Main risks related to deep geothermal energy in the world

Philippe Gombert, Franz Lahaie, Auxane Cherkaoui, Isabelle Contrucci, Francesca de Santis

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Philippe Gombert[1]*, Franz Lahaie[2], Auxane Cherkaoui[1], Isabelle Contrucci[2], Francesca de Santis[2]

[1]Ineris, Parc Technologique Alata, 60550Verneuil-en-Halatte, France

[2]Ineris, Campus Artem, CS 14234, 54042 Nancy cedex, France

* philippe.gombert@ineris.fr

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ABSTRACT

Deep geothermal is a renewable energy that is about to develop strongly in the coming decades, particularly in France. However, like any industrial activity, it carries risks for people and the environment. An appropriate management of these risks is a prerequisite for the sustainable development of this sector. Based on an international review of incidents and accidents, we present the risks and impacts that may be inferred by this industry as they are currently known. The main feared events are analysed in order to understand their causes and consequences. The goal is to achieve a comparative assessment of the risks linked with this activity. Finally, we focus on some of the recent events that have affected deep geothermal and led to serious accidents, associated with H_2S emissions and induced or triggered seismicity. Regarding seismicity, a comparison is performed with other activities that can be observed in other "geo-industrial" sectors (hydrocarbon extraction, large-scale water extraction, filling of large dams, digging of large underground structures, mining and post-mining industries, etc.). It can be seen that deep geothermal energy is responsible for fewer earthquakes and, when it is the case, ones of a smaller magnitude compared to these geo-industries.

1. INTRODUCTION

The Paris Climate Agreement, adopted in 2015 by 195 countries, reaffirmed the international will to fight against climate disruption by reducing greenhouse gas emissions. One instrument that would achieve this goal is an increase in the share of renewable energy within the global energy supply. France has become part of this process in particular by means of its recent energy transition legislation for green growth, which provides for renewable energy to contribute a 32% share of the total national energy consumption by 2030. Geothermal energy, which uses thermal energy from the subsoil in order to produce heat or electricity, is one technology that is capable of contributing to this goal.

At present, geothermal energy constitutes a tiny share (0.9%) of the production of renewable energy in France, far behind hydro-electric (20%), wind (8%), or solar (3.4%). Nevertheless, its potential has been largely unexploited and the support policies it enjoys portend an accelerated development in coming years. In this way, France is setting the goal of doubling its geothermal energy production capacity by 2023. However, only deep geothermal energy will be discussed here, that is, the direct exploitation of deep geothermal energy deposits for the production of heat or electricity.

As a renewable energy source, deep geothermal enjoys a favourable image overall, but may perhaps be confronted locally with problems of acceptability. The reluctance that may be expressed regarding this technology is associated with a collection of technical factors (induced seismicity, potential pollution of groundwater, noise, nuisance, occupation of land, etc.), economic factors (local residents not necessarily reaping the benefits), or ideological issues (opposition to any form of underground exploitation) (Chavot, 2016). Recent incidents in the Rhine Rift Valley (Basel, Landau, Staufen, etc.), even if they were the result of actions contrary to good practice within the profession (see, for example, Hervé, 2009; Goyénèche et al., 2015) have also contributed to tarnishing the image of deep geothermal energy.

After getting feedback on incidents or accidents occurring in this domain over the last decades, current knowledge on the main risks relating to deep geothermal will be presented here. These risks, in particular those of seismic origin, are then compared with those related to other geo-industries such as oil drilling (Lahaie, 2015a; Lahaie, 2015b; Lafortune, 2016).

2. IDENTIFICATION OF ACCIDENT HAZARDS

2.1 Presentation of the risk analysis process

The term "risk" refers to a potential incident involving the health or safety of persons (internal or external to the site) or the environment resulting from activities carried out at a site. There is a classic distinction between accident risks, linked to unforeseen events, and chronic risks, linked to activities being run at the site. We will focus primarily here on the former and only to potential damage to people or the environment. Risk that is technical (failure to exploit the geothermal resource), economic (loss of productivity or injectivity) or relating to work done on wells (maintenance) will not be discussed.

Risks are often depicted as a simplified chain of accident-related events (Figure 1) involving a " feared event ", its causes or " triggering mechanisms " and its consequences: these are the phenomena resulting from the feared event, likely to harm people (" dangerous " phenomenon), property, or the environment (" impacting " phenomenon). Still, we will call it an " accident " if the chain of accident-related events unfolds completely and actually impacts what is at stake (people, property, or environment), and an " incident " in all other cases. Nevertheless, the generic term " accident " will be used in this paper to refer to both accidents or incidents without distinction.

A risk analysis focuses especially on feedback from previous accidents and incidents in the domain concerned. Since no specific database for incidents or accidents relating to geothermal energy exists, such information was obtained from press reports, the internet, or technical reports. The database thus created concerns only events that are sufficiently well documented (Table 1): it comprises 37 accidents that occurred, for the most part, in the domain of deep geothermal energy. There are also some accidents relating to surface geothermal energy, feedback on which has been deemed to be applicable to deep geothermal energy. Because this is not an exhaustive database, it is difficult to derive quantitative conclusions on the accidentology of geothermal energy and, in particular, to make comparisons with other industrial sectors.

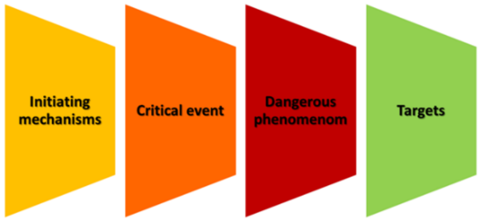

Figure 1. Simplified representation of an accident chain (Gombert et al, 2017)

2.2 Database analysis

The main lessons to be learned from analysis of the documented accidents are summarised below, taking into account the existence of a bias relating to the origin of the available sources which are essentially European.

- 51% of the cases listed occurred in Europe, in the following countries : France (8 cases), Germany (6 cases), Switzerland (2 cases), Iceland (2 cases) and Italy (1 case) ; this finding is not indicative of deteriorating safety in Europe, but results from the bias linked to the use of predominantly European information sources ;
- 89% of the cases listed specifically correspond to deep geothermal operations and 11% of cases to surface geothermal retained as relevant to the domain of deep geothermal energy.

2.2.1 Lessons learned in terms of risks to people

16% of the accidents listed gave rise to the death of one or more persons. Of all the accidents, there were 51 deaths and 44 injured persons identified bearing in mind that, in some accidents, the exact number of victims was not specified. 94% of the fatal accidents result from two particularly serious accidents which occurred in the 90s in specific contexts:

- Agua Shuca in El Salvador, which left 25 dead and 35 injured in 1990 (Escobar et al., 1992, Goff & Goff, 1997); this was a blowout due to an uncontrolled rise in the pressure of the reservoir,
- Zunil 1 in Guatemala, with 23 deaths in 1991 (Goff & Goff, 1997 ; Flynn et al., 1991) ; this was a big landslide, for which it is not known if it was induced by geothermal drilling, leading to the rupture of the casing and thence to a massive projection of hot geothermal fluid in the vicinity.

Except for these two accidents, which occurred in very specific contexts and for which the information available is not very precise, we identify only a few victims resulting from H2S releases in all of the 35 remaining accidents:

- in 1998 in Japan and in 2018 in France, 3 fatalities occurred during geothermal power plant maintenance operations; they were the result of H2S fumes which had accumulated in confined areas,
- in 1991 in Hawaii (USA) and in 2014 in Biliran (Philippines), 9 people were injured by H2S fumes during a well blowout and a production test respectively.

Table 1. Summary of accident-related events collected (after Gombert et al., 2017)

Reference	Event date	Geothermal activity	Country	Location	Critical events	Impacting or dangerous phenomena	Number of injuries	Number of deaths
Warakei	1950-1997	Deep geothermal	New Zealand	Warakei	Depletion of the reservoir	Subsidence	0	0
Svartsengi	1976-1999	Deep geothermal	Iceland	Svartsengi	Depletion of the reservoir	Subsidence	0	0
Geysers	1980-2010	Deep geothermal	USA	California	Eathquake	Felt seismic shocks	0	0
Salton Sea	1981-2012	Deep geothermal	USA	California	Eathquake	Felt seismic shocks	0	0
Lardarello	1985	Deep geothermal	Italy	Lardarello	Underground leak	Fluid emission	0	0
Agua Shuca	13 October 1990	Deep geothermal	Salvador	SW of Ahuachapan	Blowout	Fluid emission	35	25
Zunil 1	01 May 1991	Deep geothermal	Guatemala	South of Quetzaltenango	Surface leak	Fluid emission	?	23
Puna 2	15 June 1991	Deep geothermal	Hawaii	Honolulu	Blowout	Fluid emission	1	0
Berlin 1	1993-1994	Deep geothermal	Salvador	Usulutan	Surface leak	Gaseous emissions	00/01/1900	00/01/1900
Ahuachapan 2	1994	Deep geothermal	Salvador	Ahuachapan	Surface leak	Fluid emission	several	several
Ahuachapan 1	Summer 1994	Deep geothermal	Salvador	Ahuachapan	Surface leak	Fluid emission	several	several
Coulommiers	1996	Deep geothermal	France	Coulommiers	Underground leak	Fluid emission	0	0
Japon	1998	Deep geothermal	Japan		Surface leak	Fluid emission	0	1
Neustadt-Glewe	1998	Deep geothermal	Germany	Neustadt-Glewe	Injection pressure		0	0
Soultz-sous-Forêts	2003	Deep geothermal	France	Alsace	Eathquake	Felt seismic shocks	0	0
Berlin 2	16 September 2003	Deep geothermal	Salvador	Usulutan	Eathquake	Felt seismic shocks	0	0
Bâle	12 August 2006	Deep geothermal	Swiss	Basel	Eathquake	Felt seismic shocks	0	0
Hilsprich	From 2006	Superficial geothermal	France	Lorraine	Uncontrolled dissolution	Subsidence	0	0
Kircheim	2007		France	Alsace	Water intrusions in anhydrite formation	Gaseous emissions	0	0
Staufen	11 January 2007		Germany	Staufen		Gaseous emissions	0	0
Lochwiller	2008-2013		France	Alsace		Gaseous emissions	0	0
Innamincka	24 April 2009	Deep geothermal	Australia	Innamincka	Surface leak	Gaseous emissions	0	0
Landau 1	15 August 2009	Deep geothermal	Germany	Landau	Eathquake	Gaseous emissions	0	0
Rotokawa	01 January 2010	Deep geothermal	New Zealand	Rotokawa	Eathquake	Gaseous emissions	0	0
Bouillante	02 April 2010	Deep geothermal	France	Guadeloupe	-	Gaseous emissions	0	0
Insheim	April 2010	Deep geothermal	Germany	Bavaria	Eathquake	Gaseous emissions	0	0
Hengill	15 October 2011	Deep geothermal	Iceland	Hengill	Eathquake	Gaseous emissions	0	0
Habanero	November 2012	Deep geothermal	Australia	Cooper Bassin	Eathquake	Gaseous emissions	0	0
Meaux	2013	Deep geothermal	France	Meaux	-	Gaseous emissions	0	0
Saint Gall	20 July 2013	Deep geothermal	Swiss	Saint Gall	Eathquake	Gaseous emissions	0	0
Landau 2	13 March 2014	Deep geothermal	Germany	Landau	-	Gaseous emissions	0	0
Biliran	23 June 2014	Deep geothermal	Philippines	Biliran	Massive surface outgassing	Gaseous emissions	8	0
Puna 1	08 July 2014	Deep geothermal	Hawaii	Honolulu	Surface leak	Fluid emission	0	0
Margamukti	05 July 2015	Deep geothermal	Indonesia	Pangalengan (Java)	-	-	0	0
Unterhaching		Deep geothermal	Germany	Bavière	Eathquake	Felt seismic shocks	0	0
Pohang	15 novembre 2017	Deep geothermal	South Corea	Pohang	Eathquake	Felt seismic shocks	~90	0
Montesson	17 September 2018	Deep geothermal	France	Yvelines	Surface leak	Fluid emission	0	2

The 2017 Pohang accidental seismic event took place in a deep geothermal energy site situated in a naturally seismic zone (Kwang-Hee, 2018, Grigoli et al, 2018). This was an earthquake of magnitude 5.5, the second largest in the region injuring 82 persons and damaging 200 buildings. To date, the causes of the accident and its relationship with the ongoing geothermal energy site remain controversial and that is why we will not include it in the statistics.

Therefore, if the Agua Shuca, Zunil 1, and Pohang accidents (which occurred in exceptional circumstances) are excluded, deep geothermal energy benefits from quite low accidentology with 3 dead and 9 injured in almost three decades of feedback, and this based on about 1,700 geothermal power plants currently in operation. It should be noted, however, that the documentation is only partial since it is based mainly on Western sources of information, found in the public domain. We can therefore only encourage the profession through its representative structures at national and international levels, to continue the work initiated here by Ineris and to set up a systematic inventory of incidents and accidents occurring in the domain of deep geothermal energy, in order to build on what can only constitute an initial quantitative analysis in this report.

2.2.2 Lessons learned in terms of changes to safety over time

The distribution of victims is not homogeneous over time. As a result, the accidents that occurred before 2000s give a total of 89% of all victims. In addition, the severity of the events seems to have decreased over time: only 2 deaths were recorded after 2000 and only 22% of the injured persons. This reduction in the number of victims and the seriousness of their injuries over time is all the more significant since the number of geothermal installations in the world has not stopped growing during this period : in fact, installed power has multiplied by a factor of 6 since 1995 in the domain of direct heating (Lund and Boyd, 2015) and by a factor of 3 since 1985 in the domain of electricity (Bertani, 2015). This tendency is probably indicative of an improvement in safety practices and taking account of feedback from the first accidents in deep geothermal operations. We note that a similar improvement has been observed in the exploration and exploitation of hydrocarbons (Lahaie, 2015a).

2.2.3 Lessons learned in terms of the typology of accidents

The feared events most observed are induced seismicity (35% of cases), surface or underground leaks (24%), seepage of water into sensitive formations such as clays or evaporites (11%), excessive depletion of the geothermal reservoir (6%), blowouts (6%) or massive surface degassing events (3%). It should also be noted that in 17% of cases the type of accidental event is not known.

The dangerous or impacting phenomena that result from these events are felt seismic shocks (in 38% of all cases), ground movements such as uplifting or subsidence (21%), toxic or ecotoxic release (18%), gaseous emissions (6%), or explosions/projections (6%). The dangerous or impacting phenomenon is not known in 11% of all cases.

When the accident leads to uplifting or subsidence and when geothermal drilling is located in highly urbanised areas, there can be serious consequences for housing and infrastructure. This is proven by the accidents that occurred in Baden-Wurtemberg in Germany (Staufen, Landau 2, etc.) or in the Grand Est region in France (Lochwiller, Kirchheim, Hilsprich), the cause of which was the seepage of water into sensitive formations leading to their collapse by dissolution (salt, gypsum) or their swelling (anhydrite, clay) (Catoire et al., 2017). This type of seepage may result from ignorance of the site's local geology, poor cementing of the well, uncontrolled water inflow, and/or an excessive depletion of the reservoir due to there being no reinjection (or partial reinjection) of geothermal fluid into the subsoil. Even if these accidents had occurred in the context of surface geothermal energy, they reveal geological phenomena (dissolution or swelling of water-sensitive formations) that have to be taken into account during the design and completion of all wells, whether superficial or deep.

When the accident leads to felt seismic shocks, the material damage is often minimal but the psychological and media impact can be very high, especially because of the uneasiness aroused by the possibility of stronger seismic shocks to come. As a result, the St-Gall or Basel events in Switzerland, which occurred right in the middle of the urban zone, have led to the temporary or final shutdown of the respective geothermal projects. In addition, the seismicity that occurred at these two sites had not been anticipated, and it is still difficult today to account for it and therefore to completely control it. At any rate, these accidents show that the occurrence of a noticeable induced seismic event is made likely when the exploitation of geothermal energy is done in bedrock (rather than a sedimentary basin) - in deep, faulty, and tectonically active formations (see also the Pohang case). There are, however, measures to limit and control this risk, particularly by moderating the injection pressure, deploying a seismic surveillance network in order to monitor induced seismic activity and anticipate the occurrence of any noticeable seismic event, or upstream informing of the local population.

In general, it can be noted that the types of accidents observed in the context of deep geothermal energy are not specific to this domain but result from any underground deep drilling operations. Nevertheless, deep geothermal energy provides conditions more conducive to certain kinds of accidents and less conducive to others. As a result, the blowout type of accident is less probable for deep geothermal energy than for oil exploitation, for example, because the reservoirs are generally less pressurised and formations that are home to hydrocarbons or toxic gases (outside of volcanic contexts) are less often found. On the other hand, high-temperature geothermal energy, especially in tectonically active zones, seems to provide conditions more conducive to the occurrence of felt induced seismicity than low-temperature geothermal energy or conventional oil exploitation. Similarly, the opinion can be formed that the direct contact of the geothermal water with the casing makes it more likely for the latter to be perforated as a result of corrosion during geothermal drilling than in oil drilling. Preventive measures are also provided to this end: doubling the casings opposite the aquifers to be protected, extra-thick casings, etc.

3. MAIN FEARED EVENTS (MFES)

3.1 Identification of MFEs categories

The most frequent accidents occurring in the field of deep geothermal energy have been grouped into four main categories:

- accidental releases of fluids at the surface that mainly include blowouts and excessive emissions of dissolved gases, but also leaks in primary or secondary circuits, or leaks from a surface reservoir;
- pollution of the underground environment involving the seepage of fluid into an aquifer, but also joining up separate aquifers;
- seismic shocks resulting from induced earthquakes, i.e. directly associated with geothermal operations, and naturally triggered earthquakes the occurrence of which has been made more likely by these operations;
- ground movements which include subsidence or lowering of the ground surface, uplifting or raising of the ground surface, and landslides.

For each of these, the main MFEs will be presented, as well as their possible triggering mechanisms, as well as the dangerous or impacting phenomena liable to result from them, and the potential effects on and consequences for persons, property, or the environment.

3.2 Accidental release of fluids on the surface

3.2.1 Blowout

The MFE is here a blowout or uncontrolled escape of a gaseous fluid or liquid. This risk is lower in geothermal energy than in other deep drilling domains such as, for example, oil or gas drilling whose objective is to intersect horizons containing hydrocarbons. This type of accident nevertheless occurred with dramatic consequences (25 deaths) in a volcanic context at Agua Shuca (El Salvador) in 1990, Zunil 1 (Guatemala) in 1991, and Puna 2 (Hawaii) in 1991. These were countries or times, however, when Blow-Out Preventers (BOPs) were not mandatory for shallow geothermal exploratory drill holes: for example, for less than 2,500 m in the United States (Webb et al., 1984). Nowadays, these devices are systematically used, especially in France. This danger, however, materialised recently at St. Gallen (Switzerland) where 95% methane gas suddenly invaded the well (Moeck et al., 2015): it was able to be counteracted by a speedy injection of heavy sludge.

To explain this MFE, which occurs especially during the drilling phase, you have to have the following two undesirable events in succession: an inflow of fluid under pressure into the well and loss of sealing in the drilling envelope. The inflow of pressurised fluid can be linked to insufficient sludge density, to a packing manœuvre that is too fast, to the unexpected penetration of an over-pressurised formation, to a loss of sludge circulation, or to deficient cementing (Lahaie, 2015b; Galin, 2000; Hervé, 2009; Faessler, 2014; Bauer et al., 2015).

The potential effects of a surface eruption depend on the pressure, temperature and nature of the fluid emitted (Bottai and Cigni, 1985; Mendrinos and Karytsas, 2006; Marchand et al., 2015). First and foremost, there will be a projection of geothermal fluid, rock or mud which, depending on the nature of the fluid, can cause ignition or an explosion (CH_4, CO, H_2S, H_2), intoxication (CO_2, H_2S, CO), asphyxiation (all gases except O_2), burns, or greenhouse gas emissions (CO_2, CH_4, NO_X).

3.2.2 Excessive emission of dissolved gases

This MFE relates to large-scale and unexpected degassing of the geothermal fluid. It occurs mainly during the test phase (the geothermal fluid being brought up directly to the surface), but sometimes also during the operating phase (leakage in the primary circuit, see next MFE), or even during the abandonment phase (bad plugging of the well, faulty design, defective plug construction, deterioration of plugs). This type of event has also been reported several times in cases of previous drill holes for hydrocarbons (Bachu and Watson, 2009) or geological storages of CO_2 (Gombert and Thoraval, 2010; Farret, 2013).

The triggering mechanisms are two in number: a geothermal fluid abnormally rich in dissolved gas coming up and/or the existence of a leak or a sudden pressure drop, aggravated by the presence of a confined area (Kage et al. al., 1998; Kagel et al., 2007; Hervé, 2009; Rouquet, 2010; UCS, 2016; Holm, 2012; Ecogi, 2012; Cuenot, 2012; Reith et al., 2013).

The potential consequences are especially severe in confined areas (intoxication, asphyxia). Nevertheless, despite the richness of certain geothermal fluids in dissolved gases, the literature does not mention accidents resulting from large-scale degassing during drilling or test phases : during these phases, degassing actually occurs in the open air and the consequences are negligible, with the exception of potential local and temporary contamination of the atmosphere by certain gases (CO_2, CO, H_2S, NO_X ...). Still, the accidentology identifies two cases of serious intoxication: a victim of H2S release during a well blowout at Puna 2 (Hawaii) in 1991 and eight people affected by an H_2S emission during a production test in Biliran (Philippines) in 2014.

3.2.3 Leak in the primary or secondary circuit

This MFE involves the fluid that is circulating in the pipes or well spreading to the outside. In drilling and testing phases, it is either drilling fluid, geothermal fluid, or hydraulic or chemical stimulation fluid. During the exploitation phase, the problem may involve the geothermal fluid (primary circuit) or the heat transfer fluid (secondary circuit, Hirschberg et al., 2015).

The mechanisms that could lead to a leak of geothermal fluid at the surface are corrosion and sealing defects affecting this fluid's transmission lines. It's a risk cited by several authors (Galin, 2000; Kagel et al., 2007; Hervé, 2009; Rouquet, 2010; UCS, 2016; Holm, 2012; Ecogi, 2012; Cuenot, 2012; Reith et al., 2013; Bauer et al., 2015; Hirschberg et al., 2015). As for the heat transfer fluid, corroded or ruptured pipes are also mechanisms triggering leaks, but they are a priori not as severe as previously because this fluid is less hot and less aggressive.

The consequences of such a leak could be burns (see the Ahuachapan 2 accident in El Salvador), intoxication (see below) asphyxiation, irradiation in the case of some radioactive geothermal fluids (Hirschberg et al., 2015), a fire or an explosion in the case of certain heat transfer fluids. For geothermal or heat transfer fluids (some of which are ecotoxic), if the leak reaches the environment, it can contaminate the soil (see the Ahuachapan 1 accident in El Salvador), a water course, the sea, the atmosphere, or even the fauna and flora.

Such leaks have already had serious consequences in confined spaces and have led to the last three fatal accidents for the entire global geothermal energy sector : in 1998, it involved H2S intoxication of a worker who entered the oil separation compartment of a geothermal installation in Japan (Kage et al., 1998) and in 2018, it was two maintenance workers at a geothermal well dedicated to collective heating in France who also died of H2S intoxication upon entering an underground area (ARIA, 2018).

3.2.4 Leakage or overflow of a surface reservoir

The MFE here involves surface installations. This concerns leaks or overflows likely to occur in storage tanks for geothermal fluid, drilling fluid, hydrocarbons (fuels, oils) or various additives present at the drilling site, or when such products are transferred for disposal from the site or for supplying the site.

The triggering mechanism may be internal in nature (sealing defect of the storage reservoir) or external (flood or exceptional rainfall leading to the overflow of half-buried reservoirs).

The consequences of such an event could be the pollution of the soil, subsoil, aquifers, and/or the hydrographic network (Hervé, 2009, Bézèlgues-Courtade et al., 2012, Cuenot, 2012). However, while this type of event was frequently reported in the domains of civil engineering or industrial installations, no mention of it was found in the literature related to geothermal energy.

3.3 Potential contamination of the underground environment

3.3.1 Seepage of fluid into an aquifer

The MFE here concerns the seepage of fluid (drilling fluid, test fluid or geothermal fluid) into a shallow aquifer that is used or is potentially usable for purposes other than deep geothermal energy: production of drinking water, irrigation, industrial needs, surface geothermal energy, etc.

The triggering mechanisms depend on the phase in the life cycle of the geothermal installation, but mostly occur during the phases of testing or exploitation as a result of a defect in the lateral sealing of the well (ruptured or perforated casing). They can also occur in the post abandonment phase if there's a combination of a defect in the longitudinal (ring cementation or one or more plugs) and lateral (one or more casings) sealing of the well. The geothermal well casings are particularly exposed to the risk of corrosion, given the aggressive nature of geothermal fluid (Galin, 2000) and its temperature : during the pumping shutdown and resumption phases they can have big variations in temperature leading to thermal expansion and contraction effects that may affect the integrity of the wells (Galin 2000, Cuenot 2012, Reith et al. 2013, Bauer et al., 2015).

In Ile-de-France (France), several occurrences of casing perforation resulting from internal or external corrosion were observed during the first years of operation of the geothermal doublets. They did not systematically lead to seepage of geothermal fluid into the surrounding formations because production pumping induces depressions within the sites. However, in the case of the leakage of the geothermal well at Coulommiers (France) in 1996, a volume of 660,000 m3 of geothermal fluid spread for several months into the city's water supply aquifer without at the same time producing a measurable qualitative impact (Vernoux et al., 2012).

3.3.2 Connecting aquifers

The MFE here is the accidental connecting of several aquifer levels containing water bodies of different quality and pressure through geothermal drilling.

This connecting results from a defect in the well's longitudinal sealing due to faulty ring cementation, or also to a defect in the sealing of a plug during the post abandonment phase (Galin, 2000 ; Vernoux et al., 2002 ; Kaya et al., 2011 ; Ecorem, 2011 ; Bézèlgues-Courtade et al., 2012 ; Reith et al., 2013 ; Bauer et al., 2015).

Its main consequence is contamination of the receiving aquifer. One can also observe the dissolution or swelling of certain geological formations that are sensitive to water (chalk, limestone, salt, gypsum, anhydrite) because of the introduction of a fluid in physicochemical imbalance with certain rocks: this could then induce ground movements.

3.4 Felt seismic shocks

3.4.1 Feared event

Just like other numerous human activities liable to induce changes in underground stresses (exploitation of hydrocarbons, underground storage, mines, dams, etc.), deep geothermal energy can cause earthquakes and microearthquakes. The latter, while more numerous, are generally of magnitude less than 2 and are not felt at the surface. The MFE here is the occurrence of earthquakes felt at the surface that may upset the local population or cause damage to buildings.In addition, large magnitude events may not only cause surface damage but also reduce the permeability of the reservoir. Indeed, if a large magnitude event occurs it might create a preferential pathway for fluids, preventing efficient heat transfer (Zang et al. 2014).

3.4.2 Triggering mechanisms and scenarios

During the drilling phase, it may be necessary to increase the sludge pressure to control the penetration of deep fluid, possibly exceeding the resistance of the rock. This phenomenon is the source of the Saint Gall 2013 earthquake where an injection of heavy sludge under high pressure to control a gas kick at a depth of 4,500 m induced a seismic event of magnitude 3.6 that was felt by the population. In the wake of this, 120 cases of damage were reported and the project had to be abandoned.

During test phase, the risk of an excessive increase in pore pressure is more frequent during hydraulic stimulation operations (Lopez and Millot, 2008; Ecorem, 2011; Kaya et al., 2011; BRGM, 2016; Cuenot, 2012; Reith et al., 2013). For example, the following occurred:

- at Soultz-sous-Forêts in France where 9 earthquakes reached or exceeded magnitude 2 (maximum 2.3 in 2005) out a total of almost 45,000 microseismic events (ESG, 2015);
- at Basel in Switzerland in 2006 (magnitude 3.4), which led to the project being shut down;
- at Cooper Basin in Australia with more than 45,000 microseismic events between 2003 and 2012 where magnitudes peaked at 3.7 (Baish and Vörös, 2010);
- at Landau in Germany (magnitude 2.7 in 2009) and at Insheim (magnitude 2.4 in 2010) (Groos et al, 2013).

The Pohang case (South Korea) remains controversial. An earthquake of magnitude 5.4 caused many injuries and much damage in the town of Pohang, located near a geothermal well being tested. This is nevertheless a naturally active zone with historical earthquakes of magnitude 7 (Grigoli et al., 2018). This event reignited the debate in the scientific community regarding the risks of triggering earthquakes in areas where the natural state of stress in relation to the tectonic context is critical (Majer et al., 2007; Ungemach, 2002; Rivas et al., 2005; Evans et al., 2012).

During the operating phase, the excessive reinjection pressure of geothermal fluid is the primary mechanism for creating earthquakes (Webb et al., 1984). That was demonstrated at Soultz-sous-Forêts (Cuenot, 2012; ESG, 2015) and at Landau where magnitude 2.4 and 2.7 seismic events occurred two years after the start of operations (Agemar et al., 2014). Excessive cooling of the rock can also be a source of seismic events, by inducing a phenomenon of thermal fracturing (Lopez and Millot, 2008; Agemar et al., 2014). This is particularly clear in the case of The Geysers (California, USA) where the reinjection of the cooled fluid is done without overpressure (NAS, 2013) but where the induced thermomechanical stresses lead to a dozen earthquakes per year with a maximum magnitude of about 3 (Martinez-Garzón et al., 2015; Convertito et al., 2015).

3.5 Potential disorders at the surface

3.5.1 Uplifting of the land surface

This MFE results mainly from the swelling of an underground formation sensitive to water (anhydrite, swelling clay) following accidental seepage of water. This has been mentioned in the context of surface geothermal energy (Lochwiller in France, Staufen in Germany), with serious consequences for buildings, but only once in the case of deep geothermal energy where the conditions for drilling are stricter : at the Landau site (Germany) where multi-centimetre uplifting could result from water seeping into a clay formation (Braun, 2014; Heimlich et al., 2015).

Another cause of uplifting may temporarily originate from poroelastic effects induced by an excessively high flow rate or injection pressure. A piezometric dome can then be created, and temporary uplifting of the ground surface around the injection well (Lopez and Millot, 2008; Kaya et al., 2011; UCS, 2016; Bézèlgues-Courtade et al., 2012; Bauer et al., 2015). This has been described at Imperial Valley (California, USA) by Sanyal et al. (1995).

3.5.2 Subsidence or lowering of the land surface

This MFE occurs mainly during operations, potentially in response to various distinct mechanisms : excessive drawdown of the aquifer (Mendrinos and Karytsas, 2006 ; Lopez and Millot, 2008 ; Kaya et al., 2011 ; UCS, 2016 ; Bézèlgues-Courtade et al., 2012 ; Bauer et al., 2015), loss of material by hydraulic extraction (Lopez and Millot 2008, Seibt and Wolfgramm 2008, Sanyal et al., 2015), dissolution of an evaporitic formation or incomplete reinjection of geothermal fluid (Webb et al., 1984 ; Mendrinos and Karytsas, 2006 ; Hervé, 2009 ; Kaya et al., 2011 ; Cuenot, 2012). It is this last mechanism which induces the strongest impacts when reinjection is incomplete (Berrizbeitia, 2014) such as at Brady Hot Springs (Nevada, USA) where the subsidence rate is a few centimetres per year (Oppliger et al., 2006, Ali et al., 2014), or when reinjection is impossible as is the case with the geothermal fields at The Geysers in California (Mossop et al., 1997), Hatchobaru 2 in Japan (Nishijima et al., 2005), Larderello in Italy (Maréchal et al., 2008) or Wairakei, in New Zealand (Allis, 2000). In this last case, cumulative subsidence has attained 14 m at the centre of the basin, cracking the land and the linear infrastructures (pipelines, roads, drains ...). This phenomenon has been attributed to the slow compaction of lacustrine clay sediments present at depths of about 100 to 200 m.

3.5.3 Landslides

The MFE considered here is rare: it is the risk of triggering a landslide likely to reach a geothermal drilling site or to have been caused as a result of geothermal operations.

Several geothermal sites are in fact located in mountainous regions, conducive to this type of ground movement. The accidentology documents three accidents of this type and Hirschberg et al. (2015) report that, in the past, landslides have occurred near geothermal sites but that a cause and effect relationship should have been clearly established. It is thus possible that certain geothermal drilling operations could have interacted with surface discontinuities (faults, sliding interfaces) thus triggering or facilitating ground movement.

The accident that occurred in 1991 at the Zunil 1 drilling site (Guatemala) resulted from a big landslide that broke the casing of a geothermal well leading to a massive blowout. There were 23 deaths, most victims having been buried by the landslide.

4. A FOCUS ON THE SEISMIC RISK RELATED TO GEO-INDUSTRIES

4.1 Comparison between different types of anthropogenic seismicity

All subsurface industries or " geo-industries " are liable to generate seismicity, insofar as the natural balance of the subsoil is disturbed. However, the number of cases is low compared to the total number of these types of projects in existence worldwide: the digging of tunnels, the drilling of wells (hydrocarbons, shale gas, deep geothermal energy), extracting water (mining industry), filling large dams, etc. A summary report created by Ineris on anthropogenic seismicity (Contrucci and Klein, 2018) shows that the magnitudes measured are located mainly between 2 and 5 for all activities combined. The cases involving the filling of dams and extraction of hydrocarbons correspond to the highest magnitudes, higher than 6 : the first example is the dam at Zipingpu in the Sichuan region of China (Chen, 2009) which may have triggered an earthquake of magnitude 7.9 the origin of which is still disputed and, for the second, the operations in the gas field at Gazli, in Uzbekistan, with an earthquake of magnitude 7.3 occurring, nonetheless, in an aseismic area (Simpson and Leith, 1985). In the 5 to 6 range of magnitudes, besides the hydro-electric dam cases, one finds water extractions (the Lorca earthquake in Spain with magnitude 5.1, Gonzalez et al. (2012)) and salt dissolution works (the Attica earthquake in New York, USA with magnitude 5.2, Nicholson and Wesson (1992)). Deep geothermal drilling generally induces moderate maximum magnitudes, mostly in the 2 to 3 range, except for the 2017 Pohang earthquake (magnitude 5.5), the origin of which is still disputed but which does seem to have been triggered by geothermal drilling. They are on average less severe than the earthquakes induced by mining or post-mining activity. In general, the greater the scale of the industrial operations be carried out and the larger the area or volume they occupy, the greater the probability of triggering a large magnitude earthquake if local tectonic conditions are conducive (McGarr et al., 2002).

4.2 Origin of induced and triggered seismicity from geoindustry

Shear along fault planes is the most common source mechanism for earthquakes. In accordance with the Coulomb failure criterion, the shear stress (τ) required to initiate rupture is expressed as follows:

$$\tau = \tau_0 + \mu(\sigma_n - p) \quad 1$$

Where τ_0 is the cohesive strength, μ is the coefficient of friction, σ_n the normal stress applied on the fault and p the pore pressure in the fault zone.

Following Equation 1, an earthquake can be triggered because of shear stress increase (τ), or because of strength reduction due to a decrease in the normal stress (σ_n) or an increase of pore pressure (p) (e.g. Ellsworth, 2013; McGarr et al., 2002). Fluid-induced seismicity, as in the case of geothermal projects, is mainly controlled by pore pressure increase which enhances the activation of prestressed faults, releasing a fraction of the tectonic stress accumulated (Majer et al., 2007). Pore pressure increase can also be responsible for aseismic creep along faults, which in turn generates shear stress concentration within seismic asperities inducing seismicity when their strength is exceeded. This latter mechanism has been recognised by Bourouis and Bernard (2007) at the geothermal site of Soultz-sous-Forêts where repeating earthquakes with similar waveforms have been observed during a water-injection experiment. Seismic repeaters have been interpreted by the authors as the repetitive rupture of the same seismic asperities brought to failure due to aseismic creep around them. In addition to pore pressure, another mechanism triggering seismicity in geothermal fields is linked with the decrease of reservoir temperature due to heat transfer from the hot reservoir rock to the cold injected fluid. Thermoelastic strains, which cause contraction of fracture surfaces, have the effect of reducing the static friction, triggering slip (i.e. seismicity) along fractures (Majer et al., 2007).

Independently from the mechanism involved in the rupture process, two types of seismicity can generally be observed (e.g. Dham et al., 2013; Shapiro et al., 2013): the first, referred as induced, is the seismicity directly linked with stress changes caused by geothermal operations, whereas the second, called triggered seismicity, is associated with movements along favourably orientated faults. In the first case, the entire rupture process, including its size and not only its nucleation, is driven by human-induced stresses. Therefore, these events would not have occurred naturally. On the contrary, in triggered seismicity tectonic stress plays a primary role and human activities only contribute for a small fraction of the stress change (Grigoli et al., 2018). Triggered events occur along faults prone to failure, such that even small stress perturbation caused by human activities can be sufficient for triggering seismicity (Dahm et al., 2013). Therefore, triggered events can present larger magnitudes compared to induced ones, as their size is driven by the fault dimension and by the amount of elastic strain energy accumulated on the fault. Despite this differentiation being widely recognised in the scientific literature, it remains extremely challenging to distinguish between these two types of seismicity (e.g. Grigoli et al., 2018). In this paper we will not make any distinction between triggered and induced events and the word induced, when not specified any differently, will be used as a general term for both types of seismicity.

4.3 Characteristics of geothermal-induced seismicity

Seismicity induced by geothermal projects is generally characterised by small magnitude events ($M < 2$) not felt at the surface and generally referred as microseismic activity (e.g. Evans et al., 2012; Zang et al., 2014). However, as demonstrated by the case studies documented in this paper (Table 1), larger magnitude events can occur.

Despite significant improvements made in the last decades to understand the mechanisms driving fluid-induced seismicity, it remains difficult to prevent and control the occurrence of larger magnitude events. This is because induced seismicity is driven by many different factors, not only related to the industrial process (e.g. injection/extraction rate, reservoir depth, injection pressure, etc.), but also linked with the geological and tectonic setting of the site. For this reason, even taking geothermal plants with similar characteristics, the severity of the induced seismicity can be different from one project to another. In this context, in order to improve seismic hazard assessment and to minimise associated risks, it is important to investigate and identify factors influencing the seismic response and its characteristics at different geothermal sites.

Correlations between induced seismicity and injected volumes have long been investigated. McGarr (2014) stated that, using specific assumptions, the maximum magnitude of fluid-induced seismic events depends almost entirely on the total injected volume. Similarly, based on pressure diffusion theory, Shapiro et al (2007), showed the proportionality between the total number of induced seismic events and the injected fluid volume. Based on these works, it can be stated that the probability of a large magnitude event increases with injected volumes. However, when comparing different projects, no apparent correlation can be found between maximum magnitude and injected volumes, as regional differences and site-specific factors exist which do not allow determination of a general rule that is applicable to the whole world (McClure and Horne, 2014; Zang et al., 2014).

According to several studies, in addition to the amount of injected volumes, the presence of faults within or close to the geothermal reservoir seems to be a distinguishing factor in the generation of large magnitude events. McClure and Horne (2014) compared six geothermal projects where hydraulic stimulation was performed in granitic rock. Despite the similarities in the injection procedures, in terms of volumes and flow rates of the water injected, seismicity was found to be significantly greater at sites where the degree of fault development is high. Similar conclusions have been addressed by Baisch and Vörös (2010) who compared characteristics of induced seismicity observed at the geothermal sites of Basel, Soultz-sous-Forêts and Cooper Basin. The authors demonstrated that the spatial distribution of the induced seismicity primarily aligns along large-scale pre-existing faults. Therefore, large or damaging events seem to be unlikely to occur in the absence of developed fault systems. However, as demonstrated by Evans et al. (2012), injection near to or within fault zones does not necessarily produce larger magnitude events. This is because the fault needs to be critically stressed as well in order to be activated by injection operations. In addition, the magnitude of the resulting event will also depend on other factors, such as the fault dimension and stress and strength heterogeneity (Evans et al., 2012).

Whether injection depth can be a distinguishing factor for inducing large magnitude events is still debated. McClure and Horne (2014), found a correlation between depth and induced magnitude which was particularly evident at the Soultz-sous-Forêts site. This could be explained considering that stress and, consequently, stress drop are scaled linearly with depth. However, as stated by the authors, the great variability in seismic moments observed at the geothermal sites analysed, which varied over several orders of magnitude, cannot be solely explained by depth. Similar conclusions have been drawn by Evans et al. (2012), who suggested investigating multi-parameter rather than single-parameter correlations, by simultaneously analysing the influence of injection depth and volume injected on seismic response, for example.

By analysing data from different geothermal projects, it has been found that large magnitude events predominantly occur during shut-in period, once fluid injection has been terminated, and at larger distances from the injection well. Evidence from the geothermal sites of Soultz-sous-Forêts, Basel and Cooper Basin has clearly shown a spatiotemporal migration of induced seismicity from the vicinity of the injection well toward greater distances with increasing duration of the stimulation (Zang et al., 2014). Moreover, in the post-injection period, the vicinity of the well remains almost seismically quiet, as seismicity only occurs at the outer rim of the zone of previous seismic activity (Baisch and Vörös, 2010). Deeper analyses of the Basel seismic data showed also that induced earthquakes present a systematic size-distribution within space. More precisely, Bachmann et al. (2012) showed that events occurring later in the sequence and further from the injection well tend to have smaller b-values than the events that occurred during earlier stages and were located in the proximity of the well. Smaller b-values indicate a higher probability of inducing larger magnitude events, which is consistent with the observation of larger magnitude events occurring further from the injection well and during shut-in phase.

4.4 Assessment and mitigation of seismic risk in deep geothermal context

As previously discussed, the exploitation of deep geothermal reservoirs can be accompanied by significant magnitude events. This has led in the past to the abandon of several projects, as in the case of Basel and St-Gall (Switzerland), because of local population concerns, on the one hand, and a limited understanding of the physical processes involved, on the other hand (Wiemer et al., 2017). Dans d’autres contextes, comme Soultz-sous-Forêts (France) ou Landau (Allemagne), de nombreuses demandes d’information parfois suivies de plaintes ont été recensées mais sans conséquence majeure sur la suite du projet (Cuenot, 2012 ; RETS, 2011 ; Kulish and Glanz, 2009) : cela a conduit à modifier les protocoles expérimentaux en remplaçant par exemple des stimulations hydrauliques par des stimulations chimiques, en réduisant la pression d’injection ou en répartissant la réinjection de l’eau sur plusieurs puits. D’autre part, il a été mis en place des mesures d’information des riverains sous forme de conférences et de bulletins d’annonce des opérations en cours. However, the management of geothermal-induced seismicity is still challenging. In this framework it is fundamental to monitor and deeply analyse seismicity induced by geothermal power plants by means of dedicated, dense and high-resolution seismic networks. Indeed, the investigation of induced microseismic activity is an essential aspect for understanding the occurrence of larger magnitude events. Moreover, seismicity should be monitored along the entire life cycle of a geothermal project. Indeed, as previously discussed, induced seismicity can occur during different stages of geothermal projects (e.g. exploration, drilling, exploitation) and even many years later after operations (Ellsworth, 2013).

5. SUMMARY

5.1 Lessons learned from the accidentology

Over three decades and in about 1,700 sites, 36 accidents have been documented in the domain of deep geothermal energy of which 33 correspond to current safety conditions within the industry. The latter caused 3 deaths and 9 persons injured, plus material damage, pollution, or annoyance to residents. This is therefore a relatively low accidentology compared to that for other geo-industries (oil drilling, shale gas, underground operation...).

5.2 Comparative analysis of the risks relating to deep geothermal energy

First, a qualitative rating scale was created based on a 4-point scale (Table 2). The risks relating to deep geothermal energy were then grouped by type of MFE, according to all the life-cycle phases of a geothermal site (drilling, testing, operations, post-abandonment). A generic assessment has thus been created and is presented in Table 3. This analysis shows that the most frequent risks, which are more likely to occur during the test phases (earthquakes) or operating phases (leaks), are not the most serious in terms of physical or material damage.

Table 2. Assessment criteria for the risks relating to deep geothermal energy (Gombert et al., 2017)

Likelihood		Severity	
● (L0)	L0: scarcely plausible and never observed	■ (G0)	G0: no annoyance perceived and no significant impact on property or the environment
● (L1)	L1: unlikely with recent techniques or practices but already observed at least once	■ (G1)	G1: limited annoyance, environmental impact that is low in intensity or limited in extent
● (L2)	L2: probable over the lifespan of the system even with recent techniques and practices	■ (G2)	G2: significant annoyance, chronic health impact, non-structural damage to property, environmental impact that is significant in intensity and extent
● (L3)	L3: very probable, may even occur several times during the lifespan of the system	■ (G3)	G3: harm to the safety of persons, structural damage to property, environmental impact that is high in intensity and extent

[a] limited to the site's location or in the order of ten meters around the site, [b] which does not damage the overall integrity of buildings or infrastructures, [c] in the order of tens to hundreds of meters around the site, [d] beyond several hundreds of meters around the site

Table 3 Risks and impacts of potential accidents related to deep geothermal energy (Gombert et al., 2017)

Key: ● Likelihood ■ Severity N/A = not applicable

Event ↓	**Phase →**	**Drilling**	**Trials**	**Exploitation**	**Abandonment**
Risk of gaseous emissions or accidental effusions on the surface					
Eruption of fluids on the surface		● L1 ■ G3	● L1 ■ G3	● L0 ■ G3	*NA*
Escape/overflow at the surface		● L2 ■ G1	● L2 ■ G1	● L0 ■ G1	*NA*
Escape on the primary or secondary circuit		*NA*	*NA*	● L1 ■ G2	*NA*
Emission of dissolved gas		● L1 ■ G3	● L1 ■ G3	● L1 ■ G3	● L0 ■ G0
Risk of contamination of aquifers					
Connecting aquifers		● L1 ■ G2	● L1 ■ G2	● L1 ■ G2	● L1 ■ G2
Leakage from well into an aquifer		● L1 ■ G1	● L1 ■ G2	● L2 ■ G2	● L1 ■ G2
Risk of geomechanical surface disturbance					
Seismic shocks		● L1 ■ G2	● L2 ■ G2	● L1 ■ G1	*NA*
Uplifting of the surface of the ground		● L1 ■ G3	● L1 ■ G3	● L1 ■ G3	● L1 ■ G3
Subsidence of the surface of the ground		● L1 ■ G3	● L1 ■ G3	● L1 ■ G3	● L1 ■ G3
Landslides		● L1 ■ G3	● L0 ■ G3	● L0 ■ G3	● L0 ■ G2

[a] Using an additive approach, the classes of probability attributed to these risks take into account feedback from surface geothermal energy, as mentioned in sections 2.1 and 2.2.

6. CONCLUSION

Deep geothermal is a renewable and non-intermittent source of energy that can contribute to the global transition towards an energy mix with lower carbon and greenhouse gas emissions: only a small share of the world's geothermal potential is being exploited today and many countries, including France, have included in their objectives accelerated development of this renewable energy for the coming decades. Nevertheless, like any geoindustrial activity, deep geothermal is accompanied with potential inconveniences and possible risks for people and the environment. They must be clearly identified and controlled in order to make this industry fully compatible with the expectations and the needs of citizens, especially those living near such facilities.

The overall impression is that deep geothermal energy benefits from quite low accidentology: most of these types of accidents are not specific to deep geothermal energy and can appear in any well extraction of subsurface resources (hydrocarbons, drinking water supply, underground gas storage, etc.), but the context of geothermal energy offers conditions that are more favourable to certain types of accidents and less favourable to others. The main accident risks related with deep geothermal can be divided into 4 main themes: (1) Accidental release of surface fluids, (2) Contamination of sensitive aquifers, (3) Felt seismic events, and (4) Noticeable ground movements (upheaval or subsidence). All the risks and impacts have been summarised in a table with a qualitative rating scale for their comparison in terms of their likelihood of occurrence and the severity of their potential consequences.

Finally, it can be seen that deep geothermal energy is responsible for fewer earthquakes and, when it is the case, ones of a smaller magnitude compared to other geo-industries: hydrocarbon extraction, large-scale water extraction, filling of large dams, digging of large underground structures, mining and post-mining industries, etc. The maximum magnitude known at present is in fact 5.4 for the Pohang geothermal site (South Korea) while the earthquakes caused by the filling of the Zipingpu dam (China) or the operation of the Gazli gas field (Uzbekistan) reached magnitudes of 7.9 and 7.3, respectively.

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