

2023

European feedback on post-mining seismicity

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Recommended Citation

Contrucci, Isabelle; Namjesnik, Dalija; Niemz, Peter; Primo, Paloma; Kotyrba, Andrzej; Mutke, Grzegorz; Konicek, Petr; Dominique, Pascal; Rudolph, Tobias; Möllerherm, Stefan; Kinscher, Jannes; Klein, Emmanuelle; and Cesca, Simone (2023) "European feedback on post-mining seismicity," *Journal of Sustainable Mining*. Vol. 22 : Iss. 3 , Article 3.

Available at: <https://doi.org/10.46873/2300-3960.1385>

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European feedback on post-mining seismicity

Abstract

Following the Paris Agreement adopted in 2015, Europe has committed to reducing its greenhouse gas emissions. In this context, the abandonment of coal as an energy source, both in terms of consumption and production, will lead to the closure of many mines in the years to come.

Mine closure guidelines to manage residual mining risks already exist in European countries. However, they do not include post-mining seismic risk management due to a lack of sufficient studies and knowledge on this subject. After mining closure, the flooding of the mining works leads to hydromechanical loading of the underground and, in the longer term, to diffusion and an increase in the pore pressure. These conditions can lead, in certain situations, to the reactivation of tectonic faults, which may cause seismic events strong enough to be felt on the surface or even produce damage. Events of lower magnitudes, usually attributed to the remobilization of old mining works, are referred to as post-mining seismic hazards.

The European RFCS PostMinQuake project, which started in 2020, aims to study this hazard at five mining basins located in France, Germany, Poland and the Czech Republic, known to have experienced significant seismicity during their operation. This analysis, based on the feedback of the partners of the project, aims to frame an inventory of the five studied mining basins, which all encounter post-mining seismicity problem today. Three basins out of five show events with local magnitudes of the order of 3 to 3.5, which took place between nine and thirteen years after the closure of the mines. Even though the magnitudes of these earthquakes are small to moderate, they are felt on the surface as they occur at shallow depths.

In all of the considered countries, a national seismological network exists, however, none of them is fully dedicated to post-mining seismic monitoring. These networks generally consist of a sparse mesh of stations, which does not allow the detection of events of magnitude less than 1 and the location of events have high spatial uncertainties. France is not an exception, but it relies on microseismic monitoring to detect early signs of instability at the level of mining structures and to anticipate the possible appearance of surface disorders. Out of the five basins that are studied, the Gardanne basin, which has been monitored since 2008, is the most documented case study of post-mining seismicity. This article also shows the difficulty in identifying the key conditions and factors that can lead to the remobilization of faults.

Keywords

coal basin, mine closure, induced and triggered seismicity, post-mining risk

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European feedback on post-mining seismicity

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Abstract

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Keywords: coal basin, mine closure, induced and triggered seismicity, post-mining risk

1. Introduction

The European Union remains the world's third-largest producer of industrial minerals, with

around a hundred mines in operation, and there are still many exploitable resources. Half of the European Union members – as well as Norway and the United Kingdom – still have an active mining

Received 18 August 2022; revised 28 December 2022; accepted 15 January 2023.
Available online 28 July 2023

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<https://doi.org/10.46873/2300-3960.1385>

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industry today. Two countries share almost all of European production: Sweden for metals and Poland for coal. It should be noted that Germany also produces a large part of the European lignite that the country uses for its domestic consumption [1].

However, following the Paris Agreement, adopted in 2015, Europe has committed to reducing its greenhouse gas emissions. In this context, several countries have committed to gradually closing their coal mines. Thus, the number of closed mines will increase in the years to come, which means that it is time to be able to manage potential residual risk associated with these thousands of mines (Germany, Belgium, Croatia, Denmark, France, Italy, Luxembourg, Netherlands, Slovenia, Czechia, etc.) [1]. Poland, for example, aims to close them by 2050 and Germany by 2030.

National regulations relating to the closure of mines already exist in European countries to manage the residual risks and the resulting nuisances for the population and the environment. These regulations cover the issues of the stability of the overlying lands (mining subsidence and/or local collapses), the management of the rise and the quality of the groundwater, the upwelling of gas, and even the rehabilitation of sites after the cessation of mining works.

While it has been established since the late 1800s that active mining induces earthquakes [2], the cases of post-mining seismicity remain insufficiently studied. To date, the characterization and management of the post-mining seismicity hazard are poorly or not at all taken into account in public policies.

Yet, it is clearly established that mining creates voids that disturb the rock mass, especially the natural hydromechanical balance. During mine closure, flooding of the mining works due to cease of dewatering pumps leads to hydraulic loading of the underground and, in the longer term, to diffusion and an increase in pore pressure. Once the water fills the mine voids, which can take several years, changes in the groundwater level continue to occur with seasonal variations or changes in pumping capacities if the groundwater level is maintained artificially. These disturbances lead to modifications of constraints in the rock mass. If the conditions are favourable for the initiation of the phenomenon, faults can be reactivated and produce seismicity felt at the surface or even damage buildings and infrastructures.

A well-known case of post-mining seismicity occurred in South Africa with a magnitude 5.3 earthquake on March 9, 2005 [3]. It happened several years after the closure of the mine and

during its flooding. This earthquake caused two deaths (miners in the operating mine next to the closed one) and structural damage to many buildings and houses. In France, the known case is that of the old coal basin of Provence, where seismicity has been observed for more than ten years, with events regularly felt on the surface by the population. This seismicity has lasted since 2008, even though the mine was closed and flooded in 2003 [4–6].

The aim of this publication is to provide an inventory and a European-wide analysis of post-mining seismicity. After an overview of post-mining situations in Europe and around the world, the expected mechanisms behind post-mining seismicity will be presented. Then, the state regarding this seismicity of five basins chosen in Europe will be exposed. Finally, a synthesis and analysis of the various observations will be carried out. This work was done in the framework of the RFCS European project PostMinQuake launched in 2020. This project aims to identify the conditions of occurrence of post-mining seismicity in order to propose recommendations for the management of this hazard and the associated risks.

2. Closure of mines: overview

Today, abandoned mines exist all over the world. For example, in Australia 50 000 abandoned mines have been identified [7]; in the United States, there are more than 22 000 former mining sites [8]; and Canada estimates to have more than 10 000 abandoned sites [9]. Europe also has many remains of historic and even prehistoric mining sites. For example, in Germany, 50% of municipalities in the federal state of North Rhine-Westphalia (NRW) are characterized by the presence of abandoned mining sites [10]. In France, all mines are now closed (except the salt mines) [11].

The closure of a mine is an important stage in its life cycle, which can have long-term consequences on the environment. In most countries, this step is managed by the operator, who is required to stop his extractive activity while preserving the environment and implementing the necessary measures to secure the site. This closure phase is nowadays easier to carry out as it was considered before the exploitation. However, this is not often the case with the oldest mines. On the other hand, in the same territory, closed mines can coexist with mines still in operation, which can complicate the management of associated risks.

In the long term, for various reasons (especially economic), the mining operator is generally unable to manage all the environmental issues and risks. In

this case, the government or public bodies dedicated to the operational management of the post-mining phase take the place of the operators. These organizations, therefore, carry out the important work of inventorying and identifying the risks to rehabilitate these sites.

After mine closure, several harmful effects may persist over the long term. Even when mining activity has ceased, abandoned mine sites can generate nuisances that may affect people and infrastructure located under the influence of the mine workings and disturb occupation or economic development. The impacts or hazards induced by abandoned mines are of several types [12]. The first category concerns disturbances of the balance of natural aquifers and surface flows with, for example, modification of river flows or the appearance of humid zones or marshes. Surface instabilities may also appear, such as surface subsidence, surface uplift or sinkholes, due to the modifications of the mass rock equilibrium generated by mining excavations. On the other hand, mining creates artificial reservoirs of gas, which can rise to the surface by various mechanisms, such as variations of the underground water level. If the mining atmosphere presents dangerous gas mixtures, surface safety can be compromised when mine gas is trapped in non-ventilated voids (e.g. cellars). Another important negative effect that can occur after mine closure is the pollution of soil and water. The atmosphere may also be affected, particularly if ionizing radiation or toxic particles are emitted.

Thus, the hazards linked to the closure of mines concern many aspects, such as land movements, gas lift, soil decontamination and groundwater management. This last aspect is particularly important. In fact, during the production phase, groundwater is often pumped out to allow mining works to dry out. Decades later, once the ore has been extracted and the mine is closed, groundwater floods the mine when pumping ceases. The water then fills the mine voids from the deepest ground levels to a groundwater equilibrium level.

However, in a post-mining context, the underground water level is generally maintained by pumping to control the amplitude of the rise in the water table. This helps to prevent the flooding of inhabited areas on the surface, which have potentially suffered significant subsidence from mining. It also ensures that neighbouring mines still in operation are not flooded by water from the closed mine. This pumping allows also to avoid the discharge of mineralized water by channeling it to prevent its oxidation which can contaminate the water downstream (case of Gardanne mine).

On the other hand, the level of the water table can vary due to different inputs from surface water and/or aquifers, but also during pump maintenance or breakdowns. In the next section, we will see the role of water in triggering earthquakes and how the flooding of mines can lead to potentially problematic seismicity.

3. Mechanisms behind post-mining earthquakes: the role of water

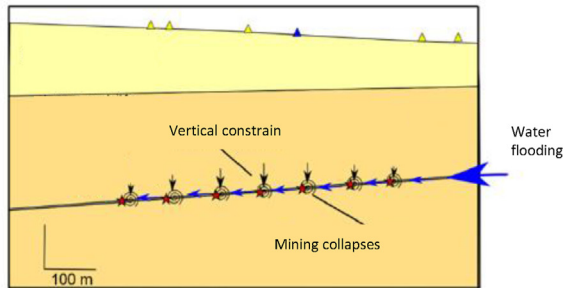
Water plays a major role in triggering natural or man-made earthquakes. This mechanism is relatively well known in industrial fields where fluids are involved in the use of the underground, such as deep geothermal energy; exploitation of conventional and unconventional hydrocarbons as well as the storage of gas; CO₂ sequestration; salt solution mining; wastewater sequestration; dam filling; and more [2,13].

In the post-mining context, when the mine is closed, groundwater usually floods the mine by cessation of the dewatering pumping. The water then fills the mining voids from the deepest underground levels to a level often maintained by pumping to control the rise in the water table (see § 2). This rise in water levels causes changes in effective constraints, already modified by mining, both by (1) gravity loading due to the water column charge; (2) an increase by diffusion of the pore pressure in the rock mass.

In this context, two types of seismicity can be observed. The first, called “induced”, can be associated with readjustments in mining works (Fig. 1 – hypothesis 1) or with their mechanical degradation. This seismicity is generally of low magnitude and appears after flooding [14]. The second (Fig. 1 – hypothesis 2), called “triggered”, is associated with the remobilization of a fault or several pre-existing faults and can be of greater magnitude. Note that the first -induced seismicity-is limited in time (i.e. once the mining works are crushed/collapsed, they have reached geomechanical equilibrium) while the second one-triggered seismicity-can last longer, as long as the pressure changes affect the faults (see Fig. 1).

Triggered seismicity is created by an increase in fluid pressure on a fault plane (Fig. 1 – hypothesis 2). This phenomenon is responsible for the decrease in shear strength, thus helping to slide on the fault plane. This process is possible when a fault is in a state of near critical stability, oriented favourably with respect to the regional or induced stress field, and is impacted by the increase in fluid pressure. This seismicity can appear after several months or years following the flooding [14,15]. It can also

Hypothesis 1 : repetitive mine collapses following flooding



Hypothesis 2 : reactivation of faults linked to a modification of hydrological conditions (anthropic aquifer)

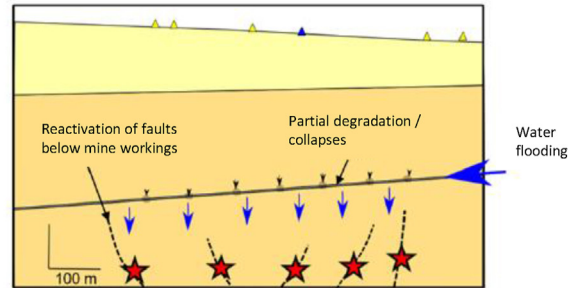


Fig. 1. Flooding of mines can destabilize mining works (left figure) and/or reduce the normal stress exerted on a fault (right figure) modified according to [14].

appear repeatedly depending on variations of the groundwater level [6,14].

4. European panorama of post-mining seismicity situations: an overview

As part of this synthesis, we consider several coal basins (CB) where coalmines have recently been closed (Fig. 2). For each of the countries, the basins considered are as follows:

- In Germany, in the Ruhr basin: Ibbebüren coal basin, mine closed in 2018; and the Hamm coal basin, “Bergwerk Ost mine” (BW Ost), closed in 2010.
- In the Czech Republic, the Czech part of the Upper Silesian basin: The Ostrava Coal Basin, closed in 1994.
- In Poland, the Polish part of the Upper Silesian basin: the Kazimierz-Juliusz mine, closed in 2016.

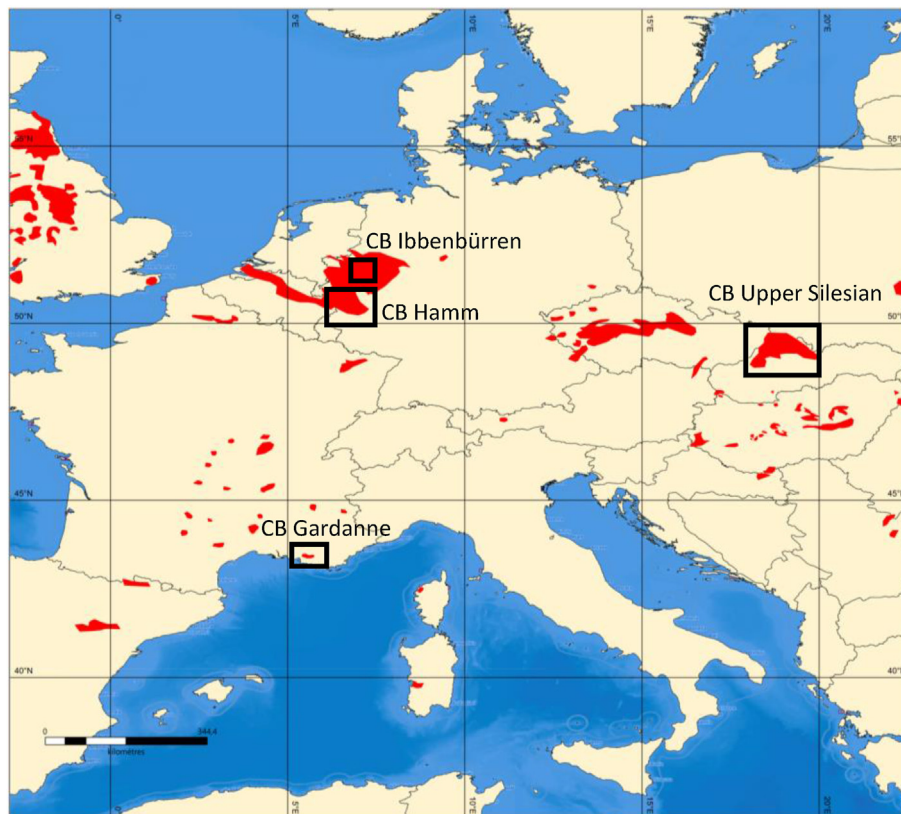


Fig. 2. Representation of the main coal deposits in red and location of the closed coal basins considered in this synthesis [17].

- In France, in Provence: Gardanne coal basin, closed in 2003.

Note that the formation of the German, Polish and Czech coal basins results from the same geological episode. These are ancient foreland Molassic basins formed during the Variscan (or Hercynian) Orogen. Their structural position is similar to other European coal basins: they lie in a belt extending from the British Isles to Germany and Poland to the eastern part of European Variscan structures [16].

The organic matter has accumulated in an aquatic environment, which was during its formation close to the coast and benefited from a continuous or intermittent connection to the sea. It is, therefore, 360 to 290 million years ago, during the Carboniferous and Permian periods, that the climatic and tectonic conditions were favourable to the formation of coal in Europe and in the world. More than half of the world's coal dates from the primary era, but it continued to be formed in later geological eras, although with a lower degree of maturation than that of the Carboniferous. In this case, when the degree of maturation is lower, the coal is in lignite form. Thus, it was in the Cretaceous (secondary era) that the lignite deposit of the Gardanne coal basin was formed in a lake-like environment.

In the following paragraphs, to better understand the issue of post-mining seismicity, we will present the information and characteristics of each of the basins likely to play a role in the genesis of post-mining seismicity, namely: (1) the geological and seismotectonic context; (2) the characteristics of the deposit; (3) the mining methods used and the mining seismicity observed during mining; (4) the hydrological context and water management during and after exploitation; (5) the spatiotemporal evolution of post-mining seismicity.

These parameters are key factors in understanding the origin of seismicity. Indeed, the rapid sliding of a pre-existing fracture or fault along which strong stresses have gradually accumulated cause an earthquake. These stresses are at the limit of the resistance that the fault opposes to tectonic forces. The earthquake, therefore, corresponds to a sudden relaxation of the stresses on a more or less extensive surface of the fault. An earthquake of anthropogenic origin results from the artificial reactivation of pre-existing faults and/or the creation of new fractures during changes in the field of natural stresses generated by industrial activity (mining extraction and flooding of works in our case) located in its field of influence. In order to understand why earthquakes can be generated, it is necessary to clarify which factors are responsible

for initiating an earthquake and which control its magnitude.

5. Post-mining seismicity in the Gardanne basin, France

The Gardanne basin, in Provence, was one of the three largest exploited coalfields in France. Close to the city of Marseille, it extends over 70 km from east to west and over 15 km from north to south (Fig. 3). The coal was mined between the 15th century and the early 2000s at depths of up to 1400 m.

When mining works are closed, France has a legislative framework (Law No. 99–245 of March 30, 1999, known as the “after-mining law”), which specifies the organization and means to manage mining risks. Thus, the State is responsible for maintaining the safety infrastructures of the former mining sites, in particular those whose initial owner has disappeared as well as those whose work has been stopped and whose mining concessions have been abandoned for more than 10 years. The expertise mission is entrusted to the public interest group GEODERIS. Operational missions have been delegated to BRGM, which has created a dedicated department, the Department of Mining Safety and Risk Prevention (DPSM). Ineris, whose mission is to contribute to the prevention of risks caused by economic activities to health, environment, and the safety of people and goods, also contributes to the prevention of residual long-term post-mining risks through expertise and research studies. The institute is also in charge of the microseismic monitoring systems installed to anticipate post-mining ground instabilities in France, as described hereafter.

After the cessation of mining in 2003, the mining works were partially and gradually flooded. Flooding progressed from west to east when dewatering pumping ceased to bring the groundwater level down from –1100 m in 2003 to –14 m in 2010 below sea level. Since 2010, this level, which is maintained by pumping, has been subject to fluctuations due to pump failures and seasonal water inflows. Pumping capacities were also increased in 2017. In the meantime, several studies were carried out to assess the long-term stability of the mining works. They ended up the identification of areas at risk of subsidence of a brittle nature [Geoderis, 2003; 2016]. To mitigate this risk, a permanent microseismic network (5 borehole stations, Fig. 4) was installed in 2007. It allows to detect and monitor the first signs of instability at the level of the mining structures and to anticipate potential disorders on the surface.

Since 2010, the basin has been periodically affected by seismic activity unexpectedly located

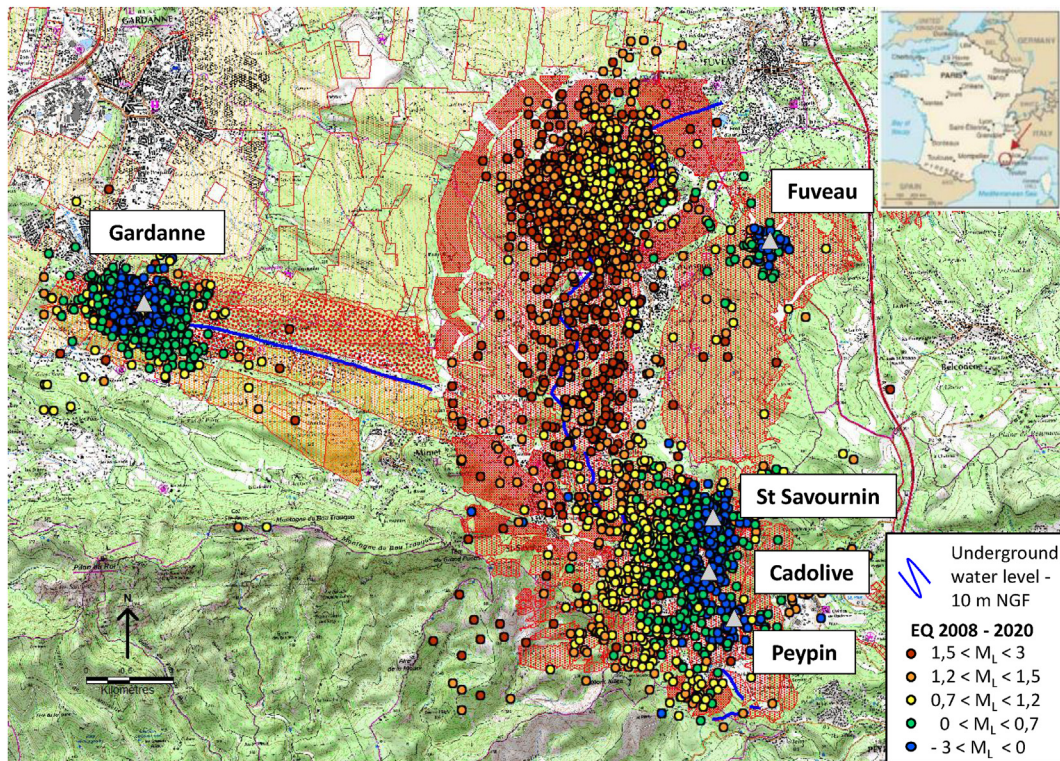


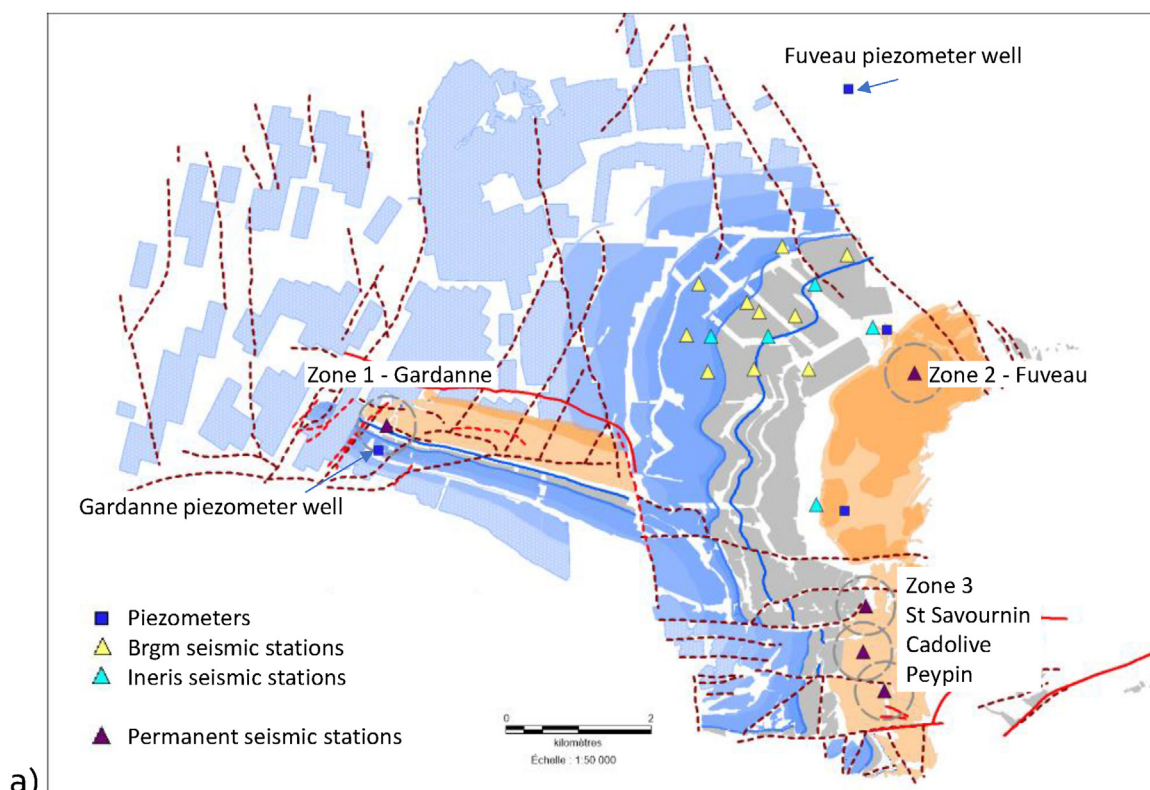
Fig. 3. General view of the Gardanne coal basins and the post-mining seismicity in the 2008–2020 period; the mining works of the “Grande Mine” layer are represented in red.

outside of the identified areas at risk. One area is particularly active: the so-called Fuveau swarm area, where seismic events occur periodically and mainly in the form of swarms. The most important seismic events recorded during these crises show magnitudes close to 3.2, the strongest of which were felt locally by the population. This seismicity led to the deployment of temporary additional surface seismic networks in order to clarify their origin (Fig. 4). This temporary system, centred on the Fuveau-Gréasque sector, was expanded between 2014 and 2018: it now includes 13 surface seismic stations and 4 piezometers (Gérard, L’Huillier, Champisse and Gréasque shown in Fig. 4) in addition to other public data available in the area, such as rainfall data from meteorological stations (Météo-France) as well as those from the national access portal to groundwater data (ADES). We particularly follow the Fuveau well piezometer measurements, which are representative of the rainfall in the area, while the Gerard well measurements are representative of the pumping performed in this area. All these data (hydrological and seismological) are centralized on the infrastructure and the web-monitoring portal e.cenaris (<https://cenaris.ineris.fr>, subject to a request for authorization of access).

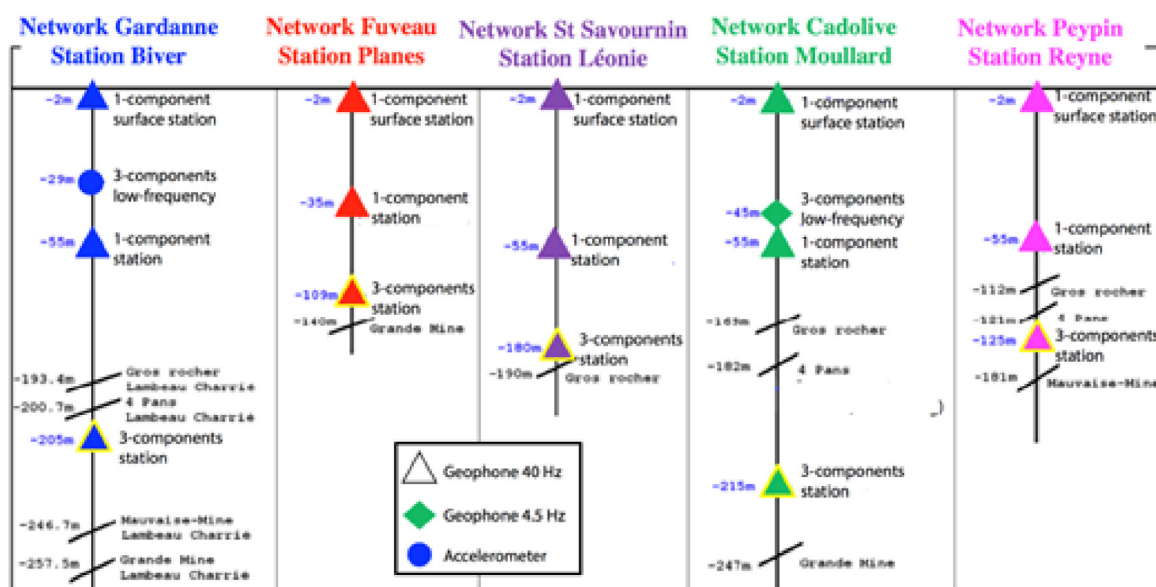
Since its installation, the permanent network has recorded more than 3200 events of low local magnitude ($-3 < M_L < 3$), see Fig. 5. This seismic activity, in monitored areas at risk of ground instabilities (near permanent stations), observed in zones 1 (Gardanne, Fig. 5) and 3 (Cadolive, Peypin and St Saviourin), with events presenting maximum detected local magnitudes of $M_L \approx 1$ (M_w 0.7) (Figs. 3 and 4). These events are very weakly felt at the surface (intensity III), and they are located at the level of the flooding limit of these two zones (Fig. 5). Zone 2 (Fuveau) is less active, which seems consistent with the fact that flooding did not reach this sector (Fig. 5).

The eastward migration of the flooding front began in 2009. At that time, the water level reached the northeast of the basin (Fig. 5), about 2 km west of the Fuveau monitoring station. Since that time, repetitive seismic activity has appeared at this location. It is spatially concentrated and continues until today. This seismic swarm has been called “the seismic swarm of Fuveau”. Six main seismic episodes were observed at this location, and more south, in the centre of the basin:

- In 2010, the seismic activity began at Mimet (from January to April) and continued at the



a)



b)

Fig. 4. a) Map of the monitoring network. The blue circle represents the monitored risk zones of 400 m around the permanent stations. The underground flooding front, located at a depth of -10 m (below sea level), is represented by a blue line. The blue zones represent the extension of the “Grande Mine” layer. The orange areas represent the hazard zones of brittle subsidence as defined in 2003. The red zones correspond to the reduced hazard zones as redefined in 2016. b) Configuration of the permanent microseismic network with stations located in the borehole.

location of the Fuveau swarm in May and June, where a significant number of events were recorded. It seems that this activity occurred in response to the significant increase in

groundwater level (Fig. 5 et Fig. 6), which varied from -120 m to -14 m in almost a year.

- In November 2012, after 4 months of rising water (floods), a seismic crisis occurred at the location

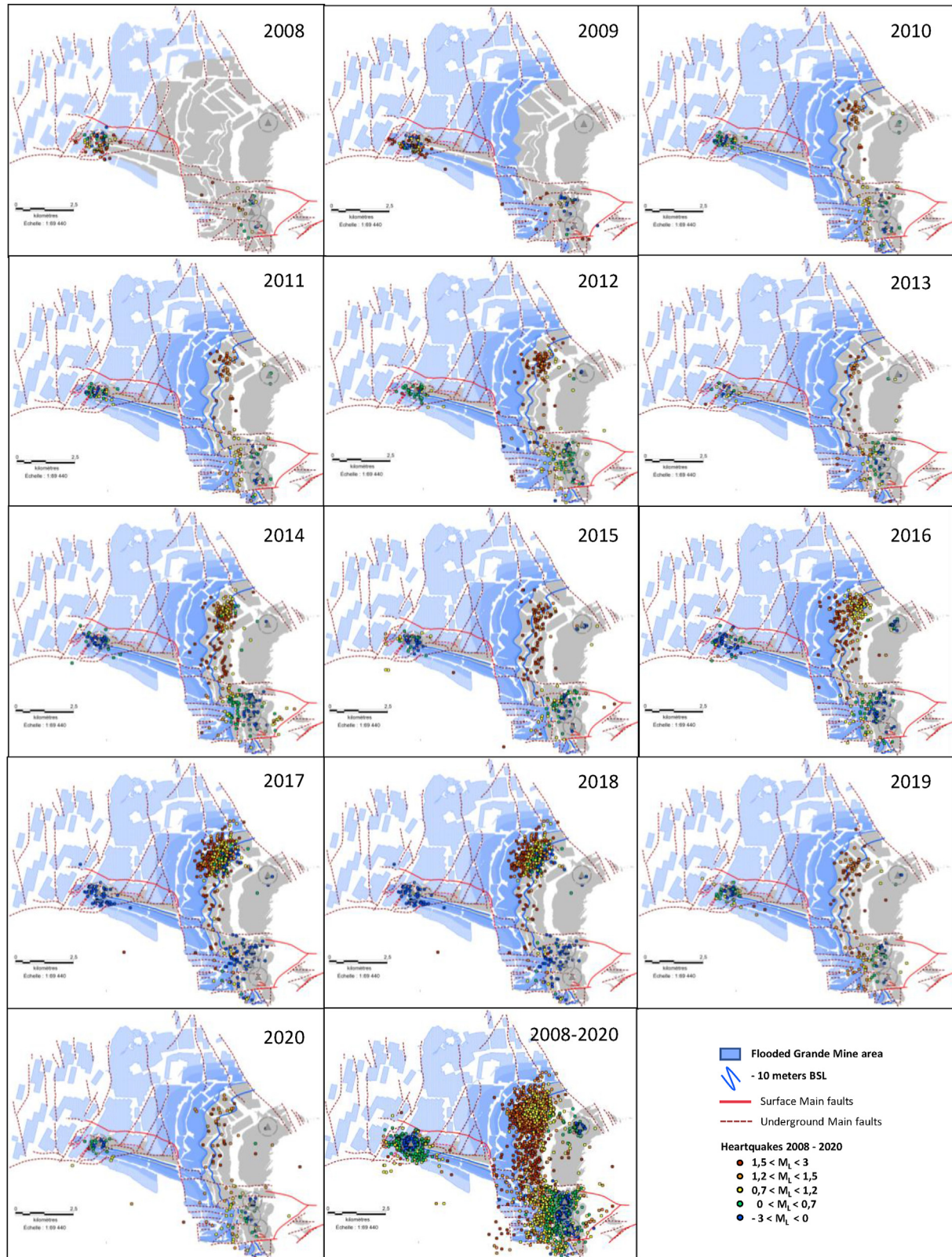


Fig. 5. Spatiotemporal evolution of post-mining seismicity recorded in the former Gardanne coal basin between 2008 and 2020.

of the Fuveau seismic swarm (Figs. 5 and 6). This seismic crisis was also felt by the local population. The strongest event had a local magnitude close to 3.2.

- At the beginning of 2014 (January to March), another seismic episode was observed (Figs. 5 and 6) with events located more south than the Fuveau seismic swarm with a maximum magnitude reaching ≈ 2.3 .
- At the end of 2014, a third seismic crisis was triggered after exceptionally strong rainfall. As a result, pumping capacities were reached in the mining area, preventing a drop in groundwater level (Figs. 5 and 6). This phenomenon would be at the origin of the second seismic crisis in December 2014.
- At the end of 2016 and beginning of 2017, another crisis occurred at the same location. This crisis is probably linked to the significant drop in the water level, which went from +10 m to -30 m below sea level, correlated to a heavy rainfall period (Figs. 5 and 6). This drop was caused by the increase in pumping capacity.
- In August 2017, an atypical seismic episode was observed. This crisis was correlated with a period of drought (Figs. 5 and 6).

Figure 6 a-b shows that most of the most important seismic episodes take place when the rainfall is the strongest, which corresponds to groundwater recharge. Except for the last crisis of 2017, where the seismic crisis occurs during a period of drought.

6. Post-mining seismicity in Germany

After a long history of hard coal mining, Germany ceased underground mining in 2018 following a government decision (surface coal mining continues). The largest exploited underground deposits were located in the state of North Rhine-Westphalia in the Ruhr area, in the Tecklenburger Land (Ibbenbüren coal area) and in the Saar region (Fig. 7). In this study, two sites are examined with regard to the management of seismicity in a post-mining context:

- the Ruhr basin, with the “Bergwerk Ost” (BW Ost) mine in Hamm, located to the east of the Ruhr mining region,
- the Ibbenbüren basin, 80 km further north of the Ruhr basin.

In Germany, post-mining is managed by the Ruhrkohle Aktiengesellschaft (RAG). Initially, this company was the largest coal mining company in

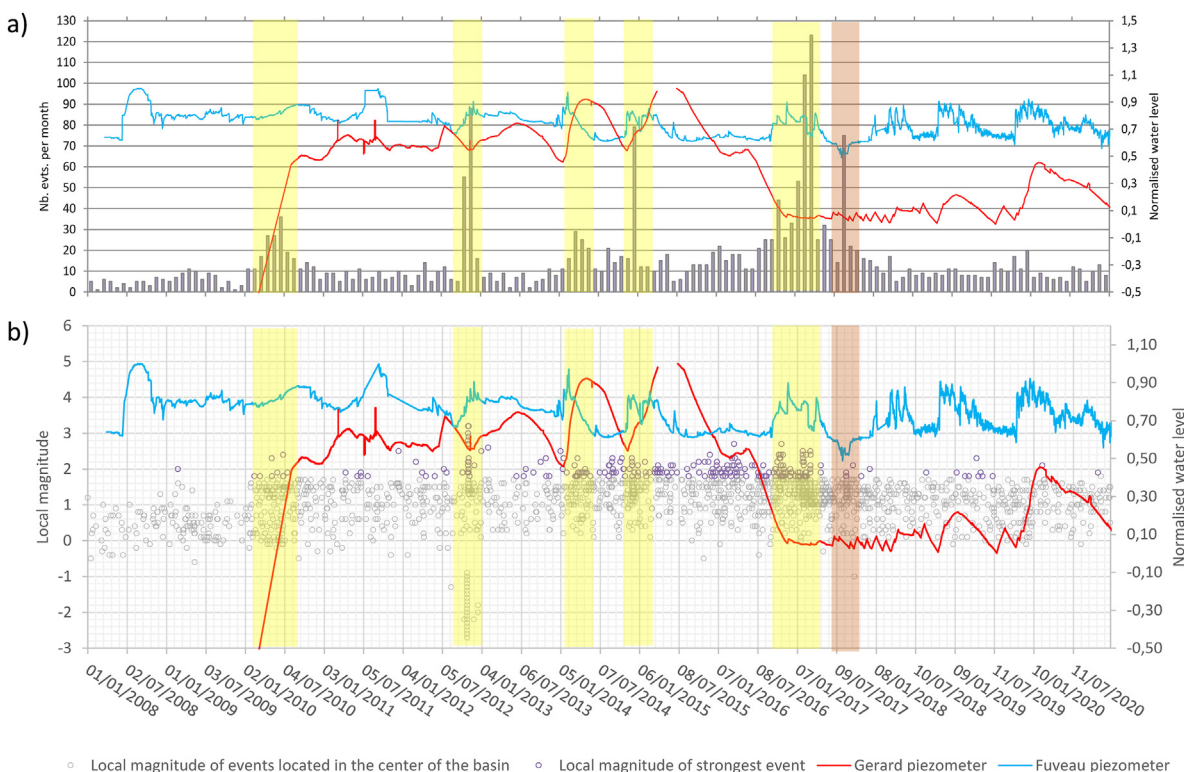


Fig. 6. a) Number of events per month located in center of the basin, outside of the risk zones, since 2008 in the former Gardanne coal basin, superimposed to the groundwater level measured at the Gerard well (located nearby the pumps) and the Fuveau well. b) Magnitude of events located in center of the basin, outside the risk zones, superimposed to the groundwater level measured at the Gerard well (located nearby the pumps) and the Fuveau well.

Germany. The RAG deals, in particular, with compensation for damage caused to buildings, land or roads related to mining. The RAG Foundation is responsible for financing mine water management operations such as the pumping of mine water and surface water, as well as the treatment of water from the former coking plants [18].

Mining in the Ruhr caused considerable damage, in particular many areas suffered significant subsidence, which reached up to 25 m [19]. To avoid flooding, more than 200 pumps have been installed in the region to drain groundwater: they pump 608 million cubic meters of water per year [19].

6.1. Post-mining seismicity in Hamm (Ruhr basin)

The “Bergwerk Ost” (BW Ost) coal mine is located in the eastern part of the Ruhr area, close to the city

of Hamm. It covers an area of 285 km² (Fig. 8-a). Mining ceased at BW Ost on 30 September 2010. After dismantling the underground installations at the end of September 2011, the BW Ost was handed over to the central water management.

The RAG maintained a monitoring network in the Ruhr Basin after the mine closure. It is made up of 3 seismic stations as well as 10 piezometers (Fig. 8-a). On the other hand, the University of Bochum (RUB) has gradually installed seismological stations, which have reached the number of 20 in 2020 (Fig. 8-a). This seismological network does not allow the detection of events of magnitude less than 1. Moreover, before 2020, the network did not have enough stations to locate events with high precision. The minimum spacing between seismological stations is of the order of 2 km. The seismic network was improved in 2021.

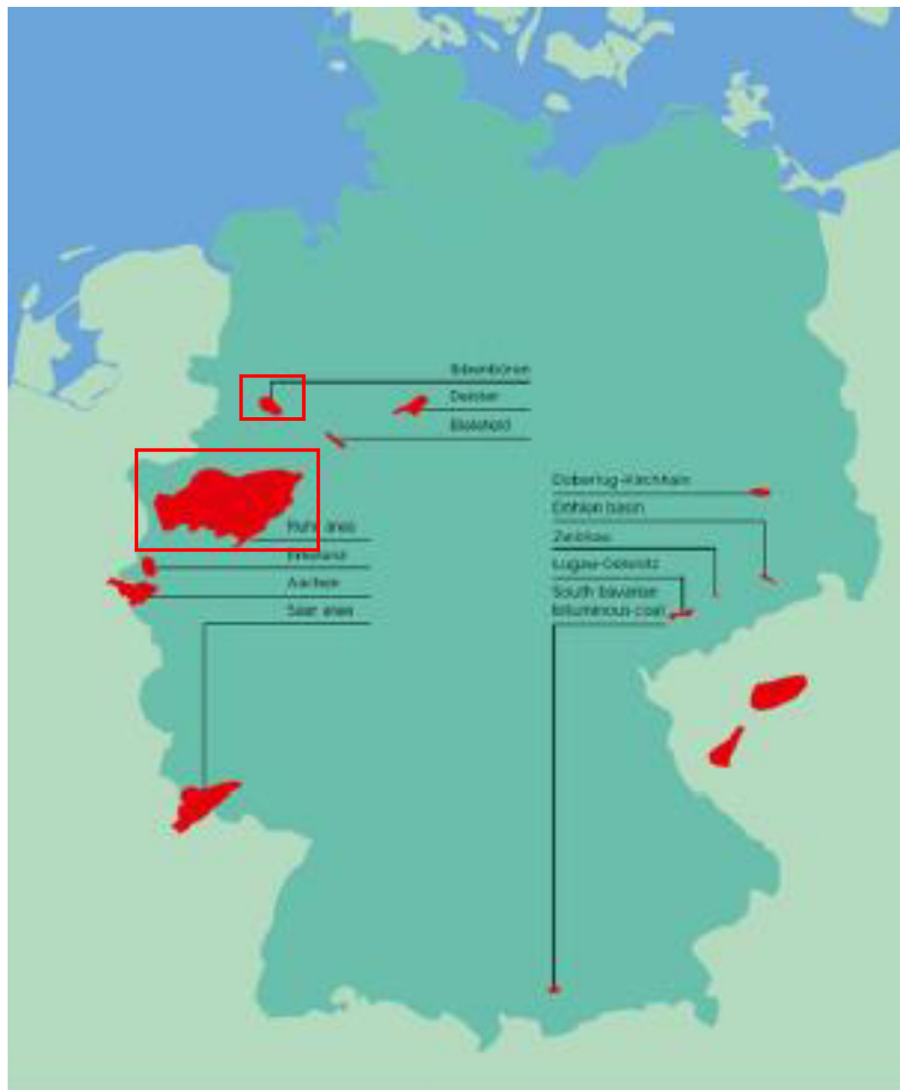


Fig. 7. Main coal basins, in red, in Germany [17].

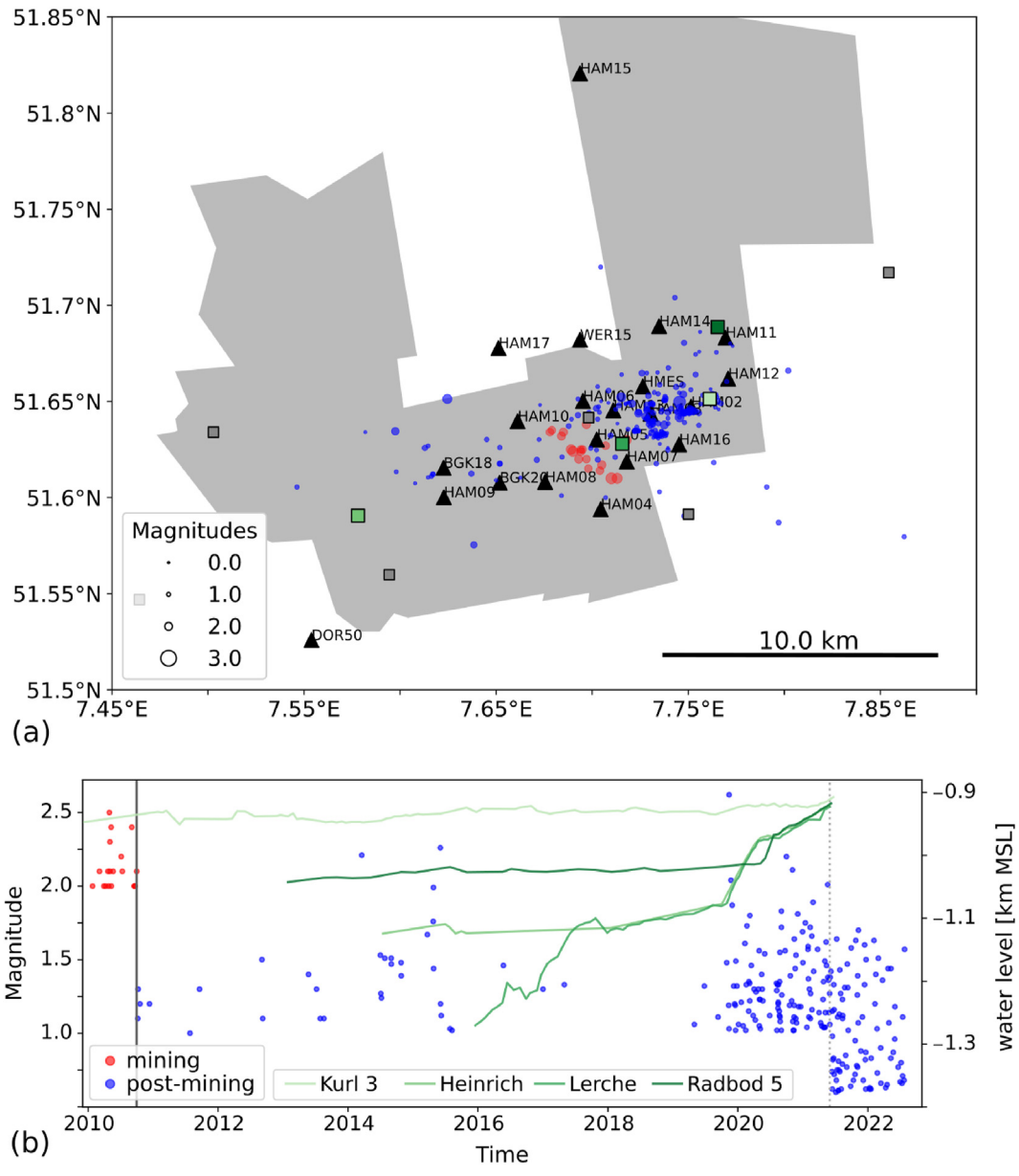


Fig. 8. (a) Location of seismological stations (black triangles) and piezometers (green squares) for the monitoring of post-mining seismicity and upflows in the Hamm basin [20] and location of seismic events recorded between 2010 and 2022 in the Hamm basin with mining (red) and post-mining seismicity (blue). (b) Magnitude of events detected in the Hamm basin as a function of time superimposed to the groundwater level measured at different piezometers in the basin [20].

In the Hamm, between 2010 and 2021, 135 seismic events occurred, of which 77 had an $M_L \leq 1.3$ and 7 events had a magnitude greater than or equal to 2 (Fig. 8-a-b). The correlation between the groundwater level and the magnitude of seismic events is shown in Fig. 8-b and indicates that:

- There was a resurgence of events in 2014 and 2015 with magnitudes that exceeded 2, with a maximum value of ≈ 2.3 . Thereafter the seismic activity decreased.
- The more sustained activity began in 2019, in correlation with the rising water.
- The strongest event took place in November 2019 with a magnitude of around 2.6 and was felt on the surface.

6.2. Post-mining seismicity in the Ibbenbüren basin

The basin of Ibbenbüren is located in the district of Steinfurt, in the administrative district of Münster. The Ibbenbüren coal deposit is divided

into two parts: the western part, which corresponds to the Bockradener graben, closed in 1979, and the eastern part, closed in 2018. The mine covers a total area of 92 km².

In Ibbenbüren, there is currently one seismic monitoring network operated by the RUB (Ruhr University of Bochum) and is composed of 3 stations. Previously, the RAG had a network of 9 stations, active at the time of operation until the mine closed in 2018.

Seismic event data was extracted from the RUB database. In the post-mining period, around 30 events were recorded, with magnitudes between 1.2 and 2.2 (Fig. 9-a-b). The seismic activity slowly ceased before the final closure of the mine. No seismicity was observed after the closing of the mine until 2020. In July 2020, the seismicity increased again, reaching a maximum local magnitude of 2.2, close to the maximum of 2.4 within the mining period. In the following years, the induced events became smaller.

7. Post-mining seismicity in the Ostrava and Petrvald sub-basins (Czech Republic)

The Czech mines considered here are located in the Upper Silesian coal basin. This basin is the largest coal basin in Europe; it covers 7000 km², of which 1550 km² are located in the Czech Republic, while the other part is in Poland. The sub-basins considered here are the Ostrava sub-basin (Fig. 10), closed in 1994, and the Petrvald, closed in 1997. The mines of these sub-basins are adjacent to that of the Karvina sub-basin, where mining is still in operation (Fig. 10).

Today, the seismic activity of the Ostrava sub-basin is detected by the seismic network of the operating Karvina sub-basin, dedicated to the prevention of rockbursts. This network makes it possible to trace the seismicity since the end of the exploitation period of the Ostrava mines, including the Petrvald mines, as well as the post-exploitation period since 1994.

The post-operation period covers the flooding of the Ostrava sub-basin, which took place from 1997 to 2001, as well as that of Petrvald. Then, from 2001, the underground water level (Fig. 11) was artificially maintained by pumping to avoid flooding of the Karvina sub-basin, where mines are still in operation and which is tectonically connected to the former sub-basins of Ostrava and Petrvald.

Over the two periods (flooding and maintenance of the groundwater level), few critical situations were recorded in terms of seismicity in the Ostrava and Petrvald basins. Here, according to the

regulations used, the magnitudes are not evaluated for weak events; only the energy is calculated. Only high-energy seismic events are evaluated in detail (seismic event energy of 10⁴ J and above).

During the flooding period from 1994 to 2001 (Fig. 12):

- only 13 seismic events with an energy of approximately 10³ J were recorded:
 - two events were located outside the mining perimeters;
 - four events were located within the mining field;
- seismic events located at the border between the Petrvald sub-basin and the Karvina sub-basin at the structure level of Michalkovice correspond to the mining activity of the Karvina basin.

There was no high-energy seismic event recorded during the flooding period.

During the period of maintaining the water level by pumping from 2001 to the present (Fig. 13):

- 11 seismic events were recorded:
 - 6 seismic events with energy up to 10² J;
 - 4 seismic events with an energy of 10³ J;
 - 1 seismic event with an energy of 10⁸ J.
- The most energetic seismic event (10⁸ J) with a magnitude of 3.5 was recorded by the national seismological network on 12 December 2017 [23].

The relationship between mining activity in the Karvina region and the flooding of the Ostrava basin has not been studied so far.

8. Post-mining seismicity in the Kazimierz-Juliusz basin (Poland)

In 2019, Poland was considered the 9th world producer of hard coal and the 2nd European producer behind Germany. Despite its strong dependence on coal, the country is committed to reducing its production and consumption. By 2050, it is expected that all coal mines in the country will be closed.

In Poland, coal deposits date from the Carboniferous. They are located in three basins: the Upper Silesian Coal Basin (USCB), the Lublin Coal Basin (LCB), and the Lower Silesian Coal Basin (LSCB). Currently, coal mining is carried out in the first two basins (USCB and LCB). In the third (LSCB), mining is completed, and all five mines have been abandoned for almost twenty years.

The Upper Silesian Basin (USCB) is the main coal basin in Poland (Fig. 14). This is the area where all the operating coal mines are located except for a

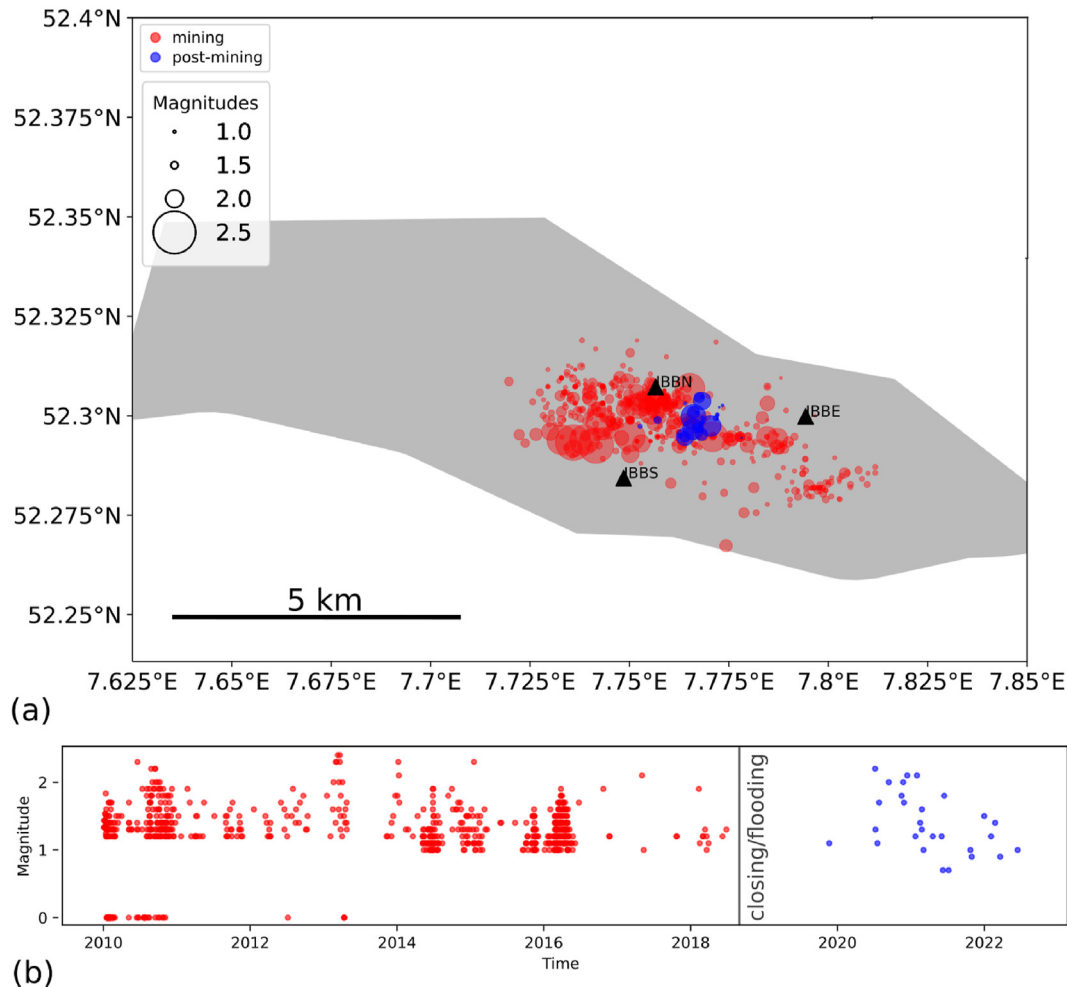


Fig. 9. (a) Location of events recorded during the mining period of 2010–2018 (in red) and the post-mining period since 2018 in the Ibbenbüren basin. (b) Timeline of the magnitude recorded in the Ibbenbüren basin during the mining period of 2010–2018 (in red) and the post-mining period since 2018.

single mine located in the LCB. The total area of the Polish part of the USCIB is estimated to be around 5600 km².

The largest number of mines were closed in the 1990s, with the closure of 30 collieries out of the 70 in operation. Between 2000 and 2016, 12 other collieries were closed. No mine has been closed since 2017. However, as of 2016, the closure of seven other mines (three of which were coal mines) has been planned in the coming years due to an agreement between the European Commission and the Polish government [24]. The mine for the study is that of Kazimierz-Juliusz, located in the USCIB, closed in 2016 (Figs. 15 and 16).

The Central Mining Institute in Katowice has been monitoring seismicity in USCIB coal mines since the 1950s, using the Upper Silesian Regional Seismological Network (USRSN, Fig. 14) [26]. This network

is currently composed of 28 three-axial stations, including seismometers (17 stations), accelerometric sensors (7 stations) and borehole accelerometers (4 stations). This network covers an area of approximately 2500 km² and allows observation of strong regional phenomena with $M_w > 1.5$ [27]. In some areas, it is possible to observe seismic phenomena from the magnitude of $M_w = 1$ (e.g. at the Śląsk mine post-mining area – currently flooded, Fig. 16).

Even though most of the events recorded by the regional network are of low energy in post-mining areas, some events of higher moment magnitude ($M_w > 1.5$) have been detected. One of the largest earthquakes recorded by this network had a magnitude of $M_L = 2.7$ on 15 August 2020 in the area of the Kleofas mine, which was closed in 2005 (Fig. 16). Increased activity was also observed in the area of the KWK Śląsk mine, closed in 2017 (Fig. 16).

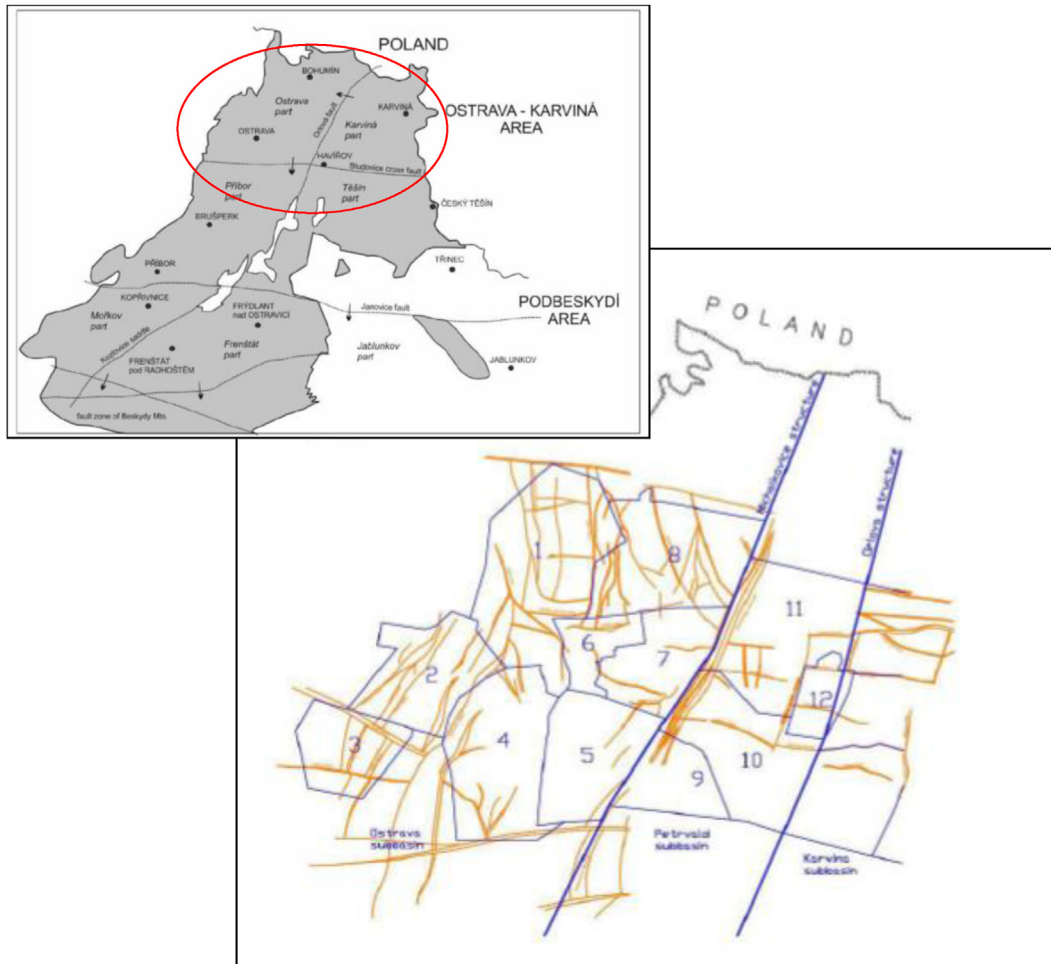


Fig. 10. (Top) representation of the Czech part of the upper Silesia coal basin. (bottom) focus on the tectonic structures in the Ostrava and Petrovald sub-basins at the -450 m altitude level [21].

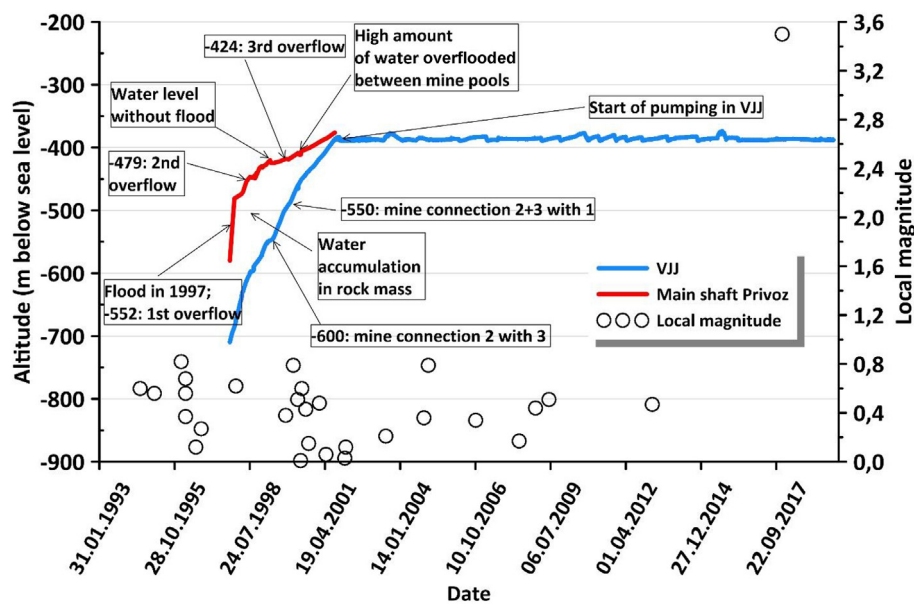


Fig. 11. Water level measured at the Jeremenko well (VJJ) and the Zofie well (OD-2) over the period from 7/1997 to 12/2001 in the Ostrava and Petrovald sub-basins [22].

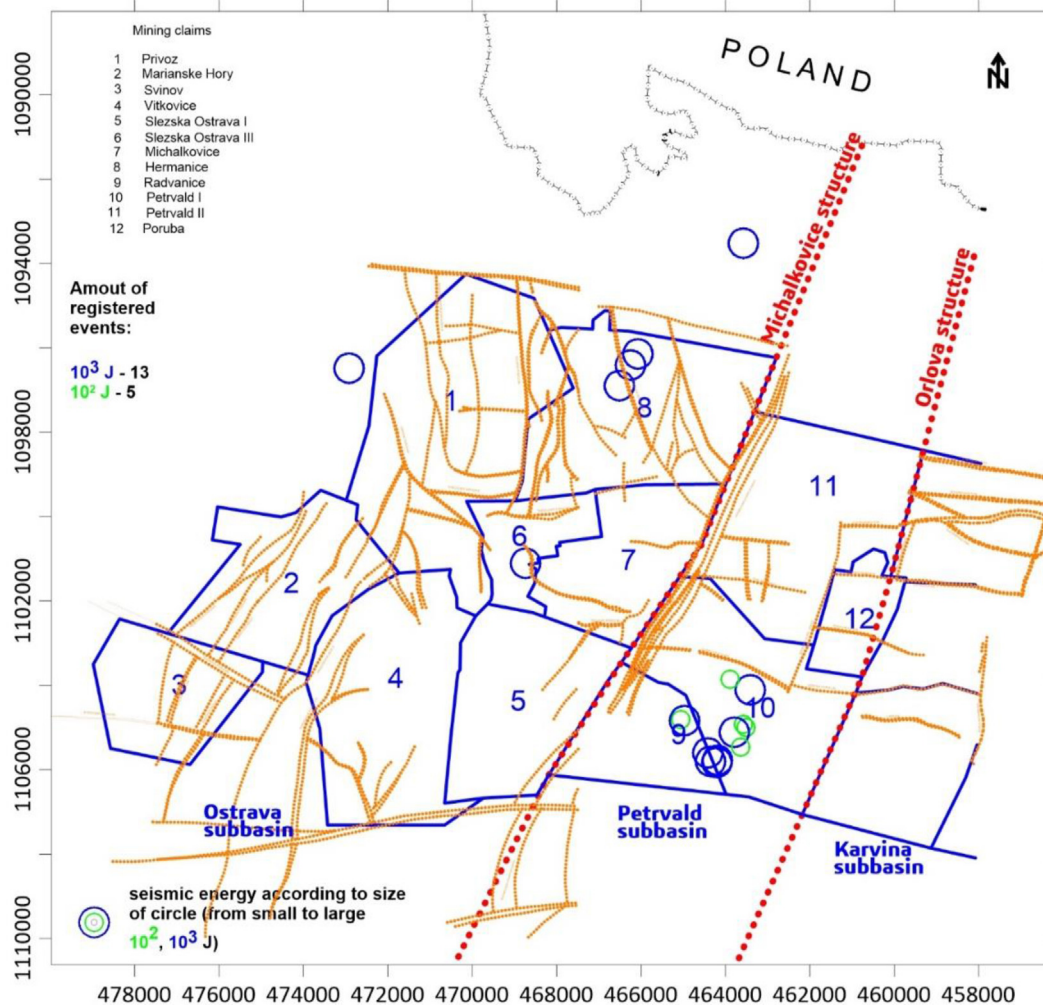


Fig. 12. Seismic activity recorded during the flooding period Ostrava and Petrovald sub-basins from 1994 to 2001 [20]. Seismicity in zones 11 and 12 is related to the mining operation in the Karvina and Petrovald mine until 1997.

Several phenomena of magnitude between 1 and 2.5 have been recorded over the past two years, with the strongest in February 2021 having a moment magnitude of 2.5 (Fig. 16).

In February 2021, as part of the RFCS project PostMinQuake, a local seismological network was installed in the mine “Kazimierz-Juliusz” (KJ network), consisting of three surface stations PM1, PM3 and PM4 (Fig. 15). Each one is equipped with three-axis 8-sec seismometers. The distance between stations oscillates around 3 km. The KJ network made it possible to record weaker seismic events of magnitude order $M_w > 0.5$. The “Kazimierz-Juliusz”, is the Polish pilot site of the Post-MinQuake project. Since 2018 in the post-mining area of “Kazimierz-Juliusz”, 21 seismic events of magnitude M_L between 0.8 and 2.1 have been recorded (Figs. 15 and 17).

The 21 earthquakes were detected by all stations, so it was possible to evaluate their location. Additional earthquakes with a magnitude of around 0.5 were as well registered, but by only a single station, so it was not possible to locate them precisely. Their sources were located somewhere between stations PM1 and PM4.

In May 2021, within the frame of the project, an automatic, hydrometric system measuring water level in carboniferous strata (deep piezometer PMG1) and in near-surface soils (two shallow piezometers PM1 and PM2) was launched at the area of the test site. The water level in the deep piezometer is measured in 1 h time intervals. The ground water level is measured in 1 s intervals of time. The deep observations of water movements in rock strata allow analyzing their general relationship with post-mining quakes (Fig. 17). The groundwater data (time

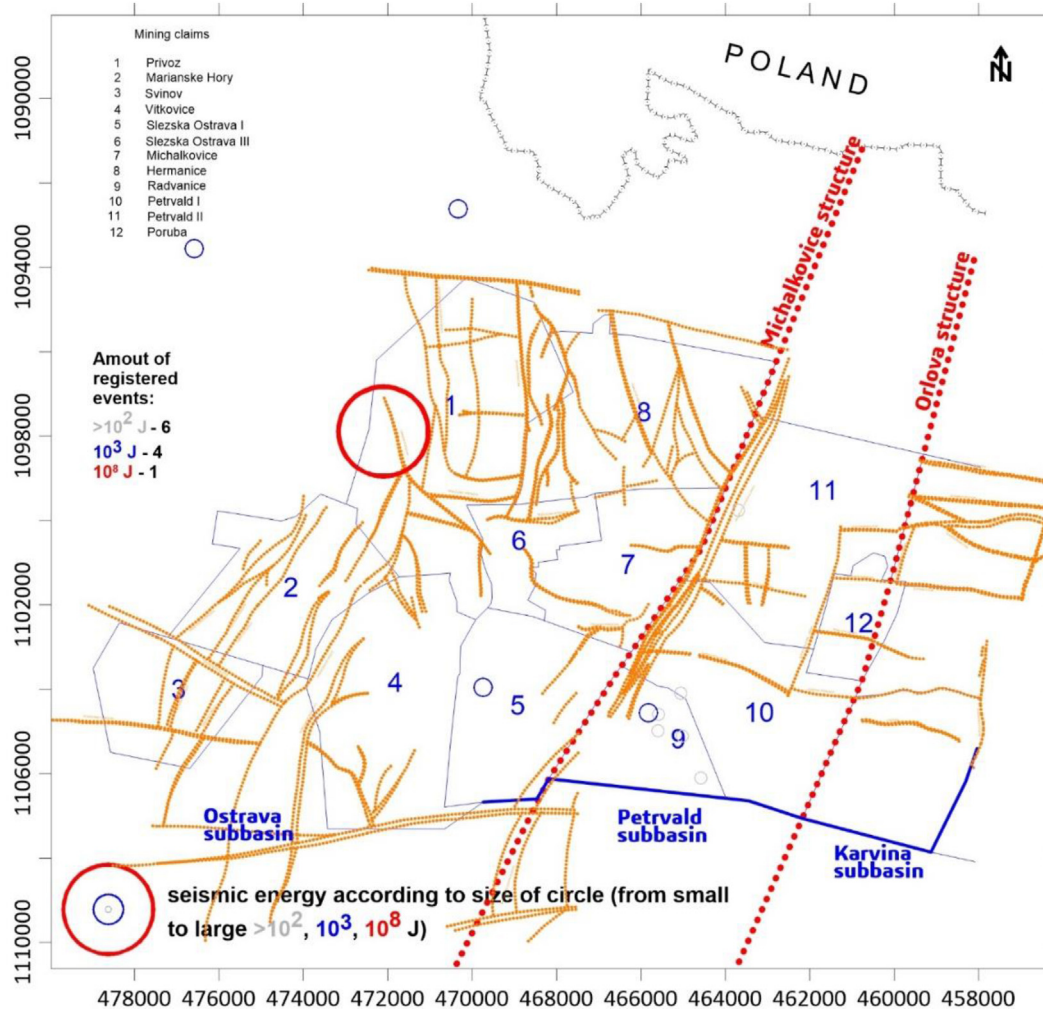


Fig. 13. Seismic activity recorded in the Ostrava and Petřvald sub-basins from 2001 to 2020 during the maintenance of the water level by pumping [20]. The major event of December 12, 2017, is located in sector 1.

series) allow analyzing co-seismic events recorded as short-term water movements (Fig. 18).

9. Synthesis and analysis of post-mining seismicity in EU

9.1. Mains lessons learned

Tables 1 and 2 resume the main characteristics of the considered basins of this study. In the former coal basin of Gardanne, all the seismic episodes were felt by the local population. It should be noted that, since 2018, seismic activity has been very low compared to previous years, with an absence of seismic episodes strictly speaking. This observation coincides with the increase in pumping capacity at the Galerie de la Mer (since 2016) by ensuring stabilization of the water level between -30 and -20 m below sea level at the Gérard well. Today, the origin

of basin-scale seismicity, both within and outside the monitoring areas, is not fully understood. Questions still arise regarding the roles played by variations in the level of the water table, the configuration and stability of the mining works, as well as the presence of natural geological faults. Apart from readjustments and/or underground collapses of mining structures, the hypothesis of the reactivation of natural faults by flooding as the origin of the seismicity of the Fuveau swarm (outside the risk zone) is probably the hypothesis that best explains the observed repetitive seismicity [4–6,14,28–32]. Observed in other industrial contexts using the subsoil, this type of phenomenon is well known when water is involved in the processes [2].

In Germany, post-mining seismic activity is monitored by the network deployed by the University of Bochum on a regional scale. This network

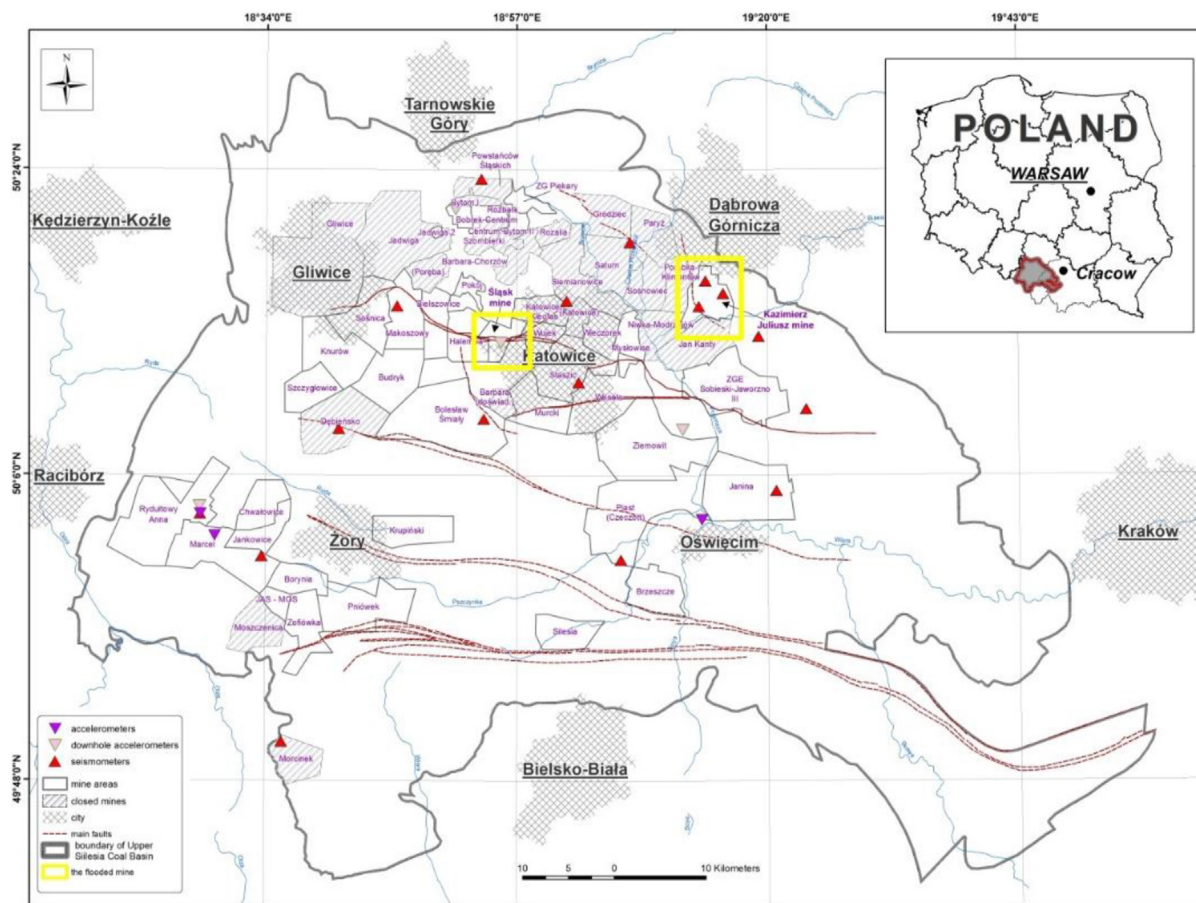


Fig. 14. Upper Silesian regional seismological network (USRSN) (red triangles – 3d seismometers, violet triangles – 3d accelerometers, light violet triangles – borehole accelerometers). The position of the Kazimierz-Juliusz mine and the Śląsk mine are shown in the yellow frame.

presents a greater concentration of stations at the level of the Ruhr basin (including the Hamm mine) than at the Ibbenbüren basin, which allows a distinction between natural or induced earthquakes. However, this network does not detect seismic events of magnitude less than 1 before 2021. For the Hamm mine, closed since 2010, it is observed that the recorded seismic activity is relatively moderate in terms of magnitude but possibly felt on the surface if the events take place at shallow depth. Indeed, events from magnitude 1.5 were felt by the population during operation, probably due to the presence of a site effect. The strongest event was magnitude 2.6 and took place in 2019. For the Ibbenbüren mine, closed in 2018, seismic activity shows few events, of rather low local magnitude (the highest being 2.2). It should be noted that in the Saar region, events relating to the flooding of the mine were felt in 2014 by the population. The strongest event had a magnitude of 2.7 and a ground particle velocity of 7.5 mm/s. Note that this mine was closed

earlier than planned in 2008 after the occurrence of a magnitude 4.5 event which caused significant damage [33].

The Czech case illustrates the problem of the coexistence of closed and active mines. The risk, in this case, affects the mine in operation which is flooded by the water of the closed mine and therefore jeopardize the safety of the miners. In this case study, there is no network dedicated to seismic monitoring of the closed Ostrava and Petřvald sub-basins. Earthquakes at the closed Ostrava and Petřvald sub-basins are detected by the network of the active Karvina sub-basin and with much less precision in terms of detection and localization because the events are located outside the network-monitored area. Seismic activity is weak in the closed Ostrava and Petřvald sub-basins, with the exception of a relatively strong event in 2017 of magnitude 3.5, which was also recorded by the Czech national network and felt by the inhabitants [23]. The origin of this event and its link with the flooding of the

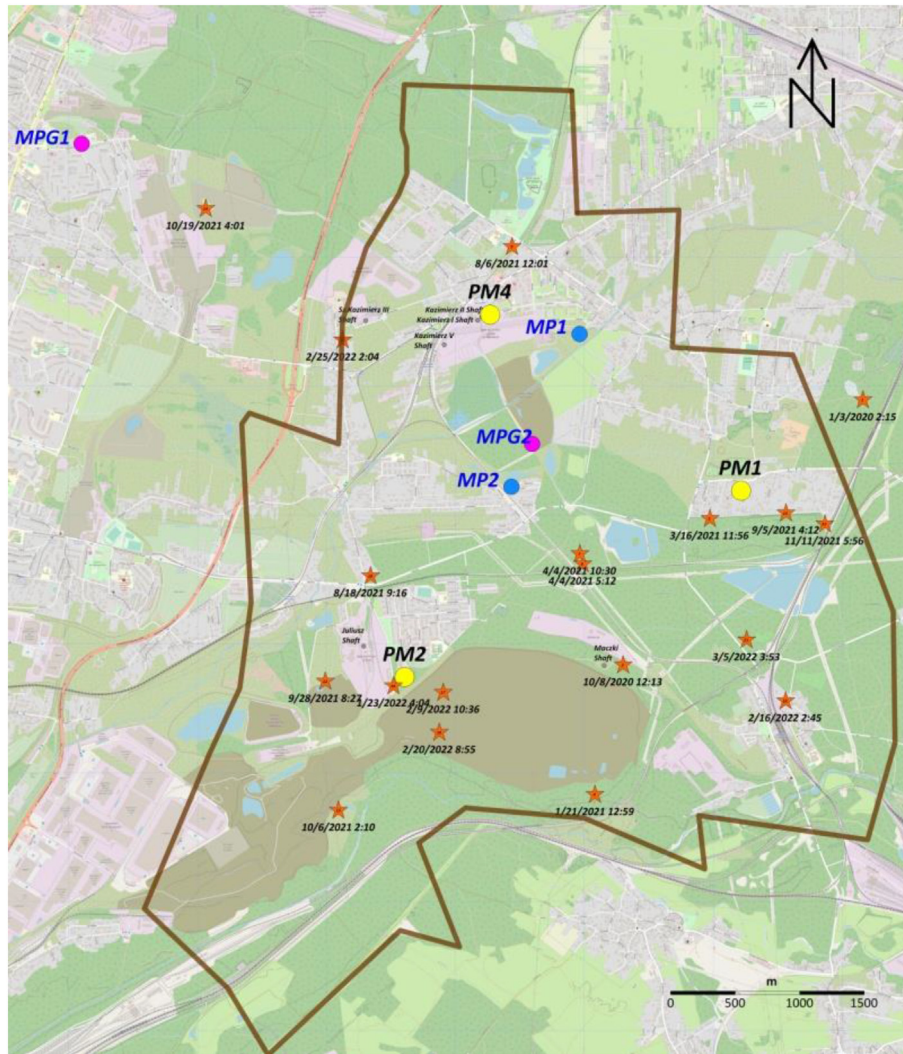


Fig. 15. Seismological (PM1, PM2, PM4) and Hydrogeological (MP1, MP2 – shallow piezometers, MPG1, MPG2 – deep piezometers) Networks set up at Kazimierz-Juliusz area (PM1, PM2, PM4) in spring, 2021 and seismic events recorded until march 2022 (red stars) on the background of topographical map [20,25].

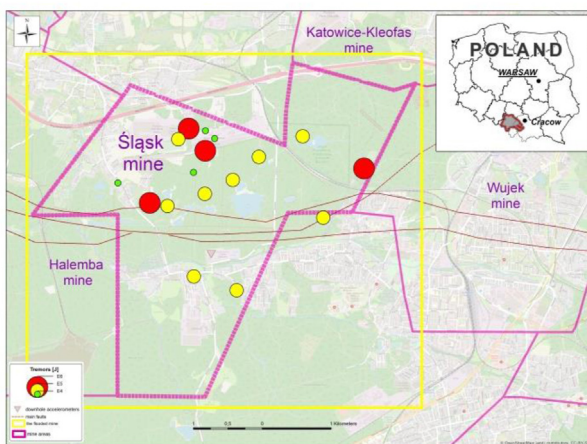


Fig. 16. Seismic events (in red: $M_w > 2$, in yellow: $1.5 < M_w \leq 2.0$, in green: $1.0 < M_w \leq 1.5$) recorded in the closed mining areas of KWK Śląsk.

Ostrava sub-basin, and the exploitation of the Karvina mine, will be studied in more detail.

In Poland, the local seismological network, installed in the Kazimierz-Juliusz test site in the frame of the PostMinQuake project, is the first network in Poland dedicated to post-mining seismicity. The data set of post-mining seismic events includes quakes detected as well by the regional (USRSN) and by local (KJ) networks. Since March 2022, USRSN and KJ networks recorded 21 events. Their magnitude ranged between 0.8 and 2.1. In addition to the Kazimierz-Juliusz seismicity, other mines in USCB also show post-mining seismic activity (KWK Śląsk and KWK Kleofas mines, westward of Katowice). The highest magnitude of events recorded in these regions was 2.7. The observed seismicity coincides with the flooding process of

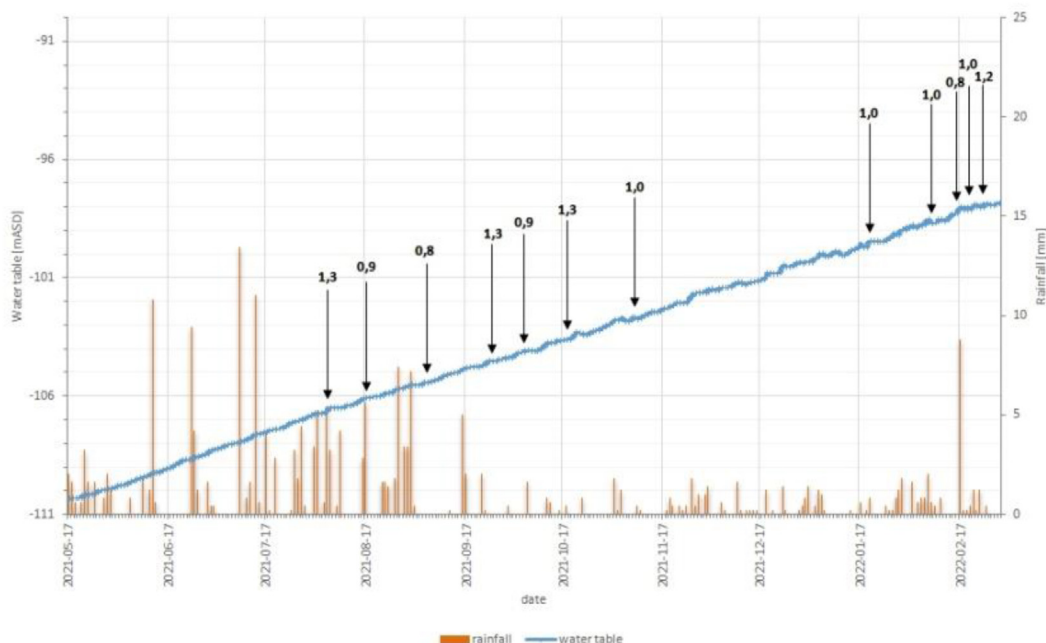


Fig. 17. Carboniferous water table time series in Porąbka Mine deep piezometer (region Adjacent from west to “Kazimierz-Julisz” mine border) against waterfall data and quakes recorded in period 17.05.2021–01.02.2022 [25].

closed mines. Some seismic events from post-mining areas were felt by the local population.

9.2. Situation regarding seismic monitoring

Post-mining seismicity is not specifically monitored in Europe, although each country considered

here has a national or regional seismological monitoring network. There are, however, different situations relating to monitoring:

- National or regional monitoring networks that only detect moderate to strong seismic events ($M > 1$): this is the case in Germany, the Czech

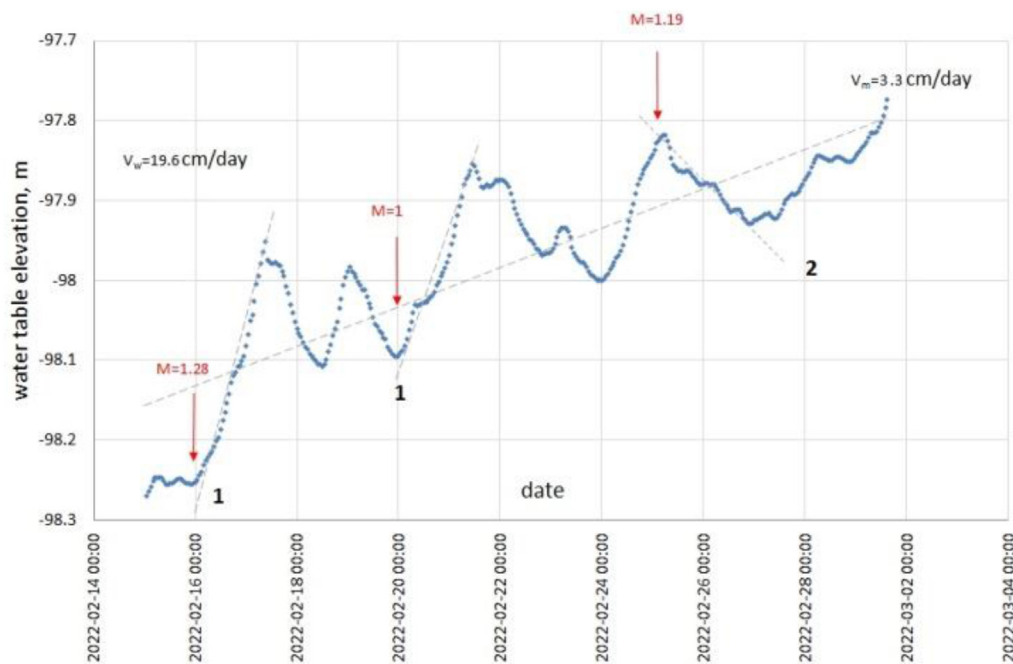


Fig. 18. Short-term water oscillations in deep piezometers PMG1 and selected quakes (magnitude and quakes marked in red).

Republic, Poland and France. There, events with magnitudes less than 1 are not detected. The Ruhr University of Bochum (Germany) has, however, intensified the number of stations in the Hamm basin; the mesh however remains large (≈ 2 km);

- Local and, therefore, more sensitive monitoring networks (detection of events with magnitudes less than 1) may exist, but they were not initially designed to monitor post-mining seismicity. This is the case:
 - in France, with monitoring networks dedicated to detecting the initiation of post-mining ground instabilities.
 - in the Czech Republic, where local monitoring networks have been installed in mines in operation (mines adjacent to closed mines) – to prevent the risk of landslides- and can therefore detect seismic events from closed mines.
 - in Poland, where configurations similar to those in the Czech Republic exist north of Katowice (operating mines adjacent to closed mines), however, this is not the case for the considered pilot site of the Kazimierz-Juliusz mine (site studied as part of the RFCS Post-MinQuake project). On this site, 3 new local seismic stations were installed, and the closest regional seismological station is located at around 10 km away.
 - In Germany, as the coal mining activity has ended, there are no more dedicated local seismological stations.

9.3. Post-mining seismic activity

Concerning seismic activity, the strongest magnitude values are of the order of 3. This is the case for the Hamm (3, Germany), the Ostrava sub-basin (3.5, Czech Republic) and that of Gardanne (3.2, France). These quoted seismic events were clearly felt by the population. We do not have precise information on the location of these events, but they probably occurred at shallow depth (of the order of a kilometre or less).

It should be noted that these basins have been closed for more than 10 years and that these “felt” events took place 9 years after the closure of the mines in the Gardanne basin, 4 years later in Hamm, and 13 years later for the Ostrava sub-basin. The basins of Ibbenbüren and Kazimierz-Juliusz were closed recently, and their situation is different because mine flooding has just started.

Due to their polyphase tectonic history, all the mining basins have complex geological features,

including pre-existing networks of fractures and faults (Table 1). Major faults can reach several kilometres in length, and in all basins, there is evidence of historical moderate natural earthquakes. Also, all basins experienced significant seismicity during mining operations, whose origin could be related to both mining and/or reactivation of natural faults in the deposit. These basins, at the time and after flooding, therefore, present a non-negligible seismic susceptibility accentuated by the presence of water (see Table 2).

Seismicity does not manifest itself in the same way in each basin. Nevertheless, differences in the observations may arise from the resolution of the deployed seismological networks, which is not identical from one country to another. This can lead to different magnitudes of completeness from one network to another, which in turn affects the seismicity rates and the so-called magnitude of completeness (M_c) that corresponds to the smallest magnitude event for which all of the events in a spatially and temporally limited volume are recorded.

However, if we consider the Gutenberg-Richter frequency–magnitude relationship, it is possible to compare the seismicity in each basin using the b -value that describes the ratio of the number of earthquakes with a small magnitude to the number of earthquakes with a large magnitude. For example, if we observe 1 event of magnitude ≈ 3 , there will be ~ 90 events of magnitude 2, 1500 of magnitude ≈ 1 , etc. Therefore, when considering the different seismic catalogues, it is highly likely that the seismic activity is significant in the Ruhr and Upper Silesian basins (Czech and Polish parts) even though small magnitude events are not detected; it is probably similar to that observed in the Gardanne basin, given that events with a magnitude close to 3 were recorded.

9.4. Hydrological situation

Triggering of seismic events on pre-existing faults due to changes in the hydrological cycle, such as seasonal groundwater re-charges and precipitation, has already been observed in both natural and anthropogenic environments. Here, the data combined with the geologic features provide sufficient evidence to conclude that, in all these basins, mine workings flooding played a role in reactivating pre-existing faults. Because the local stress state close to the faults is barely known, it cannot be compared to the regional tectonic stress regime. It is also difficult to conclude the orientation of these faults because of insufficient data.

Table 1. Summary table of the main characteristics of the considered basins.

| Mine | Basin | Country | Age of deposit | Tectonic context | Closure date | Surface of mining works [km ²] | Exploitation method | Presence of active mines in proximity | Depth of exploitation [m] |
|-------------------|-------------------|----------------|----------------|---------------------------|--------------|--|------------------------------|---------------------------------------|---------------------------|
| BW Ost | Rhur basin (Hamm) | Germany | Carboniferous | Molasse Basin | 2010 | 285 | longwall | no | 1200 to 1500 |
| Ibbenbüren | Ibbenbüren | Germany | Carboniferous | Molasse Basin + Plutonism | 2018 | 92 | longwall | no | up to 1560 |
| Ostrava | Upper Silesia | Czech Republic | Carboniferous | Molasse Basin | 1994 | 6 | rooms and pillars + longwall | yes | up to 1500 |
| Kazimierz Juliusz | Upper Silesia | Poland | Carboniferous | Molasse Basin | 2016 | 23 | longwall | no | 790 on average |
| Gardanne | Provence | France | Cretaceous | Lake Basin | 2003 | ≈ 64 | rooms and pillars + longwall | no | 0 to 1400 |

Table 2. Summary table of the main characteristics of the considered basins.

| Mine | Basin | Country | M_{\max} exploitation | Date | M_{\max} post-exploitation | Date | Mmax regional historical earthquakes | Date | Hydrological situation | Réseau sismique post-minier |
|-------------------|---------------|----------------|-------------------------|------|------------------------------|---------------|--------------------------------------|--------------|-----------------------------|--|
| BW Ost | Ruhr (Hamm) | Germany | 2,7 (?) | ? | 3 | 15.11.2014 | 5 | 1755 | level maintained by pumping | national network |
| Ibbenbüren | Ibbenbüren | | 4,5 | 1990 | 2,2 | 06.07.2020 | 6 | 1770 | level maintained by pumping | national network |
| Ostrava | Upper Silesia | Czech Republic | ? | | 3,5 | 12.12.2017 | 5 | 1895 | level maintained by pumping | national network + network of mine Karvina |
| Kazimierz Juliusz | Upper Silesia | Poland | 3,22 | 1977 | 2 | 23.06.2018 | 3 | 1837 | level maintained by pumping | national network |
| Gardanne | Provence | France | 4,5 | 1984 | 3,2 | November 2012 | 6,2 | Lambesc 1909 | level maintained by pumping | national network + local network |

The complex tectonostratigraphic framework has obviously influenced the exploitation progression as well as the mining methods implemented over time. It is, however, difficult to precisely quantify the impacts of the mining methods on the postmining seismic hazard level. It is clear that mining creates underground voids that can, after flooding, be considered an anthropogenic aquifers. The storage capacity can be huge, particularly in the context of room and pillar exploitation that leaves many voids. This post-mining aquifer can influence the stability of a fault both by hydraulic loading and/or by increasing the pore pressure. Feedback from the Gardanne basin shows that lowering the water level reduces both the rate and intensity of post-mining seismicity.

In addition, the underground water level is almost always artificially maintained at a given level for site-specific reasons. Sometimes pumping is done to prevent flooding of nearby active mines (Ostrava basin); sometimes, it is to prevent flooding of populated areas affected by mining-induced surface subsidence (Ruhr and Ibbenbüren basins). In other places, like the Gardanne basin, pumping maintains a water level that avoids overflows and visual discomfort (to prevent the discharge of “red” water into the port of Marseille).

Feedback from the Gardanne basin suggests that even small variations in the groundwater level can have an impact on the seismic rate: the strongest seismic activity correlates well with heavy rainfall periods and pumping capacity failures. For the other basins considered in this paper, the influence of the pumping capacities and the climatic conditions on seismic events triggering has not yet been analyzed.

10. Conclusion

This paper shows that microseismic monitoring can play an important role in post-mining hazard assessment in complex tectonostratigraphic frameworks where mine flooding can cause long-term post-mining induced seismicity. It also gives an overview of the post-mining risk management strategies set up in different countries as it is based on five case studies located in the coalfields of Gardanne (France), Hamm and Ibbenbüren (east and north-east of the Ruhr region, Germany), Ostrava and Kazimierz-Juliusz (in the Upper Silesian basin, Czech and Polish part respectively).

It shows that during ore production, all sites were affected by mine-induced seismicity (Rockburst) recognized as the response of the rock mass to strain changes induced by mining. All were at some point equipped with microseismic monitoring networks to control rock mass stability and prevent geotechnical

hazards. During the closure and abandonment phase, these networks were often quickly dismantled. This explains why post-mining seismicity has been poorly studied and documented until recently. It also emerges from this study that when microseismic monitoring is set up during or after mine closure, its objective is to detect and monitor early signs of instability at the level of the mining structures to anticipate post-mining ground movement on the surface, such as large-scale subsidence. The networks are not designed to monitor post-mining seismicity simply because the mechanism of induced/triggered seismicity in flooded abandoned mines is uncommon and therefore not well known or understood. The Gardanne basin can be seen as an exception, even though the post-mining risk management policy in France in that matter does not differ from the other countries: the monitoring system implemented to manage the risk of post-mining subsidence allowed to observe post-mining induced seismicity outside of the areas at risk for several years. Even though each of the considered countries has a national or regional seismological network, their performances are not sufficient to provide data for proper post-mining seismic hazard assessment.

However, the data confirm that all basins are affected by the occurrence of post-mining seismic events. In three out of five basins, closed for more than 10 years (Hamm, Gardanne and Ostrava basins), the strongest events reach local magnitudes of the order of 3–3.5; they are felt on the surface. They took place several years after the mine closure (between 4 and 13 years later). Besides, based on the classical Gutenberg-Richter law, we concluded that the basins of Gardanne, Ostrava and Hamm probably show a similar pattern in terms of the level of magnitudes, and we guess the mechanisms triggering the seismicity is also very similar. In the area covering the Kazimierz-Juliusz mine closed in 2016, post-mining seismicity has been observed since 2018. It motivated the installation in February 2021 as part of the project PostMinQuake, a local seismological network to provide data to further investigate the origin of this post-mining seismicity.

From this analysis, we can conclude that the possibility of the occurrence of post-mining seismicity is real in the presence of major pre-existing geological discontinuities and important volumes of mining voids to be flooded. Then, even if the magnitudes of the earthquakes are weak to moderate, these events are nevertheless felt as they occur at shallow depth. For this reason, also, the impacts of the vibration on buildings and infrastructures at the surface may become a problem in regions where the natural seismic hazard is low. There, constructions do not

meet seismic standards. In addition, some old structures could have been weakened by tremors generated during the mining operations. Under these conditions, the human perception and/or damage could be significant even in the event of a moderate earthquake (for example, an event of magnitude Kinscher J, Namjesnik D, Contrucci I, Dominiq \approx 4).

The experience of the Gardanne basin shows that underground water level variations, even of small amplitude, can play a major role in triggering seismicity, in particular through the reactivation of faults. This mechanism might exist in the other basins, where the water level is also maintained by pumping and where many faults have been identified. However, the correlations between post-mining seismicity, tectonic context and water level variations deserve to be better studied. Lowering the water level by pumping seems to have a beneficial effect in reducing seismic activity, as shown by feedback from the Gardanne basin. However, pumping has a high financial cost, and a breakdown or failure of equipment cannot be completely excluded.

To allow for conclusions applicable to all mines that have been abandoned or await closure, a detailed study of the correlation between seismicity and underground hydrological variation, therefore, seems essential to characterize the behaviour of the rock mass in terms of water stress, accentuated by the presence of mining works, which acted as an anthropogenic aquifer. Apart from having a local microseismic monitoring network, to increase the capability of detection of small magnitude earthquakes and improve their location accuracy, it is important to follow the rise (and then the variations) of the groundwater table by installing piezometric sensors at strategic places.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

The project PostMinQuake has received funding from the Research Fund for Coal and Steel under grant agreement No 899192. It was also co-financed by the French Ministry in Charge of the Environment and the Polish Ministry of Education and Science. The authors would like to thank all financing bodies for their support.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

We thank our colleagues for their constructive comments that helped to significantly improve the content of this manuscript. We thank anonymous reviewers who help to improve this paper.

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