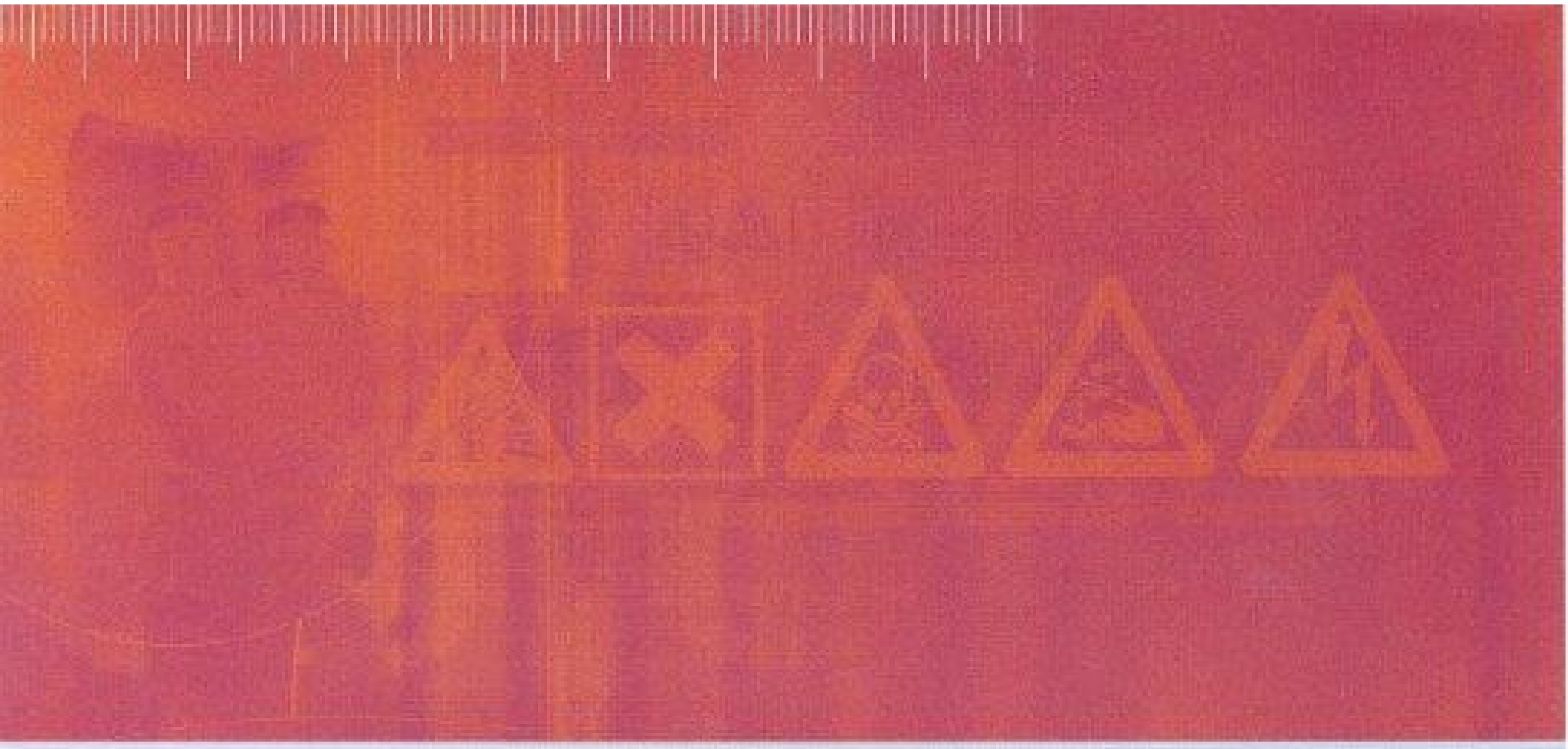

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KNOWLEDGE REVIEW CONCERNING HAZARDS AND RISKS RELATED TO ANTHROPOGENIC SEISMICITY

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Knowledge review concerning hazards and risks related to Anthropogenic Seismicity

Ground and Underground Risks Division (Ineris)

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PREAMBLE

This document was created in the context of Ineris's support mission to the Ministry for the Ecological and Inclusive Transition. It was established on the basis of Ineris's experience as well as on scientific and technical data available in the literature.

The reader shall use the results included in this report as a whole or otherwise objectively. Its use in the form of excerpts or summary notes shall be done under the sole and entire responsibility of the user. This is also true for any modification that may be brought to it.

This report was the object of an expert scientific rereading by Mr Pascal Bernard, Geophysicist at the Institut de Physique du Globe of Paris (IPGP, France) and Mr Arnaud Mignan, Seismologist at the École polytechnique fédérale of Zurich (ETHZ, Switzerland), experts in the field of anthropogenic seismicity, who we thank for their generous advice and pertinent remarks, which allowed appreciable improvement.

This report was equally reread by Mr Benjamin Leroux of the French National Institute of the Industrial Environment and Risks (Institut National de l'Environnement industriel et des Risques [Ineris]). We thank him for his perspicacious eye, which improved this report's quality.

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ABSTRACT

The relation between underground industrial activity and seismicity was made evident at the beginning of the twentieth century in the deep gold mines of South Africa. Today, as the demand for mineral resources and energy keeps increasing, the number and size of industrial projects as well as new emerging underground industries that can potentially induce seismicity is also rising. Some of the most illustrating cases are presented in this report. This report also deals with the issues related to seismic hazard assessment, risk mitigation and emerging regulations in the context of anthropogenic seismicity.

The mechanisms of anthropogenic seismicity are now relatively well understood, and researchers suggest distinguishing induced events, which result from the anthropogenic underground disturbance itself, from triggered events, which are related to the reactivation of natural geological faults due to industrial activity. In some extreme situations, anthropogenic seismicity can endanger public safety, especially when man-triggered earthquakes occur in regions with low natural seismicity and poor seismic prescription and sensitive populations. In addition, social acceptability can quickly be challenged and lead to the cessation or abandonment of industrial projects even when only rare earthquakes with very low intensity are felt. In some cases, induced seismicity can persist long after the ending of the underground operations. It can even occur several kilometres from the operations. These situations have been observed especially during fluid injection/extraction activities. So-called triggered seismicity remains the potentially most destructive threat to public safety.

Currently, microseismic monitoring has become a prominent tool for managing the risk of anthropogenic seismicity. The near to real-time processing of microseismic data, coupled with the monitoring of industrial parameters, offers a helpful approach to decision making. Similarly, solutions exist to reduce the vulnerability of buildings and infrastructures when the relocation of the project is not possible. Regarding the occupational safety of miners, operators have developed numerous approaches to limit worker exposure.

Both the world of industry and the world of research are nevertheless facing several challenges. One of them concerns the characterisation of the anthropogenic seismic hazard and the capability to distinguish natural earthquakes from anthropogenic earthquakes. This is of obvious interest for all parties involved; it may also have a significant impact in terms of responsibility of the operator. The success of future deep projects depends obviously on how well anthropogenic seismicity is managed and communicated to be acceptable to all stakeholders.

KEYWORDS

Industry, mines, hydrocarbons, geothermal, seismicity, hazard, risk, management, social acceptance.

TERRITORY

France, Europe, World

RESUME

Le lien entre activité industrielle dans le sous-sol et sismicité a été mis en évidence dès le début du XX$^{\text{ème}}$ siècle dans les mines d'or profondes d'Afrique du Sud. Aujourd'hui, l'accroissement de la demande mondiale en énergie, en ressources et en matières premières conduit à la multiplication de projets potentiellement générateurs de sismicité anthropique ressentie. Ces cas, rares au regard du nombre de projets à travers le monde, sont, pour les plus emblématiques, présentés dans ce rapport qui s'intéresse également aux questions relatives à la caractérisation de l'aléa de sismicité anthropique, à la mitigation des risques et à la règlementation.

Les mécanismes en jeu sont relativement bien connus et l'on distingue maintenant la sismicité induite, dont le principal moteur est la perturbation anthropique du sous-sol, de la sismicité déclenchée, consécutive à la réactivation de failles géologiques naturelles en quasi équilibre limite, en partie du fait de l'activité industrielle. Cette sismicité anthropique peut mettre en péril la sécurité publique, notamment lorsqu'elle a lieu dans des régions de sismicité naturelle faible où il n'existe aucune prescription parasismique. De plus, l'acceptabilité sociale peut rapidement être remise en cause et conduire à l'arrêt voire l'abandon de projets industriels y compris dans le cas de rares séismes ressentis de très faible intensité. Dans certains cas, cette sismicité peut perdurer longtemps après l'arrêt des opérations industrielles, voire se produire à plusieurs kilomètres des opérations. Ces situations ont été observées notamment lorsque des opérations d'injections / extractions de fluides sont en jeu. La sismicité dite déclenchée reste tout de même le phénomène le plus redouté car potentiellement le plus destructeur.

Des solutions, basées sur la surveillance microsismique couplée au pilotage du processus industriel, peuvent être envisagées par les exploitants pour maîtriser l'aléa de sismicité anthropique. Ainsi différentes stratégies sont développées autour des paramètres d'exploitation pour optimiser le schéma d'extraction du gisement, diminuer les pressions de fluide dans le sous-sol, ou optimiser le chargement ou déchargement gravitaire en profondeur et/ou en surface. De même des solutions existent pour réduire la vulnérabilité des enjeux (bâti, infrastructures …) quand la relocalisation du projet n'est pas possible. Concernant la sécurité des mineurs au travail, les opérateurs disposent de différentes approches pour limiter l'exposition des travailleurs.

Le monde industriel et la communauté scientifique sont néanmoins face à plusieurs défis. On peut citer notamment la caractérisation de l'aléa de sismicité anthropique et la capacité à différencier les séismes naturels des séismes anthropiques qui présentent un intérêt scientifique évident et un impact important notamment pour tout ce qui relève de la responsabilité de l'exploitant. D'autre part, la réussite et l'acceptabilité d'un projet industriel potentiellement générateur de sismicité nécessite la plus grande transparence, tout au long de la vie du projet, par la mise en place d'un programme de communication et d'information cohérent auprès des différentes parties prenantes et en particulier de la population locale.

MOTS-CLES

Industrie, mines, hydrocarbures, géothermie, sismicité, aléa, risque, gestion, acceptabilité sociale.

TERRITOIRE

France, Europe, Monde

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1. INTRODUCTION

Since the industrial revolution, the world demand for fossil fuels and mineral resources has engendered a considerable increase in underground operations. Thus, the multiplication of sites, the growing scale of projects, as well as new uses of the underground have, consequently, increased the probability of generating a so-called anthropogenic seismicity. These new uses are as diverse as the conventional and non-conventional extraction of hydrocarbons, their storage, definitive injection of wastewater, deep geothermal projects, the geological sequestration of CO_2, dam loading, or even the abandonment or flooding of subterranean works. Moreover, technological progress leads to continuously pushing back the limits of deep underground operations and increases the risk of generating anthropogenic earthquakes. The increased cadence of hydrocarbon production, in particular shale gas, is another aggravating factor for it entrains the storage of greater and greater volumes of wastewater in the deep underground.

We shall see in this report that underground industrial operations generate modifications of the natural stress field and/or the hydraulic pressure field in the surrounding massif. When these hydromechanical modifications exceed the resistance of the surrounding rocks, they can be at the origin of rupture phenomena engendering seismicity. This is generally of a low magnitude (< 2) and is only rarely felt on the surface. But, under certain conditions, these perturbations can equally reactivate the natural faults present at a site and trigger earthquakes of a greater magnitude.

Even if the relation with anthropogenic activities is clearly established and the rupture mechanisms known, as for natural earthquakes, the prediction of these hazards remains a difficult objective to reach. Thus, for a given industrial operation, it is difficult to estimate the occurrence date, the location and the intensity of an anthropogenic earthquake of significant magnitude susceptible of engendering risks. Today's research shows that many unknowns in the knowledge of the parameters that govern their occurrence remain.

This report, established in the context of the EAT-DRS06 CENARIS "Centre National de Surveillance des Risques du Sol et du Sous-sol" (National Monitoring Centre of Ground and Underground Risks) support programme to public authorities, has the objective of assessing the state of the art of current knowledge and research work on anthropogenic seismicity. It is a subject of interest as much for the industrial world as for the scientific community, and is, as we shall see, also a source of increasing anxiety for the population.

This report is based on a significant bibliographic study and feedback from numerous studies of recent or emblematic cases. It begins with a historical reminder of the phenomenon of anthropogenic seismicity and the definition of some useful notions for understanding the phenomena and mechanisms involved. Then, it describes the most emblematic accidents, covering different industry types. Approaches and questions for the evaluation of the hazard and risk, as well as monitoring methods and solutions are presented. Finally, this report describes different anthropogenic and/or triggered earthquake mitigation strategies and offers information about current regulations.

2. HISTORY, DEFINITIONS AND HIGHLIGHTS

2.1 HISTORY

The first proven cases of seismicity of anthropogenic origin were recorded in 1894 in South Africa after earthquakes were felt in the city of Johannesburg (Deichmann and Giardini, 2009). The direct influence of gold mine operations on the triggering of these earthquakes was denied for a long time, however, and it took nearly 14 years for this phenomenon to be clearly linked to the Witwatersrand's mines, which were producing nearly 40% of the world's gold at the beginning of the 1910s.

Anthropogenic seismicity from underground mining was acknowledged in Europe at the same time, and the first seismological monitoring observatory of these phenomena was deployed in 1908 at Bochum, Germany, in the carboniferous Ruhr basin. The first seismic network was installed in the coal basin of Upper Silesia, Poland, at the end of the 1920s (Gibowicz and Kijko, 1994). Since, numerous mines across the world, notably those at great depths (above 1,000 m and up to nearly 4,000 m for the deepest), have been equipped with seismic monitoring networks for risk prevention at work sites.

The relation between seismicity and large water dams was made for the first time in the 1930s during the loading of Lake Mead (the Hoover Dam, Nevada) (Carder, 1945). The seismicity related to effluent or fluid injection from deep wells is well known and has been documented since the beginning of the 1960s with the Rocky Mountains Arsenal case (Healy J. H. et al., 1968; Hoover D.B. and J.A., 1969), near Denver, Colorado (USA). The American arsenal had injected significant volumes of chemical products at depths of greater than 4,000 m for disposal. Between 1962 and 1966, the date at which the injection ended, thirteen earthquakes of a magnitude 4 or greater were recorded. In August 1967, more than one year after injection had been stopped, two seismic events of magnitudes 5.2 and 5.3 took place causing notable surface damage.

2.2 DEFINITION OF ANTHROPOGENIC SEISMICITY

If the link between human activity and certain seismic events is no longer a subject of discussion today, the technical vocabulary and definitions are still a source of debate in the scientific community. Thus, depending on the studies and authors, a distinction can be made between induced, triggered and natural earthquakes, even if the definition of these terms is not unanimous (Cesca et al., 2013; Dahm et al., 2013; Dahm et al., 2010).

However, the definitions generally used by authors (Cornet, 2007; Grasso, 1993; Majer et al., 2007; McGarr et al., 2002) are the following:

- **induced seismicity** is a seismic activity engendered by a human activity in an environment assumed to be geologically stable and that would never have appeared without human intervention. The creation of new faults or fractures are usually associated with this seismicity. This type of seismicity can manifest in areas where industrial activity is taking place in an underground little affected by faults or other geological discontinuities. It is generally of low magnitude and intensity, and manifests in the proximity of the strongest industrial perturbations transferred to the surrounding geological terrain;
- **triggered seismicity** is a seismic activity caused or accelerated by human intervention in a predisposed environment. The term "predisposed" means the presence of faults close to limit equilibrium in the proximity of the site. Otherwise said, a natural seismic event would probably have occurred in a more or less distant future without this exterior cause. Thus, this seismicity occurs generally in areas where faults are near the rupture state, but which are not necessarily reactivated by the tectonic load. It corresponds to a noticeable, even very significant increase in seismicity in frequency and magnitude;
- **natural seismicity** is a seismic activity observed at the global scale in relation to the movement of tectonic plates (collision, subduction and volcanic arch zones), but also in a more diffuse manner, within or in the proximity of pre-existing faults or discontinuities.

Its remains originated by tectonic forces. Natural seismicity is generally deeper and might reach several dozen to hundreds of kilometres;

- **microseismicity** designates all types of seismic activity of which the magnitude is less than the detection magnitude of national seismological networks. This detection magnitude is generally of the order of M=2 and approximately corresponds to the magnitude from which a natural or induced seismic event can be felt by the population at the surface.

In this report, the term **anthropogenic seismicity** will be used to designate both induced and triggered seismicity.

Let us equally note that the term **hazard** refers to a natural phenomenon of a given occurrence and intensity as defined in risk prevention. It is the standard term in the international literature.

2.3 PRINCIPAL CHARACTERISTICS OF AN EARTHQUAKE

2.3.1 MAGNITUDE

Magnitude is used to quantify an earthquake's force; it is directly related to the energy released by the earthquake's source and is correlated to the surface involved in the phenomenon and the average displacement (Hanks and Kanamori, 1979) that is to say the seismic moment. An increase of 1 in magnitude equals, on average, multiplying the rupture area by 10, the displacement by 3 (Table 1) and the released energy by 32 (Wells and Coppersmith, 1994).

Magnitude is generally used to compare earthquakes. In reality, there exist several methods to calculate it, and thus several scales, of which the most well-known is the Richter scale[1]. However, the one that is most used today is the moment magnitude, M_w, which allows to quantify unambiguously the energy released by an earthquake.

Let us recall here that magnitude can be negative or positive and that the magnitude scale is an open scale, without *a priori* limits other than the physical limits of the intra-granular fracture in a rock ($M_w \approx$ -5 to -4) to that of an intercontinental fault ($M_w \approx$ 8 to 9). In general, only natural earthquakes of a magnitude $M_w > 2$ are felt on the surface, on the condition that the source is not too deep.

In this report, magnitude generally refers to moment magnitude, denoted M or M_w. In the contrary case, it will be indicated in the text by the use of the term "local magnitude" or M_l.

[1] Scale introduced historically by C. F. Richter for Californian earthquakes in the 1930s.

Moment magnitude M_w	Rupture surface km^2	Rupture length X extension (km, km)	Displacement (m)	Rupture duration (s)	Number per year in the world
1	0.001	0.03 x 0.03	0.01	0.01	
2	0.01	0.1 x 0.1	0.03	0.03	
3	0.1	0.3 x 0.3	0.1	0.1	>> 20,000
4	1	1 x 1	0.3	0.3	20,000
5	10	3 x 3	1	1	2,000
6	100	10 x 10	3	3	200
7	1,000	30 x 30	10	10	20
8	10,000	200 x 50	60	60	1
9	100,000	670 x 150	200	200	0.05

Table 1: Orders of magnitude of earthquake rupture parameters of moment magnitude varying from 1 to 9 (Gibson and Sandiford, 2013).

2.3.2 INTENSITY

An earthquake's intensity, not to be confused with its magnitude, is used to quantify the effects produced on the surface by an earthquake. It is generally estimated on the basis of what is felt by the population, local observations of ground movements and eventually damage to buildings and infrastructures.

The intensity at a given point depends on the distance of this point from the seismic source; it is strongest at the epicentre, vertically to the seismic source, and it decreases as distance increases. It depends as well on local geological conditions that can in certain contexts cause site effects. By site effect we mean a geological or topographical configuration prone to the amplification of waves and thus to a high intensity. The presence of soft ground, little consolidated at the surface, for example, often has the effect of amplifying the amplitude and duration of seismic shocks. In sedimentary basins or valleys, wave reverberation phenomena can also cause an amplification of earthquakes.

Finally, let us note that under certain unfavourable conditions (formations that are sandy or saturated in water), a liquefaction phenomenon can appear. In this specific case, buildings are no longer held in place and can suffer considerable damages by collapsing.

There are several intensity scales, including the Mercalli scale (1902), the MSK scale (1964, modified in 1981, Table 2) and the European macroseismic scale (EMS 98), which is the most complete. All three have 12 levels. There also exists the Arias intensity scale which is related to the vibration energy.

Intensity	Observed damages
I	Only very sensitive seismographs register the vibrations.
II	Tremors hardly perceptible; some people at rest feel the earthquake.
III	Vibrations comparable to those caused by the passage of a small lorry.
IV	Vibrations comparable to those caused by the passage of a large lorry.
V	Earthquake felt outdoors. Sleeping people awake.
VI	Furniture is shifted.
VII	Some cracks appear in buildings.
VIII	House chimneys fall.
IX	Houses collapse. Underground pipelines rupture.
X	Destruction of bridges and dams. Railways are deformed.
XI	The most solid constructions are destroyed. Major landslides.
XII	Cities are completely destroyed. Major changes to topography.

Table 2: MSK earthquake intensity scale and associated damage.

2.3.3 PICK GROUND ACCELERATION OR PICK GROUND VELOCITY

Pick Ground Acceleration (PGA) or Pick Ground Velocity (PGV) are two physical magnitudes that are used to quantify the level of vibrations generated by an earthquake. PGA and PGV correspond to the maximum amplitude registered on a seismogram (in acceleration or velocity) on a given site. This measurement is not an evaluation of the total energy of an earthquake like magnitude, but a one-time measurement of vibration at a given point.

This measurement can be associated with the Mercalli scale (Table 2 and Table 3) even if the correlation is not always direct. Indeed, the intensity of an earthquake is estimated from witness accounts and ground observations, while the measurement of PGA or PGV is a physical measurement, independent of human perception. This physical parameter is the base input for the dimensioning of structures and infrastructure in earthquake engineering. PGV and PGA values are directly compared to damages observed on the surface and can thus be calibrated with the EMS 98 intensity scale.

Perceived tremors	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
Potential damage	No	No	No	Very light	Light	Moderate	Moderate/ Heavy	Heavy	Very heavy
PGA (g%)	< 0.05	0.3	2.8	6.2	12	22	40	75	> 139
PGV (cm/s)	< 0.02	0.1	1.4	4.7	9.6	20	41	86	> 178
Instrumental intensity	I	II – III	IV	V	VI	VII	VIII	IX	X+

Table 3: Mercalli intensity scale and ground vibration in PGV and PGA relationship according to USGS (Worden et al., 2012).

2.4 MECHANISMS AND FACTORS INVOLVED

When human activities perturb the stress state and interstitial pressure in rock masses, more or less significant seismic quakes can appear. Nevertheless, there is a very great variability in the conditions under which these instabilities appear.

Therefore three major groups of seismicity are generally distinguished according to the involved mechanism (see appendix A for more details): 1- the ones provoked by the extraction of mineral resources (e.g. mine), 2- the ones linked to fluid injection (e.g. wastewater disposal or geothermal projects) or 3- the ones associated with fluid extraction (e.g. hydrocarbon extraction) (Figure 1). In certain specific complex cases, several mechanisms can be involved, as we shall see at the end of this section.

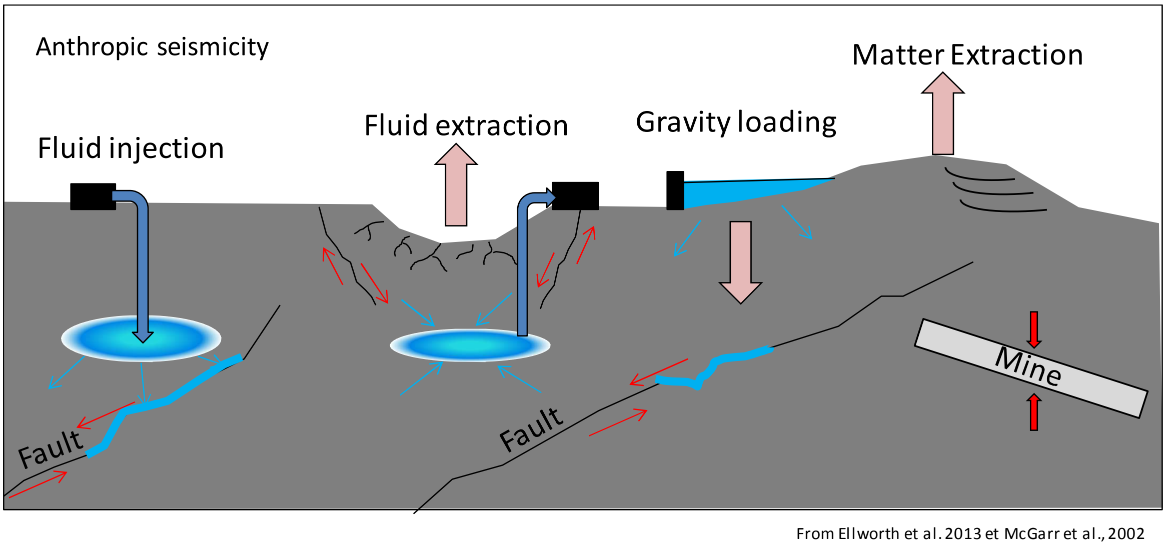

Figure 1: Simplified diagram illustrating the different solicitations of anthropogenic origin to which a rock mass can be subjected.

2.4.1 By extraction of mineral resources

Underground extraction of ore deposits provokes significant changes to the stress field (appendix A) around the cavities created by gravity unloading (Figure 1). The readjustment of these stresses is usually accompanied by seismic events of which the frequency, the magnitude and the intensity tend to amplify with the increase of extracted mineral volume as well as with the extraction depth (Hudyma, 2008).

Seismic events can also be classified into two categories (Gibowicz et al., 1990; Gibowicz and Renata, 2009):

- the first concerns events directly induced by excavation operations, which are generally located in the proximity of the rock face. In this case, the seismic response to the excavation is proportional to its dimension (Hudyma, 2008). The readjustment of stresses is local and occurs shortly after extraction operations. These seismic events, to the contrary of natural earthquakes, can present source mechanisms that are not shearing (Hasegawa et al., 1989; Sileny and Milev, 2008), which is to say that they do not correspond to sliding along a pre-existing discontinuity. Indeed, in mining, seismic waves can be generated by phenomena such as the rupture and collapse of a cavity's roof (rock fall), rockbursts and/or pillar bursts. Fractures can equally develop at the cutting face in fresh rock;
- the second category of seismic events, called triggered, concern stress readjustment at a larger scale. These events are rarer but generally more energetic than the first because they provoke movements on major pre-existing geological discontinuities (Figure 1). In this case, the rock mass is already in a near-unstable state of equilibrium on both sides of the fault, and a small variation in the stress state suffices, induced by mining operations situated in the influence field of the fault segment in the critical state, to trigger a seismic movement of potentially great magnitude (Gibowicz and Renata, 2009; Hudyma, 2008).

2.4.2 BY FLUID INJECTION

Deep fluid injection is a process used in different industrial contexts, as for example deep geothermal operations, conventional and non-conventional hydrocarbon extraction, as well as gas storage, CO_2 sequestration, salt solution mining, sequestration of wastewater, etc. These activities can generate a seismicity provoked by the increase of deep fluid pressure (Mignan, 2016). As before, two types of seismicity can be observed, one, induced, directly linked to the injection, and the other, triggered, provoked by the remobilisation of a pre-existing fault.

Concerning induced seismicity, it is often observed during the opening phase of the rock's pre-existing faults by hydraulic stimulation in the case of geothermal operations. In the case of shale gas extraction, the process is a little different as it is necessary to fracture the rock (hydraulic fracturing[2]), generally at very high pressures to extract the gas. However, in both cases, this seismicity is generally of low magnitude and often occurs with an opening mechanism notably close to the injection well (Cuenot et al., 2008). Other mechanisms, notably shearing, can as well be observed (Cuenot et al., 2008).

As for triggered seismicity, fluid injection can cause the increase of fluid pressure on a fault plane. This phenomenon is at the origin of the decrease of resistance to friction, thus allowing the fault's sliding. This process is possible when a fault close to the critical state, i.e. close to rupture and favourably oriented compared to the regional stress field, is impacted by the fluid pressure increase. All the industrial processes cited above are prone to reactivate faults by this mechanism. In this specific case, a spatio-temporal decorrelation can be observed between the seismicity's occurrence and the industrial installation, linked to the balancing underground of interstitial pressure.

2.4.3 BY FLUID EXTRACTION

In this case, the extraction of fluid from a reservoir causes a decrease of underground interstitial pressure (Figure 1). In the field of hydrocarbon extraction, for example, this decrease in pressure causes a large-scale contraction of the reservoir, which provokes a stress variation in the surrounding rock (Segall, 1989). A surface subsidence is often observed, with a remobilisation of pre-existing geological structures in a reverse fault. This type of mechanism has been documented as well in the case of a collapse caused by a salt solution mining (Kinscher et al., 2016). The gravity discharge mechanism linked to fluid extraction can equally be the origin of a fault's remobilisation (McGarr et al., 2002).

The magnitudes generated by the fluid extraction mechanism can be significant because the stress variations can occur on relatively large surfaces of the scale as the reservoir extension (McGarr et al., 2002).

2.4.4 COMPLEX CASES

Among other cases of anthropogenic seismicity, let us cite the case of the loading of large dams. This particularly complex case combines two principal mechanisms: gravity loading linked to the water loading of the reservoir and the increase of interstitial pressure in the underlying terrain, similar to the one described in the fluid injection process (2.4.2).

During the reservoir's loading, the water column's pressure modifies the stress field in the bedrock and underground, notably when the dam is tall, and/or when water level variations are great and rapid. This process is usually accompanied by a seismic activity that appears rapidly in response to the loading. Observations show that this seismicity rarely goes beyond a magnitude of 5. Furthermore, the increase of interstitial pressure in the underlying ground can correspond to a differed seismic response, which can be of several years. This response depends on the diffusion velocity of the interstitial pressure from the reservoir. The strongest earthquakes observed in this situation occurred when the tectonic context was favourable.

[2] Note that this process has been forbidden in France since 2011.

The case of flooding mines at the time of their closure, is, from the point of view of physics, rather similar to the case of loading dams. It is however necessary to take into account the geomechanical modifications that took place when the mine was still in activity to describe the seismicity's origin. This supplementary parameter makes the mechanisms' identification particularly difficult in this case.

3. CASE STUDIES

The literature on seismicity related to anthropogenic activities is significant, and it is difficult to draw up an exhaustive list here. For this study, we compiled and examined a database of approximately 260 published case studies (Appendix B). Numerous summaries have also been published recently. We can cite the following documents that are particularly well designed and pedagogical:

- the summary report of the "Committee on Induced Seismicity Potential in Energy Technologies of the National Academy of Sciences" (NRC, 2013) about industries using underground fluid injection or extraction;
- concerning seismicity induced by hydrocarbon extraction, the works of Davies et al (2013) and Suckale (2009) and Grasso and Wittlinger (1990);
- concerning seismicity induced by wastewater injection in deep formations, numerous studies led by the USGS (United States Geological Survey) with McGarr et al. (2015) and Rubinstein et al. (2014) ;
- on seismicity induced by geothermal industries: Evans et al. (2012), Majer et Peterson (2007), Majer et al. (2014), Grunthal (2014), as well as the EU project "GEISERS"[3];
- on seismicity induced by CO_2 storage activities: Nicol et al. (2013) and Zoback and Gorelick (2015);
- on seismicity induced by mining activities: Gibowicz (2009), Hasegawa et al. (1989), Hudyma and Potvin (2004), Li et al. (2007) and Richardson and Jordan (2002);
- on seismicity linked to the loading of hydraulic dams: CHEN (2009); Deng et al. (2010) and Gupta (2002).

This topic has equally been the subject of numerous workshops, conferences and congresses, amongst which:

- the "Schatzalp Workshop on Induced Seismicity" at Davos, Switzerland in March 2017, which gathered more than a hundred contributions, all accessible on-line[4];
- the "Anthropogenic Seismicity Workshop"[5] at Nancy, France in September 2016, organised by Ineris and the GeoRessources laboratory.

The different emblematic case studies illustrating the different causes of anthropogenic seismicity origin presented below in this report concern seismicity generated by different industry types, namely:

- mining extraction activities and residual seismicity related to abandoned mines;
- deep geothermal operations;
- geological gas storage;
- conventional hydrocarbon extraction: gas and oil;
- non-conventional hydrocarbon extraction: shale gas;
- definitive injection of industrial effluents in deep wells in porous and permeable rocks, coming for example from chemical industries, or shale gas extraction by hydraulic fracturing;
- loading of hydraulic dams.

Other cases will as well be mentioned, concerning geological CO_2 storage, salt solution mining and water extraction.

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[3] http://www.geiser-fp7.fr/GEISERForBeginners/Pages/Presentation.aspx

[4] http://www.seismo.ethz.ch/research/groups/schatzalp/ et http://www.seismo.ethz.ch/en/research-and-teaching/schatzalp-workshop/download-2017/

[5] http://www.ineris.fr/en/about-ineris/news/anthropogenic-seismicity-workshop-nancy/166105

3.1 THE MINING INDUSTRY

The literature on seismicity generated by the mining industry is vast. It is the most studied form of anthropogenic seismicity as it is the origin of a significant human and economic toll around the world (Gibowicz and Kijko, 1994; Gibowicz et al., 2001; Gibowicz and Renata, 2009). This industry is also the source of the greatest number of induced earthquakes in the world.

Mining extraction's impact is explained by the considerable perturbations of the stress fields around the cavities created at the sites. The excavation of galleries and massive volumes of minerals is without a doubt the most "traumatising" way to exploit the deep underground, causing fractures, breakages and reactivating natural faults.

The Upper Silesia coal basin in Poland is one of the most active mining basins at the seismic level in the world even if it is located in an area where the natural seismicity is low. Seismological observations show that more than 55,900 tremors of mining origin of a magnitude greater than 1.5 were recorded between 1950 and 2005 (Stec, 2007). In the 1980s, this seismicity decreased thanks to the implementation of new extraction means and ground release techniques at the front of mining sites (Patynska, 2013). But since the 2000s, seismicity has increased again due to the increase of extraction depths beyond 1,000 metres and more rapid production cadences.

In Newcastle, Australia, coal extraction is suspected of being the direct origin of a 5.6-magnitude earthquake in 1989 (Klose, 2007). A major fault, located 10 km deep, may have been reactivated by mining extraction but equally by the massive pumping of the water necessary to dry the mining works. This earthquake is one of the most devastating to have occurred in Australia: 13 people were killed, 160 were injured and 4 billion dollars in damage ensued. The damage was all the greater because the country, located in a low seismic hazard zone, does not have seismic constructions.

In the United States, a significant underground collapse took place in the Crandall Canyon, Utah, coal mine on 6 August 2007. At the same time and place, a 4.1-magnitude event was recorded. At the time of accident, which caused the death of 9 miners, the operator declared, that a natural earthquake had caused the collapse of mining works. However, a detailed study, led by the University of Utah (Pechmann et al., 2008), showed that the mine collapse was indeed the earthquake's origin. Following this study, the operator was sentenced for violating safety rules.

Finally, in Europe, the 3.7-magnitude earthquake that took place on 21 June 2001 in Freyming-Merlebach, France, and was the origin of a rockburst[6] in the mine works, caused the death of a miner and several injuries. This work site, located at a depth of 1,200 metres, had been closed. Another example is the earthquake of 23 February 2008 in Saarwellingen (near Saarlouis, Germany, Figure 2). This 4.3-magnitude earthquake caused significant material damage (Alber and Fritschen, 2011; Fritschen, 2010). The amount of damage and the population's emotions led German federal authorities to definitely end operations of the last mine in activity in the Saar basin.

[6] Phenomenon associated with a seismic event, which causes sudden and violent damage to an excavation

Figure 2: Example of damage in the city of Saarwellingen following a 4.3-magnitude earthquake of 23 February 2008, source http://www.saarwellingen.de/archivos/index.php?id=452.

It is important to note that seismicity related to mining works can persist a long time after the end of operations. Indeed, mine closures can lead to the abandonment of underground works and significant voids susceptible to instabilities with time, as well as during the progressive flooding of mining works. Depending on the basin's geological conditions, the filling with water of the underground cavities can be accompanied by subsidence or collapsing of overlying terrains, or their uplift, and thus potentially generate seismicity. Depending on their magnitude, these phenomena can affect the safety of people and goods, and eventually compromise the economic development of the concerned area. The notion commonly used in France in this particular case is that of residual hazard.

We can also cite the recent case of the coal basin of Gardanne in Provence, France, where mining operations stopped in 2003 and mining works were progressively flooded. Since 2008, when a microseismic monitoring network was installed, more than 2,000 events have been detected (Figure 3), located principally at the flooding front, and several microseismic crises were recorded in 2012, 2014 and 2017, with numerous events felt by the population (Ml ≈ 2.5; Mw ~ 1.8). This persisting seismicity remains nevertheless lower than what was recorded during operations; it seems to have a relation to the seasonal fluctuations of the water table, of which the mining works significantly modified the natural hydrogeological system. These modifications could be the origin of changes in the stress state of faults that are present, by gravity loading and/or by increase of interstitial pressure, leading to their ruptures (Contrucci et al., 2013; Kinscher et al., 2017; Matrullo et al., 2015).

Let us finally mention a case in Stilfontein, South Africa, where on 9 March 2005 a 5.3-magnitude seismic event of mining origin caused damage on the surface of an exceptional severity, partially destroying numerous buildings, injuring several dozen residents and causing the death of two miners in the Klerskdorp gold mining district. This seismic event of a significant magnitude is attributed to abandoned mining works located in the proximity of the active mine (Durrheim et al., 2007).

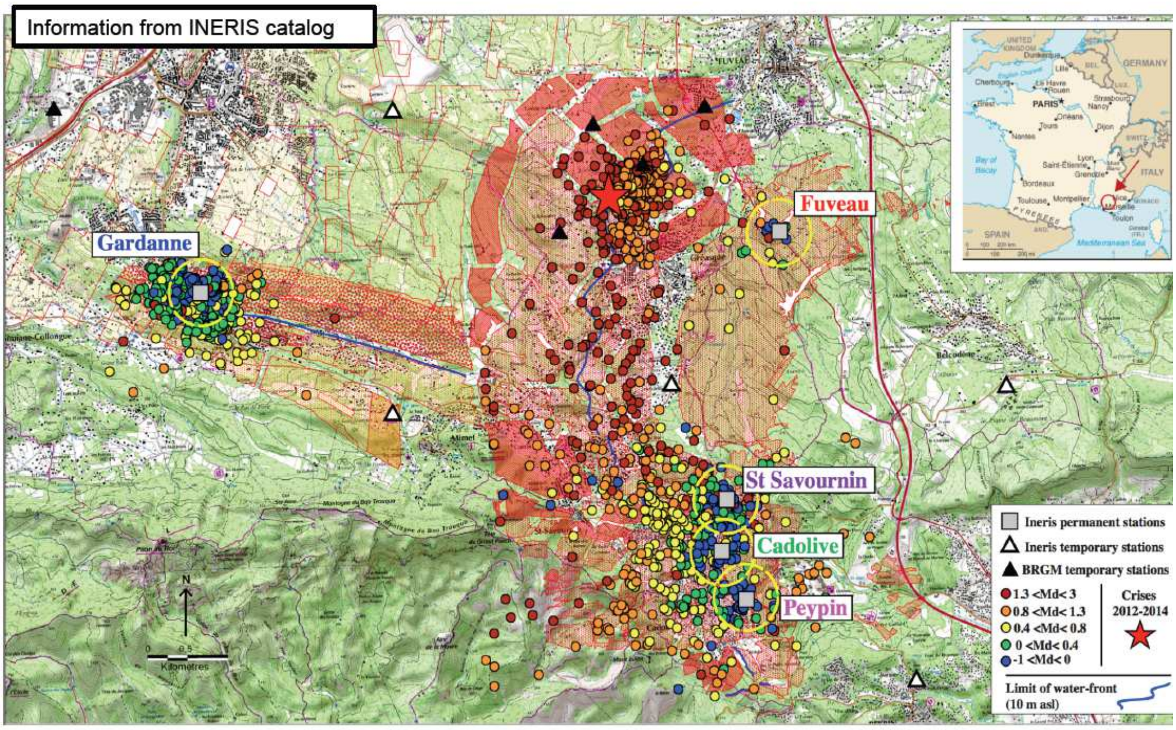


Figure 3: Post-mining seismicity recorded in the former Gardanne coal basin between 2008 and 2015 (Matrullo et al. 2015). The circles represent the location of seismic events, the associated colours correspond to the local magnitude, the blue line at the centre of the basin indicates the level of flooding in the mining works, the squares as well as the triangles correspond to seismological stations, and the red surfaces correspond to the areas of former mining works.

3.2 DEEP HIGH-TEMPERATURE GEOTHERMAL PROJECTS

Deep geothermal operations consist of using underground thermal potential to produce electricity. This industrial technique is only profitable in regions with high temperature zones (> 100° C) located at shallow depths (3 to 5 km). This is the case of the Rhine graben, where the Soultz-sous-Forêts (France) geothermal site is located. It is equally the case at Basel, Switzerland, in the southeast part of the Upper Rhine Plain, where a deep geothermal site is located.

Tapping the reservoir's thermal potential is generally only possible after a stimulation that consists of increasing the reservoir's permeability as well as the hydraulic connection between the injection and production wells. This stimulation is done by fluid injection, which causes an increase in interstitial pressure and a decrease in the normal stress in the rock mass at joints and/or pre-existing fractures. The interstitial pressure variation thus created, related to water and chemical adjuvant injection, modifies the stress state and can be at the origin of induced seismicity.

At the Soultz-sous-Forêts site, the reservoir's stimulation generated earthquakes of which the maximum magnitude reached 2.9 in 2003, which was the strongest ever felt by the local population (Cuenot et al., 2008). Following complaints by the population, stimulation protocols were modified: in 2004 and 2005 pressure and injected volumes were reduced, but earthquakes were still felt during this period. Then, in 2006-2007, chemical stimulation techniques were adopted, allowing the reduction of injected volumes and thus the associated seismicity (Portier et al., 2009). Since spring 2016, the site has entered into its industrial electrical production phase[7] and fuels the equivalent of 2,400 households.

[7] http://france3-regions.francetvinfo.fr/alsace/geothermie-profonde-soultz-sous-foret-1092809.html

The “Deep Heat Mining” project in Basel, Switzerland, did not have the same success. Indeed, in 2006, the deep drilling stimulation (5 km) was accompanied by numerous earthquakes from the start of injection operations (Figure 4). They were stopped two days after the detection of two events of magnitudes of 2.6 and 2.7 (Deichmann and Giardini, 2009; Haering et al., 2008). However, seismic activity continued, notably with a 3.4-magnitude event 5 hours after stimulations stopped. This earthquake was obviously felt by the population (Kraft et al., 2009; Majer et al., 2007). Then, three earthquakes of a magnitude greater than 3 took place two months after injection had stopped. The project was first suspended during the investigation, then definitively abandoned three years later following risk studies (Baisch et al., 2009; Mignan et al., 2017). The site’s seismic activity is estimated to return to its “normal” level not before 10 to 20 years (Bachmann et al., 2011).

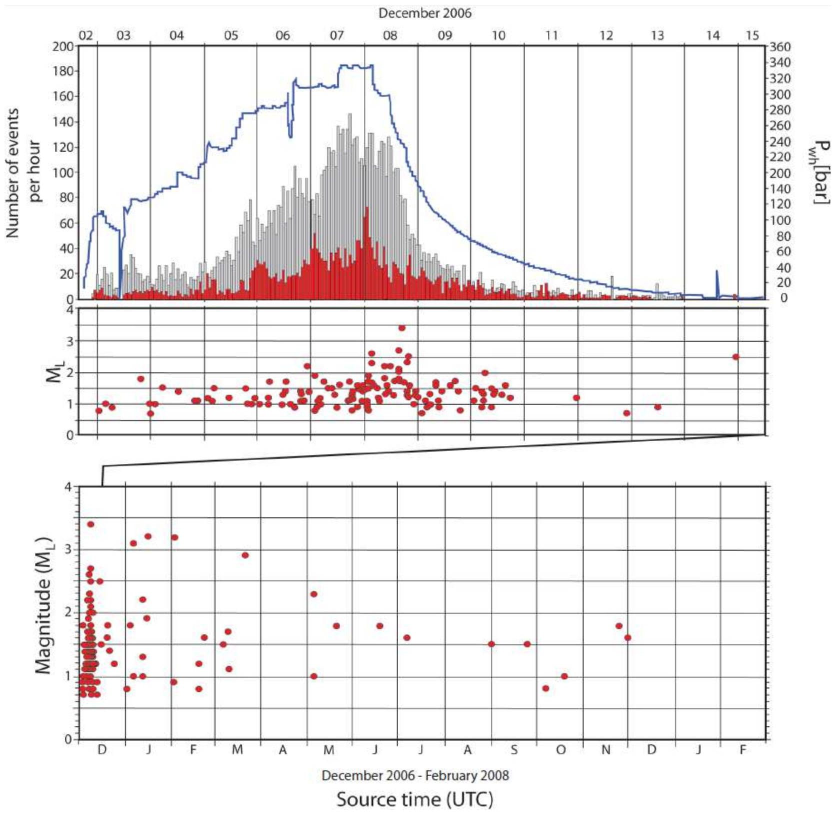


Figure 4: Anthropogenic seismicity recorded by the monitoring network installed at the deep geothermal site in Basel and injected water during reservoir stimulation operations (Kraft et al., 2009). In red: localised seismic events. In grey: total seismic events.

In the case of Basel, the anthropogenic seismicity hazard had been estimated in large part on the basis of a comparison with the Soultz-sous-Forêts project, where the magnitude of 2.9 was not surpassed (Cuenot et al., 2008). The risk analysis for such an earthquake, or for earthquakes of a greater magnitude, was not performed beforehand (Kraft et al., 2009). Yet, this region had had a devastating earthquake in 1356 of which the magnitude was estimated to be between 6.2 and 6.7 according to historic accounts.

Note that the average amount of ~ 9 million euros in damage assumed by insurance companies following the 3.4-magnitude earthquake was judged exaggerated in comparison to what had been paid in the past in Switzerland, following the occurrence of earthquakes of a comparable size (Kraft et al., 2009).

3.3 GAS STORAGE

Different types of geological reservoirs can be used for underground gas storage, such as depleted gas or oil depots, aquifers, or saline or mine cavities. Documented examples of seismicity induced by gas injection in the literature are nevertheless few. The most recently studied case is that of the CASTOR project in Spain. This gas storage site is a former depleted oil reservoir located in the Balearic Sea, a region whose natural seismicity is low. This oil reservoir was an extraction site between 1973 and 1989.

At this site, the third gas injection sequence in September 2013 generated a low magnitude seismicity (Figure 5), but two weeks after injection was stopped this seismicity amplified with more than 1,000 events over 40 days, with magnitudes up to 4.3, before returning to a normal level (Cesca et al., 2014). The most significant event took place during this post-injection phase at less than 2 km from the injection point and at an abnormally low depth (less than 3 km below sea level), at the same level as the bottom of the injection wells. Subsequent studies showed that a minor fault situated near the injection site was probably remobilised following interstitial pressure variations (Cesca et al., 2014). The CASTOR project was finally abandoned, given the difficulty of ascertaining the industrial risk concerning the seismic hazard, which had been underestimated. Even if no damage was reported, neither on the industrial facility nor on the urbanised coast approximately 40 km away, the strongest earthquakes were clearly felt by the population, causing a stir, followed by significant mobilisation. Note, however, that prior to gas injection operations, a detailed structural geological study and a two-year seismological monitoring of the site were performed. These investigations indicated that the site was stable, notably for low injection pressures, which were less than 2.5 bars (del Potro and Diez, 2015).

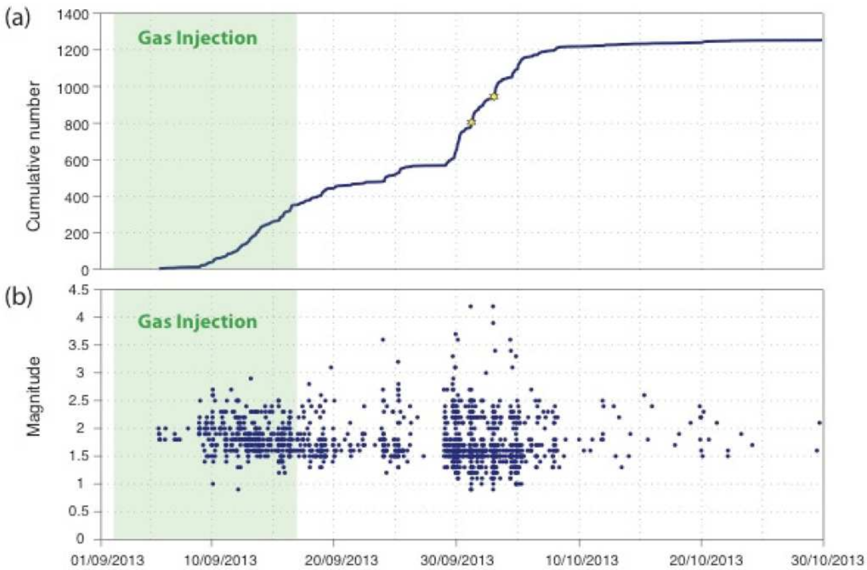


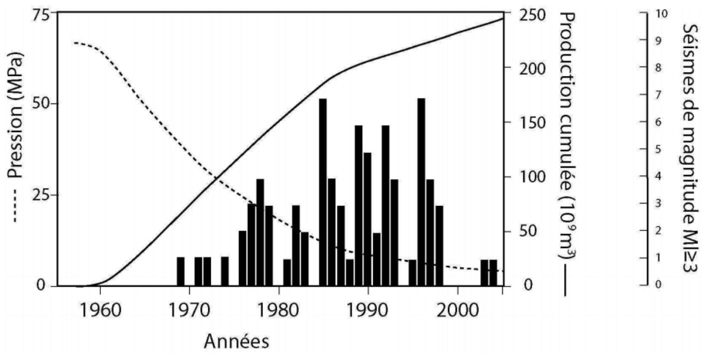
Figure 5: a) Cumulated number of seismic events and b) magnitude of recorded events from 1 September to 30 October 2013 (del Potro and Diez, 2015). The green section represents the gas injection period. Note that the greater part of activity took place after injection operations had stopped.

3.4 CONVENTIONAL HYDROCARBON EXTRACTION

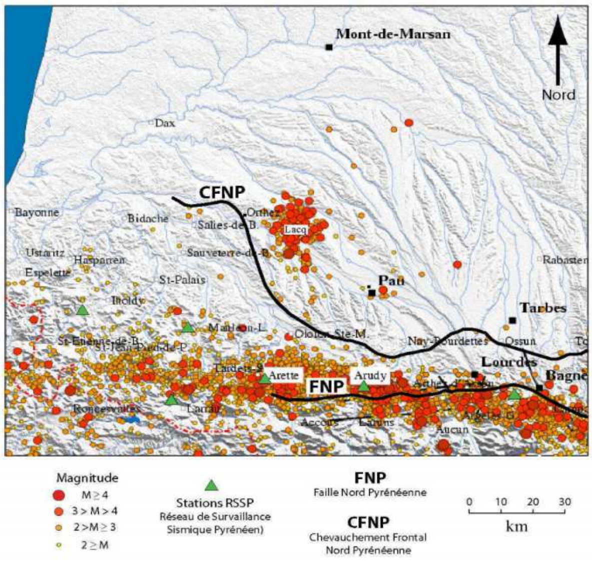
3.4.1 SEISMICITY DUE TO THE DEPLETION OF GAS RESERVOIRS

Amongst the most significant earthquakes of anthropogenic origin, we can cite those generated by recovery operations at the Gazli, Uzbekistan, gas field, in a region previously considered seismically calm (Bossu, 1996). Between 1976 and 1984, three earthquakes of a magnitude ~ 7 affected the region: 8 April 1976, 17 May 1976 and 20 March 1984. The three epicentres were located 20 km north from the gas field, at depths of the order of 10 to 15 km (Adushki et al., 2000). The decrease in pressure in the reservoir is considered to be the origin of these earthquakes (Simpson and Leith, 1985).

The Lacq gas field, located in southwest France (Figure 6), in which recovery operations began in 1957, is another example. It is one of the best documented case studies of seismicity induced by the depletion of a gas deposit (Bardainne, 2005; Bardainne et al., 2008; Grasso, 1993; Grasso and Wittlinger, 1990; Lahaie and Grasso, 1999; Segall et al., 1994). Between 1974 and 1997, more than 2,000 local events were recorded by seismic monitoring networks (Bardainne, 2005) and seismicity continues today. According to the different authors, Lacq's seismicity is clearly not directly related to the natural tectonic context of the Pyrenees, which are 30 km to the south of the deposit. Moreover, the first events in this area were felt after the beginning of gas production.



a)



b)

Figure 6: a) Production, gas pressure and earthquakes of magnitude M ≥ 3 by year at the Lacq site (Bardainne, 2005). b) Seismicity of the Pyrenees region recorded between 1989 and 2005 and localised by the Observatoire Midi-Pyrénées (Bardainne, 2005). The Lacq seismic swarm appeared when the gas reservoir was put into production.

Finally, let us cite the case of seismicity in the Dutch gas deposits, of which the most significant is the site of Groningen, in the north of the Netherlands (Figure 7). Of an area of 900 km^2 and located at a depth of approximately 3 km, it is the largest contiguous deposit in the world. Production at this site began in 1963 and the first event was recorded in 1991 (magnitude ~2.4). Then, for the next ten years, seismicity was low, with 5 events of a magnitude greater than 1.5 recorded per year (van Thienen-Visser and Breunese, 2015). The most significant event (of a magnitude of 3.6) took place in 2012, which caused the most damage to date. Studies show that there is a tight link between the seismicity and the reservoir's compaction, resulting from the gas extraction (van Thienen-Visser and Breunese, 2015; Van Wees et al., 2014). Indeed, this process causes stress changes on the faults and pre-existing geological discontinuities. Let us note that numeric modelling showed that faults were probably not close to rupture when gas depletion was initiated (Van Wees et al., 2014). This explains the time delay observed between the beginning of operations and the occurrence of seismicity. On the contrary, if these faults had been in a sub-critical state, there would have been seismicity from the beginning of operations, as was observed at the Lacq site. In January 2014, it was decided to reduce gas production in the central part of the Groningen reservoir where the subsidence was the greatest. In compensation, production was increased at the reservoir's periphery where there was less compaction. These measures were taken with the objective of decreasing seismicity.

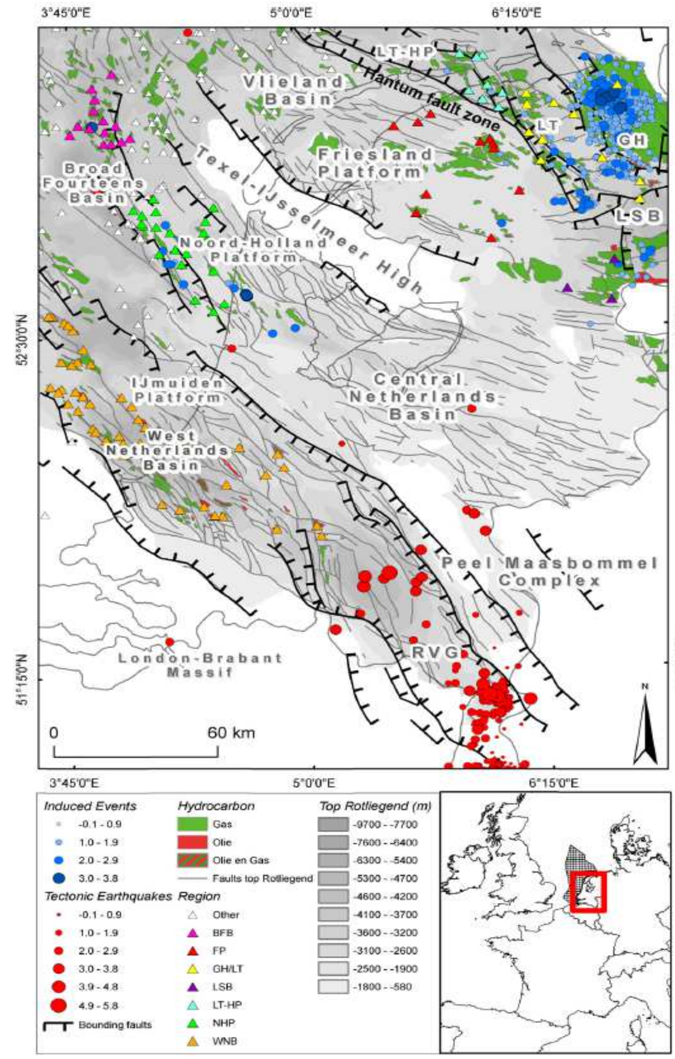


Figure 7: General tectonic map of gas fields in Holland. Natural seismicity is represented by red circles, induced / triggered seismicity by blue circles (Van Wees et al., 2014). The Groningen deposit is located in the northeast of the map and generates a seismicity that began nearly 30 years after production began.

3.4.2 SEISMICITY DUE TO OIL EXTRACTION

A series of earthquakes, with four events of a magnitude greater than 5, took place in northern Italy in the Emilia region in May – June 2012. These earthquakes caused 24 deaths, the temporary evacuation of 14,000 people and great damage to buildings and infrastructure. The ground's liquefaction was one of the most significant effects of these earthquakes (Di Manna et al., 2012). This region, located in the Po Plain, presents a relatively significant seismic risk due to an active tectonic regime (Apennine Mountains).

Figure 8: Example of damage to historic buildings in the Emilia Region following the 2012 series of earthquakes, considered to have been triggered by underground anthropogenic activity (Gasparini, 2015).

An international scientific and technical commission (ICHESE, 2014) was created to evaluate the possible relations between the different industrial activities (oil extraction, geothermal operations and gas storage) in this region and this seismic sequence (Figure 9). The commission concluded that it could not exclude that oil extraction (performed by fluid injection) at the site closest to the fault system, which was probably reactivated, was the origin of the seismic sequence. Because of these events (Gasparini, 2015), oil production in the area was stopped and the site was converted into a laboratory[8]. The commission recommended the implementation of monitoring systems in the oil fields located in the tectonically active areas of Italy. A good practices guide defining monitoring procedures of hydrocarbon extraction activities and underground storage in terms of seismicity, interstitial pressure and ground deformation was produced by a working group (MiSE, 2014). This guide was distributed to local authorities and hydrocarbon extraction companies present on the Italian territory. Finally, a law was passed (MiSE, 2015), imposing companies to monitor hydrocarbon fields in activity by following this guide's recommendations. Let us note that the study of this earthquake was the subject of several scientific publications and its origin is still a subject of debate (Albano et al., 2017; Grigoli et al., 2017; Grimaz, 2014; Juanes et al., 2016; Lavecchia et al., 2015).

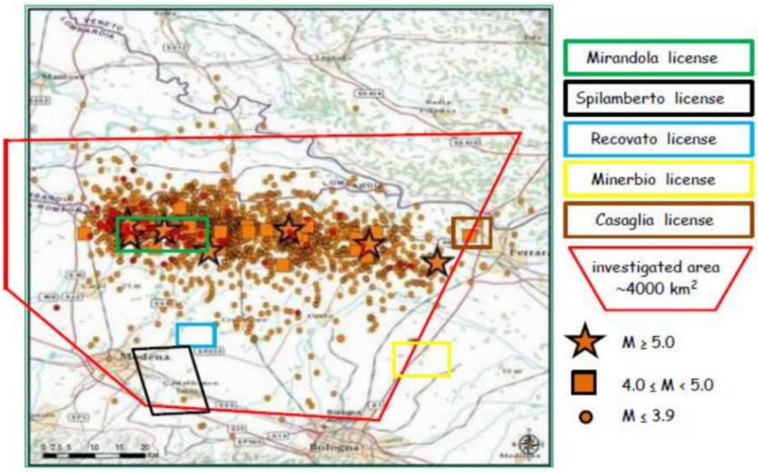


Figure 9: Location of the seismic swarm and the principal geo-industries of the region that were examined by the investigation commission to evaluate which was likely to have been the origin of the seismic swarm triggering (Gasparini, 2015).

The Ekofisk earthquake can be cited too, which occurred in an offshore oil field in the North Sea (Norway) (Cesca et al., 2011; Ottemöller et al., 2005). This 4.3-magnitude event was probably caused by water injection to maintain pressure in the reservoir. A topographical uplift was observed on the sea bottom and an overpressure in the ground was measured

[8] "Laboratorio Cavone", http://labcavone.it/

after the earthquake. The rupture took place at a shallow depth along a sub-horizontal fault situated above the reservoir in a context of ground subsidence due to oil production.

3.5 NON-CONVENTIONAL HYDROCARBON EXTRACTION: SHALE GAS AND HYDRAULIC FRACTURING

According to the United States National Research Council's synthesis report (NRC, 2013), the hydraulic fracturing process as it is currently practiced to recover schist gas does not raise any high risk in terms of induced or triggered seismicity and thereby the generation of earthquakes of a magnitude greater than 2. This opinion is drawn from feedback from the 35,000 shale gas production wells operated in the United States. Some cases have certainly been documented by the USGS[9], but only one series of earthquakes in Oklahoma has been directly attributed to hydraulic fracturing for the production of schist gas (Holland, 2011).

One documented case in Lancashire, England, a region known to be seismically calm, confirms the link between the occurrence of earthquakes and the production of shale gas by hydraulic fracturing. These events in the Northwest, near the city of Blackpool, of magnitudes 2.3 and 1.5 for the two strongest, were detected on 1 April and 27 May 2011 respectively by the BGS's regional network[10] (De Pater and Baisch., 2011; Green and Styles, 2012). Felt by the population, they were greatly spoken of in the press, and the operations were consequently suspended. In-depth studies led *a posteriori* showed that the seismic activity had been caused by fluid injection in a fault zone that was probably in a close-to-rupture state (De Pater and Baisch., 2011). This local seismic activity took place farther than foreseen, at approximately 500 metres from the injection point. Recommendations were thus made; they notably suggested implementing a monitoring system before, during and after hydraulic fracturing operations with a "traffic light" system for risk mitigation (Green and Styles, 2012). A good practices guide for industry was also published; it covers the entirety of a project's life cycle, from the hazard's evaluation until control and mitigation measures of the anthropogenic seismicity risk, for shale gas excavation operations in the United Kingdom (UKOOG, 2013).

This outcome is very different than that of the sedimentary basin of western Canada, one of the largest hydrocarbon reserves in the world (Figure 10), where the significant increase in seismicity registered since 2010 is principally attributed to the hydraulic fracturing process (Atkinson et al., 2016). Atkinson et al. (2016) affirm that nearly 60% of earthquakes of a magnitude greater than 3 recorded in this region are attributable to hydraulic fracturing operations. They also show that nearly 30% of earthquakes are induced by the injection of wastewater and approximately 10% are of tectonic origin. The authors underline, however, that a very small proportion (0.3%) of wells for hydraulic fracturing produce seismicity. However, since several thousand drills are performed each year in this region, the consequences for risk evaluation are significant.

This significant variation in feedback is explained, as is evoked in the following section, by the fact that USGS[9] scientists attribute the increase in seismicity in the centre of the United States not to hydraulic fracturing but to the definitive injection of industrial effluents, wastewater disposal, coming from schist gas production.

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[9] United States Geological Survey

[10] British Geological Survey

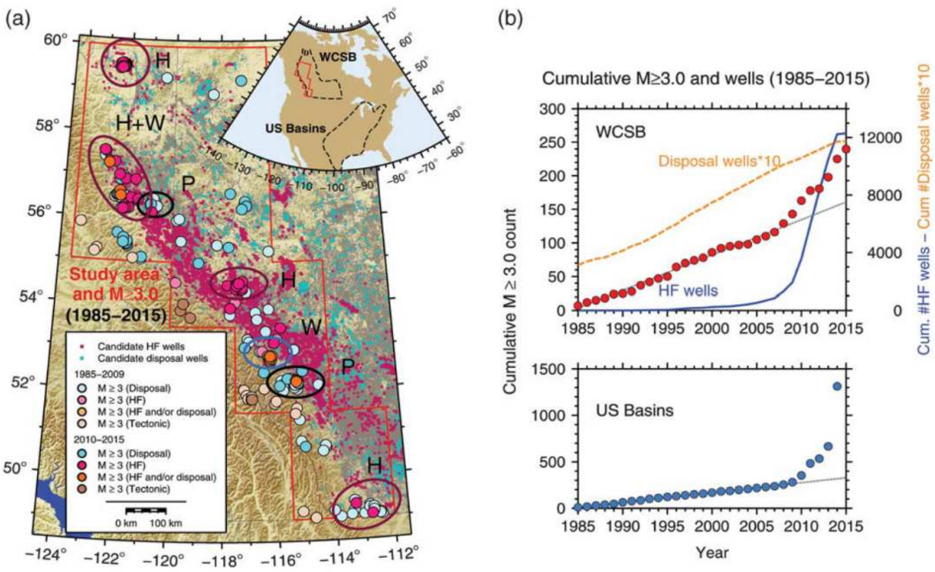

Figure 10: (a) Representation of seismicity of the sedimentary basin of western Canada (coloured circles: pink dots represent the location of wells where hydro-fracturing is practiced for the extraction of shale gas and turquois dots represent the location of wells for wastewater disposal . (b) 2 graphs representing the increase in seismicity in western Canada (above) and in the centre of the USA (below) for comparison from 1985 to 2015. Note in both cases the increase in activity a bit before 2015 with the development of the extraction of shale gases. This increase is attributed in Canada to hydraulic fracturing (HF wells in blue) while it is attributed to the wastewater disposal in the USA.

In France, there is no similar case, for hydraulic fracturing was made illegal on the national territory by the Jacob law of 13 July 2011, validated in 2013 by the Conseil Constitutionnel.

3.6 INJECTION FOR WASTEWATER DISPOSAL

The definitive injection of wastewater in deep underground formations is a very wide-spread method to eliminate large quantities of water, in general salted and polluted, notably generated by the production of conventional and non-conventional hydrocarbons. Indeed, at a global level, the production of each barrel of oil is accompanied by the production of 3 to 5 barrels of water on average, and this ratio can reach 10 to 14 in certain mature reservoir areas (IFPEN, 2011). In the United States, approximately 40% of this wastewater is deep injected in mass, i.e. 2 to 3 km under the production reservoirs in permeable formations for permanent sequestration. The injected volumes are estimated to be several million m^3 per year (NRC, 2013). Thus, the volumes are definitively injected, to the contrary of other processes in which an equilibrium is maintained between the volumes injected and extracted (hydro-fracturing, geothermal operations, secondary recovery of hydrocarbons). If this injection occurs near a favourably oriented fault system close to the critical state, the probability of triggering an earthquake felt on the surface is significant in the absence in the proximity of an extraction system allowing the balancing of the underground pressure (Rubinstein and Mahani, 2015). Earthquakes reaching magnitudes close to 6 have thus been observed in this case.

The best documented recent cases of seismicity generated by injected wastewater are located in the United States, where this practice is authorised. Since the 2000s, a significant increase in the number of earthquakes of moderate (≥ 3) to high (~ 5.7) magnitude was observed in the centre and east of the country, which are regions considered to be of low natural seismicity. In Oklahoma, for example, after decades marked by an average earthquake rate of 21 events / year, the activity jumped to 188 tremors in 2011 (Ellsworth, 2013) and culminated at 688 in 2014 (Rubinstein and Mahani, 2015), to such a point that the number of earthquakes of magnitude greater than 3 became higher in Oklahoma than in California (McGarr et al., 2015) (Figure 11). Several earthquakes caused significant damage in 2011: at Prague, Oklahoma, M 5.6, at Trinidad, Colorado, M 5.3, at Guy-Greenbrier, Arkansas, M 4.7 (Rubinstein and Mahani, 2015). Let us equally cite the case of the Pawnee earthquake in 2016 of magnitude 5.6, again in Oklahoma.

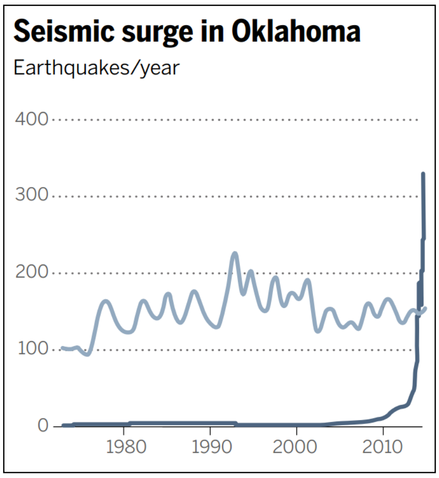

Figure 11: Number of earthquakes of magnitude ≥ 3 in California (light blue) and in Oklahoma (dark blue) since 1973 (McGarr et al., 2015)

Studies led to understand the origin of this brutal increase in seismicity show that the significant development of non-conventional shale gas operations since the 2000s doubled the quantity of water injected into the underground and, consequently, increased the probability of occurrence of significant earthquakes (Rubinstein and Mahani, 2015). It regularly appears in the press that hydraulic fracturing for the extraction of schist gases is the origin of this seismicity (for example on the site of the French newspaper *le Monde*, the article of 15/01/16 (Bussard, 2016)). Still, on the territory of the United States, hydraulic fracturing generally only causes earthquakes of low magnitude, which are not felt on the surface[11]. Actually, the cause of these earthquakes is linked to the management of this industry's effluents by injection of wastewater at sites which are generally located near non-conventional hydrocarbon production sites (where the hydraulic fracturing takes place), for obvious economic reasons. Thus, a confusion is born in our perception of the risks associated with each of these operations, which are nevertheless very distinct in nature (Rubinstein and Mahani, 2015).

Nevertheless, as mentioned in the preceding paragraph, in western Canada, the increase in seismicity since 2010 is principally attributed to hydraulic fracturing activities (Atkinson et al., 2016). The authors of this study suggest that hydrocarbon extraction in the United States, and more particularly in Oklahoma, requires significantly greater volumes of water, with the consequence of a production of wastewater volumes to be injected significantly higher than in Canada. They suggest that this massive injection of fluid in the United States could mask the seismicity directly caused by hydraulic fracturing.

One of the best documented case studies of seismicity induced by fluid injection is the one of Paradox Valley, Colorado (USA) (Figure 12-a), where naturally produced brine is reinjected through a well since 1996 (Ake et al., 2005; Block et al., 2014; Block et al., 2015; Yeck et al., 2015). The objective is to eliminate this brine from flowing into the Colorado River and modifying its salinity[12]. The well allows the brine's injection at a depth of approximately 4,500 metres (Figure 12-b). Nearly 8 million cubic metres of brine have been injected at this place (Figure 12-c). From 1997 to 2014, approximately 6,000 seismic events were detected, with magnitudes varying from 0.5 to 4.4. This seismicity was first localised

[11] Only a few cases in the world have been recorded in which hydraulic fracturing was considered to be the origin of major earthquakes (cf. § 6.5).

[12] "Colorado River Basin Salinity Control", http://www.coloradoriversalinity.org/index.php

around the well at the depth of the injection point, then further and further from the well, to reach a distance of 16 km in 2002. The last earthquake of magnitude 4.4 took place in January 2013 at more than 8 km to the northwest of the injection point. It was located near the city of Paradox, Colorado (USA) and strongly felt by the population but fortunately only caused minor damage.

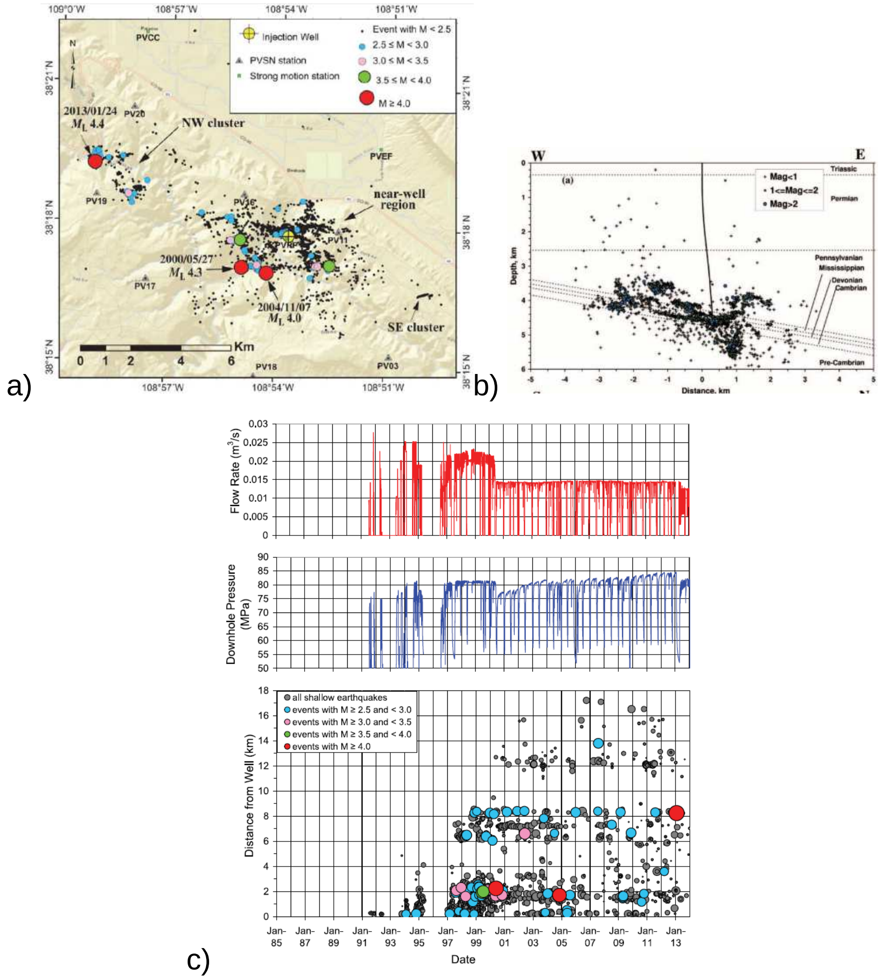

Figure 12: a) Localisation of seismicity at the Paradox Valley site (Block et al., 2014). b) injection well and associated seismicity (Ake et al., 2005). c) injection history, pressure in the injection downhole and associated seismicity represented in relation to the distance from the injection well (Block et al., 2015).

The Bureau of Reclamation[13] responsible for the site stopped the injection operations immediately. Then, changes in the injection protocol were modify to reduce the probability of causing new earthquakes in the short term. The problem is that the quantity of salt released into the Colorado River inevitably increases. Moreover, in the long term, underground pressures will increase if injection continues even at a reduced rhythm and consequently the risk of causing new earthquakes remains. If the current injection site would become totally inoperative, the salinity in the lower basin of the Colorado River (which feeds the cities of Las Vegas, Los Angeles, San Diego, Phoenix, etc.) would increase, causing annual losses evaluated at 24 million dollars (PVU, 2015). These losses could be more severe during periods of drought. Alternative solutions are being studied, such as a new injection site and/or the construction of evaporation basins (PVU, 2015).

[13] http://www.usbr.gov/. The Bureau of Reclamation, founded in 1902, is part of the U.S. Department of the Interior and supervises the management of water resources.

In France, there are two industrial effluent deep injection sites:

- The Lacq site in the Atlantic Pyrenees region, where industrial effluent injection is done in the geological structure called Cretaceous 4000 (well C4000)[14], substituting natural gas. This site is operated by Geopétrol;
- The Grandpuits-Bailly-Carrois site in Seine-et-Marne, operated by a fertiliser producer (GPN), that eliminates wastewater by injection into a deep well in the Dogger aquifer.

The first site has been performing injection since 1974 and has been equipped with a microseismic monitoring network since 2004. The registered seismicity is of low magnitude, in general less than 2.

The Grandpuits fertiliser plant eliminates wastewater by injection into a deep well in the Dogger aquifer due to the lack of an outlet drain in the proximity. These effluents are saline and released into a saline water table, according to the operator. Injection has been ongoing since the 1970s. There is no known anthropogenic seismicity phenomenon. However, only the impact of a natural earthquake was taken into account in the deep well injection perpetuation request study[15].

3.7 HYDRAULIC DAM LOADING

The relation between seismicity and large dams was made for the first time in the 1930s during the loading of Lake Mead (Hoover Dam, Nevada) (Carder, 1945). This phenomenon has been closely studied since then and is well documented in the literature (Asadollahfardi et al., 2013; Chen et al., 2014; Chen and Talwani, 2001; Gupta, 2002; Gupta and Rajendran, 1986; Hui-Hong et al., 2015; Tao et al., 2015). Bulletin n. 137 of ICOLD[16], which presents a complete state of knowledge of these phenomena, shows that these cases of seismicity are few in comparison to the considerable number of large dams in the world.

A hundred dams in the world have been linked to earthquakes (Gupta, 2002). Twenty-eight dams have triggered earthquakes of magnitudes between 4 and 4.9 and ten have triggered earthquakes of magnitudes between 5 and 5.9 (Gupta, 2002). Finally, four cases of earthquakes of magnitudes greater than 6 have been recorded:

- the Koyna dam (India), 103 m high: one 6.3-magnitude earthquake in 1967;
- the Kremasta dam (Greece), 120 m high: one 6.3-magnitude earthquake in 1967;
- the Hsingfengchian dam (or Xinfengjiang, China), 105 m high: one 6.1-magnitude earthquake in 1962;
- the Kariba dam (Zambia), 122 m high: one 6.25-magnitude earthquake in 1963.

A fifth earthquake of magnitude 7.9, which took place on 12th May 2008 in the Sichuan region (or Wenchuan, China), is suspected of having been triggered by the Zipingpu dam (156 m high). Currently, the natural or anthropogenic origin of this earthquake is still debated (Deng et al. (2010) versus Ge et al. (2009)). Indeed, this dam is located near major faults of the Himalayan Mountains, in the active tectonic context of the India-Asia continental collision (Figure 13-a). Therefore, an earthquake in this region could have been produced anyway, but certain authors believe that the dam's construction may have accelerated its occurrence (Ge et al., 2009; Klose, 2012). Klose (2012) believes that the loading of 300 million tonnes of water is the equivalent of 60 years of tectonic loading in this region, causing, according to him, the anticipated triggering of the earthquake. Partisans of the earthquake having occurred naturally suggest that the stress variation induced by the dam

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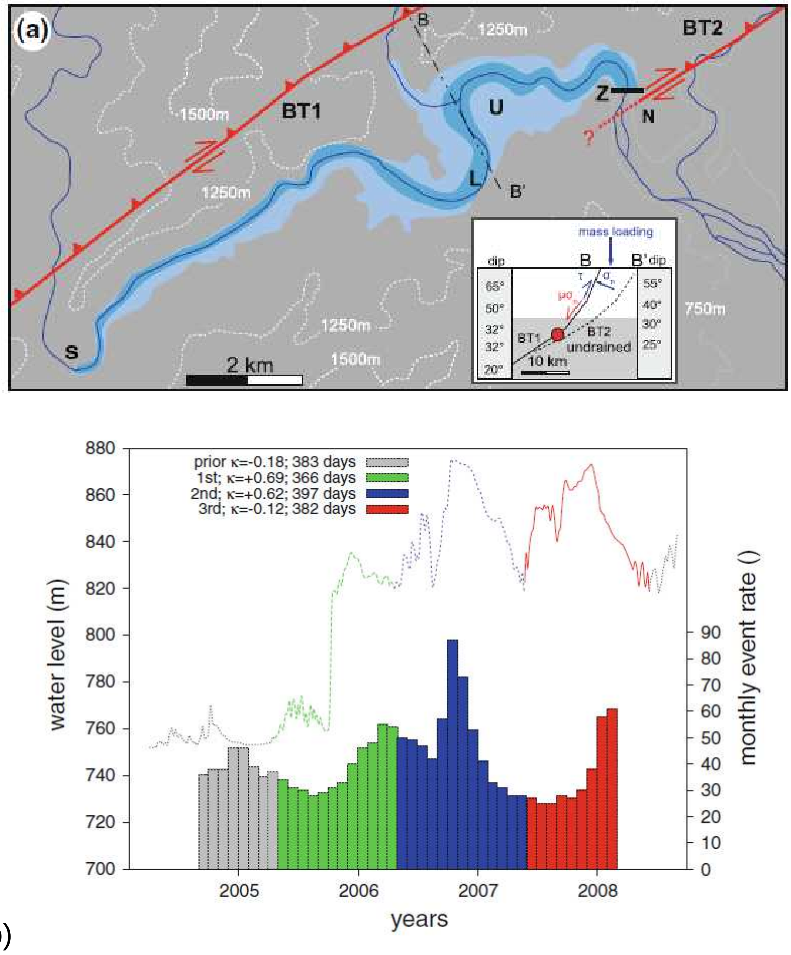
[14] http://www.pyrenees-atlantiques.gouv.fr/content/download/7629/47452/file/Geopetrol-ProjetArretePrefectoral.pdf and http://www.pyrenees-atlantiques.gouv.fr/content/download/17980/118331/file/Presentation_Geopetrol.pdf

[15] Request file for perpetuation of deep well injection: http://www.seine-et-marne.gouv.fr/content/download/2234/15596/file/Dossier_puits_profond_GPN_V1_20120206_synthese-2.pdf

[16] International Commission on Large Dams http://www.icold-cigb.org/GB/ICOLD/icold.asp

at the depth of the earthquake's source (~ 20 km) is negligible (Deng et al., 2010). Moreover, the Sichuan's earthquake sequence is very different than that of those triggered by other dams across the world (CHEN, 2009) (Figure 13-b). Finally, the magnitude of nearly 8 seems disproportional in relation to the maximum magnitudes recorded and correlated without ambiguity to the loading of water in other large dams, of the order of 6.3, thus corresponding to 200 times less released energy (CHEN, 2009).

Let us note that this earthquake occurred nearly three years after the beginning of loading in 2005. It is considered to be one of the most devastating earthquakes in the last 30 years in China, with approximately 90,000 victims, 380,000 injured, 15 million evacuated and 5 million people without shelter. The total economic loss was estimated at 67 billion euros.



a)

b)

Figure 13: a) Map of the tectonic context and the location of the Zipingpu dam, which could have been the origin of the Sichuan (China) earthquake of magnitude 7.9. b) the reservoir's water level history and the monthly seismicity rate. The water level is indicated in metres above sea level (NGF scale) (Klose, 2012; LEI Xing-lin, 2008).

In France, the case of the Monteynard dam (Vercors), of a height of 135 m, can be noted as the origin of an earthquake of magnitude 4.5 in 1963. In Europe, the loading of the Itoiz dam in Navarre (height of 122 m) in the western Spanish Pyrenees was the origin of a 5.2-magnitude earthquake on 18th September 2004 (Jiménez et al., 2009). The last earthquake felt at this site took place on 7th May 2010 and was of magnitude 3.7.

3.8 CO_2 SEQUESTRATION

To reduce CO_2 emissions in the atmosphere, one of the possible industrial solutions is underground sequestration. Several types of geological formations can be used for this storage, such as aquifers, untapped coal veins or depleted hydrocarbon reservoirs. In principle, this process is likely to generate seismicity that can be of significant magnitude if the tectonic context is favourable (Zoback and Gorelick, 2012). Indeed, existing projects, or in the process of being developed, foresee to inject significant volumes at high pressure over a long period of time. The risk of increasing the interstitial pressure in the reservoir, as we have seen in other contexts, is probable, especially because the injected volumes are not balanced. The hydro-chemical-mechanical interactions that are produced in the reservoir, such as mineral dissolution, could also amplify the problem (Espinoza et al., 2011).

However, for the time being, there are no recorded cases of earthquakes felt on the surface caused by underground CO_2 storage. The principal explanation is that there are very few projects of this type in the world (NRC, 2013). In Europe, there are two sites, Sleipner[17] in the North Sea (Arts et al., 2004) in Norway, and Ketzin[18], 40 km west of Berlin, Germany (Martens et al., 2013). These two storage reservoirs are located in saline aquifers. At the Sleipner site, where 15.5 million tonnes of CO_2 were injected between 1996 and 2015, several earthquakes of magnitude between 2 and 3 have been detected in the 50 km around the injection platform (Evans et al., 2012). The Ketzin pilot site has not felt seismicity (Evans et al., 2012).

Let us equally cite the Lacq-Rousse pilot, a Total project operated from 2010 to 2013. Operations consisted of capturing CO_2 at Lacq, then transporting it on 40 km before storing it at Rousse in a depleted natural gas reservoir located 4,500 m deep. With the modest quantity of 90,000 injected tonnes, it was only a pilot site, however it positioned France as an actor in CO_2 storage on the international stage. Low seismicity was recorded during and after injection operations[19].

3.9 OTHER CASES OF ANTHROPOGENIC SEISMICITY

Other cases of earthquakes associated with salt solution mining are mentioned in the literature (Nicholson and Wesson, 1992). In this extraction method, water is injected in wells reaching the salt layer to dissolve it. Then the brine is recovered to extract the salt. This method creates cavities that can reach critical sizes. The strongest earthquake associated with this process, of magnitude 5.3, took place in Attica, New York (USA) in 1929. Other lesser magnitude earthquakes also took place at this site in 1966 and 1967. At Cerville, Lorraine (France), where this extraction method is also used, the collapse of a saline cavity created by dissolution in 2008 did not generate earthquakes that could be felt (Contrucci et al., 2011; Kinscher et al., 2015).

A 5.1-magnitude earthquake that was probably triggered by the extraction of groundwater is described in the literature (Gonzalez et al., 2012). This tremor took place near Lorca, Spain, 11 May 2011. It caused 9 deaths, injured at least 130 people and left 15,000 without homes. Although of moderate magnitude, this earthquake was particularly devastating because of the shallow depth of its epicentre (~ 2.5 km). The Betic Cordilleras, where the city of Lorca is located, is one of the most seismically active areas of the Iberian Peninsula. The water pumped since the 1960s had lowered the water level of the natural underground reservoir by 250 metres. This massive unloading over a short period of time, which was also near a fault that was probably close to the critical state, could have created a stress

[17] http://www.globalccsinstitute.com/projects/sleipner%C2%A0co2-storage-project

[18] http://www.co2ketzin.de/nc/en/home.html

[19] http://www.pole-avenia.com/wp-content/uploads/2017/01/OPERATIONS-03-Andr%C3%A9-MARBLE.pdf

variation significant enough to trigger the earthquake according to the authors (Gonzalez et al., 2012).

3.10 SYNTHESIS OF THE CASE STUDIES AND THE RELATED INDUSTRY

Figure 14, created from the database collected in this study (cf. appendix B), represents the distribution of maximum observed magnitudes in relation to the industrial process at the origin of this seismicity. We observe that the magnitudes are for the majority between 2 and 5 for all activities together. The cases of dams (including Zipingpu (in the Sichuan region), M 7.9, of which the origin is debated) and hydrocarbon extraction (Gazli, M 7.3) correspond to the highest magnitudes (greater than 6). In the 5 to 6 magnitude range, other than cases of hydraulic dams, water extraction (Lorca, Spain earthquake, M 5.1) and salt solution mining (Attika, New York, USA earthquake, M 5.2) cases are found. The five strongest magnitudes related to anthropogenic activity are summarised in Table 4. Geothermal operations show moderate maximum magnitudes, which are for the most part between 2 and 3. They are weaker in average than those observed for mining activities. The considered cases of wastewater injection show magnitudes that can be significant (< 5). In general, the larger the industrial operation, occupying a significant surface and volume, the greater the probability of triggering a high magnitude earthquake (under favourable conditions) (McGarr et al., 2002).

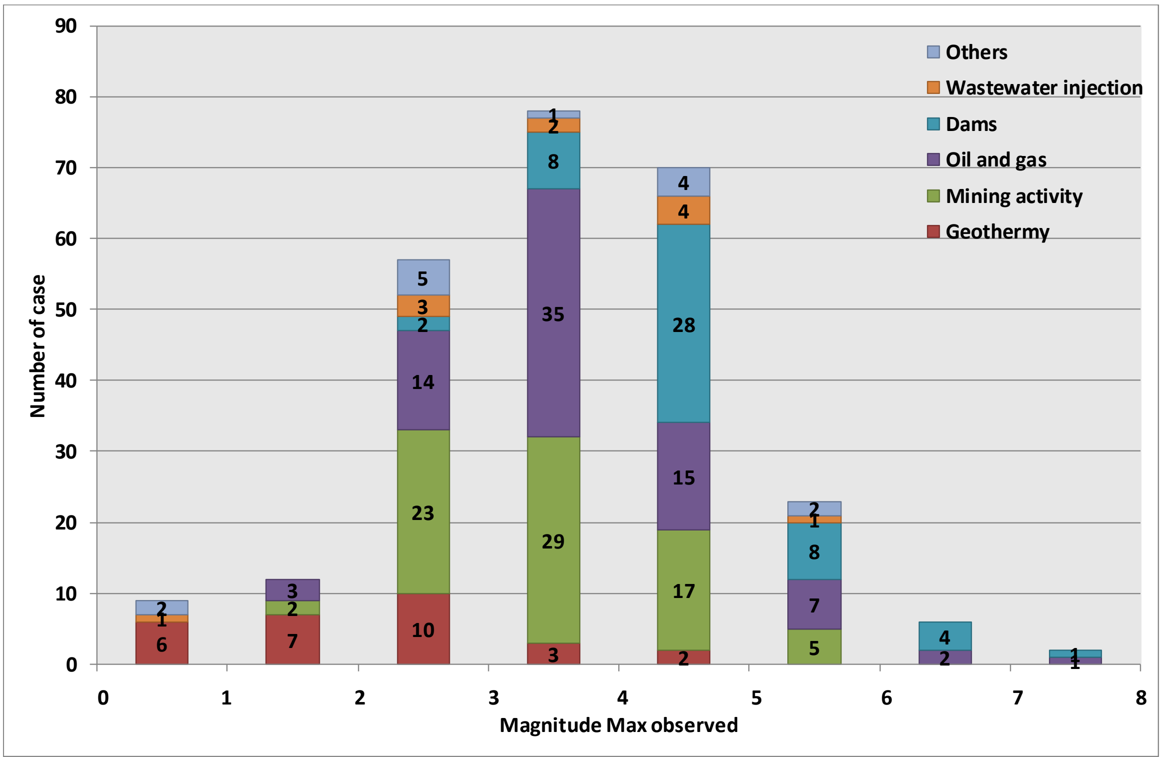


Figure 14: Representation of maximum observed magnitudes for each type of anthropogenic activity, based on the non-exhaustive database presented in appendix B of this report. The figures refer to the number of observed cases.

Site	Country	M	Industrial context	Reference	Year
Coalinga, California	USA	6.5	Hydrocarbon extraction	(McGarr, 1991)	1983
Gazli	Uzbekistan	7.3	Hydrocarbon extraction	(Adushki et al., 2000)	1976
Koyna	India	6.5	Hydraulic dams	(Gupta, 1983)	1967
Kremasta	Greece	6.3	Hydraulic dams	(Gupta, 2002)	1966
Zipingpu	China	7.9	Hydraulic dams	(Huang et al., 2008)	2008

Table 4: The five greatest seismic events suspected of being associated with anthropogenic activity.

This synthesis shows that all sub-surface industrial activities that modify the *in situ* stress field can potentially cause induced and/or triggered seismicity under certain favourable conditions. While the industrial operations are of different natures, the occurrence of a seismicity is observed in regions where natural seismicity is already significant as well as in those where it is low. The different authors agree on the fact that the underground's initial stress state and, in particular, the presence of faults in a state more or less close to the critical state are determining factors that condition the occurrence of seismicity and the time delay in which it occurs. Indeed, the closer is the system to the rupture, the less energy is necessary to destabilise it. Thus, a slight stress variation generated by the industrial process can destabilise the system and generate earthquakes. In this case, one can observe a seismicity that appears immediately after industrial operations begin. On the contrary, if the system is not yet close to this rupture state, it is the accumulation of stress variations (by extraction, injection, etc.) over a long period, in addition to the pre-existing stress field, which can cause ruptures. The main problem is that this initial stress state is generally not or little known and, in particular, if faults are present and whether they are more or less close to rupture.

Seismicity induced by the industrial process itself is often of low magnitude and is not, or is very little, felt on the surface. Under certain propitious conditions, when the orientation of the stress field's and of structures is favourable to slipping (shearing), high magnitude earthquakes can be triggered. This is possible when the structure solicited by the stress variations is of large dimensions as are, for example, pre-existing faults and mining works or reservoirs that extend over great area.

In general, a spatio-temporal correlation between the location of anthropogenic seismicity and the operations' site is observed. Also, as soon as an earthquake takes place close to an industrial activity, this activity is generally suspected of being its origin. This is all the more true when the earthquake takes place in a region where the natural seismological activity is low. However, this spatio-temporal correlation is not always observed. This is notably the case when the seismicity is triggered by underground fluid injection or infiltration with an increase in interstitial pressure: deep geothermal operations, hydrocarbon extraction, wastewater injection, gas or CO_2 storage, mine flooding, dam loading, etc. Indeed, case studies have shown that seismicity can occur far from the injection point (up to several dozen kilometres) and can be delayed on several years. Moreover, decreasing injection velocities and/or stopping injection does not always decrease the occurrence of earthquakes or their magnitude. The greatest magnitudes have been observed in situations where the injected volumes are not balanced with the extracted volumes. Authors explain these phenomena by the differed rebalancing of pressures in the rock mass in relation to the site's hydrogeological conditions.

In France, anthropogenic seismicity is of low magnitude and has not caused notable damage. Only some events have been felt, such as, for example, amongst the most recent, at the active deep geothermal site Soultz-sous-Forêts or the former coal basin of Gardanne (Table 5).

Location	Maximum magnitude	Industry type (earthquake's origin)	Date
Soultz-sous-Forêts	2.7 – 2.9	Deep geothermal operations	2003 – 2005
Rochonvillers	4	Mining activity	1974
Saar	3,7	Mining activity	2008
Lacq	4.2	Hydrocarbon extraction	1979
Grandval	Felt	Hydraulic dam	1963
Monteynard	4.9	Hydraulic dam	1963
Vouglans	4.4	Hydraulic dam	1971
Rochonvillers	4.3	Mining activity	1974
Merlebach	3.9	Mining activity	1986
Merlebach	4	Mining activity	2001
Ronchonvillers	5.2	Mining activity	1975
Gardanne	~ 3	Mining activity	1994 – 2001
Gardanne	~ 2	Abandoned mine	2012, 2014,2017
Cerville-Buissoncourt	0.9	Salt solution mining	2008
Tressange/Rochonvillers	4.3	Mining activity	1973

Table 5: summary table of anthropogenic seismic activity in France. The maximum detected magnitudes for each industrial project recorded.

4. HOW TO ASSESS THE ANTHROPOGENIC SEISMICITY HAZARD

Seismic hazard represents the probability of occurrence of a seismic event of a given intensity at a given place and allows one to determine the expected ground movement following an earthquake.

The assessment of the hazard of natural seismicity thus integrates magnitude, amplitude and the return period of natural earthquakes. It is based on the hypothesis that an earthquake that took place in the past in a given region can reappear identically in the future.

The hazard assessment of anthropogenic seismicity is based on this same approach but also integrates the fact that human activity can play a role in earthquake occurrence (in space and time), notably by taking into account considerations related to the context and involved activities. The idea here is to anticipate or try to predict the occurrence of an earthquake.

4.1 CLASSIC INPUT DATA

The first step of a hazard study consists of identifying at the local and regional scale the “seismogenic” areas and characterising the seismic sources. This is generally done by using two complementary approaches:

- the possibly most detailed cartography of the present faults to identify the segments that were active in historical and recent times and thus likely to be reactivated. Particularly, the objective is to estimate the size, the orientation in relation to the regional stress field and the geometry of the present faults on the basis of surface observations;
- the study of the regional natural seismicity retrieved from instrumental data catalogues gathered by the seismological stations of national and/or regional monitoring networks and from historical seismicity catalogues that detail the characteristics of former earthquakes, gathered from accounts and other documentary sources. In practice, these seismicity catalogues are often incomplete; they can equally lack in specifics such as the location and the magnitude of past earthquakes. This is all the more true for zones that are not very seismically active for which the recurrence times are long.

Moreover, the organisation in space of large-size faults often being complex, to refine the identification of seismogenic zones and seismic sources it can be useful to lead complementary investigations, for example, through:

- geophysical prospection techniques, to confirm or disprove indirect indications on the presence of faults on the surface or even to image deep fault structures;
- aerial photography or satellite imagery, to complete ground observations by a precise estimation of the displacement fields by past earthquakes and to understand possible interactions between local and regional fault segments;
- hydrological and geochemical surveys, to provide information on the circulation of underground water, a fault being able to act as a drain, dam or semi-dam to flows.

Let us specify that the financial cost of these investigations can rapidly become high. It can be justified when the seismotectonic context and current dynamic are compatible with the occurrence of an earthquake of magnitude greater than 4 - 5. Let us also note that these approaches, even if they provide fundamental information, do not allow one to exhaustively identify all the faults present on a site.

Once the seismic sources have been identified and described, it is necessary to develop an attenuation model of the ground’s movement amplitude, representative of the site’s geomorphological context including the eventual site effects that can noticeably modify ground movement (cf. §2.3.2).

4.2 PREDICTIVE MODELS: DETERMINISTIC AND PROBABILISTIC APPROACHES

The seismic hazard can be estimated with two different, often opposed, models, but which are nevertheless based on the same input data (cf. § 4.1):

- the deterministic approach (Reiter, 1990) to calculate by numerical modelling the effects of ground movements on the basis of a clearly identified rupture scenario (the highest magnitudes earthquake case is often considered as the unfavourable one). Modelling takes into account the local geology, geomechanical and hydrological characteristics, notably the presence and density of faults, their orientation in relation to the stress field and the industrial process's effect on the local stress field's variations (history of injection / extraction, etc.);
- the probabilistic approach (McGuire, 2004), historically based on the Guntenberg-Richter law[20] of earthquake recurrence, which expresses the relationship between earthquake magnitude and occurrence frequency. This approach gives a ground movement level with a certain probability of being exceeded over a certain period of time.

Implementation of the deterministic approach generally proves to be complex because the input data are marred by numerous uncertainties that are often difficult to quantify, notably the location of deep faults and their stress state. The faults themselves can equally be difficult to model for they induce numerical discontinuities. Finally, these seismicity forecasting models must be validated by *in situ* measurements, which is not always possible. This validation is however fundamental to understand and quantify the role of each of the physical phenomena in the triggering of an earthquake, be it natural or induced (Alber and Fritschen, 2011). In the case of a significant seismic activity, it is sometimes possible to detect and to image the presence of deep faults by means of seismic tomography and thus to provide supplementary data to improve numerical models (Baisch et al., 2009; Bruel, 2007).

The probabilistic estimation, applicable for anthropogenic and natural seismicity, consists, on the basis of the occurrence frequency of earthquakes, of estimating the probability that an earthquake of a given magnitude or intensity occurs at least once at a given site over a given time interval. One thus seeks to estimate the probability of earthquake occurrence by implementing empirical statistical models (Mignan et al., 2017; Mignan et al., 2015). In this approach, the completeness of seismicity catalogues is an essential input that fundamentally depends on the quality of instrumentation and technical means (the network's configuration and density).

There is currently no consensus on the type of approach to use to anticipate the occurrence of earthquakes and their magnitude. Both the deterministic and probabilistic approaches to estimate the seismic hazard of a particular site are generally used (Gaucher et al., 2015; Majer et al., 2012; Majer et al., 2014). Recently, hybrid models have been developed, notably in deep geothermal operations, where modelling data coming from the physical model serve as input data to the probabilistic model (Hossein Hakimhashemi et al., 2014).

4.3 REVISION OF SEISMIC HAZARD MAPS AT A TERRITORIAL SCALE

Hazard studies are generally developed in the form of isovalue maps of a ground movement parameter (acceleration, velocity, displacement) for a given return period. They are used for the dimensioning of buildings, structures and infrastructure that will be built in the concerned area[21]. Indeed, even if the seismic hazard is low, vulnerability can be significant in urban areas or at sites with sensitive infrastructure.

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[20] This relation describes the distribution of earthquakes by magnitude class or the ratio between the number of earthquakes of magnitude M and M+1.

[21] France is subject to the European earthquake building code, Eurocode 8: http://www.eurocode1.com/fr/eurocode8.html

For this reason, maps are periodically revised on the basis of newly acquired knowledge, allowing one to better take into account uncertainties related to historical seismicity data and the improvement of knowledge to take into account attenuation laws, site effects and other hazard study input parameters (e.g.: source mechanism, field effect close to a fault, etc.).

But despite the increase of anthropogenic seismicity around the world, hazard studies do not integrate anthropogenic seismicity. Seismicity catalogues are systematically purged to only take into account natural seismicity because the development of hazard maps is based on the hypothesis that seismicity is a phenomenon that is stationary in time.

With the increase in anthropogenic seismicity, new questions arise:

- how to taken into account in the estimation of the seismic hazard the anthropogenic seismicity, which varies both in time and space?
- as for meteorological forecasting, should hazard maps be produced on the basis of the week's, month's or past year's seismicity?
- what are the implications for the risk's assessment, its mitigation, and how are responsibility and eventual indemnification measures or repair of damage established / defined, depending if the hazard is natural or anthropogenic?

The scientific community has in part taken up these questions, notably the USGS[9], which for the first time produced a hazard map (Petersen et al., 2015) integrating natural and anthropogenic data at the scale of the American territory. At the date of this report's writing, these hazard maps are re-evaluated on the basis of a recurrence time of one year[22]. They show that due to anthropogenic seismicity, the annual occurrence probability of a destructive earthquake in Oklahoma is henceforth comparable to that observed in California (Figure 15).

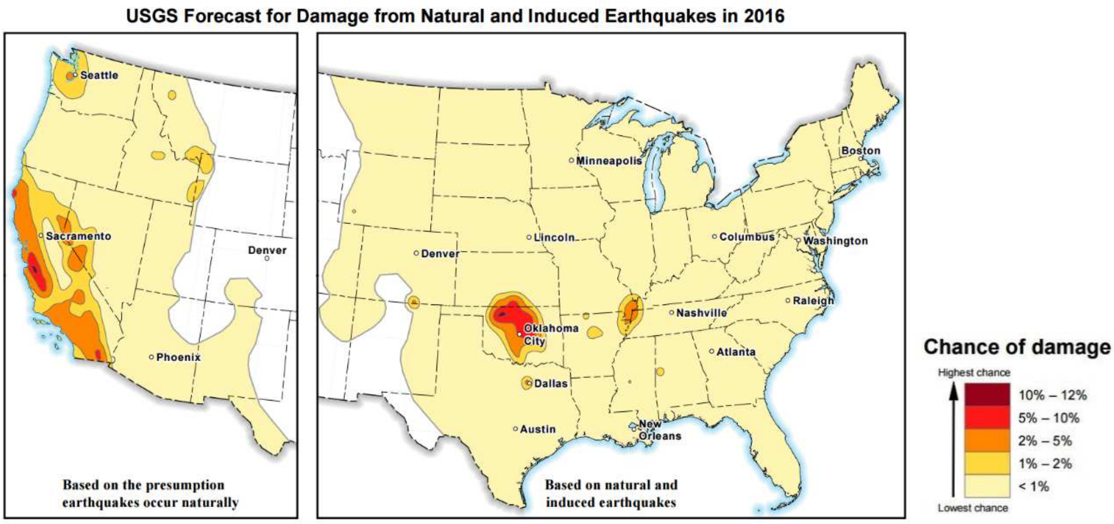


Figure 15: Map of seismic risk on the scale of the territorial United States produced by the USGS, showing the probability of damage caused by natural and anthropogenic earthquakes in 2016. Probabilities vary from less than 1% to 12%.

4.4 ASSESSMENT OF THE SEISMIC HAZARD IN THE MINING INDUSTRY

The case of the underground mining industry is exceptional because it involves the safety of miners, who are directly exposed to seismic risk. Since the beginning of the 20th century, the mining sector has thus decisively contributed to improving knowledge on this subject and to consider the hazard of anthropogenic seismicity in exploitation schemas.

Considerable progress has thus been made over the last decades, but the problem remains complex. Today, in certain deep gold mines in South Africa seismic hazard can be assessed

[22] https://pubs.er.usgs.gov/publication/ofr20161035

by mining operators over three periods of time: long term (annual), midterm (monthly) and short term (daily) (Rebuli and van Aswegen, 2013; Spottiswoode, 2010).

In the long term, the hazard is estimated according to the planning of future works from numerical modelling. In the midterm, it is about detecting abnormal responses of the rock mass to the extraction. In both approaches, the objective is to assess the highest probable magnitude in certain areas of the mine. Finally, as for the short term, hazard maps are updated in relation to the progression of works and seismological data recorded daily by monitoring networks. Here, the point is to detect, for example, a geological anomaly at the site front or a local zone in overstress due to the works' geometry or geological discontinuities. Variations of certain parameters allow the calculation of the occurrence probability of the strongest event over the considered period. This short-term prediction approach has been implemented with some success but does not work systematically (Rebuli and van Aswegen, 2013).

In general, despite the considerable progress of monitoring technologies and knowledge over the last decades, seismic risk in deep mines remains a major risk against which only prevention through the development of good operation practices and site safety allows the limitation of impact.

5. RISKS RELATED TO ANTHROPOGENIC SEISMICITY

The assessment of seismic risk consists of describing and quantifying the losses and damage that could be generated by the impact of seismic waves on the stakes present in the proximity of the epicentral zone. These stakes concern buildings, artwork, surface infrastructure and buried networks. The ground and terrain's morphology itself can be impacted when landslides are triggered or the ground's liquefaction occurs. Damage is generally on the surface, but it can equally affect underground infrastructures even if it remains less sensitive to seismic waves given the confinement in subterranean layers. The assessment of seismic risk depends both on the evaluation of the seismic hazard (location and magnitude) and on the presence of stakes and their vulnerability to seismic vibrations.

The problem of personal safety is strongly related to the vulnerability of buildings and works. Indeed, damaging building and works, or even their destruction, puts the population in danger. In the deep mining industry, miners are faced to the destruction of galleries and rock falls. The reduction of the stakes' vulnerability is achieved with earthquake building norms in the first case and mining gallery reinforcement techniques in the second case.

We are going to see in this section the risks related to seismicity of anthropogenic origin in different domains.

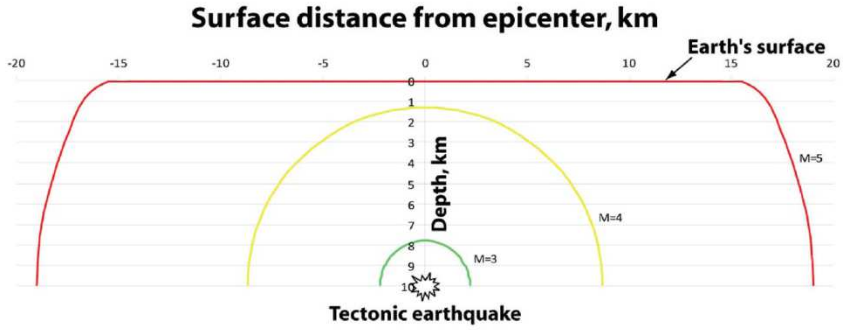
5.1 SPECIFIC NATURE OF ANTHROPOGENIC SEISMICITY AND ATTENUATION LAWS

The surface impact assessment methods for natural earthquakes cannot be directly transferred to the analysis of vibrations generated by anthropogenic earthquakes (Bommer et al., 2015). Indeed, the anthropogenic earthquakes are of shallow depth (depth < 5 km), and it is consequently difficult to directly apply attenuation (or ground vibration model) laws established from natural earthquakes. These laws relate magnitudes and distances to the seismic source to expected PGV or PGA values (cf. §2.3.3) on a point at the surface. Thus, the tremors generated by these shallow earthquakes can be significantly more harmful and damaging than tectonic earthquakes of an equivalent magnitude (NRC, 2013).

Figure 16 illustrates this principle: a 3 or 4-magnitude earthquake is not (or is little) felt on the surface in the case of a tectonic earthquake, located 10 km deep, while an anthropogenic earthquake of the same magnitude, situated 2 km deep, can be felt. It will be possible to feel a magnitude 5 earthquake in both cases, but over a greater surface in the case of a shallow anthropogenic earthquake.

Today numerous authors observe that events of low to moderate magnitude that occur at short hypocentral distances deserve meticulous assessment for national cartography of seismic risk (cf. § 4.3) and building dimensioning (Atkinson, 2015; Bommer et al., 2015; Rubinstein et al., 2014).

a)



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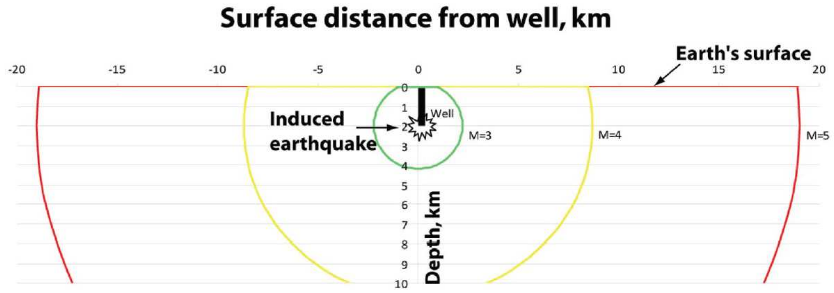

Figure 16: Cross-sectional views illustrating the maximum distance of tremors that will be produced for earthquakes of magnitude 3 (green line), 4 (yellow line) and 5 (red line) for (a) a tectonic earthquake situated at a depth of 10 km or (b) an anthropogenic earthquake situated at a depth of 2 km (NRC, 2013).

5.2 RISK FOR BUILDINGS AND SURFACE INFRASTRUCTURE

One of the major problems of anthropogenic seismicity is that it can occur in regions where natural seismic risk is low and consequently constructions are not dimensioned to resist earthquakes, even ones of low intensity (Ellsworth, 2013). As a point of comparison, a magnitude 5.6 natural earthquake in California or Japan would cause no damage, while a similar (5.7) magnitude earthquake in Prague, Oklahoma in 2011 caused several injuries and 10 million dollars in damage. Let us also cite the anthropogenic earthquake in Lorca, Spain, in 2011 of an even lesser magnitude (5.1), which was particularly devastating, or that of Newcastle, Australia, in 1989 of magnitude 5.6 (cf. §3.9 et §3.1). The heavy losses created by these last two earthquakes, attributed to underground industrial operations, resulted from the exposure of numerous fragile buildings (notably historical) to the strong shaking produced by seismic sources situated at shallow depths (van Eck et al., 2006).

Earthquakes, be they natural or anthropogenic, produce ground vibrations, displacements and accelerations. Solicited in an alternating, disorderly manner and at different frequencies, structures are subjected to horizontal, vertical and torsion oscillations that generate more or less significant efforts (Figure 17). The applied forces are essentially due to inertia, which are all the more significant as construction mass is great and ground accelerations are strong. Deformation can occur as a consequence, whose intensity may vary depending on structure types. This deformation can be worsened when the ground movement’s frequency coincides with the structure’s resonance frequency, as it leads to the movements’ progressive amplification. A building’s response to seismic solicitations depends on its architectural design, notably the used materials and the distribution of masses and volumes, load-bearing elements, and its geometry (height in particular).

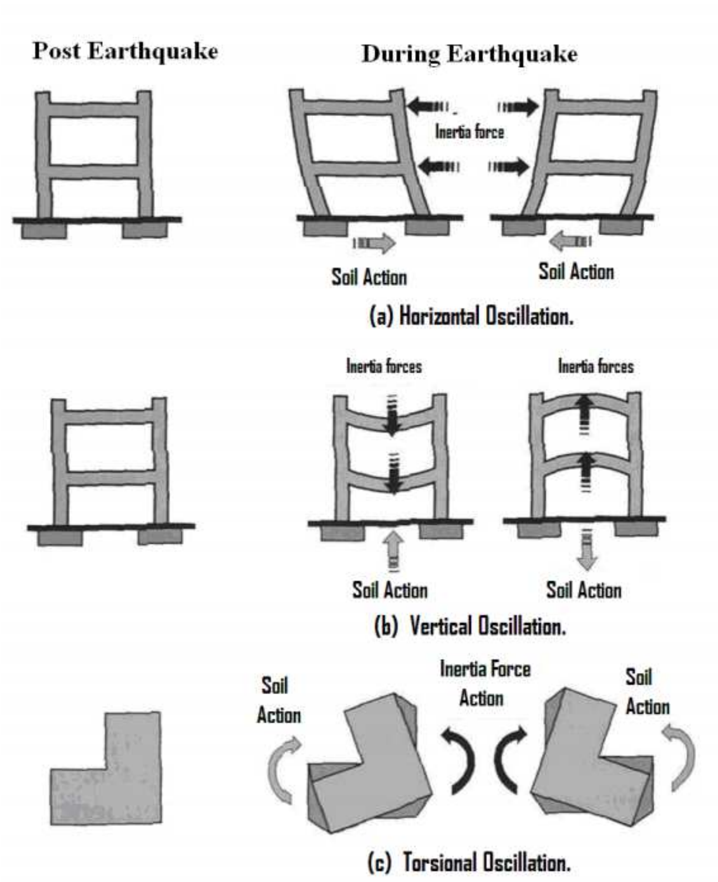

Figure 17: Illustration of three oscillation modes of a structure subjected to an earthquake (Zacek, 1996).

Knowing the seismic vulnerability of buildings can be useful even in areas with a low to moderate anthropogenic seismic hazard, since the seismic risk is potentially elevated in highly urbanised sectors and historical centres. There are different methods that allow a large-scale assessment of a site's vulnerability and a preliminary analysis to identify structures requiring a detailed study. The French Association of Earthquake Engineering (Association Française du Génie Parasismique [AFPS]) proposes a method based on eight criteria (Appendix C and Table 7). A number of points of which the total "K" gives the vulnerability is associated to each criterion (Table 6):

K vulnerability index	Diagnostic
K > 100	very high vulnerability
50 < K < 100	high vulnerability
25 < K < 50	average vulnerability
10 < K < 25	low vulnerability
K < 10	very low vulnerability

Table 6: vulnerability index K table (Zacek, 1996)

A more detailed study is advised when the K index is greater than 50. When it is smaller than 50, the damage level is estimated in relation to the maximum pick ground acceleration (PGA).

Note that PGA (Table 7) is estimated in a given frequency field, often with a low-pass filtering around 30 Hz. This field is defined for remote natural earthquakes, which in fact have little energy above 15 Hz. This could not be entirely pertinent for very close seismic sources due to the lower attenuation of higher frequencies (between 15 – 30 Hz).

PGA	K < 10	10 < K < 25	25 < K < 50
0.1 g	None or negligible damage	Negligible damage	Light damage
0.2 g	Negligible or light damage	Light damage	Moderate damage
0.3 g	Light to moderate damage	Moderate damage	Serious damage

Table 7: Evaluation of damage in relation to ground acceleration for buildings characterised by an index K < 50 (according to the AFPS)[23].

5.3 RISKS AT INDUSTRIAL FACILITIES

Earthquakes of anthropogenic origin are likely to cause the same damage, even greater, than natural earthquakes. Given that anthropogenic earthquakes have a high probability of taking place on an industrial site, we briefly recall here the consequences that could be expected on different infrastructures on the basis of a study performed by Ineris (Ayrault, 2001).

It shows that non-anchored storage tanks are more exposed to a leak risk following a deformation of the tank's base. According to the accidentology, other equipment is particularly exposed to earthquakes, such as pipelines, electrical materials as well as, to a lower extent, pumps, compressors and rotating machines. This analysis equally shows that significant damage can be caused by post-earthquake fires. These fires may come from gas leaks, fire propagation in certain businesses and ignition of liquid hydrocarbon vapours. These fires add heavily to the direct damage of an earthquake, all the more given that it is very difficult for firefighters to intervene, given the difficulties of access and degradations of the water network following the earthquake. Thus, it is necessary to protect firefighting means against seismic risk.

5.4 RISK FOR UNDERGROUND WORKS

It is recognised that natural earthquakes, i.e. of low frequencies and from remote origin, have much less severe effects on underground works than on the surface ones, given the confinement of subterranean works in a geological formation, and compared to the degree of freedom of buildings and works anchored only by their foundations to the moving ground (Dowding and Rozan, 1978).

However, anthropogenic earthquakes, situated at depths close to underground works, can generate wavelengths comparable to the structures' dimensions. In these conditions, resonance phenomena can appear and lead to damage (Dowding and Rozan, 1978). As expected, tunnels situated in massifs with a strong potential for liquefaction or tunnel entries situated in the proximity of landslide zones are more at risk than tunnels situated in solid rock (Dowding and Rozan, 1978). Finally, severe damage is inevitable when the underground work is intersected by the fault along which the earthquake occurs (Dowding and Rozan, 1978).

5.5 RISK FOR WELLS AND PIPELINES

In general, wells resist well to natural and remote earthquakes due to their dimensions. Indeed, they are confined works of small size in relation to the wavelengths of natural earthquakes. Thus, they are not very sensitive in these conditions to rupture, notably the ruptures which would be caused by the shearing waves emitted by a remote earthquake.

23 http://www.afps-seisme.org/PUBLI/Cahiers-techniques/Cahier-Technique-25-Vulnerabilite-sismique-2005

Theoretically, wells could be damaged by anthropogenic earthquakes if, like subterranean works, they are put into resonance by wavelengths of the same dimensions (Dowding, 1996; Majer et al., 2014). To our knowledge, this has not been reported in the scientific literature yet. A study led by Dowding (1996) showed that blasts performed in the proximity of water-producing wells did not bring about any production capacity loss with PGVs reaching 14.1 cm/s (Dowding, 1996; Majer et al., 2014). Nevertheless, damage can be observed in wells directly crossing fault planes. In this specific case, damage is directly due to the rock massif's differential movement (Dowding, 1996; Pratt and Hustrulid, 1978). Some damage has equally been observed on wells located in the sub-surface (< 100 m deep) and in non-consolidated sediment (Pratt and Hustrulid, 1978).

Pipelines, unlike wells, are very sensitive to earthquakes of natural origin (Berrones and Liu, 2003) and *a fortiori* to anthropogenic earthquakes (Dowding, 1996; Majer et al., 2014). Indeed, pipelines are large horizontal structures that are consequently particularly affected by the ground's differential movements caused by an earthquake. Relatively significant tensile stresses exist in the pipes' sides due to the high-pressure gas or liquid that circulates inside. These stresses superpose to the induced stresses by the passage of the ground's movement waves and can thus cause the pipeline's rupture. Moreover welding or maintenance flaws can weaken the structure. Thus, the effects of earthquakes must be taken into account during pipeline design on an industrial site likely to induce seismicity.

5.6 IMPACTS ON THE ENVIRONMENT

An earthquake can have different impacts on the territory. In terms of terrain stability, it can potentially trigger landslides, rockslides or even ground liquefaction. This type of phenomenon has been well documented for major natural earthquakes (Jibson, 1993; Keefer, 2002) but remains difficult to predict. Concerning anthropogenic earthquakes, notably when they are triggered, the reached vibration levels can be of the same order of magnitude as for natural earthquakes. Consequently, they can also produce landslides. The Zipingpu earthquake (China, 2008) can be cited for example, of which the natural or triggered origin is still controversial (cf. §3.7), and which was the origin of numerous landslides (more than 5,000) in a particularly mountainous region (Yin et al., 2009). The authors of this study specify that approximately 20,000 deaths were directly caused by the landslides triggered by this earthquake.

In terms of variation in the quality of groundwater tables and their possible pollution, for example several contamination cases by methane were reported in Pennsylvania (USA) which were detected near a schist gas extraction well and up to 1 kilometre away (Jackson et al., 2013; Osborn et al., 2011). The hydraulic fracturing process was examined to determine if fault creation could be the origin of this contamination. The authors showed that the water coming from drinking water wells was not directly contaminated by the fluids used in the fracturing process, which are particularly toxic. This contamination was rather attributed to bad drilling practices and/or sealing loss of former hydrocarbon wells situated in the proximity. However, this risk cannot be totally excluded (Howarth et al., 2011)[24].

We can as well cite the possibility of a CO_2 leak caused by an earthquake when it is sequestered underground. In general, there always exists a risk of a leak or diffusion of a polluting product when a fault zone is solicited by an industrial site.

5.7 PSYCHO-SOCIAL AND FINANCIAL RISKS

The acceptability level of disturbances created by ground vibrations and movements is subjective and difficult to quantify. Certain vibrations, or noise, even of very low amplitude, if they are repeated, can create anxiety or have a negative impact on human life. Figure 18,

[24] Series of articles on the subject in the New York Times: http://www.nytimes.com/2011/02/27/us/27gas.html?hp and http://www.nytimes.com/2011/08/04/us/04natgas.html?_r=1&ref=ianurbina

drawn from Bommer et al. 2006, illustrates the levels of human sensitivity to vibrations created by shots, road traffic and drilling public works machines.

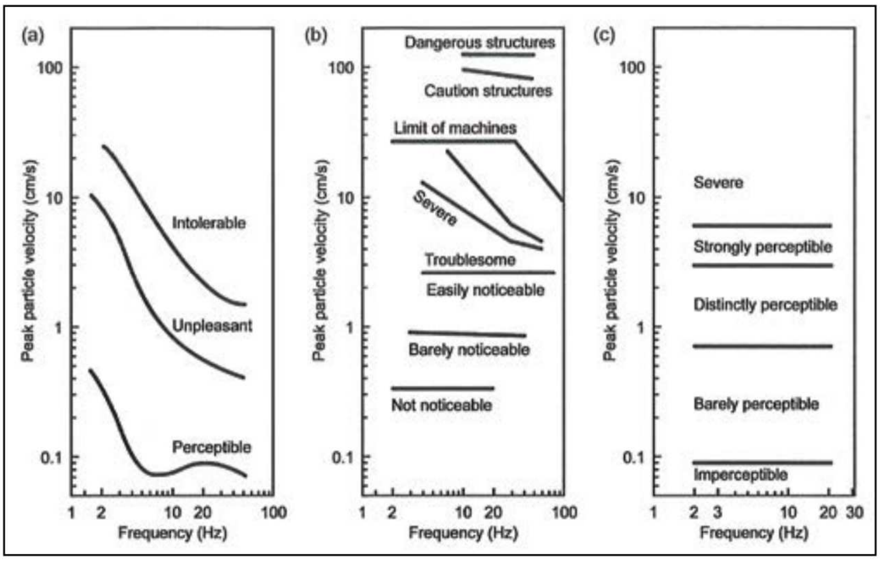

Figure 18: Levels of human sensitivity to different vibration sources (a) shots, (b) road traffic and (c) drilling public works machines (Bommer et al., 2006)

The population can also feel anxiety even when the perceived vibration level is low and causes little or no physical damage to buildings or the environment (Majer et al., 2014; van der Voort and Vanclay, 2015). A study conducted on residents living in the proximity of Groningen, the Netherlands, shows that the social and emotional impacts caused by induced seismicity led to material damage, declining home values, concerns about the possibility of pipeline rupture, feelings of anxiety and insecurity, health problems, and anger (van der Voort and Vanclay, 2015). Moreover, the authors indicate that these impacts are exacerbated by Groningen residents' growing mistrust of the national government and the industrial operator. The occurrence of earthquakes reopened discussions on the distribution of profits from gas production and the assessment of the advantages that are conserved locally.

Nowadays the societal risk related to anthropogenic seismicity does exist in Europe. This is true for territories marked by industrial aftereffects such as former mining basins with, in certain contexts, a seismicity that endures despite the closure of operations (cf. 3.1). Other recent emblematic projects have equally left a lasting mark on the collective memory. For example, the perception of risk of deep geothermal projects seems largely influenced by the recent experiences in Basel (cf. 3.2) and Saint-Gall. At Soultz-sous-Forêts (cf. 3.2), the population rates anthropogenic seismicity as one of the two major sources of "geothermal disturbance" even though felt seismicity has been low and has caused no severe damage over the last 25 years.

The population's adhesion is thus primordial today, and appropriate communication of the anthropogenic seismicity hazard and risk constitutes an important stake for an industrial project's success. Without such, industrial operators run the risk of their projects being blocked, even abandoned, as was the case for the gas storage site off the coast of Spain (project Castor, cf. 3.3), with financial losses that can rapidly run to millions of euros.

6. RISK PREVENTION AND MITIGATION

To the contrary of natural seismicity, governed by tectonic forces, and for which risk control passes above all by the reduction of the vulnerability of stakes, anthropogenic seismicity should, as much as possible, be managed by controlling the industrial parameters that are the direct origin of the seismic hazard. Numerous research projects have been undertaken with this optic, notably in the mining sector – with the first objective to assure miners' safety – and in deep geothermal projects to reduce environmental risks and favour social acceptability, as well as for hydrocarbon extraction and fluid sequestration underground. We present here anthropogenic seismicity risk prevention and mitigation concepts for these types of industrial operations.

6.1 MICROSEISMIC MONITORING

Tracking microseismic activity with a local monitoring network is the preferred tool for managing anthropogenic seismicity risk. The number, positions and types of sensors has to be well-dimensioned, so that the network can allow both localising with sufficient precision and characterising ruptures that are triggered and induced by industrial processes, including those of low magnitudes (minimum 0 or less). Given the outcome of recent studies (cf. §3), experts recommend monitoring microseismic activity throughout an industrial project's life cycle, which has several interests:

- in the exploratory phase, before operations, to allow a better assessment of the natural seismicity at the site's scale (seismic microzonation), for the evaluation of the natural seismic hazard and to define the initial or reference seismicity level;
- during operations:
    - to detect and track microearthquakes (M_w < 2) that are not detectable by regional and national networks, which do not have coverage accurate enough. Let us recall here that on average, for an event of magnitude N, 10 events of magnitude N-1 can be detected, 100 of magnitude N-2, etc. It is thus primordial to have a local monitoring network dedicated to the collection and treatment of available microseismic information;
    - to precisely detect, locate and study the most significant earthquakes (M_w > 2) potentially felt during operations by the local population and detected by the regional or national network, in order to determine if they are earthquakes induced by the operations indeed or actually natural;
    - to implement an early alert system allowing if possible the coupling of the monitoring of the spatio-temporal distribution of seismicity versus the industrial activity and thus to be able to instantly adjust or even stop operations in relation to the detected activity (e.g. modification of injection pressures, of the mining operation's schema or schedule, modification of the loading of dams) (cf. §6.2 and 6.3).
- after operations, during and after the closure phase, to assure that the site returns to a state of equilibrium with an acceptable level of seismicity.

In practice, the detection and localisation capacities of monitoring networks are tightly related to the number, spatial distribution and types of deployed measurement sensors. This dimensioning is guided by the expected performance objectives and is *in fine* constrained by ground conditions (geology, urbanised areas, etc.) and the corresponding financial costs. In particular, depth precision can be rapidly degraded in the absence of sensors positioned in wells, in and around industrial activities' area of influence (a frequent configuration in the case of deep geothermal projects, hydrocarbon production or fluid injection).

Recent feedback shows that it is important to complement the detection and analysis of microearthquakes by the continuous recording of the seismic signal. Indeed, archiving of continuous data allows the possibility of analysing the data retroactively if necessary.

Moreover, the analysis of continuous traces with new techniques such as noise correlation can potentially allow one to detect aseismic phenomena or low variations in the environment's properties (Obermann et al., 2015; Olivier et al., 2015) and thus, if necessary, modify the management of industrial activities.

Note that in any case, regional networks are not adapted to detect and localise microearthquakes. But, it is advantageous to use them to understand regional seismic activity, thanks notably to instrumental historical data. They can equally be used to study major earthquakes produced by an industrial site that is not equipped with a local monitoring network, but localisation would then be marred by significant error. Regional or national data can also serve as a basis for the possible implantation of future industries as was done on the English territory for shale gas extraction operations (Wilson et al., 2015).

Finally, a local monitoring network will allow one to better discern an earthquake's origin (natural or anthropogenic). This presents not only a scientific interest, but can also engage, or to the contrary eliminate, the operator's responsibility. As was said in the case studies, this discrimination is not always obvious. The depth of an earthquake and its distance in relation to industrial activities are the first parameters to be considered. If they do not allow a definitive verdict, probabilistic methods allowing one to affect a probability of the earthquake's origin (tectonic or anthropogenic) can be used (Dahm et al., 2015; Passarelli et al., 2013).

6.2 MULTI-PARAMETERS MONITORING

While seismic monitoring is essential for anthropogenic seismicity risk mitigation, tracking other parameters also proves particularly useful. Such tracking allows one to better assess the rock massif's reaction to stresses generated by the considered industrial processes and then to better analyse the recorded microseismicity.

Thus, for deep geothermal sites, as we shall see in the following paragraph, microseismic monitoring is generally coupled with the tracking of injected and extracted volumes, as well as *in situ* injection pressure and fluid pressure measurements. This coupling is also important in the definitive sequestration of wastewater.

In the mining sector, multi-parameters monitoring can take into account the tonnage of extracted mineral, the position of work sites or even the quantity of explosives used. It can equally integrate the tracking of geotechnical measurements for monitoring aseismic deformations through the use of measurements of continuous stress, displacement, cracking, etc. Coupling these different variables in near real-time allows one to have a view of the state of equilibrium, site by site, with the objective to cross analyse and to quantify the induced stress fields and the zones close to rupture to prevent rockbursts (cf. details in section 6.5).

6.3 TRAFFIC LIGHT SYSTEMS

A seismic risk mitigation tool for underground injection operations recommended by numerous authors (Green and Styles, 2012; Mignan et al., 2017; Raziperchikolaee and Miller, 2015; Walters et al., 2015) is the "traffic light system". This system is made up of a seismological network of which the measurements are analysed in near real-time to indicate to the operator the induced seismicity trend evolution and thus the approach to follow to best limit the occurrence of significant earthquakes. Indeed, case studies have shown that seismicity does not attenuate immediately after injection is stopped (cf. §3.2); the reservoir requires some time to diffuse pressure. Moreover, it has been observed that the magnitude of earthquakes, notably in deep geothermal projects, can be controlled through the regulation of the injected volume (Baisch et al., 2009; Mignan et al., 2017), (Figure 19).

This suggests that it is preferable to decrease pressures progressively until reaching an acceptable level of seismicity. Thus, by analogy with a traffic light, when the light is green, vibration levels are not perceptible on the surface, and injection operations can continue as foreseen. When the light is yellow, vibrations can be felt on the surface without causing damage yet, thereby injection pressures must be decreased. When the light is red, expected vibrations can cause structural damage and injection must be stopped immediately. The system's calibration is done upstream, on the basis of the hazard study and through *in situ* stimulation tests that allow one to set the traffic light system's threshold values.

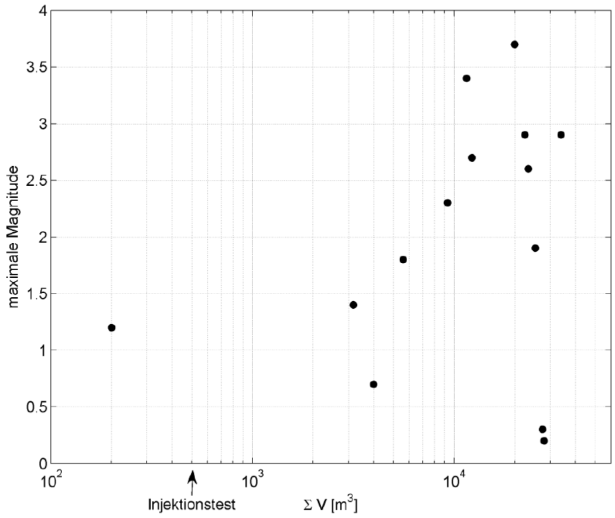

Figure 19: Maximum seismic magnitude observed in relation to the injected volume at the Basel deep geothermal site (Baisch et al., 2009). Potentially damaging earthquakes were only triggered after 10,000 m^3 of water was injected.

Experience shows, however, that seismicity continues to increase after injection has stopped with the occurrence of earthquakes of a greater magnitude (cf. § 3.2) (Baisch et al., 2009). Taking into account this "tail effect" phase is being studied in traffic light risk management systems (Mignan et al., 2017). A put forth idea is to accompany the stoppage of injection by lowering the pressure in the reservoir. Another idea is to adopt a safety margin by setting the magnitude thresholds under the value determined by the risk analysis.

Mignan et al. 2017 propose a method that models this risk on the basis of a seismicity model that depends on the injected fluid's profile as well as the hazard and risk model. This approach provides with a decision-making tool that directly calculates the magnitude at which one must stop operations for a very precise safety norm to be respected. It has been validated in numerous cases.

6.4 Controlling the industrial process / managing the hazard

With the massive development of non-conventional hydrocarbon extraction and the increase of associated wastewater injection volumes, as well as the emergence of new deep geothermal projects, since the 2000s most of the anthropogenic seismicity risk mitigation works have been performed in the field of fluid injection. Based on the understanding of the mechanisms at the origin of this seismicity, a certain number of generic recommendations have been proposed (NRC, 2013; Zoback, 2012; Zoback and Gorelick, 2015). More particularly for the deep geothermal industry, we can cite documents produced by the USGS (Majer et al., 2012; Majer et al., 2014)[25], recommendations from the GEISER project[26], those of the SERIANEX project relative to the study of the Basel (Switzerland) site[27] or the future Haute-Sorne project[28] (Switzerland), which should be operational in 2020.

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25 http://escholarship.org/uc/item/3446g9cf

26 http://www.geiser-fp7.fr/ReferenceDocuments/Deliverables/GEISER_D5.6.pdf

27 http://www.wsu.bs.ch/dms/wsu/download/abgeschlossene-dossiers/serianex_appendix_6.pdf

28 https://www.jura.ch/Htdocs/Files/v/17095.pdf/Departements/DEE/SDT/Amenagement_Territoire/Geothermie_profonde/D_06_RIE_Annexe_9_4_Sismicite.pdf

The first recommendation is to avoid injecting a fluid directly into an active fault or in a fault located in a crystalline basement. If the risk analysis has been correctly carried out (cf. § 4), faults are generally identified. However, the possibility of the presence of a fault in a sub-critical state can never completely be excluded, which might be deeply situated, not previously mapped and that could be reactivated by injection operations. Let us note that kilometre-size faults that can potentially generate magnitude 4 earthquakes are often blind, invisible from the surface and therefore undetectable, except by *in situ* imagery techniques that are not always completely reliable. Deca-kilometric faults that can potential trigger 5.5-magnitude earthquakes are often blind and undetected too.

The second recommendation is limiting the increase of deep interstitial pressure through the balancing of injected and recovered volumes. This principle is used in deep geothermal operations, but is not possible for the sequestration or elimination of wastewater. In this case, the choice of a particularly permeable geological formation and/or with a strong storage potential, such as saline aquifers or little cemented sandstone formations, allows one to diminish the increase of deep interstitial pressure. The fluid's viscosity as well influences the generation of seismicity, thus it is advised to use a fluid of low viscosity. Another approach in deep geothermal projects depends on the modification of geometry of the thermal exchange reservoir. This concept was proposed for the future Haute-Sorne project. Creating a large thermal exchange surface might generate significant earthquake when mobilising it entirely. Instead of this, the future operator[29] proposes to stimulate several small parallel surfaces that represent the same surface area on the whole, but with a lower probability of generating significant-magnitude earthquakes (Figure 20). This is made possible by means of horizontal drilling.

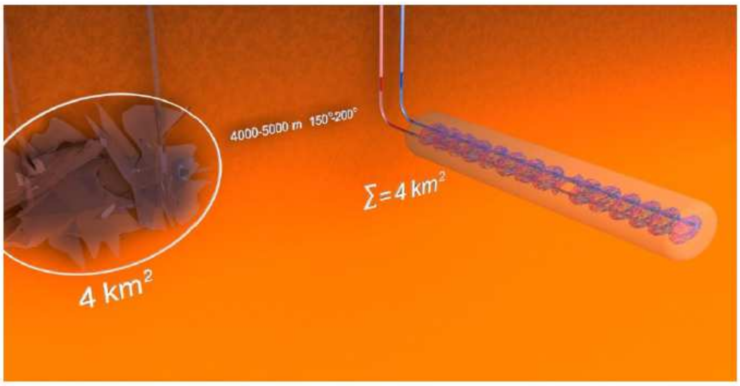

Figure 20: Schematic representation of the Basel geothermal reservoir (at left) and that of the future geothermal site at Haute - Sorne (at right). Source: Geo-Energie.

The third recommendation is based on the installation of a seismological monitoring network adapted to detection and localisation requirements of the site (cf. §6.1). Finally, injection protocols must be established beforehand to define how injection operations must be modified if seismicity is generated during injection operations. "Traffic light systems" are based on this principle (cf. §6.3). Note that this type of system is not always used in projects that can potentially generate an anthropogenic seismicity (NRC, 2013), with the exception of the mining sector (cf. §6.5) where it is essential to working safety. Indeed, the deployment of a dedicated and sufficiently performing microseismic monitoring network requires a significant financial investment, a team of specialists, centralised management of seismic data and, in parallel, the management of industrial data.

6.5 Mitigation of seismic risk in mines

The mitigation of seismic risk in mines is all the more important because miners are directly exposed to the risk, which is always higher at the site front where mineral extraction and

[29] http://www.geo-energie.ch/fr/

cavity creation are in progress. Moreover, in addition to ensuring working safety, slowing or stopping production over an extended period can have serious economic consequences should a rockburst occur. In this context, seismic risk management in deep mines has become a priority for mining operators in all modern countries (Potvin and Wesseloo, 2013).

As described in paragraph 6.1, seismic monitoring is one of the main tools of risk mitigation. It allows one to assess and to manage the seismic hazard. However, it is difficult to reduce the hazard itself in mines. Indeed, it might be difficult to anticipate some of the parameters which are determinant in triggering microearthquakes when the monitoring field is highly perturbed by massive mineral extraction, e.g. the local rheology of the surrounding rock, the local structural geology or the natural stress field. Nowadays production goes deeper and deeper, which increases the seismic risk (i.e. natural stresses). This risk is all the more severe when pressure is stored into the rock mass surrounding the excavation instead of progressively deforming. Potvin and Wesseloo (2013) synthesised the different approaches used by mine operators for seismic risk management, which are briefly summarised here.

The first approach relies on seismic hazard reduction through the optimisation of the extraction method and sequences as well as the design of mining works. The idea is to limit stress accumulation on sensitive zones (faults, dykes, contact areas, etc.). Numerical modelling is the preferred tool for evaluating and optimising the redistribution of stresses caused by a mining sequence in relation to the ore deposit’s characteristics. This approach offers the considerable advantage of allowing the comparison of numerous excavation scenarios and of retaining the one that will be optimal in terms of safety criteria.

Seismic hazard reduction by the use of stress relaxation techniques is another method used by operators. This approach requires creating fractures in the rock mass through preconditioning either by hydraulic fracturing or stress relieving blasts. This preconditioning has the objective of limiting the rock’s seismic response to excavation in the immediate environment of sites assessed as at risk. It has been practiced in the mining sector for several decades but remains difficult to quantify precisely and is still considered more of an art than a science.

Seismic risk reduction can equally be achieved by reducing vulnerability, i.e. by decreasing the consequences of damage and miners’ exposure. Mining works can be made safer through supporting works (e.g. by installing high-dynamic resilience bolts or anchoring cables, steel grills, and concrete projection, Figure 21), while cuts can be backfilled. This enables one to limit modifications of stress fields and the damage caused by a rockburst. Implementing highly mechanised, remote-controlled extraction methods allows the reduction of miners’ exposure. Also, drastic safety rules are generally applied when the excavation method is explosives. Indeed, the observed seismic response is in general the greatest after this type of operation. After each blasting, the seismic response can also be used to quantify the exposure of an excavation zone to a major seismic hazard. To this purpose, safety protocols established by operators aim at keeping away minors from sensitive zones until seismicity has returned to an acceptable level (that of background noise), meaning that stresses have been redistributed and the rock mass has retrieved a certain state of equilibrium (Hudyma, 2008). For example, in the Tasmania mine in Australia, particularly subject to rockbursts, a 24-hour evacuation period was implemented after each blasting sequence to reduce miners’ exposure to induced seismicity (Potvin and Wesseloo, 2013).

6.6 FEEDBACK ON THE USE OF THE MICROSEISMIC TOOL AS AN AID IN DECISION MAKING

The case studies presented above show that microseismic monitoring is more and more used as an aid in decision making when conducting industrial operations.

Its contribution was demonstrated in the deep geothermal sector (cf. §3.2), for example in evaluating maximum injection pressures to not be exceeded and adapting injected volumes. At Soultz-sous-Forêts, this monitoring also brought about a modification of the stimulation processes to reduce the number of felt earthquakes and to reach an acceptable vibration level. In the case of Basel, it was possible to interrupt industrial operations before earthquakes were felt, and all indicators suggest that without this prevention measure, earthquakes of greater magnitudes could have occurred and caused much destruction. That certainly did not prevent the occurrence of events of magnitudes slightly greater than 3 which occurred later, but they were without danger to the population.

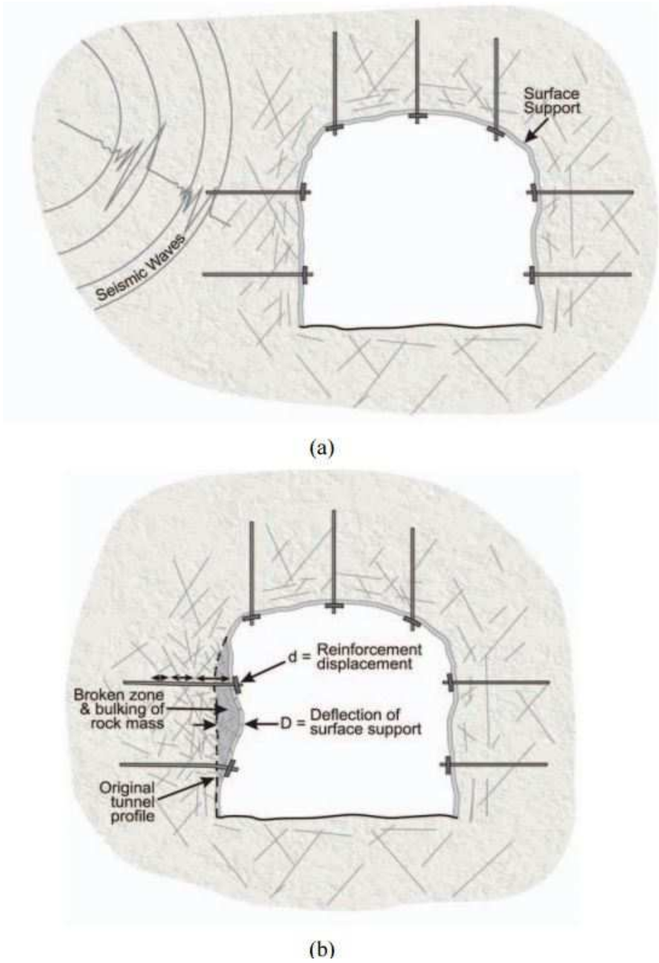

Figure 21: Example of support works resistant to the dynamic load in a mine gallery to reduce damage caused by a seismic event or a rockburst (Potvin and Wesseloo, 2013).

In the same way, in the case of the Castor gas storage project (cf. §3.3), stopping injection as soon as abnormal seismic activity was observed probably allowed the reduction of the magnitude of earthquakes that occurred after injection operations had ended.

In the mining sector (§ 3.1), the microseismic tool is used on a routine basis for safety reasons. Extraction techniques were thus modified to decrease the occurrence of rockbursts. Considering the more and more increasing extraction depths, the use of the microseismic tool becomes indispensable for risk management versus the relatively great seismicity level.

Finally, microseismic monitoring constitutes an essential instrument of risk management related to former mines in France since the end of the 1990s. It is used to detect possible ruptures and allows thus to anticipate the progression of disorder toward the surface (§ 3.1).

6.7 SHOULD ANTHROPOGENIC EARTHQUAKE RISK BE MANAGED AS NATURAL SEISMICITY?

Certain authors propose to quantify and to manage anthropogenic seismicity risk following the approach that is used for natural seismicity. Indeed, anthropogenic seismicity cannot be completely controlled because there are too many unknowns relative to the underground's properties.

Figure 22 from Bommer et al. (2015) summarises the different proposed responses to various risk levels caused by anthropogenic earthquakes.

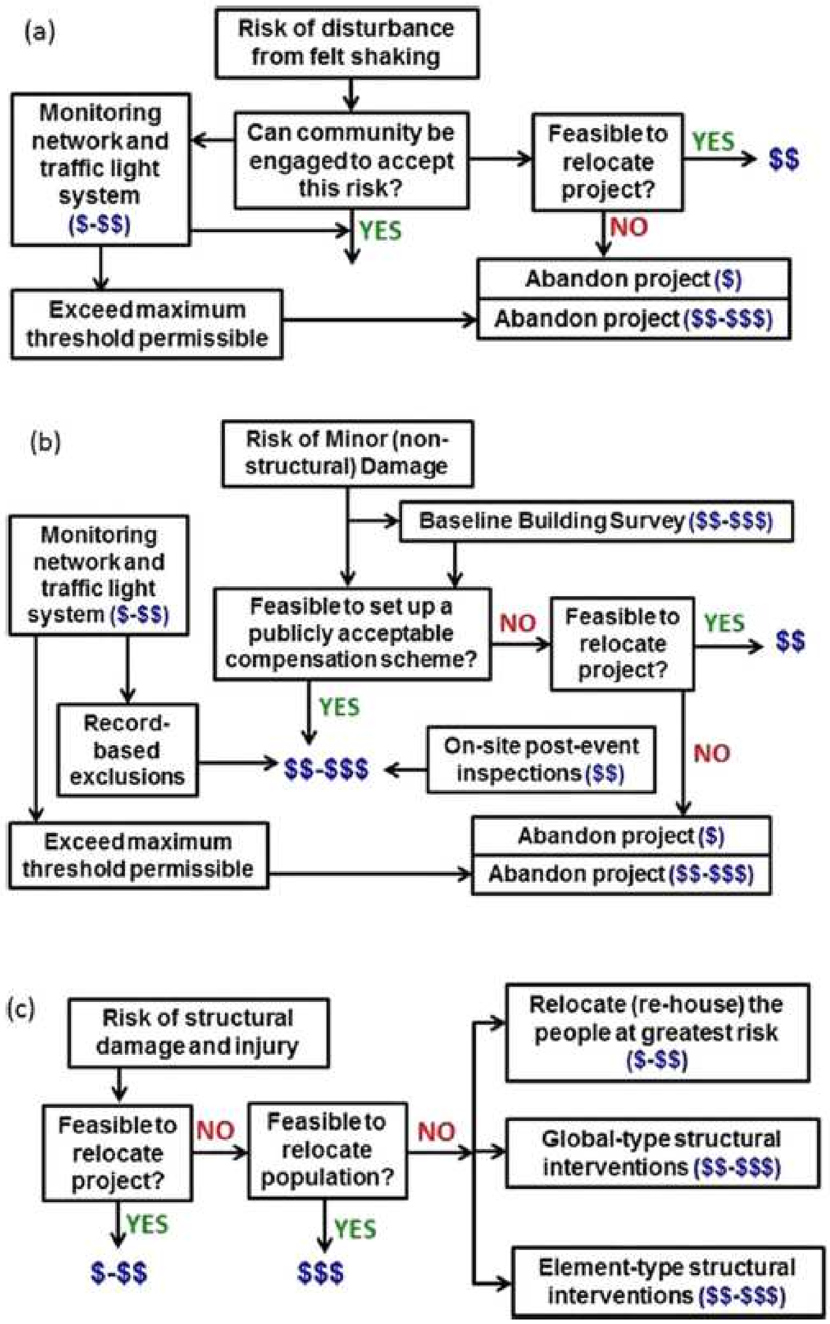

Figure 22: Flowchart indicating the proposed options for managing anthropogenic seismicity risk causing a) disturbance, b) non-structural damage at the origin of repair costs, and c) structural damage that could threaten life and physical integrity. In each case, the range of possible costs associated with each option is indicated ($: low; $$: average: $$$: high) (Bommer et al., 2015).

When the risk is estimated to be non-structural damage and relocating the project is not possible, the risk can be financially compensated. If the risk constitutes a threat for life and physical integrity, then it can be reduced by reinforcing buildings, of which the cost can be compared to the economic profits of the industrial project. However, due to the specific characteristics of anthropogenic earthquakes, which can occur in regions where there is little or no natural seismicity, the authors suggest that the procedures and norms used in earthquake engineering be modified to be applied to anthropogenic seismicity.

6.8 Regulatory aspects

Anthropogenic seismicity is a hazard whose nature is such that it is difficult to regulate uniformly all seismogenic industries. In practice, each industrial project has a specific geological context of which the structural, tectonic, geomechanical and hydrological knowledge both remains limited and still evolves in space and time. In the usual case in which extraction works are planned over the long term, it is indeed probable that operation technologies and parameters will evolve, thus modifying seismogenic susceptibility and hence the seismic risk of the site. In other words, imagining a single specific system of regulations for all possible situations in France, or in another country, that precludes the risk of heavily penalising each industrial project seems difficult.

6.8.1 The situation in France

In France, the principal cases of anthropogenic seismicity encountered and studied until now have been the natural gas extraction sites of Lacq (Midi-Pyrénées), the coal mines of Houillères in Lorraine (Grand Est) and Centre-midi (Provence-Alpes-Côte d'Azur), and deep high-temperature geothermal energy at Soultz-sous-Forêts (Alsace) (cf. Table 5). The case of the Monteynard dam in 1963 can equally be cited with the occurrence of a 4.9-magnitude earthquake after the reservoir was loaded.

From a purely regulatory point of view, for the first four sites cited above, the mining code controls the entirety of the industrial operations that were practiced or continue today. This code controls all operations aimed at recovering mineral and energy geo-resources classified as strategic, including high- and low-temperature geothermal. Let us note that the case of underground storage is under the code of the environment for it is a Classified Installation for the Protection of the Environment (Installation Classée pour la Protection de l'Environnement [ICPE]).

Entering into the details of the mining code is out of the scope of this report. Yet, as a reminder, the mining code foresees a general procedure based on submitting authorisation request dossiers to start works - first exploration, then operations - by the petitioner. After a public investigation and consultation with the competent commissions, the administration authorises works by a prefectural order, which notably determines the requirements aimed at maximally reducing the risks related to the works, including anthropogenic seismicity if this is shown. The risks being different from one context to another, these requirements will be specific to each site and proportional to the estimated risk level.

In case of an incident or accident, the mining code includes the following important provisions:

- it renders the operator liable for damage caused by its activity;
- in case of the disappearance or fault of the operator, the State guarantees repair of damage caused by the mining activity.

When it is a question of damage originated from one or more local earthquakes, possible litigation between the parties can be resolved by a third-party expertise, which will have to answer at least the first if not both of the following questions:

- can the ground's vibration level caused by the seismic waves explain the damage to such building? (cf. § 5.2)
- are the seismic events in question of natural origin or induced by the industrial operation? (cf. § 2.4)

Today, in order to anticipate these questions and the liabilities that come from them, all seismogenic industrial operations with a possible impact on stakes on the surface are required to operate a microseismic monitoring device. *A minima*, this device must allow one to detect and to localise local seismicity with the lowest level of detectability possible and to measure seismic vibration levels at stations. Through this requirement, it aims at:

1. distinguishing in a manner as unequivocally as possible natural earthquakes (generally deep) from anthropogenic earthquakes (generally located in the works' area of influence);
2. precisely studying any potential correlation and cause-and-effect relationship between the operation parameters and the detected seismic activity (extraction or injection rate, mine blasts, etc.); ground deformation measurements can prove important to complete the analysis;
3. estimating statistically the vibration level reached at any point of the surface for each seismic event, localised and classified by magnitude from an attenuation law established at the local or regional scale;
4. mapping structures that are potentially vulnerable to vibrations from an earthquake at a defined location and given magnitude in order to determine if the observed damage to particular constructions can be of anthropogenic seismic origin.

6.8.2 SOME EXAMPLES OF REGULATORY SITUATIONS OUT OF FRANCE

The situation in other modern countries does not fundamentally differ from that in France. Given the necessity of regulating in terms of the risks of industries with very different processes and operating in very distinct geological contexts, each industrial project is treated as a special case. For each case requirements coming from the authorities in charge of granting authorisations are applied either upstream from the project or during it when a significant incident occurs, for example.

In Italy, upon the request of the Ministry of Economic Development, a guide was defined in 2014 by an international expert commission. This guide presents recommendations for the proper implementation of operational instrumental monitoring of production sites at the scale of the concerned territory, be they situated or not in a natural seismic zone. It is based on significant national and international feedback and is addressed to all stakeholders, i.e. the ministry, competent regional authorities, operators and civil society. In addition, a national legal framework relating to the anthropogenic risk generated by oil field extraction was defined in 2015 following the dramatic events of 2012 at Mirandola in the Emilia Romagna region (cf. 3.4.2).

In the Netherlands, the Mining Act, which was revised in 2003, controls mineral exploration and production works. Concerning gas fields, although the regulation stipulates that the operator supplies a ground level initial state before beginning the production phase of a new field, nothing is said in regard to the risk related to anthropogenic seismicity. The maximal cumulated subsidence parameter is crucial, given the fundamental stakes that imply the country's geographic and topographical location compared to sea level. But the growth since 1991 of induced seismicity with, in 2012, the occurrence of a 3.6-magnitude event in the Groningen field, an event classified of intensity VI that caused damage to numerous residences, led authorities to first launch in-depth studies on the reasons of this rising seismicity (cf. § 3.4.1). Given that the relation between cumulated ground subsidence (deep rock compaction) and seismicity had been *a priori* established (the cause-effect relationship is still the subject of studies), it was decided to completely reconsider the Gronginen field's production schema, favouring production in areas with low cumulated subsidence and abandoning areas with high cumulated subsidence (cf. § 3.4.1).

In the United States, the emergence of high-rate induced seismicity due to the schist gas industry since 2005 revealed a veritable societal problem and led to the development of operational regulatory responses varying from State to State (cf. § 3.4 and 3.5). Remember here that unlike most mining countries including France, the private owner of land also owns the ground below it. The wastewater injection wells are controlled by the Safe Drinking Water Act, from which federal law distinguishes six types of injection wells, of class I to VI, subject to different regulations. For certain types of injection wells, application files must include a natural seismicity analysis of the concerned zone. The Bureau of Land Management also published a regulation related to the practice of hydraulic fracturing on federal and Native American lands requiring licensed petitioners to submit a geological information file allowing the analysis of the anthropogenic seismic risk.

Nowadays, numerous States that produce fossil fuels where hydraulic fracturing operations are led, such as Arkansas, California or Oklahoma, even if under different regulations, require prior studies of susceptibility to the anthropogenic seismicity hazard. Depending on the case, they might also require operational monitoring obligations, including the definition of a protocol for the seismic risk management as well as regularly supplying operational data (volume, pressure, etc.) to the appropriate State commission in charge of the monitoring and the control of oil activities on the territory.

7. RESEARCH LIMITS AND PERSPECTIVES

As we have seen, analyzing anthropogenic seismicity presents new challenges in terms of knowledge and assessment of the hazard and risk management.

Concerning the hazard, the point is to understand the cause-and-effect relationship between an industrial activity and observed or future seismicity (if the project is not operational yet). Should an industrial site be already operational, or even dismantled, how to determine its relationship with the observed seismicity? Will a future project produce an earthquake at a given site? These questions cannot easily be answered. This challenge lies primarily in the complexity of the underground's structure, which renders knowledge of its hydrogeomechanical properties and stress state difficult. Feedback shows that to apprehend better the problem, it necessitates first to acquire quality measurements and data. However, these data are not always easy to acquire and can represent a substantial financial investment.

Predictive models to define the possible anthropogenic seismicity on a site rely on these basic data. They are essential to carry out relatively precise modellings to predict the stress variations produced by the employed processes. Hence, in the case of fluid injection, before or during operations, it is possible to theoretically estimate if the employed pressures will be likely to generate earthquakes or not. In the case of matter extraction, and more particularly in mines, this approach allows one to determine if the defined operation sequence is likely to generate sufficient stress variations to trigger an earthquake. However, further researches still need to be made to be able to model both geomechanical deformation and the generation of associated earthquakes (number and magnitude). This could allow a better understanding of the processes at the origin of earthquakes as well as of the parameters that control their intensity. Thus, industrial activities could be managed better so that they generate an acceptable level of vibration for public safety, buildings and infrastructure.

Let us note that controlling the hazard can prove difficult even when detailed studies were carried out before the site was chosen. Indeed, the probability of reactivating an underground fault close to the critical state can never be totally exclude. This bibliographic review showed that this occurs generally on faults that were not previously identified and/or of which the initial stress state was unknown. Industrial processes that employ fluid injection for sequestration purposes are particularly problematic, for faults that are relatively far (several kilometres) from the site can be reactivated and this several years after the operations started.

As we have seen, low-magnitude microseismic activity is not a public safety problem. However, when a high-magnitude event takes place not far from the industrial activity, the concerned public has the right to ask if it was not caused by man, particularly in regions of low seismicity. Thus, differentiating natural earthquakes from anthropogenic earthquakes is one of the important challenges of hazard assessment. The answer to this question is not always obvious. Simply examining a seismic signal does not always allow one to distinguish between the two types of seismicity. If there is a spatio-temporal correlation between the earthquake's occurrence and the beginning of an industrial activity and no previously known seismic activity on the site, then the probability is high that the seismicity is of anthropogenic origin. However, there are situations, notably those related to processes involving fluid circulation, where this correlation is not respected. Seismic activity can be triggered late after the operations started and far from the site. In this case, it is necessary to implement approaches based either on mechanical or statistical models, or on models that combine the two approaches, in the hope of identifying the probable source. However, these approaches also require having quality input data and a certain expertise in data analysis.

Answering on whether the earthquake is of natural or anthropogenic origin is not only of scientific interest; it can also have important consequences in legal terms and implicate the operator's responsibility and impact the insurance sector. The economic consequences for all stakeholders can be even greater if the anthropogenic earthquake occurs in regions with low natural seismic risk. In fact, in these regions, constructions are not designed to resist earthquakes, even of low intensity. One of the challenges concerns taking into account anthropogenic seismicity for zoning the seismic hazard in these regions.

Concerning risk mitigation, microseismic monitoring seems to be the key element of risk management, whatever the concerned industrial sector. National networks, which are dimensioned for monitoring the natural seismicity on a region scale, do not allow the detection of low-magnitude signals that could indicate the onset of an instability or conditions that are favourable to the occurrence of an earthquake of higher amplitude. We have seen that in modern countries regulation goes in this direction. Coupling microseismic data with pertinent industrial parameters, and even other ground data, is now widely recommended. The implementation of a "traffic light system" in geothermal projects is an illustration of this. Even so, depending on the site's conditions, deviation from foreseen phenomena and expected magnitudes cannot be excluded. The collected data must be regularly compared to the initial studies and the risk management systems should be recalibrated throughout the duration of a project. Given that the concerned processes are complex and specific to each project, one of the current challenges consists therefore of continuing to improve the reliability of risk management devices, including learning from failure.

Finally, it seems necessary to pursue innovation efforts so as to reconcile the technological and financial performance of microseismic monitoring. The objective is to develop sensors that are less costly, more robust, and resistant to pressure and temperature conditions, and that allow the direct combination of other measurement types such as pressure, stresses or deformations. These technical advances must also concern the treatment and analysis of ever more numerous data and take interest in the development of new techniques based on the analysis of seismic noise.

8. CONCLUSIONS

According to the number of existing projects around the world, anthropogenic seismicity is rarely observed during ground or underground industrial operations. Nevertheless, today, the perception of anthropogenic seismicity risk is such as to put into question a certain number of projects.

The case studies summarised in this report showed that highest-magnitude seismicity is produced during the loading of hydraulic dams and hydrocarbon production. Meanwhile, mining operations and hydrocarbon production are the industries that produce the major number of events. As expected, this is due not only to the high number of such operations around the world but also to the deeper and deeper exploitation zones. In the last 10 years, an earthquake increase has been observed on the American territory linked to the exponential development of non-conventional hydrocarbon deposits.

The strongest earthquakes are observed when a fault or a system of faults close to the critical state are solicited by industrial processes. This phenomenon can occur in regions with high natural seismicity as much as in those where it is lower. In regions with low natural risk, this phenomenon can be particularly problematic for buildings and infrastructure that are not designed to resist earthquakes. The exposure of numerous fragile buildings to strong tremors was the origin of heavy human and material losses during the earthquakes in Lorca, Spain, in 2011 and in Newcastle, Australia, in 1989. How then is anthropogenic seismicity can be considered in the development of seismic hazard maps at a territorial scale? Since 2015, in the United States, seismic hazard maps take into account anthropogenic seismicity which are updated each year. In France, only natural earthquakes are considered for the assessment of this risk on the territorial scale. In the mining industry, notably in South Africa, hazard maps are developed on a smaller scale in the long, mid and short term for the safety of particularly exposed workers.

Mitigation of the anthropogenic seismic risk depends on the seismic characterisation of the site, on the monitoring, on the control of the industrial process, and on the reduction of vulnerability. The monitoring system is the key element on which depends the improvement of the hazard's characterisation and thereby the risk management. It is generally composed of a sufficiently sensitive microseismic network and allows one to monitor the spatio-temporal evolution of seismicity. Deviation from the previously studied natural seismic activity must allow quantifying the effect of the underground's industrial use. Finally, once the activity has stopped, monitoring must allow one to know whether the underground has regained a state of equilibrium or not. *In situ* stress measurement devices, which are for instance installed in wells or directly on mining works, can complement the microseismic devices.

Industries that use deep fluid injection recommend reducing deep pressures to minimise the generation of seismicity through the balancing of injected and recovered volumes. In deep geothermal projects, "traffic light systems" have been developed to control pressures in relation to recorded seismic activity. For injection operations with the objective of wastewater sequestration, the use of particularly permeable geological formations, such as saline aquifers or little cemented sandstone formations, is one of the principal recommendations.

In the mining industry, in which workers are directly exposed to the phenomenon, seismic risk mitigation relies on several approaches, involving site planning, the evolution of excavation schemas, the implementation of consolidation and reinforcement techniques, the growing use of automated machines and, of course, microseismic and geotechnical monitoring. Mitigation equally depends on describing the hazard at different temporal scales in order to anticipate risk better.

More generally, the quantification and management of anthropogenic risk can equally be addressed by following the same approach that is used for natural seismicity risk. This is possible through building earthquake constructions when relocating the project is not possible. Moreover, the success and acceptability of an industrial project which is likely to generate seismicity depend on the implementation of a communication and information programme for the project's different stakeholders and in particular the local population.

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Appendix A

Earthquake mechanisms and factors

In general, a **natural earthquake** is created by the rapid slip of a fracture or pre-existing fault, along which greater and greater stresses have accumulated and reached the limit of the resistance that the fault opposes to the existing tectonic forces. The earthquake thus corresponds to a brutal release of stresses on a more or less large fault surface. Recall that the earth's crust is a heterogeneous and discontinuous medium, crossed by numerous fracture and fault networks of different sizes and orientations, related to a region's long and complex tectonic history.

An earthquake of anthropogenic origin results from the artificial reactivation of pre-existing faults and/or the creation of new fractures due to modifications on the natural stress field generated by industrial activities located in its vicinity.

In order to understand why earthquakes can be generated during underground works, it is necessary to specify the factors responsible for the initiation of an earthquake and that control its magnitude.

1. Earthquake's occurrence conditions

a. Rupture mechanisms

Slip on a fault occurs when the shearing stresses applied on this fault exceed the fault's friction resistance. The critical conditions of the occurrence of an earthquake is quantified by the Mohr-Coulomb rupture criterion as follows:

$$\boldsymbol{\tau < \mu\ (\sigma_n - p)} \qquad (1)$$

where τ: shear strength, parallel to the fault;
μ: friction coefficient, generally between 0.6 and 1 (Byerlee, 1978; Dieterich, 1979);
σ_n: normal stress, perpendicular to the fault;
p: fluid or interstitial pressure.

Thus, the fault is stable as long as the shear strength (τ) is less than the friction force, which is represented by the term $\mu\ (\sigma_n - p)$. The term $(\sigma_n - p)$ is called effective stress (Figure 23-a). The parameters controlling the initiation of an initial slip are therefore:

- the shear strength, which tends to make the fault sections slip against each other;
- the normal stress, which tends to push the fault sections against each other;
- the fluid pressure at the fault plane, which tends to separate the fault sections.

Thus, an earthquake can occur:

- if the shear strength τ loading the fault increases;
- or if the effective stress $(\sigma_n - p)$ decreases, either due to a decrease in the normal stress (σ_n) or to an increase in fluid pressure **(p)** (Figure 23-b).

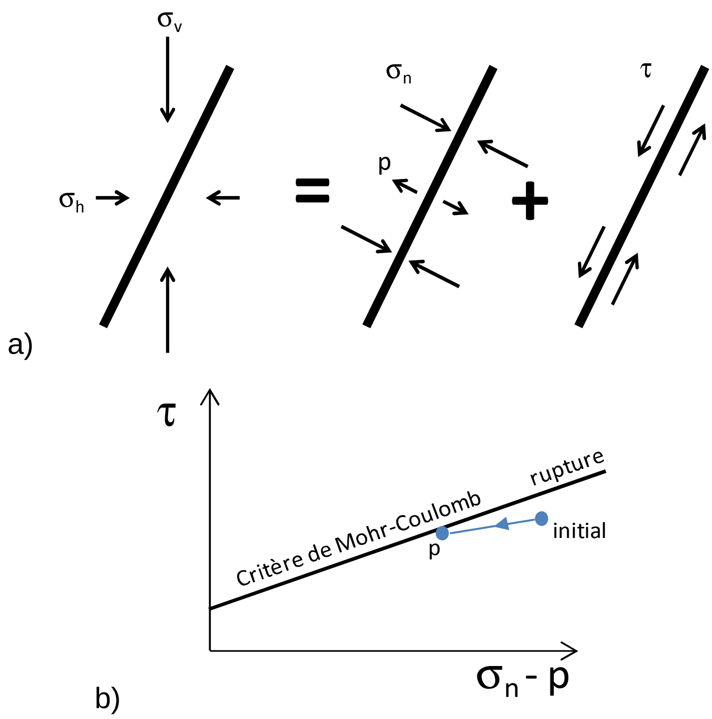

Figure 23: a) Representation of horizontal (σ_h) and vertical (σ_v) stresses that act on a fault plane and decomposition of the stress field into normal (σ_n, p) and shearing (τ) components. b) Representation of the Mohr-Coulomb rupture criterion, the blue slope illustrates an increase in fluid pressure causing the rupture criterion to be reached.

Figure 24 presents a ternary diagram (McGarr et al., 2002) in which three parameters, $\boldsymbol{\tau}$, $\boldsymbol{\sigma_n}$ and **p**, form a field in which the different seismicity types can be placed in relation to the dominant parameter. In some cases, the identification of a single mechanism is simple, such as the seismicity caused by the increase of interstitial pressure **p** related to underground fluid injection. In other cases, for example for loading hydraulic dams, the relationship can be more complex. In this case, more than one parameter is involved (shear strength and interstitial pressure) or coupled (for example normal stress and interstitial pressure).

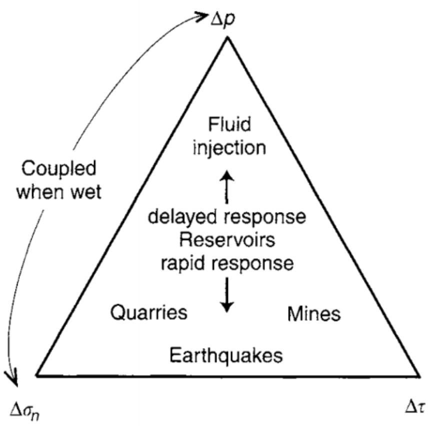

Figure 24: Simplified classification of the three parameters controlling anthropogenic and triggered seismicity (McGarr et al., 2002). Surface quarries, deep mines and regional earthquakes generate seismicity mainly through modifications of the elastic strain field. The increase of interstitial (or fluid) pressure is the dominant factor for deep fluid injection. Reservoir loading can provoke changes in all three parameters to generate earthquakes. Oil and gas depletion mainly produces changes in the stress state within the rock mass surrounding the reservoirs.

On the other hand, the normal (σ_n) and shear (τ) stresses that act on a fault plane depend on its orientation in relation to the stress state of the rock mass (Figure 23-a). Rocks in the continental earth crust are generally under stress due to the ground's weight and tectonic forces. This stress field thus varies vertically with depth but also horizontally in relation to direction. On the other hand, for a fluid at rest, the stress state is hydrostatic, which means that the stress is the same in all directions and no shear strength can be transmitted.

If the vertical stress **(σ_v)** can be estimated, in a first approach, as the earth's weight, it is not the same for horizontal stresses. Indeed, these vary from one point to another on the earth in relation to the ground's lithology, to pre-existing faults and to other discontinuities of the earth's crust. Also, determining the subsurface ground's *in situ* stress state is a complex and generally costly exercise. This information, when it exists, is often partial, which renders exact knowledge of the stress field acting on a fault difficult and thus limits forecasting its slip.

2. Other rupture mechanisms

The shear seismic rupture mechanism is the most currently used model by geophysicists to describe the event at its source. The rupture mode does not entrain any change in the earth's volume. However, in the underground mining industry, where cavities created by mineral extraction can be very large, other rupture modes, such as traction or compression (e.g. roof and/or pillar instabilities in subterranean operations), can activate. These considerations are outside of the framework of this report and are not detailed here.

Appendix B

Date	Site/City/State	Country	Max Magnitude	Technology at the seismicity's origin	Reference	Lat °	Lon °
2002	Bad Urach	Germany	1.8	Geothermal	Evans et al. (2012)	48.49 N	9.40 E
-	Basel	Switzerland	3.4	Geothermal	Giardini (2011)	47.56 N	7.59 E
16/09/2003	Berlin, Usulutàn	El Salvador	4.4	Geothermal	Bommer et al. (2006)	13.49 N	88.53 W
31/05/1905	Cesano	Italy	2	Geothermal	Evans et al. (2012)	42.50 N	12.34 E
14/11/2003	Cooper Basin	Australia	3.7	Geothermal	Majer et al. (2007)	27.82 S	140.76 W
01/03/2005	Coso, California	USA	2.6	Geothermal	Julian et al. (2007); Foulger et al. (2008)	35.98 N	117.93 W
04/06/2011	Desert Peak, Nevada	USA	0.74	Geothermal	Chabora et al. (2012)	39.19 N	118.83 W
-	Fenton Hill, New Mexico	USA	1	Geothermal	Nicholson and Wesson (1992)	35.90 N	106.67 W
1989	Fjallbacka	Sweden	-0.2	Geothermal	Evans et al. (2012)	58.60 N	11.29 E
16/06/1905	German Continental Deep Drilling Program	Germany	1.2	Geothermal	Evans et al. (2012); Emmerman and Lauterjung (1997)	49.56 N	12.04 E
1982	Geysers, California	USA	4.6	Geothermal	Majer et al. (2007)	38.79 N	122.82 W
2007	Gross Schonebeck	Germany	-1.1	Geothermal	Evans et al. (2012)	52.91 N	13.53 E
2003	Hellisheidi	Iceland	2.4	Geothermal	Evans et al. (2012)	64.04 N	21.40 W
-	Hijiori	Japan	0.3	Geothermal	Kaieda et al. (2010)	38.61 N	140.17 E
2003	Horstberg	Germany	0	Geothermal	Evans et al. (2012)	52.90 N	10.33 E
09/04/2010	Insheim	Germany	2.3	Geothermal	Grünthal (2013)	49.15 W	8.15 E
2004	Krafla	Iceland	2	Geothermal	Evans et al. (2012)	65.72 N	16.80 W
2007	Landau	Germany	2.7	Geothermal	Evans et al. (2012)	49.20 N	8.12 E
1977	Larderello-Travale	Italy	3	Geothermal	Evans et al. (2012)	43.24 N	10.88 E
1984	Latera	Italy	2.9	Geothermal	Evans et al. (2012)	42.62 N	11.82 E
22/05/1905	Monte Amiata	Italy	3.5	Geothermal	Evans et al. (2012)	42.89 N	11.62 E
-	Mutnovsky, Kamchatka	Russia	2	Geothermal	Kugaenko et al. (2005)	52.45 N	158.20 E
1991	Ogachi	Japan	2	Geothermal	Kaieda et al. (2010)	39.17 N	140.41 E

Date	Site/City/State	Country	Max Magnitude	Technology at the seismicity's origin	Reference	Lat °	Lon °
1987	Rosemanowes	UK	2	Geothermal	Evans et al. (2012)	50.17 N	5.11 W
1993	Soultz	France	2.9	Geothermal	Evans et al. (2012)	48.94 N	7.88 E
10/06/2003	Soultz sous Forêts	France	2.7	Geothermal	Grünthal (2013)	48.93 N	7.87 E
1977	Torre Alfina	Italy	3	Geothermal	Evans et al. (2012)	42.75 N	11.94 E
03/07/2008	Unterhaching	Germany	2.4	Geothermal	Evans et al. (2012); Grünthal (2013)	48.07 N	11.62 E
-	Blackpool	UK	2.3	Hydraulic fracturing	de Pater and Baisch (2011)	53.82 N	3.03 W
01/18/2011	Eola field, Oklahoma	USA	2.8	Hydraulic fracturing	Holland (2011)	34.57 N	97.43 W
13/06/2003	Bouchard-Hébert	Canada	2.5	Mining extraction	Hudyma (2008)	48.37 N	78.9 W
05/11/2005	Brunswick	Canada	3.3	Mining extraction	Hudyma (2008)	47.48 N	65.87 W
28/09/1985	Camflo	Canada	2	Mining extraction	Hudyma (2008)	48.15 N	78.04 W
06/03/2004	Campbell	Canada	3	Mining extraction	Hudyma (2008)	51.06 N	93.74 W
03/08/1996	Chimo	Canada	3.1	Mining extraction	Hudyma (2008)	48.01 N	77.26 W
29/12/2001	Craig	Canada	3.2	Mining extraction	Hudyma (2008)	46.63 N	81.37 W
29/11/2006	Creighton	Canada	4.1	Mining extraction	Hudyma (2008)	46.5 N	80.97 W
06/08/2007	Crandall (Utah)	USA	4.1	Mining extraction	Kubacki et al., 2014	39.4675 N	111.2248 W
03/02/1995	Trona Mine (Wyoming)	USA	5.1	Mining extraction	Pechmann et al. (1995)	41.623	-109.773
11/12/1987	Denison	Canada	2.7	Mining extraction	Hudyma (2008)	46.49 N	82.6 W
28/05/1995	Dickenson	Canada	2.6	Mining extraction	Hudyma (2008)	51.06 N	93.73 W
25/04/1992	Falconbridge	Canada	2.7	Mining extraction	Hudyma (2008)	46.58 N	80.81 W
19/01/1996	Frood Stobie	Canada	2.9	Mining extraction	Hudyma (2008)	46.53 N	81 W
21/01/1996	Garson	Canada	2.5	Mining extraction	Hudyma (2008)	46.57 N	80.87 W
17/12/1989	Gaspé	Canada	2.7	Mining extraction	Hudyma (2008)	48.97 N	65.52 W
30/04/1999	Heath Steel	Canada	2.6	Mining extraction	Hudyma (2008)	47.28 N	66.07 W
06/01/2003	Ibbenbühren	Germany	3.9	Mining extraction	Grünthal (2013)	52.33 N	7.76 E

Date	Site/City/State	Country	Max Magnitude	Technology at the seismicity's origin	Reference	Lat °	Lon °
30/09/1997	Kerr-Addison	Canada	3.5	Mining extraction	Hudyma (2008)	48.14 N	79.58 W
30/09/2004	Kidd Creek	Canada	3	Mining extraction	Hudyma (2008)	48.69	81.37 W
01/12/1990	Lac Shortt	Canada	2.8	Mining extraction	Hudyma (2008)	49.61 N	75.86 W
02/03/2007	Laronde	Canada	2.8	Mining extraction	Hudyma (2008)	48.25 N	78.25 W
30/12/2010	Legnica	Poland	4.2	Mining extraction	Grünthal (2013)	51.51 N	16.14 E
12/05/1989	Levack	Canada	2.7	Mining extraction	Hudyma (2008)	46.65 N	81.37 W
01/07/1974	Rochonvillers	France	4	Mining extraction	Grünthal (2013)	49.29 N	5.96 E
03/03/2002	Louvicourt	Canada	2.6	Mining extraction	Hudyma (2008)	48.1 N	77.66 W
12/04/1997	Macassa	Canada	3.7	Mining extraction	Hudyma (2008)	48.14 N	80.07 W
04/06/1996	MacLeod	Canada	2.5	Mining extraction	Hudyma (2008)	48.02 N	84.76 W
10/02/2007	Mouska	Canada	3	Mining extraction	Hudyma (2008)	48.28	78.57 W
14/03/2001	Musselwhite	Canada	2.2	Mining extraction	Hudyma (2008)	52.61 N	90.37 W
28/04/2005	Niobec	Canada	2.2	Mining extraction	Hudyma (2008)	48.53 N	71.16 W
08/01/1994	Onaping	Canada	2.5	Mining extraction	Hudyma (2008)	46.63 N	81.38 W
16/09/1967	Peissenberg	Germany	3.8	Mining extraction	Grünthal (2013)	47.83 N	11.1 E
06/04/1986	Quirke	Canada	2.8	Mining extraction	Hudyma (2008)	46.51 N	82.63 W
02/07/1983	S-Harz	Germany	3.1	Mining extraction	Grünthal (2013)	51.42 N	10.66 E
11/09/1996	Saale	Germany	4.6	Mining extraction	Grünthal (2013)	51.45 N	11.85 E
23/02/2008	Saar	France	3.7	Mining extraction	Grünthal (2013)	49.38 N	6.84 E
03/11/1936	Ruhr	Germany	4.1	Mining extraction	Grünthal (2013)	51.55 N	7.3 E
10/05/1995	Sigma	Canada	3.6	Mining extraction	Hudyma (2008)	48.1 N	77.75 W
02/08/1986	Strathcona	Canada	3.2	Mining extraction	Hudyma (2008)	46.63 N	81.38 W
13/04/2005	Thayer Lindsley	Canada	3.1	Mining extraction	Hudyma (2008)	46.56 N	81 W
13/03/1989	Werra	Germany	5.4	Mining extraction	Grünthal (2013)	50.8 N	10.05 E

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11/04/2000	Lubin Mine	Poland	4.21	Mining extraction	IGFPAS[30]	51.47	16.14
21/06/2001	Merlebach	France	4	Mining extraction	SZGRF[31]	49.14	6.73
18/07/2000	Rudna Mine	Poland	4.16	Mining extraction	IGFPAS	51.506	16.136
13/06/2002	Lazy Mine	Czech Republic	3.8	Mining extraction	IGCAS[32]	49.89	18.47
19/03/2013	Polkovice Mine	Poland	4.6	Mining extraction	IGFPAS	51.51	16.06
23/02/2008	Saarbruecken-West	Germany	4	Mining extraction	BGR[33]	49.38	6.84
06/08/2003	Sterkrade-North	Germany	3	Mining extraction	KNMI[34]	51.587	6.825
23/06/1975	Ronchonvillers	France	5.2	Mining extraction	BGR	49.286	5.957
20/04/1973	Tressange/Rochonvillers	France	4.3	Mining extraction	BGR	49.4	6
16/051991	Tecklenburg/Ibbenbueren	Germany	4.6	Mining extraction	BGR	52.28	7.7
21/08/1996	Upper Silesia	Poland	3.3	Mining extraction	IGCAS	50.06	19.06
13/01/2005	Silesia	Poland	3.8	Mining extraction	IGFPAS	50.1	18.47
06/10/1980	Mettingen	Germany	2.8	Mining extraction	BGR	52.18	7.48
12/12/2007	Moers	Germany	3.3	Mining extraction	BGR	51.409	6.566
02/12/2011	Nw.Haltern	Germany	3.3	Mining extraction	KNMI	51.767	7.098
05/03/1973	OberesVogtland	Germany	3.2	Mining extraction	KNMI	51.575	7.38
02/06/2003	Orsoy	Germany	3.4	Mining extraction	KNMI	51.518	6.715
22/01/2010	Belchatow	Poland	4.5	Mining extraction	IGFPAS	51.25	19.06
28/09/1981	Recklinghausen	Germany	3.4	Mining extraction	BGR	51.7	7.23
14/02/2007	Rheinberg	Germany	3	Mining extraction	KNMI	51.513	6.575
03/11/1936	Ruhrgebiet	Germany	3.9	Mining extraction	BGR	51.55	7.3

[30] IGFPAS: Institute of Geophysics Polish Academy of Sciences, http://www.igf.edu.pl

[31] SZGRF: The Seismological Central Observatory, https://www.szgrf.bgr.de

[32] Institute of Geophysics of the CAS: http://www.ig.cas.cz/en/structure/observatories/west-bohemia-seismic-network-webnet/map-epicenters

[33] BGR: Federal Institute for Geosciences and Natural Resources, https://www.bgr.bund.de

[34] KNMI: Royal Netherlands Meteorological Institute, http://www.knmi.nl/

Date	Site/City/State	Country	Max Magnitude	Technology at the seismicity's origin	Reference	Lat °	Lon °
17/12/1965	Unna	Germany	3.2	Mining extraction	BGR	51.567	7.833
24/11/1981	Wesel/Rhein	Germany	3.4	Mining extraction	BGR	51.64	6.63
18/03/1888	Ruhrgebiet	Germany	3.6	Mining extraction	BGR	51.53	7.45
12/09/1980	Pribram	Czech Republic	3.5	Mining extraction	IGCAS	49.65	13.96
07/01/1965	Reocin	Spain	4.1	Mining extraction	IGN	43.2	-4.1
19/04/1983	Ahrbergen	Germany	1.8	Mining extraction	BGR	52.134	9.528
04/04/1971	Aschersleben	Germany	4.6	Mining extraction	BGR	51.75	11.52
22/02/1953	Bad	Germany	5	Mining extraction	BGR	50.917	10
02/07/1983	Bleicherode	Germany	3.5	Mining extraction	BGR	51.44	10.56
21/12/1984	Salzwedel	Germany	2.6	Mining extraction	BGR	52.501	11.01
11/09/1996	Halle	Germany	4.8	Mining extraction	BGR	51.448	11.858
13/03/1989	Eisenach	Germany	5.6	Mining extraction	BGR	50.804	10.05
27/12/1989	New Castle	Australia	5.6	Mining extraction	Klose (2007)	-32.964167	151.606944
09/09/2001	Alkmar	Netherlands	3.5	Oil and gas extraction	Giardini (2011); Grünthal (2013)	52.65 N	4.71 E
1986	Assen	Netherlands	2.8	Oil and gas extraction	Grasso (1992)	53 N	6.56 E
15/07/2005	Bassum	Germany	3.7	Hydrocarbon extraction	Grünthal (2013)	52.89 N	8.75 E
09/09/2001	Bergermeer Field	Netherlands	3.5	Hydrocarbon extraction	van Eck et al. (2006)	52.64 N	4.73 E
-	Catoosa, Oklahoma1	USA	4.7	Hydrocarbon extraction	Nicholson and Wesson (1992)	36.19 N	95.74 W
-	Cleburne, Texas	USA	2.8	Hydrocarbon extraction	Howe et al. (2010)	32.35 N	97.39 W
1983	Coalinga, California	USA	6.5	Hydrocarbon extraction	McGarr (1991)	36.14 N	120.36 W
-	Dan	Denmark	4	Hydrocarbon extraction	Grasso (1992)	55.42 N	5.26 E
	East Durant, Oklahoma	USA	3.5	Hydrocarbon extraction	Nicholson and Wesson (1992)		

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20010507	Ekofisk	Norway	4.3	Hydrocarbon extraction	Cescaetal2011GJI	57.57	3.18
-	El Reno, Oklahoma4	USA	5.2	Hydrocarbon extraction	Nicholson and Wesson (1992)	35.53 N	97.95 W
	Flashing, Texas	USA	3.4	Hydrocarbon extraction	Pennington et al. (1986)		
17/05/1976	Gazli	Uzbekistan	7.3	Hydrocarbon extraction	Adushkin et al. (2000)	40.38 N	63.47 E
	Goose Creek, Texas	USA	unknown5	Hydrocarbon extraction	Nicholson and Wesson (1992)		
08/08/2006	Groningen Field	Netherlands	3.5	Hydrocarbon extraction	van Eck et al. (2006); Grünthal (2013)	53.35 N	6.69 E
	Grozny	Caucasus (Russia)	3.2	Hydrocarbon extraction	Guha (2000)		
-	Gudermes	Caucasus (Russia)	4.5	Hydrocarbon extraction	Smirnova (1968)	43.34 N	46.12 E
-	Imogene Field, Texas	USA	3.9	Hydrocarbon extraction	Pennington et al. (1986)	28.91 N	98.46 W
-	Kettleman North, California	USA	6.1	Hydrocarbon extraction	McGarr (1991)	36.02 N	120.08 W
1979	Lacq	France	4.2	Hydrocarbon extraction	Grasso and Wittlinger (1990)	43.42	-0.5
-	Lake Charles, Louisiana8	USA	3.8	Hydrocarbon extraction	Nicholson and Wesson (1990)	30.24 N	93.27 W
02/06/1993	Minagish Field	Kuwait	4.7	Hydrocarbon extraction	Bou-Rabee (1994)	28.95 N	47.55 E
-	Montebello, California	USA	5.9	Hydrocarbon extraction	Nicholson and Wesson (1992)	34.03 N	118.08 W
-	Petroleum field	Oman	2.1	Hydrocarbon extraction	Sze (2005)	22.13 N	56.01 E
	Orcutt Field, California	USA	3.5	Hydrocarbon extraction	Nicholson and Wesson (1992)		
-	Richland County, Illinois10	USA	4.9	Hydrocarbon extraction	Nicholson and Wesson (1992)	38.71 N	88.08 W
-	Rocky Mountain House, Alberta	Canada	3.4	Hydrocarbon extraction	Wetmiller (1986)	52.38 N	114.92 W
13/08/1997	Rongchang, Chongqing	China	5.2	Hydrocarbon extraction	Lei et al. (2008)	29.40 N	105.59 E

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19/02/1997	Roswinkel Field	Netherlands	3.4	Hydrocarbon extraction	van Eck et al. (2006)	52.84 N	7.04 E
20/10/2004	Rotenburg	Germany	4.3	Hydrocarbon extraction	Giardini (2011); Grünthal (2013)	53.04 N	9.54 E
-	Sleepy Hollow, Nebraska	USA	2.9	Hydrocarbon extraction	Rothe and Lui (1983)	41.36 N	96.01 W
02/06/1977	Soltau	Germany	3.7	Hydrocarbon extraction	Grünthal (2013)	52.94 N	9.94 E
	South-central Texas	USA	4.3	Hydrocarbon extraction	Davis et al. (1995)		
26/03/1971	Starogroznenskoe Oilfield	Russia	4.7	Hydrocarbon extraction	Kouznetsov et al. (1994)		
-	Strachan, Alberta	Canada	3.4	Hydrocarbon extraction	Grasso (1992)	52.26 N	115.15 W
1976/1979	War Wink Field, Texas	USA	2.9	Hydrocarbon extraction	Doser et al. (1992)	31.52 N	103.38 W
	West Texas	USA	3.1	Hydrocarbon extraction	Keller et al. (1987)		
-	Whittier Narrows, California	USA	5.9	Hydrocarbon extraction	McGarr (1991)	34.05 N	118.07 W
1951	Wilmington Field, California	USA	3.3	Hydrocarbon extraction	Kouznetsov et al. (1994)	33.78 N	118.26 W
21/09/1994	Alkmaar	Netherlands	2.5	Hydrocarbon extraction	KNMI[35]	52.658	4.708
27/06/2011	Hoeksmeer	Netherlands	3.2	Hydrocarbon extraction	KNMI	53.299	6.8
16/08/2012	Huizinge	Netherlands	3.4	Hydrocarbon extraction	KNMI	53.35	6.673
09/10/2011	Noordzee	Netherlands	3.1	Hydrocarbon extraction	KNMI	53.281	3.885
25/10/2000	Roswinkel	Netherlands	3.2	Hydrocarbon extraction	KNMI	52.832	7.052
20/10/2004	Rotenburg/Soltau	Netherlands	4.5	Hydrocarbon extraction	BGR[36]	53.039	9.537
10/11/2003	Stedum	Netherlands	3	Hydrocarbon extraction	KNMI	53.325	6.69
15/07/2005	Syke	Netherlands	3.8	Hydrocarbon extraction	BGR	52.886	8.753
08/08/2006	Westeremden	Netherlands	3.5	Hydrocarbon extraction	KNMI	53.35	6.697
08/05/2009	Zeerijp	Netherlands	3	Hydrocarbon extraction	KNMI	53.354	6.762
1951	Caviaga	Italy	5.5	Hydrocarbon extraction	Klose 2012 Jseismo	45.3	9.6
25/10/2000	Roswinkel	Netherlands	3.2	Hydrocarbon extraction	0KNMI	52.832	7.052

[35] KNMI: Royal Netherlands Meteorological Institute, http://www.knmi.nl/

[36] BGR: Federal Institute for Geosciences and Natural Resources, https://www.bgr.bund.de

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-	Love County, Oklahoma	USA	1.9	Hydrocarbon extraction	Nicholson and Wesson (1990)	33.98 N	97.22 W
	Apollo Hendrick Field, Texas	USA	2	Secondary recovery	Doser et al. (1992)		
	Barsa-Gelmes-Wishka Oilfield	Turkmenistan	6	Secondary recovery	Kouznetsov et al. (1994)		
-	Cogdell Canyon Reef, Texas	USA	4.6	Secondary recovery	Davis and Pennington (1989); Nicholson and Wesson (1990)	32.68 N	100.93 W
-	Cold Lake, Alberta	Canada	2	Secondary recovery	Nicholson and Wesson (1990)	54.46 N	110.17 W
	Dollarhide, Texas	USA	3.5	Secondary recovery	Nicholson and Wesson (1992)		
	Dora Roberts, Texas	USA	3	Secondary recovery	Nicholson and Wesson (1992)		
	East Texas, Texas	USA	4.3	Secondary recovery	Nicholson and Wesson (1992)		
-	Fort St. John, British Columbia	Canada	4.3	Secondary recovery	Horner et al. (1994)	56.25 N	120.84 W
30/12/1979	Gobles Field, Ontario	Canada	2.8	Secondary recovery	Nicholson and Wesson (1990)	43.15 N	80.57 W
	Hunt Field, Mississippi7	USA	3.6	Secondary recovery	Nicholson and Wesson (1992)		
-	Inglewood Oil Field, California	USA	3.7	Secondary recovery	Nicholson and Wesson (1992)	34 N	118.38 W
-	Kermit Field, Texas	USA	4	Secondary recovery	Nicholson and Wesson (1990)	31.85 N	103.04 W
-	Keystone I Field, Texas	USA	3.5	Secondary recovery	Nicholson and Wesson (1990)	31.88 N	102.96 W
-	Keystone II Field, Texas	USA	3.5	Secondary recovery	Nicholson and Wesson (1990)	31.88 N	102.96 W

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	Lambert Field, Texas	USA	3.4	Secondary recovery	Nicholson and Wesson (1992)		
-	Love County, Oklahoma9	USA	2.8	Secondary recovery	Nicholson and Wesson (1990)	33.98 N	97.22 W
-	Monahans, Texas	USA	3	Secondary recovery	Nicholson and Wesson (1992)	31.59 N	102.89 W
-	Northern Panhandle, Texas	USA	3.4	Secondary recovery	Nicholson and Wesson (1990)	35.66 N	101.39 W
-	Rangely, Colorado	USA	3.1	Secondary recovery	Nicholson and Wesson (1990)	40.09 N	108.80 W
-	Renqiu oil field	China	4.5	Secondary recovery	Genmo et al. (1995)	38.67 N	116.10 E
-	Romashkino, Tartarstan	Russia	4	Secondary recovery	Adushkin et al. (2000)	55.18 N	50.73 E
-	Shandong	China	2.4	Secondary recovery	Shouzhong et al. (1987)	36.67 N	117.02 E
-	Snipe Lake	Canada	5.1	Secondary recovery	Nicholson and Wesson (1992)	51.16 N	108.64 W
	Southern Alabama	USA	4.9	Secondary recovery	Gomberg and Wolf (1999)		
-	Ward-Estes Field, Texas	USA	3.5	Secondary recovery	Nicholson and Wesson (1992)	31.56 N	103.14 W
-	Ward-South Field, Texas	USA	3	Secondary recovery	Nicholson and Wesson (1992)	31.56 N	103.14 W
11/1964	Akosombo	Ghana	5.3	Dams	Guha (2000)	7.5 N	00.25 E
14/11/1981	Aswan	Egypt	5.6	Dams	Guha (2000)	23.95 N	32.86 E
03/07/1967	Bajina Basta	Yugoslavia	4.8	Dams	Guha (2000)	43.97 N	19.37 E
07/07/1966	Benmore	New Zealand	5	Dams	Guha (2000)	44.40 S	170.23 E
15/09/1983	Bhatsa	India	4.8	Dams	Guha (2000)	19.51 N	73.42 E
23/01/1972	Cajuru, Brazil	Brazil	4.7	Dams	Guha (2000)	20.30 S	44.70 W
15/04/1964	Camarillas, Spain	Spain	4.1	Dams	Guha (2000)	38.36 N	01.65 W
09/06/1962	Canelles, Spain	Spain	4.7	Dams	Guha (2000)	42.03 N	00.65 E

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15/03/1977	Charvak	Uzbekistan	4	Dams	Guha (2000)	-	-
02/08/1974	Clark Hill	USA	4.3	Dams	Guha (2000)	33.85 N	82.38 W
06/06/1962	Coyote Valley	USA	5.2	Dams	Guha (2000)	39.23 N	123.17 W
29/11/1973	Danjiangkou	China	4.7	Dams	Guha (2000)	32.69 N	111.08 E
14/04/1954	Dents du Midi	Switzerland	3.5	Dams	Grünthal (2013)	46.18 N	6.97 E
	Dhamni	India	3.8	Dams	Guha (2000)		
18/05/1959	Eucumbene	Australia	5	Dams	Guha (2000)	36.08 S	148.72 E
11/08/1963	Foziling	China	4.5	Dams	Guha (2000)	-	-
05/08/1963	Grandval	France	unknown6	Dams	Gupta (2002)	44.97 N	03.10 E
04/05/1939	Hoover	USA	5	Dams	Guha (2000)	36.0 N	114.8 W
18/03/1962	Hsinfengchiang	China	6.1	Dams	Guha (2000)	23.78 N	114.58 E
-	Idukki	India	3.5	Dams	Guha (2000)	9.84 N	76.98 E
12/1979	Ingouri	Caucasus (Russia)	4.4	Dams	Guha (2000)	-	-
13/05/1978	Itezhitezhi	Zambia	4.2	Dams	Guha (2000)	15.79 S	25.07 E
23/09/1963	Kariba	Zambia	6.2	Dams	Guha (2000)	16.93 S	27.93 E
-	Kastraki	Greece	4.6	Dams	Guha (2000)	38.67 N	21.70 E
-	Kerr	USA	4.9	Dams	Guha (2000)	47.70 N	114.17 W
13/04/1969	Kinnersani	India	5.3	Dams	Guha (2000)	17.68 N	80.67 E
10/12/1967	Koyna	India	6.5	Dams	Gupta (1983)	17.62 N	73.76 E
05/02/1966	Kremasta	Greece	6.3	Dams	Guha (2000)	38.90 N	21.53 E
19/08/1961	Kurobe	Japan	4.9	Dams	Guha (2000)	36.53 N	137.65 E
23/10/1975	Manicouagan	Canada	4.1	Dams	Guha (2000)	50.11 N	68.65 W
20/07/1938	Marathon	Greece	5.7	Dams	Guha (2000)	38.18 N	23.90 E
05/01/1974	Mica, Canada	Canada	4.1	Dams	Guha (2000)	52.07 N	118.30 W
	Montecillo, South Carolina	USA	2.8	Dams	Guha (2000)		
25/04/1963	Monteynard	France	4.9	Dams	Guha (2000)	44.90 N	05.70 E

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06/11/1972	Nurek	Tadjikstan	4.6	Dams	Guha (2000)	38.42 N	62.27 E
01/08/1975	Oroville, California	USA	5.7	Dams	Guha (2000)	39.53 N	121.43 W
07/04/1966	Piastra	Italy	4.4	Dams	Guha (2000)	44.21 N	07.21 E
13/01/1960	Pieve de Cadore	Italy	4.3	Dams	Guha (2000)	46.45 N	12.41 E
24/02/1974	Porto Colombia	Brazil	5.1	Dams	Guha (2000)	20.12 S	48.35 W
01/01/1954	Salanfe	Switzerland	3.5	Dams	Grünthal (2013)	46.18 N	6.95 E
02/08/1968	Sefia Rud	Iran	4.7	Dams	Guha (2000)	36.72 N	49.37 E
02/12/1974	Shenwo	China	4.8	Dams	Guha (2000)	-	-
	Sriramsagar	India	3.2	Dams	Guha (2000)		
09/10/1963	Vajont	Italy	3	Dams	Guha (2000)	46.15 N	12.70 E
09/03/1973	Varragamba	Australia	5.4	Dams	Guha (2000)	33.97 S	150.42 E
21/06/1971	Vouglans	France	4.4	Dams	Guha (2000)	46.35 N	05.70 E
12/05/2008	Wenchuan	China	7.9	Dams	Huang et al. (2008)	30.99 N	103.36 E
20040918	Itoiz_Dam	Spain	4.5	Dams	Ruizetal2006Tectonophysics+IGNESP_Catalogu	42.8508	-1.4506
19730503	Almendra_Dam	Spain	4	Dams	IGN-ES	41	-6.4
1985XXXX	Ridracoli	Italy	4.1	Dams	Klose2012JSeismol,aproximated_to_dam_location	43.9	11.8
1986XXXX	Fierza-Komani	Albania	4.2	Dams	Klose2012JSeismol,aproximated_to_dam_location	42.1	20.3
20000423	Tous_New_Dam	Spain	3.5	Dams	Torcaletal 2005GJ	39.239	-0.418
1987	Ashtabula, Ohio	USA	3.6	Wastewater injection	Armbruster et al. (1987)	41,86 N	80.79 W
16/05/2009	Dallas Fort Worth, Texas	USA	3.3	Wastewater injection	Frohlich et al. (2010)	32.79 N	97.02 W
09/08/1967	Denver, Colorado3	USA	4.8	Wastewater injection	Hermann et al. (1981); Ellsworth (2013)	39.81 N	104.87 W
-	El Dorado, Arkansas	USA	3	Wastewater injection	Cox (1991)	33.21 N	92.67 W

Date	Site/City/State	Country	Max Magnitude	Technology at the seismicity's origin	Reference	Lat °	Lon °
	Guy and Greenbrier, Arkansas	USA	4.7	Wastewater injection	Horton (2012)		
25/01/1970	Matsushiro	Japan	2.8	Wastewater injection	Ohtake (1974)	36.55 N	138.22 E
	Paradise Valley, Colorado	USA	0.8	Wastewater injection	Nicholson and Wesson (1992)		
27/05/2000	Paradox Valley, Colorado	USA	4.3	Wastewater injection	Ake et al. (2005)	38.32 N	108.86 W
24/01/2013	Paradox Valley 2	USA	4.4	Wastewater injection	Block et al. (2014)	38.3209 N	108.9841 W
-	Perry, Ohio	USA	2.7	Wastewater injection	Nicholson and Wesson (1992)	41.76 N	81.14 W
-	Rocky Mountain Arsenal, Denver, Colorado	USA	5.5	Wastewater injection	Guha (2000)	39.81 N	104.87 W
	Tomahawk Field, New Mexico	USA	Unknown11	Wastewater injection	Nicholson and Wesson (1992)		
08/2000	Vogtland	Germany		Wastewater injection	Baisch et al. (2002)	49.81 N	12.12 E
	Southwest of Eisenbach	Germany	5.8	Other	Giardini (2011)		
-	Belchalow	Poland	4.6	Other	Giardini (2011)	51.37 N	19.36 E
-	Cleveland, Ohio2	USA	3	Other	Nicholson and Wesson (1992)	41.5 N	81.69 W
-	Dale, New York	USA	1	Other	Nicholson and Wesson (1990)	42.82 N	78.17 W
	Harz	Germany	3.5	Other	Giardini (2011)		
	LGDD	Russia	4.2	Other	Giardini (2011)		
	Upper Silesian	Poland	4.45	Other	Giardini (2011)		
-	Attica, New York	USA	5.2	Solution mining	Nicholson and Wesson (1992)	42.87 N	78.28 W
2008	Cerville-Buissoncourt	France	0.9	Solution mining	Kinscher (2015 TZ)	48.676676	6.322583
	Lorca	Spain	5.1	Water extraction	Gonzalez et al. (2012)	37.6946	-1.6756

Date	Site/City/State	Country	Max Magnitude	Technology at the seismicity's origin	Reference	Lat °	Lon °
	Sleipner	Norway	2.5	CO2 storage	Evans et al. (2012)	58.44	1.66
01/10/2013	Castor Project	Spain	4.3	Gas storage	Cesca et al. (2013)	40.4	0.722
02/10/2013	Castor Project	Spain	4.3	Gas storage	Cesca et al. (2014)	40.4	0.722

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APPENDIX C

A Implantation du bâtiment	1 Pente générale du terrain > 40 % 5	2 Proximité d'un changement de pente D < 2H du bâtiment 15							Observations
B Environnement du bâtiment	1 Bâtiments accolés : joint = 0 ou rempli d'un matériau **25**	2 Joints entre blocs adjacents < 2 cm **25** 2 à 4 cm **10** > 4 cm **5**							
C Type de structure	1 Murs en maçonnerie de blocs **15**	2 Murs en béton non armé **10**	3 Murs en béton armé **5**	4 Ossature poteaux-poutres sans remplissage **20**	5 Ossature poteaux-poutres avec remplissage **25**	6 Système mixte murs en maçonnerie et ossature **20**	7 Panneaux de façade BA préfabriqués porteurs **10**	8 Ossature BA préfabriquée porteuse **50**	
D Forme en plan	1 Irrégulière 5	2 Elancement en plan L/l>4 5	3 Parties saillantes ou rentrantes 5						
E Forme en élévation	1 Etages en encorbellement > 2 m **15**	2 Retrait en façade >40 % **20**	3 Planchers d'un même étage situés à des hauteurs différentes **10**	4 Présence d'un plancher lourd ou d'une toiture lourde **10**	5 Absence de diaphragme horizontal en toiture **20**				
F Contreventement	1 Variation verticale croissante des rigidités **0 à 100** (voir formule 1)	2 Dissymétrie : torsion **faible : 5** **accusée : 50**	3 Absence de contreventement dans le sens des x ou y **100**	4 Densité de voiles de contreventement sens x ou y **0 à 100** (voir formule 2)					
G Zones ou éléments critiques	1 Descente de charge en baïonnette 25	2 Présence de poteaux courts ou partiellement bridés participant au contreventement **50**	3 Présence de poteaux élancés **10**	4 Percements inserts dans les poteaux e>d/3 **25**	5 Percements inserts dans les poutres e>d/3 **10**	6 Percements inserts dans les nœuds e>d/3 **50**			
	7 Présence d'un angle de façade affaibli **15**	8 Axes poteaux et poutres non concourants e>c/2 **10**	9 Diaphragmes horizontaux avec grandes ouvertures s>10 %S **10**	10 Absence de chaînages encadrant les murs de contreventement en MAC **verticaux : 25** **horizontaux : 75**					
H Divers	1 Etat de conservation du gros œuvre **médiocre : 10** **mauvais : 25**	2 Risque de chute d'éléments non structuraux **5**	3 Façade BA préfabriquée non porteuse **10**						
Total des pénalités									

Table 8: Qualitative evaluation of buildings' vulnerability K index on the basis of observations (according to the AFPS).