remains undetected in tectonically active regions, being masked by the background natural seismicity. Without a detailed study, involving seismicity analysis, pore pressure diffusion [*Shapiro and Dinske*, 2009], stress modeling, and an assessment of the geological setting of the area [*Juanes et al.*, 2016], discriminating induced from natural seismicity, is extremely challenging or even impossible. In the last years, several authors proposed their own solutions on how to address this problem. However, a standard procedure to discriminate induced seismicity does not exist. A possible reason is that often, from case to case, very heterogeneous data are available, making it difficult to adopt the same approach for every study case. In many cases, seismicity data are only available in terms of earthquake catalogs. In most fortunate cases, continuous records of seismic waveforms from dedicated monitoring networks are available, while data related to industrial operations (e.g., volume and pressure of injected fluid) and geological models are rarely available. Thus, the choice of a discrimination approach often strongly depends on the type of available data. In most cases, the spatiotemporal correlation between seismicity and industrial activities is generally the main tool to investigate the natural or the anthropic origin of earthquakes proximal to industrial sites [*Oprsal and Eisner*, 2014]. Seismic events are then considered induced by human operations if they are "close enough" both in terms of space and time to the industrial activity. However, a clear definition of spatial and temporal "closeness" is subjective, so that these approaches often do not provide a clear outcome [*Dahm et al.*, 2015].

The first attempts to address the discrimination problem between induced and natural seismicity has been made by *Davis and Frohlich* [1993] for fluid injection and by *Davis et al.* [1995] for fluid withdrawal operations. These approaches are based on a set of (seven/nine) YES-NO criteria, taking into account several factors such as the spatiotemporal correlation between seismicity and industrial activity or the change in the background seismicity rate. The former approach has been recently revisited by *Frohlich et al.* [2016a], which propose a new question-based approach broadening the target to seismicity induced by different mechanisms. The new approach aims to classify seismicity into four classes, based on the cumulative score of the answers to five questions: tectonic, possibly induced, probably induced, and almost certainly induced. The approach raised some early criticisms (in reference to the sensible problem of fluid injection-induced seismicity), because of the scoring definition, eventually weighting excessively on the spatial proximity of seismicity to injection wells, and the missing role of fluid pressure and pathways [*Everley*, 2016]. The knowledge of injected pressure and potential pathways hydraulically connecting the well to the hosting faults would be a useful information to discuss single cases of induced seismicity. However, such information is rarely available, as also pointed out by *Frohlich et al.* [2016b] in their published reply. Moreover, even the idea of a spatial proximity between operations and induced seismicity has been recently debated [*Keranen et al.*, 2014], with injection wells in Oklahoma being suspected to be responsible for induced seismicity taking place at more than 25 km distance. In this sense, the definition provided in the new questions of *Frohlich et al.* [2016a] could be even seen as a conservative choice, since induced seismicity is only supported when occurring at less than 15 km from the injection point. In general, these qualitative approaches may be successfully applied in tectonically stable regions, characterized by low natural seismicity rates. For example, the spatial and temporal correlation of injection operations and seismicity at the Castor platform [*Cesca et al.*, 2014] seems a strong argument with respect to support a case of triggered/induced seismicity, supported by a significant change in seismicity rates with respect to background seismicity. However, in tectonically active region, where earthquakes may occur within few kilometers from industrial sites (see Figures 5–7), this simple approach may not be sufficient to handle the discrimination problem [*Dahm et al.*, 2015]. In the last year, different, more quantitative approaches have been further proposed. Following *Dahm et al.* [2013], we can classify these discrimination methods in three main families: physics-based methods, statistics-based methods, and source parameters-based methods. In addition, recently proposed hybrid methods combine these approaches into common discrimination schemes [*Passarelli et al.*, 2012].

Physics-based methods often rely on the understanding of the several processes occurring at depth. In the last years the understanding of the complex interaction between fluids and seismicity has been highlighted by lab and in situ measurements [e.g., *Samuelson and Spiers*, 2012; *Guglielmi et al.*, 2015] and numerical modeling studies. For example, modeling techniques have shown that while injection-induced seismicity is often controlled by fluid overpressure and/or temperature changes [e.g., *Rinaldi et al.*, 2014, 2015], neglecting static stress transfer between neighboring asperities may result in overestimating the contribution provided by the pressure distribution at depth [e.g., *Catalli et al.*, 2013; *Rinaldi and Nespoli*, 2017]. A complex interaction between fluid and geomechanics is indeed in place, and the relative contribution of the different system components may change with time [*Catalli et al.*, 2013, 2016]. The numerical modeling of induced seismicity has flourished in the latest years, with development of fully coupled models [e.g., *Kolditz et al.*, 2012; *Juanes et al.*, 2016; *Rinaldi et al.*, 2014, 2015] as well as of so-called hybrid numerical models accounting for both physical and statistical-stochastic considerations [e.g., *Gischig and Wiemer*, 2013; *Shapiro et al.*, 2010; *Kiraly-Proag et al.*, 2016; *Rinaldi and Nespoli*, 2017]. These numerical modeling approach can be used in combination with seismicity models, e.g., Rate-and-State seismicity models [*Dieterich*, 1994; *Dieterich et al.*, 2015], to simulate seismicity catalogs, which can be compared with real seismic catalogs. A physics-based method would certainly help in discriminating natural and induced/triggered seismicity since the several approaches have the advantage to investigate the physical processes governing induced seismicity (i.e., stress and pore pressure changes). For example, a detailed model in terms of geology, hydrogeology, and tectonics, will produce a detailed pore pressure and stress variation in relation to injection activities. Such detailed model would strongly help in discriminating whether an earthquake sequence is triggered by fluid injection operations or not [*Juanes et al.*, 2016]. In this case the Coulomb stress change related to pore pressure variation can be used as an indicator of the potential failure of a target fault [*Catalli et al.*, 2013; *Hornbach et al.*, 2015; *Goebel et al.*, 2016]. However, the application of physics-based method is often hindered by limited data availability and computational capacity. Indeed, these methods require production/exploitation data, such as injection rates, injected volumes, and well pressures, plus a detailed geological/hydrogeological model of the area, which are often unavailable.

Statistics-based methods rely on the detection of changes in statistical parameters of the observed seismicity [*Hainzl and Ogata*, 2005], which may be correlated with industrial operations. These approaches do not take into account the physical mechanisms governing induced seismicity and are based only on the statistical analysis of large earthquake catalogues. Most of these methods are based on two main features of natural seismicity: a constant background seismic rate and the behavior of aftershocks sequences in accordance with the Omori law [*Utsu and Ogata*, 1995]. The union of these two features leads to the epidemic type aftershock sequence (ETAS) model which is a point process model that describes the seismicity rate observed in a region as a summation of a background rate of independent events and the aftershocks triggered by each event [*Ogata*, 1988]. In recent years statistical methods for induced seismicity discrimination in the space-time-magnitude domain have been proposed [e.g., *Zaliapin and Ben-Zion*, 2016]. *Schoenball et al.* [2015] applied one of these approaches to the induced seismicity recorded at the Coso Geothermal field (California, USA). They found that induced seismicity is statistically distinguishable from natural seismicity in a space-time-magnitude metric (defined using earthquake magnitudes, interevent times and interevent distances). In general, the main advantage of the statistical approaches is a lower requirement in terms of input data (i.e., earthquake catalogs), which make them suitable when industrial data and detailed models are not available. In recent years, statistical models that forecast induced seismicity as a function of a site-specific parameter and of the injected fluid volume have been proposed (a review of these methods applied to geothermal energy exploitation can be found in *Gaucher et al.* [2015]).

Using source parameters to differentiate among natural and induced seismicity is linked to a second question, which is whether induced earthquake ruptures are any different than those of tectonic earthquakes? Going back to the triggered-induced seismicity differentiation, it seems plausible that the source parameters of triggered events, where the rupture size, orientation, and magnitude are controlled by preexisting faults and background stresses, are not distinguishable from those of natural earthquakes, except for their hypocentral location within the volume affected by human operations, as accounted by the probabilistic approach of *Dahm et al.* [2015]. It remains questionable if, how, and how often, induced earthquakes ruptures are different from those of other earthquakes. A major, obvious difference concerns their shallow hypocentral depth, which may affect other source parameters and signal characterization. For example, *Koper et al.* [2016] found anomalous deviations among local and coda/duration magnitude for mining-induced seismicity, with respect to tectonic events and used this parameter to discriminate induced seismicity; this anomaly was interpreted as a consequence of the shallow depth of mining-induced seismicity, located within near-surface low-velocity layers acting as a waveguide for trapped waves, thus increasing the signal duration at the cost of a lower peak amplitude, as sometimes observed at volcanoes. Even a low-aftershock productivity evidenced, e.g., by *Dahm et al.* [2007] for an induced earthquake in Germany, in comparison to tectonic earthquake of similar magnitude in the same region, could be finally linked to the shallow source location within different geological units. Still linked to shallow depth and near-surface processes, *Cesca et al.* [2011] found anomalous slow rupture of about 500 m/s for an induced earthquake, taking place along a weakened shallow subhorizontal failure plane, at the Ekofisk gas field, North Sea. Recently, *Folesky et al.* [2016] studied the rupture directivity of fluid-induced microseismic events and analyzed the induced seismicity sequence related to the EDS project in Basel (Switzerland). They found that the largest events of the sequence (M_l about 2) nucleate close to the pressure front and propagate backward into the stimulated volume, implying that maximum event size is related to dimension of the fluid-perturbed volume [*Folesky et al.*, 2015, 2016]. Other cases, such as tensile cracks by fluid injection operations or rockbursts and collapses due to mining operations, can be investigated on the base of seismic source parameter, relying on more advanced seismological analysis, such as moment tensor (MT) inversion. Source mechanisms provide important information to model the rupture geometry, to recognize tensile crack processes, and to investigate the stress field perturbation in the subsurface due to external solicitations such as fluid injection/withdrawal operations. Natural earthquakes are generally characterized by nearly pure double-couple (DC) source mechanisms (non-DC earthquakes have been observed in nature, due to the simultaneous rupture of properly oriented multiple faults, e.g., *Miller et al.* [1998], *Frohlich* [1990], and *Frohlich et al.* [1989]), whereas in some cases the presence of an important non-DC component has provided a characteristic indicator of induced seismicity [*Sileny et al.*, 2009; *Cesca et al.*, 2013b; *Guilhem et al.*, 2014; *Zhang et al.*, 2016; *Martínez-Garzón et al.*, 2017]. However, moment tensor inversion procedures are still challenging for microseismic events [*Cesca and Grigoli*, 2015] for the lack of 3-D models and widely adopted inversion tools for 3-D media, which are needed to model high-frequency waveforms [*Guilhem and Dreger*, 2011]. For these reasons this discrimination approach can be applied only to large seismic events, generally with magnitude $M_L > 3$ [*Guilhem et al.*, 2014] and resolve non-DC terms. It is worth to mention that strongly anisotropic media, such as the unconventional reservoirs, can have heavy effect on the polarization, propagation, and the relationship between the source mechanism and the radiation pattern [*Chapman and Leaney*, 2012]. For these reasons moment tensor inversion in such contexts is more challenging and still an active research topic. While full waveform location methods allow to use 3-D velocity models, their implementation for MT inversions are not fully developed: although already applied at regional scales, full MT inversion using 3-D velocity models for microseismic monitoring operations is not yet a standard procedure.

Among the most recent hybrid discrimination methods, joining physical and statistical approaches and accounting for detailed seismic source parameters, the method proposed by *Dahm et al.* [2015] follows a probabilistic framework. The method requires the assessment of the background seismicity rate and the modeling of perturbed seismicity rate, through the modeling of Coulomb stress changes and rate-and-state seismicity model [*Dieterich et al.*, 2015]. Precise source parameters are required, including hypocentral location, focal mechanism, rupture plane orientation, and rupture area. The discrimination is solved through a probabilistic approach, integrating different probability density functions along the rupture area of the target earthquake; the method can potentially discriminate also among triggered and induced earthquakes, if the probability for nonnatural seismicity is large only in a small region corresponding to the rupture nucleation and along the whole rupture area, respectively.

Until today, studies aimed at discriminating induced/triggered from natural seismicity have been carried out a posteriori, several weeks/months after the observation of seismicity.

5. Challenges in Guidelines and Decisional Protocols for Safe Operations

Both the United States and the European Union have no federal laws or regulations specifically related to induced seismicity [*Trutnevyte and Wiemer*, 2017]. Decisional protocols are closely related to the activity being monitored and, in particular, to the regulations of the country (or state for the United States) where industrial activity are carried out. Thus, they may not be transferable to other situations. Most regulations, as well as guidelines and studies on induced seismicity, were published in the period 2011–2014 [*Walters et al.*, 2015a, 2015b] (see also Figure 2), as a consequence of the earthquake rate increase starting in the first decade of the 2000 years [*Ellsworth*, 2013]. In the U.S., the issue of seismicity induced or triggered by underground fluid injection was taken into consideration by regulations only after 2011 [*NRC*, 2013]. Underground fluid injection techniques started to be used in the 1930s in order to increase production from existing oil and gas fields and was used in later years to dispose of industrial wastewater, but it was unregulated until 1974 when Congress passed the Safe Drinking Water Act (SDWA). Through the action of the Environmental Protection Agency (EPA), the SDWA ensures safe drinking water for the public and establishes regulatory authority over the underground injection of fluids. EPA regulates the construction, operation, permitting, and final plugging and abandonment of injection wells, as well. However, neither SDWA nor EPA actions address any issue of seismicity induced or triggered by underground injection. A quite comprehensive summary of the federal and state regulations relevant to injection-induced seismicity can be found in *Hall* [2015]. According to the SDWA and the Bureau of Land Management (BLM) "there is no federal law whose primary purpose is to reduce the risk that fluid withdrawals or injections will trigger seismic activity." SWDA requires that "an application for a Class I or Class VI injection well includes an analysis of past seismicity in the area for which the injection well is proposed." However, this requirement appears to be motivated "by the possibility that existing seismicity will interfere with containment of the injected fluids, rather than with the possibility that the injection will induce seismicity." On the other hand, the Bureau of Land Management (BLM), "in its responses to some public comments that had urged the agency to restrict hydraulic fracturing in areas with seismic zones" declined to do so, explaining that "research on the phenomena of induced seismicity from hydraulic fracturing operations is still ongoing and inconclusive." BLM went on to state that the risk of seismicity could be addressed through the National Environmental Policy Act analysis and that the agency's new fracturing rule requires applicants for permits to submit geological information that could assist such an analysis. Many states of the U.S. including Arkansas, Colorado, Kansas, and Oklahoma have already ordered reductions or shut-in of disposal wells as a result of the increased seismicity. Ohio has released new laws regarding strict liability for concussion damage and new regulations for hydraulic fracturing that require seismic monitoring for wells within 3 miles (about 5 km) distance to known faults and injection suspension after the occurrence of seismic events with

$M_L \geq 1$ [*Kim*, 2013; *Richards*, 2015]. In California, seismic monitoring for hydraulic fracturing operations is also required and the injection must be suspended after the occurrence of $M_L \geq 2.7$ events. In Oklahoma, Traffic Light Systems have been introduced in several industrial sites performing wastewater injection operations, but there is not yet a statewide regulation on this aspect and is not based on real-time seismic monitoring. A brief overview on the current regulations and plans on induced and triggered seismicity in the United States can be found in *Folger and Tiemann* [2016]. In Canada, the Alberta Energy Regulator introduced a three-stage traffic light protocol which requires to report all events of magnitude $2.0 < M_L < 4.0$(yellow level) and to immediately halt operations in case of events with $M_L \geq 4.0$ (red level) *Schultz et al.* [2017].

In this context, seismic monitoring is not only used to detect, locate, and characterize induced seismicity but, in order to reduce the risk of critical events, it is also a valuable tool to manage the industrial activities (e.g., by scaling back operations). Threshold magnitudes, earthquake-injection well distance, alert levels, and possible related actions start to appear as key elements to be applied in procedures such as the traffic light system. Nevertheless, we find that magnitude threshold values in the range 2.0–2.7, recommended for the caution/attention level (Yellow Light Alert) by the different states might not be enough to prevent the trigger of larger earthquakes at larger distance and later times even by reducing the activity level [*Keranen et al.*, 2013, 2014; *Mulargia and Bizzarri*, 2014].

Although many European countries have a big interest in underground industrial activities related to the production of energy, such as shale gas production (which involve hydraulic fracturing operations), hydrocarbon production, and natural gas storage. European Union (EU) Directives on Environmental Impact Assessment (2014/52/EU), hydrocarbon licensing (94/22/EC), or groundwater protection (2006/118/EC) regulate the use of underground resources, covering different aspects but do not include induced seismicity. Only a few countries of the union have developed their own specific induced seismicity regulations and guidelines.

Northern European countries are generally characterized by a low level of seismicity and seismic hazard but, due to the high population density of these countries, there is a great concern about induced seismicity not only since weak, shallow earthquakes are easily felt and might likely produce some damages but also because stronger earthquakes, for which the territory is not prepared, could be triggered. On the other hand southern European countries feature a quite relevant exposure to natural earthquakes with the additional problem of discriminating induced from natural seismicity.

The Netherlands was the first nation to include seismic monitoring into its regulations [*Van Eck et al.*, 2006]. Since 2003 the Dutch mining act requires a seismic risk assessment as part of the production license application, including a description of proposed mitigation measures [*Muntendam-Bos et al.*, 2015]. These assessments set out both the expected maximum magnitude of potential seismic events and the anticipated mitigation measures. A monitoring plan has to be submitted and approved by the authorities. If seismic events occur with magnitudes or impacts exceeding what is described or approved by the plans, the authorities can intervene [*Van Eck et al.*, 2006]. In 2016 a new guideline was published by the regulator. Seismic risk assessment is divided into three levels: (1) screening of the potential risk for induced seismicity based on a deterministic hazard analysis [*Van Eijs et al.*, 2006], (2) screening of seismic risk for gas fields with medium or high potential of induced seismicity using a predefined risk matrix, and (3) full probabilistic seismic risk assessment and risk-management plan for gas fields with a high hazard and impact potential. In the Netherlands, only the Groningen gas field falls into the third level.

In Germany, the first document on the topic of induced seismicity was issued by the German Geothermal Association in 2010 [*GtV-BV*, 2010]. It comes out with a number of recommendations which have dedicated continuous seismic monitoring, liability, and insurance cover, as well as proper communication and information as key points. Among other things, GtV-BV recommends that monitoring networks be managed by public institutions or private companies contracted by public institutions and that each concession arranges and adopts a suitable reaction plan. More technical recommendations on seismic monitoring of induced seismicity were issued by the Research Council Physics of the Earth (FKPE), which coordinates the opinion of the German geophysics institutions on the occurrence of anthropogenic earthquakes [*FKPE*, 2013a, 2013b]. General recommendations are given on how to design a seismic network and perform accurate measurements, the need of integrating seismological data with the industrial activity data, as well as the need for a transparent information and access to data. However, these documents do not provide any clear indication on possible decisional procedures and how to use monitoring result within them, nor if they have been implemented in any official government or regional regulation.

In UK, the main pressure for a regulation on induced seismicity has came from the “shale gas” extraction as well as some CO_2 storage activities. Shale gas extraction activity has been mainly carried out onshore till now. The main concern is not in hydraulic fracturing itself, rather it is in the possibly large quantities of wastewater that are usually reinjected underground into the rock. The UK Department of Energy and Climate Change claims that “This practice is not likely in the UK and any application would be closely scrutinized” [*UK-DECG*, 2014]. Quite severe monitoring procedures and intervention protocols have been recommended and have consequently set up in the major activity fields (e.g., Blackpool) in order to avoid any induced seismicity that could be felt. Those protocols are based on the traffic light system and adopt severe magnitude threshold values (i.e., M_L equal to 0.0 and 0.5 for the yellow and red light, respectively).

In Italy seismic monitoring has been mandatory only for dams, while the other industrial activities were monitored in-house by the involved companies with no obligation to make data publicly available and without any requirement on the monitoring infrastructure. In the years 2008–2010, the Italian government provided that seismic monitoring had to be set up when upgrading underground gas storage facilities in order to allow for the injection of up to 100% of original pressure. After the Emilia 2012 earthquake new monitoring guidelines have been released and extended to all underground industrial activities involving the extraction/injection of fluids from/in the subsurface. The new guidelines are based on the following principles: (1) monitoring will be evaluated a posteriori on the base of its performances; (2) monitoring should be developed and managed by well-referenced, preferably public, institutions; (3) the subject which is in charge of monitoring should remain independent of the company which holds the concession; and (4) information and data should be public and, possibly, open. These guidelines were issued in November 2014 [*MiSE*, 2014] and were adopted in 2015 within the update to the license regulation for hydrocarbon exploitation [*MiSE*, 2015].

The most widely used tools so far for hazard and risk management and mitigation, and an integral part of protocols or best practice recommendations are so called traffic light systems [*Bommer et al.*, 2006]. The classical traffic-light system uses a three-stage (or in some cases four) action plan that governs the injection/extraction of fluids: (1) Normal, continued as planned (green); (2) Caution, proceeds with caution, possibly at reduced rates (amber); (3) Stop, injection/extraction is suspended (red). In order to determine the transition between two levels, a combination of observations are used; these are typically the measured local (or moment) magnitude and some ground motion parameter (e.g., peak ground velocity). The current traffic light systems are defined ad hoc and thresholds for different stages are mainly chosen on the basis of expert judgment. This implementation hinders the objectivity of these tools and does not take into consideration the full range of possible scenarios and uncertainty of the process. The failures of past European projects, such as Basel, Blackpool, and St. Gallen [*Clarke et al.*, 2014; *Edwards et al.*, 2015] denoted the lack of effectiveness of the classical traffic light systems; therefore, more advanced tools and workflows to manage induced seismicity have been developed. Recently, *Wiemer et al.* [2014] introduced the “Adaptive Traffic Light Systems” or ATLS, which is currently in test phase. In contrast with the first generation systems such as those included in the regulations of different countries (such as UK or Italy, among the European cases), these second-generation systems are fully probabilistic, adaptive (in the sense that new data is integrated on the fly to update geomechanical and seismicity forecasting models) and risk-based, integrating hazard, exposure, and vulnerability [*Wiemer et al.*, 2014] (see Figure 10).

A table summarizing the decisional procedures and regulations used in different countries is provided in the supporting information. Although the magnitude plays a central role in almost all of the regulations, other properties such as location, depth, *b* value, and seismicity rate should be taken into account. Of course, all of these properties have some measure of subjectivity associated with data quality, processing methodology, and a priori knowledge that will inexorably be passed on to the regulations themselves. We strongly believe that a more accurate and prompt processing is required before to reach the alert level, which consists of analyzing microseismicity in real time using sophisticated techniques and establishing the possible correlation with the ongoing activity [*MiSE*, 2014]. Induced seismicity risk mitigation also requires specific studies on the impact of local site effects on the shaking. An important element in the estimation of seismic hazard from induced earthquakes is the specification of ground-motion prediction equations (GMPEs), characterizing the expected ground motion amplitudes as a function of the magnitude and hypocentral distance [*Atkinson*, 2015]. More recently, specific studies on GMPEs for induced seismicity have been proposed for areas where large database of waveforms are available, such as Basel, Geysers, Soultz [*Douglas et al.*, 2013], or Groningen [*Bommer et al.*, 2016]. Recent studies suggest that, for the same focal depth and tectonic setting, the ground motions for natural and induced events appear to be similar [*Atkinson and Assatourians*, 2017]. However, the

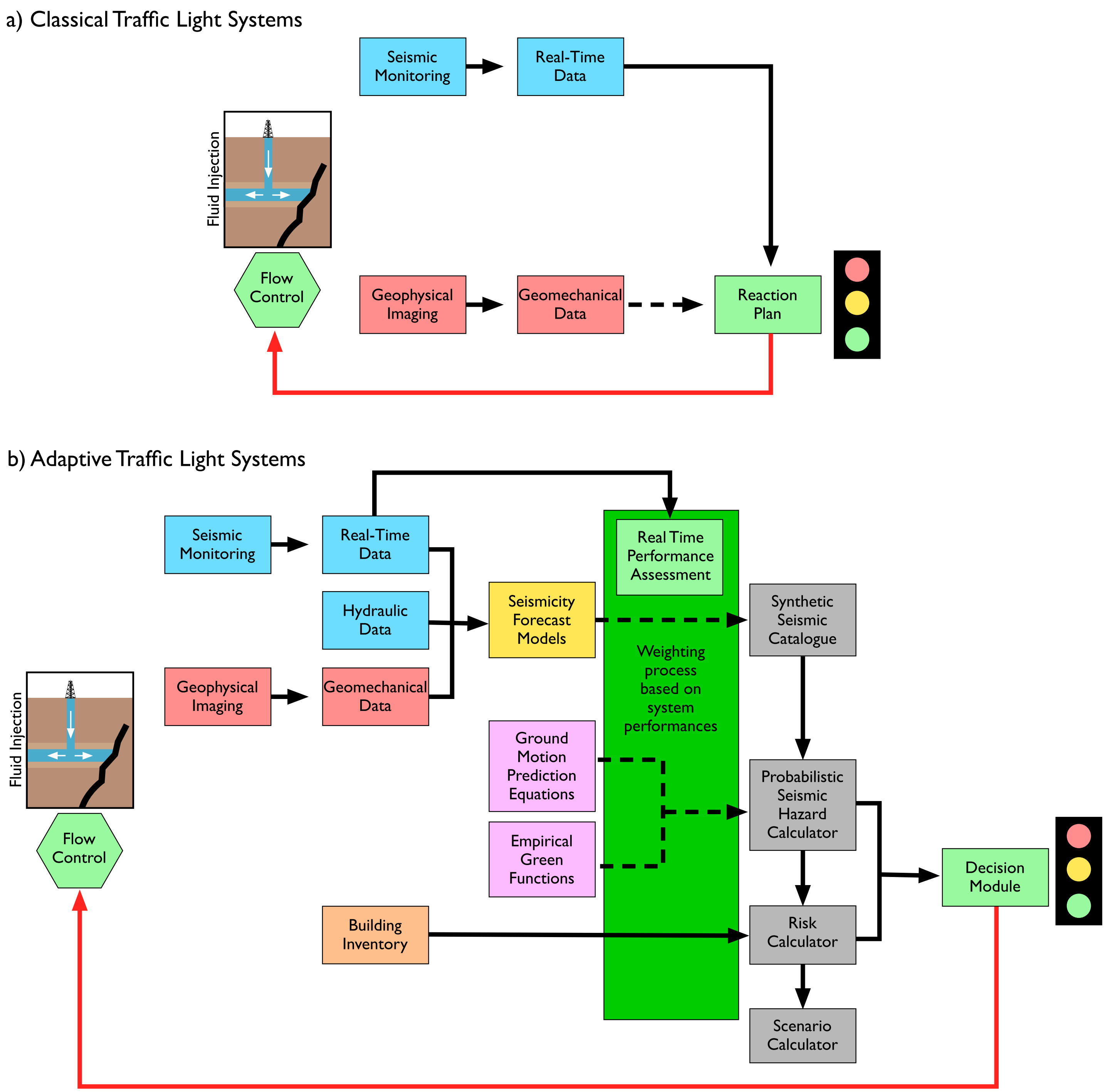


Figure 10. (a) Classical Traffic Light System. In Classical Traffic Light Systems decisions are based on magnitudes and ground motions. Thresholds are defined in a static way taking geomechanical information into account. (b) Adaptive Traffic Light System. In Adaptive Traffic Light System decisions are based on a forward looking, probabilistic, and adaptive framework [*Wiemer et al.*, 2014] (redrawn from *Wiemer et al.* [2014]).

verification of GMPEs and their application in the field of induced seismicity is still a new and challenging topic of research.

It is important to note that decisional protocols should be activity dependent. Indeed, induced seismicity related to hydraulic stimulation of geothermal and hydrocarbon reservoirs generally occur in direct vicinity of the injection well and with no sensible time lag between injection operations and seismicity onset [*Walters et al.*, 2015b]. On the other hand, earthquake triggered by a massive injection of fluids in the subsurface (e.g., wastewater injection operations) may occur at several kilometer distance from the injection wells [*Keranen et al.*, 2014]. In a critically stressed crust the pore pressure perturbation generated by such industrial operations may cause the failure of the faults which are favorably oriented with respect to the tectonic stress, identifying these faults prior to fluid injection may help to mitigate the risk associated with induced seismicity [*Walsh and Zoback*, 2016]. *Davis and Frohlich* [1993] suggests that if faults are mapped within 20 km of an injection site, that project is more likely to trigger or induce earthquakes, while, more recently, *Walsh and Zoback* [2016] developed a quantitative risk analysis (QRA) approach to estimate the probability that fluid injection operations at a certain site will trigger slip in nearby faults. Within this framework, regulations for preventing triggered earthquakes should include, before the injection operations starts, a seismotectonic assessment of the area (i.e., study of the historical seismicity, mapping the potentially active faults, etc.). Furthermore, microseismic monitoring operations should be arranged before injection begins. This allows to characterize natural seismicity (including rate, magnitude, and location) and, in combination with geomechanical modeling, will give a better understanding on the fluid interaction with preexisting faults [*Walsh and Zoback*, 2016]. With regard to the active decisional protocols (e.g., Traffic Light System), modern tools (such as the Adaptive Traffic Light Systems) should be activity-based as well as account for all site-characterization (e.g., ground motion prediction) and preliminary assessment, rather than rely only on magnitudes and/or *b* values as in the past [*Kiraly-Proag et al.*, 2016; *Trutnevyte and Wiemer*, 2017]. All these elements combined will allow a better understanding of the conditions of the site under exploitation and will possibly help in discriminating cases of induced/triggered from natural seismicity. Finally, the combination of an adequate monitoring infrastructure and advanced processing methods can help to be prepared better and earlier, e.g., promptly allowing a progressive reduction of operations and evaluating the system response before larger earthquakes may take place.

6. Conclusions

Induced seismicity is currently an in vogue and timely topic of discussion at scientific, political, and social level. The complexity of the problem, in combination with the sparse and fragmented documentation available, make it difficult to have a clear picture on how the problem of the induced seismicity is currently being managed by the different governmental agencies. The motivation of this study is to provide a unified and concise summary about the still open questions in monitoring, discrimination, and management of induced seismicity, and providing, according to our experience, possible answers.

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 $M_L < 0.0$). 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 microseismic 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 preexisting 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 socioeconomic 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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