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International Journal of Coal Science & Technology (2022) 9:90
https://doi.org/10.1007/s40789-022-00558-1

RESEARCH

Impact of past mining on public safety: seismicity in area of flooded abandoned coal Gardanne mine, France

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Received: 29 March 2022 / Accepted: 21 October 2022

Abstract
This paper focuses on the impact of past mining on public safety. It emphasizes the need to understand the induced seismic hazard and consequently improve the post-mining management procedures and legislations, as many mining sites are located in proximity to populated areas. Due to many challenges and complexity of the post-mining environments, induced seismic hazard nowadays remains largely unknown. However, the return experience of several post-mining sites in recent decades have shown us that the mine flooding and/or degradation of mining works can lead to the stress perturbations, inducing the seismicity and the reactivation of the surrounding geological faults. Hence, it is important to advance the seismic monitoring and research of seismicity in flooded post-mining districts. As the number of mine closures worldwide is rising, it can be expected that flooding induced reactivation of the surrounding faults becomes a more often observed phenomenon. We present in this paper the experience of the abandoned flooded coal mine of Gardanne in France, which has been experiencing post-mining seismicity problems since its closure in 2010. We show the results of a recent study of seismic multiplets and clustering of seismic events, as well as their spatio-temporal activity compared to meteorological conditions. These results provide us new insights as well as lead to raising new questions on seismic sources and triggering mechanisms.

Keywords Post-mining seismicity · Seismic origin · Seismic hazard · Multiplets · Clusters

1 Introduction

Historically, mining has had a significant role in the industrial and economic development of many countries worldwide. As the number of mine closures is on the rise in recent decades, and the evidence of its impacts and threats to the environment and public safety have been emerging consequently, more and more countries have been establishing legal frameworks for the mine closures. Several major potential environmental and safety issues that have been recognized so far include ground instability problems, the changes of circulation of the underground water flow, emission or discharge of potentially dangerous chemicals or toxic gases into the environment or the underground water, as well as the health hazard from the dust of old waste disposal sites (Van Zyl et al. 2002; Didier et al. 2008). The potential for the manifestation of each of these phenomena is specific to a mining site.

The seismic hazard however is a poorly known hazard in flooded post-mining districts, and therefore usually non-considered in post-mining management procedures. It is related to dynamic ground motions generated by seismic waves emitted from induced seismic sources. In post-mining environments, seismic events are expected to be of smaller magnitude than natural events (typically magnitudes lower than 4), but due to the shallow depth of the source, their impact on the surface may be more intense and represent safety issues in populated areas. On contrary to the seismicity which has been attributed to the mining production processes since the early twentieth century,(Simons 1986; McGarr et al. 2002) and whose mechanisms are generally well known, in post-mining environments, seismicity mechanisms are still not very well researched. They are generally seen to be similar to those observed in active mining regions, but the knowledge and classification cannot be applied entirely. In active mining, seismic events can be recognized as induced, if they are related to redistribution of stresses in the proximity of created voids in the rockmass

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Published online: 03 December 2022

(often in form of the creation of fractures, rupture of pillars, roof falls or rock mass failure), or as triggered, if they are related to the reactivation of critically stressed preexisting faults (Gibowicz 1990). In post-mining environments, we can recognize two main differences (Namjesnik 2021 and references therein):

(1) Induced seismicity in post-mining cases does not result from active excavation, but rather from the degradation of abandoned mine workings leading to failures, due to a combination of factors such as weakening of mechanical properties of rock, the influence of environmental factors such as flooding, decreasing stability of pillars depending on their design and extracted rock volume etc. (e.g., F.T. Lee and F. Abel Jr. 1983; Didier 2008; Schuchová & Lenart 2020). Mining failures that can potentially have a severe impact on the surface and lead to ground instabilities (such as sinkholes, collapses of underground mining works or pillar failures,), are often accompanied with the seismic activity which is hence considered as a precursory signal of potential failures.
(2) Aside from accelerating the degradation or remobilization of mine workings leading to seismicity described under 1), flooding of the mines can also lead to perturbation and redistribution of the environmental stresses around the excavations, leading to the reactivation of pre-existing fault structures or the initiation of the aseismic slip next to the mining district (e.g., Miller et al. 1988; Wetmiller et al. 1993; Goldbach 2009b; Kinscher et al. 2015). Stress perturbations, although often quite small, can result in the generation of seismicity because near-failure conditions are common in both active and stable tectonic environments (Gibowicz and Lasocki 2002).

Nowadays, microseismic monitoring plays an important role in post-mining management and prevention of risk of ground instabilities, especially in the cases where mine remediation is not possible nor other options such as backfilling due to its high cost (e.g., Couffin et al. 2003; Contrucci et al. 2008, 2011, 2019; Didier et al. 2008). In France, the first tests of monitoring of precursory seismic signals were implemented in Lorraine iron basin by Ineris (Bennani et al. 2003 and references within), after the occurrences of mining collapses following the iron mines closures in the 90 s. Generally, seismic monitoring can be challenging to set up due to difficulties to prioritize monitoring zones in the case of large mining areas. This is especially the case for the older mines for which data with precise details about the mining have been lost with time.

As opposed to the monitoring of seismicity as a precursory signal in areas recognized to have the risk of mining failures, the potential for fluid-induced seismicity due to reactivation of faults in areas close to the flooded mining works is usually not part of post-mining management procedures. Even though it is monitored, seismicity itself has not been recognized as a potential safety issue.

In general, estimation of induced seismic hazard in the post-mining period is a challenging task. As mentioned priorly, this hazard can be related to earthquakes seismic events that accompany the underground collapses or result from the reactivation of pre-existing fault structures next to the mining district. Each case carries different consequences regarding the potential maximum magnitude of events and duration of seismic activity, hence seismic hazard is not the same. In the case of seismicity connected to mining collapses, we can expect usually smaller magnitude events and reduction of seismic activity after collapses, while the magnitude of events originating on reactivated fault depends, among others, on fault size and persistence of triggering factors.

Apart from the complexity of the mining environment which includes factors such as mine geometry, alteration and stability of the mine works, geology, hydrogeology, meteorological impact, and unknown presence of pre-existing faults structures, reasons for lack of consideration of seismic hazard in post-mining procedures is the limited number of available research studies in the literature on the subject of post-mining seismicity (e.g., Ogasawara et al. 2002; Goldbach 2009a), especially when compared to research of seismicity in active mining, or research covering other cases of anthropogenically fluid-induced seismicity (e.g., in oil and gas industry or geothermal exploration, Foulger et al. 2018). This may be related to the fact that mine abandonment and flooding has been intensified in the last 10 to 20 years, as well as to the lack of seismic monitoring in post-mining sites and hence lack of recorded seismic events. Consequently, the mechanism of seismicity in flooded mining sites is still not very well understood, and the determination of induced seismic hazard remains a mainly unconsidered task. Raising awareness of its potential impact on public safety is an important step towards the improvement of the management procedures of the mining site closures.

2 Gardanne mine

2.1 General context

In the former coal mining site in the Gardanne basin in Southeastern France, industrial exploitation lasted from the eighteenth century until the closure in 2003. The mining started at depths of a few meters (shallow mine on the east of the mining area) and progressed gradually to the west of the basin to depths of more than 1000 m. On the eastern part, the mining method that was used was rooms-and-pillars, while the modernization of the equipment with time led to switching to longwall methods with progress to the deeper parts in the west. The direction of the progress of mining works was affected by natural constraints, as well as by the flow of groundwater. As the infiltration of waters in the mining infrastructures was one of the problems miners were facing, pumping devices were installed to lower the water level sufficiently to allow the miners to work in dry and access the deeper levels.

After the mine was closed, water pumping was stopped as well. Mine was gradually flooded as the water was filling the mining voids from deeper parts on the west towards the shallower parts on the east. As a part of post-mining management procedures, zones with a high risk of ground instabilities were determined and a permanent microseismic monitoring network was established to detect early signs of damage in the mining works.

With the gradual advance of the flooding front, i.e., the rise of water levels from deeper mine in the west towards the shallower part in the east, a significant microseismicity has started appearing periodically. This seismicity was occasionally felt by the population, as the strongest events have a local magnitude close to 2. At the time, pumping of the water was restarted in the Gerard well (approximately 6 km distance to the seismically active area) and the ironized mining water is delivered to the port of Marseille. As the observed seismicity was localized outside of the determined risk zones, where mining works were assessed to be already in the post rupture state (Didier et al. 2003), this led to new concerns regarding the seismic hazard and risk. Following the period of increased seismic activity in 2012, a temporary scientific seismic monitoring network of four surface stations was installed in 2013–2014 for research purposes to study this seismicity more precisely, since the permanent monitoring network is not optimized for detecting of events in this area due to distance (Contrucci and Bennani 2013). No impact on the surface has been observed in post mining period that would indicate collapses of underground mining works. Figure 1 shows the mining site, monitoring networks, direction of progress of flooding front, seismic activity recorded by permanent monitoring network and focus area of this study.

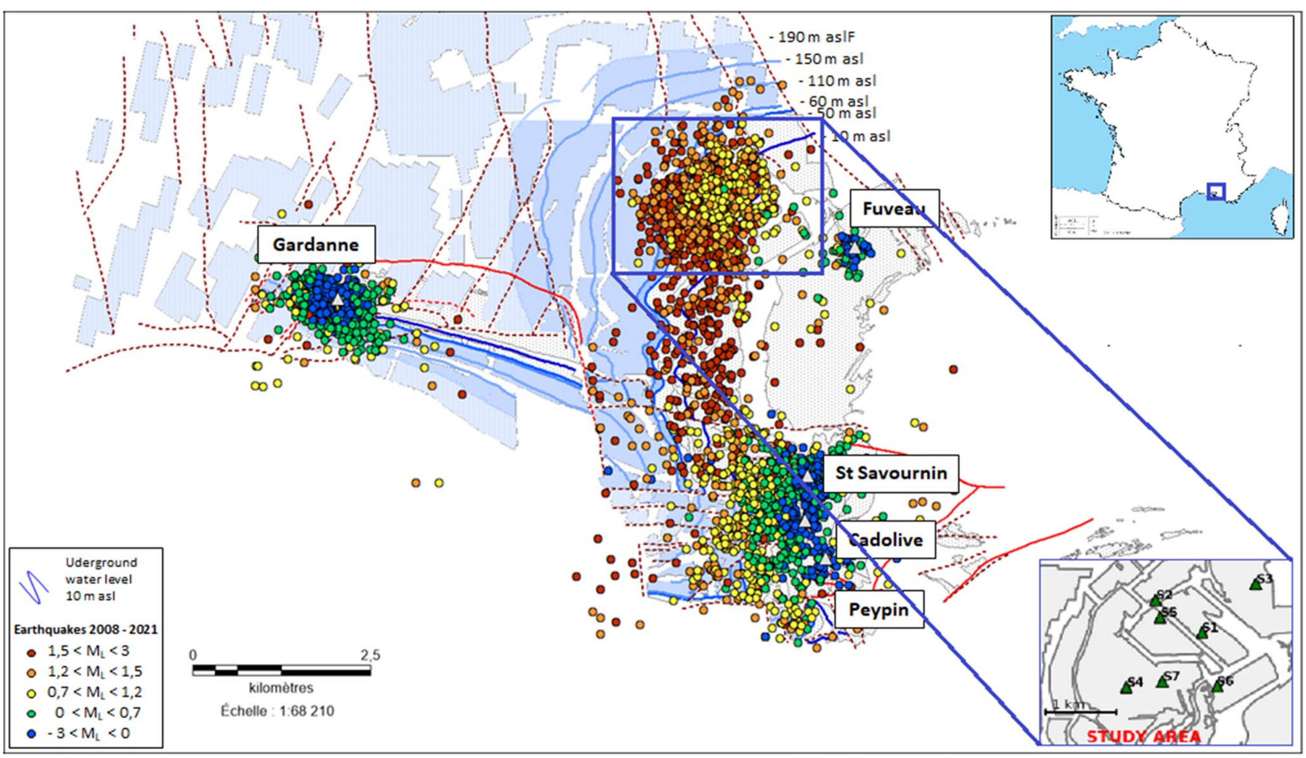

Fig. 1 Flooded abandoned Gardanne mine with observed seismicity and monitoring networks. Stations of permanent monitoring network are marked with white triangles and the names are written next to it, accordingly. Temporary network installed in study area is shown within inset figure in lower right corner, where grey areas indicate excavated parts of mine. Flooded part of mine works shown in blue. Seismicity shown as a function of magnitude by colored dots, observed by Ineris monitoring network in period 2008–June 2020. Flooding front progress through mine works is indicated by dark blue lines and corresponding depths. Gardanne mine location is indicated by blue square on the inset map of France in upper right corner (URL source of original map: https://d-maps.com/carte.php?num_car=2812)

2.2 Study objectives

The first seismic data analysis focused on a dataset recorded during the crisis of December 2014 and contradicted the hypothesis that the origin of the seismicity is linked to underground collapses, as seismic sources seem to be mostly located below the mining works (Matrullo et al. 2015; Kinscher 2017). The first analyses also have shown indications that the seismicity is in correlation with the underground water level changes, which are under influence of the pumping, as well as meteorological conditions. The presence of multiplet-type events was also discovered (Kinscher 2017). Dominique et al. (2022) characterized the source parameters of several strongest events, showing that the normal faulting is principally oriented NW–SE, consistent with the spatial distribution of the seismicity.

Consequently, observations of the first seismicity analyses led to new questions and concerns regarding seismicity origin. New hypotheses were brought up, one connecting the seismicity to ongoing deformation in the mining works and overburden, and the other one proposing the reactivation of deeper faults below the mine. Two hypotheses carry different consequences in terms of seismic hazard. Based on analysis of the 4 years of continuous seismic data recorded in period 2014–2017 by temporary network, as well as analysis of seismic data recorded by station of permanent network closest to study area, recent analyses provided new evidence that seismicity is likely related to rupture on faults located below the mine workings (Namjesnik 2021).

In this paper, we present the multiplets analysis, which is part of the research of doctoral thesis of Namjesnik (2021). We focus on events of the detailed seismic catalogue for the period 2014–2017 by Namjesnik et al. (2021), based on and recorded continuous data on a temporary network, and newly developed methodology for automated detection and location of events for the sparse networks. However, due to relatively shallow source depths and a low number of stations, the depth of events could not be inferred with high precision and question on seismic origin remained open.

Analysis presented here focused on exploring further previously observed multiplet phenomena, as well as previously observed spatial event clustering (Namjesnik et al. 2021). These phenomena provide us with insight into seismic source origin and underlying triggering mechanisms, as well as its connection with variations in the underground water levels.

Generally, the presence of multiplet events is often observed within spatially clustered seismicity, characterized as a group of earthquakes with similar waveforms that occur close to each other, at different times (e.g., Geller & Mueller 1980; Poupinet et al. 1984). The different driving forces or cross-triggering mechanisms (which can involve stress transfer, creep and fluid pressure changes) may lead to high waveform similarity between events, which are interpreted either as a partial repeated rupture on the same and/or neighbored asperities on the same fault segment or a subsequent rupture on neighboring interacting faults. Hence, they can be very close events, or co-located events, both of which can have variety of implications (e.g., Uchida & Bürgmann 2019).

2.3 Data and methods

Following the previous research study of Namjesnik et al. (2021), total of 1986 events of the new catalogue for the period 2014–2017, classified as highest quality events (A and B class) and separated into clusters by K-means analysis, were analyzed (Fig. 2).

For detection of highly similar waveforms in our datasets, a commonly used crosscorrelation method was applied, using the one-station approach. After testing a range of values, the cross-correlation threshold value between event-pairs was set to 0.8. This threshold is also the most often used value in other similar studies (e.g., Chen et al. 2008; W. Yu et al. 2013; Uchida 2019 and references within). Identification of multiplet families by grouping similar events was based on the equivalence class algorithm (Aster & Scott 1993).

Before cross-correlation, waveforms of events were demeaned and band-pass filtered to the frequency range of 1–100 Hz. For each event-pair, a cross-correlation value is determined as a mean of cross-correlation values separately across all 3 components (vertical, N-S, E-W).

For further relocation of most important resulting multiplet families, to assure better location accuracy, a probabilistic approach following Contrucci et al. (2010) was applied. The method solves the inverse problem of Moser et al. (1992) and Tarantola and Valette (1982), by maximizing the probability density function of the hypocenter at a given point using the equal differential time (EDT) or Euclidean (L2) norm, by minimizing the misfit between observed and calculated arrival times. Manual picks of P- and S-wave phases from 3 component waveforms were used, recorded on all available stations of temporary microseismic network, with constant uncertainty for P and S picks 0.05 s and 0.20 s respectively, identified from seismogram inspection. The hypocenter with the maximum likelihood is determined by using the Oct-Tree nonlinear method of Lomax & Curtis (2001). The velocity model used was homogeneous, with P wave velocity $V_P = 4.1$ km/s and S wave velocity $V_S = 1.8$ km/s (Kinscher 2017; Kinscher et al. 2020). Event location search was limited to grid corresponding to Lambert III coordinates from 857,000 to 861,000 m in easting direction, from 130,500 to 133,500 m in northing direction, both with 10 m in resolution and vertically limited from

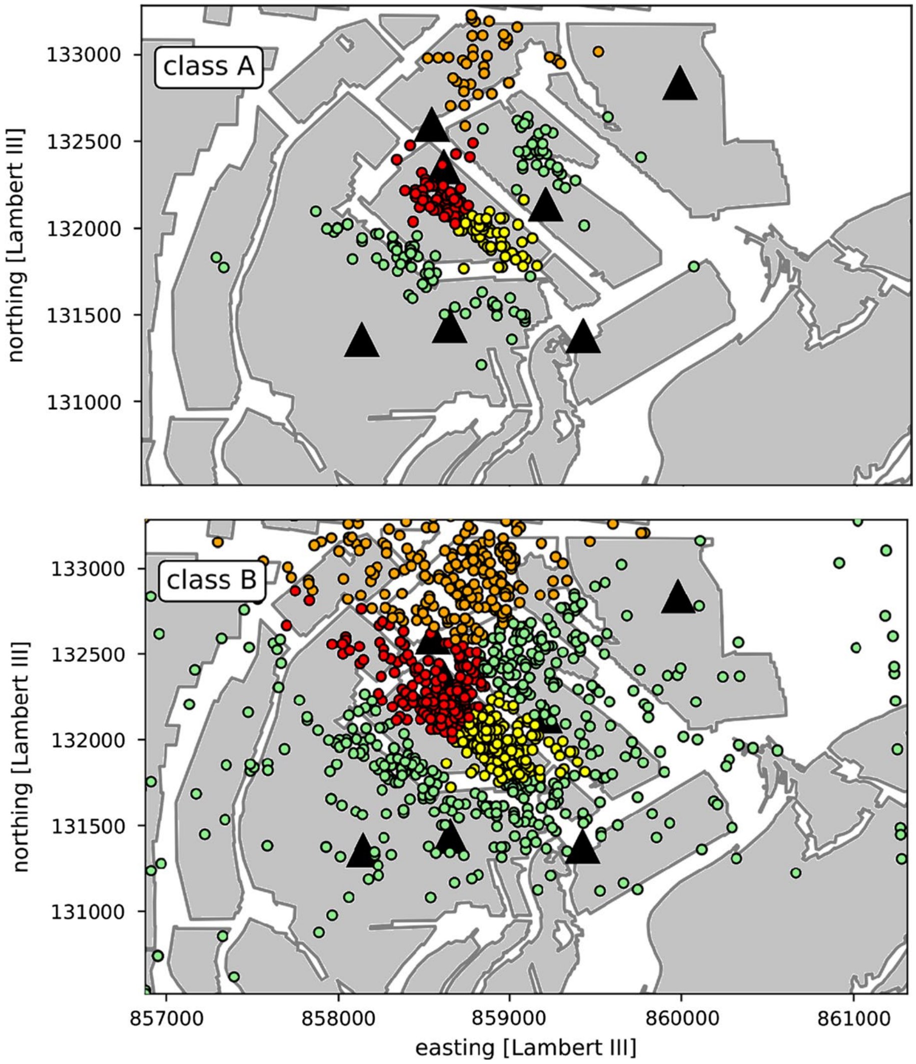

Fig. 2 Classification of the highest quality events in catalogue 2014–2017 according to data published by Namjesnik et al (2021). Yellow (cluster **A**) and red (cluster **B**) are part of the "central cluster", orange (cluster **C**) marks the "north" cluster. The seismically less active clusters are colored with light green

the depth of −1000 asl (m) to surface at 300 asl (m) with a resolution of 100 m.

2.4 Results and discussion

Firstly, we take a closer look at the temporal distribution of events' magnitudes together with the cumulative number of events, respectively, focusing on seismically most active central cluster and the north cluster (Fig. 3).

As we can observe, even though moderate seismic activity can be seen throughout the entire period of 4 years, the increase in the number of events clearly indicates the 3 periods of seismic crises, with no clear mainshock-aftershock sequences, indicating that the activity of each cluster can be characterized as a seismic swarm. Colors in Fig. 3 correspond to clusters' colours in Fig. 2. During crises of December 2014, the total number of events is highest in cluster A (yellow), which is also the only cluster where earthquakes reach magnitude $M_L = 1$, while the magnitude of events in other areas remains below 1, closer to 0.

When looking at the sequence of end 2016–early 2017, we can observe magnitude increase compared to the previous crisis is observed in all three clusters, as magnitude reach over $M_L = 1$. Seismic activity in central cluster expands from southest (cluster A) to nothwest (cluster B), while north cluster (cluster C) starts showing moderate activity throughout this crisis as well. However, the seismic activity of this cluster is strongest during the crises of August 2017. Its' activity dominates, compared to other clusters, with maximum magnitude observed $M_L = 1.3$. The magnitude of

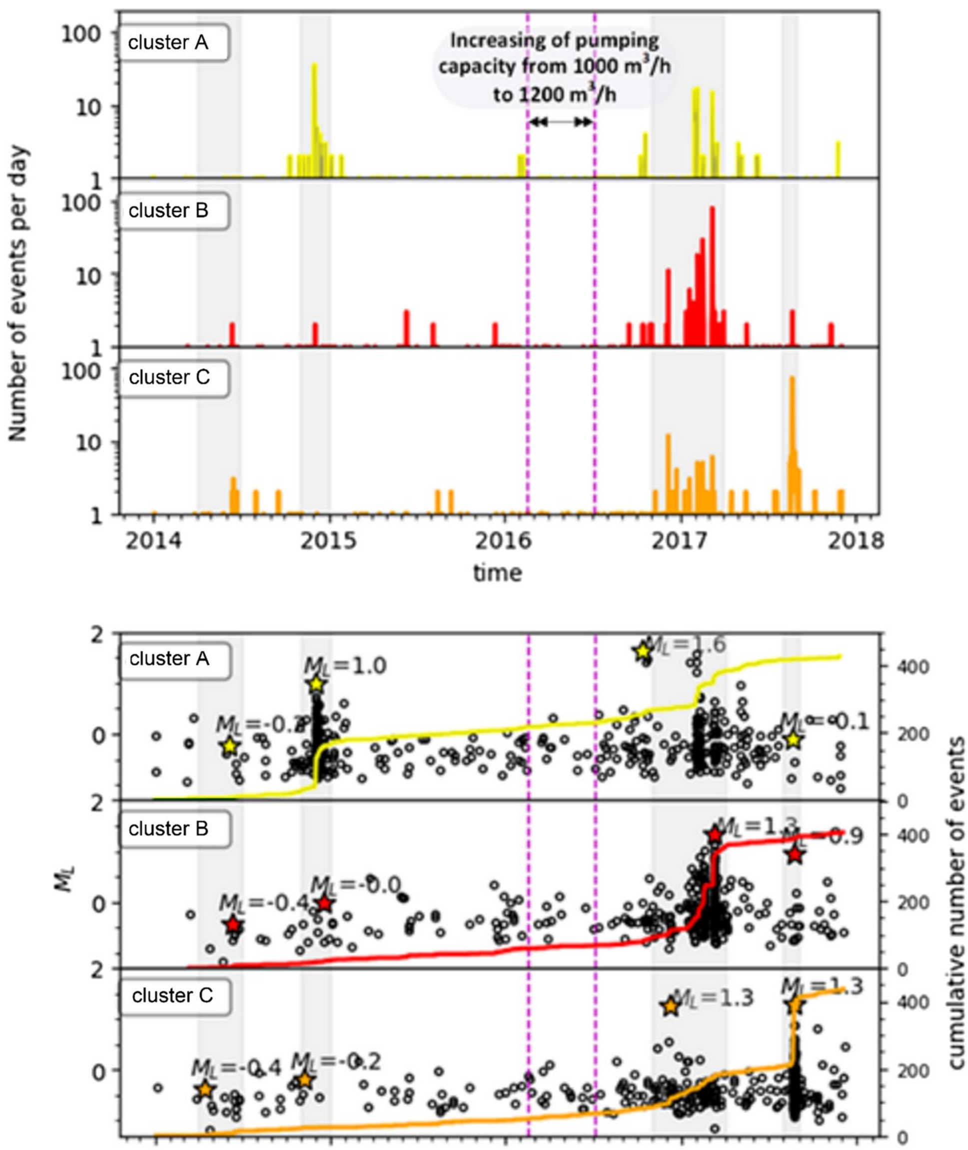

Fig. 3 Temporal distribution of seismic activity for A and B class events, for central and north clusters: **a** Total seismic activity per day (top), and each cluster separately (figures below), compared with water levels at Fuveau Regagnas well, presenting efficient rainfall (blue line); **b** The local magnitude of corresponding events with the cumulative number of events

events in other clusters during August 2017 is in decline compared to the crisis of late 2016–early 2017.

As a next step. events were crosscorelated in order to search for multiplet families observed in earlier research. The results can be observed in the correlation matrix in Fig. 4, which presents the final cross-correlation values, for all event pairs calculated as a mean value across all 3 components.

In the figure, we can observe the presence of three larger cross-correlation clusters (further: CC-cluster) which seem to correspond to the three main seismic crises: December 2014, late 2016–early 2017 and August 2017. We can also observe the connection of the CC-clusters of the first two crises, with the waveform similarity between them corresponding to cross-correlation value 0.7 (blue). It implies they are at small enough inter-event distances and most likely both located at the central cluster (yellow and red color in the Figs. 2 and 3) The final CC-cluster shows low waveform similarity with the preceding CC-clusters, thus most likely involving multiplets located in the most northern cluster.

Results revealed that in total 342 out of 1986 events are grouped into 121 multiplet families. The multiplet family with the highest number of events is shown in Fig. 5, confirming the high similarity of waveforms and consequently justifying the choice of the cross-correlation threshold.

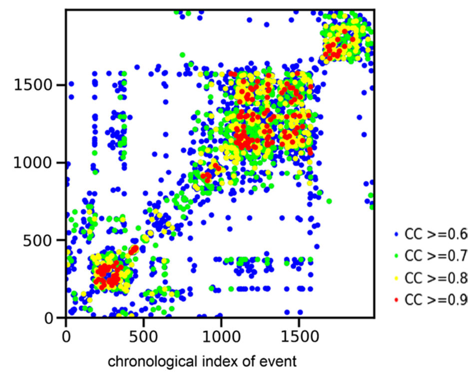

Fig. 4 Crosscorelation matrix showing cross-correlation values, for all event pairs calculated as a mean value across all 3 components. Only event pairs with crosscorelation values of 0.6 and higher are shown (adapted from Namjesnik 2021)

For further analysis, the 21 families with a minimum of 4 events were chosen. A total of 109 events were relocated, 6 of which are A class events and 103 B class events.

Figure 6 shows event relocation results, where circles with the same color correspond to events in the same family. Grey circles represent larger events associated with $M_w > 1$. Multiplet families seem to be mostly present in the central cluster. They appear to group into two separate seismically active areas. The largest number of families are located in the southeast of the central cluster (ie., cluster A). Their activity is initiated either during the crisis of December 2014 or during the crisis of late 2016–early 2017. Several families are located in the northwest part of the central cluster (i.e.., cluster B), which is reactivated during late 2016–early 2017.

Some families are also found in a northern cluster, which is most seismically active during the seismic crises of

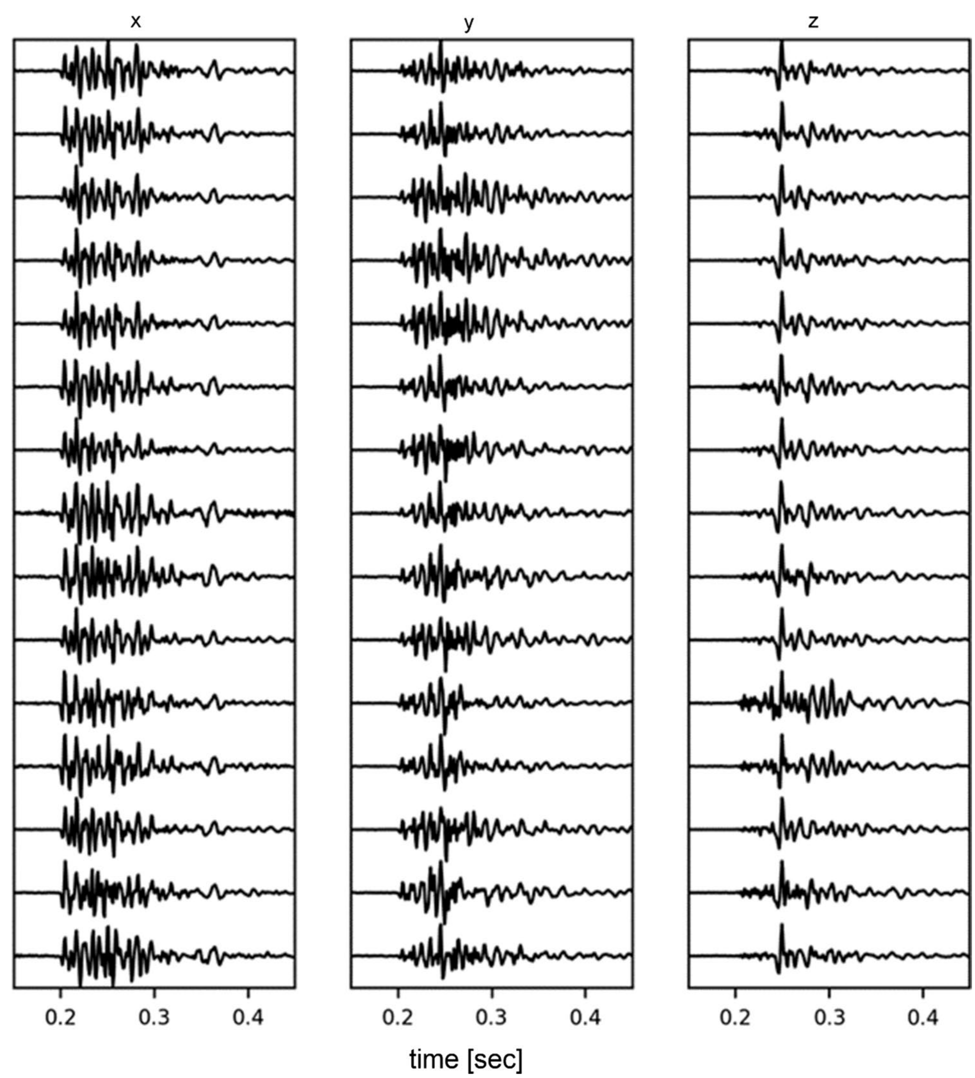

Fig. 5 A multiplet family, with the highest number of events, based on data temporary scientific monitoring network and new catalogue 2014–2017 (adapted from Namjesnik 2021)

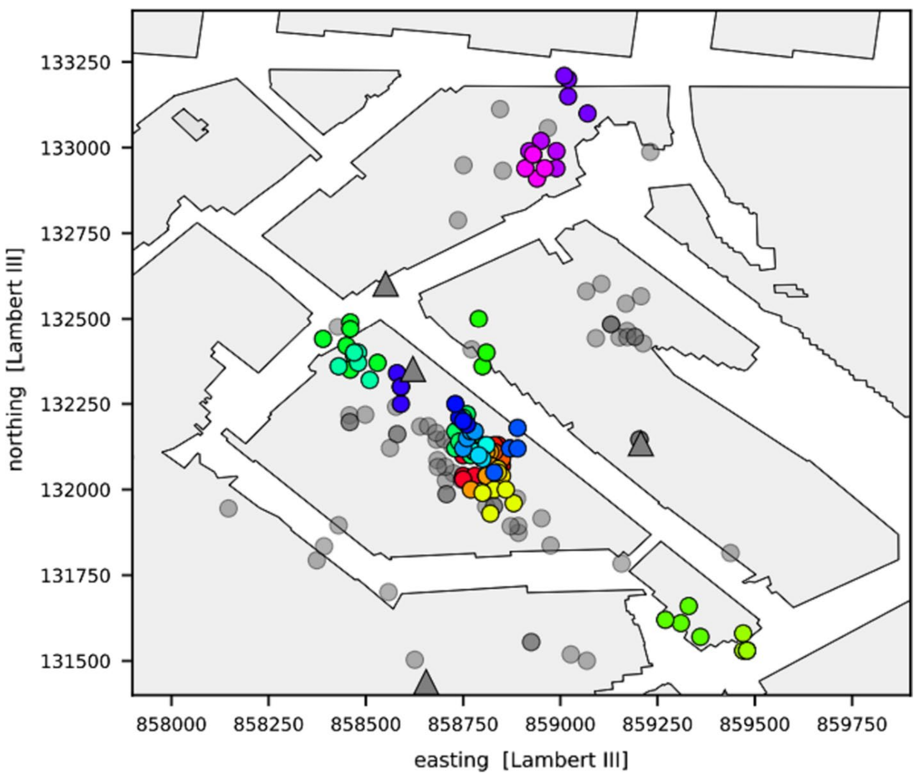

Fig. 6 Location of events of main multiplet families with more than 3 events. Grey circles indicate higher magnitude events ($M_w > 1$) that are not part of multiplet families (adapted from Namjesnik 2021)

August 2017. Among the observed multiplet families, none were found in other surrounding clusters.

Further, we qualitatively analyze the temporal distribution of multiplet families in Fig. 7a). The colors of each family match the colors in Fig. 6 for main families with more than 3 events, while families with 3 or fewer are marked with white circles. We can observe that the multiplet families mostly occur in form of transients—with temporary,

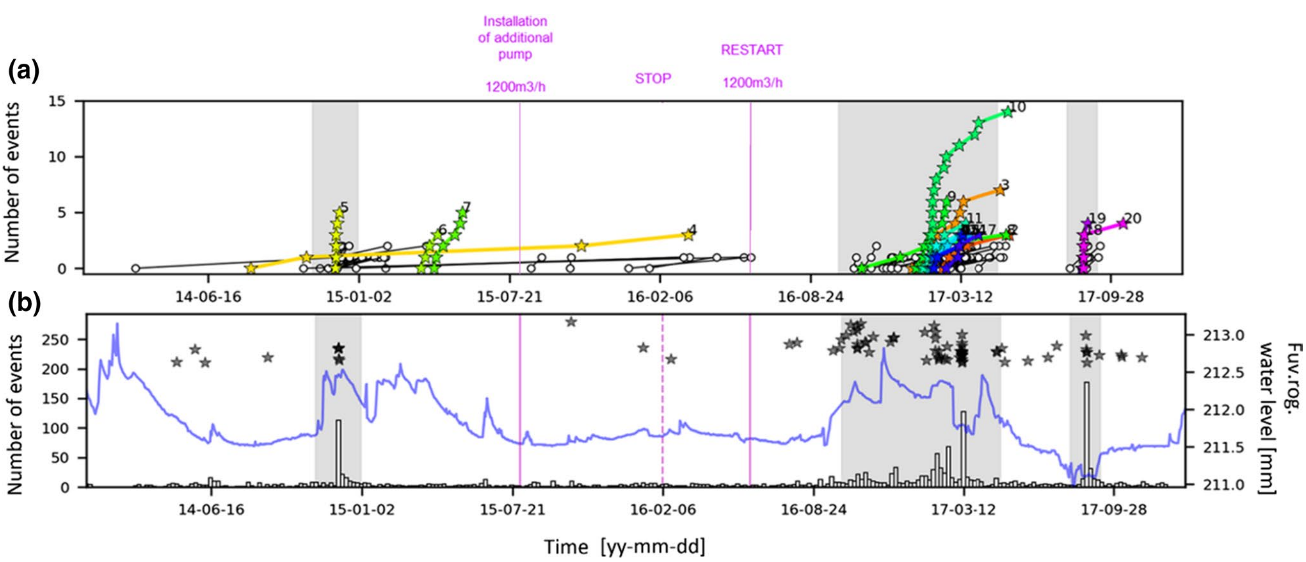

Fig. 7 Temporal distribution of seismic activity **a** Events of each family and **b** Compared with water levels measured at Fuveau Rognacien well (around 2 km distance), corresponding to the rainfall data. Pumping capacity changes are marked with pink lines

relatively short-lived activity, which can cover periods from weeks to months before disappearing. Most of the families are active only during the period of seismic crises with short interevent times for events in the family, while some are continuously active or triggered for the first time during periods in between the seismic crises. The recurrence period of events in families varies. Some families show Omori decay power-law type behavior, which is often interpreted as the creeping behavior of the fault, (e.g., Marone et al. 1991) and loading of the seismic asperity (Schaff et al. 1998; Bourouis and Bernard 2007; Kinscher et al. 2020). In other families, periodic recurrence can be observed, which is in some cases interpreted as continuously creeping fault around the same mechanical asperity where recurrence rate depends on tectonic loading rate (e.g. (Nadeau and Johnson 1998; Mesimeri and Karakostas 2018).

In Fig. 7b we can observe the influence of the hydro-meteorological conditions on the seismicity triggering (pumping and the rainfall). Seismic rates seem to increase during periods of intense rainfall, implying that the pore pressure increases at the faults interfaces as potential main trigger of seismicity during first two crises, when central cluster has strongest seismic activity. In contrast, last seismic crises in august 2017, corresponding to activity in the north cluster, seems to occur during a dry period, indicating activity when pore pressures decrease.

3 Conclusions

The analysis presented in this paper provided us with two main elements: detailed classification of different multiplet families over space and time, and new insight into their connection with hydrogeological system. Based on the location of found multiplet families as well as their spatio-temporal activity compared to meteorological conditions (Fig. 6 and Fig. 7), the analysis indicated different nature of triggering mechanisms between the different clusters, which raises new questions. Seismic activity depends on complex interaction between the local state of stress, the fault mechanical properties and their hydrological connection to the mine layer. However, as we do not dispose until now the precise information on the range of variation of the water levels in study area, exact mechanism of the seismicity triggering is not easy to interpret at this time.

In order to better understand the faults in study area, and due to the limitations of the current seismic dataset which is recorded by only 3–5 stations depending on the period, the seismic network has been enhanced in 2019 by 8 additional stations.

Ongoing research further focuses on the determination of fault geometry, understanding the seismo-hydrogeology and triggering mechanism, driving forces behind the repetitive behavior and potential creep. More specifically, analyses will focus on clustering and waveform similarity as well as determination of source parameters, source mechanisms and discriminating between repeated ruptured asperities and neighboring faults, indicating the nature of rupture processes.

Due to extremely complicated environment of Gardanne mine, estimation of seismic hazard at this point is still difficult. In general, many interacting factors need to be taken into account: seismicity and known faults, conditions of mining works and risk of ground instabilities, a hydrogeological situation which is very complicated and includes interaction between newly established underground water flow through mining works, varying capacities of pumping of mining water and meteorological conditions.

The case of flooded abandoned Gardanne mine however provides a good example for discussion and further research on the subject of induced seismic hazard in post-mining conditions. Even though conditions of each mine are specific to the site, it shows the potential of what could be expected in future, in terms of the potential impact of mine flooding and/or degradation of mining works on the stress perturbations leading to the reactivation of the surrounding geological faults, leading to additional safety concerns. In conclusion, we highlight the importance of taking into account the induced seismic hazard in mine-closure procedures.

Acknowledgements We would like to thank the Prof. Stanisław Prusek for the invite to submit our manuscript to this special issue of IJCST. We thank the editors and reviewers for their thoughtful comments and suggestions which helped improve this manuscript. This work has been conducted in the framework of the scientific collaboration of Ineris and the BRGM (French geological survey). Data acquisition and processing were performed using the Cenaris e.insfrascture (https://cenaris.ineris.fr) and SYTMIS software (Contrucci et al. 2010). Part of the data analysis was implemented using ObsPy (Beyreuther et al. 2010; Megies et al. 2011) Figures were prepared using Matplotlib (Hunter 2007).

Funding Information that explains whether and by whom the research was supported) This work was conducted with the financial support of the French Ministry of Ecological transition.

Availability of data and material Data used in this article are properties of Ineris and BRGM.

Declarations

Conflicts of interest/Competing interest We declare that we have no competing interests.

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