Dynamic triggering of microseismicity in a mine setting

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SUMMARY
We examine spatio-temporal patterns of microseismicity recorded during one month in an underground mine by addressing three key questions: (1) where does the seismicity occur? (2) Why does it occur in these locations? and (3) what triggers it? To obtain accurate locations, we perform a multiplet analysis and use a modified version of the double-difference (DD) relocation method. This approach leads to highly accurate relative event locations and requires groups of multiplets only. Most of the 281 relocated events are close to the main shaft and tunnels; thus we postulate seismicity is facilitated by stresses associated with the potential for subsidence in addition to the hoop stresses acting on the two vertical shafts. Most events occurred during certain hours of the day and there is a 68 per cent correlation with reported rock removal; therefore, it is likely they were triggered by static and dynamic stress perturbations caused by the transportation of debris along tunnels instead of our initial guess that blasting was the principal causative mechanism. Given that seismicity is present around the main shaft but absent close to the second one, we conclude that for seismicity to occur both a favourable stress state and additional external perturbing forces must exist, thus leading to dynamic event triggering in an initially stable stress situation. This analysis provides more insight into anthropogenic processes that might trigger seismicity, thereby facilitating identification of hazardous and potential damage areas in mine settings.

Key words: Time-series analysis; Downhole methods; Earthquake dynamics; Early warning; Computational seismology.

1 INTRODUCTION
Over the last several years there has been significant public interest in possible increased earthquake hazard due to anthropogenic activities (Ellsworth 2013). Some recent examples include the 2009 unusual sequence of seismicity caused by fluid injection during hydraulic fracturing in the Horn River Basin of British Columbia, with the largest event at $M_w = 3.6$ (BCOGC 2012); and the 2011 central Oklahoma earthquake sequence (including a $M_w \sim 4.1$ and a $M_w \sim 5.1$ event) located close to two wastewater-injection wells that occurred 18 yr after disposal operations began, even though this has historically been considered a quiet seismic region (Holland 2013; Keranen et al. 2013). Others concerns include potential seismic activity related to activities such as CO$_2$ sequestration (Zoback & Gorelick 2012), hydraulic fracturing for geothermal energy and surface reservoir impoundment (Mcclure 2012). In all these cases there is often significant discussion if variations in earthquake seismicity rates are due to anthropogenic activities or part of natural earthquake cycles (Ellsworth 2013; Llenos & Michael 2013). Others concern include potential seismic activity related to activities such as CO$_2$ sequestration (Zoback & Gorelick 2012), hydraulic fracturing for geothermal energy and surface reservoir impoundment (Mcclure 2012). In all these cases there is often significant discussion if variations in earthquake seismicity rates are due to anthropogenic activities or part of natural earthquake cycles (Ellsworth 2013; Llenos & Michael 2013).

Mining-induced seismicity has unfortunately also generated catastrophic events in the past to infrastructure and workers. For instance, the rockburst that occurred in June 1984 at the Falconbridge Mine, Canada, damaged the mine workings and killed four miners (Wetmiller et al. 1993). The 1989 Volkershausen, Germany, magnitude 5.4 is a clear example of remarkable damage, where 3200 pillars collapsed at depths between 800 and 900 m (Knoll 1990). More recently, in 2007 part of the Crandall Canyon Mine, USA, collapsed and trapped workers underground and a rescue attempt through the reopening of a collapsed mine entry generated a violent burst of coal, injuring more rescue workers (Kubacki et al. 2014). As a result, health and safety concerns in mines have risen in order to minimize the occurrence of such undesired events, for example rockburst, flooding and underground gas emissions.

Mining seismicity is usually complex as it is likely to be affected by the mine geometry, depth, current stress state as well as excavation and exploitation processes. Thus, a key step is to analyse the relationship between anthropogenic activities and microseismic locations. Microseismic events usually occur as clusters, so relative location methods have been extensively used in mining to track the direction of tunnelling, fault structures or changes in rock mass with more accuracy than absolute methods (Abdul-Wahed et al. 2006; Boltz et al. 2013; Kubacki et al. 2014). This has allowed enhanced assessment of potential damage zones and areas where seismic activity and hazards are more likely to increase.
In this work, we study one month of microseismicity recorded during drilling and tunnelling in an underground mine. We address three key questions: Where is the seismicity located? Why does it occur in these locations and not somewhere else? And what specifically triggers their occurrence? To achieve that, we perform multiplet analysis based on a modified version of the double-difference technique (Poupinet et al. 1984; Got et al. 1994; Waldhauser & Ellsworth 2000; De Meersman et al. 2009; Boltz et al. 2013) to obtain highly accurate relative microseismic locations. Our initial assumption is that blasting is the main dynamic triggering mechanism, since the seismicity is located close to the main tunnels and the main access shaft. Counterintuitive, no immediate seismicity follow these detonations. In fact, most of the seismicity correlates with scheduled rock removal. These findings lead us to postulate that for microseismic activity to occur two conditions should be met: (1) a favourable stress state in the neighbouring area (Evans et al. 2012) and (2) unless the in situ static stresses exceed some critical threshold, an additional dynamic triggering mechanism must be present (Freed 2005). We assume that a favourable stress state is created both by the hoop stresses around the vertical shafts (Zoback 2007) and the presence of horizontal tunnels which create a tendency for subsidence of the overburden similar to a depleting hydrocarbon reservoir (Segall 1989).

2 THEORY

2.1 Multiplet locations

Multiplet analysis is performed using a modified version of the double-difference method, to get highly accurate relative multiplet locations (Poupinet et al. 1984; Got et al. 1994; Waldhauser & Ellsworth 2000; De Meersman et al. 2009). The main assumption in the DD method is that ray paths between two events are very similar if their hypocentral separation is small compared to the source–receiver distances; therefore, relative traveltimes difference at a common station will be due to the spatial offset between both events. In other words, the effects of most velocity heterogeneities cancel out, such that only knowledge of the velocities in the source region is required. The double-difference residuals for pairs of events at each station are minimized, with the locations and partial derivatives being updated after each iteration, solving the relative hypocentral parameters for each event (Waldhauser & Ellsworth 2000).

Unlike Waldhauser & Ellsworth (2000) who relocate correlated and uncorrelated events simultaneously, our approach relocates multiplet groups independently (Castellanos & Van der Baan 2013). By grouping well-connected events, we ensure more stability in the inversion, although the number of useful events is reduced. Another difference is that in Waldhauser & Ellsworth (2000), initial absolute locations are first determined using catalogue data, next final relative relocations are obtained as more weight is given to cross-correlation data, whereas in our approach, initial absolute locations are first determined using a grid search algorithm; next relative locations are determined using cross-correlation data (only multiplets). The output locations are relative, so we keep fixed each multiplet group centroid before and after relocation assuming that initial locations provide a large-scale picture. Similar to Waldhauser & Ellsworth (2000), we use exponential functions based on cross-correlation values and interevent distances to emphasize observations from doublet pairs. This weighting scheme is key in the inversion as it controls which observations will impact more the final locations (Poupinet et al. 1984; Got et al. 1994). Full details on the implemented weighting scheme can be found in Castellanos & Van der Baan (2013).

2.2 Stress perturbations around shafts and tunnels

A favourable, near-critical, stress state is a necessary condition for the occurrence of triggered seismicity (Mcgarr & Simpson 1997; Freed 2005; Evans et al. 2012). If the virgin rockmass before creation of the underground mine is mostly homogeneous then the local stress field is highly similar to the regional one since this limits spatial variations in differential stresses due to lithological layering and other heterogeneities (Roche et al. 2013; Roche & Van der Baan 2015). Moreover, if no active faulting is present within the mine, engineering operations such as the opening of shafts and tunnels will likely be the main cause for perturbing the in situ virgin stress state.

For instance, the creation of a vertical shaft induces hoop and radial stresses in the horizontal plane, similar to those for a vertical borehole (Zoback 2007). Hoop stresses act parallel to the shaft wall in a circumferential manner, whereas the radial stresses act perpendicular to it. These are created to compensate for the removed material yielding local stress concentrations and are described by the Kirsch equations (Zoback 2007). In other words, we anticipate seismicity to be centred around any shafts due to these induced local stress concentrations.

Similarly, the opening of horizontal tunnels at the excavation levels also perturbs the local stress field due to hoop and radial stresses in the vertical plane, in addition to gravitational pull and push in the overburden and underburden, respectively, causing potential subsidence (Young et al. 2004; Cai & Kaiser 2005). These effects are similar to those experienced by compacting hydrocarbon reservoirs due to fluid extraction (Segall 1989; Scott 2005). By modelling the hydrocarbon reservoir as a poroelastic medium in an impermeable elastic half-space, Segall (1989) states that after fluid extraction, the rock compacts vertically at the centre, that is subsidence; whereas more shear failures and extension dominate at the lateral regions. As a result, we also expect seismicity in the overburden around the main tunnels due to these imposed stress changes.

2.3 Microseismic triggering

Current thoughts are that both static and dynamic stress perturbations can trigger seismicity by overcoming either the tensile or compressive rock strengths and any additional shear friction along fault surfaces (Kilb et al. 2000; Freed 2005). More specifically, the likelihood of shear and tensile failure is described by the Mohr–Coulomb and Griffith criteria, respectively (Davis et al. 2011; Roche et al. 2013; Roche & Van der Baan 2015). In this context, static triggering occurs due to large-scale variations in the local and regional stress changes over relatively long periods of time, for example, due to past slip on a fault, solid Earth tides or pull by the Sun and Moon and the excavation of tunnels and shafts, whereas dynamic triggering implies seismicity due to the passage of transient waves which leave no permanent imprint on the in situ stress field (Stein 1999).

For instance, blast detonations are commonly used in mining exploitation and can produce energy outputs on the order of magnitude 1 events or above (Adushkin 2013). Following a larger event, Omori’s law stipulates that aftershocks (i.e. events with generally smaller magnitudes) are likely to occur with a frequency inversely
proportional to the time since the main shock (Stein & Wyses-
son 2003). In other words, mine blasts may trigger other seis-
mic events in the vicinity of the mine and pose risks (Pomeroy
et al. 1976; Martin & Young 1993). Blasting operations are thus a
common dynamic triggering agent in the mining industry (Young
et al. 1992; Read 2004; Cai & Kaiser 2005). These detonations
are usually followed by transportation of the debris hours or days
later, so this transportation can also represent a mechanism for
stress transfer to shaft and tunnel walls as well as surrounding
rocks.

3 DATA BACKGROUND AND PROCESSING
A microseismic monitoring system was installed at an underground
mine to continuously detect zones of potential hazards, instabili-
ties and water flooding. Data recorded during January 2011 by 28
three-component geophones distributed in seven vertical boreholes
are used to investigate microseismic activity in the area. 24 821
seismograms were recorded but the vast majority of them contain
purely noise. We apply a standard pre-processing workflow to ob-
tain absolute event locations. First, the data, recorded using 2 ms
as sample rate, is bandpass filtered using corner frequencies of 60–
80–170–180 Hz. Also a notch filter is applied to remove high-peak
amplitudes at 60 Hz and overtones, producing waveforms with an
average signal-to-noise ratio of 3. 488 events are detected using a
STA/LTA method with a short and long time window of 30 and
300 ms, respectively, and a fixed threshold of 3. P-wave arrivals are
picked using autoregressive modelling and the application of the
Akaike Information Criterion (Sleeman & van Eck 1999), and then
repicked manually if necessary. Most events have short moveout
times between P and S waves; as a result, no S waves are picked. We
originally used a calibrated 1-D velocity model for P waves but this
produced highly scattered event locations possibly due to the pres-
ence of abrupt velocity changes imposed by the shafts and tunnels.
So we simplify the model to a homogeneous P-wave velocity of
3700 m s\(^{-1}\) to determine initial event locations using a grid search
algorithm (Sambridge & Kennett 1986; Billings 1994), prior to the
multiplet relocation.

During the post-processing stage, multiplet groups, that is groups
of events with nearly identical waveforms and source mecha-
nisms are detected via cross-correlation based on the methodol-
ogy of Arrowsmith & Eisner (2006). We set a maximum cross-
correlation threshold of 0.8 and allow events within each separate
group to be linked in a chain-like fashion, so mutual similarity is
not required. This allowed gathering 281 events among 21 mul-
tiple groups, which represent 58 per cent of the total detected
seismicity.

The absolute locations of these multiplet groups determined via
grid search are the input to the multiplet analysis described in the
previous section. The same velocity model as in the grid search
is used in the multiplet relocation inversion, thus we rely on the
assumption that results depend only weakly on the chosen velocity
model and that a simpler model may give better final results than
a highly complex model which aims at accounting for the presence
of tunnels and shafts.

4 RESULTS
The 21 multiplet groups detected during January 2011 are relocated
using the multiplet methods. One of the assumptions of the method
is that similar events should have similar time picks. For instance,
Fig. 1 shows the time delays, expressed as number of samples for
doublets in multiplet group 1. Most inconsistencies are limited to
10 samples (20 ms) which can produce spatial shifts in locations
up to 74 m assuming an average P-wave velocity of 3700 m s\(^{-1}\).
As a result, 20 ms could be used as a default time pick uncertainty.
The algorithm corrects these inconsistencies between doublets by
aligning their corresponding time picks to the same onset, thus
contributing to a more accurate location.

Fig. 2 shows the locations of the three largest multiplet groups
before and after multiplet analysis. In general, most events are tight-
ened after relocation, as seismicity is located at the centre of the
mine infrastructure, surrounding shaft 1 and the tunnels, especially
between 400 and 500 m depth. Group 1 (179 events) surrounds the
465 and 480 m levels, while there are some events farther away
due to a low mutual correlation with respect to most events within
the group. Group 3 (38 events) is located close to the main vertical
shaft (420–460 m depth) whereas group 4 (10 events) locates above
and below the 420 m level. Surprisingly, there is no seismicity spa-
tially correlated with shaft 2, which is mainly used for ventilation
purposes.

The improvement when using this relative relocation method in
the data is also confirmed by plotting cross-correlation coefficients
as a function of separation distances between event pairs before
and after relocation for multiplet group 1 (Fig. 3). Before reloca-
tion, Fig. 3(a) shows event pairs with high cross-correlation values
and large separation distances, which suggest location errors prob-
dably due to mispicks. Note that after relocation (Fig. 3b), events
with high cross-correlation have reduced their inter-event distance,
since high cross-correlation values (above 0.8) imply near-identical
source locations. There are a few event pairs which have increased
their separation distance after relocation, mainly due to poor linking
as they are not mutual doublets (below 0.8). In addition, the dense
scatter of points above the horizontal threshold yields an estimate
of location resolution of 40 m for that specific group. Details on
Figure 2. Hypocentre locations before (a, c and e in left-hand panel) and after (b, d and f in right-hand panel) multiplet analysis for the three largest groups: Group 1 (black), 3 (red) and 4 (green). Compared to initial locations, these groups have been tightened after relocation. Receiver boreholes indicated by coloured open diamonds (only geophones closer to the mine are shown). Tunnels and shafts shown in blue.
the various multiplet groups can be found in Castellanos & Van der Baan (2013).

The multiplet analysis results reveal the spatial distribution of the largest detected groups are located close to the main shaft and working tunnels; therefore, our next step is to analyse the temporal occurrence of the seismicity. Fig. 4 is a Gantt chart showing the occurrence of the 21 multiplet groups over time. Evidently, multiplet groups 1, 3 and 4 largely dominate the seismicity. In the first week (Fig. 4a), groups 1–10 occur. During the second week (Fig. 4b), there is a quieter period with less seismicity, except for groups 1 and 3. In the third week (Fig. 4c), group 1 continues dominating the seismicity and new smaller groups are generated, groups 14–21. In general, different multiplet groups occur at the same period. This is most evident during January 5–8, 12, 16 and 20–21. This temporal pattern reveals relationships among multiplet groups, possibly because the same causative process generated the microseismicity.

Figs 5(a)–(d) show the hourly event distribution for the entire month for all events as well as the three main multiplet groups. It is evident most of the seismicity occurs at specific times during the day, especially around 2 am, 4 pm and 10 pm. Mine blasting generally occurs on a regular schedule around 7 am or 7 pm (Fig. 5e). After these detonations there is a period of quiescence of at least one hour, so neither multiplets nor other events occur immediately following blasting. It is thus unlikely that the blasts cause the microseismicity. These histograms help identify periods of quiescence but do not causally link seismicity and blasts as they could have occurred during similar hours but in different days.

To confirm this we looked closely at the temporal distribution of triggered events versus blasting activity on a daily basis. Fig. 6(a) shows an example for 2011 January 4. No events follow the blasts at 7 am and 7 pm for up to 2–3 hr, confirming that blasting is unlikely a cause for static or dynamic triggering of microseismic events. We exclude the possibility for delayed triggering since, for instance, Fig. 6(a) shows that microseismicity resumed 4–8 hr after the morning blasts but within 2 hr following an evening blast. This is observed for nearly all detonated blasts throughout the month (Figs 6b, c and d).

Since blast detonations do not trigger here seismicity and the likelihood of an active fault in the centre of the mine is unlikely, we assess the transportation of debris as another possible triggering agent. Fig. 7 show the amount of removed rock volume per day compared to detected seismicity of the three main groups. Rocks removed during 3–4 January coincide with microseismic activity during those and the next four days. Few rocks are transported during 9–11 January, also coinciding with a lack of microseismicity. After 16 January rock volumes increase, matching renewed multiplet activity, especially between 20 and 22 January. Treating both removed rock volume and detected daily events as 20 samples time-series, we calculate their normalized cross-correlation and find a 68 per cent cross-correlation between multiplet activity and removed rock mass, which suggests a causal relationship may exist. Unfortunately no data are available in the period 2011 January 22–31, preventing scrutiny of further correlations, but this value suggests a causal relationship may exist.

5 DISCUSSION

We take advantage of the assumption that highly similar waveforms correspond to events originating in the same source region and with near-identical source mechanisms to determine accurate multiplet locations in an underground mine and address where does seismicity occur? What triggers it and why? By using multiplet analysis, we
Figure 4. Gantt chart showing temporal multiplets occurrence during January 2011: (a) 2011 January 3–9, (b) 2011 January 10–16 and (c) 2011 January 17–23. Each multiplet group is shown with a different colour. Most events from the largest multiplet group (red) occur during the third week, compared to the second largest group (orange) which occurs during the first 2 weeks. During 2011 January 24–31 no data are recorded.

Figure 5. Histogram of hourly seismicity and blasting times during January 2011. (a) 488 microseismic recorded events, (b) multiplet group 1, (c) multiplet group 3, (d) multiplet group 4 and (e) blasting activities. Two features are visible: (i) the seismicity seems to occur at specific hours of the day and (ii) blasting activities are scheduled around 6–7 am and 6–7 pm and they do not seem to trigger immediate seismicity.
assume ray path similarity, so the effects of velocity heterogeneities are reduced (Got et al. 1994; Waldhauser & Ellsworth 2000).

There is a trade-off when choosing the minimum correlation threshold. We chose a minimum correlation of 0.8 (80 per cent), which is sufficiently low to detect multiplets, but sufficiently high to differentiate between different groups. A higher threshold (0.9) only detects four doublets. On the other hand, using a lower threshold of 0.7, 440 events (90 per cent of total events) are gathered into several groups; however, most of these events are poorly linked. Given our chain-like approach, the algorithm can consider that an event belongs to certain group even though it is highly connected to only one event, the reason why some events within a multiplet group appear spatially extended. Multiplet group 1 is the largest, hence the most affected. Nevertheless, we consider an appropriate approach since in general most events show improvement compared to the grid-search based initial locations. To counteract the effect of poorly linked events, relocation results depend strongly on the chosen weighting scheme; thus we recommend setting distance weights such that they do not exclude any highly correlated doublets and correlation weights are to be set such that correlations below a set threshold are downweighted (Castellanos & Van der Baan 2013).

A cross-correlation-based method has the advantage of correcting for potential mispicks and also acts as a quality control measure for picking and location accuracy, evidenced by time delays histograms (Fig. 1) and correlation versus distance crossplots (Fig. 3), respectively.

For both initial and final locations, we use a \(P\)-wave homogeneous velocity model. This simple assumption is justified since we are interested in relative relocations and the approach accounts for shared ray paths irrespective of the complexity of the velocity model. These relative relocations are largely insensitive to inaccuracies in the local, homogeneous velocity model except for relative distances as they are mapped out in a contracting or expanding microseismic cloud for respective underestimated or overestimated velocities.

Static or dynamic stress changes caused by anthropogenic activities are likely to generate seismic events (Kilb et al. 2000; Freed 2005); the analysis of spatio/temporal patterns of microseismicity in mining settings is key to gaining insight into pertinent questions such as whether seismicity is caused by scheduled mining activities or part of earthquake cycles. We focus our study on the three largest multiplet groups, located at the centre of the mine infrastructure. These groups cluster around shaft 1 and main working tunnels that provide access to the ore body (420, 465 and 480 m levels). More specifically, group 4 is confined close to the shallow 420 m level.
Microseismic dynamic triggering

Thus it is very likely they occurred as a result of mining activities along that tunnel. Similarly for multiplet group 3, whose deeper range (420–465 m) and locations suggest it might be associated with activities along the main shaft. Group 1 has a mean depth of 465 m and is located in a more complex area due to the presence of the 465, 480 and 500 m levels as well as the main shaft. Despite the locations are improved after multiplet analysis, the complexity of the area does not allow to relate this group with a specific anthropogenic activity, except for when we include the striking temporal pattern in the analysis. In general, the seismicity occurs at the centre of the observation wells, producing well sampled ray paths, and we are thus confident in the event locations. This is also confirmed by the various quality control analyses performed in Castellanos & Van der Baan (2013) to scrutinize traveltime picks and event locations.

We postulate that the locations of the microseismic events centred predominantly around shaft 1 and the centre of the tunnels can be explained by a favourable stress state caused by the hoop stresses around these openings. This is similar to the case study presented by Husen et al. (2013), where earthquake clusters occur close to tunnels levels due to stress redistribution. A major difference is that the observed clusters show a striking trend similar to pre-existing faults, whereas in our case study there is no evidence of faulting but the close proximity of the hypocentres to the main tunnels and main shaft provides an important criterion to consider dynamic triggering of events. However, the absence of seismicity around the second air shaft implies that the magnitude of the hoop stresses is not sufficient to statically trigger seismicity. Thus, a likely dynamic triggering mechanism is required.

The detected seismicity occurs almost systematically at specific times during the day, strongly suggesting they are caused by anthropogenic origins and not tectonic events. Blasting operations come first to mind as a dynamic triggering mechanism since their seismic amplitudes are orders of magnitude larger than those of the recorded microseismic events. However, the absence of seismicity after blasts implies their dynamic (i.e. transient) stress perturbations are insufficient to overcome the Coulomb failure criterion in the area (Jaeger et al. 2007). We also exclude delayed triggering (Freed 2005) due to blasting since microseismicity resumes after different time intervals after the 7 am and 7 pm blasts.

Given that multiplet activity rate increases following rock removal, we postulate that the transportation of the excavated rock mass via the main tunnels and shaft 1 triggers most of the recorded seismicity. In other words, we come to a model where static stresses exerted on the surrounding rock mass due to the existence and creation of new tunnels and shafts facilitates but are not sufficient to trigger seismicity unless additional dynamic stress variations are present. The latter are not caused by the initially most obvious explanation of blast detonations, but due to large volumes of rock being transported to the surface via the main shaft. To put this hypothesis into perspective, if we assume a rock density of 2800 kg m$^{-3}$ and an average removed volume of 100 m$^3$, 280 000 kg is being transported daily. The debris transportation creates a net transfer of mass, which affects the in situ stresses surrounding these newly created opening tunnels and the main shaft. This would explain (i) why the seismicity is located in that area but absent around the air shaft and (ii) why most seismic activity is occurring at specific hours and correlates with days of rock removal. Noticeably, the correspondence between seismicity and debris transportation is not one-to-one, for example, we observe on January 12th there is seismicity but no rock removal associated, which do not follow our model but indicates that the work and vibrations exerted by the lift engines may play a role to trigger dynamic stress variations so their effects should not be overlooked.

This case study provides a clear example that the transportation of debris, which has historically been considered not relevant as a triggering mechanism, can play a significant role during dynamic stress transfer and act as a major initiator of the seismicity in mining exploration settings. Finally, it also favours the condition that a pre-existent, near critical, stress state must exist to dynamically trigger seismicity due to anthropogenic or natural processes.

Figure 7. (a) Amount of removed rock volume per day during month. (b) Number of detected events per day (sum of the three largest multiplet groups). There is some indication of a temporal correlation between seismicity and debris transportation suggesting the latter could have acted as a dynamic triggering agent.
6 CONCLUSIONS

Multiplet event relocations determined using a slightly modified version of the double-difference method indicate that seismicity occurs spatially in the centre of a tunnel network, close to the main shaft. No seismicity is detected near a second air shaft despite that area is well covered by receivers in surrounding observation wells. Contrary to initial notions, their time of occurrence correlate with scheduled rock removal (68 per cent) and not with blasting operations.

This confirms that two conditions must be met to explain the spatial and temporal occurrence of microseismicity: (i) a favourable stress state must exist, here caused by the hoop stresses exerted by the tunnels and both shafts. In this case, evidenced by the seismicity located above/below the main tunnels and around the main shaft and (ii) a dynamic triggering mechanism must be present to induce local failure. Such a failure mechanism may be counterintuitive. In this case, transient stress changes due to blasting are not sufficient, but local rock removal, possibly coupled with the vibrations from lift engines are. This model may explain why the seismicity is located only around the main shaft. These results point to the necessity of more investigations with respect to uncommon causes of seismicity for enhanced forecasting of possible damage and collapse zones as a result of routine mining activities.

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