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Monitoring the Onset of Seismicity

By M H Turner [1] & D A Beck [2]

Introduction

A number of mines in Western Australia are now operating at depths and in stress regimes where seismicity is being more frequently reported. The severity of this seismicity ranges from minor (infrequently reported rock noise) to major (frequent large events with associated excavation damage). Geotechnical Engineers and Mine Management are becoming more aware of the benefits of seismic monitoring and as a consequence mines are tending to install small-scale seismic monitoring systems before seismicity and rockbursting affect production. These small systems range from 6 to 16-channel temporary (portable) units to small, permanent installations. As these systems are mainly based on uniaxial sensors (geophones or accelerometers) the data output and interpretation are severely limited when compared to full scale, mine-wide systems. The information obtainable from these small scale systems is still of immense benefit to operations and is used to highlight critical, seismically active structures and to compare the seismic risk associated with alternative mine designs and extraction sequences.

The monitoring methods and results of associated analyses are summarised for a number of case studies in Western Australia. The associated management and engineering techniques used to minimise the effects of seismicity on these operations are also discussed.

One objective of presenting this paper is to generate more awareness of available small-scale seismic systems and how even the simplest data can provide very good information for appropriate decision making. These systems are easy to use, low cost and the data can be analysed initially using the software provided with the systems. Additional, more useful analyses can be undertaken using readily available spreadsheet software such as Excel. Analysing seismicity is not the end product – input into mine designs, mine extraction sequencing and support systems should also be expected.

Sources of and Reasons For Seismicity

Seismicity in its simplest form can be defined as the sound of rock breaking. Rock failure due to high stresses around mining excavations is common in most medium to deep mines. In Western Australia stress related fracturing around mining excavations starts becoming apparent below 300m in weaker rocks and below 600m in strong rocks, with increasing fracture intensity at greater depths.

Virgin stresses invariably increase with depth, whilst rock properties remain similar, and flexibility regarding mining methods is limited. Seismic activity on susceptible mines generally commences and increases as the mined out voids increase in extent and depth due to ever-increasing mining induced stress components and in some cases as a result of the selected mine sequence.

Western Australian virgin stresses, as measured mainly using the Hollow Inclusion (HI) Cell are high and highly deviatoric (Lee, Pascoe and Mikula, 2001) (Figure 1). Evident from stress measurement results to date is the wide range, with major principal stresses over 60MPa measured in a number of mines.

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These mines have also coincidently experienced seismicity – Perseverance, Kundana, Big Bell, Kanowna Belle, Mt Charlotte, Longshaft, Otter-Juan, Bounty, Black Swan. These mines also all currently use seismic systems to monitor seismicity.

An important point is that while in each of these mines stress increases generally with depth, there are many instances where measured stress was anomalously high for a particular level, and between mines, the stress gradient and depth for onset of seismicity varied greatly.

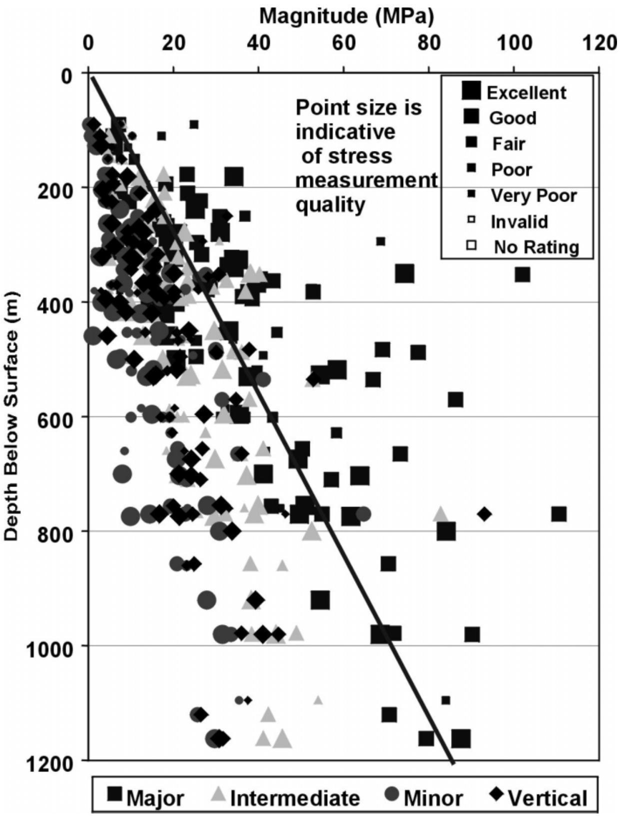
Seismicity can also be observed in areas where there are high local stresses due to ‘locked in’ geological or structural stresses; where there are significant differences between rockmass properties; where mining (development of stoping) approaches faults and other structures; for certain combinations of joint orientations and properties in combination with changes to stress magnitudes and directions and where the selected mining sequence is inappropriate for the conditions. In most cases the cause can be determined from analysis of seismic data and action can then be taken to mitigate associated risks. In the case of an inappropriate mining sequence, the seismic system can rapidly identify this as the cause and may allow development of criteria for designing a new mine plan.

Signs of Seismicity

Where mining continues to advance deeper, as with most Western Australian decline-accessed mines, stresses increase and eventually leads to seismic related rock failure around excavations. This fracturing would initially be minor, only located in the top corners of drives where there would already be blast damage and a concentration of stresses due to the drive shape. Such failure could go unnoticed, especially if there was no adverse impact, and where drives were meshed.

The first observable sign of seismic related rock failure is generally rocknoise, and this could take the form of small 'cracking' noises around recently developed excavations or the occasional 'rumbling' noise from movement around sometimes extensive previously mined stoping voids.

Figure 1 - ***Measurements of principal stress magnitude versus depth in Western Australia***



Another sign of seismicity is rockfalls, noticed at the start of the shift, which could take the form of scattered falls along drives (without mesh), or slabbing on corners. Many such falls are initiated by seismicity that follows formation of new excavations, hence being found the following shift on re-entry. In mines with seismicity, there are always other signs of stress damage.

A more serious sign is damage to split set rings and plates, which are the support units generally first to fail under either dynamic loading or convergence in a drive. This is an indication that more serious failures could be possible. Damage to service reticulation eg pipes, electric cables etc would be the next most serious sign.

Observed rock failure, such as spitting and ejection of rock from fresh development faces or smaller pillars is even more serious as employees are then being directly exposed to hazards.

As seismic events generate larger amounts of energy they will be associated with broken rockbolts, eg fully grouted bolts; loud rocknoise; seismic waves felt underground and on surface; bulking of mesh; loss of blastholes; cutting of initiation cords, and larger rockfalls associated with support system failure.

Monitoring

If seismicity has not caused problems, and evidence of rock damage is only encountered infrequently, seismic monitoring might not be required. In such cases experience shows that records should still be maintained of rocknoise, scattered falls or other damage. The importance of recording this information is that most mines that become seismically active have many preceding symptoms. For example, a common transition is from no damage, to limited stress damage and popping, to difficulties in maintaining access or with pillar stability, and finally intense stress damage with seismic activity. The 'rules' governing rock damage and seismicity in all these phases are usually the same, and it is only the intensity that changes with the increased stress, extracted volume or inappropriate sequence.

If rocknoise or rock damage becomes more noticeable it is well worth considering the installation of a seismic system as early as possible. Not large, expensive minewide systems, but relatively cheap and easy to operate systems.

A few mines have monitored seismicity using small-scale systems only to find that seismicity is not an issue and monitoring has subsequently been discontinued.

Other mines have used small-scale systems and have found that seismicity is an issue or is expected to be an issue at deeper levels. This provides an opportunity to analyse relative seismicity prior to purchasing a costly minewide seismic system. In the event of seismicity related damage subsequently increasing in severity, such records could be analysed to assess damage locations relative to stoping etc. This can provide a quick insight into possible causes of damaging events especially when combined with numerical modelling, such as with Map3D. These cause may be avoided or controlled to some extent with appropriate mine planning.

Small-Scale Seismic Systems

The simplest type of seismic monitoring is a rocknoise counter, which provides data on the number of triggers above pre-set peak particle velocities or accelerations. These units provide no information on location or magnitude, but can be set-up with a datalogger to provide the time of the events. They can be used to indicate if there is rocknoise after blast time, during the re-entry period when employees are outside the working areas. Some explosives manufacturers are able to offer rocknoise counters as a free service to customers.

Small scale seismic systems can be installed with 1 to 3 channels which will provide information on time and relative size/magnitude. Even the smallest system should be able to provide waveforms to distinguish between blasts and 'real' events. With 4 or more sensors it should also be possible to locate events. Tri-axial sensors are required to determine waveform calculated properties (uni-axial sensor based systems, can only calculate approximations of moment, energy and magnitude).
Single sensor triaxial station set-ups can be used for larger events – and the magnitudes from these sensors can be calibrated with regional (eg AGSO) stations. Regional locations can sometimes be estimated but are generally not relied on.

All multi-channel systems generally have software capabilities to graph events against time, days, location, energy and region (eg stoping areas) etc. In all cases the data can be exported to perform this task, and this is often preferred by mines with seismic problems.

Seismic event location and time are generally the most significant items of interest for initial monitoring and correlating system time to real time at the set-up is important. The set-up of the sensor array is critical to maximise the 3-dimensional view of the area of interest, especially with the limited number of sensors. The array design will be influenced by access limitations, power (interference) sources, orebody and stope geometry and seismic history to date, etc. There is still usually one side of the orebody or stope that is more difficult to cover and maximum use of cabling lengths should be utilised to overcome this, combined with the use of boreholes for cables. Cable lengths of over 200m between the central unit and the sensors can be used without significant deterioration of signal, and this is generally more than sufficient for initial monitoring of stoping sections.

Small scale systems are generally set-up with temporary, reclaimable sensor installation, attached to sidewalls with epoxy for example. If systems are required for periods longer than a year, consideration should be given to permanent sensor installations, with the units grouted into boreholes. Readily available shielded data cable or coaxial cable is used between the geophones and the central data acquisition unit.

The 3 manufacturers of systems used in Western Australia by mining companies are ESG (Engineering Seismology Group) from Canada, ISS (ISS International) from South Africa, and Snowdens (CSIR-MiningTech systems), also from South Africa. Systems are generally available for purchase within a few months. Manufacturers and consultancies also have systems available for rental at short notice, with typical rental rates of $1,000 to $1,500 per month.

Purchase prices for each of the systems are listed in Table 1, based on 2001 quotes, and these can vary depending on exchange rates, availability, maintenance agreements etc.

Table 1 - ***Small Scale Systems***

SYSTEM	DESCRIPTION	QUANTITY	(A$)
ESG (Canada)	Ruggedized 8-channel HyperPAC seismic monitoring system complete with eight uniaxial A1030 accelerometers. HMS v7.0 software including acquisition, seismic processing & visualization modules, manual or remote download. Windows based.	1	$ 25,200
	Annual Software subscription	1	$1,500/pa
		Total	**$ 26,700**
ISS (South Africa)	Standalone SAQS6G: 6 geophone channels, DC power, internal GPS, removable firewire disk, manual or remote download. Linux based.	1	$9,700
	RTS/stw Run Time System per channel (seismic triggered) @ $970.00 per channel	6	$5,820
	RMTS-Routine Moment Tensor Source Seismic Processing Software	1	$9,625
	SM15B – 14Hz geophone elements @ $104 each	6	$624
		Total	**$25,769**
GMM (Snowdens)	8 Channel, D-Cell Battery powered, manual download. Windows based.	1	$10,000
	Aura 32 Software – annual fee	1	$7,500
	14Hz geophone elements @ $104 each	8	$832
		Total	**$18,124**
Impulse (Snowdens)	16 Channel, mains or battery powered, manual or remote download	1	$20,000
	Aura 32 Software – annual fee	1	$7,500
	14Hz geophone elements @ $104 each	16	$1,664
		Total	**$29,164**

All of the systems above are based on a similar number of sensors (6 to 16), all sufficient for monitoring initial seismicity and to cover a volume of rock 200m x 200m x 200m. The Impulse system with 16 channels could cover a larger volume of rock. The GMM only has sufficient memory for around 240 events, whereas the other systems can be downloaded remotely. The exchangeable firewire disk facility of the ISS system allows a huge number of events to be accumulated between disk changes. The data acquisition units of all systems can be downloaded manually to a laptop PC either underground or on surface to eliminate the need for extensive cabling to surface. The memory capabilities of all systems are sufficient for initial monitoring.

Each manufacturer offers different software and the capabilities of all 3 extend to full scale minewide systems and easily cover the requirements of small scale monitoring. Regarding ease of use, the Aura 32 software is probably the easiest, followed by the ESG Hyperion software, with the ISS software the most complex. The ISS system is also dependent on Linux, which is not supported by some major mining companies.

Minewide Seismic Systems

The same 3 manufacturers of small scale seismic systems also manufacture minewide systems. Prices can range from $40,000 to $400,000. The total price is dependent on the number of sensors, lengths of cabling, power management, etc. Fibre optic cables improve data transfer capabilities from underground and are favoured for larger systems and for the more seismically active mines where real time automated analyses are required, but cabled systems can perform equally well and should not be discounted. The existing means of data transmission (electrical cable, fibre optic etc) is probably the most important consideration.

Prior to committing to major expenditure on a seismic system it could be prudent to install a smaller scale system to assess whether there is a seismic related issue and to estimate the severity and scale of the seismicity.

The top of the range seismic systems will provide some degree of automatic processing, including locations, energy, rudimentary analysis of parameters, reports, alarms etc. Automatic P and S picking, and hence locations, are nowhere near foolproof and engineers are generally required to check all events on a daily basis. The less expensive multi-channel systems require manual picking of all events – this work can expand to a significant amount of time.

It is important to note that any sort of automatic system or processing, analysis or reporting can probably never automatically account for the most important change in the environment affecting seismicity – excavation. Common sense interpretation using underground observations and a knowledge of the mine plan is probably the most important pre-requisite for seismic processing.

Seismic Investigation Programme

Once management perceives seismicity is or could be a risk to continued production and profitability a study into the benefits of seismic monitoring should be undertaken. A typical investigation into seismicity at a mine could include the following steps;

- Analysing records of seismicity experienced (history, location, magnitude, time, mode)
- Discussions with on-site staff to assess possible sources
- Appraisal of mining method, access development, stope sequencing (using, for example; plans, Datamine and MAP3D modelling results)
- Appraisal of support and reinforcement designs and installation quality
- Understanding of short/medium and long term mining plans
- System array options (coverage, accessibility, security, cabling)
- System objectives (location, magnitude, trends, re-entry)
- Estimated required monitoring period
- Purchase or rental of system
- Operational logistics – downloads, analyses, site based or external
- Analysis objectives
- Installation – 1 or 2 days for a small scale seismic system
- Downloads
- Seismic Analyses
- Geological/Mining/Geotechnical Interpretation
- Feedback into mining - designs, extraction sequence and support modifications where required.

If there is already evidence of damaging seismic activity on a mine (strainburst or rockburst) a system should be considered as a matter of urgency. The source of such seismicity might not be easy to locate without a seismic system.

If seismic activity is observed in the data (most mines would have at least some, following blasting) there would be a requirement to determine what is causing the activity. With a seismic system the source of such activity can be located with reasonable accuracy if the event is within the array of geophones. The source would be assessed from void and geological models and from an assessment of the blasting and mining history.

Initial analysis of the results after the system has been installed for a sufficient period should indicate the scale of the problem. The location of events alone would also probably highlight the structures or regions susceptible to seismicity, and will give feedback on suitable re-entry times for stopes close to sources of seismic activity.

The next stages of a study into mining related seismicity using a small scale system could involve the use of probabilistic distributions, seismic benchmarking, event distribution analyses and numerical modelling. These are discussed in the following sections.

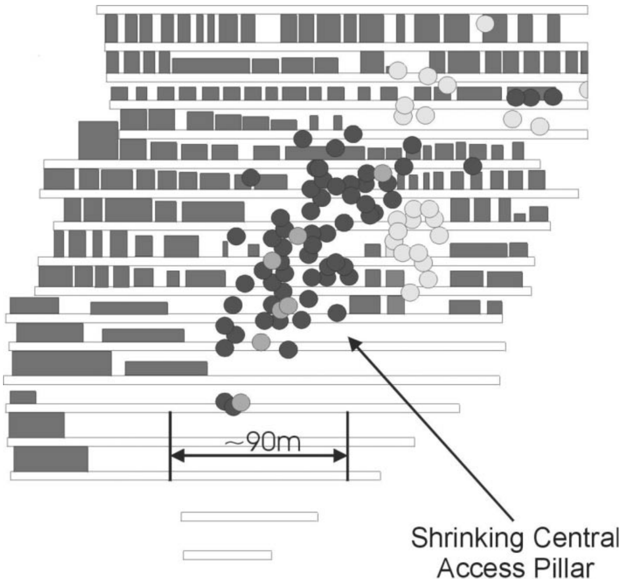
Everyday Interpretation

The following is case study from a mine that shows how interpretations could be drawn from plots of event occurrence. The most common form of these plots is the Gutenberg-Richter plot. Decision making using this type of analysis is not recommended, as this can be very misleading. As discussed above, this is because as the analysis is unable to account for the changes induced by the mining process.

Historically, the example mine was mining back on each level towards a centrally located decline using an uphole retreat method. This is a method often associated with intense seismicity in susceptible mines. The shrinking central pillars were becoming more seismic with each successive level (Figure 2), until the design limitations were assessed and the mine adopted a continuous, pillar-less sequence. This resulted in improved ground conditions in access development and a reduced seismic hazard for all areas. The seismic analysis and design changes only occurred after a cathartic flurry of seismic activity, and a significant reduction in the remaining mineral resource.

Figure 3 shows the 50th, 90th percentiles and the largest recorded event for each month in the mine, for the period including the flurry and then the subsequent sequence change. The central pillar was left unmined on the levels affected by seismicity as it was unmineable due to intense seismic related fracturing.

Figure 2 - ***Longitudinal Section of Example Mine, Showing the Concentration of Seismic Events***



A Gutenberg Richter plot is also shown for comparison in Figure 4.

The 90th and 50th percentile are relatively constant, but the largest event occurring in any month is steadily decreasing. If histograms were plotted of event magnitude for each month (as a percentage), it would be apparent that they are basically similar between months, except for the ‘upper-tails’, showing that at that mine, the incidences of the large events is being reduced.

This reduced incidence of large, damaging events was the objective of the change in the mining extraction sequence. The ground is still deforming (the 90th percentile confirms that a significant amount of deformation is still occurring) as this is unavoidable, but the largest event mechanism has been eliminated.

Underground observations were used in conjunction with the seismic analysis to come to this conclusion, but the plots supported the theory.

The initial analysis using the Gutenberg-Richter plot was ambiguous and the changes are clearer in the alternative ‘percentile’ plot.

Figure 3 - ***Magnitude and Percentage of Large Events over time***

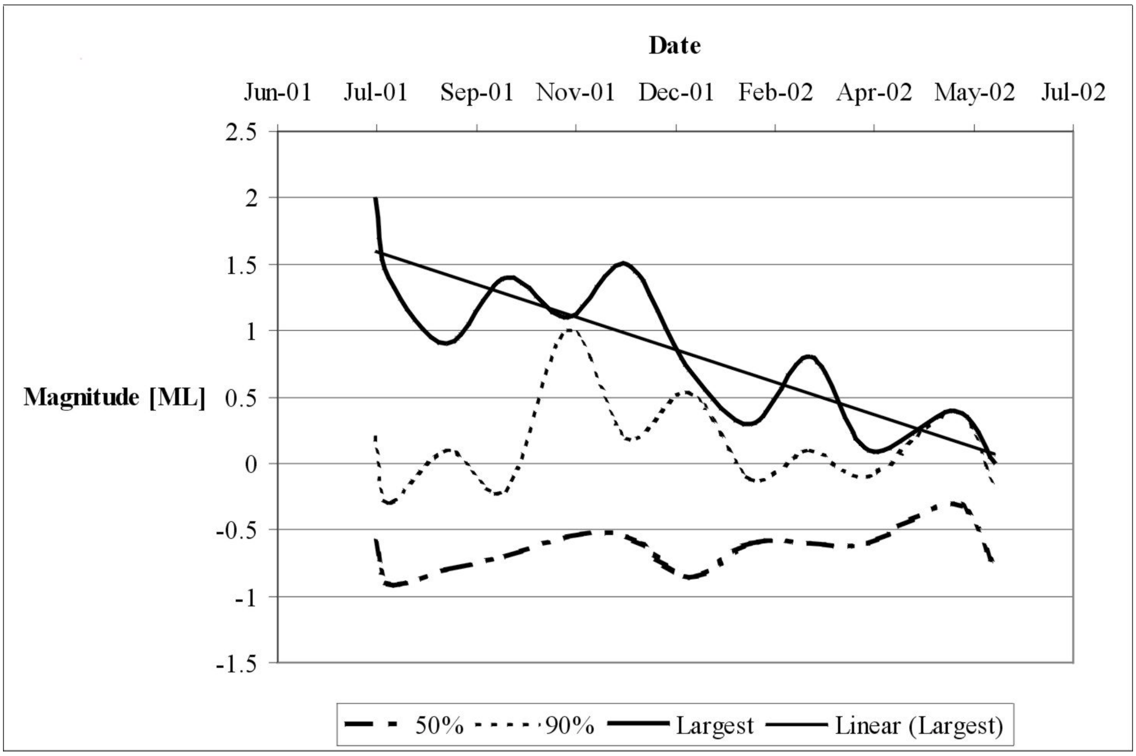
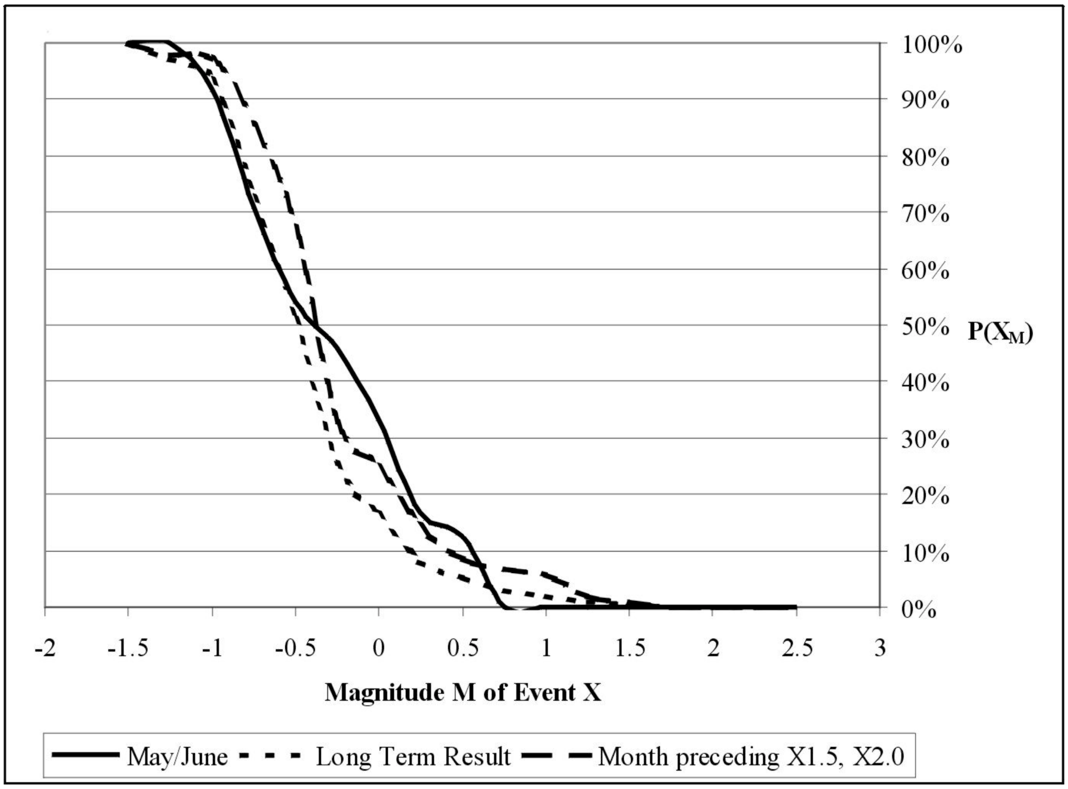


Figure 4 - Gutenberg-Richter Representation



Seismic Benchmarking

A comparison of seismic installations can be undertaken by simply evaluating the Magnitude-Occurrence relations for a series of mines or comparing sections within larger mines. An example is presented in Figure 5, using data obtained from identical seismic systems and geophones. The magnitude-occurrence relation describes the proportion of events that occur above any given magnitude. For example, in the magnitude-occurrence relation presented in Figure 5, 43% of Mine E events exceed magnitude –2.

The following section includes an example of a benchmarking exercise. This type of exercise takes about one day and requires knowledge of the mine layout. extraction sequences and the limitations of the analysis. Similar comparisons could be undertaken for different sections within a mine to assess relative seismicity and exposure to possible larger events. Moving the smaller scale seismic systems for comparative purposes should only take a shift, including cabling, attaching sensors and modifying coordinates in the software.

It is important to note that each of the different brands of seismic system measures magnitude differently, so it is difficult to benchmark between mines with different seismic systems.

Example results of comparative benchmarking

In the example case below, Mine E was interested in a comparison. Visually, it can be seen that for the middle-range of magnitudes observed at the benchmarked mines, Mine E is the most seismically energetic mine (ignoring Mine F for reasons stated below). However, for the highest measurable magnitudes, greater than magnitude 0, no events have been recorded at Mine E. Mines A, B and F have experienced events larger than those observed at Mine E during the monitoring period.

This initially suggests that the most damaging magnitude of events observed at Mines A, B and F do not occur at Mine E. There could however be insufficient events to make this assessment due to a limited monitoring period and it is possible that such events could occur in future. The frequency of occurrence of moderately sized events is also worthy of note and the relationship between the mines is useful for deriving meaning from this observation, especially where support damage or other experiences are documented.

Mine A

An open stoping mine with a low areal extraction ratio, low stress and moderate to high strength rock. Currently operating in relatively low stress conditions and experiencing no stress related problems or seismicity other than micro-seismicity which does not cause damage. Where large or moderate events have occurred, it has been where structures have been undercut by stoping and de-stressed. In any mine experiencing this mechanism as the only means of generating large events, it is common to observe no damage as a result of the events, especially where there is little development above the stope crowns or intersecting the ‘active’ fault.

Mine B

This is a very highly stressed top-down SLC operation. At the time of monitoring the selected sequence at this mine was unfavourable for the management of seismicity and large events occurred frequently, occasionally resulting in damage. The rock is weak relative to the stress, and the induced damage due to high stress is also a significant problem.

Where seismicity has been associated with rock related incidents it has principally damaged the walls, ejected loose or broken material or shaken down unstable blocks. The combined effects of seismicity and difficult ground conditions are a large impost to production.

Mine C

Stoping in this mine is subject to difficult conditions and instability resulting from moderate strength rock. These are the major problems for the mines, but at times the mine sequence has isolated major structures in regional or crown pillars and large events have occurred. Fortunately, the location of large events is normally in advance of stoping or in the crown pillar and seismic risk to infrastructure and personnel is relatively low. In some cases the large events have been associated with or occurred at a similar time to hangingwall and crown failures, and this is the greatest "seismic" risk to the mine even though such events probably occur quietly throughout the mine as well, and the hazards or costs from such events are probably not exacerbated by the simultaneous seismic energy release.

Some rockbursts have occurred in development, but these are a small contributor to the total number of observed events. Normal development and small scale stoping operations away from major geological structures and crown pillars is relatively quiet.

Because occasional practice or occasional geometry accounts for the large events, and because yield in this mine is otherwise relatively continuous, the mine is on the whole relatively quiet.

Mine D

Mine D operates using top down, continuous open stoping and benching. The mine is generally seismically quiet, with the exception of occasional mining of remnant pillars, which has tended to generate small events.

Mine E

Top down, continuous open stoping mine. The larger events have a significant regional component.

The rock at Mine E is very strong, with the result that there are relatively few problems at present. It is thought that this is at least partly due to the continuous mine sequence and current objective to minimise seismic risk at the mine planning stage.

Mine F

Mine F is a large top down, SLC operation in relatively weak ground. The events on first appraisal apparently have a significant regional component.

Subsequent re-analysis of data confirmed the ‘events’ included a sufficient number of blasts to cause a bias towards higher magnitudes. This highlights the critical aspect of data analysis even at the initial stage of event location – blasts or events that could be blasts should be discarded or at least stored where they cannot be confused with real events.

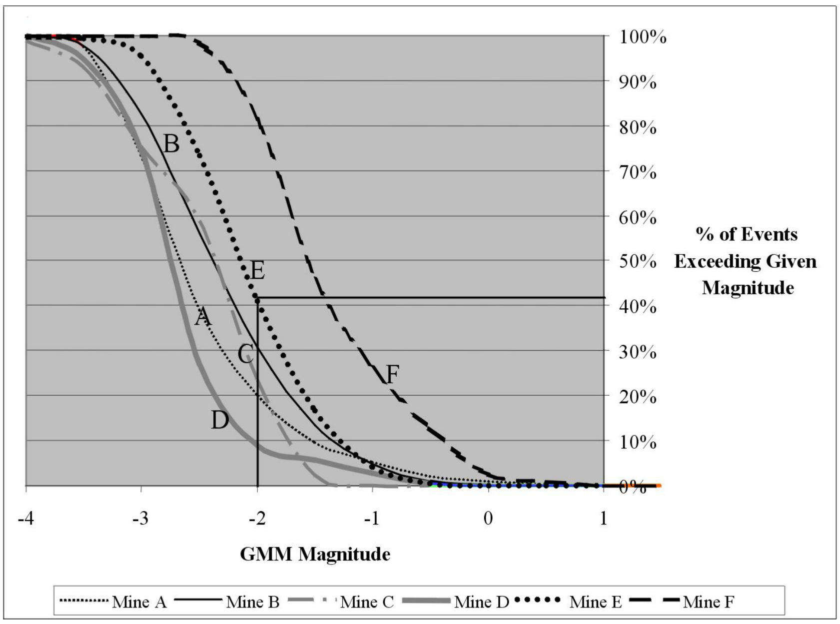
Comparison

The mining phases at the various mines during the periods of monitoring have to be taken in to account when comparing the relative seismicity to avoid giving a false impression of either high or low levels of seismicity.

For example at Mine B, sequencing of shrinking pillars (stoping converging onto central accesses) and a general flat bottom for the mine over a long strike length has resulted in a few very large events not in keeping with other observations of strength and seismicity at the mine in general.

Cognisance has to be taken of the scale and location of present stoping versus historical stoping as current mining may only be inducing minor, local-to-stope changes. Larger scale regional changes and very large events would probably require the contribution to stress and energy changes resulting from the mining of many stopes in an area. These large events might not be possible for the current phase. If mining is to continue on an expanded basis large events might be possible in the future. Analysis of seismicity to predict conditions should always take into account possible changes to mining, especially stope designs, geological structures and extraction sequences.

Figure 5 - ***Magnitude-Occurrence Relations for a Selection of Mines***



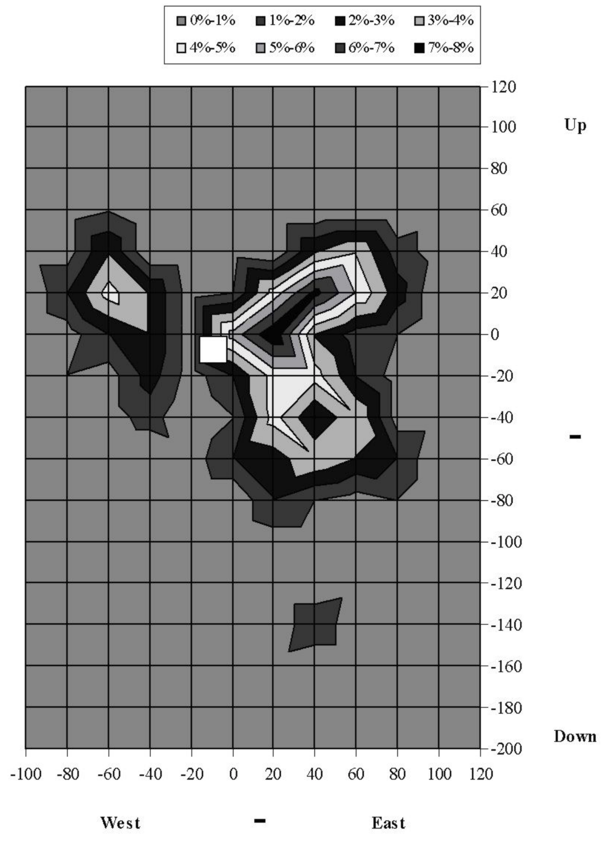
Observed Distribution of Events

The observed seismicity at the various example mines was all related to active stoping. This is presented for one of these mines in Figure 6, where the average distribution of events about blasts is shown on a section. The results from all the firings have been combined, and normalised against an origin by calculating the east-west and vertical distance between the events that followed each firing and the centroid of the firing. The percentage quoted in the Figure is effectively the percentage of events that occur that far east-west and that far north-south of the blast.

It is clear from the Figure that either fewer events occur west of the orebody, or the system does not detect events there as well. That latter is more likely and is common where sensors are located on only one side of the orebody.

In itself, this Figure probably only represents stoping where there is a significant void adjacent, and the stoping is unlikely to result in regional changes to the stress field. When stoping in a regional pillar, as between orebodies or approaching faults, it is possible that a more widespread occurrence of seismicity may be observed due to the severe stress changes associated with such blasting.

Figure 6 - *Sectional Distribution of Events about Firings*



This analysis and presentation can be automated using Excel and can give a good representation of changes over time. Plots of events on sections and plans can also be generated using Excel. The specialist software packages, generally do not incorporate any information about new excavations and so cannot generate these plots.

Numerical analysis to estimate the "stress path" histories of areas within the monitored sections provides information on the likely causes of the seismicity and this should match the plot of event distribution around firings.

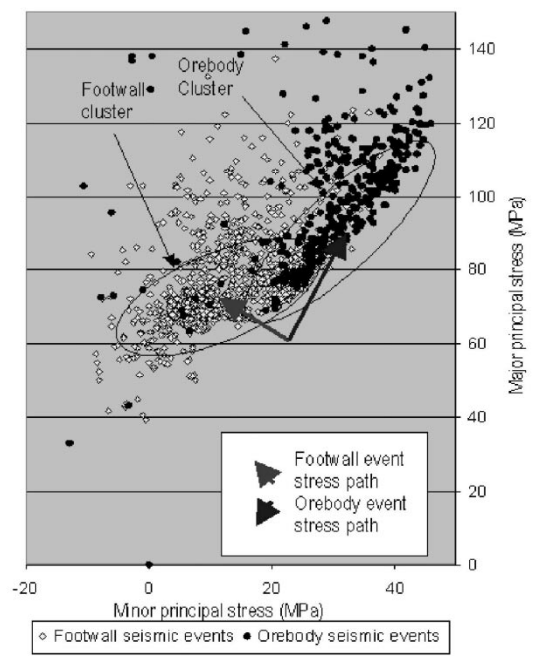
Basic Numerical Modelling - Interpreting Failure Mechanisms Associated With Seismicity

As with the previous discussion, most of the benefit in terms of managing mines on a very short-term basis can be gained from the simplest numerical analysis. Figures 7 and 8 are examples of this. They are simply the modelled major and minor principal stress for events from two different mines. The plots show that events defined by other means as being the results of a particular mechanism, also results from unique stress conditions.

Generally, some form of modelling should be conducted on mine designs and extraction sequences that have been identified as being related to seismicity. The relative impact of these aspects on the stress path required to generate the events provides the knowledge of rock failure and seismic trigger mechanisms. This in turn points to where changes should be implemented to mine designs or extraction sequences in order to reduce damaging activity.

Regarding the examples in particular, there is nothing surprising that the stress path was different for footwall and orebody events at the Figure 7 Mine, or that when the 'shear' events are delineated from the 'unclassified' events at the Figure 8 mine these also had a different stress path to the 'non-shear'. In their simplest form, the differences in the stress path, general trends etc give a good idea what we should try and avoid doing. They also give a good idea why one cluster or another in that mine is more likely to produce larger events and what mining decisions resulted in the nature of the seismicity.
In an uphole retreat, benching mine or sub-level cave, this kind of analysis can give ideas for the best direction of advance, lead-lag distances, sublevel lag etc.

Figure 7 - *Modelled Estimates of Major and Minor Principal Stress for Footwall and Orebody Events.*



This analysis could be undertaken by a site-based (geotechnical) engineer, with good numerical skills and does not require the services of a seismologist. Once again, an excellent knowledge of the mine plan is key to interpretation.

Figure 8 - ***Modelled Estimates of Major and Minor Principal Stress***

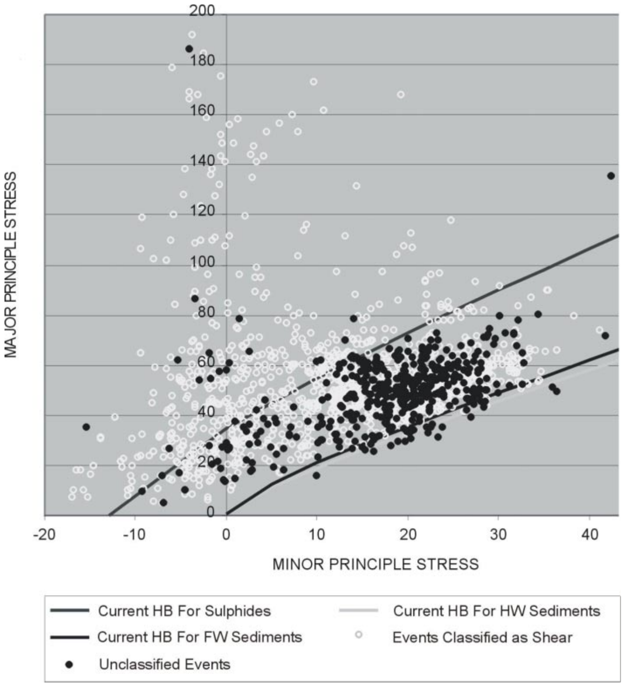
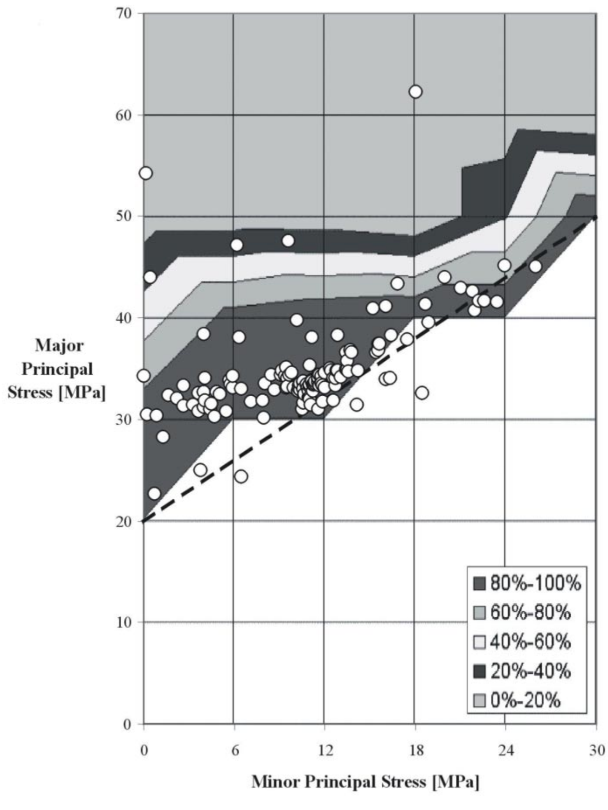


Figure 9 - ***Major-Versus Minor Principal Stress for some events at a mine***



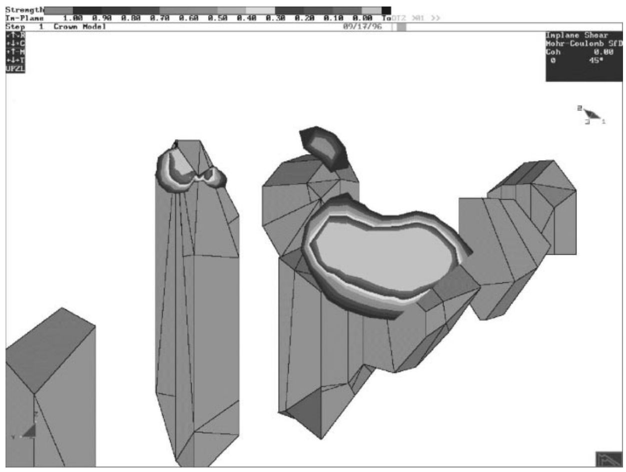
With respect to Figure 9, the events labelled as shear were determined to be so numerically. An algorithm has been developed for delineating event mechanisms from masses of seismic data, once they have been numerically modelled (using Map3D for example). In the case of Figure 9 it was satisfying that the events not classified as shear (usually the simplest to find) could be classified by the known Hoek-Brown strength relation for the rock where these events were located in the mine.

The result of the above is that relevant yield criteria for the rock can be developed. The yield criteria are generally observed to independent of event magnitude, as seismicity is just the wave energy generated by the breaking of rock, and the same rules govern strength for both small and large events.

Some examples from application for forecasting are presented in Figures 10 and 11. These types of figures are used to compare mining alternatives and to best manage the growth in yielded areas (continuous, regular and proportional growth etc).

Figure 10 - ***Area of modelled Coulomb fault slip prior to and following extraction of a stope, which resulted in a ML 1.6 seismic event.***

(i) Prior to extraction of the stope



(ii) After extraction of the stope

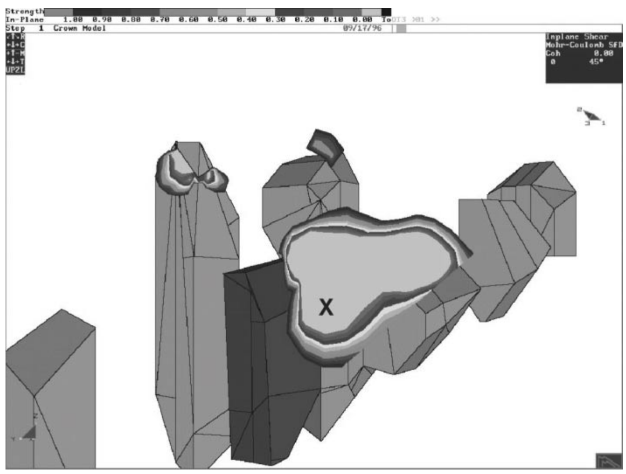
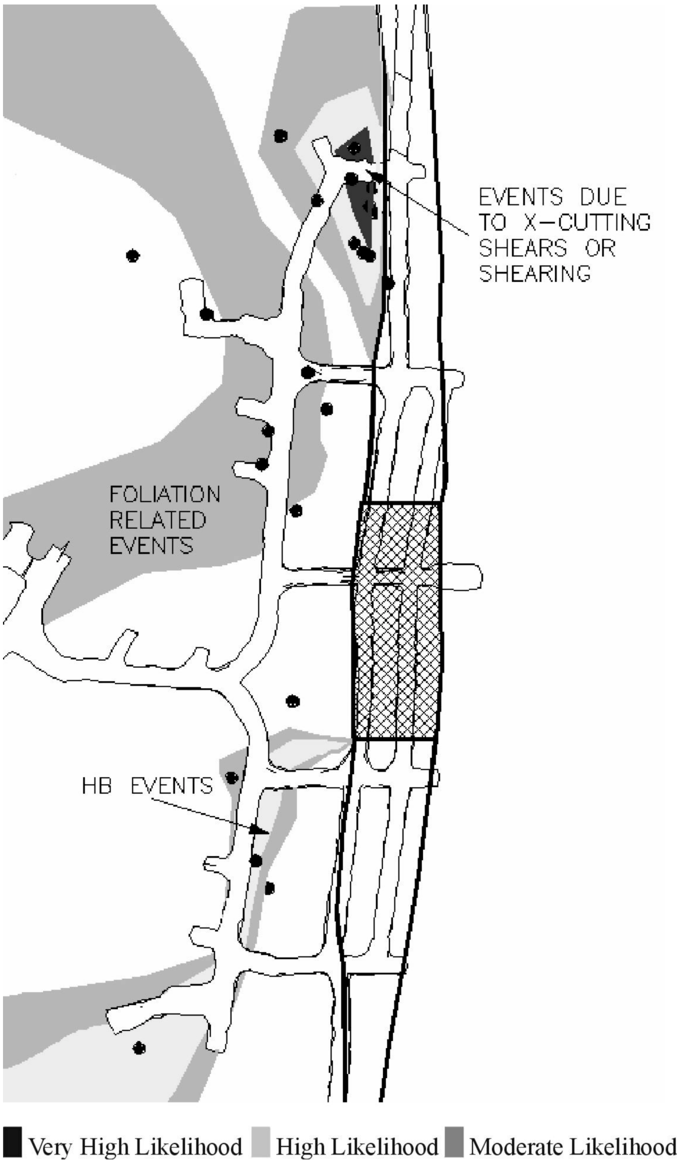


Figure 11 - ***Areas exceeding numerically determined yield criteria in a mine and resulting seismic events***



Management Issues

Once the seismicity has been quantified and the source(s) located and the failure modes determined, we also need to determine if there are ways of reducing the activity.

The effect of alternative stope designs and sequencing on damaging seismicity needs to be assessed by correlating the seismically active areas with results from numerical modelling. The objective of such work would be to find the mining option with minimal seismic risk and maximum profitability (Turner, 1999, Potvin, 2000) and to determine the likelihood of actually achieving each of the alternatives being considered. This is important as there are now many Western Australian Mines that have failed, at least in part due to induced seismicity that was exacerbated by the selected mining method or sequence.

This type of study requires the analysis of alternatives from modelling simulations in conjunction with grade-tonnages, mining costs and extra development.

Changes to support and reinforcement systems could also be required in areas determined to be exposed to higher risk of damaging seismic activity.

Support and reinforcement systems are available which can control/reduce peripheral rock mass movement, fly rock and falls associated with seismic events. The design of practical, dynamically yielding and 'rockburst resistant' support systems should then be evaluated, taking into account local factors such as excavation size, equipment, contractor skills, excavation and mine life and cost etc.. Mesh will usually be the final preferred controlling support layer in burst prone areas.

One possible outcome of monitoring the onset of seismic activity using a small scale system is the conclusion that a minewide system is required. As discussed previously these could easily cost upwards of $200,000. Another issue to be discussed at this stage is expectations regarding a minewide system - and manning requirements for data processing and interpretation. Minewide systems also imply a need for numerical modelling, preferably to be undertaken on site, and this could result in a requirement for an additional geotechnical engineer.

Conclusion

There are currently only a limited number of different small-scale seismic systems with sufficient software and hardware support for use when a mine starts to experience seismicity. These systems are not expensive and can be purchased or leased at short notice and the systems are relatively easy to install and operate. Processing of events and analysis of the resultant data are also reasonably straightforward, and some limited analysis could be undertaken by third parties if mine-based personnel are not available or are too busy.

One of the major objectives should be to commission a suitable seismic system as early as possible. If cognisance is taken of mining induced stress changes and rock conditions then the onset of seismicity can generally be predicted, allowing seismic monitoring systems to be commissioned prior to the onset of damaging seismicity. Such early monitoring enables the use of data from seismic systems to be used pro-actively in mine-planning and extraction sequencing to minimise the risks associated with seismic activity.

Seismic monitoring can enable simple but useful data analyses that can be used to indicate the cause of seismicity and any 'hotspots'. Presentation of event location alone can sometimes be sufficient to indicate failure modes relative to stope designs and extraction sequences.

Seismic monitoring data can also enable more detailed analyses to evaluate the relationship between seismicity and stress components. The failure criteria indicated for seismic event initiation can then be determined.
The results of seismic analyses can and should be used to assist with mine planning, extraction sequencing and support system designs.

One of the outcomes of monitoring the initial seismicity should also be to determine the necessity (or not) of continued monitoring using either a small or full-scale seismic system. The data analyses described in this paper are also valid for full-scale, minewide seismic systems.

References

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