Mine seismicity: prediction or forecasting?

by S.M. Spottiswoode*

Synopsis

Much as one hopes to predict whether damaging seismicity might occur somewhere in the next shift, this is not possible at present. Recently, an analysis of seismicity at two mines has shown that a small increase in seismicity occasionally occurs before both large and small events. This analysis is extended here to five mines, with the same results.

Earthquake seismologists forecast hazard in terms of the average incidence of earthquakes over the last 50 years, adjusted on an hourly basis according to the possibility of aftershocks of events that have happened.

The rate of seismicity in any area remains approximately constant when expressed as seismicity per area mined, or better still, per unit of elastic strain energy released. It is suggested that seismic hazard in mines be estimated using historical seismicity and forward modelling, adjusted according to the possibility of aftershocks.

In summary, medium-term forecasting of seismicity is viable; short-term prediction of large events is not.

Introduction

Accurate short-term prediction of potentially damaging earthquakes is not possible. A recent paper (Spottiswoode, 2009) suggests that, unfortunately, the same appears to be the case for deep mine seismic events, based on analysis of data from two mines. This paper summarizes the analysis performed by Spottiswoode (2009), extends the analysis, analyses data from five mines and discusses the implication for managing the seismic hazard.

The title of this paper (Mine seismicity: prediction or forecasting?) was chosen because earthquake seismologists make a clear distinction between 'prediction' and 'forecasting' (Jordan, 2009). Forecasting is currently applied in various levels of detail over the entire earth. Detailed forecasts are routinely provided for California (USGS, 2009). The method is neatly summarized on the website as:

➤ The 24 hour probability of strong earthquake shaking is updated every hour. It starts with a background probability based on geological and earthquake information. (See the USGS National Seismic Hazard Maps website.)

➤ Usually this information is shown for 50 years; we convert it to show 24 hours. The system then considers all the earthquakes, large and small, that are recorded by the California Integrated Seismic Network (CISN). For each event, the probability that it will be followed by an earthquake large enough to cause strong shaking is calculated from the known behaviour of aftershocks. The shaking that would be produced by such an earthquake is then predicted from the known relations between earthquake size and shaking patterns. The likelihood of that shaking is then added to the background probability on the map.

The probability of the defined 'strong shaking' in any day can vary from less than 1/1 000 000 to more than 1/10, with the higher probabilities being associated with aftershocks.

The only seismic parameter that is used by the USGS earthquake forecasting system is Richter Magnitude (Gerstenberger *et al.*, 2004). Their forecasting system is also being used as a null hypothesis against which other forecasting ideas are being developed or tested. (See http://relm.cseptesting.org/)

In contrast, short-term prediction is viewed with great suspicion by earthquake seismologists as numerous attempts at prediction have failed.

* *Florida Park, Johannesburg, South Africa.*

Mine seismicity: prediction or forecasting?

Short-term hazard assessment in South African mines is frequently performed by studying time variations of a variety of seismic parameters (Van Aswegen, 2005 and 2007). Van Aswegen's methods were motivated by Mendecki *et al.* (1997) and based on a theory of 'seismic flow of rock' that has since been largely abandoned by, amongst others, one of its main authors, Kagan, in Geller *et al.* (1997). The purpose of the paper by Spottiswoode (2009) was to assess whether there are any indications that large events were preceded by characteristic seismicity that does not precede small events.

The standard reference for South African hard rock mining is Jager and Ryder (1999). In Chapter 9 of this handbook, Mendecki, Van Aswegen and Mountfort expounded further on the work of Mendecki (1997) and advocate studying changes in seismicity to 'warn' of potential rockbursts on the basis of 'unexpected strong changes' in seismic parameters or patterns. 23 seismicity parameters are listed in Mendecki and Van Aswegen (2001). Application of some of these parameters is common practice on many mines, as described by Van Aswegen (2005, 2007). Van Aswegen (2003 and 2005) claimed some success with hazard assessments.

More recently, Durrheim *et al.* (2007) reported on work towards 'best practice' on mines. Two quotes are relevant to the work presented here:

'Dr G. Van Aswegen (ISSI, pers. comm., 2007) comments that the short-term seismic hazard assessment procedures have not changed significantly since 1995, the success rates are variable, and in some cases the seismic rockmass response to mining is too fast or too slow for the methods to be useful on a daily basis.' (p. 55) and.

'Mines should continue with their current practice, evaluating retrospectively whether working places receiving high hazard ratings was actually exposed to greater event frequency and/or severity. Concurrently, seismic analysts should seek to supplement the existing parameters with any found useful by other mines. If, after two years, a parameter and/or method cannot be demonstrated to provide useful results, it use should be discontinued. *(sic)* (p. 56)

In this paper, I extend the work of Spottiswoode (2009) to provide further evidence that there is no significant change in seismicity shortly before large events that does not also occur before the more numerous small events. The previous analysis was based on two data-sets; here data from five mines are analysed, yielding similar results.

The previous analysis could not be applied directly to data from one of the mines and some additional analysis was needed. Firstly the Type 'A' events (Richardson and Jordan, 2002) posed a particular problem. Secondly the data from the same mine appeared to disagree with the hypothesis described here and some additional analysis was developed to clear up the discrepancy. This additional work is described below in Appendix I ('Removing Type 'A' events') and Appendix II ('Foreshocks and prediction').

Hypothesis

The analysis presented here is aimed at further testing the truth of two statements made by Spottiswoode (2009):

➤ The event rate or event character changes before large events and

➤ The event rate or event character does not change in a similar manner before the more numerous small events.

If the answer to both of these questions is 'yes', then useful prediction or short-term hazard estimation is possible. If the answer to either question is 'no', then useful prediction is not possible, due to either or both of two situations:

➤ If the event rate or event character does not change before large events, then prediction is not possible at all and

➤ If the event rate or event character changes in the same way before numerous small events, then too many false alarms (false positives) would be issued to be useful.

I will test the seismicity prior to large and small events over time scales of minutes to two weeks.

'Large' events are taken as the largest 100 events, while 'small' events were defined as the largest 100 events with magnitude below M=0.0. In all cases, there were many events smaller than the lower threshold.

Although this paper does not go into any detail, it is suggested that the probability of seismicity at any time is controlled by a combination of two factors:

➤ A background rate controlled by mining and geological factors (e.g. Spottiswoode *et al.*, 2008) and

➤ Aftershocks of large events and of blasting (e.g. Kgarume *et al.*, 2009, Spottiswoode, 2000 and Appendix I and Appendix II in this paper).

Case studies

Seismic data was obtained from five mines representing a range of deep mining methods from gold and platinum mines. Two case studies came from gold mined from the Carbon Leader Reef (CLR1 and CLR2) and one each from the Ventersdorp Contact Reef (VCR) and the Vaal Reef (VR). Platinum mining took place on the Merensky and UG2 reefs (Plat). The abbreviations in brackets will be used for the rest of this paper.

Mining took place using dip, strike and in-stope pillars or fault loss areas for regional or local support.

Mining and seismic parameters for the five mines are listed in Table I. Types 'A' events are not used in this study as they appear to be development blasts, as shown in Appendix I.

The average rate of seismicity prior to large events to the seismicity before small events. This is done by 'stacking' all events is compared within the magnitude ranges listed in Table I relative to their time and location in X and Y (Figure 1).

Analysis and results

Daily hazard assessments should be at their most successful if large seismic events are preceded by significant changes in seismicity that do not also precede small events. To test whether this is the case, the main shocks at time zero and distance zero are 'stacked' to see whether large events are, on average, preceded by changes in seismicity that do not precede small events. (Main shocks are normally large events, but small events are also considered separately as main shocks in this study.) Events before and after main
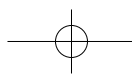
Mine seismicity: prediction or forecasting?

Table I

Seismic data selection for comparing seismicity before and after large events with seismicity before and after small events

	Label	CLR1	CLR2	VCR	VR	Plat
Mining	Reef mined	Carbon Leader	Carbon Leader	Ventersdorp Contact	Vaal	Merensky and UG2
	Regional support	Dip pillars	Strike pillars	Dip pillars	Faults, Dykes, scattered	Potholes, scattered
Seismic events	Type 'A'	49 367	13 234	30 338	85 206	104
	Type 'B' used	79 669	96 327	109 630	14 908	1 7642
	Type 'B' not used	0	0	0	37 383	0
	M_{PEAK}	-0.80	-2.0	-1.4	-0.2 and -1.7	-0.6
	M_{MIN}	-2.2	-3.0	-3.0	-0.8	-2.4
	M_{LARGE}	2.8 to 3.5	2.2 to 3.6	2.2 to 4.7	3.6 to 4.7	1.3 to 3.0
	Days recorded	3098	3588s	1487	2058	1594
Distance: main to after	200 m	200 m	200 m	300 m	200 m	
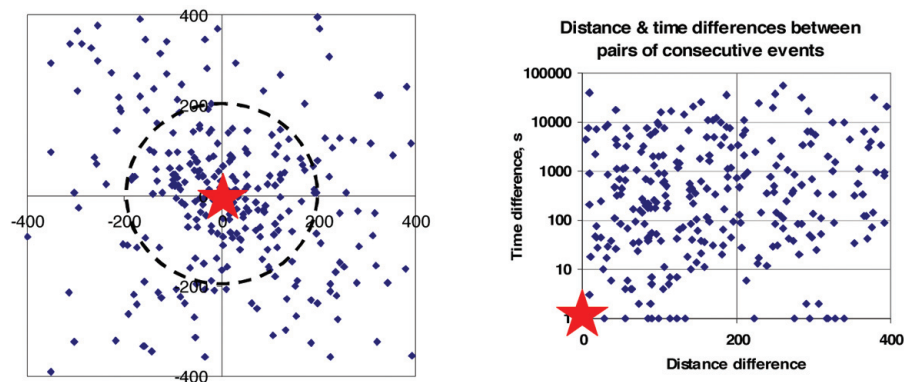
Figure 1—Illustration of stacking main shocks at time and distance zero, using consecutive pairs of events. Left: X-Y distances showing pairs within 200 m of one another. Right: distance-time plot

shocks within a radius of 200 m in plan were chosen after discussions with Mendecki *et al.* (2009). A radius of 300 m was used for the VR data as there were fewer events and the large events were larger than in the other data-sets. Earlier work using data within a radius of 100 m gave similar results.

The stacking method applied here is aimed at giving the best possible chance of finding consistent precursory behaviour, if such behaviour exists. To avoid missing useful predictors for individual events, large events that are preceded by a higher event rate than usual are analysed individually.

Seismicity rate

The average time sequence of seismicity is calculated over two weeks before and one week after main shocks. The cumulated rate of seismicity over the days before and after the stacked main shocks is constant to the first order (Figure 3). Detailed graphs also show the cumulated seismicity two days before and one day after main shocks. As found previously by Spottiswoode (2009), there are several deviations from a constant rate of seismicity:

➤ The increased rate of seismicity immediately following the main shocks can be attributed to aftershocks (Kgarume *et al.*, 2009 and Figure 9)

➤ A ripple with peaks at multiples of 24 hours occurs because events, both large and small, take place preferentially soon after the daily face blasts
➤ An increased rate of seismicity over a few hours prior to large and small events and
➤ More events followed large events than small events. (Figure 2.)

At the suggestions of G. van Aswegen (Mendecki *et al.*, 2009), Apparent Volume was also plotted against time in the same way as is shown in Figure 3. The graphs are not shown here, as they are highly similar to the graphs of Figure 3 except for 'noise' when large events caused 'jumps' in the values. These jumps did not preferentially occur soon before main shocks.

In summary, the rate of seismicity before large main shocks is highly similar to the rate before small events. VR is a possible exception, but the difference is an artefact of the recording system, partly associated with the high rate of aftershocks (Appendix II).

High event rates in previous 24 hours

Individual main shocks with the highest number of fore-shocks were identified and the sequence of fore-shocks studied. One of the difficulties in interpreting the graphs in Figure 3 is the high event rate at blasting time. Anticipating
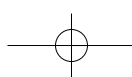
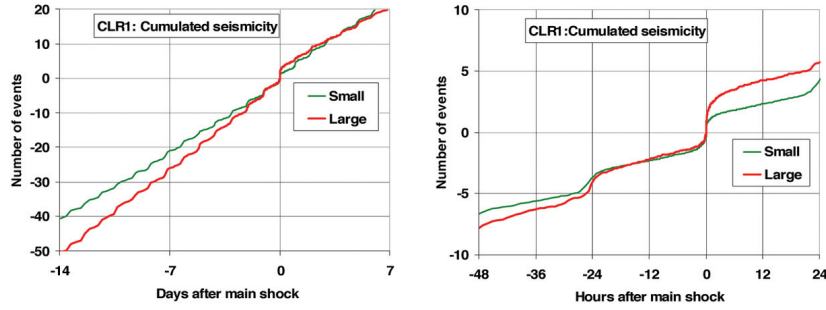# Mine seismicity: prediction or forecasting?

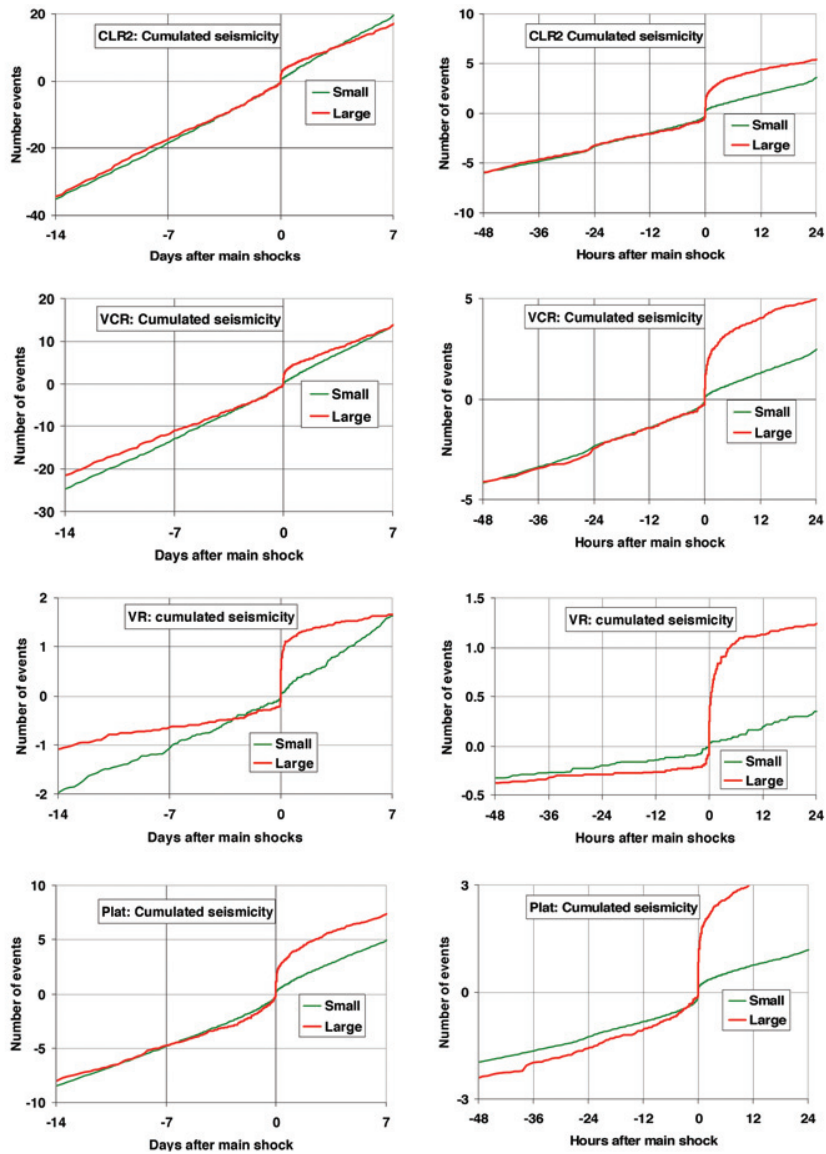Figure 2—More aftershocks occur after large events than after small events

Figure 3—Cumulated number of seismic events within 200 m or 300 m before and after 100 small and 100 large main shocks, normalized by the number of main shocks

individual seismic events at the blasting time is also of limited value as nobody is in the stopes at these times. It was decided to concentrate on main shocks that took place outside of blasting time. As the blasting time across the mines varied from early to late afternoon, only main shocks during the morning (0:00 to 12:00) were chosen.

Figure 4 shows seismicity before four large events outside of blasting time that were preceded by more than 10 events in the previous 24 hours, and equivalent data for foreshocks of small events. Two other events on other mines were preceded by 10 events or more within 200 m and in the previous 24 hours and show similar behaviour.

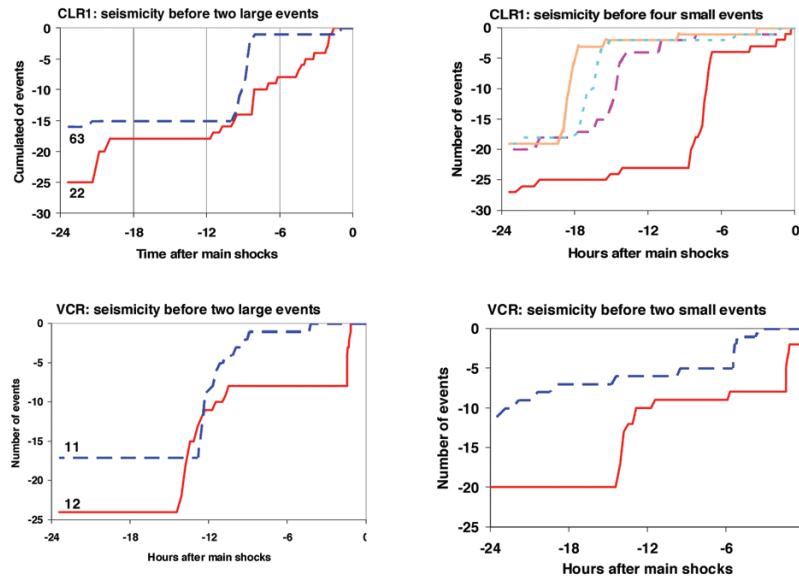# Mine seismicity: prediction or forecasting?

Figure 4—Cumulated number of events prior to large events (left) and small events (right). Only data for events with the largest number of precursors is shown
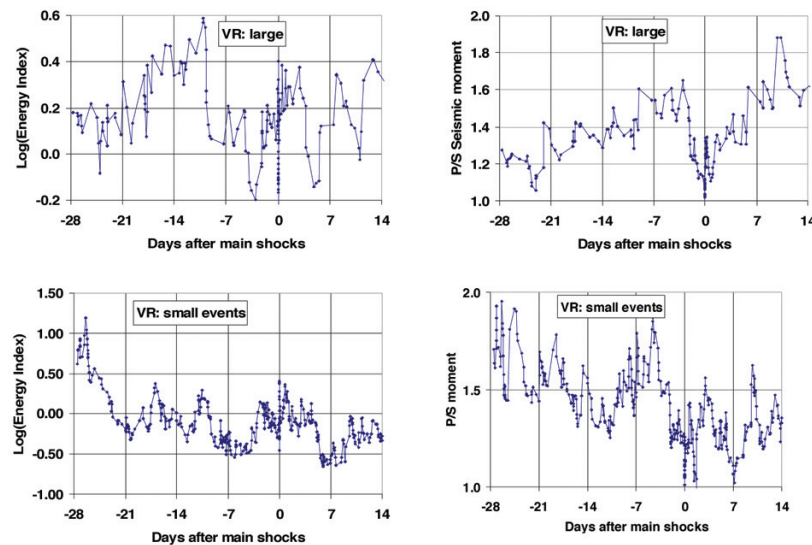

Figure 5—Variations in event characteristics before and after main shocks. Each event is marked with a small diamond for the VR data

Most of the foreshocks sequences in Figure 4 were dominated by seismicity that followed the characteristic logarithmic curve for aftershocks of large events (e.g. Appendix I). The seismicity prior to CLR1 event number 22 included 18 events at an approximately constant rate of seismicity.

Character of seismicity

Earthquakes are most commonly described in terms of the magnitude. Earthquake magnitudes are defined in terms of the seismic moment, a measure of the amount of deformation that occurs around the earthquake source. In mines, it is common practice to describe seismic sources in terms of two independent parameters such as seismic moment and radiated energy. When combined with distances and times

between events, seismicity can be characterized in many different ways (e.g. Mendecki and van Aswegen (2001). Spottiswoode (2009) showed that data from the mines CLR1 and VCR did not show any consistent changes in four different parameters prior to large events. CLR2 and Plat data did not show any consistent trends prior to large events.

The time variation of the characteristics of seismic data are shown in (Figure 5) for VR. A 10-point causal smoothing function was applied to reduce the noise in the data. There is a decrease in the value of Energy Index at about nine and four days prior to large and small events and a decrease in the P/S moment ratios about three days before large and small events (Figure 5). Unfortunately, as there are very few events involved (less than one per main shock, Figure 3), the data is very noisy and the time period of apparent anomalous

Mine seismicity: prediction or forecasting?

behaviour differs between the parameters shown in Figure 5, the data is not very convincing as a precursory signal. It is perhaps ironical that the P/S moment ratio (Figure 5 right) shows the most consistent signal when it is not used for routine hazard assessment (Van Aswegen, 2005).

Conclusions and discussion

Are large events predictable in the short term? It is clear from the analysis in the previous section that any short-term precursors to large events in the two data-sets are also precursors to small events. This appears to be in direct contradiction to the work of Van Aswegen (2003, p. 130) who reported results that were considerably better than random. Van Aswegen's positive results could possibly be explained by the use of factors other than day-to-day variations in seismicity, such as hazard magnitude or the mine's panel-rating system, as well as by combining results from area of high and low rate of seismicity.

As short-term prediction does not seem to be feasible, are there indicators on a day-to-day basis that indicate significantly increased hazard? The data presented here do not show any clear change in the seismicity rate in the days before large events that do not also precede the more numerous small events.

Issuing of routine daily hazard assessments for South African gold mines based on daily changes in seismicity does not provide a clear indication of the potential of large events in particular. It is suggest that they be scrapped and that hazard assessments be presented in three forms, namely:

➤ An immediate response to large events on account of possible damage and aftershocks
➤ A monthly assessment based on overall seismicity rate, wih due account of expected changes in mining rate
➤ Long-term planning.

Acknowledgments

This work follows on from an earlier paper that was partially supported by the CSIR and by Harmony Gold Mining Company Limited. Thanks to Shaun Murphy, Kevin Riemer and Shana Ebrahim-Trollope for discussions and Gerhard Morkel and Johann Scheepers for supplying data and management of the mines concerned for use of their data.

References

DURRHEIM, R.J., CICHOWICZ, A., EBRAHIM-TROLLOPE, R., ESSRICH, F., GOLDBACH, O., LINZER, L., SPOTTISWOODE, S.M., STANKIEWICZ, T., and VAN ASWEGEN, G. Guidelines, Standards and Best Practice for Seismic Hazard Assessment and Rockburst Risk Management, Final Project number: SIM 05 03 02 Output 3 (6 March 2007), Safety in Mines Research Advisory Committee. 2007.

GELLER, R.J., JACKSON D.D., KAGAN, Y.Y., and MULARGIA, F. Earthquakes cannot be predicted, *Science 14,* March 1997, vol. 275. no. 5306, pp. 1616–0, DOI: 10.1126/science.275.5306.1616 (Enhanced version at: http://www.sciencemag.org/cgi/content/full/275/5306/1616). 1997.

GERSTENBERGER, M., WIEMER, S., and JONES, L. Real-time Forecasts of Tomorrow's Earthquakes in California: a New Mapping Tool, USGS Open-File Report 2004-1390. 2004.

JAGER, A.J. and RYDER, J.A. *A handbook on rock engineering practice for tabular hard rock mines*, SIMRAC, Johannesburg. 1999.

JORDAN, T.H. Earthquake prediction: The unsolved problem, Keynote Lecture at the *General Assembly of the International Association of Seismology and Physics of the Earth's Interior* (IASPEI), 10–16 January 2009, Cape Town, South Africa. 2009.

KGARUME, T.E., SPOTTISWOODE, S.M., and DURRHEIM, R.J. Statistical properties of mine tremor aftershocks, submitted to Pageoph special issue: Induced seismicity. 2009.

MENDECKI, A.J. (ed.) *Seismic monitoring in mines*. Chapman & Hall, London. 1997.

MENDECKI, A.J. and VAN ASWEGEN, G.A. Seismic monitoring in mines: selected terms and definitions. *Proc. In the 5th Int. Symp. on Rockbursts and seismicity in Mines* (RaiSim 5), G. van Aswegen, R.J. Durrheim and W.D. Ortlepp (eds.) South Afric. Inst. Min. Metall., 2001. pp. 563–570.

Mendecki, et al. Discussions at ISSI seminar, Stellenbosch, South Africa, 4 May 2009.

RICHARDSON, E. and JORDAN, T.J. Seismicity in deep gold mines of South Africa: Implications for tectonic earthquakes, *Bull. Seism. Soc. Amer.*, 92, 2002. pp. 1766–1782.

SPOTTISWOODE, S.M. Aftershocks and foreshocks of mine seismic events. 3rd international workshop on the application of geophysics to rock and soil engineering, *GeoEng2000*, Melbourne Australia. 2000.

SPOTTISWOODE, S.M., LINZER, L.M., and MAJIET, S. Energy and stiffness of mine models and seismicity, *SHIRMS 2008* – Y. Potvin, J. Carter, A. Dyskin, R. Jeffrey (eds.) Australian Centre for Geomechanics, Perth, ISBN 978-0-9804185-5-2, vol. 1, 2008. pp. 693–707.

SPOTTISWOODE, S.M. Is mine earthquake prediction possible? *Rockbursts and Seismicity in Mines*, Dalian, China. 2009.

USGS 24-Hour Aftershock Forecast Map, http://earthquake.usgs.gov/eqcenter/step//, accessed on 27th July 2009.

VAN ASWEGEN, G. Towards Best Practice for Routine Seismic Hazard Assessment in Mines. *30th International Conference of Safety in Mines Research Institutes*, South African Institute of Mining and Metallurgy, Johannesburg, South Africa. 2003.

VAN ASWEGEN, G. Routine seismic hazard assessment in South African mines. *6th Intl Symposium on Rockbursts and Seismicity in mines*, Perth, Australia, 2005. pp. 437–444.

VAN ASWEGEN, G. Routine Seismic Hazard Assessment for some S.A. mines, unpublished ISSI document, Western Levels, September 2007.

## Appendix I

Removing Type 'A' events

Several authors have noted that mine networks locate many small events that do not fit the same pattern as larger events. Ebrahim-Trollope (1998) was possibly the first author to comment on events that formed a discrete population in the seismic energy-seismic moment plot. Finnie *et al.* (2000) noted that Type 'A' events (as they were already called by Richardson and Jordan, 2001) occurred in areas of development blasting with no stoping and wrote that:

'The simplest theory that can account for these observations is that Type 'A' events are the actual blasts themselves and not some or other effect of the blasts.'

Richardson and Jordan (2002) described Type 'A' events as follows:

'Type A events are tightly clustered in time and space and generally occur within 100 m of an active mining face or development tunnel; their spectra are comparatively enriched in high frequencies, and they have an upper moment-magnitude cutoff at $M_{max} < 1$. We associate these events with the 'fracture-dominated' rupture of competent rock induced by dynamic stresses during blasting and quasi-static stress perturbations from the excavation and closure of individual stopes.'

The other events, or Type 'B' events, cover a wide range of Magnitudes and are similar to natural tectonic earthquakes. What distinguished the work of Richardson and Jordan (2002) from this earlier work was that it concentrated on Types 'A' and 'B', as listed above, and the fact that their paper was published in a high quality journal.
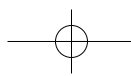
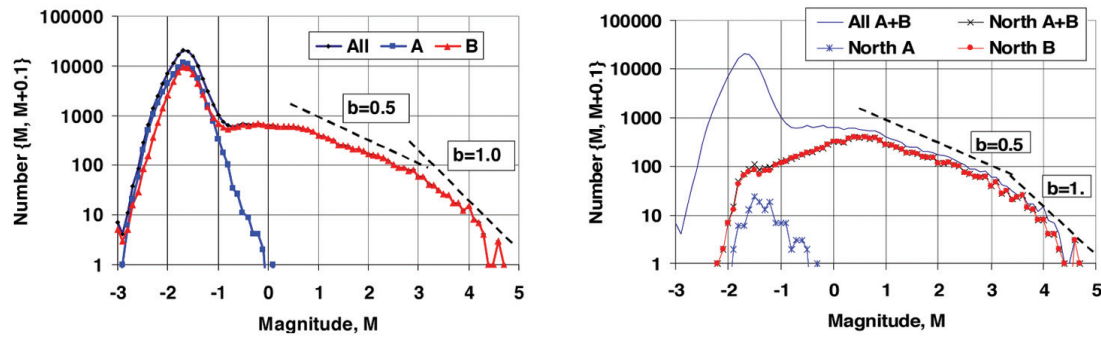# Mine seismicity: prediction or forecasting?

Figure 6—Distribution of magnitudes of Types 'A' and 'B' events in the VR data. Left shows all events and right, only events north of the line marked in Figure 7

Spottiswoode and Linzer (2005 and in Cichowicz *et al.* 2005, Appendix I, pp. 59–66) provided further evidence in support of the theory of Finnie *et al.* (2000) that Type 'A' events are development blasts themselves.

Durrheim *et al.* (2007 p. 36) wrote a 200-page report on standards for operating mine seismic networks. They wrote that:

'Blast events are characterized by:

➤ Many similar events (tens) that occur within a short period (minutes) in areas of active stoping or development at known blasting times (e.g. 14h00–18h00)

➤ Short duration and high frequency, and successive events have similar looking waveforms

➤ Multiple events with similar looking waveforms (similar shape, duration, frequency content and P-S separation) occur on the same seismogram'.

and recommended to:

'Exclude or flag blast events or the database used for seismic hazard assessment will be contaminated.'

Unfortunately, the data that was received from most mines was contaminated by Type 'A' events that were not flagged in the seismic catalogue. Following Richardson and Jordan's (2002) method of identification, Type 'A' events were identified as those that were within 100 m in plan and 30 s in time of one another and had magnitude less than 0.5. To reduce the chance of discarding induced events, the rule was applied to three events in succession instead of only two.

This filter worked well for four of the mines, but the process did not eliminate the excess of small events at mine VR even when the definition of Type 'A' events was loosened to pairs with inter-event distance less than 100 m in plan and 100 s in time. (Figure 6).

More than 50% of the 137 000 seismic events in the VR mining were identified as Type 'A' events using the simple rule described above. The Type 'A' events behaved differently from Type 'B' events in terms of distribution in time, location, and magnitudes, as shown below.

Figure 6 show the magnitude-frequency distribution for the VR data. About one half of the events are identified as Type 'A' events (Table I and Figure 6, left). Removal of Type 'A' events only slightly reduces the 'bump' of the distribution between magnitude -2 and -1.

Figure 7 shows that Type 'A' events are also spatially separated from Type 'B' events.

Type 'A' events occurred in clusters of up to 47 events with the average time between events varying from two to 20 seconds (Figure 8, left). Note that large events are followed by, on average, less than one aftershock within 600 s and that the rate is not constant (Figure 8, right). Also note that the sequences of Type 'A' events do not last longer than 550 s whereas aftershocks continue for much longer (Figure 8, right and Figure 9).

The aftershocks of large events shown in Figure 8 (right) are drawn again in Figure 9 illustrating that the time sequence follows Omori's law as quantified in Equations [1] and [2] in Appendix II, with c=50s and p=1.0.

The largest group of clusters of Type 'A' events was studied in more detail. 1 376 events formed into 72 clusters (on 72 days) and clearly progress along a straight line on plan at a rate of about 0.77 m/day (Figure 10).

It is most likely that the Type 'A' events identified in the data from mine VR are development blasts. This needs to be verified from mine plans. There is also a good opportunity to use them for improving the seismic velocity model for the mines, as was done by Spottiswoode and Linzer (2005).

Further analysis of data from the VR mine was performed only for events with Magnitude greater than -0.8. This unfortunately also severely reduced the number of unambiguous Type 'B' events from 68 654 to 9 282.
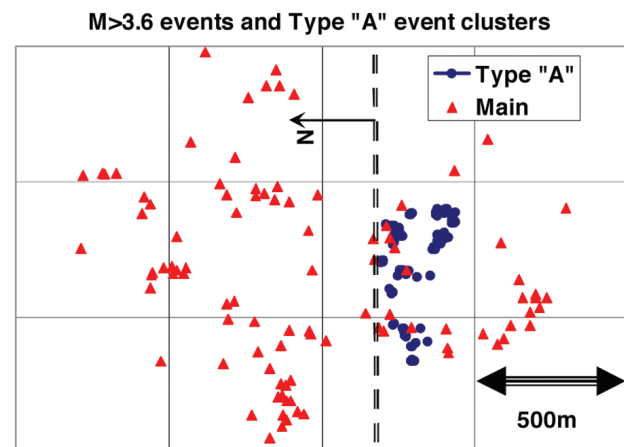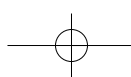

Figure 7—Location of 100 largest events and groups of Type 'A' groups from the VR mine
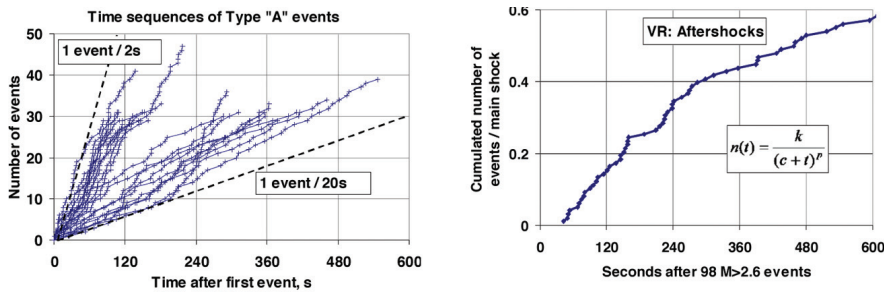
Mine seismicity: prediction or forecasting?

Figure 8—Time sequences of clusters of Type 'A' events and the stacked time sequence over the same time period following large Type 'B' events
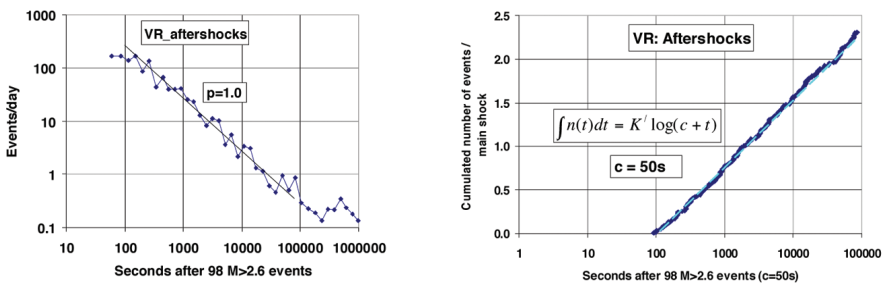

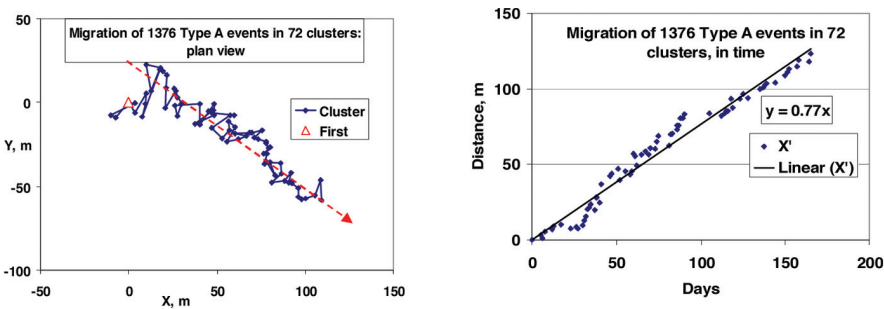**Figure 9—Aftershocks following large events. Each point on the left is derived from binning five or more events**

Figure 10—Time and space analysis of 72 clusters of 1 376 Type 'A' events

References

CICHOWICZ, A., SPOTTISWOODE, S.M., LINZER,L.M., DRENT, D., HEYNS, P.S., and HANDLEY, M.F. Improved seismic locations and location techniques, Safety in Mines Research Advisory Committee, Final Project Report SIM020304. (www.mhsc.org.za). 2005.

DURRHEIM, R.J., CICHOWICZ, A., EBRAHIM-TROLLOPE, R., ESSRICH, F., GOLDBACH, O., LINZER, L., SPOTTISWOODE, S.M., STANKIEWICZ T., and VAN ASWEGEN, G. Guidelines, Standards and Best Practice for Seismic Hazard Assessment and Rockburst Risk Management, Final Project number: SIM 05 03 02 Output 3 (6 March 2007), *Safety in Mines Research Advisory Committee*. 2007.

EBRAHIM-TROLLOPE, R. Seismological analysis for a scattered mining environment—methods and their limitations. *Proc. 2nd Southern African Rock Engineering Symposium*, T.O. Hagan (ed.), *ISRM Regional Symposium,* 1999. p. 140.

FINNIE, G.J., SPOTTISWOODE, S.M. and AMIDZIC, D. Observations of bimodal seismicity in deep gold mines, Extended abstract, *ISSI Seminar*. 2000.

RICHARDSON, E. and JORDAN, T.J. Some properties of gold-mine seismicity and implications for techtonic earthquakes, *Proc. In the 5th Int. Symp. on Rockbursts and seismicity in Mines* (RaiSim 5), G. van Aswegen, R.J. Durrheim and W.D. Ortlepp (eds.) South Afric. Inst. Min. Metall., 2001. pp. 149–156.

RICHARDSON, E. and JORDAN, T.J. Seismicity in deep gold mines of South Africa: Implications for tectonic earthquakes, *Bull. Seism. Soc. Amer.,* vol. 92: 2002. pp. 1766–1782.

SPOTTISWOODE, S.M AND LINZER, L.M. A Hybrid Location Methodology, *J.S.A. Inst. Min. Metall.*, vol. 105, 2005. pp. 417–426.

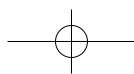## Appendix II

Foreshocks and prediction

Introduction

Aftershocks and foreshocks

The rate of seismicity per unit time ($n(t)$) following large events and blasts can be described by the Omori law of aftershocks:

$$n(t) = k / (c + t)^p \qquad [1]$$

Where k, c and p are constants and t is the time following the main shock.

Mine seismicity: prediction or forecasting?

Typically p has a value close to 1.0. c is a small time constant that is commonly attributed to seismic events that were not extracted from the reverberating coda waves that follow the well-defined body and surface waves.

When Equation [1] is integrated over time for the case of p=1.0, the cumulated rate of seismicity can be described as:

$$\int_{c}^{c} k \times \ln(1+t/c) \qquad [2]$$

For prediction of seismic events, the 'time to failure' concept as described by Mendecki and Van Aswegen (2001) would be ideal as the time of failure can be calculated from the data (Figure 11). This is their only concept that is described in terms of instability. The two measured quantities that they suggested were unclear in Mendecki and Van Aswegen (2001) due to typographic errors and have been removed in Figure 11. There is no knowledge of any case study of a deep-level mine that validates the concept of 'time to failure'.

The mathematics of the concept is the same as that for Omori's law if the flow of time is reversed. The quantity a is equivalent to p in Equation [1] above.

Accelerated rate of foreshocks

The 100 large events at VR data were preceded by more events than was the case for the 100 small events at this mine (Figure 3). To explain the reason for this, it is necessary to consider aftershock behaviour. (In this section, a departure is taken from the proper definitions of foreshocks and aftershocks as being smaller than main shocks and just consider them to occur before or after 'main' shocks within chosen magnitude ranges.) The data in Figure 9 are reproduced in Figure 12 together with aftershocks of events of smaller sizes. Whereas data were averaged over 100 large events, the number of main shock events was increased to 1 000 as the main shock magnitude decreased to have more events with fewer aftershocks each for averaging. Several features of Figure 12 are relevant to the current work:

➤ All aftershock sequences have a constant slope of -1,

corresponding to a p value of about 1.0
➤ All decay to a background value of about 0.2 events per day

Time to failure, $(t_f - t)$
$d\Omega/dt = k(t_f-t)^{\alpha}$
Ω - measure quantity t - current time
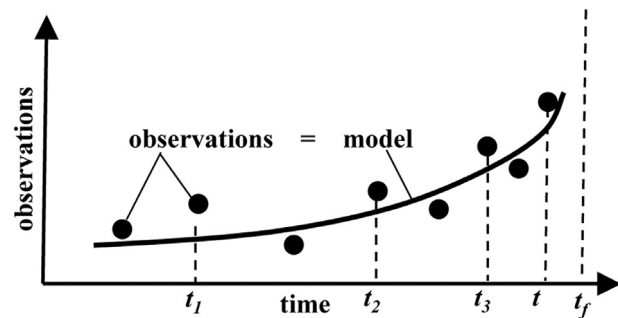t_f - time of failure k,α - constants

Figure 11—The concept of 'time to failure', redrawn after Mendecki and Van Aswegen (2001). Failure is predicted to occur at time t_f at the right
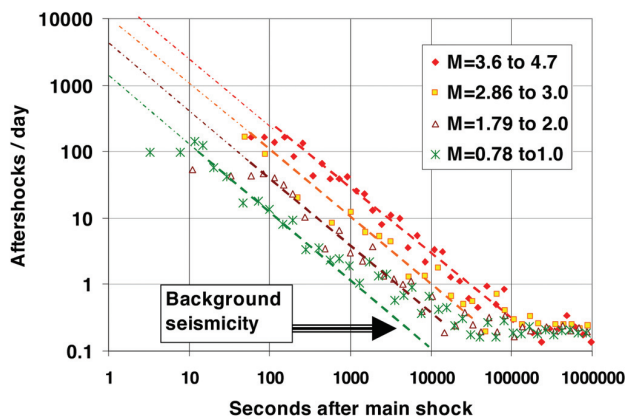

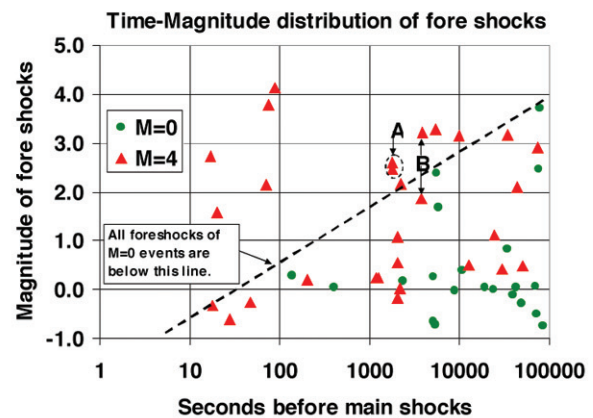Figure 12—Aftershocks rate following main shocks of different magnitudes
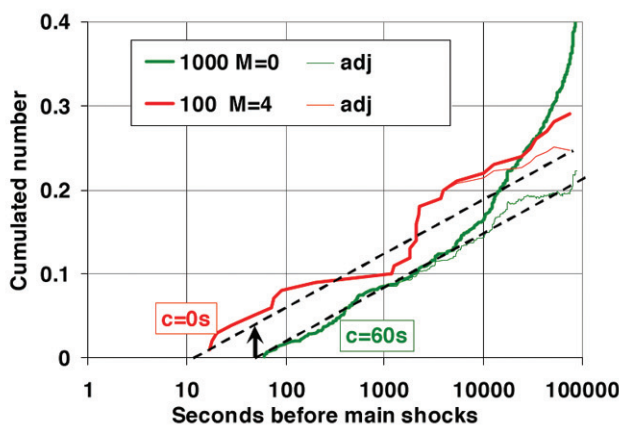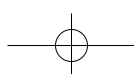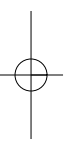

Figure 13—Distribution of foreshocks with time and magnitude. Partial adjustment of cumulated number of events to correct for the background rate of seismicity (left). Event pairs A and B at right are the only examples of more than one foreshock per main shock

Mine seismicity: prediction or forecasting?

➤ The maximum event rate was about 100 events per day
➤ The number of events (productivity; K) at any magnitude value is proportional to $10^{M/2}$ and
➤ The earliest aftershock is later for large events than it is for small events. In effect, this means that the c value increases for large events, confirming the suggestion that a non-zero c value results from the recording system and not from physical processes. Why would the Earth 'want' to wait longer before generating aftershocks of large events than of small events.

As can be seen in Figure 12, the parameter c decreases with increasing magnitude when foreshocks are considered whereas c increases with increasing magnitude for aftershocks. The type of graphing is changed from Figure 12 to Figure 13 because there are fewer foreshocks than aftershocks and the time of every foreshock adds value directly to the graph.

Only two large events are preceded by more than one foreshock in Figure 13 (right) and are identified as pairs of events A and B.

In summary, large events appear to have more foreshocks than is the case for small events because small aftershocks are not recorded soon after large main shocks. Therefore the increase in the number of foreshocks of large events compared to foreshocks of small events is an artefact of the recording system.

If two events occur in quick succession, the second will more likely be missed if it is smaller than the first.

References

MENDECKI, A.J. AND VAN ASWEGEN, G. Seismic monitoring in mines: selected terms and definitions. Van Aswegen, G., Durrheim, R.J. and Ortlepp, W.D. (eds.) *Rockbursts and Seismicity in Mines—RaSiM5*, South African Institute of Mining and Metallurgy, Johannesburg, South Africa. 2001. ◆