SECTION 5

MANAGEMENT OF SEISMICITY USING PORTABLE SEISMIC SYSTEMS

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Over the last 8 years in Australia there has been a steadily increasing awareness of the importance of monitoring seismicity in underground mines. This has followed the increased safety awareness trend and the introduction of Geotechnical Engineers into operations. Collection of data and quantification of exposure to hazards has also become a more regular requirement for corporate and regulatory compliance.

If a deep orebody is to be mined, if there have been reports of rocknoise or if there has been evidence of stress damage, seismic monitoring is becoming more of a requirement than a choice. Seismic monitoring is used to locate where the activity is and which structures, domains, mine designs and extraction sequences could be causing such activity.

The main objective of this Section is to increase the awareness of small-scale seismic systems and to discuss the use of the results to manage seismicity on mines. Whilst primarily covering recorded seismicity in underground mines, many of the details and aspects are also applicable to open pit mining.

The analyses covered in this section and in Section 4 are applicable both to full scale and small-scale systems.

The following sections are covered in this Section:

- Legal and Corporate Requirements
- Seismicity
- When to start monitoring
    - Virgin Stress
    - Signs of Stress and Seismicity
- Seismic Investigation Programme
- Monitoring
- Seismic Systems
    - Cable
    - System Maintenance

- System Time
- Sensors
- Data Transfer
- Event Processing

- Initial Data Interpretation
  - Spatial Distribution of Events
  - Temporal Distribution of Events
  - Number and Magnitude
- Further Analysis
  - Number of Triggers
  - Location Error
  - Frequency Magnitude
  - Peak Particle Velocity
  - Energy etc
  - Re-entry Periods
- Source Failure Mechanisms
  - Relating Seismicity to Modelled Stresses
- Conclusions
- References

5.1 LEGAL AND CORPORATE REQUIREMENTS

There is a legal requirement in many States and Countries to quantify the rockmass conditions in underground mines in order to implement suitable mining methods and to design and install effective support. In many cases the broad requirements stated in Regulations (eg WA-DOIR, 1995) are backed up by more detail in Guidelines (eg WA-DME, 1997) and Codes of Practice (eg Moshab, 1999).

Section 10.28 of the Western Australian Regulations is an example:

> "*(3) The principal employer at, and the manager of, an underground mine must ensure that the following things are done in relation to all development openings and stoping systems underground in the mine -*
>
> *a) geotechnical data (**including monitoring** of openings when appropriate) is systematically **collected, analysed and interpreted**;*
>
> *b) appropriate stope and pillar dimensions are determined;*

c) *rationale for sequencing stope extraction and filling (if appropriate) is determined;*

d) *there is adequate design, control and monitoring of production blasts; and*

e) *rock support and reinforcement are adequately designed and installed."*

(Reference: Mines Safety and Inspection Regulations 1995).

One could interpret section 3 (a) as indicating there should be seismic monitoring if there is seismicity.

Over the last few decades there has also been an ever-increasing level of social pressure on the mining industry to eliminate fatalities and serious accidents. With regards to falls of ground and seismicity, this has resulted in mining companies employing more geotechnical engineers, installing more suitable ground support, and implementing more ground-monitoring systems.

The level of seismic activity that triggers a requirement for seismic monitoring on mines has reduced over the last 10 years due to these legal, corporate and social requirements. Combined with the increase in the number of Australian mines operating in higher stressed ground, it is apparent why there have been more seismic systems installed.

For many mines it is difficult to obtain approval for capital expenditure at short notice for full-scale, minewide systems prior to experiencing damage and lost production. Once damage has occurred, the opportunity to introduce pro-active changes is greatly reduced (access and stope development already in-place and supported). The option of installing a lower cost portable system at short notice is therefore a good tool for management to quantify the seismic activity before they consider purchasing a full-scale system.

The trigger for purchasing or renting a small-scale seismic system could range from minor, infrequently reported rocknoise to major unexpected events and excavation damage. The timing of the decision to rent or purchase a system following reported seismicity depends on the geotechnical awareness of technical staff and management.

Ideally, systems should be installed early, **before** seismicity and rockbursting affect production and in time to allow adjustments to support, designs and extraction sequencing. This requires awareness by Geotechnical Engineers and Mine Management of the potential for problems under certain circumstances, such as:

- High measured virgin stresses
- Deep mining
- Large mined out expanses
- History of seismicity in neighbouring mines

- Shrinking-pillar extraction sequencing
- Minor rocknoise reports
- Occasional strainbursts

The small-scale systems are easy to use and low cost. Downloaded data is processed by software provided with the systems. This initial processing produces the time and location of the events, with a relative quantification of event size/magnitude. Additional useful analyses can be undertaken using Excel, and the results interpreted in relation to excavation damage, mine designs, mine extraction sequencing, re-entry periods and support systems.

5.2 SEISMICITY

A seismic event can be defined as ‘a sudden inelastic deformation within a given volume of rock, ie a seismic source, that radiates detectable seismic waves’ (Jager and Ryder, 1999). In terms of mining, this equates to either brittle failure of rock under high stress conditions or slippage along a structure.

Seismic failure of rock can occur at very shallow depths if mining induced stress levels are high, in high extraction, pillar methods. Generally, the deeper the mine, the higher the likelihood of mining being associated with seismicity. This will be especially true in mines with extended lifespans, as the extent of mined-out voids becomes greater with time, leading to further increases in the mining induced stress component.

Many mines can cope with the experienced level of seismicity without having to change support, designs, extraction sequencing or re-entry periods. Such low-level activity is only related to localised rock fracturing around excavations. This readily becomes apparent after the installation of a small-scale system following reports of rocknoise – and in such cases it might not be necessary to continue monitoring.

If seismicity becomes an issue on the mine, the data collected from small-scale seismic systems can prove a useful inclusion for the studies required by many companies prior to the purchase of full-scale, minewide systems.

5.3 WHEN TO START MONITORING

The early commencement of seismic monitoring on mines is critical in order to accumulate sufficient data and analyses in time for possible changes to mine designs, extraction sequences and support. The later the monitoring starts, the more difficulty there is in implementing changes, as more development will have already been excavated and support already installed.

Monitoring can commence before reported damage or rocknoise if mining is planned in a section where virgin or mining induced stresses are expected to be high and/or there are strainburst-prone rocks.

Small-scale systems can be installed within a day at most mines, although there are generally delays of a few days due to the purchase of cable.

Geotechnical Engineers and Mine Management should consider installing monitoring systems once rocknoise or support damage is reported, or if stope fall-off increases beyond ‘normal’ levels. The potential benefits of early monitoring far outweigh the low cost of such monitoring.

5.3.1 Virgin Stress

Before mining commences in a new mine, or a new section of a mine, a simple comparison of measured virgin stress levels can give an initial indication whether seismicity could be expected. Figure 1 shows the fairly wide distribution of measured virgin stresses against depth in Western Australia using the Hi-cell (Lee, Pascoe and Mikula, 2001). The results also show the expected increase in stress magnitude with depth.

A large proportion of these mines have been assessed with regards to reported seismic activity. The results (Figure 2) show that there is a relationship between the measured Major Principal Stress and seismicity:

- If the measured Major Principal Stress is less than 41MPa, it is unlikely that there will be reported seismic events.
- Conversely, if the measured Major Principal Stress is greater than 54MPa, it is extremely likely that there will be seismic events.

If measured stress levels are higher than 41MPa, it is likely that there will be some seismic activity and that a seismic system would be required at some stage to monitor the activity.

These results are as expected for sidewall rock failure with typical rock strengths and with the three-fold increase in sidewall stresses due to the presence of the excavation.

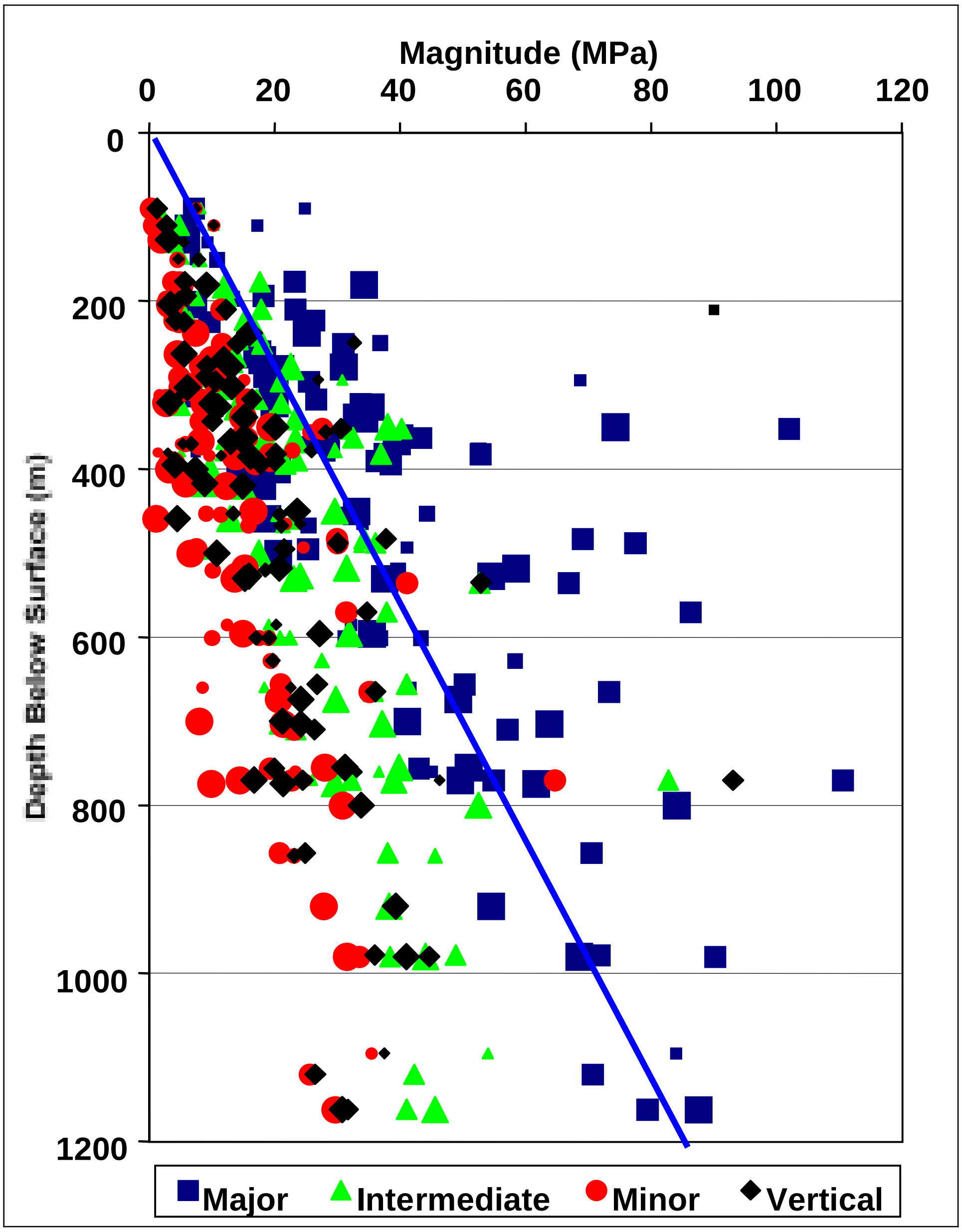

Figure 1 **Principal Stress versus depth in Western Australia**

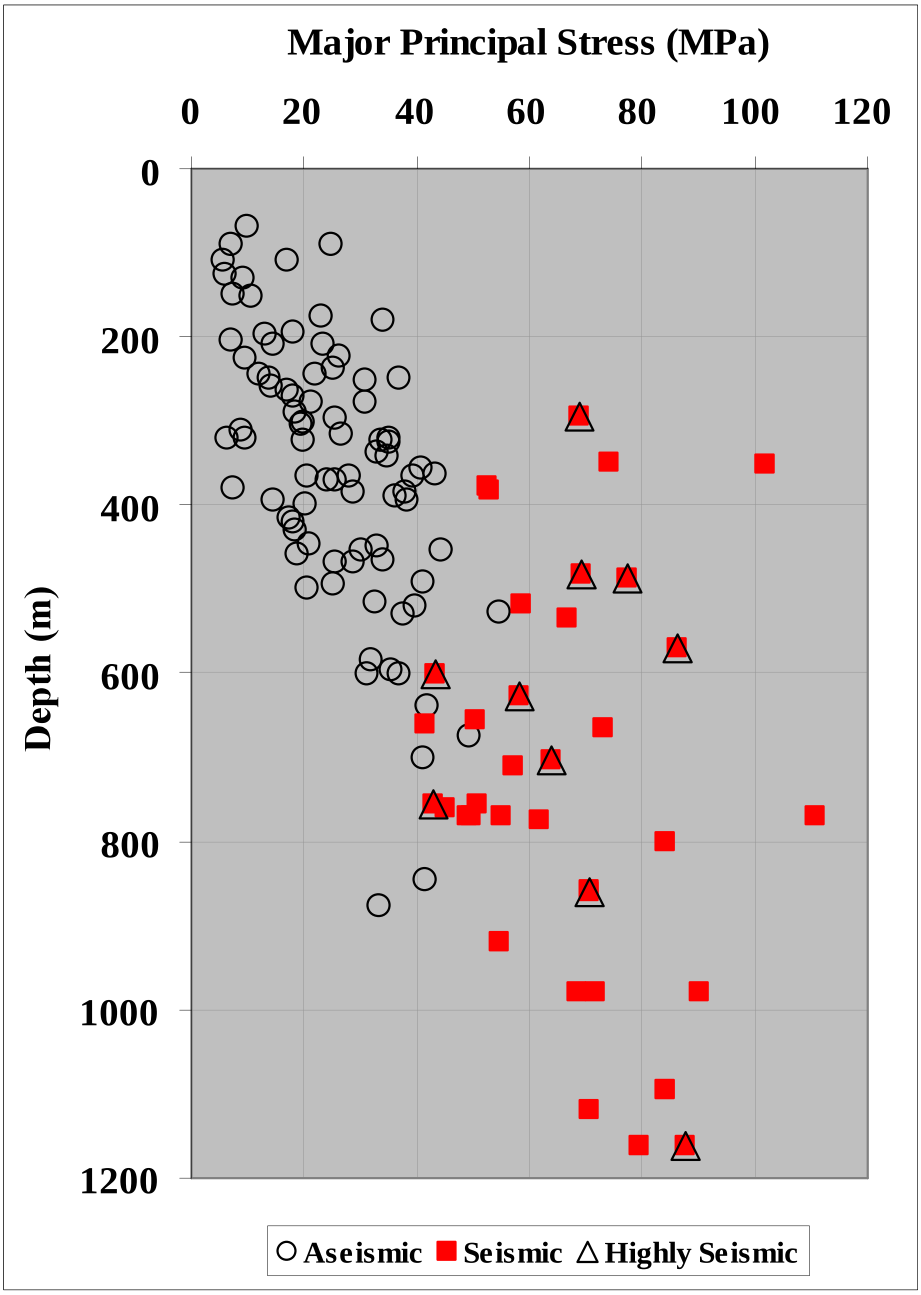

Figure 2 Seismicity, Principal Measured Virgin Stress and Depth

5.3.2 Signs of Stress and Seismicity

An early sign of seismicity is rockfalls reported on re-entry at the start of the shift, especially if the drives are not supported with mesh. Many such falls are caused by blast vibrations and seismicity associated with blasting, hence being found on re-entry.

Generally if there is evidence of stress-related rock damage there will be seismicity. Such evidence includes fracturing on drive shoulders, slabbing on corners, fractures through pillars, stope back failures.

Damage to support is also a sign of stress-related rock failure, with the rockmass deformation exceeding the capabilities of the support elements (or components of support elements). One of the early indicators is damage to split set rings and plates, which are the support units generally first to fail under large deformations and dynamic loading. 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 potential injury.

As seismic events generate larger amounts of energy, they will be associated with:

- broken rockbolts (especially for fully grouted bolts)
- split set ring failure
- loud rocknoise
- seismic waves felt underground and on surface
- bulking of mesh
- loss of blastholes
- cutting of initiation cords/wires
- larger rockfalls associated with support system failure.

5.4 SEISMIC INVESTIGATION PROGRAMME

Once management perceives seismicity is or could be a risk to 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.

After the system has been installed for a sufficient period, analysis of the results 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 more detailed analysis of the data and numerical modelling. These are discussed in the later sections.

Once the cause of the seismicity and the scale of the activity have been determined, possible changes to mine designs, sequencing and support need to be determined and discussed with the mining engineers.

5.5 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. In the event of seismicity related damage subsequently increasing in severity, such records can 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.

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 small-scale 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. This could be due to generally low stress levels, or the monitoring could have been undertaken during extraction of isolated high stress pillars.

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.

5.6 SEISMIC SYSTEMS

The seismic systems used for short-term monitoring all have the following basic properties:

- 6 to 16-channels
- Generally based on uniaxial geophones
- Geophones can be stuck on excavation walls with epoxy and are reclaimable
- Battery powered
- Can be downloaded underground onto data storage device or transferred to PC underground
- Low-cost twin-strand or coax cable
- 1-day installation.

The three main manufacturers of systems suitable for use by mining companies are ESG from Canada, ISS from South Africa, and the CSIR, also from South Africa. Systems are generally available for purchase within a month. Manufacturers and consultancies also have systems available for rental at short notice, with typical rental rates of $1,200 to $2,000 per month.

Purchase prices for each of the systems are listed in Table 1, based on 2004 quotes. The prices can vary depending on exchange rates, availability, maintenance agreements etc.

The systems include a sufficient number of sensors to cover a volume of rock 500m x 500m x 500m. The limit to this volume is generally due to a requirement to limit the lengths of cable from the system storage unit to each sensor to less than 300m. Longer cable lengths are possible (cable lengths of up to 500m have been used by the author) but signal loss due to cable resistance and due to external electrical interference reduce the clarity of the waveform.

The Impulse system with 16 channels can cover a larger volume of rock. The GMM only has sufficient memory for around 240 events, whereas the other systems can cope with considerably more events. The data acquisition units of all systems can be downloaded manually underground to eliminate the need for extensive cabling to surface. The memory capabilities of all systems are sufficient for initial monitoring. FireWire disks with 60Gb capacity are currently being used for the Standalone ISS systems, sufficient for months of continuous monitoring.

Table 1 Seismic Systems

SYSTEM	DESCRIPTION	QUANTITY	(A$)
ESG Paladin (Canada)	6-channel seismic monitoring system with six uniaxial geophones. Including acquisition, processing & visualization modules, manual or remote download. Windows based.	1	$ 8,280
	HSS V10 Software	1	$5,000
	15Hz geophone elements @ $660 ea	6	$3,960
	Annual Software subscription	1	$1,380/pa
		Total	**$ 18,620**
ISS Standalone SAQS6G (S. Africa)	6 geophone channels, DC power, internal GPS, removable firewire disk, manual or remote download. Linux based.	1	$8,750
	RTS/stw Run Time System per channel (seismic triggered) @ $1,050 per channel	6	$6,300
	MTSM and JMTS Seismic Processing Software	1	$14,000
	Spare FireWire disk		$550
	14Hz geophone elements @ $330 ea	6	$1,980
		Total	**$31,580**
GMM (CSIR)	8 Channel, D-Cell Battery powered, manual download. Windows based.	1	$10,000
	Aura 32 Software – annual fee	1	$7,500
	14Hz geophone elements @ $330 ea	8	$2,640
		Total	**$20,140**
Impulse (CSIR)	16 Channel, mains or battery powered, manual or remote download. Windows based.	1	$20,000
	Aura 32 Software – annual fee	1	$7,500
	14Hz geophone elements @ $330 ea	16	$5,280
		Total	**$32,164**

5.6.1 Cable

RG58 co-axial cable is used by the author for small-scale systems – and this can be sourced with a solid copper-core (far easier underground connections) and with additional shielding to reduce external interference. The cost of RG58 cable ranges from $0.56 to $1.20 per metre (it pays to search around for low-cost suppliers) and is supplied in 100m and 500m rolls (if you plan to install the cable by walking down drives, do not order the 500m rolls). Twin-strand cable can also be used and can also be supplied with shielding. RG58 cable can easily be joined and connected to sensors using crimp-on BNC connectors, which tend to produce good connections that withstand the wet, corrosive underground environments.

The cables are generally suspended with cable-ties to mesh or rockbolts on excavation backs (from an IT basket) – away from power, leaky feeder and blasting cables. Fans, pumps, transformers and other power sources should also be avoided.

The use of ladderways and boreholes between levels is a good way to minimise cable length.

5.6.2 System Maintenance

The small-scale seismic systems are all based on battery power and cable continuity can be checked by geotechnical engineers due to the very low voltage (some mining companies insist on electricians undertaking all repairs etc, which invariably increases the down-time of systems). At the processing stage it is critical to assess how many sensors are operating. If some of the sensors are not working, this information needs to be fed back to the geotechnical engineer or electrician responsible for the system. Testing of cable continuity for each system is straightforward and consists of unplugging each sensor cable in turn, testing the resistance with a multi-meter, and noting which channels require further checking.

The main cause of problems is damage to cables by boggers close to the sensor.

5.6.3 System Time

Correlating system time to real time at the set-up is important in order to relate events to blasts and rocknoise. The ISS Standalone systems have a GPS attached to enable the system time to be updated if the box is taken to surface and powered up. Unless connected to a computer network the time on the other systems has to be manually changed when connected to a PC. All systems except the GMM have the capability to be connected to a network or modem to enable the time to be updated remotely.

5.6.4 Sensors

Small-scale systems are generally set-up with temporary, reclaimable sensor elements. These units can be attached to excavation sidewalls or backs with epoxy. A wire brush is required to clean the rock surface prior to attaching the sensor. The rock surface should be solid (not hollow sounding), and the sensor should be places out of range of equipment, and preferably behind mesh (bolt-cutters could be required to provide a working opening). The use of an 2-component epoxy adhesive that sets in around 3 minutes is generally suited to the application, although in cooler mines a 'quick-set' epoxy will be required (the '3-minute' adhesive can take 5 minutes to set when cold). In warm mines the '3-minute' adhesive can set a less than a minute – it is worth having a range of adhesives with different setting times. Epoxy putty can also be used. When the sensor is to be moved to another location, the bond between the sensor and the rock can be broken with a scaling bar.

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 single pair telephone or coax cable is used between the geophones and the central data acquisition unit.

An example of a high quality sensor is the SM6 omni-directional 14Hz element, costing around $330 per element (see data sheets at end of section). The element has to be connected to wiring and protected from impact, normally using an epoxy filled 'boat'. The price of a professionally manufactured unit is around $980 (ISS 1G14S). This omni-directional sensor can be installed in any orientation – ideal of the small-scale systems where sensors are attached to excavation walls with epoxy adhesive.

The set-up of the sensor array is also very critical in order to maximise the 3-dimensional view of the area of interest, especially with the limited number of sensors. It is important to check the array using mine planning software to ensure the sensors are not located on a single plane, as this will give erroneous results.

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 300m 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.

5.6.5 Data Transfer

Seismic data stored on the small-scale systems has to be transferred to a network or computer for event processing. This is undertaken in different ways for the systems:

- ISS Standalone – a FireWire disk is unplugged from the system and replaced with an empty disk. The disk with data on is plugged in to the processing computer and the data transferred.
- ESG Paladin – The data is transferred using a USB storage device and then transferred to the processing computer (can be via another computer, network, email or the Internet).
- CSIR – Data can be transferred to a notebook computer underground and transferred via a network, email or Internet to the processing computer.

All the systems apart from the GMM can be connected directly to a computer network or to a modem, allowing data transfer remotely. In most cases, however, this step is left until a permanent system is installed.

5.6.6 Event Processing

Software is included with all systems for processing the events, which involves picking the P-wave and S-wave arrival times and locating the events. Data required for these calculations includes the coordinates of the sensors, P-wave velocity and S-wave velocity.

Each manufacturer offers different software, each of which extend to full-scale minewide systems and therefore easily cover the requirements of small-scale monitoring. Regarding ease of use, the CSIR software is probably the easiest, followed by the ESG, and then the ISS. The ISS system runs on Linux, which can lead to difficulties with the IT departments of some major mining companies. All of the processing software can be learnt within a day to a stage where waveforms are downloaded, transferred, processed and exported to Excel.

The software provides information on time, location, relative size/magnitude and provides waveforms to distinguish between blasts and ‘real’ events. 4 or more sensors are required to locate events.

5.7 INITIAL DATA INTERPRETATION

Spatial and temporal distributions are generally the most significant items of interest in initial monitoring. These results are available once the events have been located, which could be within hours if processing is undertaken on site.

Some of the software provided with the systems also produce graphs of events against time, events per day, plots of locations, energy and moment graphs, and events per level or region (eg stoping area) etc. Some of the software is limited, however and such work might have to be undertaken using a program such as Excel. Software such as Jdi has been designed for analyses and can be leased from ISS.

5.7.1 Spatial Distribution of Events

The distribution of events relative to excavations, geological boundaries and geotechnical domains is the most useful output from seismic systems, and is available once events have been located. Clustering of events and the location of individual large events can be used to determine what causes the seismicity – geological structures, different rock properties, or mine designs and extraction sequencing.

The small-scale systems all include basic visualisation software to view events. Excel can also be used, with images of mine plans used for the background of the plots (Figure 3). Visualisation is much improved with the use of Jdi (Figure 4), Datamine (Figure 5), Surpac, Vulcan, Map3D etc, and events can then be related to excavations and geological boundaries and structures.

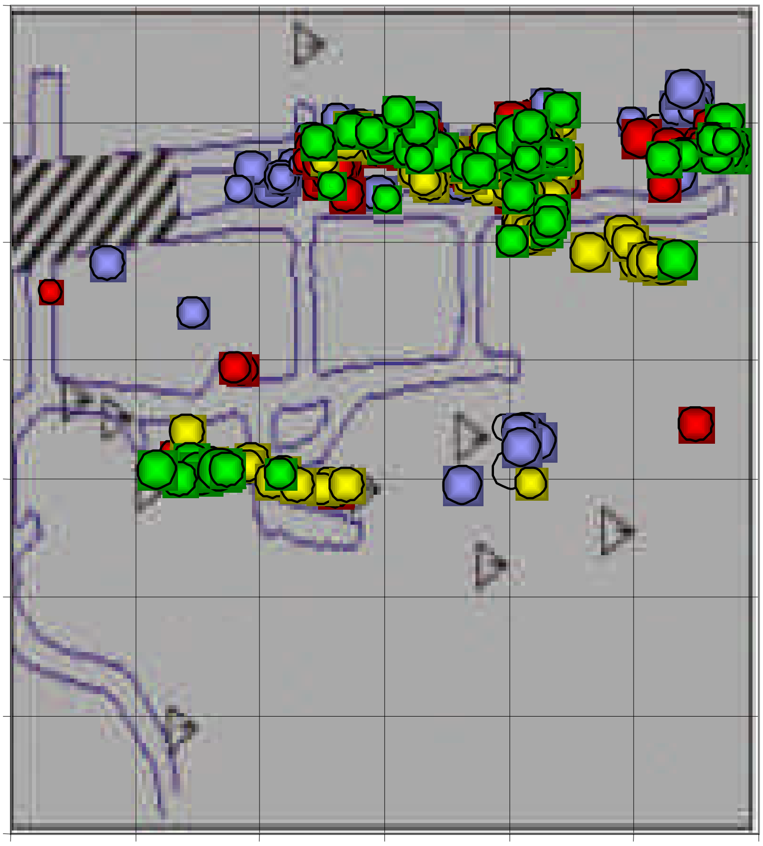

Figure 3 Plotting of Events using Excel

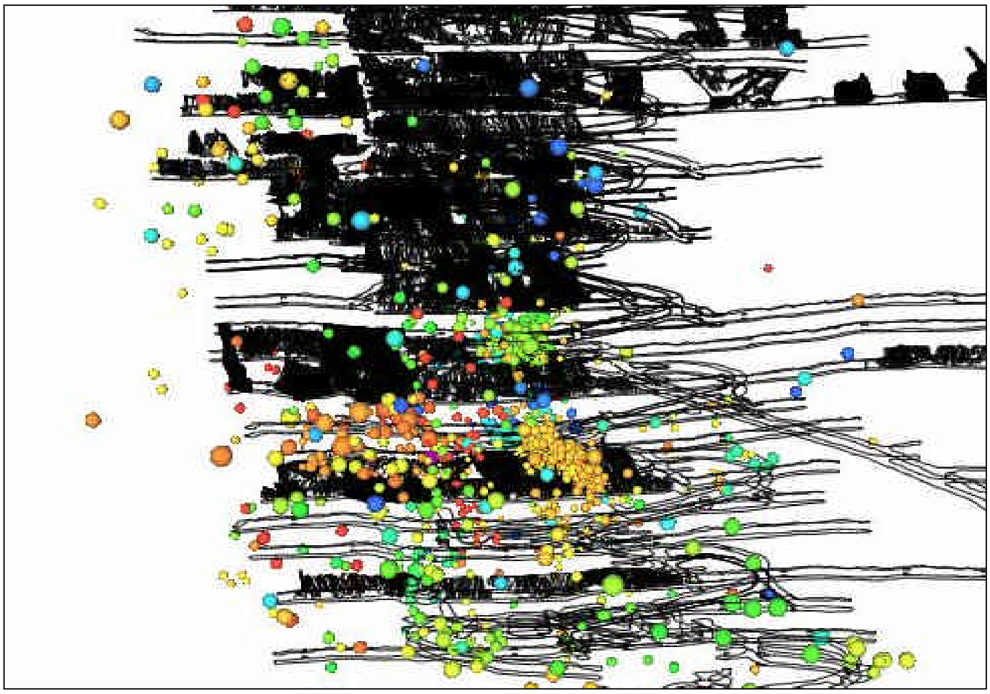

Figure 4 Plotting of Events using Jdi

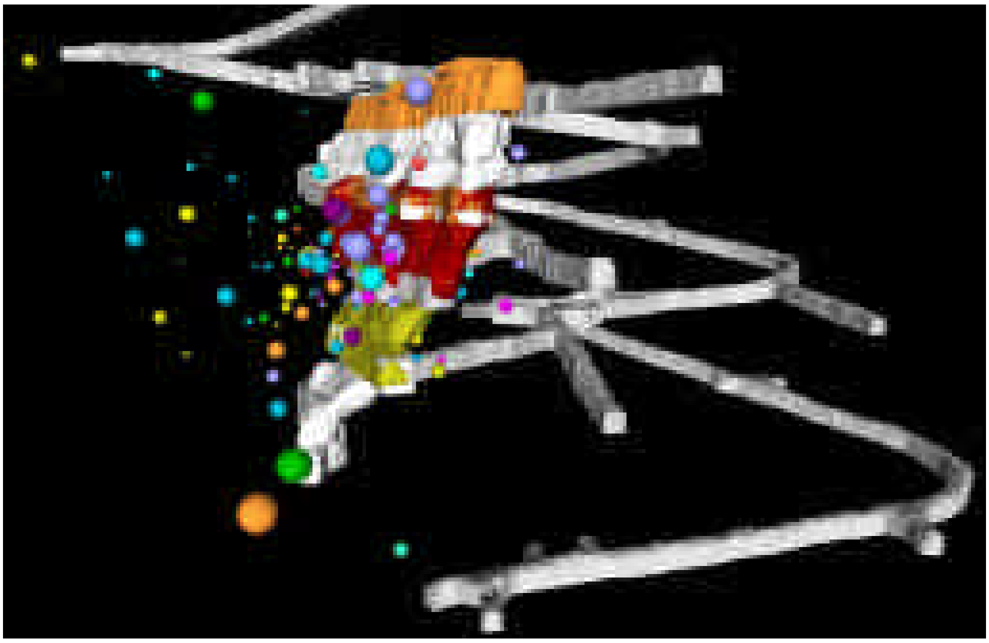

Figure 5 Plotting of Events using Datamine

5.7.2 Temporal Distribution of Events

Seismic activity tends to vary from quiet periods to peak levels after blasting or large seismic events. Plotting the number of events over time can give an indication of the decay rate and at what stage the activity has reduced to 'background' levels.

The rate of seismic activity, ie the number of events over time, gives an indication of whether the activity is increasing, decreasing, which times are more active than others and which days are more active. Plotted per hour on a daily period this should indicate peak levels of activity during and immediately after blast-times. The plot can also show a smaller peak on re-entry, when faces are watered down, boggers start operating in stopes and when jumbos start drilling.

When plotted daily, over a week, the plot of events should show the days during which most blasting occurs. When plotted a longer period (Figure 6) the increases in event frequency can be related to certain stages in the mining cycle (eg slot opening, pillar mining, stresses affecting larger geological structures, stopes exceeding critical spans, mining through brittle zones etc).

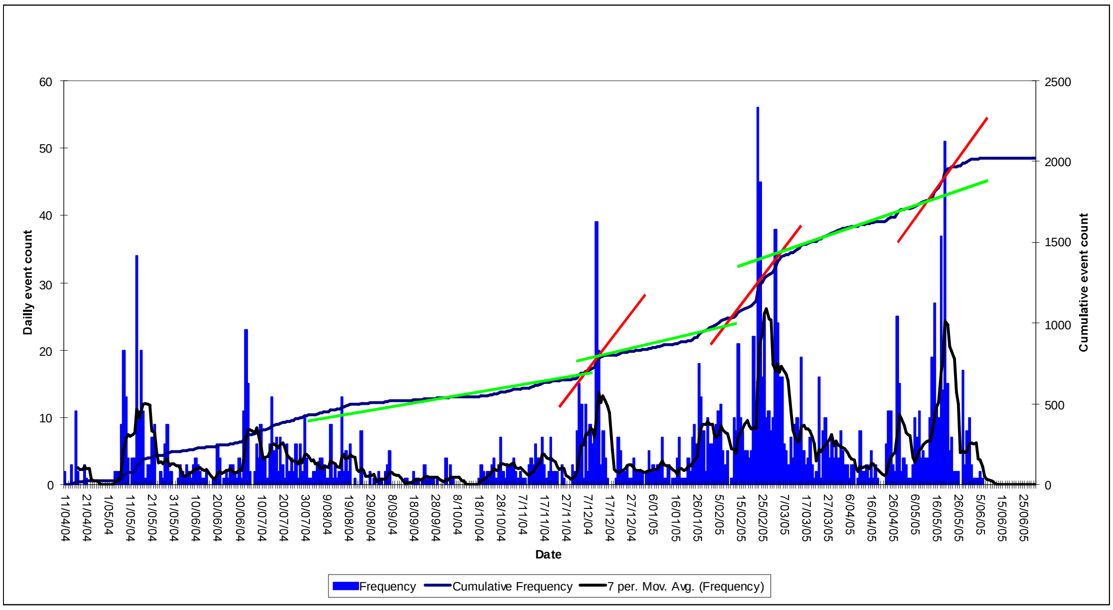

Figure 6 Event Frequency and Cumulative Frequency

5.7.3 Number and Magnitude of Events

Plotting event magnitude over time is another way of assessing the activity against time and mining activities. The previous method of just plotting the number of events tends to underestimate the effect of very large events. Larger fault-slip events for example might not be associated with the same number of smaller events as in a large pillar-burst or intact rock failure event.

Figure 7 shows a simple plot using Excel, whilst Figure 8 shows an improved plot using Jdi, overlain with event frequency.

Figure 9 illustrates that such a simple plot can also show when changes in magnitude calculations were instituted. Such changes make it difficult to compare event magnitudes between the different periods.

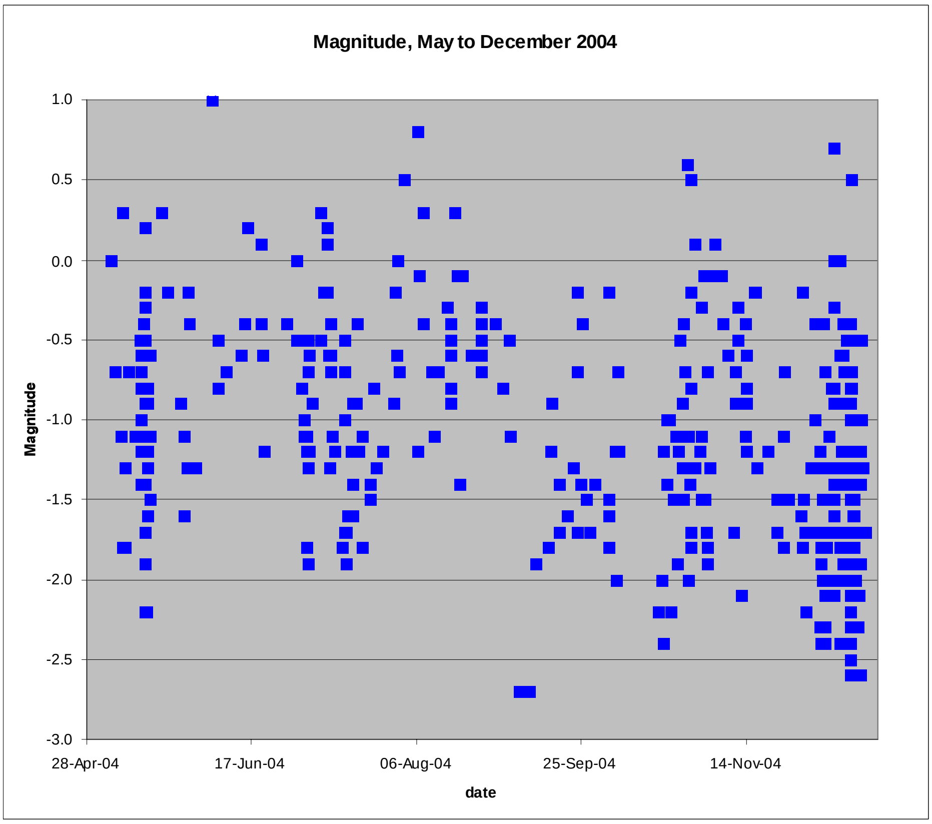

Figure 7 Event Magnitude over Time

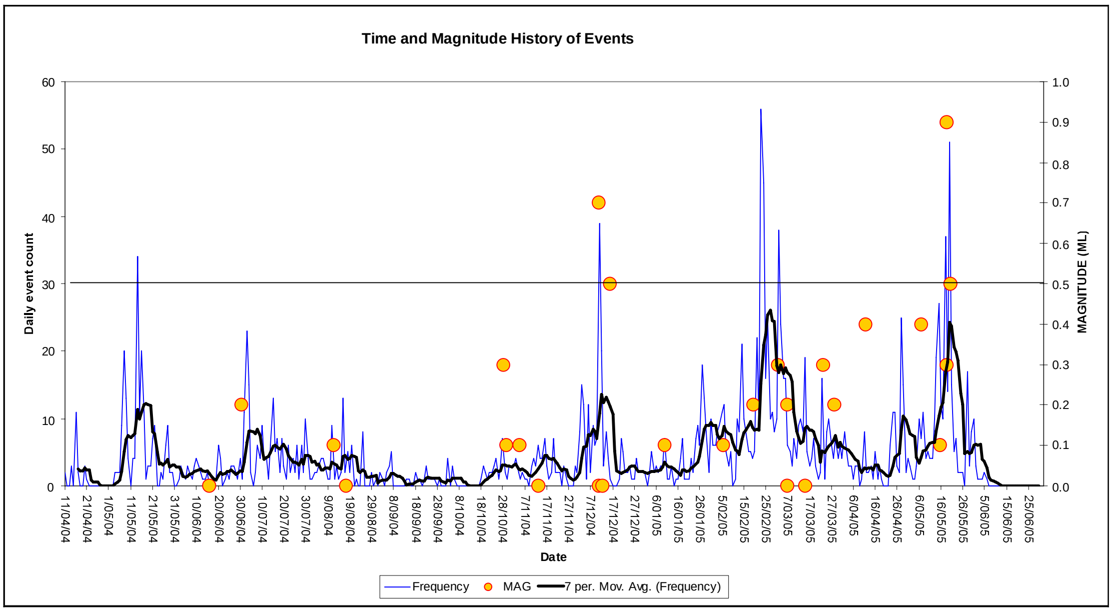

Figure 8 Magnitude and Event count over time

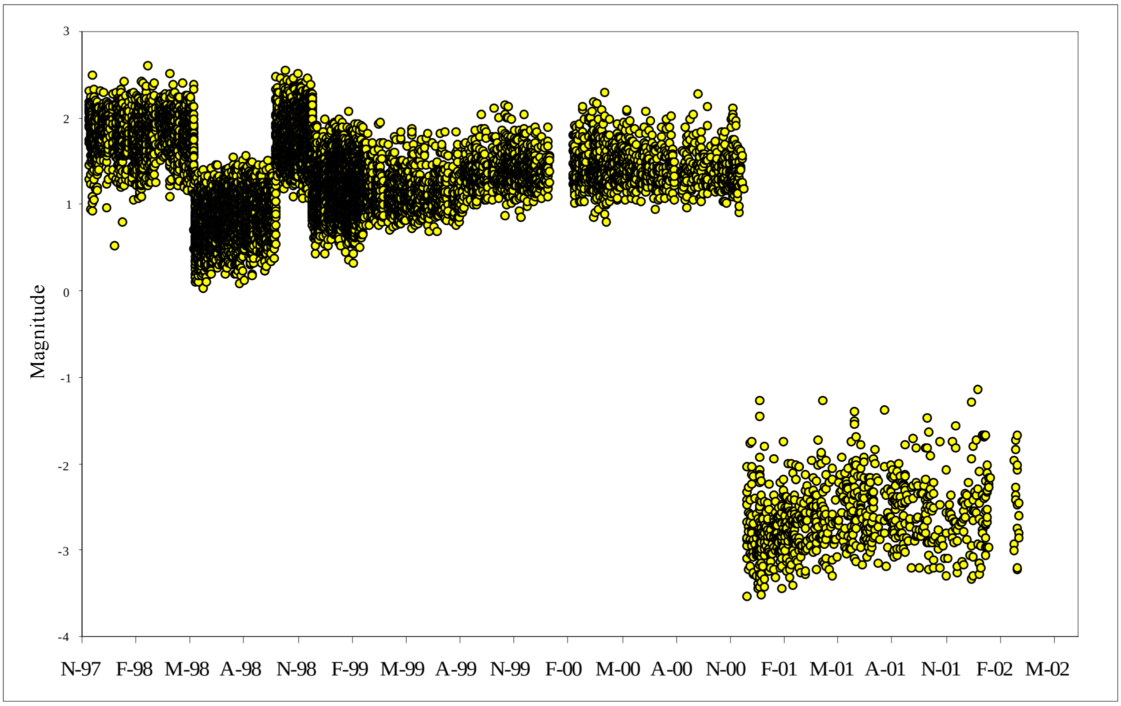

Figure 9 Event Magnitude over Time – System Changes Evident

5.8 FURTHER ANALYSIS

The data can be analysed in great detail, but the greatest value is often obtained from relatively simple analyses. One of the initial tasks is to split the mine into blocks/volumes, for each mining district and for each geotechnical domain where different seismic activity is expected. Noting down the coordinate limits for x, y and z for each block is relatively easy using Surpac/Datamine/Vulcan etc. These coordinates can then be used to set up the blocks, in Access, Excel or Jdi. An example of blocks specified per stope is included in Figure 10.

Analysis of the data per block can subsequently be automated and the results analysed for each block as well as for the whole area covered by the seismic system.

This type of analysis allows the impact of stope-specific extraction sequencing, blast sizes, stress and geology to be taken into account. Stope specific re-entry periods and exclusion zones can then be determined, incorporating sections that could include designs and extraction sequences expected to lead to elevated levels of activity.

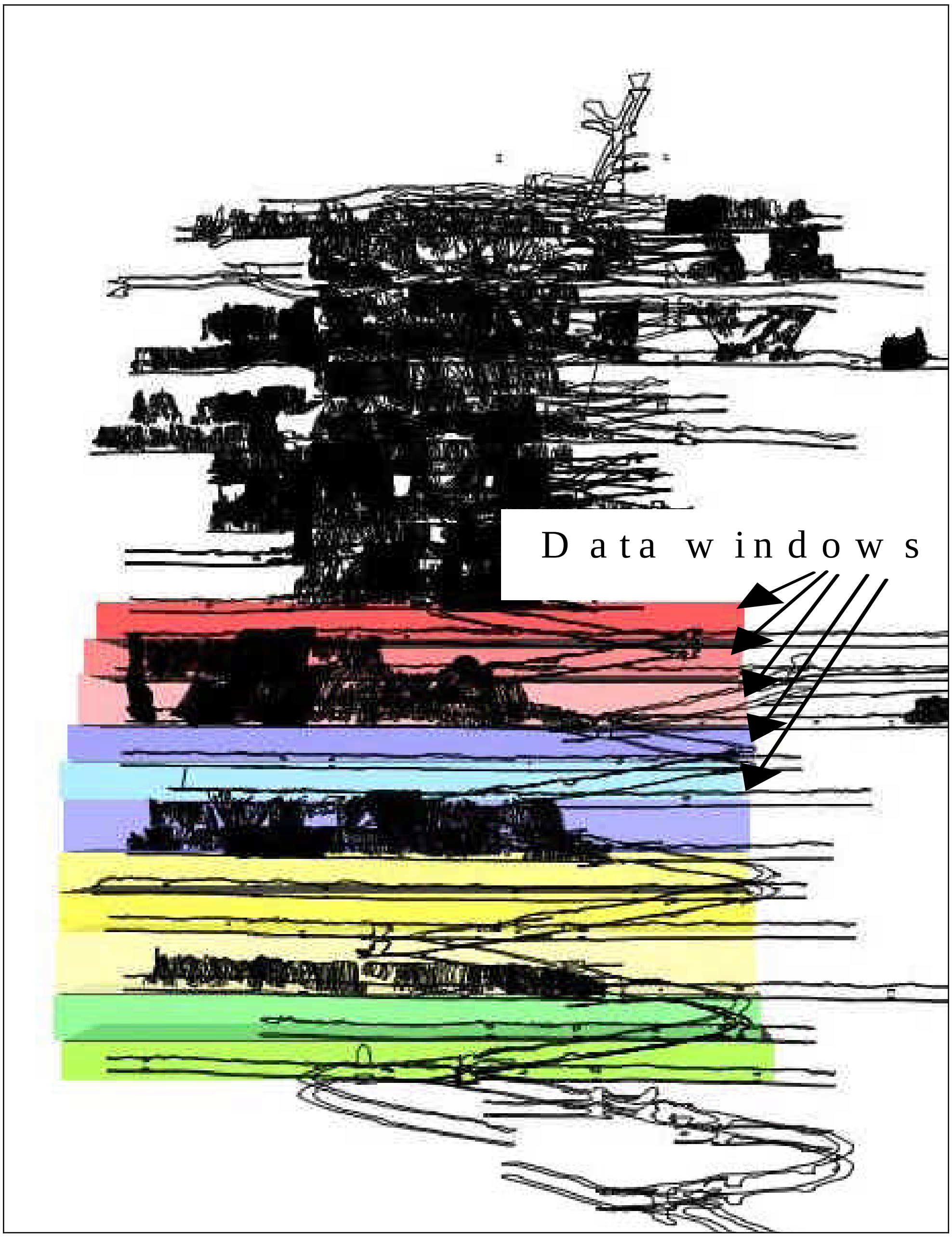

Figure 10 Example of Geometry Confined Data Windows

5.8.1 Number of Triggers

A plot of the number of triggers per sensor (Figure 11) can provide an insight into the number of non-locatable events (ie those not picked up by 4 or more sensors). The number of these events can be a few orders of magnitude more than locatable events. The activity for each sensor relative to each other can be useful – and might indicate for example that 1 sensor needs to be brought in closer to the activity or stoping section being monitored. Such plots can also show straight away if a sensor is not working.

In Figure 11, the system was not working on 5th May and on 7th and 8th June 2005. Sensor 4 was also not working from 3rd to 12th May 2005 and Sensor 5 from 16th to 23rd May. Sensors 3 and 4 are also located closer to the activity than the other sensors. This information is used by the geotechnical engineer to maintain the system and possibly re-locate 'quiet' sensors.

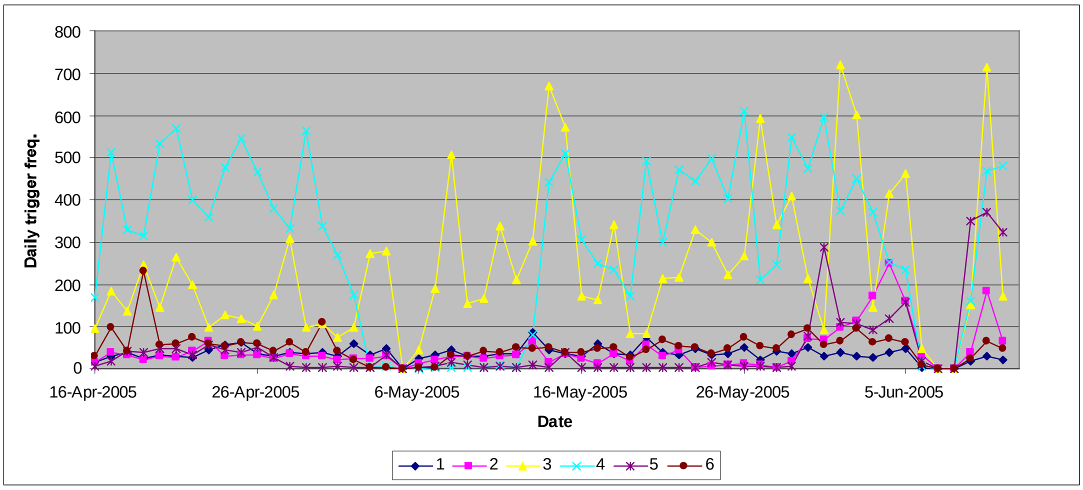

Figure 11 Triggers per Sensor

5.8.2 Location Error

In general analyses are only conducted on events with location errors of 10m or less using small-scale systems. The close proximity of the sensors to the activity means that location errors are normally less than 5m. Plotting location error over time for the (located) events (Figure 12) shows trends in the activity – whether the activity is located within the array or if it is moving away. For the example shown, the activity has progressed towards/within the array.

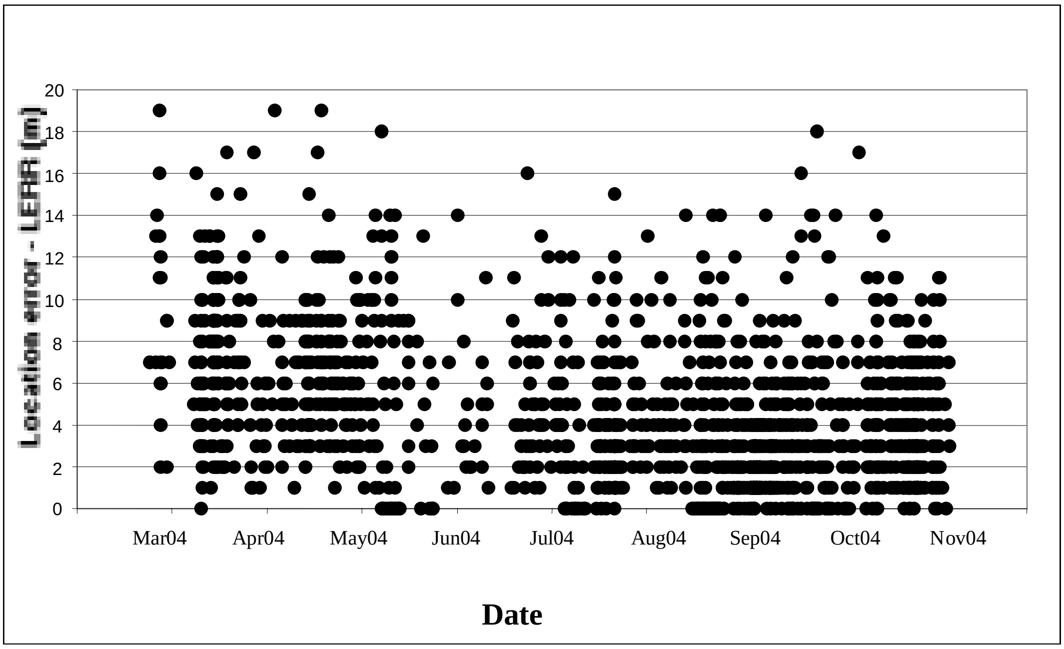

Figure 12 Location error

5.8.3 Frequency Magnitude

Plotting the frequency of events against magnitude, as per Figure 13, is a method initiated by earthquake seismologists to estimate the maximum possible size of seismic event indicated from the data (for a set volume of rock and for a set time period). The graphs are called Gutenberg-Richter plots and the 2 main points to extract are the intercept of the trend of the major data along the x-axis and the gradient of the major slope. This analysis is useful to determine changes – especially where the maximum magnitude (x-axis intercept) increases over time and which is also indicated by a lower b-value (negative value of slope of main section of graph). Table 2 includes example data, with increasing values of Mmax (due to mining of pillars) occurring every few months.

This type of analysis can be used to give an indication of the potential damage for specific sections of the mine. If a potential for larger events is indicated in a section, this information could be used to increase the re-entry period and increase the size of the respective exclusion zone. The number of activities taking place in such an area might also be reduced, and the number of separate blasts reduced by blasting multiple rings instead of individual rings.

The lower (left-hand) half of the data distribution is an indication of the system sensitivity. From the example shown (Figure 13) the cumulative number of events below a Magnitude of around M = -1.7 shows a reduced rate of increase. This is an indication of the lower end sensitivity of the system.

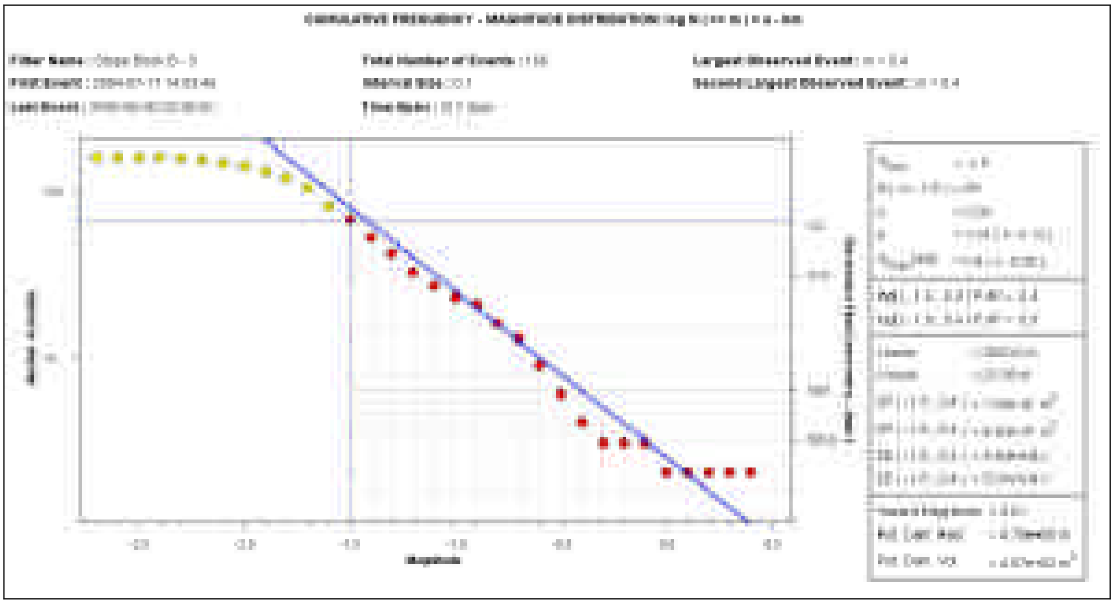

Figure 13 Gutenberg-Richter Plot

Month	Number of events	b-value (gradient)	M max (x – intercept)
Sept 04	24	0.88	0.1
Oct 04	34	0.64	0.9
Nov 04	70	0.74	1.1
Dec 04	121	0.75	1.2
Jan 05	108	0.83	0.7
Feb 05	156	1.01	0.4
Mar 05	185	0.91	0.7
Apr 05	101	0.82	0.8
May 05	168	0.78	0.9

Table 2 Example Results from Monthly Gutenberg-Richter Plots

5.8.4 Peak Particle Velocity

Peak particle velocity (ppv) analysis has been made more user-friendly by the Jdi program (ISS). The program contours the calculated source ppv values (Figure 14). This allows a relationship to be built between ppv and support damage. This of course implies that the monitoring has been continuing for a period that includes rockburst damage to support.

Such analysis can be used to specify areas requiring upgraded support. It is important to separate the data into time periods in order to relate seismicity to damage and stope positions.

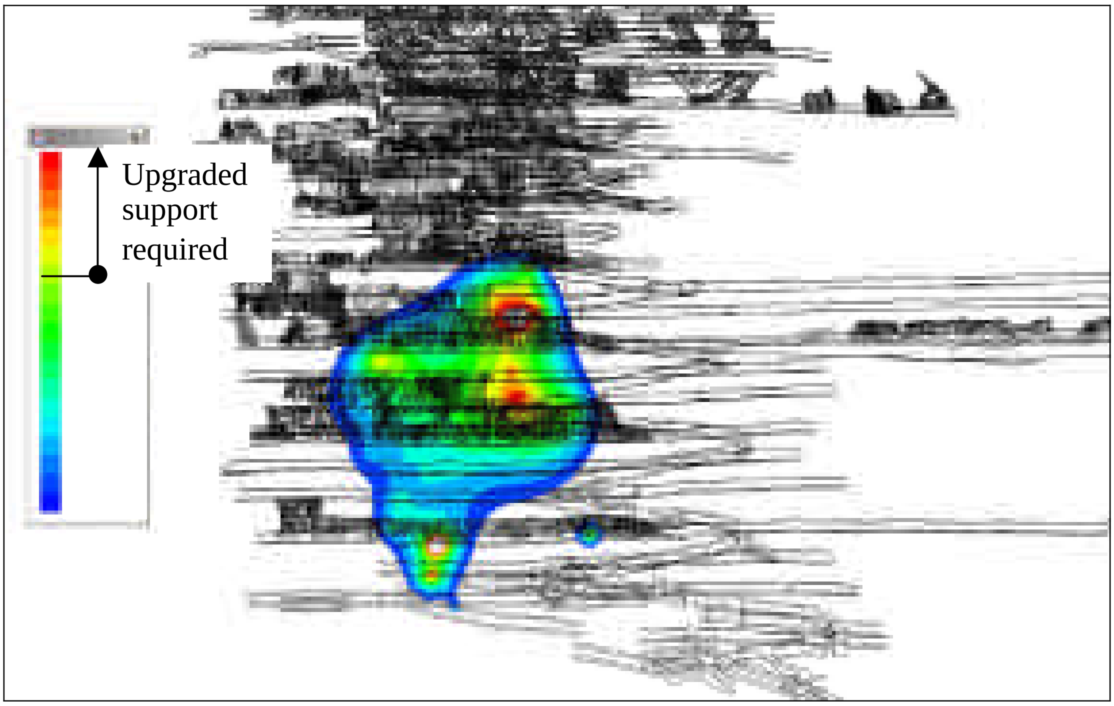

Figure 14 Peak Particle Velocity Contours

5.8.5 Energy etc

Plots of cumulative Energy, Moment, Apparent Volume etc over time can be used to gauge the typical change in response of the rockmass prior to large events (Figure 15). In theory this could enable a mine to predict a coming large event. In practice this is not possible until immediately before the event, by which stage it is difficult to use the knowledge. Generally with portable, small-scale systems the data is not processed on a real-time basis so this type of analysis is only useful to analyse the activity before and after events that have already occurred.

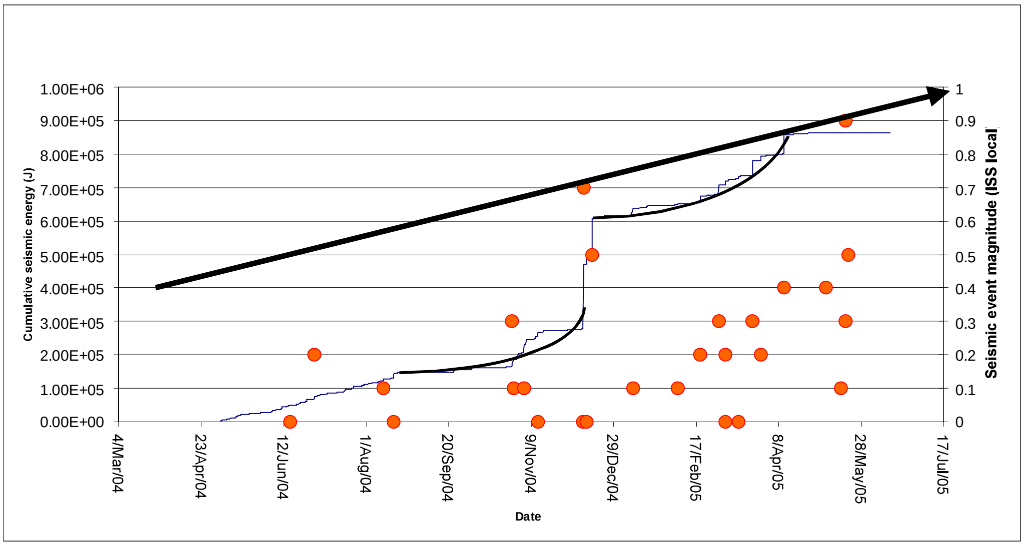

Figure 15 Cumulative Energy Release Vs Time

Plots of Energy Vs Moment are also useful to quickly determine of there is more than 1 distinct population of activity. Generally the plot will show a cluster of events with a linear relationship between Energy and Moment (Figure 16).

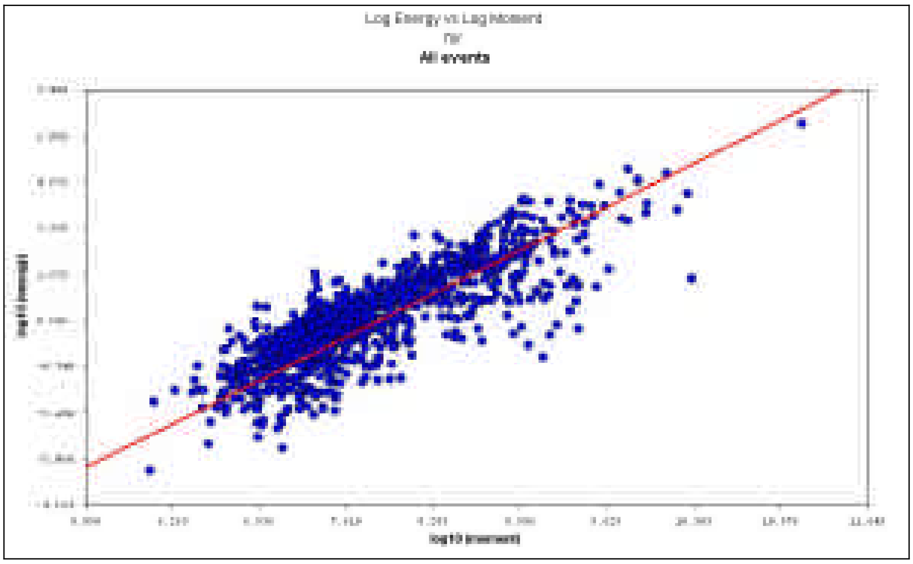

Figure 16 Energy-Moment Graph

5.8.6 Re-entry Periods

The frequency of seismic events (eg number of events per half hour) is generally highest at blast time, and then decays back to background levels over a period of time (Figure 17). One of the benefits of having a seismic system installed is that this decay rate can be monitored. By separating the data into volumes per stope or level, different re-entry periods can be specified for each main working section.

For the example shown, the background level of activity is around 1 event per half hour, and ranges from 0 to 2. The re-entry period for this particular working place should be 3 to 3.5 hours.

The decay of activity after major events tends to follow a hyperbolic time dependency, known as the Omori Law (see below), where n is the rate of occurrence of aftershocks, t is the time from the origin of the main event, and c and p are constants (Gibowicz and Kijko, 1994). Once sufficient data is available it is possible to derive a best-fit for the formula.

$$\text{Omori Law:} \quad n = \frac{c}{(1+t)^p}$$

In many seismically active areas, however, the activity following large events tends to extend past the next blasting time. This results in the inclusion of additional events triggered by an event other than the main event – and in some cases it is difficult to obtain a clean data set showing the decay of seismicity solely due to a single large event.

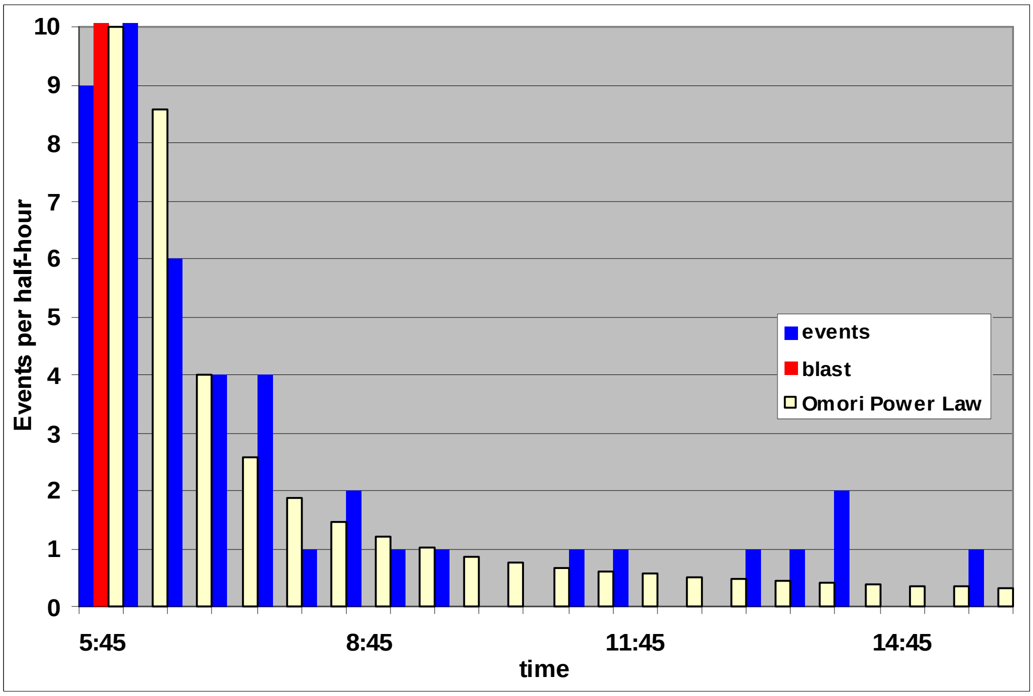

Figure 17 Post-Blast Seismic Events per Half-Hour

5.9 SOURCE FAILURE MECHANISMS

The determination of source failure mechanisms using first-arrival waveform directional analyses cannot be undertaken with small-scale seismic systems as the systems generally use only uniaxial sensors stuck onto excavation walls. The direction of the wave relative to the sensor cannot therefore be determined.

Source failure mechanisms can still be determined using a combination of data sources whilst using only uniaxial sensors:

- the spatial distribution of the activity
- geological boundaries and faults
- visual and photographic evidence
- analysing the mine designs and extraction sequencing relative to the activity
- assessing the source velocities
- by assessing the relative magnitude of the ratio between the P and S-waveforms (Energy or Moment)
- relating seismicity to modelled stresses.

The use of spatial distribution has been discussed earlier and when combined with knowledge of the geology, mining layout and extraction sequencing, the failure mechanisms can be determined.

Geological boundaries and faults and zones of brittle, strainburst-prone ground can be major causes of seismic activity. A comparison of seismic locations with such boundaries should indicate whether such features are major sources of activity. Slip failure can be interpreted from low-friction and planar surfaces (eg faults or shale bands) and intact rock failure can be interpreted from brittle zones (eg porphyry intrusives, siliceous bands).

Visual evidence of source locations can also give an indication of the failure mechanisms. Minor slip events are sometimes very difficult to observe underground, however.

Analysing mine designs and extraction sequences can also indicate whether there is a high likelihood of brow or pillar failure, whether stope hangingwalls are likely to fail, and whether increased stresses could cause fault slip.

Assessing calculated source velocities (Figure 18) can also be used to interpret whether the events are due to fault slip or intact rock failure. The cut-off between the two mechanisms is not straightforward, however, and varies per mine. Analysis of historical data is required before such interpretation could be deemed qualitative and in many cases there are insufficient fault slip and intact rock failures, especially with small-scale systems.

The ratio between the calculated P and S Energy (Figure 19) or Moment has also been used to determine whether the events are due to slip or intact rock failure. Events with an Es/Ep ratio greater than 10 have been shown to be fault-slip related. The vast majority of events include combined failure modes and proven examples are needed for this method to be used with a high level of confidence.

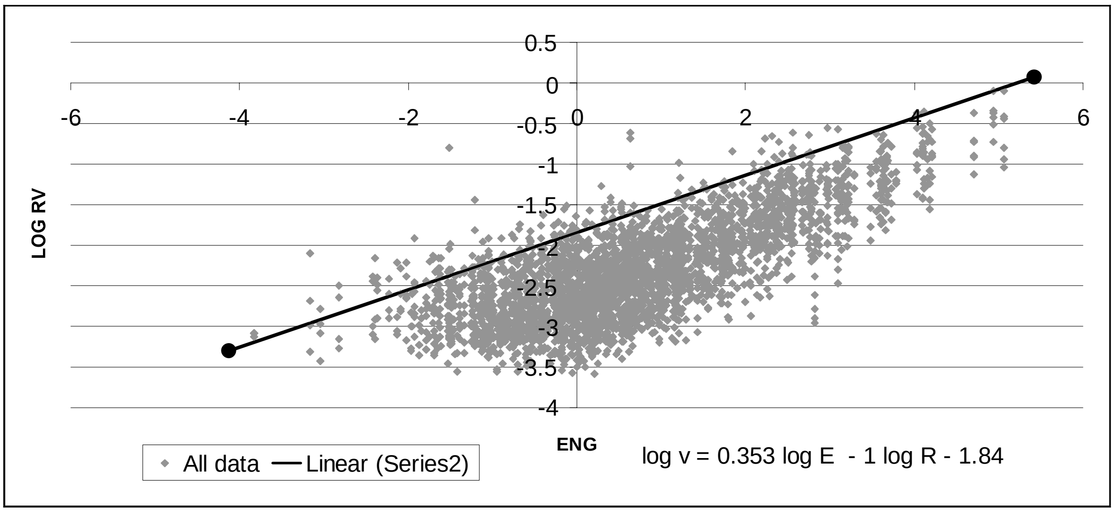

Figure 18 LogRV and Energy

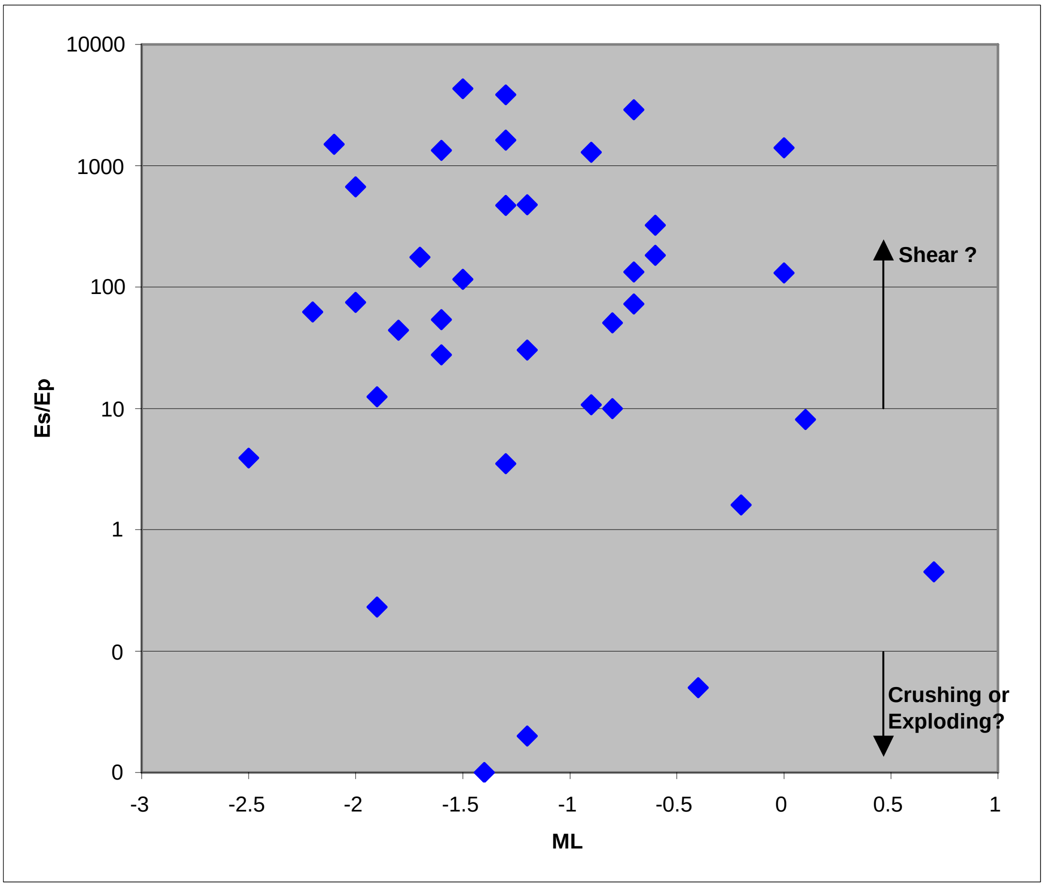

Figure 19 Es/Ep and Magnitude

5.9.1 Relating Seismicity to Modelled Stresses

Numerical modelling, combining extraction with seismicity can be undertaken once a number of 'quality' seismic events have been processed. Quality events are those using a high number of sensors, with low errors (less than 10m), with calculated properties for both P and S sections of the waveform, and located within the array. The number required for modelling should be in the hundreds.

The extraction causing the seismicity is modelled in a series of mining steps, eg the mining in March 2005 is modelled together with the seismic events in March 2005. The objective is to determine failure criteria (eg Mohr-Coulomb) that can be used for modelling alternative mine designs and/or extraction sequences, to minimise seismicity. Such techniques have been discussed in previous papers, eg Turner and Beck, 2002 and mitigating changes to mine designs discussed in Turner, 1999, and Potvin, 2000.

5.10 CONCLUSION

The availability and low cost of small-scale seismic systems mean that monitoring is within the cost range of all mines. The systems can also be installed at short notice, with a total installation time around 1 to 2 days.

Geotechnical Engineers and Mine Management should be made aware of such monitoring systems and of the benefits of early monitoring. 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 a seismic monitoring system 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.

The earlier such monitoring commences the better, especially before the seismicity becomes difficult to manage and in order to provide sufficient time to change designs, support and extraction sequences.

Event processing can be undertaken by engineers on site after only basic training and the initial results in the form of location, time and magnitude are generally sufficient to give a preliminary indication of the cause of the activity. The output from small-scale seismic monitoring systems can be used quickly 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.

Further analysis of the data is also reasonably straightforward, and can be undertaken by third parties, if mine-based personnel are not available or are too busy. Most of the more detailed analysis can be undertaken using Excel.

Seismic monitoring data can also be used for determining re-entry periods and for more detailed analyses to evaluate the relationship between seismicity and stress components (using Map3D for example). The failure criteria indicated for seismic event initiation can then be determined.

Seismic monitoring and data analysis should result in quantification of the activity in terms of the source, frequency, magnitude, spatial and temporal distributions, and the potential impact on production.

The potential beneficial impact of alternative mining methods, mine designs and extraction sequencing on seismicity should be thoroughly examined if seismicity is an issue on the mine. The output from a small-scale seismic system can be used as input to modelling for this purpose.

Changes to support and reinforcement systems could also be required in areas exposed to a high risk of damaging seismic activity. Such areas can be highlighted by using peak-particle-velocity studies and numerical modelling.

One possible outcome of monitoring the onset of seismic activity using a small-scale system is that a larger permanent system is required. These cost upwards of $120,000. The results of the small-scale system monitoring should provide an indication of the area to be covered by a permanent system, the number of sensors required and the number of locatable events.

The results of seismic analyses can and should be used to assist with mine planning, extraction sequencing and support system designs.

The analysis methods described in this Section are also used for permanent minewide seismic systems.

5.11 REFERENCES

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SM-6 Omni-directional Data Sheets:

INPUT/OUTPUT, INC.

SENSOR Nederland b.v.

SM-6 Omni-directional Geophone

- Design adapted from popular omni-directional geophone used extensively in industrial applications
- Coil travel 4mm peak to peak
- High sensitivity version available (80V/m/s)
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The SM-6 Omni-directional geophone has been specially designed for non-gimballed 3C applications, in particular Ocean Bottom and Down-hole 4D/4C applications where high repeatability and reliability are key performance characteristics.

The Sensor Omni-directional geophone has the lowest (14 Hz) natural frequency in the seismic industry.

This geophone will operate in any orientation, maintaining sufficient coil-to-case movement to provide a signal dynamic range comparable with the successful SM-24 geophone.

Small variations of the typical geophone response over the full 360 degrees rotation angle guarantee good vector fidelity.

A variety of I/O Sensor enclosures can accommodate the SM-6 , making the SM-6 Omni-directional geophone suitable for an extensive range of field applications.

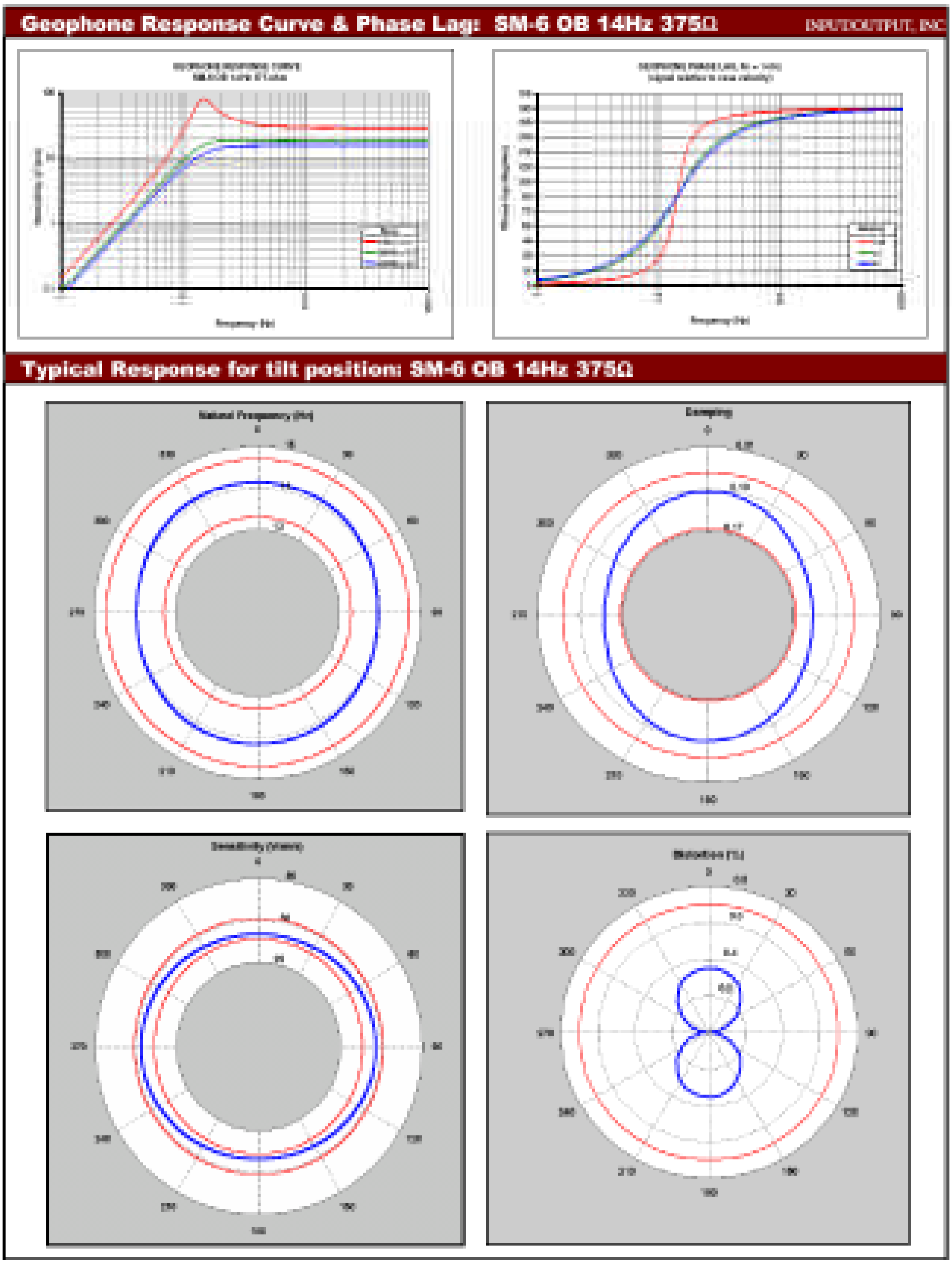
Specifications: SM-6 14Hz Omni-directional Geophone

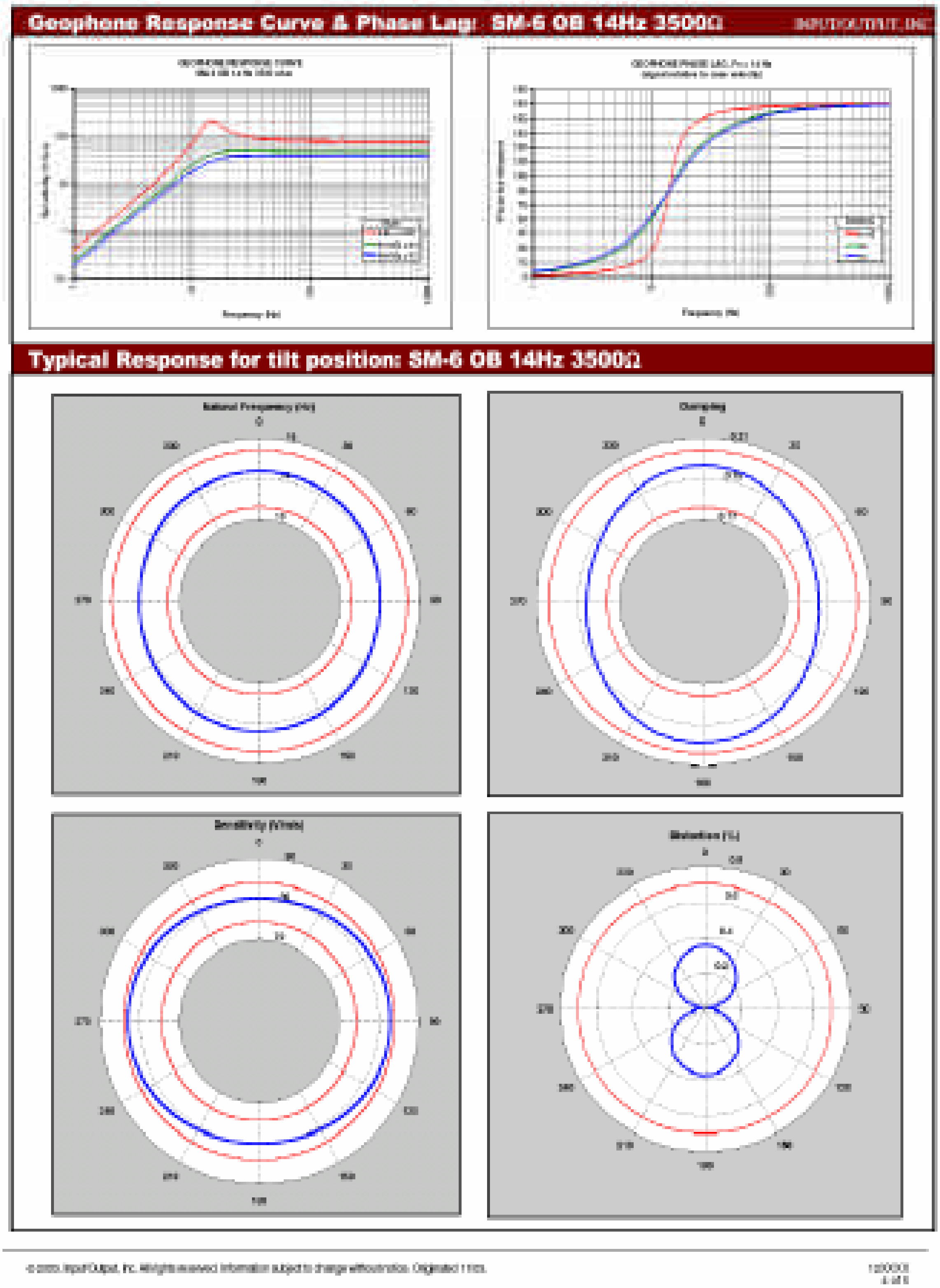
INPUT/OUTPUT, INC.

Working position:	**Omni-directional**	
	375 Ω	**3500Ω**
Frequency		
Natural frequency	14 Hz	14 Hz
Tolerance	± 7%	± 7%
Maximum tilt angle for specified Fn	360°	360°
Distortion		
Distortion with 0.7 in/s p.p. coil to case velocity	<0.70%	<0.70%
Distortion measurement frequency	14 Hz	14 Hz
Damping		
Open circuit	0.180	0.185
Tolerance	+10 / -5%	+10 / -5%
Resistance		
Standard coil	375 Ω	3500 Ω
Tolerance	± 5%	± 5%
Sensitivity		
Open circuit sensitivity	28.8 V/m/s	80.0 V/m/s
Tolerance	+5 / -10%	+5 / -10%
RtBoFn	5950 Ω Hz	49931 Ω Hz
Typical Spurious frequency	190 Hz	190 Hz
Moving mass	11.1 g	10.2 g
Maximum coil excursion p.p.	0.5 mm	0.5 mm
Physical Characteristics		
Diameter	24.1 mm	(0.95 in)
Height (including terminals)	30.0 mm	(1.18 in)
Diagonal	32.0 mm	(1.26 in)
Weight	53.3 g	(1.88 oz)
Operating temperature range	-40°C to 100°C (-40°F to 212°F)	
Working position	Omni-directional	
Polarity	Positive indicated by raised dot adjacent to positive terminal	
Limited warranty period*	2 years	

(*) Warranty excludes damage caused by high voltage and physical damage to the element case

All parameters are specified at 20°C in the working position unless otherwise stated


Geophone Response Curve & Phase Lag: SM-6 OB 14Hz 375Ω
INPUT/OUTPUT, INC
Typical Response for tilt position: SM-6 OB 14Hz 375Ω
Natural Frequency (Hz)
Damping
Sensitivity (V/m/s)
Distortion (%)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