

**PROJECT**      GAP017              Seismology for rockbursts prevention, control and prediction.

**PROJECT LEADER**    Dr Aleksander J Mendecki - ISS International Limited

**PRIMARY OUTPUT**    Strategies, methodologies and technologies for seismic monitoring, analysis and interpretation in rockburst prone mines.

**HOW USED?**    Guides preventative and control measures and predicts rockbursts.

**BY WHOM?**    Mine seismologists and rock mechanics engineers.

**CRITERIA FOR USE**    Quality controlled, on-line quantification of rock mass response to mining.

**POTENTIAL IMPACT**    Should define where and indicate when sudden release of large amount of energy can occur allowing action to avoid minimise losses and save lives.

**OTHER OUTPUTS**    Described under methodology.

#### **ENABLING OUTPUT AND METHODOLOGY (MILESTONE DATES)**

**1. ROCKBURSTS ALERT** - procedures/technologies and guidelines to detect and delineate areas/volumes in the rock mass WHERE a certain increase or pattern in seismic and non-seismic parameters (that relates to stress change and/or stress transfer) take place, so preventative action could be taken (mine layout, sequences/rate of mining, support etc.). **(Dec 93)**

1.1 PROCEDURE for rock mass parameters (velocity, attenuation) determination from waveforms (seismic tomography) for seismic source parameters determination.

1.2 PROCEDURE for quality controlled seismic source parameters determination and the detection of complexities of the sources from the near/intermediate field waveforms.

1.3 CONCEPT/theoretical basis for delineation of sources of potential seismic events (WHERE).

1.4 CASE STUDIES (OFS, KLP, FWR) of monitoring for areas of potential instabilities associated with natural discontinuities (faults, dykes) and induced discontinuities (sources of recent events, abutments). Numerous case studies are required to eliminate site dependant/based results.

1.5 GUIDE to seismic monitoring/analysis/interpretation for rockburst prevention.

**2 ROCKBURST ALARM** - procedures/technologies and guidelines to detect and delineate areas/volumes in the rock mass which could be close to instability, so control measures could be applied; procedures for triggering through blasting; procedures to evaluate efficiency of control measures. **(Dec 93 &94)**

2.1 MODEL based on on-line microseismic data including blasts, for probability of occurrence of seismic event in given volume with ground motion and inelastic co-seismic deformation exceeding a critical level in given time (WHEN).

2.2 PROCEDURE, based on gradient of coseismic deformation and energy, to delineate the most appropriate areas/volumes in the rock mass for triggering/prefracturing.

2.3 PROCEDURE to evaluate the effectiveness of triggering/prefracturing.

2.4 CASE STUDIES: triggering/prefracturing exercises planned at WRR and/or VRR and/or FREEGOLD (provision made for two sites).

2.5 GUIDE to seismic monitoring/interpretation for rockburst control.

**3. ROCKBURST SCRAM** - procedures/technologies to detect the beginning of self nucleation of rockbursts (chaotic behaviour of dynamic system) to evacuate people from specific working places. (Dec 93, 94 and 95).

3.1 PRECURSORS - analysis of the most informative and mutually independent parameters as potential short term pre-cursors to rockburst.

3.2 TECHNIQUES to monitor and PROCEDURES based on dynamic chaos/pattern/cluster analysis, to analyse in real time the behaviour of defects (micro-cracking) in a given volume of rock.

3.3 CASE STUDIES: at least three sites at WRR/VRR/FREEGOLD.

3.4 GUIDE to seismic monitoring/analyses/interpretation for short term rockburst prediction.

### **MOTIVATION AND CURRENT POSITION**

It is suggested that a seismic event be considered described quantitatively when, apart from its timing and location, at least two independent parameters pertaining to the seismic source namely: radiated energy and seismic moment are given. Real time implies, immediate, quality controlled, automatic and quantitative seismological processing with built in functions to respond in case certain pre-set conditions are met.

From 1986, the Integrated Seismic System (the digital intelligent seismic network with on-line seismological processing capabilities) has been developed and implemented in selected mines. Today, almost 150 three component seismic station (450 geophones and accelerometers) are covering all AAC gold mines. Hartebeestfontein and partly Buffelsfontein, providing high quality data for analyses and interpretation. A number of cases are being documented where it has been possible to indicate WHERE a significant seismic event would occur. By the end of March 1993 WDL and selected areas at Vaal Reefs and at Freegold should be equipped with a very dense new generation ISS system to test the ALERT/ALARM/SCRAM strategy. At WDL alone the ISS will consist of 56 three-component processing seismometers and 3 nine-component clusters, pushing the total number of sensors to 195. At the same time different novel methods of seismic data processing/analyses and interpretation are being tested e.g.:

- polarization analyses for the P and S wave onsets and for Q-coda analysis,
- cepstral analysis for echo's filtering,
- multitaper for spectra evaluation,
- non-linear way of moment tensors calculations,
- array processing techniques for imaging source dynamics, Q-coda and noise analysis,
- near source polarization for mechanism,
- finite difference scheme for wave front tracing and LSQR algorithm for inversion in seismic tomography,
- single link cluster analyses, multi-precursors system and chaos detection for prediction.

Most of these methods have been adopted and modified from Theoretical and Computational Seismology and from Systems and Control Theory.

Results to date indicate relation between the inelastic coseismic deformation, radiated seismic energy and the ambient stress - high stress drop events to occur in high ambient stress environment. However, in cases of so-called complex events, a quasi-dynamic build-up of stress during the rupture and deformations process itself, can produce high stress drop sub-event that need not be an indication of high localized stress prior to the event. That is why the complexity of the event should be tested before the meaningful interpretation can be given. Larger seismic events have frequently been located in areas of a high gradient in the apparent stress distribution indicating where control action should be directed.

This project is proposed to complete the development of methodologies and procedures for quantitative, real time seismology in mines and incorporate it in the strategy that will guide preventative and control measures and predict rockbursts. Any future work will then be directed to increase the success rate in the application of the proposed methods.

SAFETY IN MINES RESEARCH AND ADVISORY COMMITTEE

# SIMRAC

## Final Project report

Title : **Audit of SIMRAC project GAP 017**

Author : SM Spottiswoode

Research

Agency: CSIR Mining Technology, Rock Engineering

Project No: GAP 345

Date : June, 1997

## **Review of work done under SIMRAC project GAP017 : Seismology for rockbursts prevention, control and prediction.**

The annual reports of 1993 and 1994 and the final project report, marked DRAFT and dated April 1996, were used as a measure of the work done under GAP017. The reports were assessed on their own merit and according to the GAP017 project proposal dated 95/04/28. This reviews contains suggestions for consideration by SIMRAC or the ISS team.

### **Summary**

The GAP017 project focused directly on predicting the time and place of impending rockbursts, on three time scales that are called *alert*, *alarm* and *scram*. The project aimed at using improved seismic systems, analysis methods and phenomenological models of rockmass behaviour for successful rockburst prediction.

The quantity and quality of seismological work presented in the annual and final reports is indeed impressive and Dr Mendecki and his team at ISS is to be congratulated on the range of work done. His recent book “Seismic Monitoring in Mines” summarises the more important theories and results of the SIMRAC reports, but not in the same level of detail.

The GAP reports document a variety of methods and technologies. In the final analysis, time plots of various parameters, such as energy index, seismic diffusion, Schmidt number and cumulative apparent volume were plotted for selected areas. Other seismic methods, such as seismic tomography and near-source polarisation, were not used for predictions. I feel that they were included in the report to document the mathematics involved and to meet the letter, if not the spirit, of the project proposal. The extensive use of complex mathematical methods partially obscures the use of *incorrect physics* in the application of the JHVD method in chapter 3.

A number of *alert* and *alarm* warnings were issued and were broadly successful in that the incidences of larger events within identified regions were identified in advance. Because the daily blast triggers seismicity, the ideal time window for mining *alarms* is less than 24 hours. This time window was stretched and success rates of 35% to 60% were quoted, but it is not clear how much better this is than predictions simply based on the rate of previous seismicity. The evidence for successful short-term predictions, in the sense of escalating seismicity to a single large event, is limited to perhaps one case, the Trough Fault event.

The concept of softening in the same sense as the post-failure region in a standard stiff-testing laboratory experiment is an important physical concept introduced in the reports. The concept is well documented in the WH6# pillar extraction (pp 21-26).

The work is supported by a wide body of literature, both from classical earthquake seismological sources, as well as from outside this literature.

The concept of seismicity as a the “turbulent part of the flow of rock” was suggested by Kagan in 1992 (no reference quoted; probably Kagan, 1994) and has been strongly espoused in the GAP017 project reports. However, in 1996, Kagan stated that “.. not one precursor has been demonstrated to have statistically significant predictive power”. More thoughts by Kagan follow in the next section.

Reference to a number of previous papers on mine seismology have been omitted. Relevant papers will be mentioned in this review. Also, there are several references in the text that were not included in the reference list, but this is not surprising given the size of the documents and the short time window for preparation.

I have one strong reservation about the claimed prediction successes, namely that the same methodical approach to quantifying seismic parameters has not been extended to measuring the success of the proposed prediction methodology. I suggest that the proposition be tested that the probability of a seismic event of any magnitude, below a maximum magnitude that can be “hosted” within any region, might simply be proportional to the current rate of seismicity, with some adjustment for blasting.

This review is divided into four sections :

1. Comments on each chapter.
2. An evaluation of project objectives and how they were met.
3. Discussions on the feasibility of accurate predictions and on the benefits of risk assessment in preference to predictions.

This section summarises arguments by earthquake seismologists against the central thesis presented in the GAP017 project, namely that seismic events are predictable if previous seismicity is sufficiently closely monitored and analysed.

4. References

I suggest that more SIMRAC research is needed on seismic risk and hazard assessment. Prediction research *per se* should be relegated to a lesser role and should include further thoughts on those mining conditions in which predictions are more likely to occur and on more careful statistical analysis of the accuracy or reliability of any predictions.

The author wishes the comments to be seen as a positive contribution to the very difficult and wide-ranging task that Dr Mendecki and his team tackled during the work undertaken in GAP 017, especially considering that the ISS and some mines with ISS systems are continuing with seismic prediction research.

## **Section 1 : Comments on each chapter.**

Here follows specific comments on the final report, with some reference to the 1993 and 1994 reports.

### **Summary**

The summary is meant to distil the salient details out of the body of the report. This was particularly necessary because each chapter was written by different authors.

The summary starts by attributing previous lack of success with rockburst prediction to two reasons :

1. the focus on Magnitudes and the Gutenberg-Richter frequency-magnitude relationship and
2. the use of analogue seismic systems.

According to the report, the first shortcoming should be overcome by the use of two source parameters, energy and moment, instead of magnitude. Other studies have used cumulative energy or moment, often estimated from magnitude, as indicators of “total seismicity”. A variety of time-series plots are introduced in the GAP017 report, all of which are derived from the basic parameters of location, time, energy and moment.

Other SIMRAC project areas that study seismicity in terms of mine layouts and the characteristics of geological features are dismissed in one paragraph as being not entirely objective or not reproducible.

The summary is not always well supported in the main text. For example, in the summary geophones are considered unsuitable for frequencies above 300 Hz, while accelerometers are given a wide bandwidth of 1 Hz to 10 kHz. The main text, especially in the 1993 report, points out that geophone response is well behaved to 2 kHz, except for spurious resonances at about 170 Hz that occur for badly aligned geophones. On the other hand, accelerometers require an extra stage of integration for determining seismic moments and spurious noise can be seen at frequencies below 50 Hz.

### **Chapter 1 : Characteristics of seismic monitoring systems for mines.**

This chapter is a monument to the wide knowledge of Dr Rod Green, ably supported by ISS staff. Much more detail is available in the 1993 and 1994 reports.

One area of improvement would be consideration of the effect of attenuation ( $Q$  and  $f_{\max}$ ) on the amplitude and useful frequencies of small events at great distance.

Equations such as

$$\text{Log } V = 0.463 \text{ Log } E - 1.402 \text{ Log } R + 0.988 \quad (1.1)$$

cannot be extrapolated to very large distances or small events as attenuation behaves as :

$V \propto \exp(-cR)$  for any particular frequency.

The effect of attenuation on reduction of V and E was addressed in a paper by Spottiswoode (1993) : one of the papers not included in the reference list.

Regarding seismic system and support design for strong ground motion, a recent paper by Maloney and Kaiser (1996) has suggested using the 90 percentile value, rather than a 50 percentile, such as is used in equation 1.1 above.

### **Chapter 2 : Configuration and sensitivity of seismic networks.**

This chapter is a useful text-book approach to formally optimising the potential location accuracy of a given seismic network. The author is Prof. Kijko, an acknowledged expert in this area.

### **Chapter 3 : Location of seismic events and velocity inversion.**

The use of  $L_1$  and  $L_p$  adaptive norms (p4) is suggested on the basis of large time residuals (outliers) that can result from automatic arrival-time picking or hasty manual picks. Straight outlier rejection is not practical for a small number of arrival times. A better way of handling outliers might be, for events with unacceptably large location errors, to find possible arrival times in the vicinity of the theoretical arrival based on the location obtained using the other arrivals. A slightly lower “quality” arrival might be much more compatible with the other arrival times.

This chapter uses a simplified version of the method of Joint Hypocentral and Velocity Determination (JHVD) (pp13-22). This method has been applied successfully using natural earthquakes to obtain velocity structure in a number of cases. In this chapter a simplified application of the JHVD procedure is used, in which constant P- and S-wave velocities between all events in a defined cluster to each individual geophone site is assumed. This simplification has been used previously, by Mendecki (1987) for example, and *the assumption of constant velocity is non-physical*, a fact that is not mentioned in this chapter.

Consider the following simplified geometry (1) in which events **1** and **2** occurred on the straight line between geophones A and B and a slightly different geometry (2) in which **1'** and **2'** are both 600m to the right of **1** and **2** and the wave velocities are slightly different.

|     |          |          |           |         |           |         |          |
|-----|----------|----------|-----------|---------|-----------|---------|----------|
| (1) | A        | ←6.0km→  | <b>1</b>  | ←0.6km→ | <b>2</b>  | ←6.0km→ | <b>B</b> |
|     | Velocity | 6.0 km/s |           | 6.0km/s |           | 6.0km/s |          |
|     | Time     | 1.0 s    |           | 0.1 s   |           | 1.0 s   |          |
|     |          |          |           |         |           |         |          |
| (2) | A        | ←6.6km→  | <b>1'</b> | ←0.6km→ | <b>2'</b> | ←5.4km→ | <b>B</b> |
|     | Velocity | 6.6km/s  |           | 6.0km/s |           | 5.4km/s |          |
|     | Time     | 1.0 s    |           | 0.1 s   |           | 1.0 s   |          |

The travel times are identical in both cases and, without independent information on either velocities or locations, the two physical situations cannot be distinguished from one another on the basis of arrival times. The simplified JHVD would require the physical impossibility that, in case 2, the waves travel from geophone **1'** to geophone

2' travel at 5.4 km/s, while those travelling the same ray path in the opposite direction, 2' to 1', travel at 6.6 km/s.

No geometry would be more favourable for obtaining the real location or the real velocity to either geophone. In the limit of all events at a point, this simplified JHVD reduces to velocities to each geophone that would generate zero RMS location errors, regardless of the true location of the events in the cluster.

It would appear that all the mathematics in the 13 sets of equations from 3.19 to 3.31 hides the incorrect physics of its application in this chapter. This application of JHVD obtains neither more accurate locations nor a better velocity structure, but is simply a complex extension of the standard master event method in which events are relocated relative to a single chosen master event.

#### **Chapter 4 : Seismic Ray tracing**

This work could lead to more accurate locations in the long term. For example, corrections for ray-tracing across known geological boundaries at Vaal Reefs moved the seismic location by some 200m from its previous location based on a constant velocity model.

#### **Chapter 5 Seismic Wave Attenuation and Site Effect**

This chapter is confusing in a number of places, in the maths and physics. In addition, the English was not always clear.

Some examples :

Q and  $Q_0$  are used, but the distinction between them is not clear.

Equation 5.2 has amplitude spectral decay of  $f^{-2}$  at high frequencies. This negative power is then given variable  $\gamma$  (conventional) and then  $\nu$ . Finally, again, a value of 2 is taken. The value of 2 has been the standard value for earthquakes for some years and was one of the conclusions of Spottiswoode (1993) using data from mine events. The use of a single value of Q for all ray-paths for a single event, but allowing each site to have its own corner frequency  $f_0$  (equation 5.7) is not well justified.

No explanation is offered for the increase in Q with distance. The obvious explanation is that both the source and receiver are within or near fractured ground with low Q and long paths are more likely to traverse rock with high values of Q. It might be worth considering a solid-rock Q value of, say, 500 with lower attenuation over a constant distance for each event.

The error bars presented in table 5.2 are obviously very optimistic as variations in  $Q_0$  for adjacent groups of distance or maximum frequency often exceed the error value : a very unlikely situation in practice.

With high-quality underground recordings, surface recordings are best not used for seismic source parameters. Especially for poor outcrops or sites on Karoo deposits.



Site effects on surface were mentioned, but no mention was made of avoiding the use of SV waves at incident angles greater than the critical angle of about  $30^{\circ}$ .

Examples of “site effects” due to the placement of geophones in footwall drives are presented in the recent paper by Handley et al. (1996) in which they showed the strong and complex effect of stopes on seismograms.

## **Chapter 6 : Source Parameters**

This chapter contains considerable overlap of content with the previous chapter, but there is not consistency in the methods used for inversion of  $\Omega(0)$ ,  $f_0$  and  $Q$  or in some of the symbols used, for example  $f^{-\gamma}$  &  $f^{-\omega}$  for spectral fall-off rates.

Polarisation analysis as a method of determining P- and S-wave arrivals was described by Cichowicz (1993). This local reference is omitted in favour of several other references.

The meaning of  $Q$  and  $Q_0$  in equation 6.13 is clear, unlike the use of these values in the previous chapter. In contrast, the minimisation function for spectral inversion, equation 5.5, is a better choice than the unlabeled equation between (6.15) and (6.16).

The equation 6.28 from Brune (1970, 1971) was developed principally for S-wave pulses and has been extended by a number of authors for more consistent use for P waves. In particular, Hanks (1981) argued that the P-wave corner frequency should be higher than the S-wave corner frequency in the ratio of the phase velocities. This then lead to :

$$r_0 = 2.34 * c / (2\pi f_0),$$

where  $c$  = phase velocity.

The observation of higher P-wave corner frequency for mine seismic events was made by Spottiswoode (1984) and is clearly visible on most ISS seismograms.

Use of equation 6.28 by the ISS system will have the effect of underestimating the source radius for P waves. This is not a very serious problem as the physical extent, or “size”, of seismic events is characterised in the GAP017 reports in terms of apparent volume.

Hamming & Hanning windows applicable for power spectra. Cosine tapers are more commonly used for seismograms where the edges of the window represent “noise” in any case. Further work by the ISS and others indicates that multitaper is the most promising approach. Use of a misfit function based directly on the value of the amplitude spectrum is very sensitive to the details of the spectrum at about  $f \approx f_0$  and insensitive for  $f \gg f_0$  and is not recommended.

In section 6.4, mention is made of the amplification effect on the surface of a half-space. The report neglects to mention the effect of Karoo sediments overlying the OFS goldfields. These sediments have considerably lower velocities and are weathered deeply. Special corrections are therefore needed for the effect of the surface. In

addition, if these geophones are placed in boreholes 10's of metres deep, then additional corrections must be applied. In essence, doubling of amplitude occurs only at low frequencies, with wavelengths much larger than the depth of burial, and complex positive and negative interference occur at higher frequencies.

## **Chapter 7 : Statistical Analysis of Seismicity.**

The statistical analysis of seismicity is a subject close to Dr. Kijko's heart and this chapter contains some useful insights into risk analysis using the familiar Gutenberg-Richter relationship  $\log N = a - bM$ .

It is suggested that  $m_{\max}$  can also be estimated simply by considering the largest seismic event that could be hosted within a particular mine geometry. This readily explains the larger events in the Klerksdorp region as well as the decrease in  $m_{\max}$  when Blyvooruitzicht and Western Deep Levels broke their longwalls up into mini-longwalls.

The role of the daily blast was not considered in section 7.3 (**space-time clustering**).

“..  $c$  is the constant of the log of seismic moment versus magnitude relation. According to Kanamori and Anderson (1975),  $c$  is close to 1.5.” Actually, Hanks and Kanamori (1978) went further and suggested that the equation

$$\log M_0 (N-m) = 1.5M + 9.1$$

should be used as a definition of magnitude, a recommendation that is universally adopted for earthquakes. The term moment-magnitude is used by seismologists, and by news media when referring to the “open-ended Richter scale”.

Figure 7.6 is a plot of the probability of a larger event occurring within a time period (of 10 days) based on previous seismicity. By eye one can see a broad positive correlation between higher probability and the incidence of larger events. It is a pity that formalism such as that suggested by Evison and Rhoades (1993) or by Stewart and Spottiswoode (1993) was not used to measure the value of this and other predictors.

## **Chapter 8 : Limits of Predictability.**

This chapter is an essay, with some analysis, on the topics of non-linearity and chaos. The title “limits of predictability” is somewhat of a misnomer as it implies that seismicity should be predictable within certain limits that will be defined at some time.

Looking beyond the mathematics and jargon, the message of this chapter is that a number of seismic parameters behave independently of one another, but show a degree of persistent similarity over some time period. This chapter reports that seismic parameters show similar behaviour over time periods that varied between 3.8 hours and 25.6 days.

The role of the daily blast cycle is not discussed. A blast and the associated face advance will effect the rock mass for some metres around the advancing face.

The report does not discuss what happens after the time of the “limit of predictability” expires, but it would seem that the behaviour then returns to the long-term normal, or unpredictable, behaviour.

## **Chapter 9 : Quantitative Seismology and Rock Mass Stability.**

The “possible physical realisations of CLVD” (p3) exclude the most likely source of CLVD, namely the effect of anisotropy, heterogeneity or non-linearity of the rock mass. Every seismogram is proof of departure from the usual assumptions of idealised rock mass behaviour : they do not only consist of short P- and S-wave pulses. The effect of **open stopes** is not mentioned at all as they pose a major departure from straight rays when, for example, hanging-wall seismicity is recorded at geophone sites at follow-behind footwall drives.

The statement that apparent stress,  $\sigma_A$ , is a more reliable and model-independent parameter than the static stress drop,  $\Delta\sigma$  or  $\Delta\tau$ , is not well proven. In fact, they are proportional to one another within a factor related to the actual shape of the source spectrum (see fig. 9.5) and within the variations created by averaging between sites. As was pointed out by Spottiswoode and McGarr (1975), the spectral shape with  $f^{-2}$  high-frequency fall-off has energy proportional to  $M^2 f_0^3$  and therefore  $\sigma_A = GE/M = \text{const} \times \Delta\sigma$ .

If the corner frequency and spectral plateau are constrained by the radiated energy, then both measures of stress are equally constrained by the choice of either spectral plateau or corner frequency. Estimates of apparent stress are probably more stable in practice as it is calculated from the ratio of average energy to average moment. The stability of averaging source radius for static stress drop is more critical as this radius must be cubed in the final calculation.

The relationship between seismic moment and the volume of stope closure has been addressed by McGarr (1993). Figure 9.10 d, e and f show some situations in which stope closure results from shear slip. The report then defines apparent volume,  $V_A$ , as a measure of the source volume, or that volume involved in the stress change associated with the apparent stress. No causal connection is suggested between volume of stope closure and apparent volume.

Figure 9.11 shows a remarkable degree of similarity in the shape of the rate of fault creep and cumulative apparent volume along and around a fault in Free State mine. This graph is presented to support the use of plots of cumulative apparent volume.

Further support for the use of cumulative apparent volume is presented in Figure 9.12 (after Mendecki, 1993), namely the change in slope for three months prior to a large seismic event. In contrast, the more classical cumulative energy and moment plots did not show clear precursory behaviour. However, the statement “There is no precursory behaviour on cumulative energy or cumulative moment plots both being one-dimensional descriptions of the source” is strange as energy and moment are no more fundamental, or “one-dimensional” parameters than is apparent volume.

I suggest that the basic reason for using cumulative apparent volume is that it provides a measure of the seismicity rate that gives greater weight to the larger events, but to a lesser extent than for cumulative moment or energy. Cumulative apparent volume plots are therefore smoother and easier to read.

The concept of **seismic softening** is introduced in this chapter in section 9.6 and is illustrated using the familiar stress-strain curve in Figure 9.14. This figure raises the possibility that a steeper load line results in lower stress drop, and potentially less damaging, events. As the load line is proportional to ERR, we have a paradox that the same magnitude event associated with lower ERR faces could be more damaging.

The discussion on **seismic diffusion** (section 9.8), overlooks the paradox, as did McGarr (1976), that the additional slope convergence associated with seismicity generally **increases** the overall strain energy in the same fashion as elastic convergence until complete slope convergence takes place. By expanding the region of reduced vertical stresses, a more extensive region of increased stresses is created. Seismicity reduces the short wavelength strain energy, but increases the long-wavelength energy. This paradox is widely overlooked by Rock Engineers in South Africa.

The section on **nucleation of instability** provides the principal theory behind earthquake prediction. In section 3 of this review, it is pointed out that many seismologists are pessimistic about the possibility of prediction. I suggest that the success of ISS ALARMS was made possible by identifying times of increased risk and not through accelerated deformation such as is suggested in the concept of accelerated deformation up to the “time to failure”.

The whole concept of **seismic softening** is a **significant contribution by the ISS** and I suggest that rock-mass modelling studies be performed to test this concept further. System softness at the face is equivalent to ERR for elastic rockmass, but is more complex when plastic or other inelastic rockmass behaviour is occurs.

## **Chapter 10 : Application of Quantitative Seismology in Mines.**

In section 10.4.5, it is pointed out that seismicity provides a more detailed and accurate picture of rock deformation at any moment than does numerical modelling as currently practised. This is in agreement with Spottiswoode (1988) who showed that the incidence of large seismic events was more closely predicted by the rate of seismicity than by either the volume of convergence (ERR) or changes in ESS.

The work done under section 10.5, **velocity of ground motion estimates**, discusses the problems of using ground velocity measurements in the far field to predict damage in the source region. The most extreme rockburst damage occurs in the near field where ground velocity is variable and controlled by unknown source complexities. The argument for using cumulative displacements, that it captures “both the effect of repeated vibrations and specific incidences of very strong vibrations” is not clear. The argument that the analysis is “of course” enriched by including corner frequency in addition to peak velocity is wishful thinking. A combination of two parameters is not *a priori* more useful than one parameter on its own.

## Section 2

### Evaluation of project objectives and how they were met.

The enabling outputs and methodologies of the original project proposal are repeated here and *comments are added in italics*.

1. ROCKBURSTS ALERT - procedures/technologies and guidelines to detect and delineate areas/volumes in the rock mass WHERE a certain increase or pattern in seismic and non-seismic parameters (that relates to stress change and/or stress transfer) take place, so preventative action could be taken (mine layout, sequences/rate of mining, support etc.). **(Dec 93)**

1.1 PROCEDURE for rock mass parameters (velocity, attenuation) determination from waveforms (seismic tomography) for seismic source parameters determination.

*The reports do not show examples of 2-D or 3-D tomography.*

1.2 PROCEDURE for quality controlled seismic source parameters determination (1) and the detection of complexities of the sources from the near/intermediate field waveforms (2).

*The Seismic source parameters appear to be well determined using far-field seismograms, with the unimportant exception of source radius determined from P-wave corner frequency.*

*No study of complexities of the sources from the near/intermediate field waveforms was presented. Such a study would probably not have added value to the work on prediction.*

1.3 CONCEPT/theoretical basis for delineation of sources of potential seismic events (WHERE).

*The concept of softening through accelerated deformation and reduced stress drops was well presented.*

1.4 CASE STUDIES (OFS, KLP, FWR) of monitoring for areas of potential instabilities associated with natural discontinuities (faults, dykes) and induced discontinuities (sources of recent events, abutments). Numerous case studies are required to eliminate site dependant/based results.

*Many case studies were presented.*

1.5 GUIDE to seismic monitoring/analysis/interpretation for rockburst prevention.

*This objective was well met by stopping mining through proactive ALERTS and ALARMS when the situation looked as if it was becoming more hazardous.*

2 **ROCKBURST ALARM** - procedures/technologies and guidelines to detect and delineate areas/volumes in the rock mass which could be close to instability, so control measures could be applied; procedures for triggering through blasting; procedures to evaluate efficiency of control measures. **(Dec 93 &94)**

2.1 **MODEL** based on on-line microseismic data including blasts, for probability of occurrence of seismic event in given volume with ground motion and inelastic coseismic deformation exceeding a critical level in given time (**WHEN**).

*Detailed work was done to address this issue based on classical statistics, but was given little attention in the final analysis.*

2.2 **PROCEDURE**, based on gradient of coseismic deformation and energy, to delineate the most appropriate areas/volumes in the rock mass for triggering/pre-fracturing.

*Work on gradients was mentioned but not presented in the reports.*

2.3 **PROCEDURE** to evaluate the effectiveness of triggering/pre-fracturing.

*See 2.4 below.*

2.4 **CASE STUDIES**: triggering/pre-fracturing exercises planned at WRR and/or VRR and/or FREEGOLD (provision made for two sites).

*No triggering or pre-fracturing exercises were presented.*

2.5 **GUIDE** to seismic monitoring/interpretation for rockburst control.

*The chapters on seismic monitoring make up an excellent text-book on the topic.*

3. **ROCKBURST SCRAM** - procedures/technologies to detect the beginning of self nucleation of rockbursts (chaotic behaviour of dynamic system) to evacuate people from specific working places. **(Dec 93, 94 and 95).**

*The theory of self-nucleation was presented, but not well supported by data. In particular, accelerating deformation prior to failure has only been observed in a few cases.*

3.1 **PRECURSORS** - analysis of the most informative and mutually independent parameters as potential short term precursors to rockburst.

*Cumulative apparent volume is the most favoured parameter.*

3.2 **TECHNIQUES** to monitor and **PROCEDURES** based on dynamic chaos/pattern/cluster analysis, to analyse in real time the behaviour of defects (micro-cracking) in a given volume of rock.

*An interesting chapter on chaos theory was presented as part of the prediction methodology and should give useful insights into any further work on seismic risk assessment.*

*Cluster identification was well described.*

3.3 CASE STUDIES: at least three sites at WRR/VRR/FREEGOLD.

*The Trough event was an example of rockburst scam, but was an isolated case.*

3.4 GUIDE to seismic monitoring/analyses/interpretation for short term rockburst prediction.

*As the results do not clearly support this concept, the guidelines consist of the model of self-nucleation and exhortations for more dense monitoring. The section on “limits of predictability” presents a good argument for good network sensitivity when re-interpreted in terms of the risk of a seismic event occurring at any time or place.*

## Section 3

### **Discussions on the feasibility of accurate predictions and on the benefits of risk assessment in preference to predictions.**

#### **Earthquakes : Thinking About the Unpredictable**

This was the title of a discussion meeting held in London in November, 1996. There are some very salient points that were made that are equally relevant to prediction of rockbursts. The following discussion is based on a report on this meeting by Robert J Geller and published in EOS, February 11, 1997. It is important that SIMRAC be aware that all techniques and procedures for earthquake prediction, including those used by ISS, are intrinsically uncertain. Prediction research should include a more thorough assessment of the statistical accuracy of predictions and in managing uncertainties. I have often heard mine managers say that uncertain predictions are more difficult to manage than no prediction at all. They require 100% accuracy.

“The overwhelming consensus of the meeting was that earthquake prediction, in the popular sense of deterministic short-term prediction, is not possible at present. Most of the participants also agreed that the chaotic, highly non-linear, nature of the earthquake source process makes prediction an inherently unrealisable goal.”

and in summary

“This meeting suggests that we’re overdue for a paradigm shift: it appears likely that the occurrence of individual earthquakes is inherently unpredictable.”

The meeting was divided into 5 topics :

1. Case studies
2. Methodologies for earthquake prediction
3. Methodologies for assessment of earthquake prediction schemes.
4. Communication and conflict 1 : Greek earthquakes.
5. Communication and conflict 2 : Differences in perception between scientists and the public.

Y.Y. Kagan was a keynote speaker on topic 3. Geller’s summary :

“In Kagan’s opinion the case study approach has now reached the point of diminishing returns.”

and

“He argued that the rupture process is inherently unstable, and that the size of each earthquake appears to be determined only while it is taking place”



This is the same Kagan who introduced the concept of turbulent flow of rock that has been a corner-stone of the ISS approach (summary, p16).

At the ISS seminar on 3<sup>rd</sup> and 4<sup>th</sup> March, 1997, Dr Mendecki and the keynote speaker, Prof. Didier Sornette, said that they had been at the discussion meeting. They suggested that the reason seismologists have been moving away from event prediction towards hazard assessment was caused by previous failures to predict. There were also more statisticians than physicists at the meeting. When I suggested to both that there was little evidence of successful predictions presented at the ISS seminar and asked them to suggest the type of earthquake or mine seismic event that stood the best chance of success, Prof. Sornette answered that the largest events would be the most predictable.

### **Mine seismicity, predictions, risk and hazard.**

The main thesis underlying the concepts of alert, alarm and scam were presented in on pages 17 and 18 of the final report. Under the heading, “PHENOMENOLOGICAL MODEL AND TIME TO FAILURE” it is argued that

“there must be a degree of softening in the system before instability ..  
within the critical volume of rock”.

The report continues with :

“Additionally, it is the nature of rock fracture and friction that the  
breakdown instability does not occur without some preceding phase of  
accelerating deformation”.

This is certainly true during the rupture process itself as initial rupture builds up within less than a second for the case of earthquakes with  $M < 5$ . However, this statement is only supported by the seismologists who feel that predictions **must** be possible. However, it is accepted as an article of faith by the ISS.

It is suggested in the report that accelerating deformation follows a relationship similar to:

$$\theta = \frac{k}{(t_f - t)^\alpha} \quad (0.1)$$

where

$\theta$  = probability or activity rate,

$t_f$  = time of failure

$t$  = current time and

$\alpha \gg 1$ .

Ian Main, in his abstract submitted to the discussion meeting “Earthquakes : Thinking About the Unpredictable” mentioned above, shows the same level of appreciation of

chaos and non-linear dynamics as shown in the GAP017 report (summary, p14). In common with many (or most?) seismologists, he considers

“ .. the non-linearity of the physics of fracture and friction, combined with the inherent heterogeneity of the Earth.”

and that

“ .. we may be forced to conclude that the reliable prediction of individual earthquakes may be inherently unattainable.”

Main then goes on to echo the feelings of most earthquake seismologists by advocating the use of probabilistic seismic hazard, which

“.. involves determining the distribution of probabilities of a population of earthquakes of different magnitudes.”

This boils down to a simple statement that the probability of an event occurring is, in general, proportional to the rate of recent seismicity.

Not all is gloom for prediction under certain ideal conditions. Main himself, as well as other workers, has been able to predict final failure of samples under controlled laboratory conditions. If I understand these conditions correctly, then failure of a fault previously clamped by a remnant being mined might be a close analogy.

A positive aspect of the work done under GAP017 and the work done for SIMRAC by Dr. Artur Cichowicz (GAP 112) is that we can extend this probabilistic approach further for mine seismicity. Cichowicz found that events of any particular magnitude were more damaging if they had higher stress drops. Conversely, lower stress drop events (softer system) would be less damaging.

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