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PostMinQuake: Seismicity of selected closed European hard coal mines during flooding

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Abstract: Mining of hard coal creates large underground cavities, which significantly affect the subsurface and land surface. Observations of land surface behaviour after the closure of mines demonstrate that these threats do not disappear. During mine water rebound in the post-mining phase of underground coalmines, the water flows into the open mine workings and other altered or fissured areas.

This paper provides early observations from the PostMinQuake project, which is designed to identify mechanisms, relevant parameters and dependencies of mining and geological parameters causing post-mining seismicity in several European coal regions. It also presents the correlation between seismicity and water table level in the studied basins that has been observed during the post-mining phase and shows the necessity of implementing new procedures to monitor these seismic events.

Kurzfassung: Durch den Abbau von Steinkohle entstehen große unterirdische Hohlräume, die den Untergrund und die Landoberfläche erheblich beeinträchtigen. Beobachtungen des Verhaltens der Landoberfläche nach der Schließung von Bergwerken zeigen, dass diese Gefahren nicht verschwinden. In der Nachbergbauphase kommt es zu einem Grubenwasseranstieg in untertägigen Kohlebergwerken. Hierbei fließt das Wasser in den offenen Grubenbau und andere veränderte oder durchbrochene Bereiche.

In diesem Beitrag werden die ersten Erkenntnisse aus dem PostMinQuake-Projekt vorgestellt. Dieses zielt darauf ab, Mechanismen, relevante Parameter und Abhängigkeiten von bergbaulichen und geologischen Parametern zu ermitteln, die in mehreren europäischen Kohleregionen Seismizität nach dem Abbau verursachen. Außerdem wird die Korrelation zwischen Seismizität und Grundwasserspiegel in den untersuchten Gebieten dargestellt, die während der Nachbergbauphase beobachtet wurde. Dabei wird aufgezeigt, dass es notwendig ist, neue Maßnahmen zur Überwachung dieser seismischen Ereignisse einzuführen.

Keywords: post-mining, microseismicity, flooding, water table, hard coal

Schlüsselwörter: Nachbergbau, Mikroseismizität, Bergwerksflutung, Grubenwasserspiegel, Steinkohle

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1. Introduction

Seismic events can be classified into natural and anthropogenic earthquakes, the latter ones being induced or triggered by human related operations, such as fluid injection, extraction or mass shifts (McGarr et al. 2002; Dahm et al. 2013; Grigoli et al. 2017; Foulger et al. 2018). Mining operations can produce induced seismicity in response to mass shifts and induced stress perturbations in the shallow underground (McGarr & Simpson 1997); indeed seismicity in mines represents the first form of anthropogenic seismicity which has been identified and described in the literature, with a first record already in 1908 (Mintrop 1909). Mining operations are responsible for stress loads in the area of the seams, which appear in form of fractures. Within deeper strata, these fractures can have a larger impact and are typically referred to as rockburst in mining terms.

Underground mining methods used to extract minerals from the subsurface have an influence on the geological environment and the use of the land surface. This influence is even stronger in mines in which coal and metal ores are being extracted, since large quantities of rock are extracted and transported to the surface (Didier et al. 2008). The most important effects concern continuous and non-continuous land deformations and dynamic impact of rock mass tremors on people and structures (Kotyrba 2005; Kotyrba & Mutke 2015). Such extraction of these large quantities of rock lead to free cavities and fractures where the water would flow easily, and therefore underground mining requires drainage of the rock mass.

In the post-mining phase of underground coal mines, the mine water will no longer be pumped and therefore the water can flow into the mine workings and altered or fissured areas (Wolkersdorfer 1996). While transporting the water, coalmine gases might also be displaced and, along with other factors, can cause roadways to collapse (Melchers et al. 2019). According to Busch et al. (2012) ground movements can be caused, amongst others, by hydrogeological and hydrological changes through water drainage and flooding. These ground movements that occur during mine water's rebound, which affect the stress field of the rock mass, may, in the end, cause damage to buildings and other infrastructures in the surface (Melchers et al. 2019).

The cessation of drainage systems causes the groundwater to return to its primary state, which existed in the geological environment before the construction of mines. Re-saturation of the transformed rock mass by mining works is an important factor affecting its internal mechanical stability and land surface behaviour. Therefore, observations of the groundwater and rainfall water become important factors for long-term assessment and safe use of post-mining lands (Frolik et al. 2020). The monitoring of threats to land use and related issues with novel technologies are the subject of many international and national scientific initiatives (Leptokaropoulos et al. 2019; Mutke et al. 2019; Kotyrba et al. 2020). One of such initiatives is the PostMinQuake project (Chodacki et al. 2021), which is a European research project funded by the Research Fund for Coal and Steel (RFCS), with the task to study several European coal regions and identify mechanisms, relevant parameters and dependencies causing post-mining seismicity. The partners participating in the project are located in France, Germany, Czech Republic and Poland.

2. Methodology

The PostMinQuake project aims to help identify the effect between groundwater and induced seismic events in former hard coal regions. For this purpose, each partner chose a different hard coal basin of interest for the research, which is shown in Fig. 1.

Once the region was chosen, it was necessary to gather data, analyse and compare it. Therefore, the same process was followed for each region, which will be described in the following. First, it was necessary to gather information about induced seismicity in the area during the post-mining phase. For this purpose, in each country it was necessary to retrieve the data from the institutions that had installed the seismological network. Then, the data for the water table level was also gathered. Finally, the data was combined to analyse the relation between water table level and seismic events.

In order to have a better overview, all the material will be described below and classified per basin and country. First, there is background information regarding the location of the basin, geology, mining, monitoring of seismicity and water table level, along with its legal framework during post-mining in the country. Then, the data related to the monitoring during post-mining will be presented. To conclude, there will be an interpretation of these data.

2.1 Gardanne (France)

2.1.1 Background of Gardanne

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, from Saint-Maximin to Etang de Berre, and over 15 km from north to south between Aix-en-Provence and Marignane (Fig. 3). Western Provence is part of the Pyrenean-Provencal domain in Southern France. The tectonic formation of western Provence occurred at the end of the Eocene. The Gardanne Basin lies between the North Provencal and South Provencal overlaps (thrust belt). In the west, it disappears beneath the Rhodanian Quaternary. Locally, the Gardanne Basin is limited to the south by the east–west running Diote Fault (Fig. 2).

The coal mine was mined between the 15th century and the early 2000s, at depths of up to 1,400 metres. After the cessation of mining and the halt of pumping operations in 2003, the mine was partially and gradually submerged. Flooding progressed from west to east, in order to bring the groundwater level up from -1,100 m below sea level in 2003 to -14 m below sea level in 2010. In 2010, pumping resumed and several fluctuations affected this water level, such as

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Fig. 1: Location of mining regions (dotted circles): Gardanne in France, Hamm in Germany, Upper Silesian Coal Basin in the Czech Republic and in Poland.

seasonal water inflows, breakdowns of the pumps or the increase in their capacity.

When the operations began, the stability of underground structures was a major concern for the operator. After its closure in 2003, studies on the long-term stability led to the identification of areas at risk of subsidence due to the soft/brittle nature of the overburden (Geoderis 2003, 2016). Since 2007, a permanent microseismic network (five borehole stations) has monitored these areas to detect and observe the precursor signs of mechanical instabilities at the mining galleries to prevent possible surface deformations (ground motions) below inhabited areas (Fig. 3).

Since 2010, the basin has been periodically affected by seismic activity, located outside the areas monitored by the

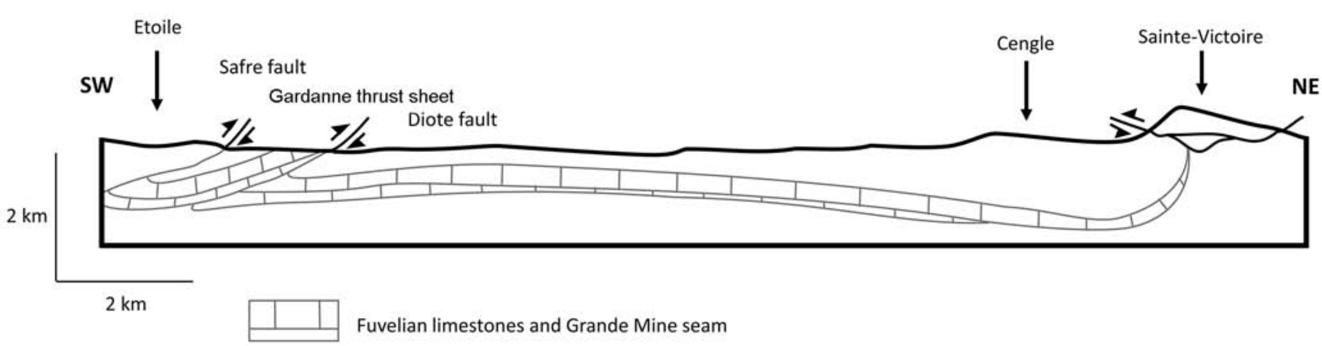

Fig. 2: Geological structure of the Gardanne Basin (based on Durand & Guieu 1980).

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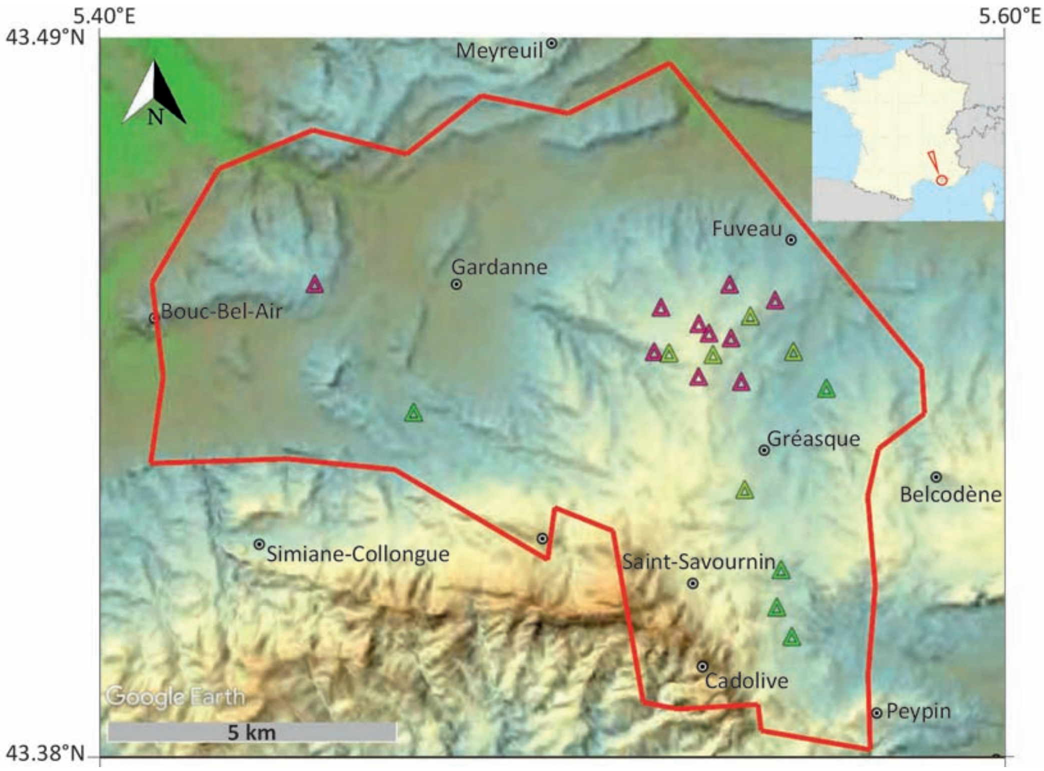

Fig. 3: General view of the Gardanne coal basin. Permanent seismic network (dark green triangles), temporary seismic networks (Ineris stations: light green triangles; BRGM stations: purple triangles).

permanent seismic network. This seismicity led to the deployment of temporary additional surface seismic networks in order to specify their origin. This temporary system located on the Fuveau-Gréasque sector expanded between 2013 and 2018: it now includes 14 surface seismic stations and 4 piezometers (Gérard, L'Huillier, Champisse and Gréasque), which are complemented with 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 (HAS). All these datasets (hydrological and seismological) are managed in the web-monitoring portal e.cenaris (https://cenaris.ineris.fr), subject to request for authorisation of access). Fig. 3 shows the seismic network in Gardanne.

In France, the legal framework for post-mining risks management does not take into account the observed seismicity in order to be able to define post-mining hazard zones based on ground instabilities. The approach used is purely geomechanical, based on the mine's stability. The seismicity felt in the northeast of the basin (Fuveau swarm) is not integrated into the risk management, as it is located in a zone of low hazard (soft subsidence). To improve post-mining risk management in this region, we suggest considering the observed seismicity as an input data to define post-mining hazard areas.

2.1.2 Post-mining monitoring at Gardanne: seismicity and water table

Since 2008, the permanent network has recorded more than 3,200 events of low to moderate local magnitude ($-3 < M_L < 3$), see Fig. 4. The eastward migration of the flooding front began after the halt of pumping operations in 2003. In 2009, the water level reached the Regagnas mining area (Fig. 4), located northeast of the basin, west of the Fuveau seismic monitoring station. Since that time, repetitive seismic activity has appeared at this location. It is spatially concentrated and it has continued until today in the form of swarms. This seismic swarm is referred to as "the seismic swarm of Fuveau". The most important seismic events recorded during these events show magnitudes close to 2.

Five main seismic episodes were observed at this location that correlated with water level variations: in 2010, in November 2012, in December 2014, at the end of 2016 and beginning of 2017, and in August 2017. All these episodes were felt by the population. It should be noted that since 2018 seismic activity has been very low, compared to previous years; there has only been one swarm that has not been perceived by the population on June 12 and 13, 2021 (Dominique et al. 2022) with more than 70 events. This low seismicity coincides with the increase in the pumping capacity at the Galerie de la Mer (since 2016) by ensuring a stabilisation of the water level between -30 and -20 metres below sea level at the Gérard well.

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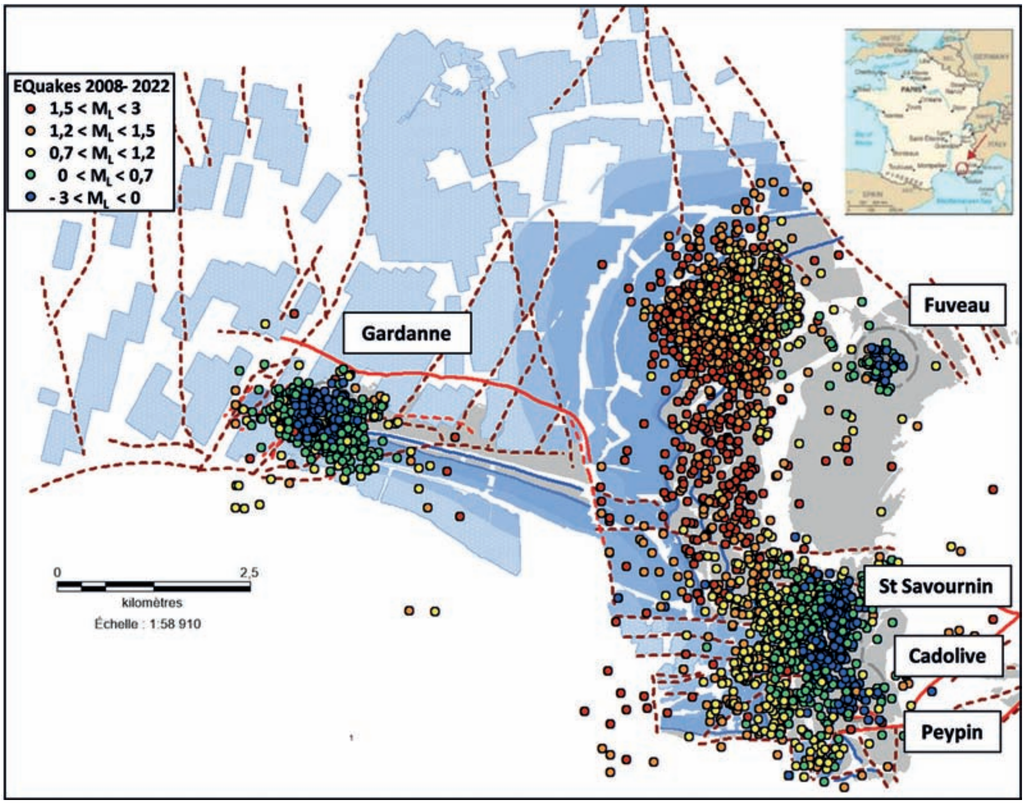


Fig. 4: Location of post-mining seismicity recorded in the Gardanne Basin (France) between 2008 and 2021.

Today, the origin of basin-scale seismicity is still not fully understood (Dominique 2015; Matrullo et al. 2015; Kinscher et al. 2017; Kinscher et al. 2018; Kinscher et al. 2021; Namjesnik et al. 2021; Dominique et al. 2022). Questions arise as to the roles played by variations in the level of the water table, the configuration and stability of mining structures, as well as the presence of natural geological faults. Beyond the ground motion (compensation motion) 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 monitoring zone), is probably the main explanation for the repetitive seismicity detected (Namjesnik et al. 2021; Dominique et al. 2022). In other industrial contexts related to the underground, this type of phenomenon related to the effect of water is well known (Contrucci & Klein 2018).

2.1.3 Analysis of Gardanne

The former coal basin of Provence shows significant post-mining seismicity with more than 3,200 events of local magnitude between $-3 < M_L < 3$, recorded since the establishment of the permanent seismic network in 2008. Thus, this phenomenon, which could be described as a post-mining seismic hazard, has a significant impact in this region, with the occurrence of several seismic episodes felt by the local populations in 2010, 2012, 2014, at the end of 2016, early 2017 and August 2017.

These seismic episodes show that the seismicity of the entire basin is dependent on variations in the underground water level, maintained artificially by pumping. Since the end of 2017, there has been a significant drop in seismic activity in connection with the increase in pumping capacity, which makes it possible to maintain the water level at a quasi-constant level. Research work is nevertheless helpful in better understanding this hazard, in particular the phenomenon of reactivation of faults located under the mine. In the current state of knowledge and despite the limitations in terms of available data, the geometry and dimensions of the fault structures involved could produce events of M_L ~3.5 (Dominique et al. 2022).

2.2 Hamm (Germany)

2.2.1 Background of Hamm

Germany has had a long history of hard coal mining. Hard coal mining ceased in 2018, after the government agreed to put an end to hard coal production (Melchers et al. 2019). The most important deposits (Fig. 5) that were mined are located in the state of North Rhine-Westphalia (NRW), such as in the Ruhr Area and in the Tecklenburger Land (Ibbenbüren's hard coal area), and in the region of Saarland. Nevertheless, it is also important to mention former coal deposits, whose production had ceased a long time before, such as

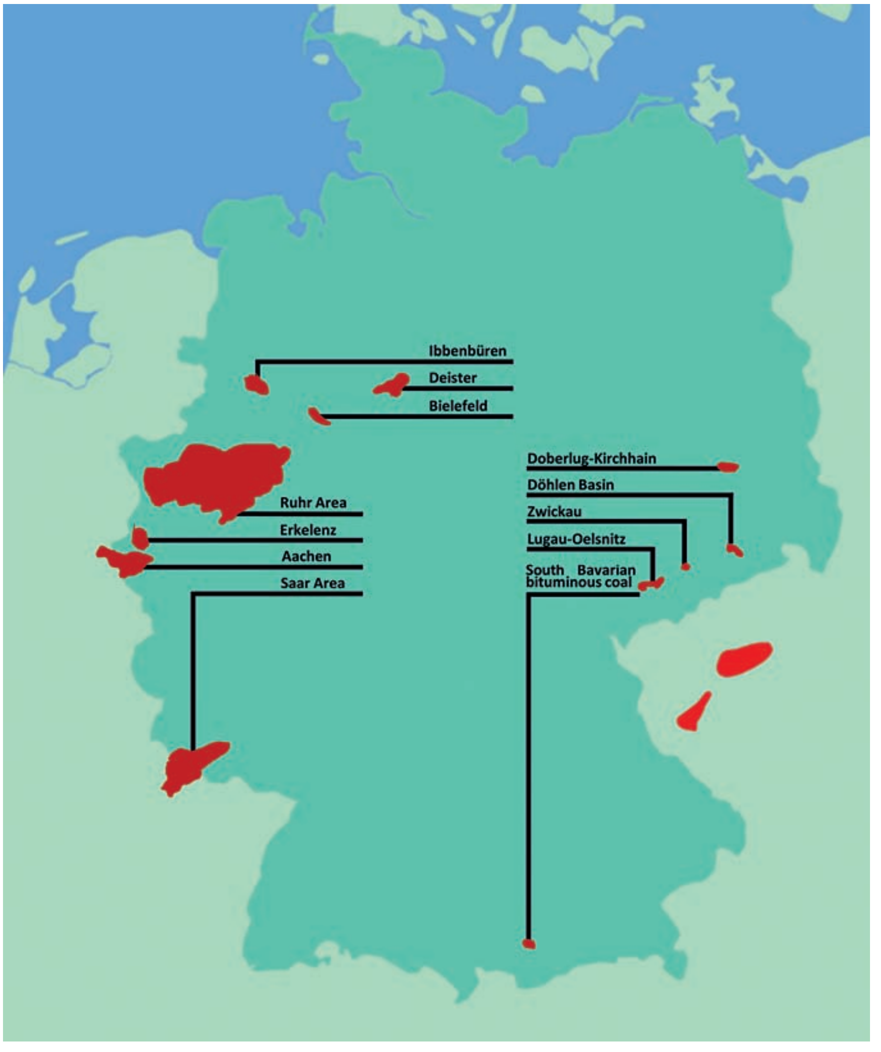


Fig. 5: Main hard coal basins in Germany (Melchers et al. 2019).

the Aachen and Erkelenz Area (NRW), Lugau-Oelsnitz (Saxony) and Zwickau (Saxony). This paper focuses on Hamm in the Ruhr Area.

The coal strata in the Ruhr Basin originated around 300 million years ago during the Carboniferous and consist of an alternating sequence of clay, silt and sandstones up to 2,500 m thick with embedded coal seams (Hahne & Schmidt 1982). Towards the end of the Carboniferous, the deposits were folded, broken and segmented into numerous horst- and graben structures by mountain-building processes. The folded structure contains several saddles, whose main axes' trend is southwest–northeast. During later tectonic active periods, large cross-cutting faults developed and cut into the existing structures. The Carboniferous surface observed in the south of the area at a height of approximately 100 m above sea level also emerged due to recent lifting processes in the south, around 2° to 3° to the northern limit of the lower part, located approximately 750 m above sea level. The basement, made up of rocks from the Palaeozoic Era, was essentially formed during the Variscan Orogeny in the Upper Carboniferous (Fig. 6).

The mine "Bergwerk Ost" (BW Ost) is the result of the merging of the former mines Haus Aden (Oberaden), Heinrich Robert (Hamm) and Monopol (Bergkamen) in 1998, which covered an area of 285 km² in the end. It is located in the eastern part of the Ruhr Area, specifically belonging to the Kernmünsterland and the southern part to the Hellwegbörden. The choice of the mining method for the extraction of mineral resources depends on the deposit conditions. According to Preuße (2002) modern German hard coal mining used long wall mining. This is an underground method, in which an almost rectangular section of the seam is extracted between two parallel mining drifts. While the long wall mining area ("face length") progresses, the goaf increases, which can then be treated as quarry mining or as backfill.

In the investigation area (BW Ost), the earth tremors are monitored by the seismological observatory of the Ruhr University Bochum (RUB). Detected earthquakes are located in

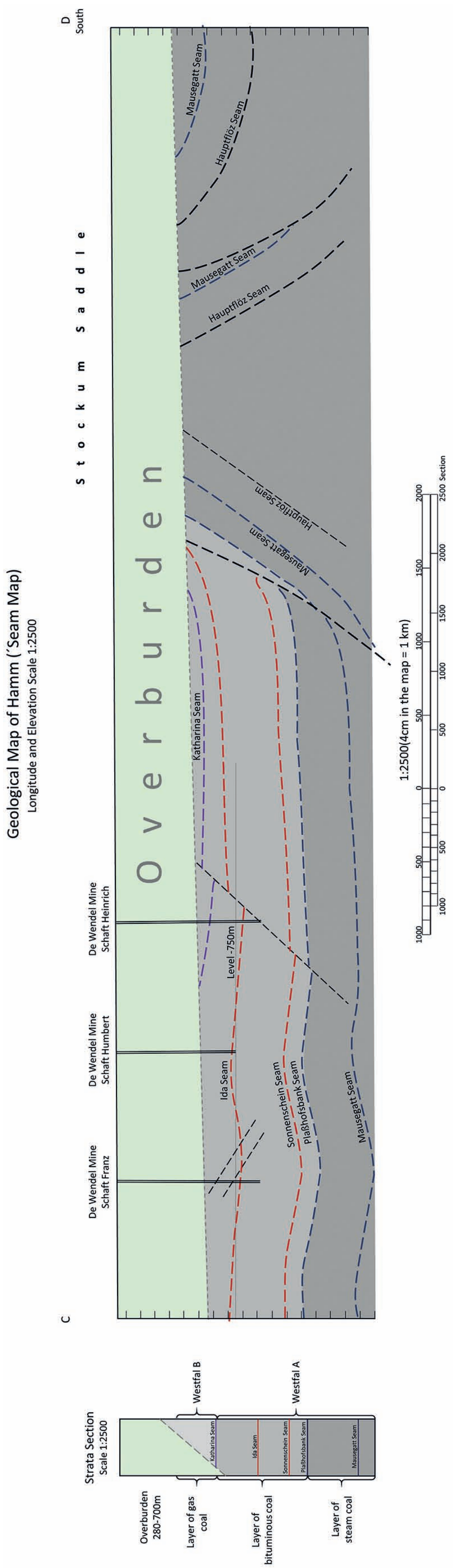


Fig. 6: Geological structure of Hamm (based on Busch et al. 2017).

the Ruhr Area, with an estimated location accuracy of ~2 km in the western Ruhr Area and ~5 km in the peripheral areas. The anthropogenic, mining-induced tremors cluster at a depth of less than 1 km below the surface, which is much shallower than for natural earthquakes (Busch et al. 2017). In Germany, the monitoring of the water level is being carried out by the RAG Aktiengesellschaft in former coal mine regions, such as Hamm.

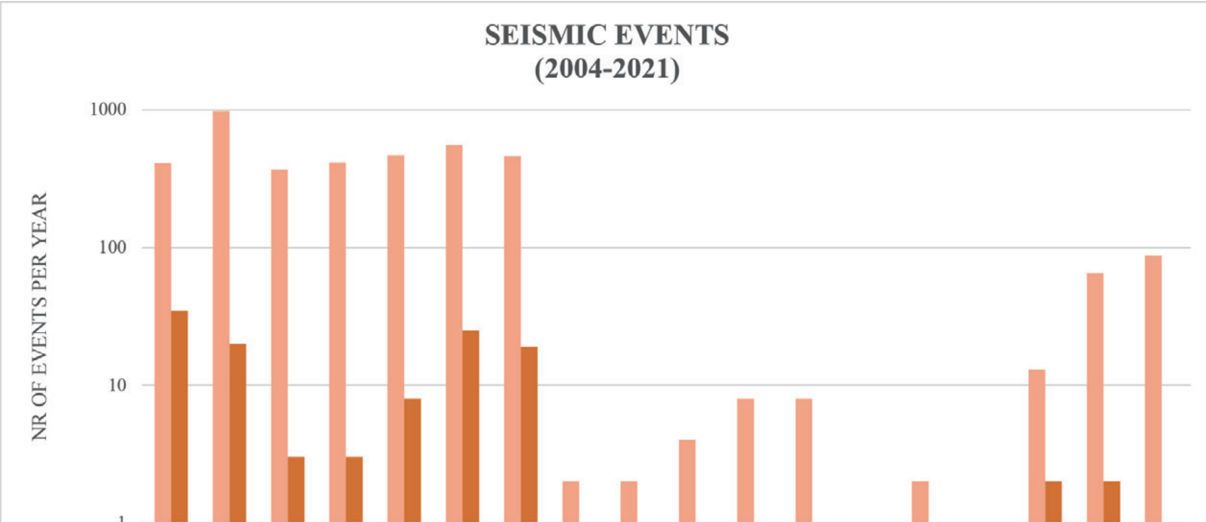
In terms of post-mining law, it is also not mandatory in Germany to monitor post-mining seismicity or the mine water level, it is only necessary to hand in the plan for water management and ground movement monitoring. Nevertheless, regional mining and post-mining seismicity is well recorded by different institutions such as the RUB or the Geological Survey NRW, but there is not a common seismic catalogue or database.

2.2.2 Post-mining monitoring at Hamm: seismicity and water table

The catalogue compiled by the Seismological Observatory of the RUB between 1 January 2004 and 30 September 2010 (Fig. 7) reports a total of 3,770 earth tremors that occurred in Hamm. Whereby 3,657 of these earthquakes had a magnitude $M_L < 2$ and went unnoticed by the general population since the geological structure in this area absorbs the energy that reaches the surface.

The seismic activity ended abruptly with the cessation of production at BW Ost on 30 September 2010, so from 2011 onwards there was low seismic activity (Busch et al. 2017). The catalogue reports only 204 tremors in the period between 1 October 2010 and 31 December 2021, when only seven had a magnitude $M_L > 2.0$ (Fig. 7). Seismicity is located close to the mined area (delimited by the blue dash line in Fig. 8). Since the end of 2019 the seismicity rate substantially increased and has remained steady to date within the range of ~57 per events/year.

The piezometers from the RAG Aktiengesellschaft that continued measuring the water level since the mine's closure in 2010 are Heinrich, Kurl 3, Lerche and Radbod; further piezometers will continue measuring in the future. The location of these stations can be seen in Fig. 8, in which the former coal mine's border is marked by the light blue dashed line. As can be seen in Fig. 9, the substantial increase in the rate of induced seismic events since the end of 2019 coincides with the moment in which the water level increased, reaching closer to the surface, and when it also ascended more rapidly. It is worth noting that not only did the events occur more often, but also their depth became shallower. The magnitude of these induced events remains low, generally with M_L between 1 and 2. Seismicity displayed some lateral migration, with epicentres moving towards SE when compared to those that took place at the beginning of the post-mining phase.



	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
1<ML<2	412	981	370	415	466	554	463	2	2	4	8	8	1	2	0	13	65	88
2<ML<2.7	35	20	3	3	8	25	19				1	1			0	2	2	1

Fig. 7: Seismic events with ML >1.0 in Hamm during last years of mining phase 2004–2010 (after Busch et al. 2017) and during post-mining phase 2010–2021 (based on data from Seismologisches Observatorium der Ruhr Universität Bochum 2021).

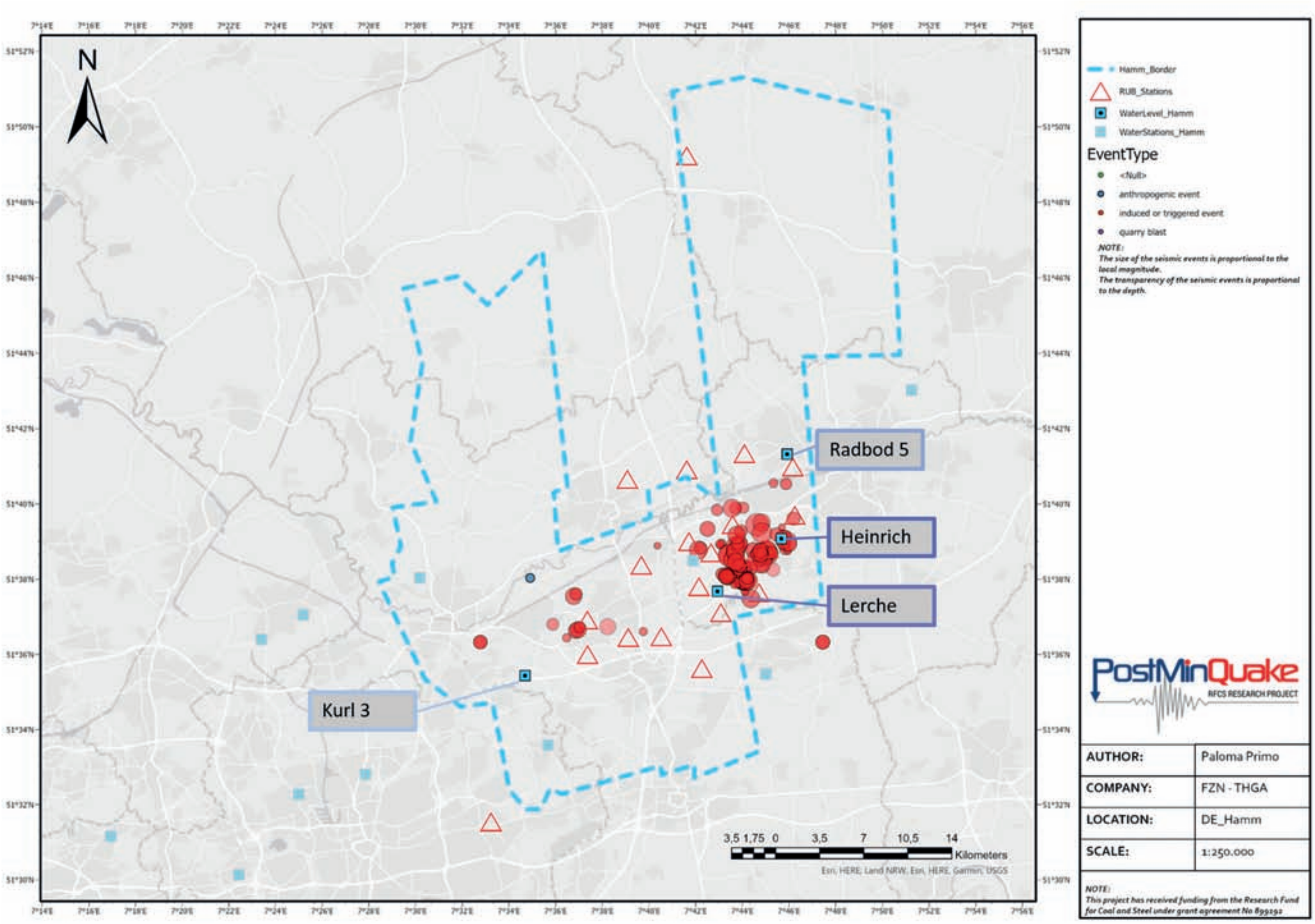


Fig. 8: Spatial distribution of post-mining seismicity in Hamm for the time period 2010–2021. Circles denote earthquake epicentral locations (size proportional to the local magnitude). Red triangles denote the locations of seismic stations, and blue squares RAG's water stations (based on data from Seismologisches Observatorium der Ruhr Universität Bochum 2021, RAG Deutsche Steinkohle 2021).

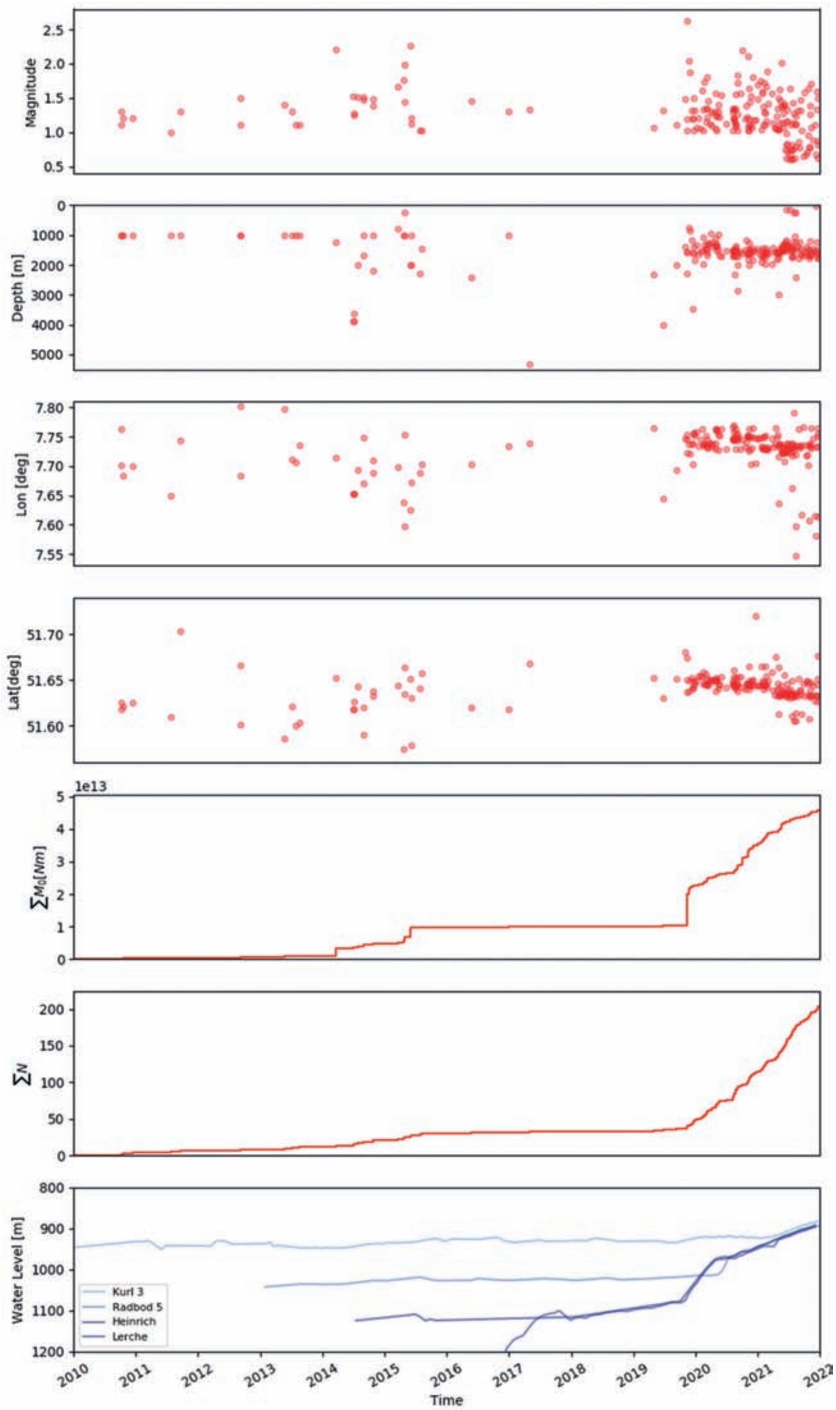


Fig. 9: Overview of the time evolution of seismicity and water level during post-mining. From top to bottom the different diagrams show the local magnitude, depth, longitude, latitude, cumulative number and cumulative scalar moment of the seismicity induced during post-mining from 2010 to 2022, as well as the evolution of the water level at four measuring stations. Seismic events in the first four panels are marked by circles; note that the depths were fixed to 1,000 m by the Seismological Observatory of the RUB until 2014 due to lack of accurate data at the time.

2.2.3 Analysis of Hamm

As shown in Fig. 9, the substantial increase in the rate of induced seismic events since the end of 2019 coincides with the moment when the water level increased, reaching closer to the surface, and when it also ascended more rapidly. The local magnitude of these induced events is considered to be low, generally with M_L between 1 and 2. Seismicity displayed some lateral migration, with epicentres moving towards SE when compared to those that occurred at the beginning of the post-mining phase, which also coincides with the direction of the rising water table.

2.3 Upper Silesian Coal Basin (Czech Republic)

2.3.1 Background of Ostrava, Petrvald and Karvina subbasins

The Upper Silesian Coal Basin (USCB) is located on the border of the Czech Republic and Poland and is one of the largest coal basins in Europe. The estimated bituminous coal reserves in the Czech Republic are around 3.7 billion tons. The USCB was formed in the final stages of the evolution of the extensive Moravo-Silesian Palaeozoic Basin situated in the eastern blocks of the Central European Variscides. The geological character of the Czech part of the USCB, called Ostrava-Karvina Coal Basin, has been described in several publications. Dopita et al. (1997) summarised the existing knowledge of the geology of the basin. Chemical-technological parameters of the coal and reserves calculations for the individual mining areas are described in Sivek et al. (2003). Properties of coal matter are discussed in Martinec et al. (2006).

The Upper Carboniferous sediments containing bituminous coal deposits are divided into the Ostrava and Karvina formations (Fig. 10). Between the Ostrava and Karvina formations, there is erosional contact associated with a hiatus (Dopita et al. 1997). In the USCB there are two structural domains divided by the Orlova structure (Fig. 10). The Ostrava and Petrvald subbasins are located in the west, with a complicated tectonic structure, and in the east lies the Karvina Subbasin with a predominance of transtensional fault tectonic (Grygar & Waclawik 2011).

The USCB belongs to the tectonically most complicated Palaeozoic molasse basins of the European Variscides. The basin has a polytype character and an asymmetric structure. The main expression of this basin is a W–E oriented tectonic asymmetry (Fig. 10). The basin has a complex tectonic style.

Hydrogeological conditions in the Czech part of the USCB are heavily influenced by anthropogenic activities. Impacts of workings and exploitation, including the subsidence induced deep hydraulic de-watering of the rock complex, have changed the natural geo-hydro-dynamic systems. Originally separated groundwater bodies have been interconnected.

Younger et al. (2002) used the conception of "compartments" (denoted as "ponds") for evaluation of post-mining flooding of mines and the definition of hydraulic connectivity on the borders of compartments. Inherent in the definition of a compartment is the concept that the mine workings within a compartment are extensively interconnected (often on multiple levels, if mining was undertaken on more than one horizon) so that water rising within a compartment will display a common level throughout that compartment. At certain elevations, adjoining compartments may be connected via discrete fluid pathways (Younger et al. 2002). Typical decant features include (Younger et al. 2002):

- Areas in which two adjoining goafed panels coalesce,
- Old exploration boreholes,
- Permeable geological features (e.g. the margins of a basaltic dyke, a limestone bed, or an open fault plane).

The industrial coal mining began at the turn of the 18th century to the first quarter of the 19th century. After World War II, the demand for coal tended to rise. The highest values of coal mining were reached in the mid-1970s (Sivek et al. 2020; Sivek & Pesek 2016). The original mining method was coal mining through galleries built within the coal seam.

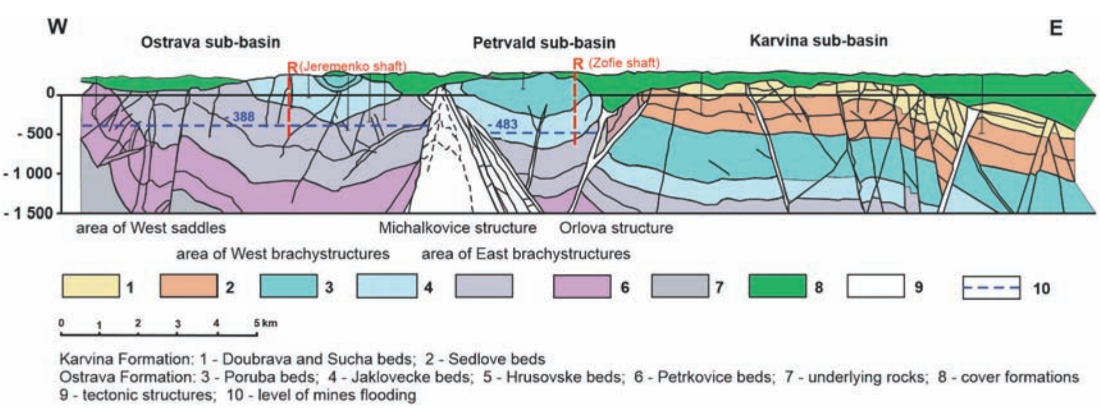


Fig. 10: W–E cross section in the northern part of the Czech part of the USCB showing major geological units (modified following Dopita et al. 1997).

From the 1880s onwards, the room and pillar method was used with several modifications. Long wall mining has been the prevailing mining method from the 1940s onwards, both with control caving as well as with backfilling.

Mined thickness of coal seams depends on the structure unit and its variability is extremely high. The mining thickness in the Ostrava and Petrvald subbasins is generally ranging from 0.4 to 1.1 m, in specific conditions up to 1.5 m or exceptionally to 4 m. The thickness of coal seams in the Kavina Subbasin is ranging from 2 to 8 m, in specific conditions of connected coal seams up to 15 m.

Recorded seismicity is mostly connected to underground mining in the USCB. Exhausted description of seismic observation development in the Czech part of the USCB was provided by Ptacek et al. (2017). Seismic monitoring in the Czech part of the USCB began in the 1980s. The seismological system's use is for rockburst prevention (Ptacek et al. 2017) and is focused on monitoring the induced seismicity in the active mining area of the Karvina subbasin. Therefore, this system can detect seismicity in the Ostrava and Petrvald subbasins but with lower sensitivity. The seismological monitoring combines two seismic networks, where the data is evaluated together, regional seismic network and local seismic network. The regional seismic network consists of ten triaxial short-period WDS seismometers. Whereas the local seismic network on every colliery is equipped with uniaxial, low-frequency and low-periodical vertical SM-3 seismometers.

During the period of mining in the Ostrava and Petrvald subbasins and operation of seismological monitoring (1988–1993), seismic events were mainly recorded in the southern part of the Petrvald Subbasin and in the central part of the Ostrava Subbasin (Fig. 11A). 121 seismic events have been registered, 108 with local magnitude from 0 to 1 and 13 with local magnitude from 1 to 2. During this period, no critical situation in the light of induced seismicity in rock mass (rockburst) or induced seismicity with surface impact was registered.

Currently, there is no legal regulation requiring the integrated measurement of the water level, ground control and seismicity in combination with the flooding of mines after their closure in the Czech Republic. The District Mining Authority may order the monitoring as part of the approval of the liquidation of the shafts, but no further monitoring is mandatory.

2.3.2 Post-mining monitoring at Ostrava, Petrvald and Karvina: seismicity and water table

Mining was gradually scaled down from the 1990s onwards. The last coal operating mines in the Karvina Subbasin (CSA, Lazy, Darkov, CSM Sever and CSM Jih) are in the process of closing. Mining finished in the Ostrava Subbasin in 1994 and the flooding of mines began immediately. Since 2001, the preserving water level is ca. 40 m below the deepest Ostrava and Petrvald subbasins connection on an altitude of ca. -388.5 m, i.e. in a depth approx. 600 m below surface, due to water pumping in the Jeremenko water shaft (Fig. 10). The main reason is to prevent a water overflow into the Karvina subbasin due to the connection of all of the subbasins because of the tectonic structures and the underground openings. Pumping volume from the Ostrava subbasin is stable on the level at ca. 170–200 $l \cdot s^{-1}$.

Mining in the Petrvald Subbasin was terminated in 1999. All mines in the Petrvald Subbasin are considered as a hydraulically connected (communicating vessels) system. The process of flooding was monitored in the Zofie water shaft. The period of mine flooding was terminated in October 2001 when the pumping began. The water level is preserved on an altitude of ca. -483 m, i.e. approx. 680 m below surface

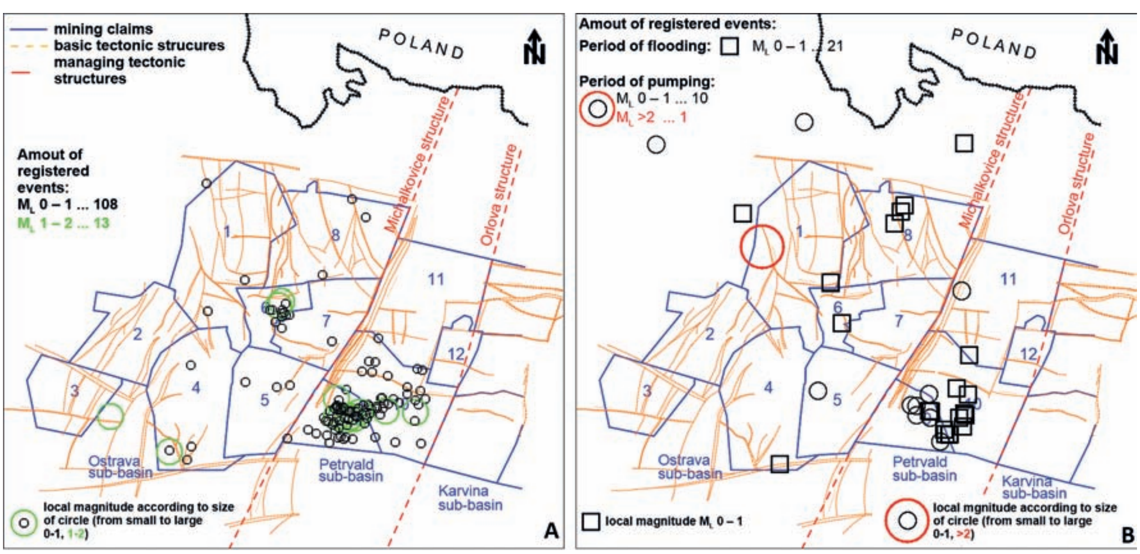


Fig. 11: Location map of seismic events registered during period of mining (**A**; 1988–1993) and period of mine flooding (**B**; 1994–2001), resp. water pumping (**B**; 2002–2021) in the area of the Ostrava and the Petrvald subbasins in the Czech Part of the USCB.

(Fig. 10). The pumping rate from the Petrvald subbasin is stable on the level at ca. 38 l · s^{-1}.

Due to the flooding of the Ostrava and Petrvald subbasins, low seismic activity was registered (Fig. 11B). Only 21 seismic events with a local magnitude from 0 to 1 have been registered during the period of flooding. Most of the seismic events were registered in the southern part of the Petrvald Subbasin and some events took place sporadically in the Ostrava Subbasin area.

During the period of preservation of water level in a stated altitude, low seismic activity in the Ostrava and Petrvald subbasins was registered (Fig. 11B). Only one seismic event with a local magnitude higher than 2 (3.5) and 10 seismic events with local magnitude from 0 to 1 were registered. Most of the seismic events occurred in the southern part of the Petrvald Subbasin and some events sporadically in the Ostrava Subbasin area, including a high energetic seismic event in December 2017 which was recorded also by the Czech national seismological network and classified as an earthquake with local magnitude of 3.5 (Sileny & Zednik 2018).

2.3.3 Analysis of the Ostrava, Petrvald and Karvina subbasins

The observed induced seismicity during flooding and subsequent pumping of mines in the area of the Ostrava and Petrvald subbasins is low if compared to other flooded coal mining regions, e.g. Ruhr and Ibbenbüren in Germany (Rische et al. 2021) or the Provence region in France (Matrullo et al. 2015). There were also no recorded damages on the surface related to mines' flooding in the Ostrava and Petrvald subbasins. The main reasons for low seismicity during mine flooding are the partial flooding of a single mine. The seismic networks were designed for different purposes (e.g. rockburst prevention in the Karvina Subbasin) that resulted in a lower detection ability of low-magnitude seismic events.

2.4 Upper Silesian Coal Basin (Poland)

2.4.1 Background of the Kazimierz-Juliusz mine

The Kazimierz-Juliusz mine is located in the northwestern part of the Upper Silesia Coal Basin (USCB). In the geological structure of the mine, Quaternary, Triassic and Carboniferous sediments are involved (Buła & Kotas 1994). The Kazimierz-Juliusz coal deposit lies within the Bytom-Kazimierz Subbasin and the Maczek dome, which is an extension of the main saddle in the USCB to the east. The Kazimierz Basin is located in the central part of the deposit. It has an asymmetrical structure with NWW–SEE main axis orientation. Its northern part has a gentle slope, while the southern part is steep. The strike direction of the layers in both parts is approximately parallel to the basin axis, and their slope varies from 15 to 50°. The rock mass is intersected by a dense network of faults, created in the Variscan Orogeny. The fol-

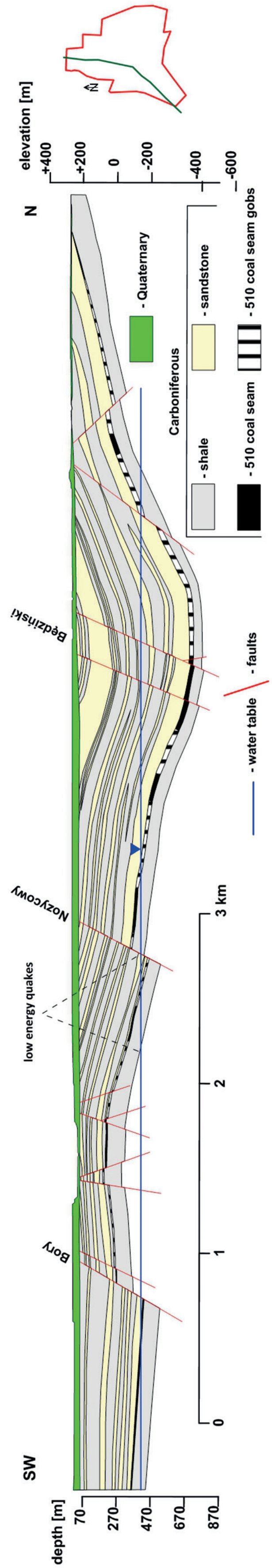


Fig. 12: Geological cross section through Kazimierz-Juliusz coal deposit.

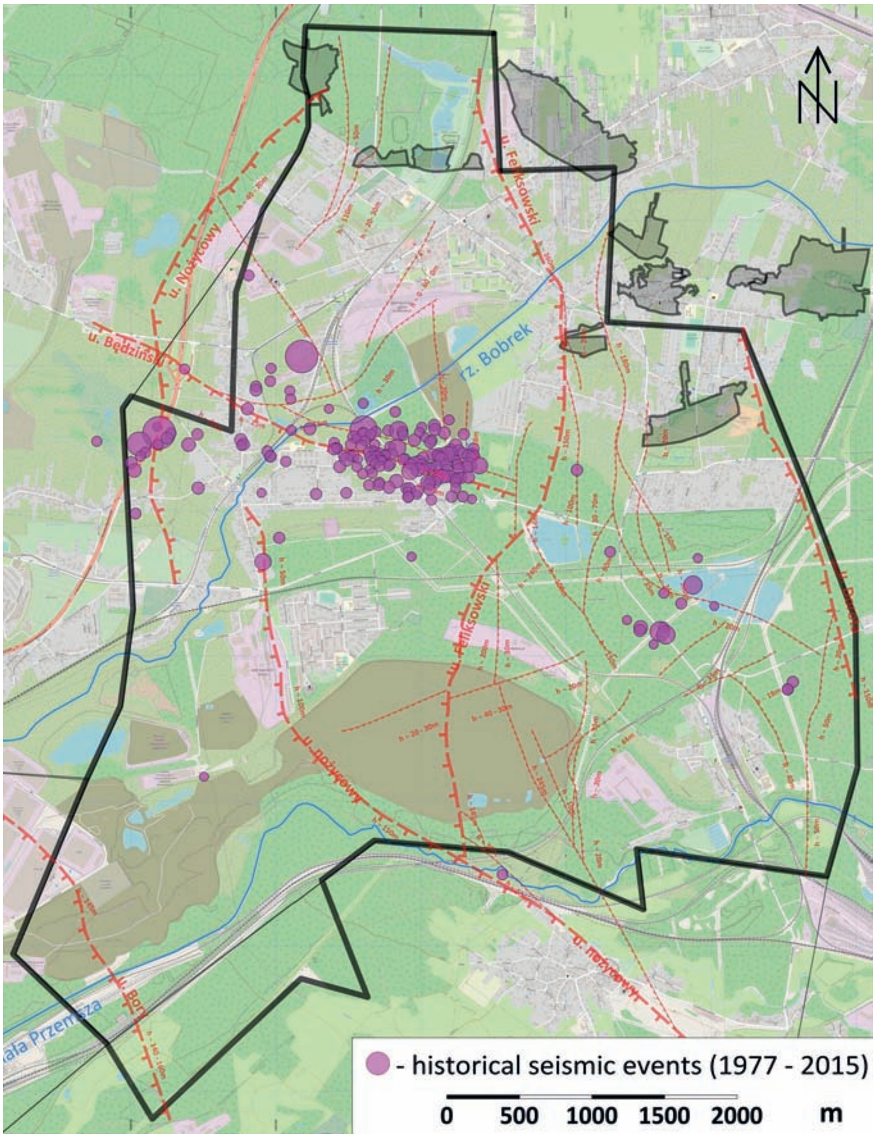


Fig. 13: Location of mining induced seismic events with magnitude ML >1.7 which were recorded in the Kazimierz-Juliusz coal mine between 1977 and 2015 (pink dots). In the northeast regions of shallow coal exploitation are shown (Chodacki et al. 2021). Red dashed lines – faults.

lowing faults should be distinguished due to their length and high amplitude of throw:

- Jakubowski – with throw amplitude ranging from 0 to 270 m,
- Feliksowski – with throw amplitude ranging from 100 to 250 m,
- Nożycowy – the amplitude of its throw ranges from 0 to 230 m,
- Będziński – is located in the central part of the mine. In the area of the Kazimierz-Juliusz mine, this fault fades away and has a relatively small throw (maximum 60 m). Outside the mine border, the fault's throw increases to 250 m and extends for several kilometres in northwest direction. Along this fault, there is concentrated seismic activity during mining operations in the coal deposit. The Będziński fault was reactivated during the Alpine Orogeny (Buła & Kotas 1994). Its rupture zone (fissure) can be observed in places where the Triassic sediments outcrop on the surface. The geological structure of the basin is shown in Fig. 12.

The Kazimierz-Juliusz mine exploited the Kazimierz-Juliusz hard coal deposits. The main part of this area is located within the administrative boundaries of the town of Sosnowiec and partly of the towns Dąbrowa Górnicza and Jaworzno. In the northern and northeastern parts, apart from the mine area border, the coal seams within Gruszowskie strata were exploited by several mines such as Paryż, Kazimierz, Jakub I, Jakub II and Dorota, in the years 1880–1944. The Kazimierz-Juliusz mine exploited the following coal

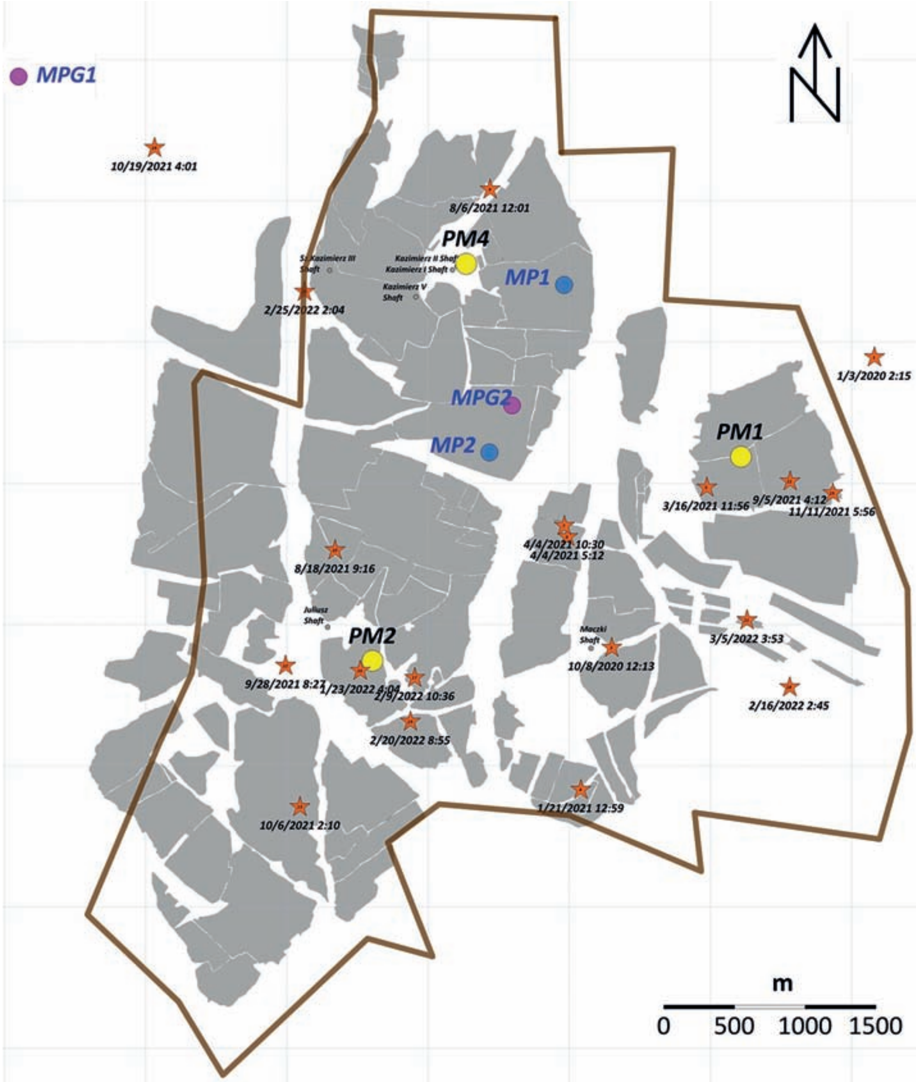


Fig. 14: Locations of post-mining micro-seismicity events recorded until March 2022 at the area of the Kazimierz Juliusz mine in the background of coal extraction regions and the location of seismic and water monitoring stations (Chodacki et al. 2021).

seams in the Carboniferous series Rudzkie and Siodłowe: 409/1–2, 418, 420 and 510, with a thickness ranging from 1.2 to 22.0 m (seam 510), at a depth range from 0 to 740 m (Fig. 12). The Carboniferous series is composed of sandstones and shales. The extraction of coal started by mining from its outcrops (northern part of the mine) using an opencast method in the first half of the 19th century (northeastern part of the mine area).

During mining operations (before 2006), the Kazimierz-Juliusz mine had a relatively high induced seismicity (Mutke et al. 2019). There were observed about 200 seismic events with energy above 1E5 J (M_L ≈1.7) recorded between 1977 and 2015 (Fig. 13). The strongest one had the energy of 6E7 J (M_L ≈3.15). The vast majority of these events occurred nearby the Będziński fault as well as the Nożycowy fault.

In May 2015, the Kazimierz-Juliusz mine finished coal exploitation and, at the end of 2016, the underground workings of the mine were abandoned. At the end of 2018, the mining plant was completely locked (Kotyrba et al. 2016; www.zapadliska.gig.eu/en). At that time, the drainage system ceased and the process of the mine flooding began.

A net of three surface stations (MP1, MP2, MP4) detects the seismic events. The measurement data from the mentioned devices are transmitted through a GSM net to the local data centre in Katowice, where they are stored and processed. Variations related to flooding phenomena, such as surface deformations and rock mass density, are observed by periodic gravity and geodetic land and satellite surveys (levelling, GNSS, InSAR). In addition, these data are stored in a local data centre. All monitoring systems were implemented for operation in the first half of 2021.

In terms of legal regulation, it is necessary to obtain the permits and approvals of the corresponding regulators before decommissioning an underground mine. In terms of monitoring a closed underground mine, it is only necessary to supervise surface transformations, deep behaviour of the rock mass, and hydrogeological, gas and thermal phenomena. There is currently no requirement to monitor the seismicity in closed underground mines. Hence, no seismic network is installed at these sites.

2.4.2 Post-mining monitoring at the Kazimierz-Juliusz mine: seismicity and water table

Seismicity in the area of the Kazimierz-Juliusz mine in the first period of flooding (before 2021) is only roughly known. Some events from this area were recorded by distant seismic stations belonging to the regional Upper Silesian Seismological Network. The exact locations of these events were quite uncertain. We began to collect more reliable data after the installation of a local seismic network in 2021. In the area of the mine, there were 21 registered seismic events, with a local magnitude between 0.8 and 1.6 (which corresponds to the seismic energy range between 2.1E3 J and 6.9E4 J). The seismic events were recorded at various locations. The prevailing number of them corresponds to the regions of performed coal exploitation. The location of these events is shown in Fig. 14.

The process of mine flooding is monitored by one water table measuring device, mounted in deep piezometer MPG1 and two shallow probes, installed in piezometers PM1and PM2 (shown in Fig. 14). The first one monitors the water table in the Carboniferous rock mass. The other ones are monitoring the water table in Quaternary sediments.

The piezometer MPG1, located in the area of the Porąbka mine (a mine adjacent to the tested one) was drilled in the year 2016. At that time, the water level in the Carboniferous rock mass was at ordinate -121 m (app. depth 400 m). In the period 2016–2021, the position of water was monitored manually by hydrogeological whistle measurements. These measurements were carried out periodically in 1–2 month increments of time. After the installation of the automatic hydro probe in the MPG1 piezometer, on 17 May 2021, we get the position of the water table in 1-hour increments. These data are stored and processed in the local data centre at the Central Mining Institute (GIG) facility in Katowice. Preliminary observations of the time of tremors recording and water table position in the Carboniferous rock mass indicate that they occur when the water table begins to oscillate in short periods. According to the data from periodic measurements of the water level in MPG1, it is moving up with an average daily rate of 3–5 cm. In the data set, already collected from the monitoring system, the water movement daily rates, analysed in shorter periods (several hours, days), change from -5 to 18 cm/day. The average value of the daily flow rate, calculated for longer periods, oscillates around the value determined from periodic measurement data.

2.4.3 Analysis of the Kazimierz-Juliusz mine

The Upper Silesian Regional Seismological Network (USRSN) in Poland is monitoring energetically stronger seismic events (magnitude M_L >2) in the Upper Silesia Region (USR). Although the network is constantly being expanded with new stations, the number of them is still too small to detect weaker energy tremors, due to the large area of the coal basin. We began to record such events after the installation of a dedicated local seismic network (2021) in the area of the Kazimierz-Juliusz mine (within the frame of the PostMinQuake project). Since March 2021 in the monitored area, several seismic events with local magnitudes between 0.8 and 1.6 occurred. They were recorded in various locations, but all within regions of former coal exploitation. After comparing the moment at which the tremors occurred with the water table level in the Carboniferous rock mass, it revealed that the seismicity occurs when the water table begins to oscillate in short periods.

3. Conclusions

In terms of legal framework, there is a lack of mandatory seismic monitoring legislation in former hard coal mines in the countries of the project. It is currently only mandatory to perform a ground movement monitoring. Therefore, it was difficult to gather all the relevant data for the study in the basins.

The effect of the water table level on seismicity is obvious in the different coal basins. In France, the recurrent seismic activity that had even been felt by the population between 2010 and 2017, while the water table level was increasing. The seismicity reduced significantly after 2018 when the water was pumped to maintain it at a constant level. In Germany was observed, not only that the epicentres of the induced seismic events are moving along the direction of the flooding, but also that there were more induced events when the water table level increased rapidly. In the Czech Republic part of the Upper Silesian Basin, the amount of induced seismic events during the flooding phase was double as those during the pumping phase to maintain the water table level. Even though the seismic data from the basin in Poland was not as complete as in the other basins, it was observed that the seismicity occurred when the water table began to vary significantly in a short period.

The first results of the project PostMinQuake show a direct correlation between the speed at which the water table raises (e.g. stop of pumping) and the occurrence of microseismic events. The data of this study show that these events are sometimes felt by the population but usually with local magnitudes lower than 3. Only in special occasions and special regional geological setups, some damages were recorded, but by reducing the speed of the rising water table, the risks of damages were avoided. Further research work is necessary to fully understand this process and the geomechanical correlation of the induced seismicity and the rising water table. Of particular interest is the phenomenon of reactivation of faults located under the mine.

Overall, the project PostMinQuake shows that there is a necessity of implementing new procedures to monitor microseismic events in former mining regions to gain a full process understanding of the subsurface.

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