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# Seismically Active Mines – To Buy or Not to Buy

**By M H Turner [1]**


## Abstract

*In recent years there have been many changes in mine ownership due to the ongoing rationalisation towards larger mining companies. Larger companies inevitably find it hard to manage small mining operations and in many cases smaller mines do not fit corporate resource, production and profit criteria. Smaller companies are more suited to managing these medium or small scale mines and are tendering for the purchase or lease of mines that larger companies wish to dispose of.*

*In addition to these factors there has also been a trend (especially in Western Australia) for mines to continue operating at ever increasing depths. This in turn has led to more mines operating in high stress environments and experiencing damaging seismicity.*

*Assessing the viability of seismically active mines from a takeover or purchase point of view should involve analysing the risk profile of every aspect on mining that could be affected by adverse seismicity. This includes assessing current and alternative mining methods, mine designs, support systems, extraction sequencing, monitoring and blasting.*

*This paper includes discussion on items that need to be assessed when considering the purchase of seismically active mines, with experience gained from some recent studies in Western Australia. In these cases it was apparent that quantification of previous seismic history on it's own was a totally inadequate method of assessing minewide seismic risk potential. A more holistic approach is required, taking into account all aspects of relevant data, all the minewide effects of seismic activity and all possible means of mitigating those effects.*


## Prospective Purchaser

When assessing a seismically active mine for a prospective purchaser a number of different issues have to be evaluated to determine whether the mine is (or can be made to be) economically viable and whether it can fit into the company's risk profile.

Different companies have different acceptable risk profiles regarding safety, security of investment capital and continuity of production. As a consultant or advisor to prospective purchasers it is important to understand what is 'acceptable risk' this is normally based on a qualitative judgement rather than fact – most, if not all companies operating in Australia state that their primary aim is the safety of their employees. What is acceptable in terms of risk varies per company though, as an example, some companies have totally banned the use of airleg developed rises, whereas others continue their use in even highly stressed ground and other mining companies only use them in low stress environments.

If the mine will be used as the main source of ore to a mill there will be a low acceptance of potential breaks in production due to seismically related problems. If the prospective purchase has a number of alternative sources of mill feed the effect of such problems will be reduced, and even further reduced if there are alternative working places for the workforce.

Corporate obligations regarding minimum mining standards can affect the profitability of operations (Turner, 1999) and also have to be considered during the due diligence stage.

The potential for damaging seismicity will have a major impact on whether a seismically active mine will prove to be economical. The additional costs compared to non-seismic mines can be quite high in some cases and could make the difference between profit and loss.

A study into the effects of seismicity on a mine purchase investigation would include quite a few sections (Table 1). The outcomes would generally be used in an overall document including (amongst other issues) details on lease boundaries, product sale, native title, environmental issues, labour and contractor requirements, production schedules and cost/revenue/profit analyses.

### History

The main source of information relating to seismic activity and its impact on the mine will be from historical documents but where possible these should be backed up with underground observations.

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**Table 1 - *Assessment Priorities***

| Criteria | Priority | Comments |
|---|---|---|
| History | 1 | Determine previous safety and production issues. |
| Mining Method | 1 | Assess suitability to conditions. Assess alternativemethods. |
| Mine Designs - Overall | 1 | Assess suitability to conditions, proposed mining method and extraction sequence. |
| Support Systems | 2 | Assess suitability to conditions. Assess modifications or alternative systems. |
| Extraction Sequencing | 1 | Assess current method and sequence and assess alternative sequences for proposed mining method. |
| Seismic Monitoring | 2 | Assess system and data quality and analyse critical aspects. |
| Other Monitoring | 4 | Determine usefulness of other rock or stress monitoring and analyse critical aspects. |
| Rock Mass Properties | 1 | Assess relevant aspects regarding mining method and seismicity. |
| Blasting | 3 | Assess previous designs and determine improvements for proposed mining method. |

1= highest, 5 = lowest

It is also important to consider the general industry opinion regarding seismicity at the mine and the effect of seismicity on costs, safety and continuity of production etc. Discussions should be held with the current owners/contractor, ex-employees (including management, consultants, supervisors and operators), staff from neighbouring mines and mining inspectors to gauge an impression on seismicity at the mine.

Documents are usually available covering historical production and comparisons of monthly tonnages in the last year or two should indicate if continuity of production was an issue. Survey plans will provide details on the extent of mining and the location of pillars that could assist in regional stability and if there are small pillars that could aggravate seismicity.

Extraction percentages can be calculated by comparing geological resource, mining reserve and production figures per mining block. Low extraction percentages could be an indication that some kind of difficulty prematurely brought mining to a halt, and conversely high extraction percentages, eg over 125% could indicate that there were ground control problems.

Reports on falls of ground, accidents and incidents are important documents and the Statutory Inspector’s Record Book could also provide information relating to seismicity. Some mines maintain a Rock Noise Report Book and also Scaling Record Books. By sifting through these report books and historical reports it is possible to list the frequency and magnitude of seismic related events and to gauge what aspect of stope design, support or extraction sequencing was the basic cause of the damage.

Documented damage to major infrastructure and other current excavations should be visited to assess the relationship between the documented damage and the actual damage, and to assess for additional, ongoing or fresh damage. Ore passes close to other passes or shafts in high stress mines are very susceptible to wear, overbreak and then self generating seismic failure and if they are critical to the future operation of the mine an extra effort should be made to assess their condition.

## Mining Method

Some mining methods are more suited to coping with seismicity than others and the attached comparison is used to give an initial indication of suitability (Table 2). It is critically important to determine if the current method (for which all access is in place) can cope with seismicity even with a few alterations, or if the method is totally unsuitable. In the latter case there could be a considerable cost associated with the development of alternative access development.

It is useful to determine through which route the mining method evolved. Has the mining method evolved and changed as required by changing rock and stress conditions or because of equipment and orebody changes? This would involve a listing of the methods that have been tried at the mine, and what have been the successes, problems or failures associated with these methods (especially regarding seismically related problems, safety, dilution, extraction and continuity of production). Such a study should bear in mind the many factors that could change between the implementation of such mining methods, eg changes in the orebody and rock mass, the use of different support systems (eg spot bolting versus mesh, stiff versus yielding), the size of development excavations, location of development relative to stoping excavations, sizes of pillars, increases in stress with depth etc.

The access development in place would all be designed to service the current mining method and the lowest cost option could be to re-commence production using that method. It is extremely important to determine if the current mining method is designed for low, high stress or seismic conditions and to assess the risks associated with the current mining method (in particular those due to seismicity). The risk of unacceptable safety, excessive dilution, low recoveries and extraction percentages and lack of continuity of production should all be evaluated.

Bearing in mind the current method it is also important to assess what mining method options there are for the remainder of the resource and what are the risks associated with these methods when the mine is seismically active? Note that the current mining methods in most mines are generally reasonably close to that required for seismic conditions, and would only require moderate additional access development and changes to stope designs and extraction sequencing. Mines using stope and pillar open stoping or uphole retreat stoping could require significant re-development. Mining methods with comments on seismic related aspects are discussed below.

### Cut and Fill

Flatback cut and fill mining is a method suited to poor ground conditions and variable orebodies but the method inherently leads to full exposure of personnel during production. As a consequence, in seismic conditions rockburst resistant support such as fibrecrete and/or cone bolts is required for every lift. This substantially increases the mining cost and reduces the production rates.

**Table 2 –** ***Mining method risk categories***

| Mining Method | Elevated Risk Category | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Personnel Exposure** | **Access** | **Dilution** | **Unstable Pillars** | **Low Recovery** | **Seismicity** | **Summed Total** |
| Cut and Fill | 5 | 5 | 2 | 4 | 2 | 5 | 23 |
| Room and Pillar | 4 | 4 | 2 | 5 | 4 | 5 | 24 |
| Airleg Slot Rising | 5 | 5 | 2 | 4 | 4 | 4 | 24 |
| Uphole Retreat | 3 | 4 | 4 | 3 | 4 | 4 | 22 |
| Bench and Fill | 3 | 3 | 3 | 2 | 3 | 3 | 17 |
| Longhole Open Stoping | 3 | 3 | 4 | 4 | 4 | 4 | 22 |
| Sub-level Caving | 2 | 4 | 1 | 2 | 2 | 3 | 14 |
| Block Caving | 2 | 4 | 1 | 2 | 2 | 4 | 14 |

Note: 1 = Low risk
2 = Moderately low risk
3 = Medium risk
4 = Moderately high risk
5 = High risk

Cut and fill mining is also a bottom-up method with a limited number of mining lifts possible per access ramp. The stopes inevitably lead to a reducing crown pillar and increasing stress levels as they approach the mined area on the level above. The effects of this can be reduced by the introduction of uphole retreat for the final lift, with a requirement for longhole drilling, cablebolting of the hangingwall and cemented waste-filling of the initial cut and fill lift.

Cemented paste or high density hydraulic fill can assist in the redistribution of stresses away from the working face and can be considered in highly stressed and seismically active ground (Rocque, 2001), but the final crown pillar lift will still be a focal point of stress related problems. Underhand cut and fill using cemented fill is more suited, as the face advance is from mined ground towards unmined ground, with an engineered excavation back. For high grade, highly stressed and seismic ground this method provides an expensive solution but the fill has to be engineered to fully cope with and absorb seismicity and in many cases the access drives are still vulnerable.

## Room and Pillar

Room and pillar mining of shallow dipping deposits also leads to full exposure of personnel during production. The backs can be fully supported with permanent support and can be reinforce as a beam, but failure or punching of the pillars will normally be the critical source seismicity. If seismicity is an issue all working areas will require seismic support. This would include the sidewalls of pillars due to the ever-increasing stress levels in pillars. Design of pillars to yield once they are cut is an option to reduce the energy storage capacity of the pillars and this method is used routinely in some South African gold, platinum and chrome mines.

## Airleg Slot Rising

Airleg slot rising with scraper cleaning is an established method still being used in highly stressed and seismically active mines. Airleg and scraper operators are exposed to high stress excavations and pillar dimensions and support systems have to be designed to suit the rock mass deformations. Yield pillars can be considered in competent ground, or with sufficient support to maintain good back conditions. Seismic monitoring, especially during any secondary pillar stripping phase is essential.

## Uphole Retreat

Uphole retreat is a popular method for steep, relatively narrow orebodies due to the low cost of stoping. At shallow depth the method is based on a central access with ore drives extending to the limits of the orebody, followed by uphole retreat stoping back towards the access. In deeper sections severe problems can commence within a very short time period, and can include brow failures, rib pillar failures (or punching into the hangingwall and footwall) and recovery problems with the final shrinking pillar. This method can be associated with severe seismic activity once stress levels increase with depth and the extent of the mined void. Modification of the method to cope with the seismicity can be costly, with additional ore drive support, footwall development and sterilisation of reserves. A severe airblast hazard can develop once the mined out void becomes expansive and pillar and large-scale hangingwall failures commence.

Operators are exposed to highly stressed rock during drilling, charging and bogging operations and currently only bogging is considered viable for tele-remote equipment. The Mining Automation Program in Canada, a partnership between Inco, Tamrock, Dyno and Canmet has made some significant advances in tele-remote drilling and charging since it’s inception in 1996.

Full support of ore drives with rockburst resistant support systems is required for uphole retreat in highly stressed, seismically active areas.

Slot rising can be a major issue in high stress uphole retreat mining. Slot rising using airlegs in highly stressed ground is regarded as unsafe by many mining companies and longhole-rising can lead to problems in highly stressed ground. Slot rises developed using small blind-boring raiseboring equipment or specialised equipment such as the Cubex Megamatic with Roger V30 Drill are ideal for this purpose.

## Bench and Fill

Bench and fill is a natural progression from uphole retreat for deeper, more highly stressed operations. Brow and pillar stability are improved compared to uphole retreat but can both still be sources of seismicity.

The method incorporates a general top-down extraction sequence, but bottom-up in individual mining blocks for groups of 2 to 4 sub-levels. The final crown pillars between mining blocks can become very highly stressed and seismically active and reduced recoveries should be expected. Footwall drives and drawpoint cross-cuts with fans of production blastholes can be used for high grade crown pillars.

Central access and shrinking pillar layouts can be avoided with end access but this involves limitations. Access at both ends of an orebody greatly increases the development cost per tonne, and access at only one end results in greatly reduced production rates. Extraction sequencing and face advance away from poor, highly stressed and mined out ground should be a major planning objective.

Slot rising is as critical, if not more so in bench stoping as in uphole retreat mining and the comments in the previous section are especially valid. Bench mining in highly stressed and seismically active ground should generally be adjusted so that smaller strike spans are mined, then filled, followed by re-slotting etc. Filling can be with waste fill (if pillars are left between the stoped out void and the slot rise to control the fill) with paste fill (using polystyrene slots or paste fill reaming drills (Grenier and Gauthier, 2001)). Modified Avoca is used in a few operations but results in slot rising damage and additional waste dilution and/or ore loss.

Minimising the number of blasts per stope by blasting multiple rings can also be used to reduce the number of brow positions that have to be supported and the time the hangingwall is exposed. Some mines in Canada and the USA in highly stressed, poor ground are blasting 15m long stopes in a single blast with multiple delays ((Makuch, 2001).

Underhand bench stoping using cemented fill is suitable for highly stressed and seismically active ground if the grades of the orebody can afford the cement and additional development requirements.

### Longhole Open Stoping with Fill

Stope sizes are critical to open stope stability and the determination of critical spans is only really possible from historical performance and seismic monitoring. Empirical design methods such as the Stability Graph method (Hutchinson and Diederichs, 1996) do not cater for highly stressed environments where $\sigma 1$ in the stope hangingwall or back is greater than 50% of the UCS.

The fill medium used for open stoping can result in safety issues, such as liquefaction due to seismic waves, premature failure and energy absorption capacity.

The extraction sequence employed using long hole open stoping will be critical to the viability of the project in seismically active mines. Secondary stopes or pillars should be mined as soon as possible and in some cases the production rate has to be compromised to allow time for the fill to cure. Continuous face advance sequencing is sometimes also necessary to avoid the generation of pillars with the fill curing before the adjacent stopes are mined. In some larger orebodies longhole open stoping with fill is one of the few viable methods and modelling to determine optimum extraction sequences is critically important.

Drawpoint and access stability close to large stopes can be an issue, as can the risk of airblasts due to large collapses.

### Sub Level Caving (SLC)

Sub-level caving can be undertaken in very poor ground and in highly stressed and seismically active mines (Turner and Player, 2000). Lower production rates will generally be attainable in seismically active mines, and this is particularly the case in SLC mines as the cave advance is continuous and delays in one heading will inevitably affect the overall production.

The sub-level interval and the leads and lags between subsequent levels is important for the management of stress redistributions around the bottom of the sometimes very extensive cave zone. Cross-cut spacing for transverse SLC operations is also extremely critical. Brow stability and the support of excavations both within the orebody and providing access are also critical to the success of the method in highly stressed and seismically active mines.
The stand-off distances and orientation of access development are important, as in all mining methods in highly stressed mines.

Some design issues in larger SLC operations would take longer and be more difficult to adjust due to the length of time taken to pre-develop extraction levels.

### Block Caving

Seismicity in generally large-scale block caving mines can sometimes be difficult to mitigate once it starts. Once developed there is little flexibility to adjust designs on a production level, and there is a limit to the amount of support that can be installed. At the design stage the undercut method and drawpoint designs can take into account the likelihood of seismic activity, but the designs could result in reduced production rates and cave effectiveness due to increased pillar sizes.

The location of the access development and the haulage decline and/or shaft or conveyor drive should be sufficiently far from the cave to minimise the effects of cave related stress redistributions. The locations relative to future cave lifts should also be evaluated and estimates will have to be made for future cave limits.

### Automation

There have been many advances to date in the area of automation in the mining industry and these are particularly relevant to high seismic risk mines (Vagenas, Baiden and Scoble, 1999). The elevated exposure risk to operators could be eliminated by the use of remotely controlled or fully automatic surveying, bogging, sampling, trucking, drilling, charging. This is applicable to all mining methods and a study of a seismically active mine should also consider the available state-of-the-art equipment.

## Mine Designs

It is critical in seismically active mines to maintain stable and well supported means of primary, emergency and secondary egress. A number of older, seismically active mines fall down in this area, with older sections of declines spot bolted or supported without mesh, or with bolts that are too stiff, soft or even corroded.

### Development

The size, shape, orientation and stand-off distance from the orebody all impact on stability and should be assessed. If these factors lead to a higher than acceptable risk of damage from seismicity the option of installing rockburst resistant support, re-developing more suitable excavations, reducing extraction tonnages, or modifying the stoping method or extraction sequence could be considered.

The size of excavations is directly related to the susceptibility to damage during seismic activity. The necessity to design excavations smaller generally requires additional stockpile bays and ventilation rises and modified possibly rockbolt drilling equipment but the benefits will outweigh the costs in seismically active mines.

The shape of excavations in seismically active mines can either aggravate or mitigate the severity of damage during seismic activity. Rounded or arched backs are generally accepted as being beneficial to stability and reduce the volume of fractured rock that could be ejected or dislodged during seismic activity. It is rarely an option to change the shape of current excavations but the increased risk of damage from seismicity in current excavations due to shape should be considered. Quantification of possible additional support to reduce the risk or limit the extent of damage could be required, together with improved excavation shapes for future development.

The orientation of excavations is also related to stability, generally and especially during seismic activity. Excavations developed along foliation and weak structures will be far more liable to suffer major damage than excavations orientated across foliation or weak structures. This also applies to straight sections of access drives and declines. It is important to assess the relative damage in excavations at different orientations and to highlight which if any of the current excavations are at risk of damage. Additional support requirements for high-risk excavations would require quantification, together with possible by-pass excavations for sections that are deemed to be at an unacceptable risk.

The location of the decline and main access drives relative to the orebody and structures that will be affected by mining induced stresses could affect the exposure to seismic risk. At least four mines in Western Australia (Long, Victor, Strzelecki, Big Bell) have suffered major decline and access drive damage due to seismic activity. The severity of this damage would have been greatly reduced by increasing the distance from the orebody to the excavations and by adjusting the orientation of the straight sections of the declines away from foliation and major structures. In many cases there will be constraints and limitations imposed by access design and location on alternative mining methods and extraction sequences. Centrally located declines and access cross-cuts associated with uphole retreat and cut and fill designs are the most common example of this. Modification of the mining method and designs to suit seismically active situations from central access designs can lead to sterilisation of ore and significant additional development.

If numerical modelling has previously been used to assess the stability of alternative designs these results should be assessed, but are generally only of limited use. Discussion with the engineer who undertook the modelling would greatly increase the usefulness of previous modelling. The limited time period generally available during due diligence exercises is not generally sufficient for modelling.

### Stoping

The existing stope designs would have to be assessed with regards to the mining method most suited to the orebody and seismicity. The changes required to the stope designs, especially regarding additional development, would have to be generated in string formats in a mine design package, eg Datamine, Surpac, Vulcan. The length of additional development can then be calculated and costed, per ton, per mining domain and for the whole mine.

Stoping span limits would have to be estimated from historical stope performances or calculated using an empirical method (see section on Rock Mass Properties). Suitable stand-off distances would also have to be estimated from current excavation performance, relative to stoping blocks of a similar sizes to those proposed if the mine was purchased.

## Support Systems

The current or most recent support standards should be assessed with regards to underground observations and comments on performance in historical documentation. Support systems can be designed to cope with just about any ground conditions, including large-scale deformation and seismicity (Potvin, 2000), but the cost and installation time of some of these systems can affect profitability.

The support standards on paper should be compared to that observed, and operator based adjustments could be an indication of problems – especially regarding multiple layers of mesh and additional bolts in both the backs and sidewalls. Support systems in many established mines have evolved through experience with conditions and many separate standards could have been used per rock type; per mining domain; per mining crew or even operator; per geotechnical domain and could have varied depending on the mining contractor.

The support systems in seismic mines must be capable of retaining scats and coping with large and sometimes very rapid deformation.

### Designed?

It should be possible during evaluation of the documentation (including support standards) and from underground visits to determine if the current or latest support system was primarily designed to cope with seismic activity or whether it evolved to cope as conditions deteriorated. Was the inter-relationship between support capacities and rock mass deformation used in the support system design?

Stiff support elements, such as plain shotcrete, grouted split sets, grouted Gewi bars, Hollow Groutable Bolts (HGBs), Stelpipe Tubular Groutable Bolts (TGBs), CT-Bolts and even cable bolts are all susceptible to failure during severe seismic activity due to rapid rock movement and the bolt's inability to yield and cope with the rock mass deformations. Support systems that have evolved and are not specifically designed to cope with seismic activity in many cases include redundant components such as grouted bolts or excessive fibrecrete for example. This could give an initially misleading impression that support costs will be prohibitive whereas on re-opening the implementation of a suitable system primarily designed to cope with seismic activity could lead to significant reductions in support costs.

Rock mass movements associated with minor seismic activity can be controlled with jumbo installed split sets (not airleg installed) and mesh (at least F51). Severe seismic activity would require specific support systems, usually installed in at least 2 passes such as:

- Fibrecrete, split sets and mesh, followed by cone bolts or
- Split sets and mesh, followed cut by cut with cone bolts to the face.

The support systems in many established mines are also restricted by equipment capabilities. In some operations additional or alternative support elements could be considered that would be more applicable to the conditions but require different equipment specifications. One common limitation is the restriction on bolt length and installation angle due to fixed boom jumbos, when the use of telescopic or sliding booms would facilitate vastly improved support systems and support effectiveness. Tailor-made drilling units for narrow drive widths and even the use of airlegs can also be considered.

### Condition

The condition of support in excavations is critical to their expected performance during seismic activity. Even remote seismic activity many hundreds of metres away could lead to failure of weak, corroded bolts. Evidence of damage in documentation should be checked, and during underground visits associated with the due diligence study.

Most mines maintain records of pull testing results and these should be checked, although the tests are usually only conducted on freshly installed good quality bolts, and are conducted by the supplier. The frequency of the tests, the testing standards, and the procedure for coping with failures should also be briefly assessed.

## Extraction Sequencing

Extraction sequencing in combination with good mine design is the main method of reducing the seismic potential to levels acceptable to mine owners. The stope face and development positions need to be assessed with regards to the re-commencement of mining operations.

Could the existing layout be used with an extraction sequence to minimise seismic potential? Or will additional alternative development be required to enable a more suitable extraction sequence?

Some orebodies and mining methods (eg longitudinal sub-level caving, room and pillar, longwall mining) limit the options regarding extraction sequence and have an inherent risk of generating seismic activity. In such cases alternative means of reducing the seismic potential could be considered, such as adjusting sub-level intervals, face shapes (eg leads and lags) and adjusting development size and locations.

Many mining methods, designs and layouts are also constrained regarding alternative sequencing options due to the fill system; access development; adverse stress magnitudes and directions; weak or strainburst prone rocks; the extent of previously mined orebodies; ventilation requirements and the location of critical Infrastructure (such as shafts, ore passes, declines, etc).

### Numerical Modelling

Numerical modelling is the main tool for comparing extraction sequence options. The options considered by previous or current owners are unlikely to be relevant to prospective owners, however. If time is available during the due diligence exercise, numerical modelling could be undertaken to compare alternative stoping methods, designs and extraction sequences on stresses and seismicity.

The use of 3-Dimensional boundary element programs such as Map3D or Examine$^{3D}$ to analyse the variation in stress fields due to mining has become an accepted geotechnical standard. If seismic data is available and it can be related to mining configurations these software programs can also be used to determine the relationships between various stress components resulting in aseismic or seismic rock failure. The resultant failure criteria can be used to assess whether proposed designs and sequences can be expected to generate seismicity.

2-Dimensional geotechnical modelling programs are generally not of use in the evaluation stage, especially in Western Australian mines as the mine geometries, stresses and seismicity are truly 3-dimensional. Non-linear software such as Map3D-NL, Flac, Flac3D, Udec and 3Dec are also too complex to be used during the evaluation stage.

Numerical modelling could be conducted on a minewide basis to evaluate the effect of each mining block on all others, but time limitations and the number of possible scenarios generally renders this impractical.

Specific blocks where alternative mining methods and extraction sequences are seen as the difference between purchase or not are all that are generally modelled.

## Measurements and Monitoring

A number of measuring and monitoring methods are used on mines and these can provide vast amounts of data on the in-situ properties and stress state and the response of the rock mass to mining. In some cases the volume of data available is difficult to analyse during the period allowed for due diligence evaluations, and sometimes there is only a bare minimum of data.

### Intact Rock Tests

Many mines have undertaken a minimal programme for the laboratory testing of intact rock strengths. Properties usually tested include UCS, Young’s Modulus and Poisson’s ratio. Quantitatively there is not much that can be undertaken with these values but it is important to determine if they are representative and also to relate the relative strengths of rock types that are present next to each other in underground excavations? Materials with vastly different properties existing next to each other in excavations will exhibit different deformation performance when exposed to high stresses. Softer (low Young’s modulus) and weaker (low UCS) rocks will deform more than stronger and stiffer rocks – in different mines this has been observed to lead to excessive deformation in the softer rocks followed by seismic related failure of the harder, stiffer rocks.

There are more relevant intact rock tests to determine if the rocks are prone to strain bursting, including the Fracture Toughness tests. The results of this test can give an indication of the susceptibility of intact rock to brittle fracturing.

### Stress Measurements

Seismicity is generally related to high stresses and seismically active mines would generally have been expected to have undertaken stress measurements. A number of mines in Western Australia have measured significantly high stress levels relative to rock strength (Lee, Pascoe and Mikula, 2001). Even if there are no reports of rock noise or seismicity engineers should make note of stress measurements especially if the results indicated high stress levels – if the orebody extends to depth the conditions could change rapidly, with an onset of stress related damage and seismicity. It is important to relate the measurement results with existing regional data in order to determine if stresses are expected to increase to a level when stress related deformation and seismicity could affect production.

A few mines have also undertaken stress change monitoring using HI-Cells or vibrating wire gauges and occasionally these produce useful results. If the results of such monitoring have been summarised they could give an indication of the change in magnitude and direction of stresses relating to mining.

## Seismic Monitoring

Many mines that have experienced seismicity in recent years have installed some form of seismic monitoring system. It is important before analysing data to determine what system is installed (ESG, ISS etc) and a number of other issues that would affect the reliability of data:

- Was there a full time geotechnical engineer on the mine, and if not, who processed the data?
- How long has the system been installed? Has the system been upgraded regarding software, and has the system been regularly extended as mining areas have advanced?
- How many sensors are installed and what is the coverage (eg minewide or just a section, or stope?) and what is the coverage regarding hangingwall and footwall (field depth).
- How does the system trigger configuration work? (eg fixed or variable trigger level, trigger sensors fixed or variable, minimum number of trigger sensors (or channels – does a tri-axial count as 3 sensors?). This also affects the coverage and some areas might only be able to trigger sufficient sensors/channels for very large events, with small and medium events rejected.
- What is the location accuracy? This will vary per mining area and could be very good in one section and poor in another.

Examples of data plots from systems with inherent deficiencies are included in Figures 1 to 3, all from seismically active mines sold to new owners in the last two years. Figures 1 and 2 show the sometimes extreme variations in event magnitude in mine seismic databases due to software and hardware changes. Detailed seismic analyses for such mines would be of little benefit for periods longer than a few months. Figure 3 includes a scatter plot of events from a mine with uneven coverage – whilst there are obvious areas with higher seismicity, there are a few areas with very poor coverage as indicated. The seismicity in these areas is not lower than the other areas, rather the events have not been stored by the seismic system due to the trigger criteria not having been met.

**Figure 1 – *Magnitude variation over time – example 1***

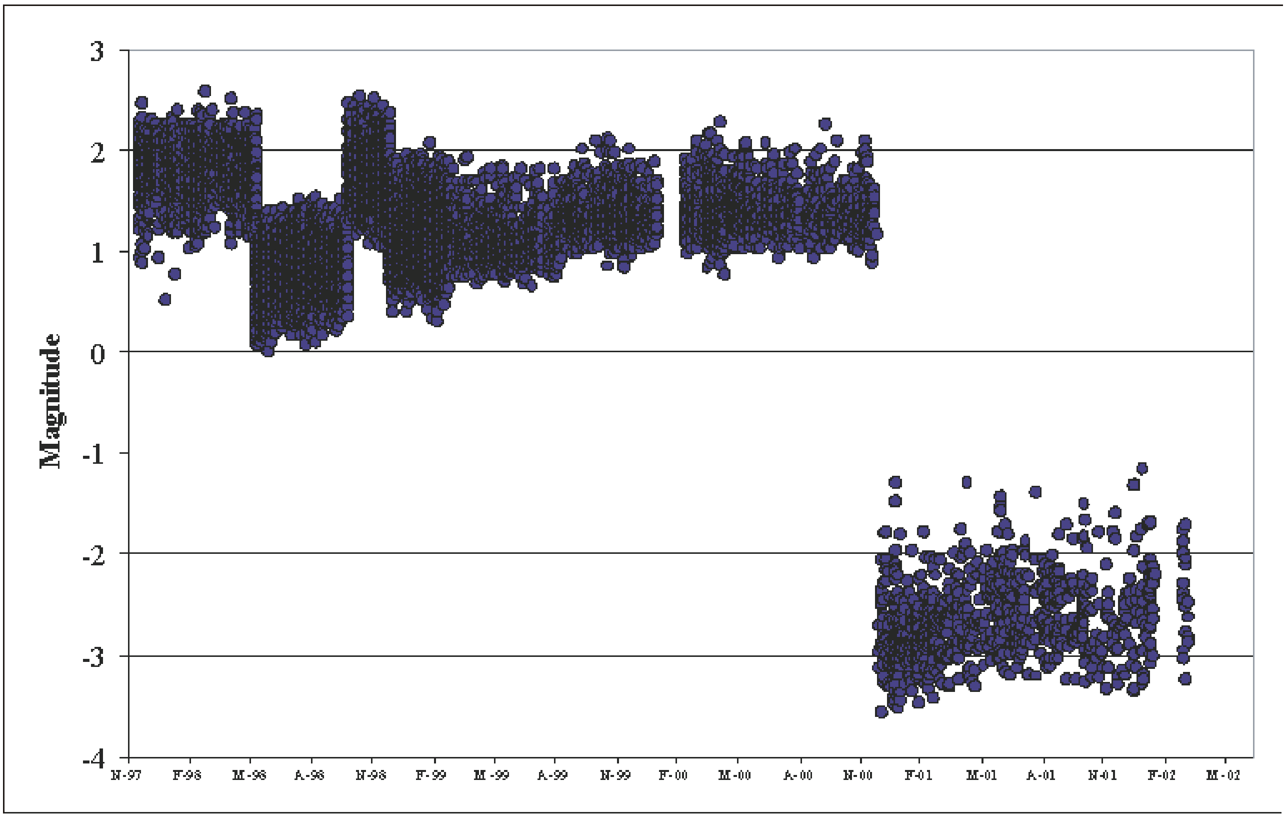
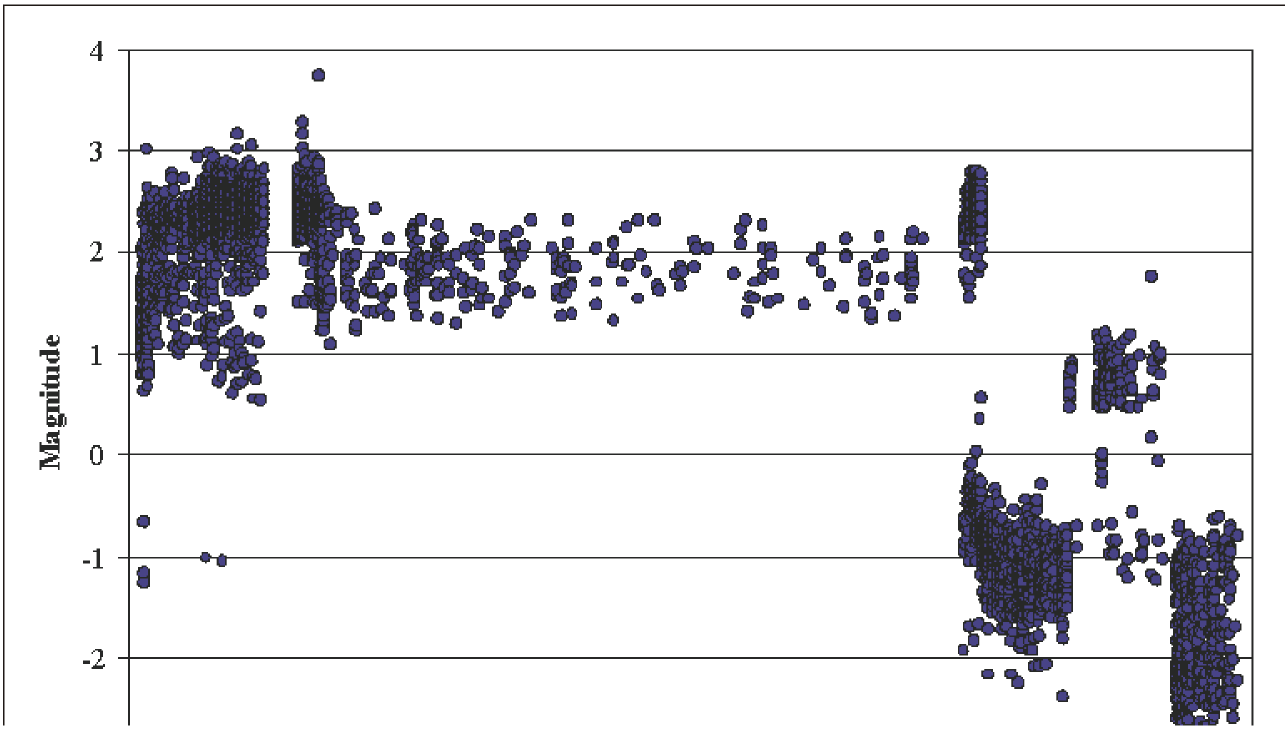
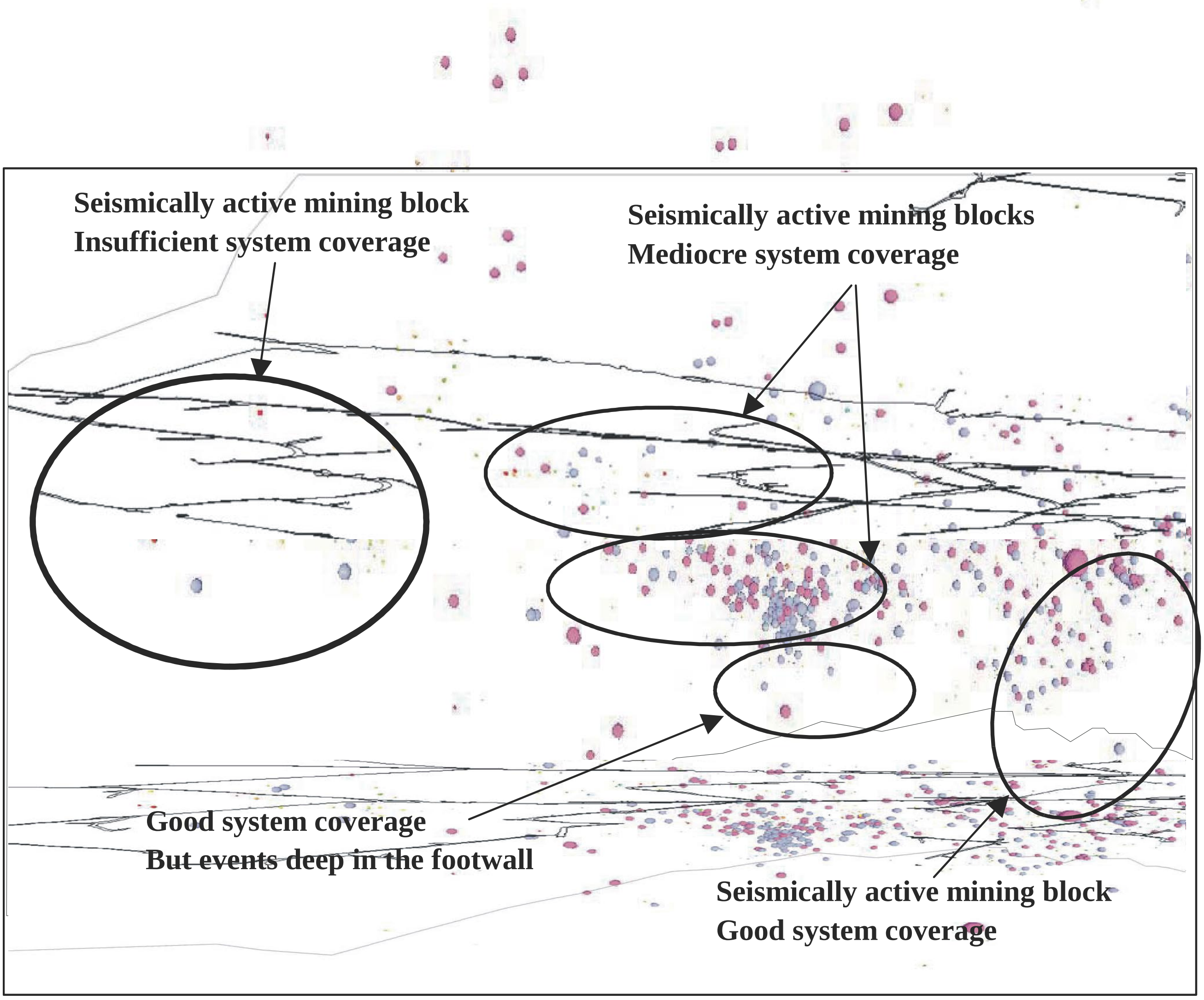


**Figure 2 – *Magnitude variation over time – example 2***



Regarding data analysis:

- Have the locations been manually checked? – many systems have automatic location algorithms but all need checking, and in a lot of cases the P and S-arrival times need manually adjusting for every ‘real’ event.
- Have any analyses been conducted on the data? If so, what were the objectives? What kind of analyses were undertaken? Who undertook the analyses? – seismologist (one who is acquainted with underground mining *or not*?); geologist; mining engineer; student (experienced or not, with interest or not?); geophysicist or geotechnical engineer (geology or mining based)?
- What were the conclusions from the seismic analyses? Did the analysis cover the whole mine and did it differentiate between sections within the mine?
- Can the data and the analyses be trusted? Many seismic systems and the analysis methods have so many faults that the results are difficult to use or trust from a quantification point of view and tend to only be useful qualitatively. As an example, the seismic data at one mine assessed included erroneous magnitudes – many events around $M_L$= 0.5 to 2.5, whereas the true magnitudes were probably closer to --3 to –1.5, giving a false impression that there was a high frequency of damaging seismic events (Figures 1 and 2). At another mine the coverage of the system was extremely uneven and a whole mining district was indicated as low-seismicity (Figure 3). This was due mainly to the fact that there was only a limited number of sensors covering that section and only very large events could pass the trigger criteria.

At most mines the hardware and software settings have changed throughout the period the seismic system was operating and the location of stopes being mined have changed dramatically. This makes comparisons of seismicity over different time periods very difficult.

‘Seismic risk’ has been quoted by various sources as being quantifiable based on seismic data. Such analyses could be based on:

- The number of events per rock domain (per set volume of rock) over certain time periods (relevant to mining in certain zones).
- Seismic Energy or Moment per mining domain.
- Changes in b-values over time and per mining domain.
- If the full database of events is available and the events are all compatible, numerical modelling could be considered. Modelling of mining steps using Map3D for example, in relation to the generated seismicity can be used as a fairly basic predictive tool for future mining blocks. Are there time, money and resources available for this at the evaluation stage (rarely) or should this type of study be left until the mine has been purchased (likely).

One must consider if quantification and analyses of seismic data and seismic risk can be used by the potential purchaser. In the majority of cases the sole analysis undertaken is based on event location and the distribution across the mine. If the system generated automatic locations that were not all manually checked, should even these be trusted?

**Rock Mass Deformation Monitoring**

Quite a few mines have installed various monitoring instruments such as extensometers, closure meters, stress cells/gauges etc. When assessing a seismically active mine the results of such monitoring are not generally of critical importance unless specifically aimed at quantifying deformation around excavations. Such data would be useful in determining the required deformation capacities of support elements.

## Rock Mass Properties

Empirical methods are used in most mines at some stage in their life cycle to assess critical mining spans based on rock mass classification data (Barton, Lien and Lunde, 1974 and Laubscher, 1990). It is important to assess each factor on which the rock mass classification calculations are based. Some factors have changed from the original designs, and of specific interest to highly stressed and seismically active mines is the change in the Stress Reduction Factor (SRF) for the calculation of Q (Barton, Lien and Lunde, 1974, Grimstad and Barton, 1993 and Peck 2000). Re-calculation using the updated parameters might be necessary.

The use of the rock reinforcement design chart (Grimstad and Barton, 1993) can indicate quickly if the support system is of the right order of magnitude but the method tends to jump from ‘unsupported’ to ‘shotcrete’ without an intermediate category incorporating mesh and various types of bolts. The method also *under-estimates* meshing as a requirement for Western Australian mines under the Moshab Code of Practice for Surface Rock Support for Underground Mines (Moshab, 1999).

The Stability Graph method (Hutchinson and Diederichs, 1996) is also used for the determination of initial estimates for critical mining spans but as discussed in the section on Longhole Stoping, the method does not cater for highly stressed environments where s1 in the stope hangingwall or back is greater than 50% of the UCS. The critical spans indicated by that method are based on regularly spaced cable bolts installed into the backs and hangingwall and in many cases this is not possible due to drive location. A very conservative approach should be made towards critical spans calculated using the Stability graph method for highly stressed and seismically active mines. The use of strike spans that are only 50% of those indicated is realistic for planning purposes.

## Blasting

A number of blasting variables can affect the severity of the damage during seismic activity. This can be critical especially if poor or unsuitable blasting has led to previous problems and if these could be prevented or at least reduced with changes to the blasting techniques. It is important but sometimes not easy to determine what system was used, and could it have caused problems. Documentation of the blasting system used for specific stopes is sometimes not readily available as there could have been changes on an ad-hoc basis or per operator. Observations underground can usually highlight problems if current or recently blasted stopes are open.

Poor blasting techniques can cause excessive rock damage to walls in both development and stoping excavations. If the cause of this damage can be determined then it should be possible to assess the adjustments required to alleviate such problems. A list of blasting variables with comments is contained in Table 3.

**Table 3 –** ***Blasting Criteria***

| Blasting | Comments |
|---|---|
| Hole size | The hole size should be related to the usual design parameters but larger holes could be required to cope with hole closures. |
| Explosive type | In many highly stressed mines the use of ANFO explosives aggravates ground conditions, with large volumes of gas entering pre-existing stress fractures, further damaging the rock mass around excavations. |
| Detonator timing and delays | There is a possibility that more seismic events could be triggered by the use of millisecond delays and by blasting all stopes at the same time. Long detonator delays in multiple hole blasts also run the risk of cut-offs due to seismicity related falls of ground. |
| Decoupled perimeter holes | To reduce damage to excavation walls decoupled explosives such as Trimmex should be used, and this applies whether the mine is seismically active or not. |
| Reduced energy penultimate holes. | Reduced energy explosives(eg Isonol 50) should also be used in the penultimate row of holes in development to reduce damage to excavation walls. This should also be considered in stope blasts. |
| Initiation location, centralised blasting. | Centralised blasting location using electric initiation is far better than stope based initiation. |
| Safe blasting stations | Safe blasting locations well supported or well away from production sections in case blasting triggers seismic events. |
| Re-entry times and exclusion zones. | Blasting at different times can result in seismic activity peaking a few times during the shift whereas blasting once per shift should result in the seismic activity occurring during shift change. |
| De-stress blasting (development or stoping). | De-stress blasting is not a quick-answer to strainbursting of rockbursting and trials require detailed monitoring to determine whether or not it is or could be of benefit. Stope de-stressing should be modelled in detail as the magnitude of the stress redistributions could cause more harm than benefits. |

## Conclusions

Once a mine starts experiencing seismicity there is a good chance that the frequency and severity of the events will increase with continued mining. Generally orebodies only contain a finite tonnage of reserves and in Western Australia at least, the orebodies are generally mined from the top-down due to the popularity of decline access as opposed to shaft access. The finite size of the orebodies in combination with most mining methods leads to pillars being generated and more difficult ground being left for final mining stages.

The bottom line when evaluating mines is to assess whether the operation will be profitable (all mines can be made safe, but for some the costs involved would be prohibitive).

The prospective purchaser should consider all aspects of seismic issues on the mine, including previous mining methods, designs and support, safety issues and seismic monitoring and data analysis. There is a need to determine the base causes of seismicity and to gauge whether the cause and extent of activity can be mitigated through *reduced extraction* or *production rates*, improved *sequencing* and *design*, and *equipment* or *support modifications*. If a mine has previously closed due to seismic related problems the prospective purchaser should consider these aspects in greater detail than if the mine closed solely for economic reasons. Only rarely, however, has there been a mine that has closed solely due to seismic activity as most problems resulting form this can be resolved through the abovementioned modifications.

The implementation of exclusion zones and re-entry periods following blasting is also an option for purchasers to limit the exposure to risk. The designs for these require seismic data relevant to the planned mine design, method and blasting techniques and inevitably leads to reduced production capacities.

For a prospective purchaser to make use of such a study into the effect of seismicity on a mine it is important to quantify the following:

- The support cost per metre of new development.
- The rehabilitation cost of development per metre.
- The cablebolting per metre of ore drive or per tonne of ore.
- An estimate of the required re-entry times per production blast.
- The dilution per mining method and domain.
- The possible percentage of stopes not producing due to seismic activity.
- The development changes required to service an improved mining method.
- The risk of seismic activity affecting production and dilution – this critical issue will still be based on qualitative issues but the following questions will need answering:

*Is there a risk that seismicity at the mine will cause a serious injury and is there a risk that the mine will not be able to maintain the required production level because of seismicity?*

By investigating all issues discussed in the paper the answer to the last question will hopefully be apparent.

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