Automatic data selection, worker exclusion zones and an attempt to identify precursory activity in real time: Routine and research activities in seismology at Sibanye-Stillwater Ltd

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Abstract

Underground mining in high rock-stress environments can induce unanticipated dynamic rockmass deformation, posing a serious risk to the workforce. Data collected by seismic networks are imperative for the design-as-you-mine process. Often an inappropriate assessment of the seismic hazard is done when unnecessary data are included in analytical techniques, particularly short-term time frames. Depending on the methodology or application of data analysis and interpretation, some of the information may not be relevant and even detract from the objective. By using the spatial event clusters associated with active workplaces to define the shape and size of the polygons for data selection for subsequent analysis, a problematic subjective component can be eliminated.

The mining of tabular reefs in South Africa, be they gold- or platinum group metals, is very extensive, and underground workplaces are often widespread. Production stoppages are very costly, especially for marginal mines, so there is just cause not to evacuate an entire operation's workforce following the occurrence of a large mining-induced seismic event. A rationale based on the damaging peak particle velocities (PPV) of the past seismicity can exclude the unaffected underground personnel and allow a quick orderly withdrawal where required.

Micro-deformation may precede rockbursting, which can occur on-shift close to the workface. A mine-wide array of geophones suitable for the accurate location and analysis of seismicity may not be able to detect these higher-frequency emissions. Inexpensive but fit-for-purpose accelerometers, providing real-time, continuous measurement of acoustic rockmass deformation near the workplace, integrated through underground and surface communications networks, are shown to record 'rock-talk', clearly distinguishable from the instrument background noise, which can be in the order of hours leading up to an imminent damaging seismic event.

Keywords

seismicity, risk, workforce, evacuation, safety, warning, short-term, precursory

Introduction

Mining in deep and high-stress environments is often accompanied by dynamic rockmass deformation, the consequences of which can be severe to underground workers and infrastructure. In trying to understand and limit these negative factors, the selection of recorded seismic data in space and time for subsequent analysis and interpretation should be as relevant, accurate and objective as possible. User-defined polygons (i.e., enclosed three-dimensional volumes in space) for the selection of a statistically significant number of seismic events associated with individual workplaces have sometimes included irrelevant seismicity that clouded the desired interpretation results or failed to include some that were relevant. Very often, a lack of regular verification of acceptable polygon geometries causes a mixture of these two problems. In short-term analysis we aim to eliminate this very subjective component and allow the spatial event clusters associated with active workplaces to define the shape and size of the polygons used for data selection. Distant, but also possibly relevant large seismic events are included in these 'automatic' polygons.

Sibanye Stillwater's Driefontein, Beatrix, and Kloof gold mines have been in operation for many decades, employing a non-mechanised method of reef extraction, requiring a large workforce. Such mature gold mines, exploiting the tabular reefs along the rim of the rich Witwatersrand Basin, may have widespread active stopes kilometers distant from each other. Following the occurrence of mining-induced seismicity on-shift or when the elevated seismic risk demands it, the size of a worker impact zone requires quick definition for workforce evacuation. The threshold distance of observable damage due to past seismicity

can be ascertained from mine records, if available. Having the magnitudes of causative events coupled to the calculated ground motions experienced at these distances, the baseline peak particle velocity (PPV) associated with damage can be determined. This knowledge can be extended to calculating the radius around the focus of all future events of M_L1.0 and greater (established locally as damaging events), where the baseline PPV is reached. Personnel whose workplaces are located within the volume defined by this radius will receive notification to move to a safe place and then return to the surface in an orderly fashion, or until such time as safe re-entry, post-inspection, is declared.

Analogous to a rock specimen in a laboratory stress test, the rockmass around mining excavations may experience an increased rate of deformation with respect to load just before the onset of catastrophic rock failure, and release energy in the process. This release can manifest as an increase in acoustic micro-seismic deformation, recordable with a nearby instrument having the required sensitivity. We used accelerometers to detect and record the activity preceding seismicity near the reef and close to the immediate face, which could be characterised, principally, as 'rockbursts' (i.e., crush-type events), posing a serious hazard on-shift. The aim is to understand immediate seismic risk better and eventually warn the workforce timeously.

Seismological setting

Sibanye-Stillwater's Driefontein gold mine in South Africa, amongst others, exploits narrow tabular reefs and often operates in a deep and high-stress environment. It performs mining at shallow-to-intermediate depth but, by virtue of the multi-reef environment, the presence of geological discontinuities and the legacy of long spans of mining, the seismic hazard is ever-present, and the occurrence of large dynamic ground motions is frequent.

Figure 1 indicates the mining plan of Driefontein operations, bound by the mine lease area (each square represents 16 km^2, oriented to local mine coordinates), and locations of 15 seismic events of local magnitude M_L3.0 and larger over the three-year period from 1 April 2021 to 31 March 2024 (the largest event was M_L3.8). A period of protracted industrial action, workplace lockdown, and production disruptions occurred between April and June 2022.

A minimum of three tri-axial geophone sites provides the time of occurrence and location of the seismic events in space and ascribe another two independent seismic parameters to the seismic source: seismic potency (P) and radiated seismic energy (E), from which several derivatives quantify the seismicity and provide insight into the changing conditions of the rockmass. The calculation of M_L, P, peak particle velocity (PPV), and other seismological parameters relevant to the topics at hand are fully described by Mendecki (2013, 2016) and covered in Ferreira et al. (2023a), which will not be repeated here.

A workshop held by the International Society of Rock Mechanics (ISRM, 2024) aptly redefined a rockburst as "a sudden failure of rock mass surrounding the excavations caused by the rapid release of stored energy when induced stresses exceed the rock strength." In a practical sense underscored by experience, events with local magnitudes of up to M_L2.0 coupled with violent ejection of rock from the face may constitute a rockburst. Such event magnitudes usually fall within the expected normal range of energy dissipation around the stope with mining, often triggered by, and ordinarily occurring shortly after blasting. The geomechanical engineering design and support of excavations strive to contain the seismic hazard, but unanticipated rockbursting can still occur on-shift. The geometry of mining layout and geological complexity exerts great influence on the seismic response, and much consideration and due diligence need to be expended to contend with this.

Although an M_L3.0 event can have devastating shake-down effects and the ground motions are felt over a large distance from the source, it is well understood that its source mechanism is usually associated with sudden relative dislocation of the rockmass along a geological feature on a large scale, possibly along bedding planes, or shearing of intact rock, typically at highly stressed abutments. They normally occur in back areas, fortunately distant from working places, but are more random in time than rockbursts.

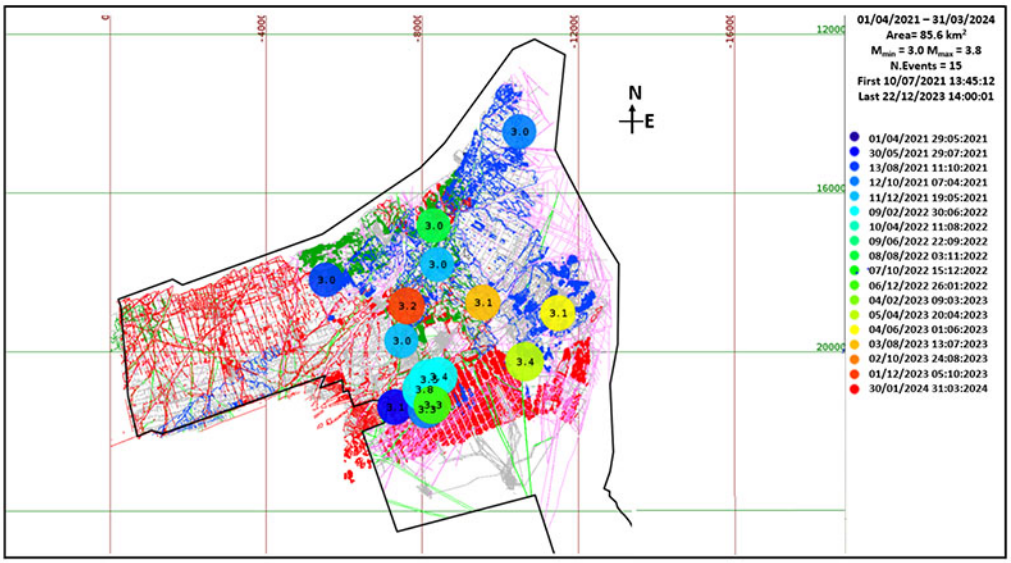


Figure 1— Mining plan of the three tabular reefs (red, green, and blue) extracted at Driefontein Gold Mine. The middling between the reefs is around 60 m. Depth of mining increases towards the South with an inclination of approximately 260; deepest mining approaches 3400 m. Major geological features are delineated. The location and magnitude of events M_L3.0 and greater (15 in total) are shown by discs, warmer colours indicating the latest, in the time period 1 April 2021 to 31 March 2024. Frequency-magnitude distributions reveal the sensitivity of the seismic network to events as small as M_{min}-2.0 (or better) near current working places. Maximum magnitudes (M_{max}) in excess of M_L3.8 can be expected

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The seismic coverage and sensitivity to ground motions are in accordance with the density of the geophone array used for event locations and are generally good. Driefontein mine benefits from 42 4.5 Hz ground motion sensors (tri-axial geophones, orthogonally oriented, in a sealed unit), all strategically located for optimum seismic coverage of workplaces. New sensors are installed when the extended mining face necessitates it. The seismic system is given high importance and is efficiently maintained. Location accuracy (usually better than 50 m), frequency-magnitude and temporal distributions attest to this.

Automatic short-term data selection

The size of the seismological database is voluminous, stretching back from the current seismic system in use to 1996 (and to 1983 with older technology), and is augmented with processed waveforms daily. Proper data selection in space and time for interpretation (long- or short-term, very much depending on analytical methodology) is not straightforward, and some past efforts to automatically generate seismicity polygons have endeavored to minimise user influence. The method of Wesseloo et al. (2014), for example, although only partially automated, is still affected by the chosen analysis parameters and not free of user subjectivity. In a more recent development, instead of having a subjective user-delineated polygon for the selection of relevant short-term historical seismicity for each working area, a novel procedure saw a polygon automatically constructed as an envelope, starting with a specified radius, around the active panels (Ferreira et al., 2023a).

Polygon size and geometry

The initial radius is user-specified, usually starting from 50 m (according to location accuracy), and automatically increasing in increments until a statistically significant number of seismic events are included in the search, or until a maximum radius (also predefined) is attained. The polygons around panels merge until the entire workplace is incorporated into a single polygon. A 'cluster' is defined as several events occurring in some finite space and time. Cluster recognition involves a user-defined near-history of events (usually hours), a size of search (a radius of 50 m) and a minimum number of events in the cluster (usually at least ten). If a cluster of events occurs and part of it lies in a working area polygon, then all events from this cluster will be included, and the polygon volume or shape self-adjusts accordingly. Figure 2 illustrates the concept.

Possible influence of nearby large events

If one or more events of sufficiently large magnitude occurred nearby, they can be included into the set of events contained by the geometry of the polygon. These events are classified as 'damaging' events, usually M_L1.0 or greater. When such events occur, a radius of possibly damaging ground motions is calculated, centered on the focus of the event, and used to assist with the notification of the workforce and workplace evacuation efforts when the seismic risk is elevated. Such an event will be included if the distance from the working area is contained within the volume affected by damage-causing ground motions, previously established as at least 0.08 m/s through in situ inspection. For wider application across the mine, we employ a factor of safety and reduce the threshold of damaging ground motions to 0.06 m/s.

Seismic damage and threshold of observable damage

An increase in event magnitude is linked to an increase in the dimensions of the source. Even though not all seismic events result in damage, as the magnitude of seismic events increases, there is a corresponding and exponential increase in reportable damage (Jager and Ryder, 1999). A larger volume of the mining excavations is affected by higher ground motions and velocities, and a greater likelihood of damage and worker exposure. Accordingly, a worker withdrawal zone scales according to the magnitude.

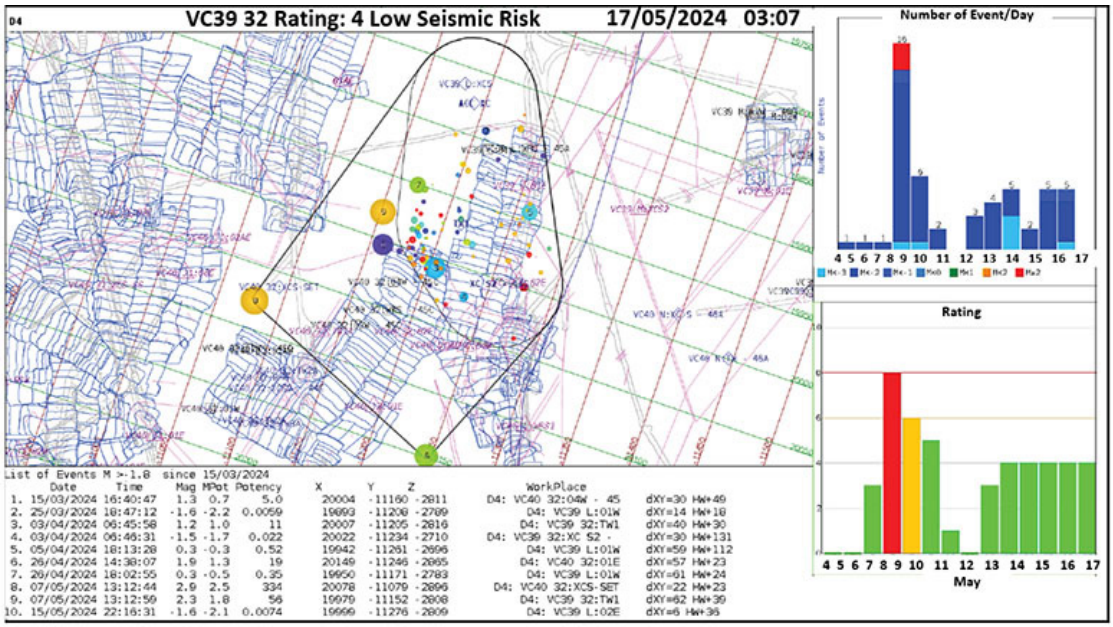


Figure 2— The delineation of a 'polygon' for the exclusive selection of events in the direct vicinity of nearby working places is exemplified in this diagram. The polygons are determined automatically to include clusters of seismic events and incorporate sufficiently close large events, which may not necessarily form part of the clusters. The report format includes a plan diagram of the working place, spatial cluster and listing of selected seismicity, and graphical time-history of seismicity and ratings for the past week. This encompasses a daily workplace seismic hazard assessment

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The relevant mines' Codes of Practice (e.g., Code of Practice, 2021) and internal records reveal M_L2.0 and greater events are more often associated with damage further afield than the immediate stope face. It further points out that smaller-sized events normally cluster close to the active workings, while a different subset of larger events, with different source mechanisms, are usually associated with more distant geological features or the shearing of intact rock. A typical microseismic network, as used at Driefontein, can provide information on likely modes of deformation and seismic risk. Many factors contribute to rockmass damage, for example, the formation of cracks and fractures as mining disrupts the balance of stress, the ejection of rock from the face, severe excavation deformation, and shakedown when support systems fail. Most seismic activity tends to be centered around the stope face directly after blasting. In these cases, damage, when it happens, is very localised. Mid-range to large damaging events (conservatively M_L1.0 and larger) with possible aftershock occurrence can occur on-shift, and pose a greater potential risk, particularly to the workforce in adjacent areas or further afield.

Ferreira et al. (2023b) reported on the extent of damage produced by 27 events from one of Driefontein's deeper shafts, spread over a period of 20 months (demonstrated in Figure 3). The occurrences ranged in magnitude from M_L0.9 to M_L3.4. The information was recognised as being limited, but established the distances from event sources to the point where no more damage is apparent to an observer during subsequent in situ investigation. The corresponding PPV was then calculated at those distances.

Worker exclusion zones

When and where possible, a record of damage due to seismicity is usually kept for later rockmass re-support or rehabilitation efforts. This information is regularly updated in the mines' Codes of Practice. The records are expected to be incomplete since access to older accessways and workings is restricted, and often impossible due to personnel barricades and ventilation seals. Given a significant number of large-event occurrences, the threshold

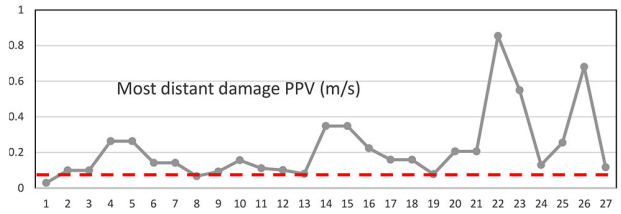
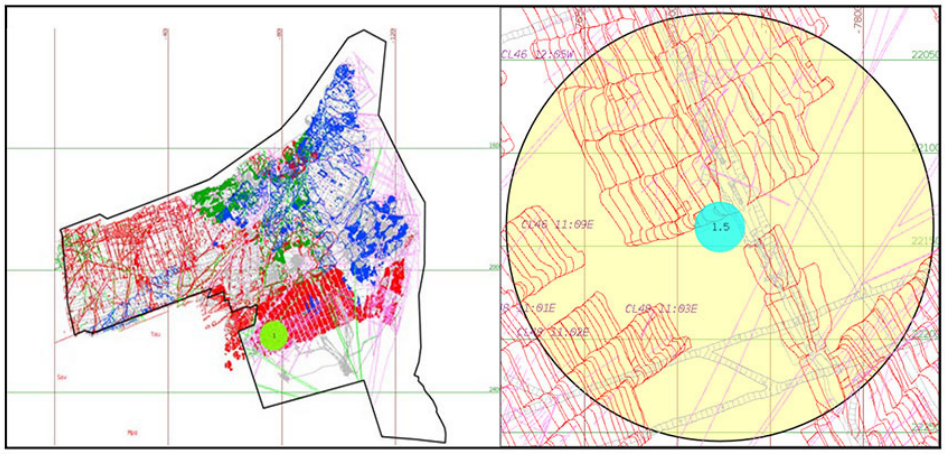


Figure 3—The information provided by in situ inspection of 27 events at Driefontein mine reveals a threshold of ground motion of approximately 0.08 m/s (dashed line) below which damage in stopes, tunnels and ancillary excavations is not visually apparent anymore. This value is further reduced to 0.06 m/s with a factor of safety of 1.5, to account for various unknowns and wider application across the operations. These quantities should be reviewed whenever the ground motion equations are revised

distance of observable damage can nonetheless be ascertained. The magnitudes of causative events coupled with the calculated ground motions experienced at these distances provide the baseline PPV associated with damage. The radius around the focus of all future events of M_L1.0 and greater, where the baseline PPV is reached underground, can then be calculated. Personnel working within the volume defined by this radius will receive notification to move to a safe place. Workplace evacuation can be accomplished in an orderly fashion and a safe re-entry is declared after an in situ inspection is done.

Radii of influence and communication with the workforce

Visual displays on screens at various points at the mines provide a list of all active workplaces located within the volume defined by the PPV of at least 0.06 m/s following an event of M_L1.0 or greater. Work crews are notified telephonically to withdraw if they are located within the zone of potential damage. The displayed list of affected workplaces may be overwritten in quick succession by subsequent large aftershocks or large tremors elsewhere; to ensure the list is maintained for record-keeping, this information is also relayed by electronic mail. Figure 4 shows an actual example of a seismic event (M_L1.5 in this case; picture cropped to fit) as it



Event Mag=1.5 at 17:56:43 on 13/05/2024
Location = 22140 -7723 -3183
MPot=1.1 Potency=12m3 LogMoment=11.61 LogEnergy=6.14
WorkPlace CL48 11:03E dXY=54 HW+11 PPV=168.2 mm/s
Affected Area: Radius = 115 m

Shaft	Affected Workplace/Panel	Distance XY	Elevation
D5	CL48 11:03E	54 m	HW +11 m
D5	CL46 11:09E	87 m	FW -143 m
D5	CL48 11:02E	106 m	HW +6 m

Figure 4—An example of the information communicated via email after a possibly damaging seismic event, showing some event details, its location, and a listing of affected workplaces. A similar display appears at remote terminals in multiple office locations and control rooms across the mines, providing information that may be required for rescue or workplace evacuation efforts

would be displayed on remote screens, its location in relation to the entire mine, and a zoomed-in view of the affected areas with a listing thereof. A control facility, manned around the clock, would also sense the shaking by the tremor on surface, verify the location by the seismic network, and relay the information to the relevant decisionmakers for immediate action.

Microseismicity preceding a possibly damaging seismic event

The onset of production blasting disrupts the state of stress at the mining face and often precipitates seismicity, which can be detected and recorded by an adequate regional seismic system. The failure behaviour of rockmass is complex and strongly influenced by various mining elements, including geological structures, on a micro to macro scale. A thorough understanding of the failure mechanism around an underground excavation needs to include an investigation of the cracking processes of the rockmass and how micro-cracking around the excavation progresses to macro-cracking of the rock fabric, leading to failure (Cai et al., 2004). Prior efforts to investigate reliable precursors of large (damaging) seismic events have failed to produce convincing results (Durrheim and Ogasawara, 2012), although there was postulation that physical changes to the rockmass under load could be measured. Spottiswoode (2010) investigated foreshock activity using data collected by mine-wide seismic networks from five mines, representing a range of deep mining methods, and attempted to establish whether any change in seismic character or event rate preceding large events could be inferred. A statistically significant difference in foreshock statistics could not be found, with the conclusion that short-term prediction was not feasible based on seismicity rate alone. Many short-term seismic hazard assessment schemes (SHA) have been derived for rockburst risk management in South African mines (e.g., Durrheim and Ogasawara, 2012; Ferreira et al., 2023a) but reliable and accurate rockburst prediction remains a difficult and elusive goal.

Any large-scale effort to analyse high frequency micro-cracking processes with exceptionally sensitive state-of-the-art sensors quickly runs into cost barriers. A networked array of mine-wide geophones, as normally employed in deep mines to locate and quantify seismicity according to some desired level of sensitivity and accuracy of locations, may not register many micro events located between the sensors, due to rapid high frequency signal attenuation with increasing distance, as opposed to accelerometers installed close to working areas of the mine. We used two inexpensive and relatively insensitive accelerometers, covering three workplaces and separated by 167 m, each with an effective range less than 150 m, installed within 50 m of the active stopes to monitor the cracking process around the excavation in real-time and to explore the rock mass behaviour more deeply. The response limit of the accelerometers is 1 kHz, and sampling frequency is 4 kHz, with 8G full scale range. This differs from previous attempts in that only nearby microseismicity is recorded.

Distance between a ground motion sensor and the seismic source

Given P-wave (V_P) and S-wave (V_S) velocities of 6200 m/s and 3650 m/s, respectively, as used by Driefontein mine's geophone array to determine the location of seismic events, it is easily shown that the distance (D) between a recording sensor and the seismic source can be approximated (with some subjective P- and S-wave first arrival picks) by

$$D = (t_S - t_P).C \text{ (m)} \quad [1]$$

where ($t_S - t_P$) is the time difference between the P- and S-wave picks (s) and C is 8875 m/s.

Microseismicity selection criteria

The initial focus is on unanticipated rockbursting, which can occur on-shift (the effects are – for all intents and purposes of the exercise – inconsequential during off-shift times) and any possible precursory activity that may be recorded in the direct vicinity. We considered events in the magnitude range $0.0 < M_L < 2.0$ (i.e., rockburst-type likely to affect the stope face), restricted to the location of the immediate reef plane (and from the two possible locations, the one closest to the subsequent 'large' event) and sought the prior micro-events preferably within 50 m of the main event using Equation 1. Most seismicity occurs concurrent with or soon after blasting (as expected, nucleation processes may have been in formation, and the blast may have introduced further instability into the rockmass). At this stage the two accelerometers work independently with common time only. The locations of main events were established with the regional geophone array. It was hypothesised that any preceding micro-events were closely clustered and associated in some way to the main event. This proved not to be to be entirely correct, as some of the micro-events located by the regional network were shown to be scattered (see Figure 5), which reinforces the need to obtain locations from the accelerometers to define clustering, not yet possible without further software development and installation of additional accelerometers. Not all recorded micro-seismicity by the accelerometers is accepted. A discernible signal-to-noise ratio with clear P- and S-wave arrivals (see Figure 6) allows accurate selection of first motions and distances to the seismic sources to be calculated. Faraway sources are discarded.

In the three-month period of 2 February to 2 May 2024 we identified 15 occurrences (magnitude ranging from M_L0.2 to M_L2.6), which could potentially be considered 'damaging' events. Clear precedence of nearby 'rock-talk' was not always found: one (M_L2.0 on 20 April at 11:07:42) practically displayed no measurable precursory activity at all, although other instances produced encouraging results. Some events were discarded because of distance (sensor limits). Most of the events almost immediately followed the blasting; one other, an M_L1.6, occurred an hour after the blast (which likely precipitated an M_L0.5), but showed prior activity throughout the day (see Figures 7 and 8). The M_L2.6 event was followed by several smaller aftershocks (M_L2.1, M_L0.3 in quick succession, and an M_L2.1 an hour later). It was interpreted to be the result of shear driven failure on an existing fault some 120 m away. In this instance one accelerometer was closer than the second one (approximately 100 m, as opposed to 170 m) and registered a much greater incidence of preceding micro-events.

The study is ongoing. Preliminary results indicate a newly established viability of the recording of possible precursory activity in the near field, which the regional geophone array does not correspondingly register. Also, microseismic patterns before an imminent large event differ in the continuous record in the absence of a sizeable event. Insomuch that the results obtained thus far hold scintillating promise of proactive warning and orderly evacuation of affected workplaces, the concept needs to be investigated in greater detail.

Challenges

The accelerometers need to be close to the working environment,

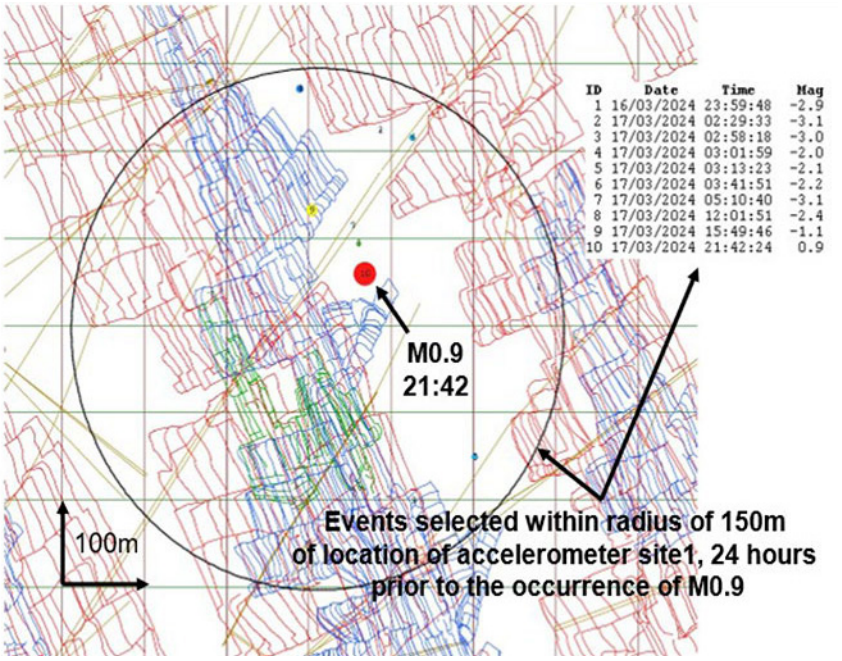


Figure 5—An M_L0.9 rockburst-type event occurred very close to active stope faces on a Sunday evening (off-shift). It is represented here by the filled circle in relation to stope plans in a sequential dip-pillar mining configuration. Although some micr-seismicity was detected in the direct environs of the main event, some were scattered further afield. A list of these is provided (1–9, preceding the M_L0.9 event). They were selected within 150 m of one of the accelerometer sites. Interestingly, events as small as M_L-3.1 could be located with several triggered geophones in this region of the mine, attesting to network sensitivity

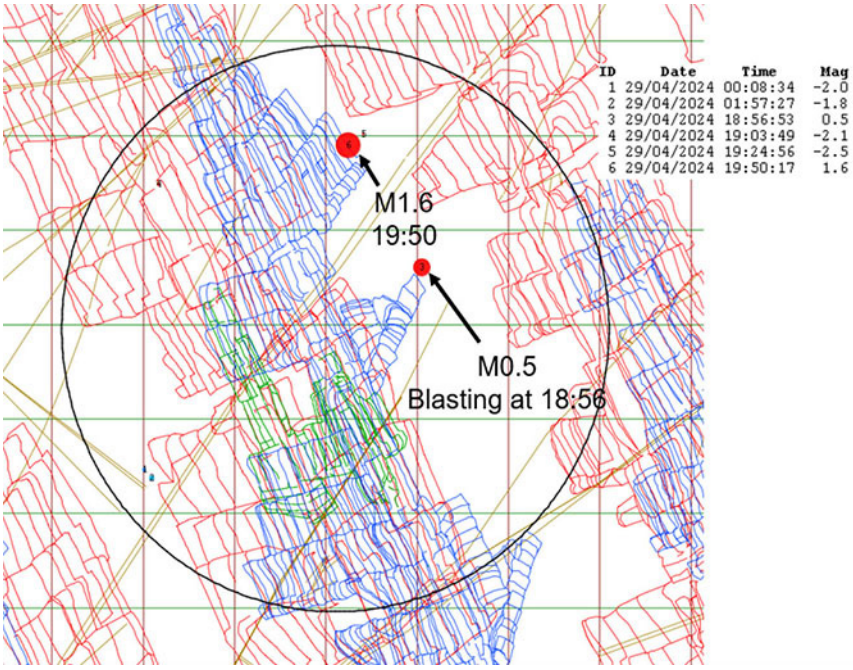


Figure 6—A 24-hour trace of continuous accelerometer data, with the M_L0.9 event on Sunday 17 March 2024 (off-shift) at 21:42, preceded by numerous micro-events (inverted top arrows) and some corresponding activity recorded by the regional geophone network (indicated by bottom arrows). An example of a typical micro-event as recorded by the accelerometer and decomposed into three components is shown. Clear P- and S-wave arrivals can be identified

with regular replacements as stoping advances, requiring a dedicated installation and maintenance crew to oversee the logistics. Large numbers of instruments produce vast amounts of data (transfer, storage, and quick access), requiring secondary management systems. Software development to recognise and flag pertinent microseismic events, and associating these with increased seismic risk to the workforce, needs to be done. The delivery of accurate danger signals to the relevant workplace(s) with few false alarms, needs to be established. Possible integration of data with the recordings of the mine-wide geophone network may be advantageous. These, and other practical considerations, require further investigation.

In closing

Production stoppages are very costly, especially for marginal mines. The management of seismic risk should encompass those

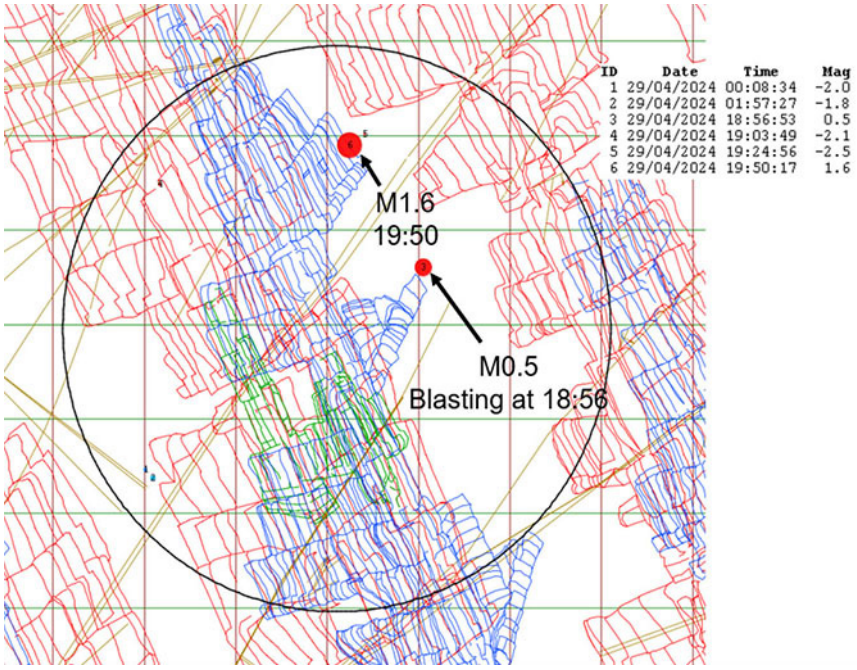


Figure 7—Similar to Figure 5 but showing the locations of an M_L0.5 associated with blasting and an M_L1.6 almost an hour later. The latter event was shown by the regional network to be preceded by only one micro-event (M_L-2.5)

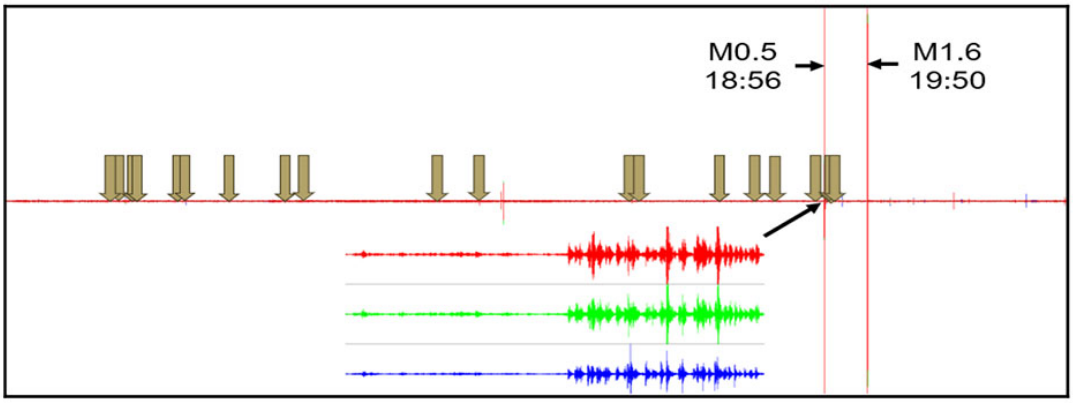


Figure 8—A 24-hour continuous accelerometer trace of ground motions, with reference to Figure 7. An M_L1.6 seismic event occurred almost an hour after blasting; inverted arrows point to prior nearby micro-events throughout the day, as recorded by one of the accelerometers, unlike the regional geophone array. A decomposition of waveforms (separate X, Y, and Z components) of the blasting is shown just before the M_L0.5 event

workplaces affected when seismicity occurs, quickly and effectively. A rock engineering solution needs to define the extent of damage associated with strong dynamic ground motions and evacuate the affected workforce from the zones prone to damage and possible aftershocks. A practical but robust methodology that considers the historical behaviour of the rockmass and establishes a minimum damaging PPV, is then translated into an exclusion zone following the occurrence of events with $M_L \geq 1.0$. This information is readily and widely communicated across the operations, both electronically and telephonically.

The problematic selection of seismicity for short-term analysis, which has been rather subjective in the past, can be automated for objective, less error-prone assessments. A better approach has produced a very autonomous workplace seismic hazard assessment procedure, defined according to clusters of seismic events in space-time, where the polygons are created with each run of dedicated software at predetermined times of the day. The possible effects of larger events further afield, likely to cause damage, are incorporated in the seismic trend analysis. Abnormal conditions draw the attention of geotechnical engineers and mine seismologists for closer scrutiny. The workforce is assured of a fresh overview of seismic behaviour just before entering the workplace and on-shift if seismicity occurs.

The continuous measurement of rockmass deformation very close to the workplace can be done with inexpensive sensitivity-limited accelerometers, purposely disregarding microseismicity further afield. The instruments are initially installed as close as possible to the progressing faces of workplaces and replaced as required. The communication networks are integrated through existing underground and surface infrastructure, providing real-time oversight of changing seismological patterns. This research, though at an early stage, shows that it is viable to identify precursory

activity in the environs of an imminent rockburst-type event and that this activity differs from earlier or subsequent patterns in the absence of a sizeable event. This opens the door to the exciting possibility of detection, early warning, and evacuation of affected workplaces proactively.

An extension of this work will consider the continuous record of individual geophones from the mine-wide array, close to accelerometers, and compare the response. We anticipate a good correlation of signals, but the geophones are likely to introduce undesired triggers from further afield. Farther geophones in the array (separated by hundreds of metres) are expected to show insensitivity to the high frequency acoustic emissions. Dense, sensitive, and expensive geophone arrays have enabled the location of very small events, which in hindsight have added little to the reported low success rate or accuracy of short-term warnings (with advocated network sensitivity of M_{min}-2.0 or better, as an objective of monitoring). It should be explored whether a wide spread of tri-axial low-cost accelerometers integrated with a sparser regional seismic network might enhance the monitoring objectives. Future work will shed more light on these and other questions.

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