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# Microseismic Monitoring of Underground Coal Mines: Objectives, Warnings and Sensor Array Design

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# MICROSEISMIC MONITORING OF UNDERGROUND COAL MINES: OBJECTIVES, WARNINGS AND SENSOR ARRAY DESIGN

**Richard Lynch[1]**

*ABSTRACT:* Microseismic monitoring is the only technique to provide 3D data to geotechnical engineers at underground mines and has become a standard tool in the deeper metalliferous and coal mines around the world. Objectives of the monitoring are typically rescue, prevention, control, warnings (which include identification of precursors for goafs and for large seismic events which may be associated with rock/coal-bursts) and back-analysis. Depending on the monitoring objectives, the required monitoring system sensitivity – the minimum moment magnitude above which seismic events are reliably recorded and quantified – would be between magnitude -2.0 and magnitude +1.0. While simple seismic activity – crack counting – is sometimes good enough for warnings of impending goaf occurance, precursors of large seismic events associated with rock-bursts or coal-bursts are more difficult to identify. There have been some sporadic successes in metalliferous mines with high levels of seismic activity – and thus lots of large seismic events to calibrate against. The design of the seismic sensor array depends on the objectives, but typically involves sensors installed in the main and tail gates either side of the panel. Current best practice involves permanent installation into long up- and down-holes to achieve the 3D configuration required for reliable 3D location of seismic sources. A more cost-effective solution is to use temporarily-installed geophones along with a surface seismic station.

## INTRODUCTION

Microseismic monitoring of mines is a technique routinely applied at over 300 mines around the world. It is the only technique capable of providing real-time 3D data on how the rock mass is responding to mining, and the field has matured considerably over the past 25 years [for example, see proceedings of the *Rockbursts and Seismicity in Mines* symposia from 1988-2017].

Routine passive microseismic monitoring of underground hard rock (metalliferous) mines has been common since the 1990's [Mendecki, 1993] and has also been applied in the hard rock open pit environment [Lynch at el, 2005; Lynch and Malovichko, 2006; Meyer, 2015] and in the underground coal mine environment [Arabasz et al, 1997; Hatherly et al, 1997; Minney et al, 1997; Hayes, 2000]. Underground coalmines are different to underground hard rock mines in many aspects, which have significant implications for the design and operation of microseismic monitoring systems. Indeed, while some of the monitoring objectives are common, there are some objectives specific to coal mines – for example, using the microseismic data to warn of an impending goaf fall.

## OBJECTIVES

In general, routine microseismic monitoring in underground coalmines facilitates the quantification of exposure to seismicity and provides data for efforts into prevention, control and prediction or warning of potential rockmass instabilities that could result in rock- or coal-bursts. The following specific objectives of monitoring the seismic rockmass response to mining can be defined [following Mendecki 1999 and 2001] in the following ways:

*Rescue:* To detect and locate dynamic rock mass instabilities, alert management to potential rock-related accidents and assist in possible rescue operations – including by monitoring of aftershocks.

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*Prevention:* To quantify the exposure to seismicity, confirm the rock mass stability-related design assumptions and to enable an audit of the particulars of a given design while mining. This assists in guiding of preventive measures, e.g. corrections to the designed layout, sequence of mining, rates of mining and support strategy.

*Control:* To detect spatio-temporal patterns of seismological parameters – for example an increase in the number of seismic events located on a stability pillar or geological feature, or an increase of the statistical seismic hazard, or changes of volumetric stress by analysis of ambient seismic noise – and relate them to the expected short to medium term behaviour within the volume of interest. This would facilitate and guide control measures, for example a change to the planned end position of a particular panel or temporary changes to personnel exposure. Also to integrate seismic event data into suitable 3D numerical stress models to enhance their predictive capabilities.

*Warnings:* To detect unexpected strong changes in the spatial and/or temporal behaviour of seismic parameters or certain defined characteristic patterns – for example increasing microseismic activity - that could lead to dynamic instabilities affecting working places immediately or in the short term. This would facilitate warnings to manage the exposure to potential goaf falls (and the possibly accompanying air-blasts), rock-bursts or coal-bursts.

*Back-analysis:* To improve the efficiency of both the design and the monitoring processes for stability of mine workings. Specifically important is thorough seismic and numerical modelling back-analysis of large instabilities even if they did not result in loss of life or in considerable damage. Back analysis of seismic rock mass behaviour associated with pillars, geological features and different mining rates, is an important tool in the quest for safer and more productive mining.

The following table contains the required seismic array capabilities to meet each of the standard objectives of monitoring.

**Table1: Microseismic sensor array requirements for the different objectives of monitoring.**

| ***Objective*** | ***3D location error [m]*** | ***Minimum magnitude above which events consistently recorded*** | ***Typical inter-sensor spacing [m]*** |
|---|---|---|---|
| Rescue | ≤ 100 | ≤ 1.0 | 3000 |
| Prevention and Back-Analysis | ≤ 50-75 | ≤ 0.0 to 0.5 | 1000 – 1700 |
| Control | ≤ 15-20 | ≤ -1.0 to -0.5 | 350 – 600 |
| Warnings | ≤ 10 | ≤ -2.0 to -1.5 | 100 – 200 |

## WARNINGS

### Goaf falls

One of the main seismic hazards in underground coalmines is violent failure of the roof strata – goafing – and the possible attendant air blasts. Fortunately, in this environment the simple indicator of increasing microseismic activity is often correlated with goafing [de Beer, 2000]. In an early study at Moonee colliery in New South Wales, Australia [Edwards, 1998], it was found that warnings based on increased seismic activity resulted in false alarms 46% of the time. However, 76% of significant goafs and all of the major goafs were successfully forewarned in this manner. Warning times were between a few seconds and 150 minutes, averaging about 50 minutes, which is quite practical for mining operations.

A later analysis of the seismic and goaf data [Iannacchione, *et.al*., 2005] showed that increased seismic activity was a reliable indicator of impending goaf fall about 90% of the time at Moonnee. An example of a successfully predicted goaf is shown in Figure 1, and more examples of both successful and unsuccessful predictions are given in Figure 2.

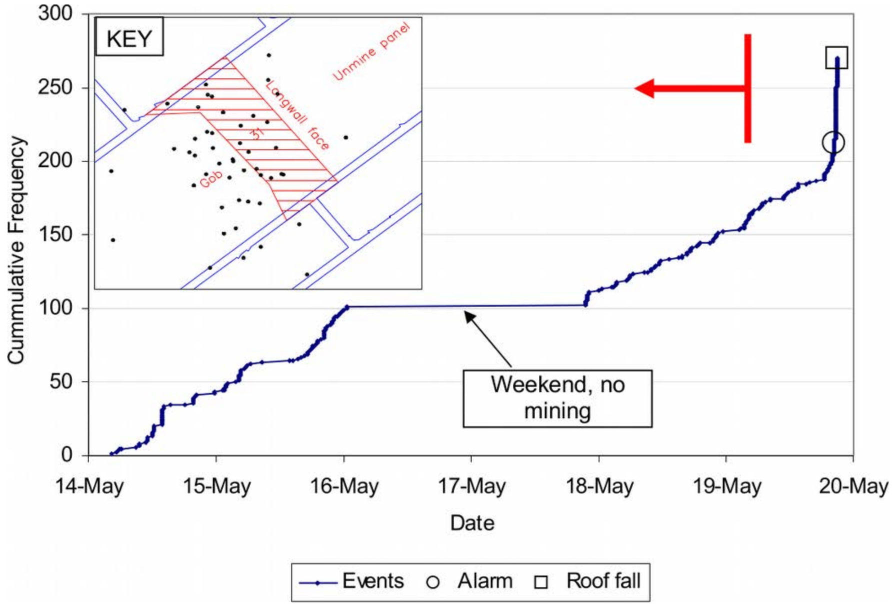


**Figure 1: The cumulative number of accepted and located microseismic events vs time. The alarm was raised after activity kicked up (circle) and 24 minutes later the major goaf fall took place (square). The location of the microseismic events associated with the increased activity is also shown (inset). (Iannacchione, *et al*., 2005).**

**Rockbursts and coalbursts**

Seismological precursors to rockbursts or coalbursts in underground coal mines in Australia have not been studied to date. There have been some results published for the Polish hard coal mines (Mutke et al, 2009) in which rockburst-prone zones were identified using seismic tomography. However, it is still not clear how to indicate when an impending instability would occur.

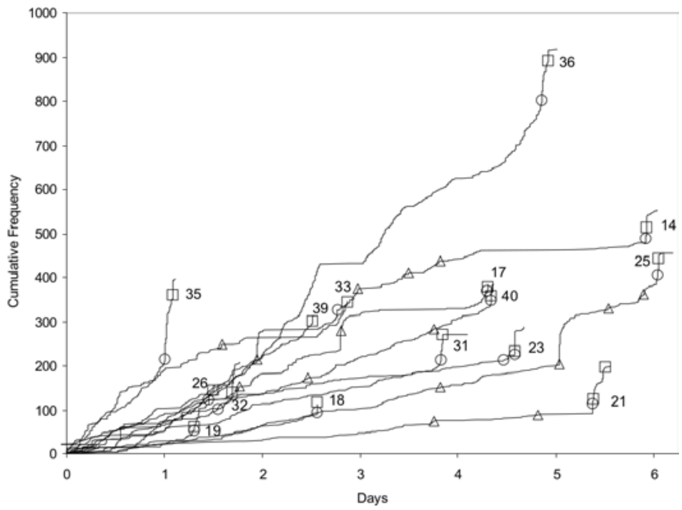


**Figure 2: The cumulative number of microseismic events vs time for a number of goafs (square symbols). Successful warnings are indicated by circles, unsuccessful warnings by triangles. Over 90% of the goafs are indicated in advance by increased microseismic activity. (Iannacchione, *et.al.,* 2005).**

Rockbursts have been a significant problem for many hard rock underground mines for over 30 years [Gay and Wainwright, 1984] and there was extensive research conducted into the problem of rockburst prediction in South Africa in the 1990's [MHSC, 2016]. While simple increases to microseismic activity rate is not a reliable precursor in this brittle environment, derived parameters like Energy Index [van Aswegen and Butler, 1993], Apparent Volume and Schmidt number [Mendecki, 1993] have been shown to provide some predictive success in the South African gold mines [van Aswegen and Mendecki, 1999]. Figure 3 shows an example where these trends in cumulative apparent volume and Energy Index were observed before a large event in a South African gold mine.

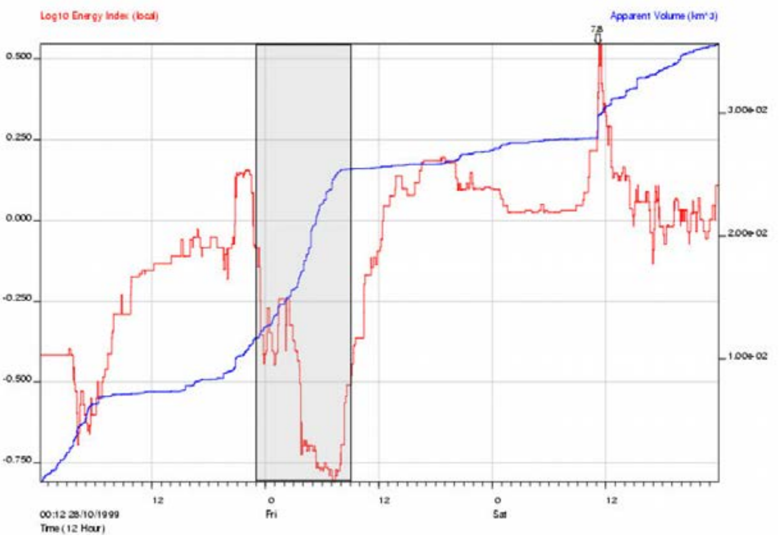


**Figure 3: A large magnitude 2.4 seismic event at TauTona gold mine in South Africa is indicated 30 hours in advance by the characteristic pattern of dropping energy index (red line) and accelerating cumulative apparent volume (blue line). Seismic events from the period of stress softening (shaded zone) can be used to identify the location of the future instability to within about 100 m. (Lynch and Mendecki, 2001).**


Similar precursory patterns have been observed in some Australian underground hard rock mines – for example at Beaconsfield mine in Tasmania (Hills et al, 2013) – see Figure 4.

**Figure 4: Time history of cumulative apparent volume (blue) and energy index (red). From around 20th March 2008 the cumulative apparent volume was starting to accelerate. By 3rd April 2008 the energy index was at its lowest level since October 2007. At the time indicated by the vertical back marker, a potential instability was identified and the mine was notified. A large (magnitude 1.9) seismic event occurred in that region five days afterwards. (Hills *et al*, 2013*).***

Despite these notable successes, only a few mines around the world routinely practice “earthquake prediction”. This is due to the lack of data in most mines: many large seismic events are required to calibrate these methods, and most mines do not experience large seismic events with such regularity. Another reason is that these techniques are not 100% reliable: despite best efforts with careful seismic monitoring, many false alarms are issued and many large events are missed. This problem has not been solved yet.

For these reasons, how to reliably warn of impending rockbursts or coalbursts in underground Australia coalmines remains a difficult and open question. Addressing this question satisfactorily will require good quality microseismic data and careful research.

## SEISMIC SENSOR CONFIGURATION

Underground coalmines are typically mining a planar ore body, and naturally the tunnels and access roads all lie on this plane. A planar configuration of seismic sensors allows reliable in-plane seismic event locations but very unreliable location in the direction perpendicular to the plane. This is a problem since knowledge of whether the seismic event took place in the roof or floor strata is important for interpretation.

To solve this, geophones are usually installed into 50 m boreholes drilled upwards and downwards from the main and tail gates. This aspect ratio – 100 m of vertical separation compared with 200-300m of horizontal separation – allows reliable 3D location of seismic sources with an adequate seismic velocity model. The geophones are permanently grouted into the long boreholes for the best quality seismograms.

The expected 3D location accuracy obtained from any particular configuration of seismic sensors can be modelled if suitable assumptions are made about seismic velocity model uncertainty, seismic sensor position uncertainty and body wave arrival time uncertainties [Mendecki, 1997]. Table 2 lists the assumptions used in modelling an example 4-geophone array in the long borehole configuration just described – Figure 5 contains the results.

**Table 2: The parameters used in modelling the expected 3D location accuracy for particular sensor arrays.**

| | |
|---|---|
| Homogeneous P-wave velocity | 4300m/s ± 5% |
| Homogeneous S-wave velocity | 2500m/s ± 5% |
| Sensor position uncertainty | 1m |
| P- and S-wave arrival time errors | 0.001s |

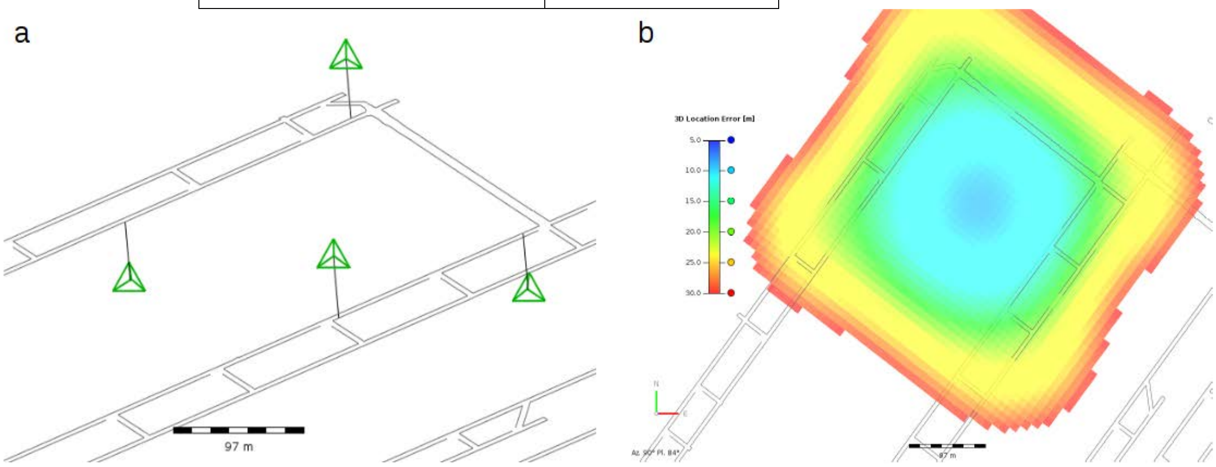


**Figure 5L: A typical long-borehole seismic sensor array for monitoring a coal longwall (left, with geophones as green triangles) and the expected 3D location accuracy for this array on the plane of the coal seam, under the assumptions given in Table 2. Such an array would be expected to provide a 3D location error of around 12 m or better**.

While this standard arrangement provides good coverage, it relies on long borehole and permanently installed geophones. Given the speed of mining, this is a relatively expensive solution. A more cost effective arrangement would be to use removable sensors. These can range from sensors bolted to the sidewall (which do not provide very good data) to cementatious "swallow's nests" (average data quality) to spring-loaded short-borehole sondes (best data quality). Figure 6 contains an image of the spring-loaded short-borehole sonde along with a comparison of data recorded by this removable geophone against data recorded by a permanently grouted geophone at the same position.

The use of removable geophones would result in a planar sensor configuration, leading to large out-of-plane location errors. To circumvent this problem, a surface seismic station can sometimes be used. When temporarily installed in a field 300-800 m above the mining, a surface geophone provides the necessary constraints to Z-coordinate error, resulting in satisfactory 3D location accuracy. Figure 7 presents the expected array performance for such a configuration.

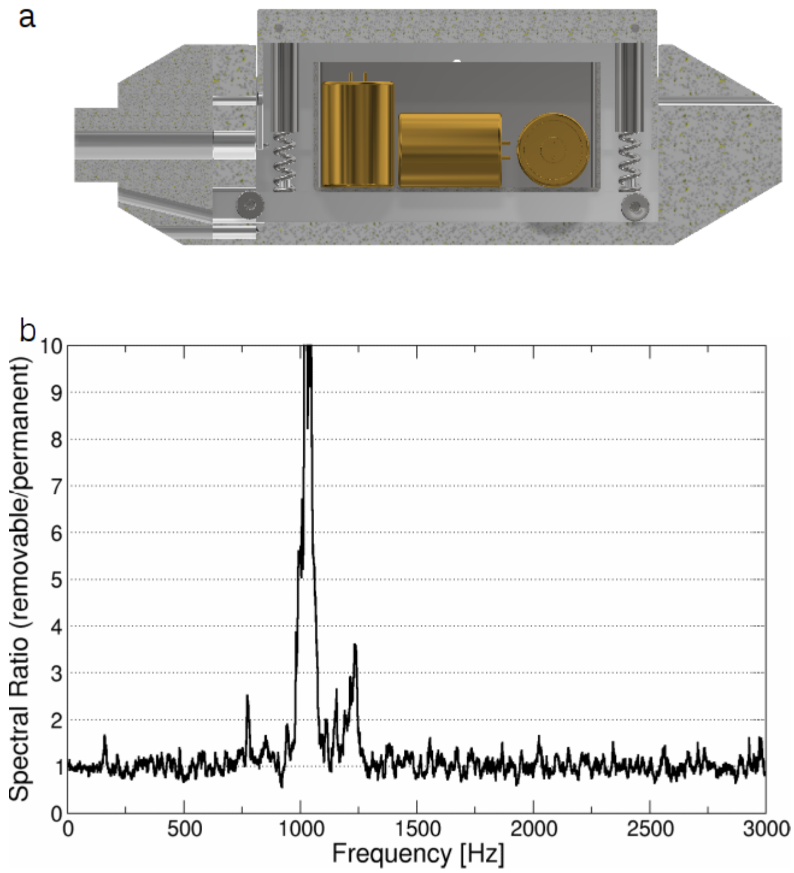


**Figure 6: A section through a removable spring-loaded geophone (above, with three orthogonal geophone elements in copper colour) and a graph showing the ratio of spectral response between the removable and permanent geophones at the same position. The shallow (1 m) borehole removable sonde gives a clean response for frequencies below 750Hz, making it suitable for use in coal mine microseismic monitoring systems.**

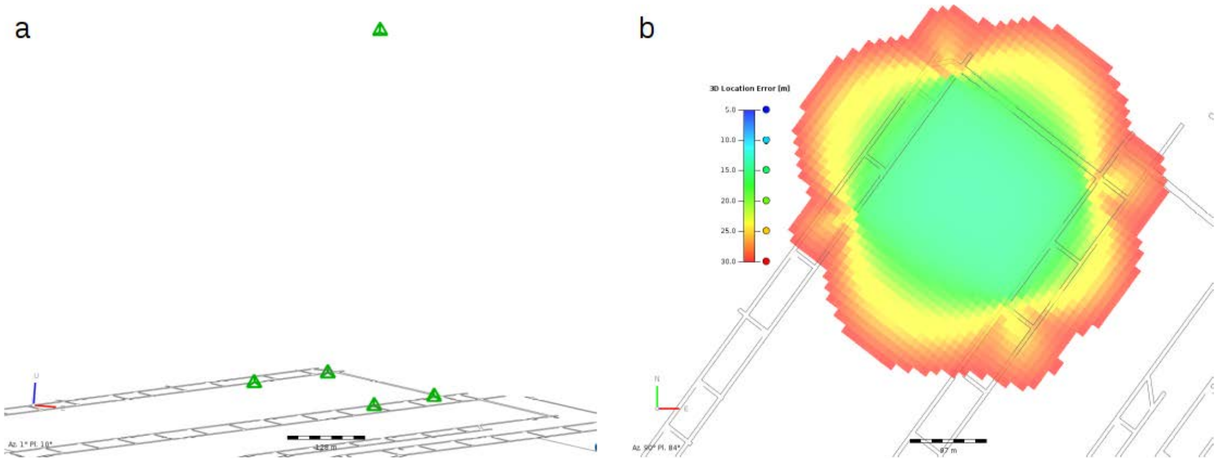


**Figure 7: A microseismic monitoring array consisting of 4 underground removable sensors and one surface removable sensor 600 m above (oblique view, left) with the expected 3D location accuracy in the plane of mining, under the assumptions listed in Table 2. Such an arrangement is expected to locate seismic events near the longwall with a 3D error of 15 m or better.**

## CONCLUSIONS

The objectives of seismic monitoring in underground coalmines typically include rescue, prevention, control, warnings and back-analysis. The seismic monitoring array requirements for rescue, prevention and back-analysis are fairly loose, with geophones spaced every 1-2 km or so. However, more careful monitoring of the rock mass response to coal seam mining – the objectives of control and warning – require geophone spacing of a few hundred meters and so sensors are installed in the main and tail gates either side of the panel being mined.

The objectives of warnings are of particular interest. While warnings of impending large goaf falls has been shown to be feasible at Moonee colliery, warnings of rock- or coal-bursts is much more challenging. Goaf warnings are based on simple microseismic event activity, but this is not good enough for warnings of rock- or coal-bursts. In hard rock mines, there has been some success in warning of impending large seismic events ("rockbursts" when these are located close to excavations) based on analysis of energy index and apparent volume, which are derived from seismic event source parameters. However, before this can be applied to underground coal mines, there needs to be more quality seismic data collected and case studies compiled.

Removable borehole geophones produce good quality signals at frequencies up to at least 750 Hz and so are recommended for monitoring of individual panels. The high speed of mining means that monitoring of such panels would only be for a few months, and so it is relatively expensive to use permanently installed borehole geophones. The planar nature of the resulting sensor array results in very unreliable vertical locations of seismic events, but this can be fixed by a surface seismic station where possible.

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