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Mining-Induced Seismicity in the Saarland, Germany

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Abstract—Coal mining in the Saar mine, Germany, is accompanied by mining-induced seismic events. Strong events occur only in certain areas of the mine, other areas exhibit almost no seismicity. Shear events occur simultaneously to non-shear events. The shear events occur in different depths but their epicenters do concentrate in bands. The strike of the bands coincides with the strike of larger regional faults in the area. The seismic events of the Saar mine show some characteristics which distinguish them from seismic events observed in other German coalfields. The Gutenberg–Richter relation, for example, does not hold for these events. Furthermore, radiated seismic energy and extracted coal volume are not correlated. In the Primsmulde field a strong seismic event was observed even before mining in that region started. The event was triggered just by driving roadways into the field. The shear events cannot be explained by the mining process alone. They are presumably induced in certain regions (bands) under tectonic load by an interaction of mining-induced and tectonic stresses. In February 2008, extraction in the Primsmulde field induced a seismic event of magnitude 4, which led to surface vibrations reaching 93 mm/s. After this event, the Primsmulde field had to be abandoned. Future extraction of the Saar mine will be restricted to some small areas not intersected by the event bands found in the Dilsburg Ost and Primsmulde fields. The Saar mine will close in 2011.

Key words: Triggering, Mining induced seismicity, Gutenberg–Richter-Relation.

1. Introduction

As in many other regions worldwide, coal mining in Germany is accompanied by mining induced events. Today three areas hold active coal mines; one of them is located in the Saarland, in the far west of Germany (Fig. 1). Although industrial mining in the Saar region started in the middle of the eighteenth century, only a few cases of mining-induced events were reported before the 1990. In 1997, however, several strong seismic events were felt by the population of the villages in the area of the Saar mine. As a result, the Saar mine decided to install a local seismic network in order to determine the peak particle velocities (PPVs) on site and to investigate possible relations between mining and seismicity. Quickly it became clear that the observed seismicity was directly related to mining activities in the Schwalbach seam. Most all seismic events were located in the vicinity of active longwall faces. From 1997 to 2006, these were basically located in the Dilsburg field of the Saar mine. The Dilsburg field consists of an eastern (Dilsburg Ost) and a western (Dilsburg West) part. The parts are separated by an unmined area, protecting the main shaft of the mine (Fig. 2). In 2006, mining of the Schwalbach seam started in the Primsmulde field, planned as the mine's new main production field.

Figure 3 shows the number of seismic events that were recorded since continuous monitoring started in July 1997. Comparison with Table 1, which lists the periods of mining, shows the dependency of seismicity on mining. Particularly mining in the eastern part of the Dilsburg field and in the Primsmulde field led to high seismicity.

Figure 4 depicts the epicenters of seismic events with PPVs > 1 mm/s, which could be located between 1997 and 2008. Clusters of seismic events are located in the northeast and the northwest, corresponding to the location of the Dilsburg Ost and Primsmulde fields. Minimal seismicity was observed in the Dilsburg West field.

Analysis will be focused on the Dilsburg Ost and Primsmulde fields in the following and will show some characteristics of the observed strong seismic events, which particularly distinguish them from most other induced seismic events in that region and especially from those observed in the other German coal regions.

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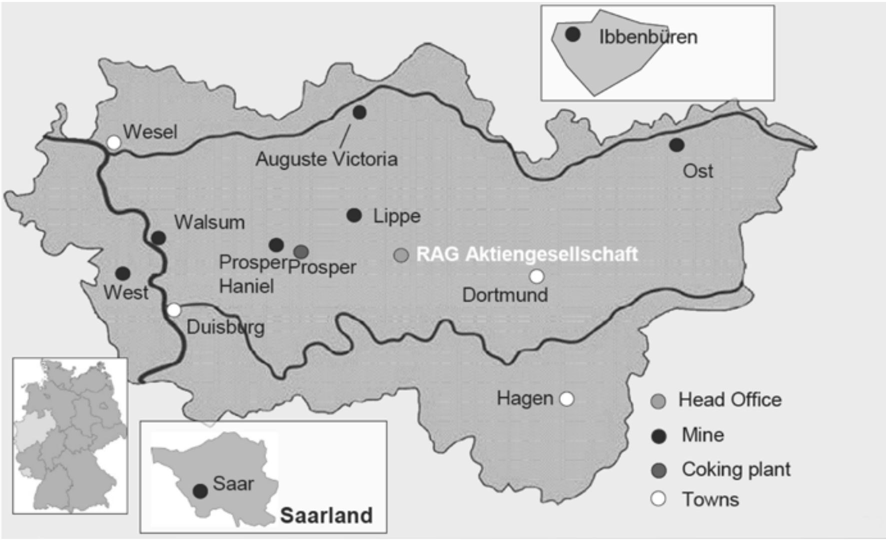

Figure 1
Map of German coal mines (*left inlet* Germany, *right inlet* Ibbenbüren, *middle inlet* Saarland, *big map* Ruhr area). Coal mining is taking place in three German regions: in the Ruhr area and Ibbenbüren, which are both located in the state of North Rhine-Westfalia, and in the Saarland, a small state in the southwest of Germany

2. *Location and Fault Plane Solution*

In 1997, the seismic network of the Saar mine consisted of just four surface stations. The network was not optimized for locating seismic events, but was primarily installed to determine the intensities of the mining induced events. The intensities were measured as PPV values at buildings basements. The recording was done with 3C geophones with flat velocity amplitude responses ranging between 1 and 80 Hz. Over the course of the measurements the network was continuously extended. When the excavation of panels 8.7 o and 8.8 o started in December 1999 the seismic events could be located with an accuracy of 80 m in epicenter position and 150 m in depth. Later, when the network was completed with underground stations, event depths and epicenter positions could be determined with an accuracy of 50 m.

2.1. *Dilsburg Ost Field*

Mining of the Schwalbach seam started in the south of the Dilsburg Ost field in 1979 at a depth of about 500 m. The excavation proceeded to the north. Since the Schwalbach seam is dipping to the north, the working panels reached greater depths from year to year. When mining took place in the panels 8.5 o and 8.6 o at depths of 850 m, seismic events were felt at the surface. In 1998, the extraction of 8.5 and 8.6 Ost was finished and after that no seismicity was observed until mining started again in Dilsburg Ost in January, 2000.

2.1.1 *Mining of Panels 8.7 o and 8.8 o*

Seismicity set in shortly after starting extraction in panels 8.7 o and 8.8 o in January 2000 at a depth of approximately 1,000 m below the surface. The epicenters of the events were located in the middle roadway between the panels, slightly in front of the advancing panel 8.7. They did migrate together with the advancing panels towards the northwest. At first, only relatively small seismic events with PPVs < 3 mm/s occurred, corresponding roughly to local magnitudes $M_l < 2.5$ (Fig. 6). The situation changed in November 2000 with the occurrence of a group of strong seismic events which reached PPVs of about 23 mm/s ($M_l = 3.5$). Fault plane solutions showed that all recorded seismic events could be classified into three different event types corresponding to three different types of rupture: two of them (Types 2 and 3)

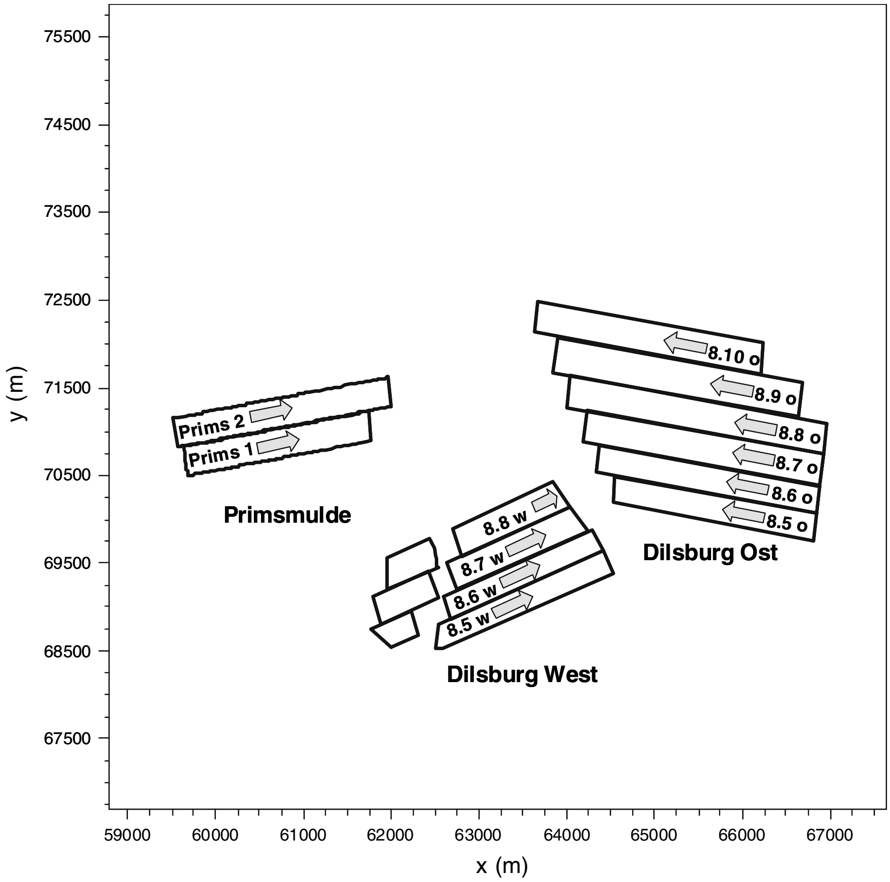

Figure 2
Working panels in the Schwalbach seam at Saar mine since 1997. The *arrows* indicate the direction of mining. Always two working panels were moved together, i.e., panel 8.5 o was directly followed by 8.6 o, 8.7 o was directly followed by 8.8 o aso. The panels are located at a depth from approximately 1,000 m (Dilsburg Ost) to 1,400 m (Primsmulde)

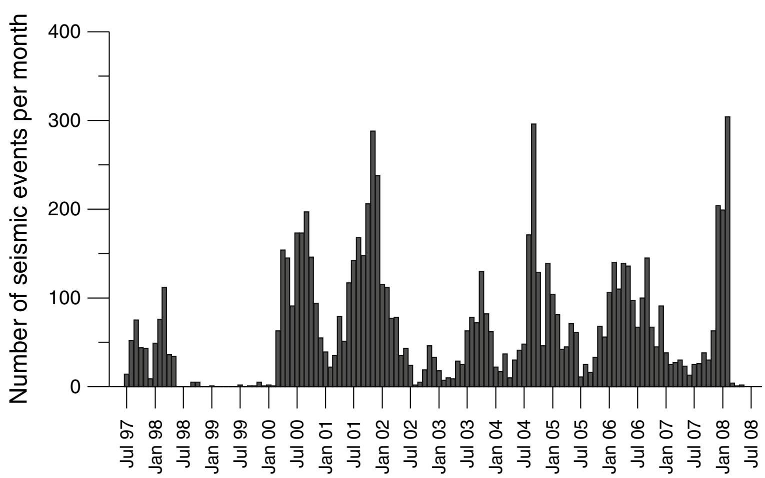

Figure 3
Number of seismic events that were recorded at the surface stations. The highly active times in 2000–2002 are associated with panels 8.7 and 8.8 Ost, the active times in 2004–2005 are associated with panels 8.9 and 8.10 Ost and the activities after December 2007 were caused by Prims 1 and Prims 2

Table 1

Working panels in the Schwalbach seam at Saar mine since 1997

Seam	Panel	Start	End
Schwalbach	8.5/8.6 Ost	January 1996	July 1998
Schwalbach	8.5/8.6 West	December 1997	December 1999
Schwalbach	8.7/8.8 Ost	December 1999	January 2003
Schwalbach	8.7/8.8 West	April 2002	July 2004
Schwalbach	8.9/8.10 Ost	July 2004	October 2007
Schwalbach	Prims 1/2	September 2006	February 2008

were caused by shear failures on fault planes in the rockmass, the third one (Type 1) could not be explained by shear failures. The events of this type showed negative P-wave polarities at all surface stations (Fig. 5). All seismic events that caused strong vibrations at the surface were shear failures, i.e., were of Type 2 or Type 3, and most shear failures led to strong vibrations at the surface. The two planes of the fault-plane solution were for both types approximately vertical and horizontal. The event types differed only in the direction of slip, which was in both cases almost vertical but points in opposite directions. With the help of the underground stations it was possible to determine the depths of several seismic events relative to the Schwalbach seam. The seismic events of Type 2 were all located around 150 m above the seam and the events of Type 3 were located around 20 m below.

Location and fault-plane solution made it possible to assign all recorded seismic events to the three event types. This allowed a differentiated investigation of possible relations between mining, geology and seismicity and particularly allowed separation of the non-shear events of Type 1 from the shear events of Type 2 and Type 3. The Saar mine started a comprehensive geological research program after the first events with PPVs of more than 20 mm/s occurred and their approximate depths of origin were determined. Several boreholes were drilled into the

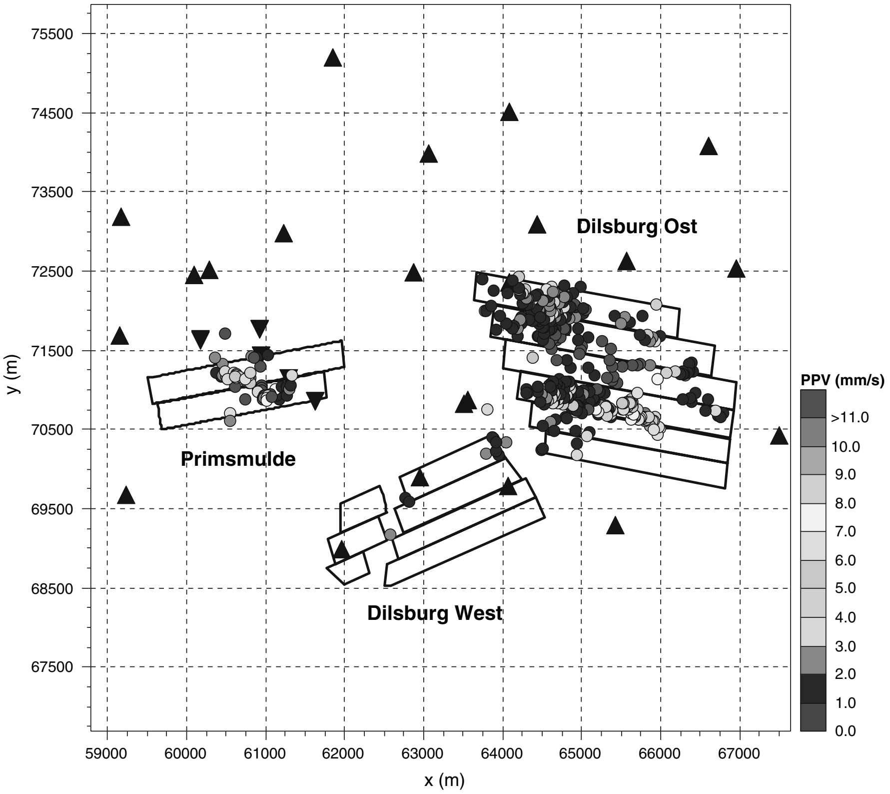

Figure 4

The local seismic network of the Saar mine. The map shows the station locations (*triangles*) and the panel outlines of the Dilsburg West, Dilsburg Ost and Primsmulde fields, where the Schwalbach seam was mined. The epicenters of mining induced seismic events that occurred between 1997 and 2008 with peak particle velocities (PPVs) of more than 1 mm/s are marked as *circles*

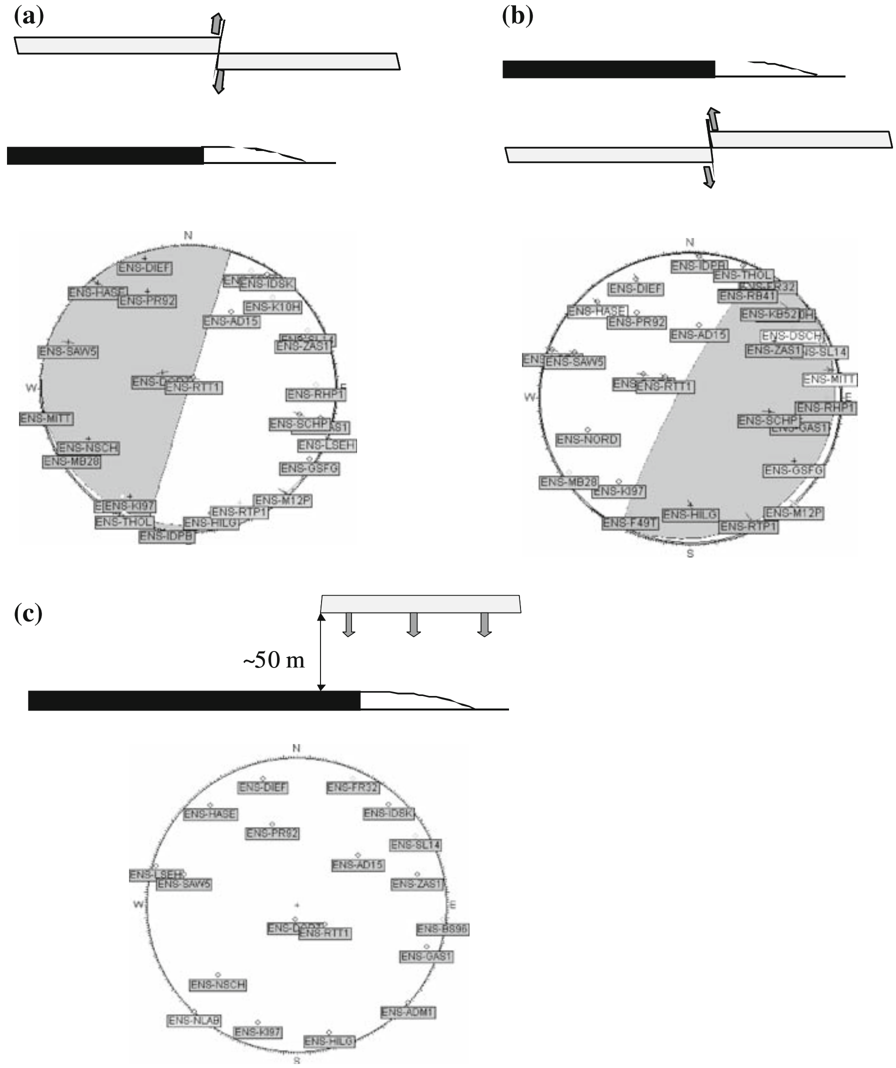

Figure 5
Fault plane solution and the proposed mechanism of typical seismic events: **a** Type 2, approximately 150 m above the Schwalbach seam; **b** Type 3, approximately 30 m below the seam and Type 1, approximately 50 m above the Schwalbach seam. The *upper half* of the focal sphere is shown with possible fault plane orientations for the shear events of Types 2 and 3 that fit to the observed P-wave polarizations and S-wave polarization angles. Type 1 is no shear event and has only negative polarizations at the surface stations

hanging and foot wall to find possible correlations between the seismic events and the rock mass surrounding the Schwalbach seam.

At first, it appeared that the shear events corresponded to two channel sandstones with thicknesses of up to 10 m each, deposited by meandering carboniferous river systems in the footwall about 20–30 m below the Schwalbach seam. The strongest seismic events of Type 3 were recorded when the region, where the two channel sandstones overlap, was overmined by panels 8.7 o and 8.8 o. It was therefore assumed initially that the failure of the channel sandstones was the main cause of the strong seismic events, following the simple concept of a beam under load, which is able to withstand mining-induced stresses up to a certain point until it fails. That competent sandstone layers may be responsible for the generation of strong seismic events was also found by Fritschen *et al*. (1999) for seismic events in another mining area. Interestingly these were also of

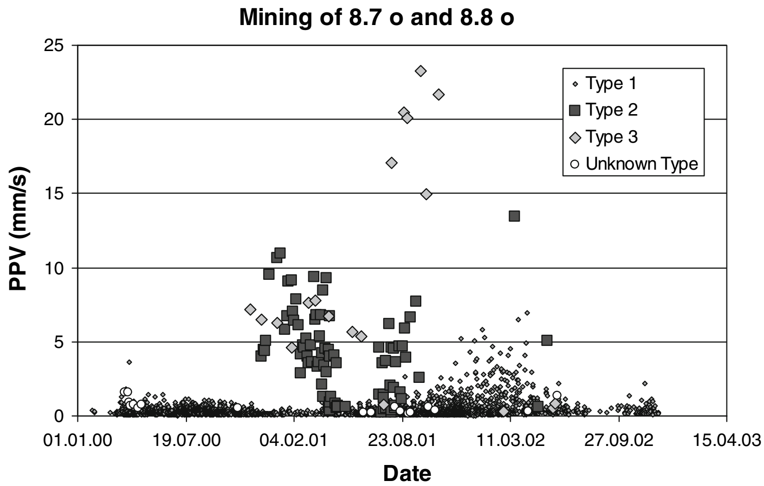

Figure 6
Seismicity during the mining of 8.7 o and 8.8 o. Most of the strong seismic events are of Types 2 and 3, i.e. are shear events, and most of the shear events lead to high PPVs at the surface. When the first shear events occurred in September 2000, the number of Type 1 events considerably decreased

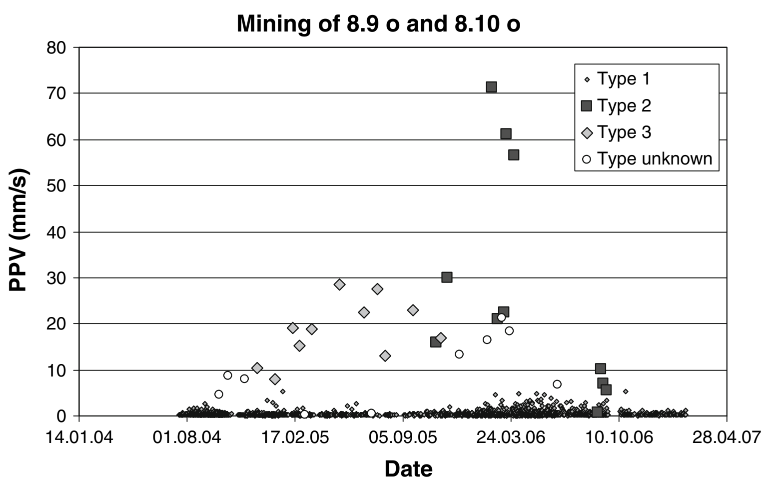

Figure 7
Seismicity during the mining of 8.9 o and 8.10 o. Most of the strong seismic events are of Types 2 and 3, i.e., are shear events, and most of the shear events lead to high PPVs at the surface

Types 2 and 3, i.e., they were shear events with steep fracture planes parallel to the working face with slip directions both towards and away from the gob.

However, the concurrences of competent layers, in this case the channel sandstones, and mining induced stresses cannot explain the occurrence of the strong shear type events alone. Initially, there is the remarkable coincidence in space and time of Type 3 events, about 30 m below the seam, and of Type 2 events, about 150 m above the Schwalbach seam, which suggests, that these events have a similar if not the same cause. It is unlikely that channel sandstones 30 m below the seam have something to do with seismic events 150 m above seam Schwalbach. Secondly, the panels 8.9 o and 8.10 o did cause seismic events which were also of Types 2 and 3 and were closely correlated to the events induced by 8.7 o and 8.8 o. However, not all of these events could be associated with channel sandstones.

2.1.2 Mining of Panels 8.9 o and 8.10 o

Mining of the double system 8.9 o and 8.10 o started in July 2004 at a depth of approximately 1,100 m and almost immediately induced seismic events of Type 1. When the face reached the region where Types 2 and 3 events were induced by the preceding panels 8.7 o and 8.8 o, again Type 2 and Type 3 events with considerable intensity occurred (Figs. 7, 10). The Type 2 and Type 3 events of both double systems together jointly formed a pattern, i.e., the epicenters of the events were not evenly distributed around the panels but laid in certain "bands" as depicted in Fig. 8.

2.2. Primsmulde Field

In 2004, the Saar Mine started to develop the Schwalbach coal seam in the new Primsmulde coalfield at a depth of approximately 1,400 m. The development of the field started 2 years before coal extraction with the driving of roadways, which later formed the longwall panels. As in the Dilsburg Ost and Dilsburg West fields the extraction of the Schwalbach seam in the Primsmulde was planned as a double panel system. It was not known if this system in the new part of the mine would induce seismic events of considerable intensity because at that time both double panel systems with strong seismic events (Dilsburg Ost) and double panel systems without significant seismicity (Dilsburg West) had been observed. A reliable explanation of the contrary seismicity found in these two fields was not available at the time.

Soon afterwards it was clear that the extraction of coal in the Primsmulde could lead to strong seismic events. In May 2005, after driving the first roadways into the Primsmulde field, a seismic event of $M_l = 3.3$ was induced (Fig. 9). This was the first time that an event, which was considerably felt at surface, was induced in a German coal mine just by developing a new field. No other seismicity was observed after that event in the Primsmulde field, until mining started in October 2006. However, even then seismicity was moderate with events that were hardly detected and not felt at the surface (Fig. 10). The situation changed dramatically in June 2007, approximately 9 months after the start of extraction in the Primsmulde, when a Magnitude 3.6 event with a PPV of 29 mm/s was induced in the seam level, more than 300 m in front of the double seam system.

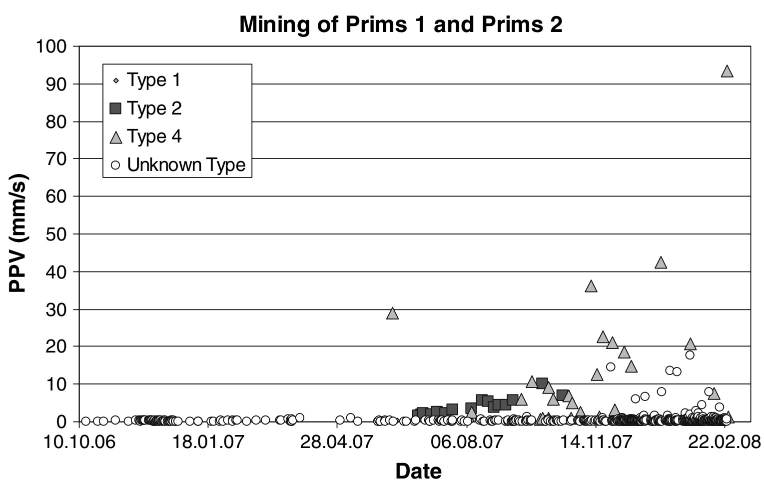

Figure 8

Seismicity during the mining of Prims 1 and Prims 2. Most of the strong seismic events are of Types 2 and 4, i.e. are shear events, and most of the shear events lead to high PPVs at the surface. After the 93 mm/s event of 23 February 2008 mining was abandoned and seismicity stopped the day after

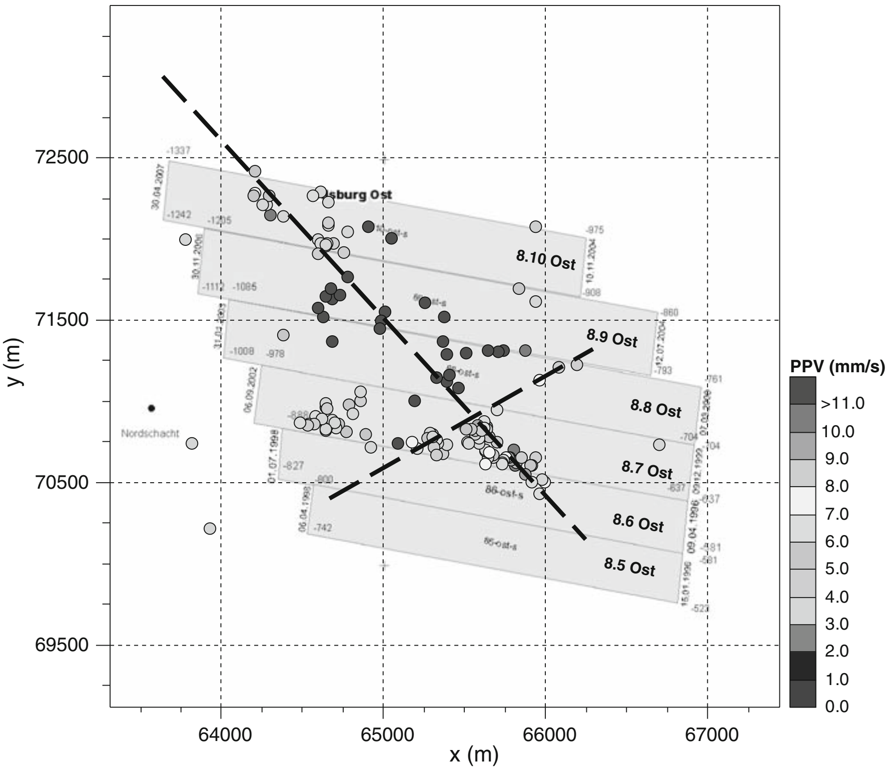

Figure 9
Location of seismic events with PPVs > 3 mm/s. The epicenters of most of the strong shear of the Dilsburg Ost field line up along SE–NW and SW–NE striking bands (*thick dashed lines*)

The event, located approximately. 180 m away from the May 2005 event, marked the beginning of a series of strong seismic events, culminating in a $M_l = 4.0$ event with a PPV of 94 mm/s on 23 February 2008. The event caused considerable damage to buildings on the surface. Immediately afterwards mining was abandoned in the Primsmulde field. The 94 mm/s event was followed by a single event of 1.2 mm/s 1 day after, which was the last seismic event in the Primsmulde field that could be felt at the surface.

Fault-plane solutions of the seismic events in the Primsmulde field showed, as in the Dilsburg Ost field, small events with implosional focal mechanisms (Type 1 events), which were located in the first 100 m above the Schwalbach seam, and strong seismic events of shear type, which were in the Primsmulde located at seam level or approximately 300 m above the seam level. In addition to a NW–SE striking Type 2 event, i.e., with a strike almost parallel to the working face, a new event type (Type 4) with a NE-SW striking steep fault plane (one of the two possible planes of course) occurred. As in the Dilsburg Ost field, the epicenters of the shear type laid along structures, which formed up from NW to SW and SW to NE. More unusual events occurred, which were located for example more than 400 m horizontally from the panels or more than 100 m below the seam. The very deep events showed in particular that even small changes in stress could lead to, in this case, very small seismic events. After passing the intersection of the two bands with the advancing face Prims 1 (Fig. 11), the epicenters of the events fell back and concentrated furthermore at the intersection region. The $M_l = 4.0$ event of 23 February 2008 was also located in that region and, remarkably, was 174 m behind the advancing working face of Prims 1. The event was composed of Type 3 with a hypocenter laying 300 m above the Schwalbach seam.

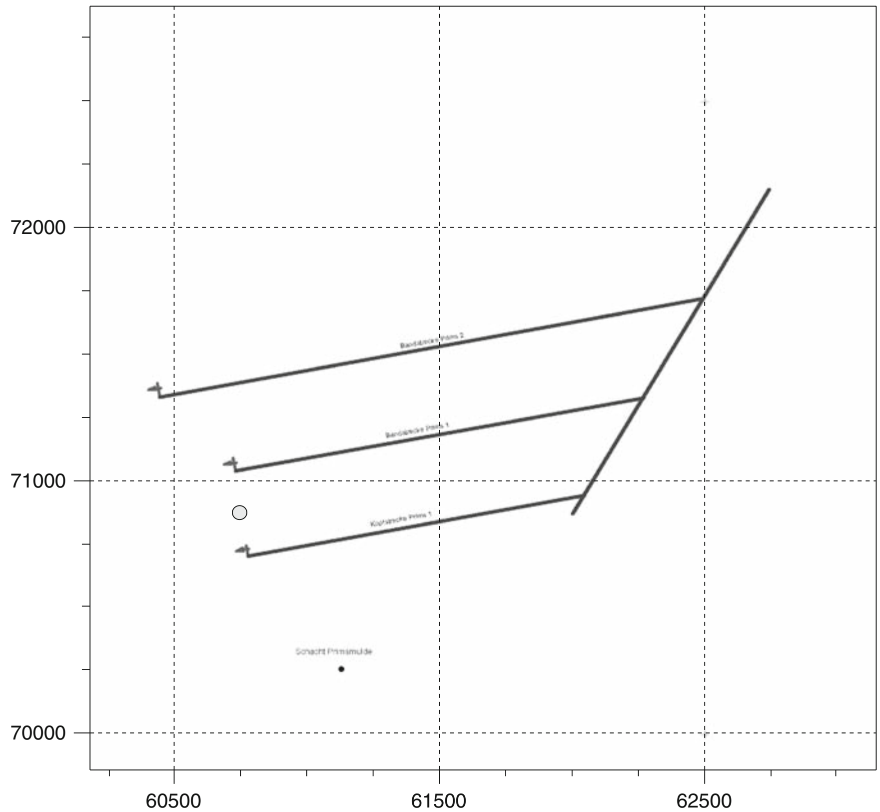

Figure 10
The Primsmulde field was developed by driving roadways into the Schwalbach seam at a depth of approximately 1,400 m. In the middle of the field a magnitude 3.3 event was induced at seam depth (*circle*) in May 2005, before any extraction in the field started

It is notable that the event bands were aligned parallel to the strike of the fault planes. They also coincided with the strike of larger regional faults. The Primsmulde field itself, however, is not intersected by fault systems, as is known from 3-D exploration and driving of underground roadways.

3. Characteristics of the Seismicity in Dilsburg Ost and Primsmulde

The strong seismic events that were induced by mining in the fields of Dilsburg Ost and Primsmulde exhibit some characteristics which distinguish them from seismic events observed in other German coalfields. This is at first the occurrence of numerous very strong seismic events, i.e., events with PPVs > 20 mm/s, in a region not influenced by old workings. Also characteristic is the occurrence of strong events in notably a different depth but similar horizontal location, for example in the foot wall and hanging wall in the Dilsburg field or in the seam level and 300 m above in the Primsmulde field. Furthermore the evolution of a band (or region) with strong seismic events that are not only in their horizontal location but also in their depth and fault mechanism distinguishable from the other seismic events, is unusual for German coalmines.

There are two further observations which indicate that the strong seismic events have causes other than the small ones and which also indicate the differences between the observations at the Dilsburg Ost and Primsmulde fields and all other coalfields at Ruhr and Saar: these are on the one hand the correlation between extracted coal volume and seismicity and on the other hand the number of seismic events as a function of seismic energy (or magnitude)—the Gutenberg Richter relation.

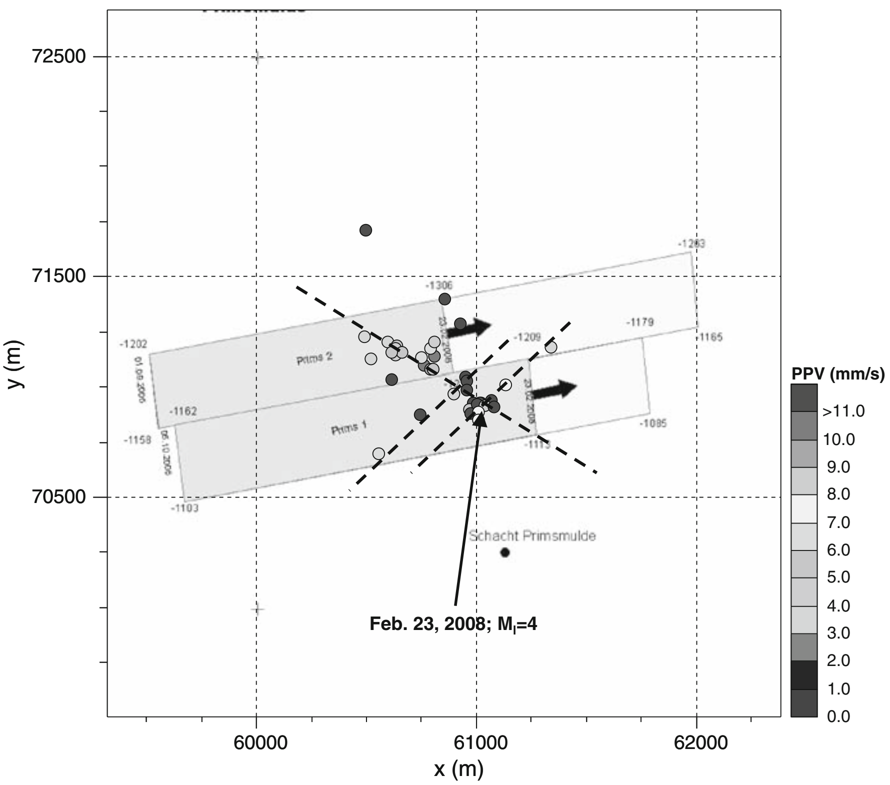

Figure 11
Location of seismic events with PPVs > 3 mm/s. The epicenters of the events in the Primsmulde field are lying, like the epicenters in the Dilsburg Ost field, along the SE–NW and SW–NE striking structures (*thick dashed lines*). The figure shows the face positions of 23 February 2008, when the $M_l = 4$ event occurred after which mining in the Primsmulde field was abandoned

3.1. Correlation between Seismicity and Coal Extraction

The strong dependence of seismicity on the volume of extracted coal is well known and was shown for Czech and Polish mines by GLOWACKA (1992) and for mines in the German Ruhr area by FRITSCHEN (2002). This dependence follows from the proportionality between the cumulative seismic moment and the induced volume change in a rockmass that was shown by MCGARR (1976). Assuming that the volume of extracted coal is proportional to the induced volume change and that the cumulative seismic energy is in average proportional to the cumulative seismic moment, it follows that the volume of extracted coal is proportional to the amount of seismic energy released.

Figure 12(left) shows as an example the monthly values for the volume of extracted coal together with the seismic energy per month for a German coal mine. The seismic energy was calculated as the mean value of the integrals of the squared particle velocities at the seismic stations, which were corrected for attenuation and geometrical spreading according to BOATWRIGHT and FLETCHER (1984), neglecting the correction for the radiation patterns.

The correlation between seismic energy and volume in Fig. 12(left) is obvious. A similar correlation is found for several other mines in the Ruhr area, particularly when a certain working is not influenced by abandoned workings. The workings in the Dilsburg Ost and Primsmulde fields did not display this relationship, which indicates that the stresses induced by the extraction of coal are not solely responsible for the generation of the observed seismic events.

3.2. Gutenberg–Richter-Relation

The frequency-magnitude or frequency-energy relation, take on a logarithmic scale, the form $\log n = a - bm$, where n is the cumulative number

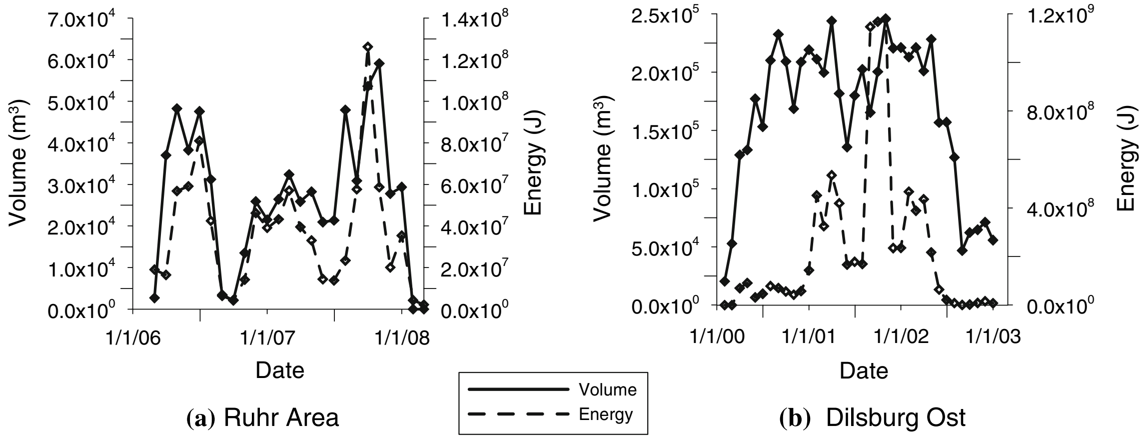

Figure 12
Seismic energy and extracted coal volume per month for two different mining regions. The connection between extracted volume and radiated seismic energy is generally observed in German coal mines (**a**—Ruhr Area). The seismic events observed in Dilsburg Ost and Primsmulde did not follow this rule. There is no direct connection between extracted coal volume and radiated seismic energy (**b**—Dilsburg 8.7 o and 8.8 o). There is even no connection between extracted coal volume and radiated seismic energy when only Type 1 events are taken into account (not displayed)

of seismic events above a magnitude m or above a certain seismic energy log E_s, a and b are parameters. Many observations worldwide indicate that seismic events induced by mining follow this rule in general as do tectonic earthquakes and laboratory experiments. This indicates the self-similarity of observed seismic events, i.e., of the fracture processes involved. Self-similarity means here the absence of a characteristic scale length or order of magnitude determining the occurrence of the seismic events.

Figure 13 shows as an example the relation for events induced by mining in the Ruhr area. The log-linear Gutenberg–Richter Relation does not hold for the seismic events observed in the Dilsburg Ost and Primsmulde fields. Here the events follow a bimodal distribution, i.e., the large events do not follow the same power relation as the small events. However, a range of energies develops, in which the number of events does not decrease with greater energy but stays at the same level. For even greater energies, the cumulative number of seismic events drops again. Similar distributions are described by Gibowicz and Kijko (1994) for mining-induced events in Poland. They provide two possible explanations for the bimodal distribution. On the one hand, a bimodal Gutenberg–Richter Relation can be an indication of a change in geology in the course of the ongoing working face. On the other hand the low energy part of the distribution can be explained by mining-induced relaxation processes around the working and the high energy part by an interaction of mining-induced and tectonic stresses. The interaction of mining-induced stresses with prevailing tectonic stresses or with critically stressed rock may also result, as described by Schneider (2004), in developing strong events at the expense of small ones, which would, however, cause an absence of seismic events in a certain energy range. That the strong shear events of Types 2 and 3 seem to interact with the weaker events of Type 1 can be seen in Fig. 6. After the first shear events in September 2000, the number of recorded Type 1 events considerably dropped. Though when plotting the Gutenberg–Richter-Relation for the Type 1 events alone, it perfectly fits the observations, indicating that altogether no Type 1 events “are missing” (Fig. 13). That only a few shear-type events of small energy exist is remarkable. This is possibly a consequence of a predominant spatial scale, which may be caused by the width of the double panel system influencing a critically stressed region.

Interestingly similar event types, weak implosional events and stronger shear events, were found by Kusznir *et al.* (1980, 1984) for seismic events induced by coal mining in North Staffordshire, UK. Kusznir *et al.* found, however, no violation of the Gutenberg–Richter Relation. Other possible occurrences of

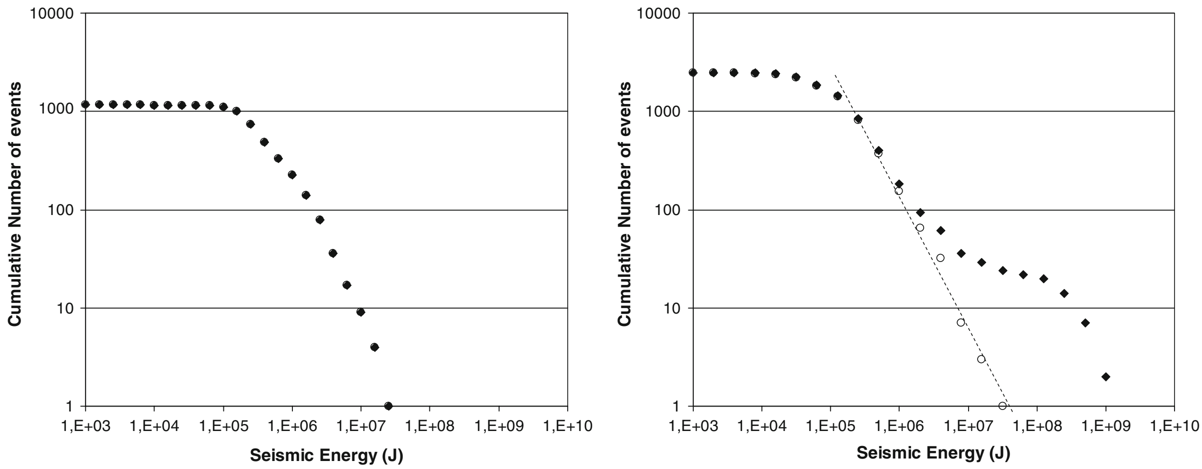

Figure 13
Number of seismic events with energies above a certain value as a function of that value (Gutenberg–Richter-Relation). Generally, a linear trend in the log–log plot is observed for mining-induced seismic events in Germany as is shown in the left figure (eastern part of the Ruhr Area). The right figure shows the relation for Dilsburg Ost (Primsmulde looks, similar). The filled symbols show the relation for all events (Type 1, Type 2 and Type 3). The Type 1 events alone (*open circles*) follow the Gutenberg–Richter Relation remarkably well

implosional events were reviewed by Wong and McGarr (1990).

3.3. *Triggered versus Induced Seismicity*

Following Gibowicz and Kijko (1994), two broad types of mine tremors are observed almost universally: Those directly connected with mining operations, that is, associated with the formation of fractures at stope faces, and those associated with movement on major geologic discontinuities. In the Ruhr area, where seismic events have been recorded with local networks for several decades, most recorded seismic events are directly connected with the advancing working faces and there is no evidence, that strong seismic events, that are caused by the movement of major geological faults, do exist. The two broad types of mining induced events in the Saarland (the shear-type events and the non-shear events) bring to mind the two types described by Gibowicz and Kijko. In the Dilsburg Ost and Primsmulde fields, however, no geological faults were mapped in the vicinity of the strong seismic events. In the Primsmulde field, even 3-D seismic did not discover any major discontinuities in the entire field.

The observed seismicity fits, however, perfectly into the more general concept of triggered vs. induced seismicity (e.g., McGarr and Simpson 1997 or Wang 1993). Here, induced seismicity is that for which the causative activity can account for either most of the stress change or most of the energy required to produce the seismic events (non-shear events of Type 1 in our case). Triggered events in contrast can be caused by only a small fraction of stress change or energy, associated with the event. Tectonic loading plays here, according to McGarr and Simpson, the primary role (shear events of Types 2 and 3). Recognizing that especially the strong events may be caused by tectonic stress changes has important implications for extraction planning. In the case of Saar mine, the whole mine—not only the work in the affected working panel—was temporarily closed after the magnitude 4 event in February 2008. The state authorities only allowed reopening of the mine after a concept of how to avoid strong seismic events was presented. It is now believed that the strong seismic events were caused by activating (triggering) an area, which was under tectonic load. Since the driving of roadways already suffices to trigger the events, the changing of mining parameters like working speed or panel width would have presumably not helped to change the condition. Consequently the only way to avoid the generation of strong events was to avoid mining areas under tectonic load. Future extractions of the Saar mine will therefore be restricted to only some small areas not intersected by the bands found in the Dilsburg Ost and Primsmulde fields, and the extraction in these areas will be carefully accompanied by seismic monitoring in order to find areas under tectonic load at an early stage. The Saar mine will close in 2011.

4. Conclusions

The extraction of the Schwalbach seam at the Saar mine, Germany, led to the generation of different types of seismic events. All strong seismic events were shear failures, which were restricted to certain areas of the mine. These events occurred at different depths but their epicenters were concentrated in certain regions (bands) in the Dilsburg Ost and Primsmulde fields, which indicated that mining was influenced by tectonic stresses. The strong shear events occurred simultaneously to non-shear events induced by mining. The different nature of the shear type events is illustrated by the Gutenberg–Richter Relation, which is not log-linear when considering all events collectively.

At present, the only approach to avoid strong seismic events is to stay away from areas under tectonic load. In the meantime, numerical studies are performed in order to reproduce the generation of the strong seismic events and to find possible conditions that allow mining in regions under tectonic load that do not lead to the generation of strong seismic events.

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