Relevance of Seismic Risk Assessment in Abandoned Mining Districts : the Case of the Gardanne Coal Mine, Provence, France

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Abstract

Mining shutdowns have increased significantly in last century, but seismic risk in post- mining districts and consequent damage from ground shaking is still poorly understood. Large induced seismic events with M > 5 are known from active mining districts. Their origin is widely directly linked to stress perturbations related to mining activity. In post-mining districts, especially when they are flooded, the bandwidth of potential seismic source origins is comparatively large and has been observed in the context of partial underground collapses, fluid induced redistribution of the environmental stresses, and reactivation of pre-existing fault structures next to the mining district. The estimation of the associated seismic hazard is quite challenging, depending on many complexly interacting factors, such as the mine geometry and geological constitution, its long-term alteration behaviour (modified by the presence of fluids), meteorological impacts and climate changes, triggering from regional or global natural earthquakes, and the presence of pre-existing fault structures and tectonic stresses.

Such challenges are today encountered in the case of the underground flooded, abandoned coal mine at Gardanne in the Provence region (in SE France). Local microseismic monitoring highlights the presence of significant periodic seismic swarming activity, including events of magnitudes close to 2 which have been several times felt by the nearby living population. Seismic analysis demonstrates that most of the events appear to be located below the excavated, flooded mine workings and seems to be spatially and temporally correlated with the flooding evolution, controlled by meteorological conditions and active pumping operations. Results from source mechanism analysis showed that swarming activity is probably related to rupture along a network of pre-existing fault structures, which are favourably oriented with respect to the local tectonic stress field. Based on these observations, we suggest that some mine workings (especially room and pillar) act as a very efficient "anthropogenic" aquifer, whose water level fluctuations trigger reactivation of these faults, e.g. via a poroelastic effect or pore pressure increase. The nature of the detailed triggering mechanism remains however speculative and is part of currently ongoing investigations. This example shows the necessity and relevance of the understanding of this mechanism in order to reason if variations of the mine water level might potentially trigger larger local tectonic events, as recorded in the past (Mw 3.6, 1984), or simply episodes of swarm activity associated to small transient creep. In the light of these developments, seismic hazard analysis in post-mining risk assessment, which is non-standard today, could be assessed.

Keywords: *Flooded post-mining, seismic risk, microseismic and hydrological monitoring, source analysis*

1 Introduction

The closure of mines may pose significant environmental problems related to ground and surface stability. These problems can affect public safety and the sustainable development of mining regions. When mines are abandoned, ground water pumping is usually stopped, such that water floods residual voids. Such water intrusion may affect the mechanical stability of the underground structures and perturb the local state of stress sometimes leading to different forms of mine collapses. In France, these events have been a great concern for the population of the Lorraine region (France) after the closure of iron mines in the 90's (Didier, 2008). Surface subsidence due to mine collapses reached two meters in some places and more than five hundred buildings have been damaged due to these disorders.

In contrast to such well known static deformation phenomena, the potential seismic risk in flooded, post-mining districts and consequent damage from ground shaking is poorly understood. Large seismic events with M > 5 are known from active mining districts. These events are often directly induced by mining activity and thus, could be in some cases anticipated from local seismic monitoring. In flooded post-mining districts, seismic events have been observed in the context of partial underground collapses, fluid induced redistribution of the environmental stresses, and the reactivation of pre-existing fault structures next to the mining district (e. g. Miller, et al., 1988; Miller, et al., 1989; Ogasawara, et al., 2002; Goldbach, 2009; Srinivasan, et al., 2000; Senfaute, et al., 2008; Wetmiller, et al., 1993; Dominique, et al 2012). The estimation of the associated seismic risk is quite challenging, depending on many complexly interacting factors, such as the mine geometry and geological constitution, its long-term alteration behaviour (modified by the presence of fluids), meteorological impacts and climate changes, triggering from regional or global natural earthquakes, and the presence of pre-existing fault structures and tectonic stresses.

Such a degree in complexity is today encountered at the abandoned and flooded Gardanne coal mine in the Provence region in SE France, where close living habitants frequently feel seismic ground motions. With this case study, we would like to attract attention to the need of further developments and progress in knowledge of proper seismic hazard and risk assessment in post-mining management.

1.1 Gardanne mine: flooding history and seismicity

The Gardanne coal mine basin has been exploited for over more than a century and was finally shutdown in 2000. Main parts of the exploited lignite deposit occurred in the so called Grande-Mine (GM) layer, dipping from the East to the West, covering an area of more than 100 km^2(Figure 1). A wide area has been exploited by room and pillar technique between50 m and 700 m depth, which has left residual, potentially unstable voids with possible surface impact. A residual zonation was obtained (by GEODERIS), distinguishing zones of low hazard (subsidence, eventual limited damage to buildings), generally located westward beyond 250 m depth, and areas of surface subsidence collapse hazard located generally to the East in areas where the exploited layer extends up to 250 m (Figure 1).

Associated risk zones have been monitored in real time since 2008 by a network of 5 seismic stations (boreholes equipped with4.5 Hz–40 Hz geophones from 2m to 250 m depth) installed by the CENARIS (National Monitoring Center created by Ineris; http://cenaris.ineris.fr) at the request of the BRGM-DPSM (Figure 1). With the cessation of mine water pumping in 2003, these mine workings flooded progressively from the West towards the East of the mine basin. In 2010, the flooding front reached the mining sector of Regagnas, located about 2 km West of the Fuveau monitoring station (located at the NE of the basin), what coincided with the birth of a spatially concentrated periodic seismic activity called the "Fuveau swarm". A total of more than 1,500 seismic events have been since recorded from the monitoring network, which mainly occurred in form crisis, notably in 2010, 2012, 2014, 2016 and lately in 2017 (Figure 2). Largest events reached local magnitudes close to almost 2 (regional SiSMOAZUR network) and have been significantly felt by local population. Seismic activity seems to be generally linked to water level variation in the mine working controlled from seasonal rain fall and active pumping at the Gerard well towards the Mediterranean Sea via an old mining gallery (Galerie de la mer, Figure 1). Most of the seismic crisis appeared in rather wet periods associated with significant rainfall events, as demonstrated by a good first order correlation of shallow aquifer level recorded at the Fuveau Rognacian well at 7m depth and the number of recorded seismic events (Figure 1 and 2). In contrast, a seismic crisis has been recently observed during a dry period in August 2017, indicating that water level changes and rainfall are probably not the only determining factor generating seismic activity (Figure 2). Unfortunately, today there are no in-situ measurements of the mining water level available in the seismic active area allowing to precisely understand in detail the link to seismicity.

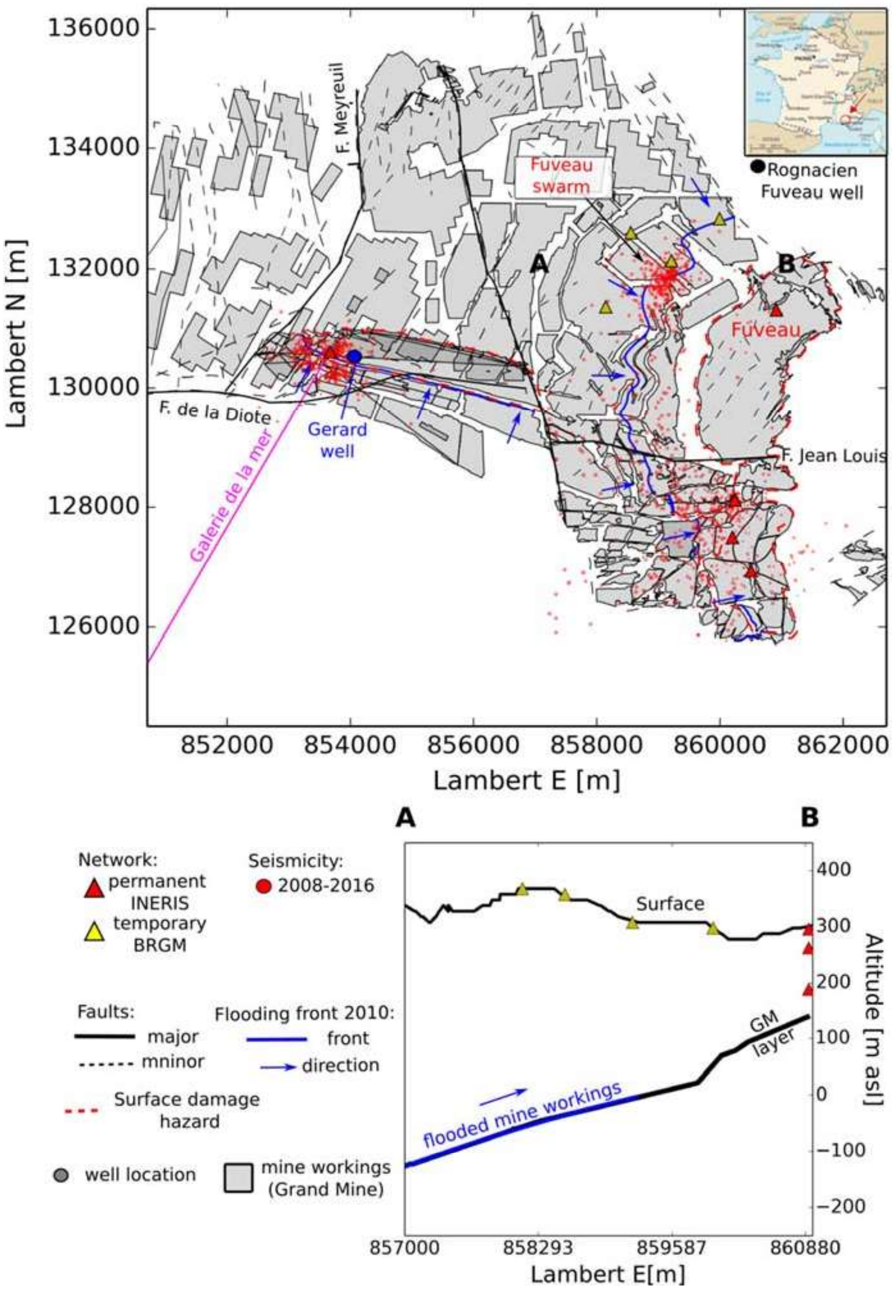

Figure 1 Microseismic monitoring of the Gardanne coal basin. The flooding front (blue lines) at the level of the mine workings (gray polygons) progressed from west to east, towards the center of the basin and was accompanied by microseismic events recorded by the permanent network (red triangles) from 2008 to 2016. The flooding front is represented by the intersection of the mine workings with the water level (-10 m asl) measured at the beginning of 2010 at the Gerard well (gray circle). The set of faults is taken from Gaviglio (1980). Permanent Ineris network, installed in 2008, is composed of high-frequency (4.5 Hz and 40 Hz) geophones (red triangles) installed in boreholes. Temporary BRGM network, installed in 2013, (yellow triangles) is composed by 3-component of 1 Hz accelerometers.

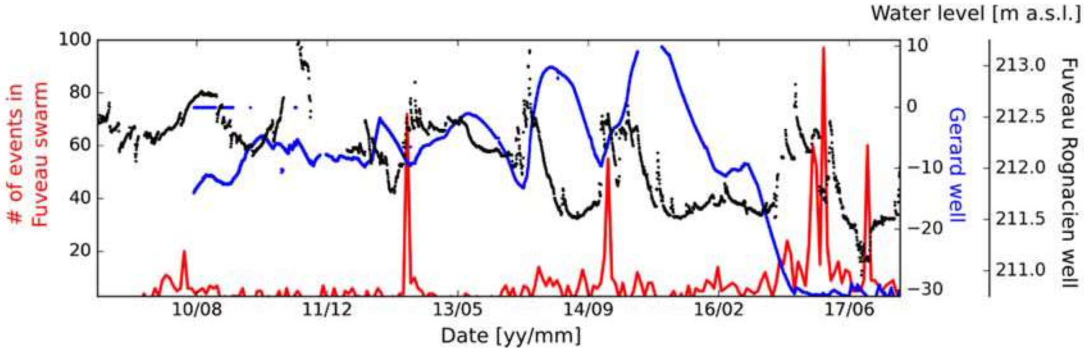

Figure 2 **Seismicity (red curve) and water level changes recorded at the Gerard well (blue curve), connected to the Grande Mine layer at the west of the basin and the Fuveau Rognacian well (black curve) reaching 7 m depth**

2 Seismic source analysis

2.1 General characteristics from 2010-2016

Based on the data from the permanent monitoring station Fuveau (Figure 1), we estimated moment magnitudes for strongest events by using Brune's model (Brune, 1970) and source spectral fit method (e.g. Kinscher, 2015) which ranged between 0.6 to 1.4 (Figure 3). Magnitudes for smaller events do not respect Bath's law (Bath, 1965) indicating absence of typical main shock-aftershock sequences as known from natural earthquakes, which is typical for seismic swarms (Malone et al. 1975; Mogi 1963). Seismic wave forms for strongest events do not show similarities indicating significant differences in source location and mechanism. In addition, partially events represent multi shock (Figure 3b) and double shock (Figure 3a) signature (multiple superposed P and S wave phases) indicating complexities in the rupture mechanism.

Although waveforms for strongest events are not alike, almost every event is associated with "multiplet" occurrences, i.e. events of lower magnitudes with very similar waveforms. Multiplets have been observed in many contexts, tectonic (Poupinet, et al., 1984; Augliera, et al., 1995), volcanic (Lees, 1998), geothermal (Moriya, et al., 2002), mining (Maisons, et al., 1997; Gibowicz, 2006), or during fluid injections (Baisch& Harjes, 2003) and are generally indicative for multiple stress release on the same seismogenic structure (fault) (Geller & Mueller, 1980, Poupinet, et al., 1984, Moriya, et al., 2002). An example of a multiplet is shown in Figure 4. These events are associated with the Mw 0.9 event of the 28th of July 2012 shown in Figure 3. The events corresponding to this multiplet group appeared over almost the entire duration of the Fuveau swarm from 2011 to 2016. The origin of this multiplet family is likely related to a fault segment, which ruptured gradually over a period of approximately 5 years.

2.2 Detailed source analysis for the 2014 crisis

Seismic sources have been analysed more in detail in terms of location, source mechanism and source parameters for events recorded during the seismic crisis in December 2014 by a temporary network installed by the BRGM in 2013 (Dominique 2015, Figure 1 and 5). Locations have been refined for a total of 140 events, recorded between 1st and 28th of December 2014 using double difference based relocation technique (Matrullo, 2015). Location results outlined a microseismic cloud in the southern part of Regagnas sector with a NW-SE alignment (Figure 5), being consistent with the orientation of the geological faults and mining sector. The depth of these events varies between 500 m and 900 m with an average of 700 m. The average depth of 700 m lies below the mine workings, which are at a depth of about 300 m (Figure 5).Sensitivity tests on the velocity model, polarization angle analysis and detailed seismogram simulation showed that source location below mine working is most probable, however, seismic event occurrences within or above the mine workings cannot be completely excluded.

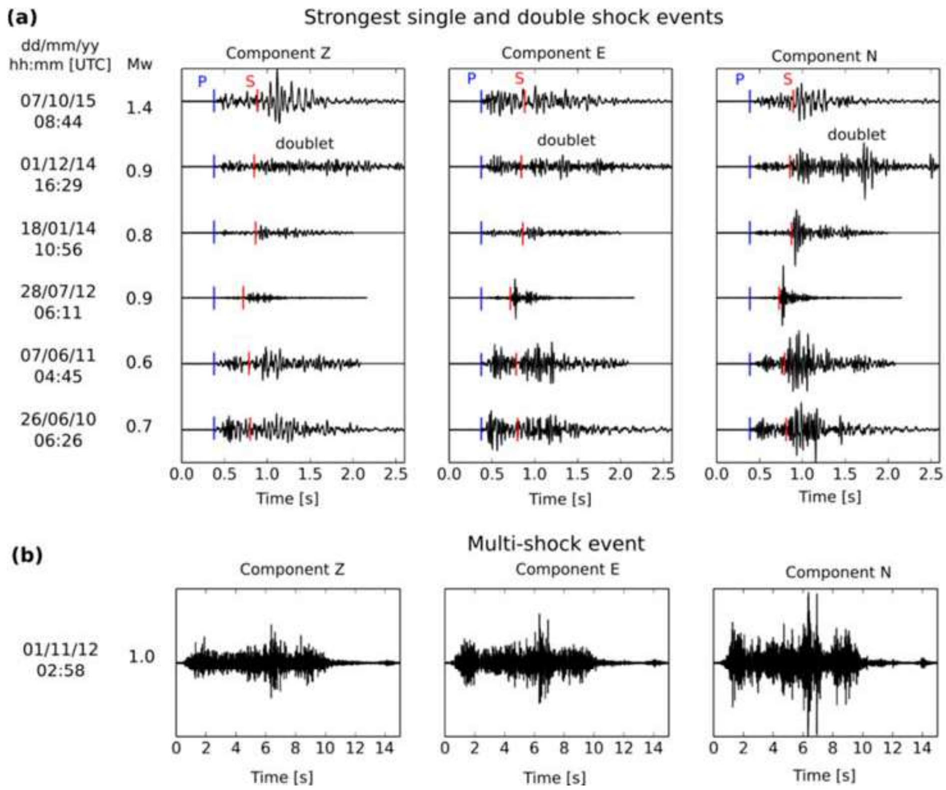

Figure 3 (a) Seismograms for the six strongest events recorded from Fuveau monitoring station between 2008 and 2016. (b) example of a multi-hock event

Source mechanisms have been investigated using a classical "double-couple" source model, representing shearing along a fault. The choice of a shear model is generally justified by the presence of multiplet families and significant fraction of SH wave energy relative to the P and SV waves (see N component in Figure 3), which is indicative for a significant shearing component in the mechanism. Two methods were used to estimate the double-couple mechanism, namely: (i) wave form inversion for the five strongest events and (ii) a composite method based on the spectral ratio of P and S waves applied to a set of 60 events with very similar wave forms and thus likely to be associated with a similar source mechanism. Both approaches followed methodology as used by Kinscher (2015) and Kinscher et al (2016). Results from both approaches demonstrated coherently convergence to a normal faulting mechanisms with main orientation N120-160 ° (NW-SE)being in agreement with pre-existing faults documented at the north of the Regagnas sector (Figure 5).

Source parameters in form of seismic moment and source radius have been determined for 60 events using a spectral fit approach (Kinscher, 2015) and Brune's models (Brune, 1970). Obtained moment magnitudes vary between -0.2 and 1.2 which is consistent with magnitudes obtained from Fuveau monitoring station. Obtained source radii vary between 10 m and 90 m.

3 Results and discussion

3.1 Origin of seismic sources

Summarizing results of the preceding chapters we conclude that:

(i) seismic activity at the Fuveau swarm is characterized by low magnitude (Mw < 1.4) events that are spatially constrained and appear in form of periodic crisis which seems to be linked to variation in the mine water level;

(ii) seismic sources seem to be mainly located below the mining works, between 400 m and 900 m depth;

(iii) the vast majority of seismic events seem to be related to rupture along NW-SE oriented normal faults, consistent with normal faults documented by in situ geological observations further north of the sector;

(iv) the characteristic size of these faults was estimated at a few tens of meters.

Results suggest that seismicity is linked to the reactivation of a network of faults, constituted by different discrete segments of small dimension (a few tens of meters). In addition, the presence of "multiplet" type events (Figure 4) indicates repetitive rupture on distinct segments partially over periods of at least 5 years. An origin of seismicity related to occurrences of disorders in the mine workings itself seems thus less likely, but cannot be totally excluded. Indeed, previous geotechnical studies suggest that the abandoned mining area is rather in a "post-collapsed" state where most of the overlying formations, composed of resistant calcareous beds, are probably widely plasticised (free of elastic energy). Nonetheless, the presence of some non-collapsed areas cannot be completely excluded as potentially able to produce significant seismic activity.

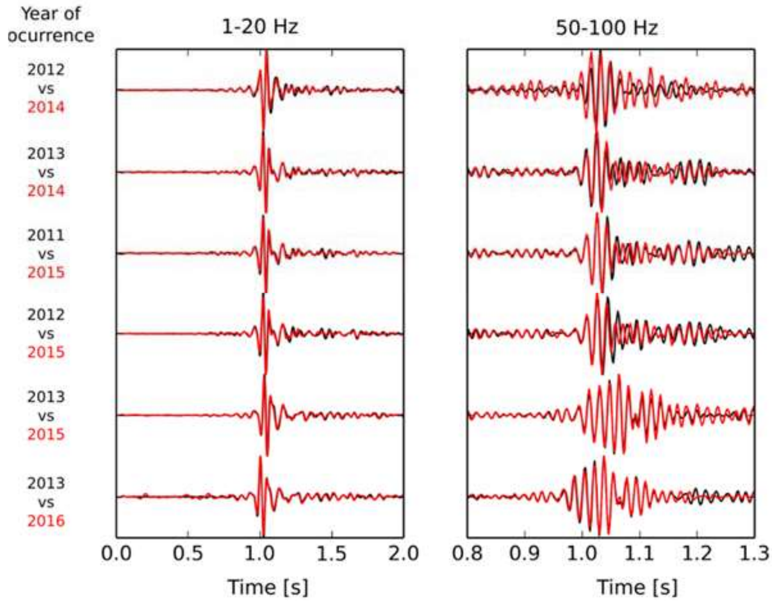

Figure 4 Normalized seismograms of multiplet group corresponding to the Mw 0.8 event of the 28th of July 2012 (Figure 3) recorded by Fuveau monitoring station.

3.2 Triggering mechanism

Next to the water level variation in the mine workings, we believe that the natural tectonic regime plays a major role in the triggering of seismicity. Indeed previous studies have shown that regional tectonic stress has played an important role in the generation of several rockburst events during the exploitation of the Gardanne coalfield(Jarlier, 1925;Josien, 1980;Gaviglio, 1985).The maximum horizontal compressive stress SH is expected to be approximately NW-SE oriented(Baroux, et al., 2001;Heidbach, et al., 2008) (Figure 5). Measurements of in situ stress at a depth of 390 m in the Sainte Victoire sector to the north of Regagnas confirm this conclusion (Gaviglio, 1985). Main horizontal stress orientation is in agreement with NW-SE normal faulting (Anderson, 1905). Hence, it seems that regional tectonic stress contributes significantly to the shear stress applied to the normal faults in the Regagnas sector, due to their favourable orientation. As a result, these faults have been possibly already close to rupture before flooding of the mine workings which finally provoked minor stress changes sufficiently high to trigger seismicity.

The interpretation of the detailed relationship between the hydrological and seismic system remains highly speculative. The difficulty of this analysis comes from the fact that hydrological measurements are not made directly in the mining sector where seismicity is observed. Interpretation from the data of the Gerard well is not feasible without having a precise knowledge of mine water circulation which seems rather complex (Chalumeau, 2000; Dheilly& Brigati, 2015). Indeed, curves between Rognacian Fuveau and the Gerard well seem to be shifted in the order of months, which might indicate complexities in the water transport from the East to the West of the mine, maybe as a result of damming effects from the backfilled mining parts (Figure 5). Furthermore, there seems to be a remarkable spatial correlation of the area marked by the minimum and maximum flooding front level which seems to clearly constrain the spatial area where seismicity is observed (Figure 5).

Hence, it seems evident that water level variation triggers seismicity; however the exact triggering mechanism remains unknown. We suggest that the temporal occurrence of seismicity is determined by an overload and depletion effect of the aquifer formed by the unfilled (room and pillar exploited) part of the Grande Mine layer during very wet/saturated and dry periods, respectively (Figure 5b-c).These hydraulic load modifications can result in two potentially seismic triggering processes either (i) by vertical loading and unloading by the water column or (ii) by an increase in pore pressures reducing the normal stress and causing slips along fault planes (e.g. McGarr, et al.2002; Bell & Nur, 1978). Apart from fault reactivation hypothesis, remobilization of already demolished area in mine workings and overburden cannot be completely excluded as seismic source origin.

3.3 Implications for seismic hazard

At this stage of the study, it is difficult to estimate the seismic hazard, which depends heavily on the precise knowledge of the triggering mechanism of the observed seismicity. Seismic hazard and the generation of larger events will mainly depend on the nature and distribution of pre-existing faults (depth, tectonic role) releasing either (i) minor stresses in form of transient tectonic creep (earthquake creep) at shallow depth or (ii) release significant tectonic stress along larger deeper structures (Johnston & Linde, 2002). Both models bear very different consequences in terms of seismic hazard.

Assuming the case of transient creep, the Fuveau swarm will be interpreted as a network of small fault segments, which react progressively to external stresses not being able to accumulate significant and sufficient stresses that would be released by a single seismic event with a magnitude much greater than the magnitudes already observed and felt. Although this model explains the vast majority of the results obtained by this study, it is not entirely compatible with the observation of an apparent increase of magnitudes of recently recorded events (October 2016 - February 2017). Increases in magnitudes may potentially indicate stress increase and/or a growth of active fault segment sizes.

The Provence region represents one of the most active seismic zones in France and has experienced a major earthquake in history (e.g. Lambesc earthquake, 1909, Mw = 5.7). Also, the Gardanne region is known for moderate earthquakes, e.g. Ml 3.5 in April 1969, Ml 3.0 in October 1973 and the Ml 3.6 (Io = VI) Mimet event of the 19thof February in 1984 (Haessler, et al., 1984), which indicates the presence of an active fault segment being in the order of one kilometer long. Exact fault location and mechanism of this event are highly uncertain as demonstrated by fairly ambiguous previous results (Haessler, et al., 1984; Nicolas et al., 1990, Figure 5). So location of larger structures are not very well known, which implies significant uncertainties for seismic hazard assessment. Also rupture events along well known main fault structures as the Diote and the Meyreuil fault (several km long) have clearly the potential to generate larger events as already observed.

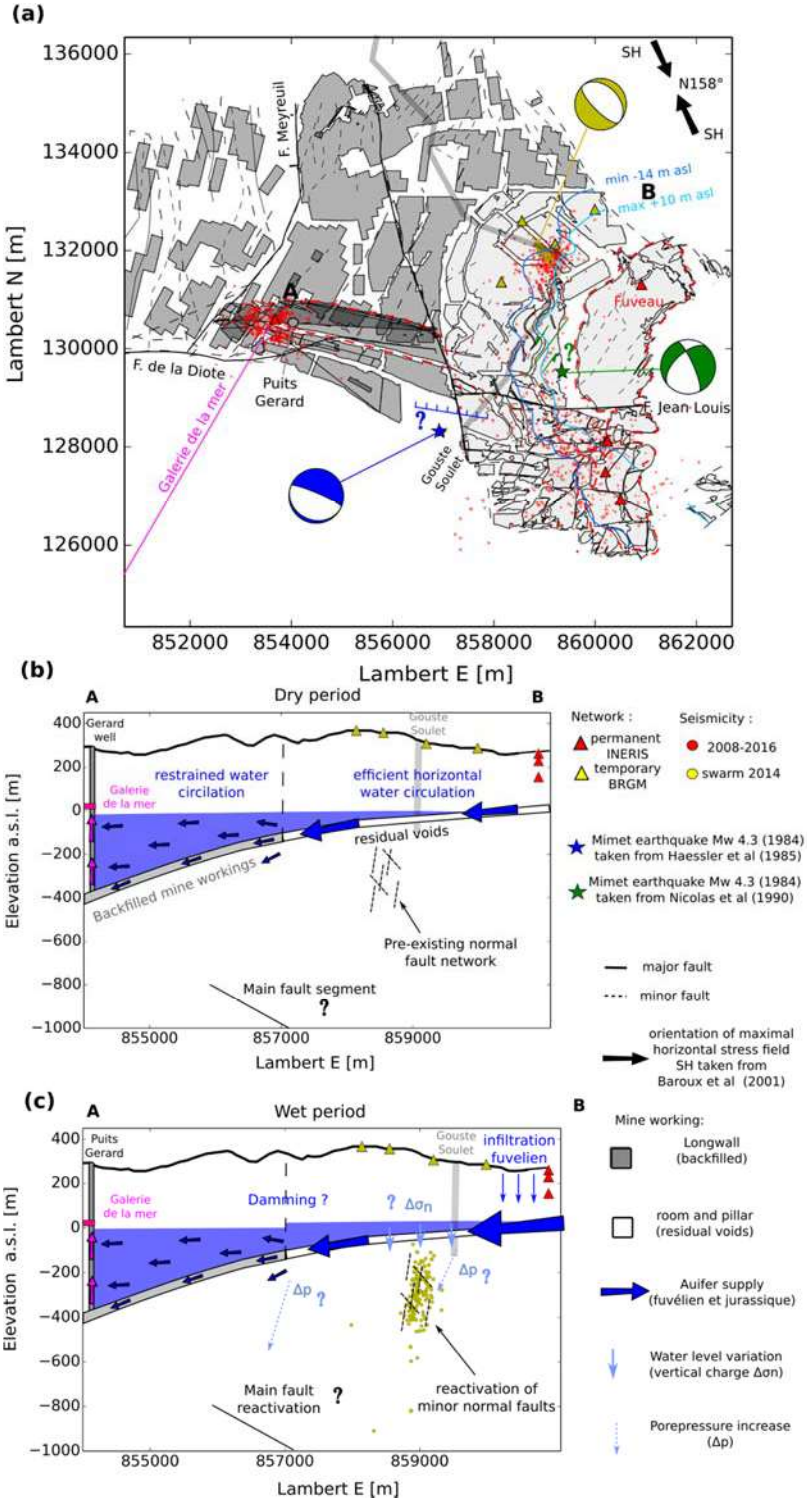

Figure 5 Synthesis of data (a) and final model (b) - (c), describing the origin of recorded seismicity. The dominant normal fault source mechanisms is shown for the Fuveau swarm (yellow beachball) and two different mechanisms and locations proposed for the Mimet Mw3.6 earthquake in 1984 by Nicolas et al., (1990) (green beachball) and Haessler et al (1985) (blue beachball), as well as their tectonic interpretations (green arrows and blue lines respectively). The regional stress measurements, represented by the maximum horizontal stress SH (black arrows) adapted from Baroux et al. (2001). The flooding fronts is approximated and are represented by the intersections of the mine workings with the minimum water level (-14 m asl) and maximum water level (10 m asl) measured since 2010 at the Gérard well (gray circle).

4 Conclusion

During monitoring in the Provence region at Gardanne (in SE France), we experience the high degree of complexity in which an abandoned, flooded mine can interact with its local tectonic setting. In this case, excessive and long-term excavation has led to the formation of very efficient “anthropogenic” aquifer which, especially in wet periods seems to modify the local state of stress, resulting in induced seismicity. The modification of the hydrogeological system seems to be the today’s cause of significant seismic swarming activity, including local magnitudes close to 2 that have been several times felt by the nearby living population. Seismic source analysis suggests that swarming activity is related to the reactivation of minor fault segments being favourably oriented with respect to the local tectonic stress field. However, It remains still unknown if the meteorologically and active “anthropogenic” pumping operations controlled variations of the mine water level, might potentially trigger larger local tectonic events, as recorded in the past (Mw 3.6, 1984), or if swarming represents simply episodes of small transient creep. Further seismic and hydrological measuring campaigns and investigations are planned to understand in detail the triggering mechanisms, evaluate potential reactivation of larger fault segments and to exclude presence of other potential source origins located within and above the mine layer. This study case clearly underlines the importance of seismic hazard assessment studies (ground motion hazard) in flooded post-mining regions which are today mostly not taken into account in local risk analysis.

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