



Comparative seismology of the Witwatersrand Basin and Bushveld Complex and emerging technologies to manage the risk of rockbursting

by R.J. Durrheim*, S.M. Spottiswoode*, M.K.C. Roberts* and A. van Z. Brink*

Synopsis

The seismicity of the Witwatersrand Basin and Bushveld Complex has been analysed, revealing significant differences in source and damage mechanisms. A comparison of mining taking place at similar depths and extraction ratios indicates that the seismic energy release rate is considerably lower in the Bushveld Complex. Technologies introduced in the past decade to manage the risk of rockbursting are reviewed and assessed. These include geophysical methods to detect hazardous structures ahead of mining, new mining layouts and support systems, and the mechanization of in-stope processes. Despite important differences in geology, *in situ* stress, mining layouts and methods, there are many opportunities for the reciprocal transfer of knowledge, experience and technology between the gold and platinum mining sectors to improve the management of the rockburst risk.

Introduction

South Africa has two of the world's great orebodies: the gold-bearing reefs of the Witwatersrand Basin and the platinum-bearing reefs of the Bushveld Complex. Mining-induced seismicity and its hazardous manifestation, rockbursting, were encountered in the first decade of the 20th century when gold mines reached a depth of several hundred feet below the outcrop, forming extensive excavations supported solely by small reef pillars (Cook *et al.*, 1966). Research into the phenomena was carried out in an ad hoc way until the 1960s, when the first seismic monitoring systems were installed. Bushveld Complex seismicity has only become a source of concern more recently, as mining depths approached 1 km. A few surface seismometer stations were established in the 1980s. Systematic research commenced in the 1990s with the installation of the first underground and mine-wide networks.

It is hoped that rockbursting can be prevented from becoming a serious problem in Bushveld Complex mines by applying the hard-won experience gained in the Witwatersrand Basin. In this paper we review the substantial body of work carried out in the

past decade, much of it by researchers at CSIR Mining Technology under the auspices of the SIMRAC, DeepMine and PlatMine research programmes. The opportunities to transfer knowledge and technologies from a sedimentary to an igneous environment are assessed, and emerging technologies that may ameliorate the risk of rockbursting are identified.

Factors affecting seismicity and rockburst risk

Tectonic history and *in situ* stress

A mine tremor occurs when rock is strained to breaking point by mining-induced and/or tectonic stresses. The rock either ruptures or slips along a pre-existing geological weakness, releasing some of the accumulated strain energy and causing the rock surrounding the excavation to shake violently. The rocks of the Witwatersrand Basin and Bushveld Complex are over two billion years old, and have been subjected to many tectonic episodes that have created faults in the crust. However, the South African subcontinent is a tectonically stable region. It has been surrounded entirely by constructive plate boundaries (spreading ridges) since the break-up of Gondwana about 120 million years ago, and the stresses in the crust are largely lithostatic (i.e. dominated by the overburden load). While the region experiences little natural seismicity, the perturbation of the stress field by mining may trigger slip on faults that are in unstable equilibrium or rupture previously intact rock and release vast amounts of energy. The movement on a fault may be only a few millimetres, but could involve billions of tons of rock, which translates into enormous energy changes.

* CSIR Division of Mining Technology.

© The South African Institute of Mining and Metallurgy, 2005. SA ISSN 0038-223X/3.00 + 0.00. Paper received Jan. 2005; revised paper received Jun. 2005.

Comparative seismology of the Witwatersrand Basin and Bushveld Complex

Crushing and heating of the rock absorb most of the energy released by such a slip or rupture. Only a small fraction of the released energy, typically less than 1%, is manifested as seismic shaking.

Geology, mining layouts and methods

The amount of strain energy that is released is largely controlled by the mining geometry, strength and modulus of rocks surrounding the excavations, and the virgin and mining-induced stress fields (Table I). Compared to the strata containing the platinum orebodies, the Witwatersrand Basin strata tend to have higher uniaxial compressive strengths (notably the Alberton Porphyry and Elsburg Quartzite formations) and somewhat lower Young's moduli. This means that more elastic energy is stored in the rock at the time of failure. There may also be differences in rock mass behaviour within a mining region due to changes in geotechnical area (Schweitzer and Johnson, 1997; Roberts and Schweitzer, 1999). For example, the hangingwall of the Ventersdorp Contact Reef (VCR) may be either the Westonaria Formation or the Alberton Porphyry Formation, known colloquially as the 'soft' and 'hard' lavas, respectively. The VCR was deposited on an unconformity surface, so the footwall may be formed by one of several formations. The orientation and intensity of mining-induced fracturing differs significantly between geotechnical areas, with important implications for rock mass stability and hence the design of layout and support systems. Similarly, 'geotechnical districts' have been identified in Bushveld Complex mines by practitioners when formulating the mandatory 'Codes of Practice to Combat Rockfall and Rockburst Accidents'.

Mining layouts and methods are dictated principally by the depth and geometry of the orebody and the degree of geological disturbance. The character of seismicity differs

significantly between the Klerksdorp and Carletonville goldfields, even though the average depth of mining in these regions (2–3 km) is similar (Gay *et al.*, 1995). The number of seismic events is far greater in the Carletonville region, while the Klerksdorp region has a propensity for large magnitude ($M_L > 4$) events. These differences are manifested by different slopes of the Gutenberg-Richter frequency-magnitude distribution and explained by differences in geological structure and the consequent mining layouts. The Klerksdorp region is intersected by dykes and faults with throws of 1 km or more, and most large seismic events are produced by slip on these geological structures. Scattered layouts are used to mine the blocks of reef.

The geology of the Carletonville area is relatively undisturbed, and it is possible to mine in a more systematic fashion using longwall or dip pillar layouts. Many of the seismic events in this mining area occur close to the working face, and may involve the creation of new ruptures and facebursting.

The ratio γ_M (cumulative seismic moment/cumulative volume mined) in the Klerksdorp region is almost double that for the Carletonville region. A high value ratio of γ_M has often been interpreted to indicate a greater rockburst hazard. This is a simplistic interpretation, however, as the large cumulative seismic moment in the Klerksdorp region is due to the bigger events ($M_L > 4$) that often occur on structures tens to hundreds of metres distant from excavations. The damage caused by these large events is often more extensive but less intense than the damage caused by $M_L = 2$ events located close to the stopes. Thus, it is important to distinguish between the seismic and the rockburst hazard, as regions characterized by larger magnitude or more numerous seismic events do not necessarily pose the greatest rockburst risk, which depends on the intensity of damage caused to excavations.

Table I

Stress field and properties of seismogenic strata of the Witwatersrand Basin and Bushveld Complex

Witwatersrand Basin Schweitzer and Johnson (1997); Manganye <i>et al.</i> (2001)				Bushveld Complex Haile and Jager (1995); L. Gardner and A. Day (pers. comm., 2005)			
Orebody	Typical rock engineering properties			Rock engineering properties of strata forming the hangingwall of the Merensky Reef, 22/8 stope, Richard Shaft, RPM			
Hangingwall Reef Footwall rocks	UCS (MPa)	Young's Modulus (GPa)	Poisson's ratio	Rock Type	UCS (MPa)	Young's Modulus (GPa)	Poisson's ratio
Alberton Formation (hard lava) Westonaria Formation (soft lava) Ventersdorp Contact Reef Booysen Shale Elsburg Quartzite	318 164 - 144 270	66–80 60–71 - 65 64–84	0.19–0.24 0.19–0.27 - 0.18–0.25 0.09–0.17	Anorthosite (mottled) Pyroxenite (Bastard Reef) Anorthosite (spotted) Leuconorite Melanorite Norite Pyroxinite (Merensky Reef)	196 (44) 167 (38) 180 (16) 189 (7) 137 (29) 209 (24) 133 (6)	80 (19) 104 (21) 74 (12) 81 (5) 74 (16) 96 (5) 104 (9)	0.20 (0.04) 0.21 (0.07) 0.23 (0.02) 0.23 (0.02) 0.23 (0.02) - 0.20 (0.02)
Quartzite Green bar Quartzite Carbon Leader Footwall quartzite Upper square pebble quartzite	218 (58) 222 (85) 250 (105) - 202 (45) 255 (107)	87 (15) 87 (5) 87 (5) - 74 (10) 78 (11)	0.20 (0.03) 0.24 (0.05) 0.17 (0.01) - 0.19 (0.02) 0.20 (0.04)				

Comparative seismology of the Witwatersrand Basin and Bushveld Complex

The level of seismicity in the western Bushveld Complex platinum mines is relatively low due to generally shallow (< 1 km) mining depths, the use of closely spaced yielding or crushing pillars, and high horizontal stress (Gay *et al.*, 1995). Significant differences in seismic character are also found between platinum mining regions. Durrheim *et al.* (1997) analysed seismic data from three mines in the western Bushveld Complex (Frank Shaft, Rustenburg Platinum Mines; 10 Shaft, Wildebeestfontein North Section, Impala Platinum Mines; and 12 Shaft, Bafokeng North Mine, Impala Platinum Mines) and found that seismic activity is a function of many factors, including the regional support system, size and spacing of pillars, geotechnical area, depth of mining and stress regime. They concluded that the experience gained in the gold mines of the Witwatersrand Basin cannot simply be applied to the Bushveld Complex as the geotechnical properties and stress regime differ considerably.

Source mechanisms

The Brune model, based on the slip along a penny-shaped crack, is commonly used to analyse Witwatersrand Basin tremors and estimate parameters such as source dimensions and stress drop. Recent unpublished research by one of the authors (Dr S. Spottiswoode) suggests that this model may not be appropriate to describe a type of pillar failure commonly observed in Bushveld Complex mines. Very few in-stope pillars in Bushveld Complex mines actually crush at the face in response to blasting. The majority yield or crush towards the back areas. Occasionally a pillar may burst violently, though little damage is generally caused to the surrounding area (L. Gardner, personal communication, Impala Platinum, 2005). With this type of failure mechanism, almost all of the strain energy liberated by the pillar failure is radiated as seismic energy because the residual stress is very small and only a small amount of the energy is expended doing work on the failed material. Consequently, conventional seismic analysis would overestimate both the energy and moment of the source. This failure mechanism contrasts with a pillar foundation failure, which is associated with shearing of the hanging- and footwall. In such cases there is only a partial stress drop, much of the energy is absorbed by pulverization and heating of the rock, and co-seismic deformation extends beyond the close environs of the pillar.

Peak ground velocity

The criterion generally used by the South African mining industry to design support is based on the absorption of the kinetic energy associated with a hangingwall beam (thickness H , density ρ) moving downwards at a given take-off velocity (v). The support should be able to stop the hangingwall within a short distance (h), generally taken as 0.2 m. The potential and kinetic energy that has to be absorbed by the support is:

$$E = \rho H (gh + \frac{1}{2} v^2) \text{ Joules/m}^2 \quad [1]$$

The amount of kinetic energy to be absorbed exceeds the potential energy when $v > 2$ m/s. This ground velocity is often taken as a benchmark when computing the risk of rockburst damage. Milev *et al.* (2003) report several field measurements of peak particle velocities greater than 2 m/s

(and less than 3 m/s) in several Witwatersrand Basin mines. As there are very few actual measurements of ground velocity close to the source, a model to extrapolate far-field observations of the ground motion to regions closer to the source was developed. To simplify the analysis, it is assumed that:

- all seismic events occur on Brune-type circular slip zones centered on each event location
- the ground motions are well described by the equation developed by McGarr (1991), but with one alteration motivated below
- the rock mass is elastic and homogeneous
- site effects and amplification at the skin of the stope are neglected, and
- future seismicity is likely to be similar to historical seismicity (this assumption can obviously be qualified by considering likely changes as new mining layouts encounter new geological features).

Models of seismic sources generally consider strong ground motion either in the near field or in the far field. The near-field peak velocity (v_N) is

$$v_N = V_S \Delta \sigma / G \quad [2]$$

where V_S = shear-wave velocity

$\Delta \sigma$ = static stress drop

and G = modulus of rigidity.

Similarly, in the far field (McGarr, 1991), we have the following:

$$R_F = f_{\theta\phi} V_S \Delta \sigma r_o / G \quad [3]$$

where v_F = far field peak velocity,

R = $(x^2 + y^2 + z^2)^{1/2}$

$f_{\theta\phi}$ = radiation pattern for S waves

and r_o = source radius.

McGarr (1991) used the median value of $f_{\theta\phi} = 0.57$.

Using the most conservative value, namely $f_{\theta\phi} = 1.0$, we have $v_N = v_F$ at $R = r_o$. Equations [2] and [3] then reduce into a single equation:

$$v = (V_S \Delta \sigma / G) \quad \text{for } R \leq r_o \quad [4]$$

$$\text{and } v = (V_S \Delta \sigma / G)(r_o / R) \quad \text{for } R > r_o$$

By considering a circular source in the X-Y plane, $r_o = (x_o^2 + y_o^2)^{1/2}$, we can define the hypocentral distance ' R' ' in terms of elliptical functions around this source as:

$$R' = (((r - r_o)^2 + z^2)^{1/2} + ((r + r_o)^2 + z^2)^{1/2}) / 2 \quad [5]$$

where r is the distance from the source centre in the X-Y plane, and where z is the distance from the X-Y plane.

The peak velocity can then be expressed as:

$$v = (V_S \Delta \sigma / G)(r_o / R') \quad [6]$$

This peak velocity attenuation function can be used to estimate the peak ground velocity in the region surrounding a seismic source (Figure 1).

Comparative study

The rockburst risk in Witwatersrand Basin and Bushveld Complex mines was compared using data from the deepest parts of Northam Platinum mine (depth about 2 100 m), and

Comparative seismology of the Witwatersrand Basin and Bushveld Complex

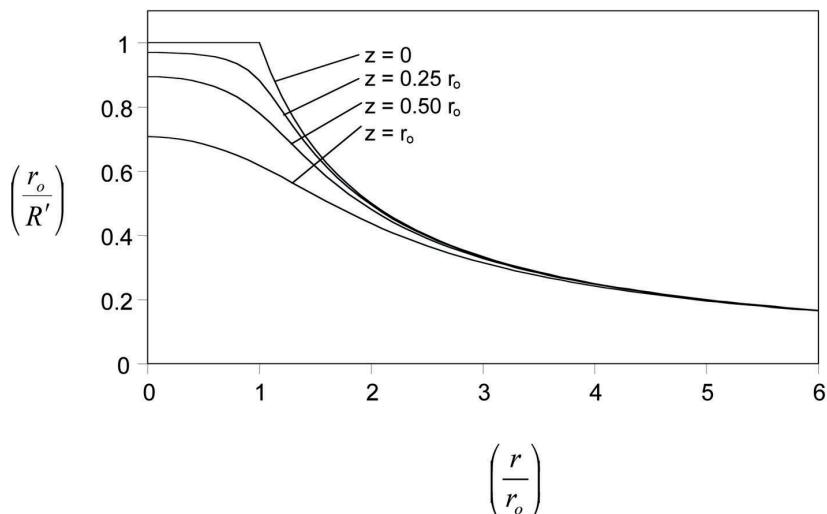


Figure 1—Peak particle velocity attenuation as a function of distance from a Brune-type circular slip source (radius r_o in x-y plane)

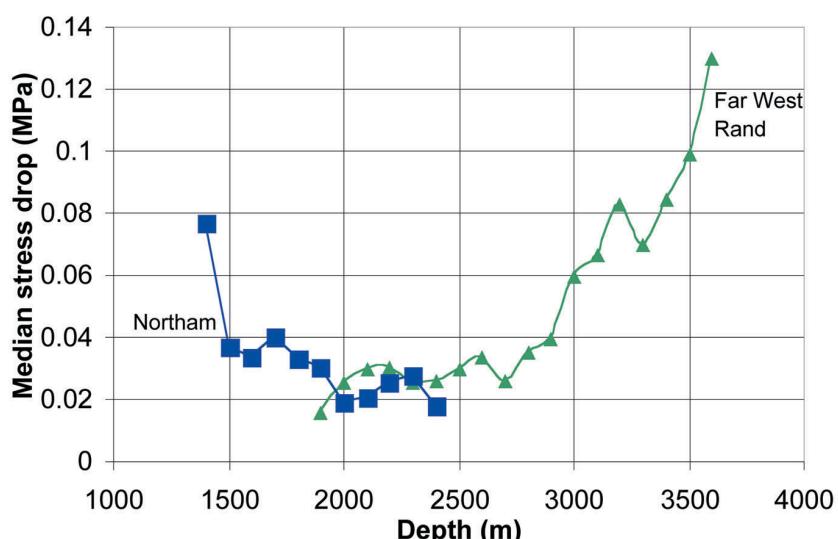


Figure 2—The relationship between the median stress drop and depth for Northam platinum mine and a Far West Rand gold mine

VCR and Carbon Leader stopes (depths about 2 100 m and 3 300 m, respectively) in a Far West Rand gold mine (Brink *et al.*, 2002). In other respects the three areas were very similar: a face length of 200 m to 250 m, span of about 150 m, extensively mined areas up dip, and a six-month monitoring period. The data set comprised some 2675 and 10300 events for Northam and the Far West Rand, respectively. The data were sorted into bins defined by 100 m depth intervals. While the mining conditions and methods at Northam differ considerably from the Rustenburg area, they may be more representative of future mining in the Bushveld Complex.

Stress drop

In the Far West Rand the median stress drop increased non-linearly with depth. The Northam data showed the opposite trend (Figure 2), with the median stress drop surprisingly decreasing with depth, to values similar to those measured in the Far West Rand in the overlapping depth range (1 700 m

to 2 400 m). This may be due to different source mechanisms: most Northam events are caused by the failure of pillars and remnants, while the Far West Rand events are mostly located in the rock ahead of the mining faces. The Northam observations should be treated with some circumspection because seismic stress drops typically vary by a factor of 10 or more within any population, and need further investigation.

Peak ground velocity

The Brune-type circular slip model was used to calculate the peak ground velocities in nearby stopes using the observed source locations, and derived source dimensions and stress drops (Equation [6]). The rockburst hazard in the stopes was estimated by determining the number of times the calculated peak ground velocities exceeded certain thresholds. While the assumptions are broad, it was concluded that the rockburst hazard at Northam was 1/6 the hazard of VCR mining at a similar depth (2 100 m), and 1/12 the hazard of Carbon

Comparative seismology of the Witwatersrand Basin and Bushveld Complex

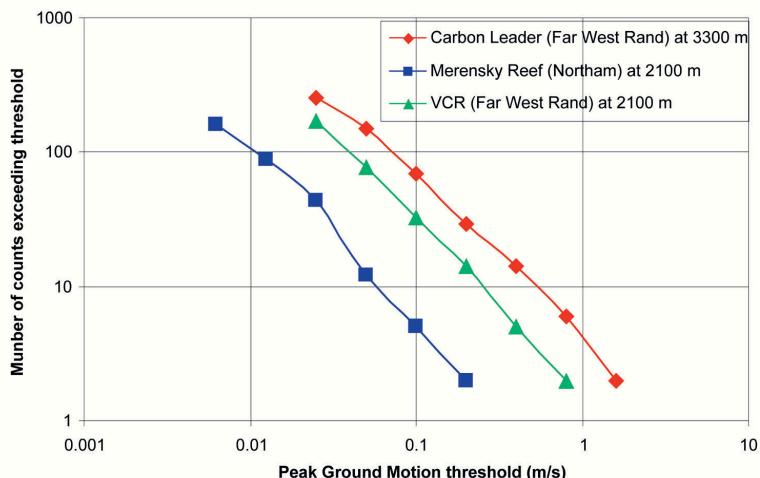


Figure 3—A comparison of the number of times that the calculated peak ground motion exceeded threshold values

Leader mining at 3 300 m, for similar volumes of mining (Figure 3).

Time

Events associated with the mining of the VCR were found to cluster strongly in the 6-hour period following the blast, with 81 per cent of events with $M_L > 0$ occurring between 15h00 and 21h00 (Figure 4a). The Northam events had a far greater spread in time, with only 59 per cent of events with $M_L > 0$ occurring between 14h00 and 21h00 (Figure 4b). These differences can be explained in terms of the failure mechanism. VCR events mostly occur ahead of the face and are thus triggered by the large stress change caused by blasting. Northam events mostly occur on pillars that may be some distance from the face and not subject to as great a stress change at blast time (see also Durrheim *et al.*, 1997).

Energy absorption

The 95 per cent cumulative fall-out thicknesses for the VCR and Merensky Reef hangingwalls are 1.4 m and 1.0 m, respectively (Brink *et al.*, 2002). The 95 per cent cumulative ejection thickness for the VCR is 1.8 m. The ejection thickness has not been systematically measured on Bushveld platinum mines, but based on the fall-out thickness statistics and assuming a ratio similar to that observed in the VCR, it is expected to be about 1.3 m. The energy absorption criterion used to design support systems depends on the ejection thickness and the expected peak ground velocity (see Equation [1]). For design purposes, a peak ground velocity of 1 m/s has been proposed for the Bushveld Complex, as compared to 3 m/s for deep gold mines (Brink *et al.*, 2002). Both ejection thickness and peak ground velocity are thus smaller for the Northam stopes than for VCR stopes, and the energy absorption criterion is correspondingly smaller, 9.6 kJ/m² as compared to 34 kJ/m². This is easily achieved with modern support components and systems.

Strategies for the prevention and control of rockbursts

Emergent technologies have been classified in terms of the

risk management strategy, maturity, time needed to implement, and their impact on other mining systems (Table II).

Mine planning and development phase

The first steps in any risk management strategy are measures to avoid the hazard in the first place. In the past decade, there have been advances in technologies to detect hazardous geological structures such as dykes and faults ahead of mining. Reflection seismology has been widely used to explore for gold and platinum deposits, the first survey taking place in 1982. The demand for 2D reconnaissance surveys had largely tapered off by 1993. Since then most of the work has been for 3D surveys to assist mine planning and development (Pretorius *et al.*, 2003). Owing to attenuation of the shorter seismic wavelengths, the smallest fault that can be reliably detected by surface seismics at depths greater than a kilometre or so, when rockbursting starts to emerge as a problem, has a throw of about 10 m (Pretorius *et al.*, 2003; Trickett *et al.*, 2004). Seismic stratigraphic techniques have been used in the Bushveld Complex to distinguish areas of 'pothole' reef from areas of 'normal' reef (Stevenson *et al.*, 2003; Trickett *et al.*, 2004). Thus, surface seismics is essentially a strategic tool complementing borehole information and geological interpretation, used to site shafts and plan the macro-layout.

Macro-layouts and regional support

The limitation of closure by means of regional support pillars and backfilling has been a key strategy to reduce mining-induced seismicity. Since the early 1990s, there has been a major change in layout philosophy on gold mines: the favoured orientation of stabilizing pillars has changed from strike to dip, with the predevelopment of tunnels allowing hazardous structures to be detected and bracket pillars to be planned prior to stoping (Vieira *et al.*, 2001). Dip pillar layouts also have sufficient flexibility to keep energy release rates (ERR) below design criteria. It has been argued that backfill can be dispensed with in some situations, though the collateral benefits with respect to ventilation and cooling are lost.

Comparative seismology of the Witwatersrand Basin and Bushveld Complex

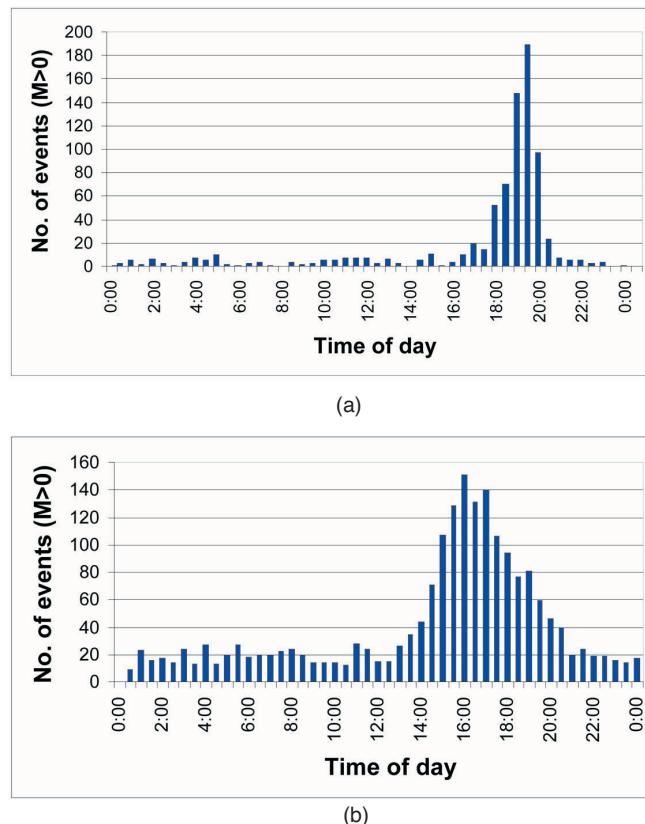


Figure 4—Time distribution of all seismic events larger than magnitude 0 induced by mining at depths of approximately 2 100 m. (a) VCR stopes in a Far West Rand gold mine, and (b) Northam platinum mine

Table II

Technologies for managing the rockburst risks that have emerged in the past two decades

Risk management strategy	Nature of technology/Time to implement/Impact on other mining systems		
	Strategic, or years to months to implement, or major impact on other systems	Tactical, or months to weeks to implement, or moderate impact on other systems	Operational, or weeks to days to implement, or minor impact on other systems
Identifying hazardous structures and stress regimes	3D reflection seismics* Mine-wide seismic networks* Integration of numerical modelling and seismic observations†	Local seismic networks* Borehole radar† Seismic hazard assessment techniques† Techniques to measure stress in high-stress conditions‡	Rapid deployment seismic monitors* Techniques to predict seismicity‡
Reducing strain accumulation through regional support	Dip pillar layouts* Backfill†		
Protecting the worker through better support systems or by stress-relieving the rock		Yielding pre-stressed props and headboards* Yielding tunnel support* Roofbolting in the face area† Nets† Thin spray-on liners‡	Preconditioning*
Removing the worker from the hazardous area through mechanization	Long-hole drilling† Impact mining system† Activated rock cutting system‡ Mini-disk rock cutting system‡	Remote-controlled LHDs and dozers† 'Walking' face area support‡	Drill rigs and jigs† Remote-controlled drills†

*Mature, implementation widespread

†Field-proven in certain environments, some research and development required

‡Concept or prototype, considerable research and development required

Bushveld Complex mines, with the exception of Northam, are at 'intermediate' rather than 'deep' levels. Widespread use is made of yielding and crushing pillars. Backfill is not used, though its adoption may be required at deeper levels for ventilation and cooling reasons owing to the higher geothermal gradient in the Bushveld Complex. In addition,

backfill will assist in controlling the stability of the hangingwall in the poor ground conditions that exist in certain ground control districts on some of the platinum mines. Backfill may also be used to provide support in stopes mined by mechanized rock-cutting systems so that the need to cut in-stope pillars is avoided (DP Roberts *et al.*, 2004)

Comparative seismology of the Witwatersrand Basin and Bushveld Complex

and also where mining of the UG2 Reef takes place below remnants on the Merensky Reef and where the middling between the two reefs is less than about 30 m thick i.e. on the north-western rim.

Mine-wide seismic networks are installed on virtually all rockburst prone mines, and can provide useful warnings of hazardous structures ahead of mining and to evaluate different layout and regional support strategies. In the early 1990s, much effort was devoted to seismic prediction, but this proved to be an extremely difficult problem to solve. The focus has since turned to the management of risk through the continuous assessment of the seismic hazard and the creation of rockburst-resistant excavations through optimum layouts and support systems. Early work concentrated on understanding and describing the seismic source mechanism, with attention subsequently being given to the rockburst damage mechanism. Recent work in this area has focused on the integration of seismic observations and numerical modelling, which will lead to better simulations of rock mass behaviour.

Micro-layouts and local support

Since the early 1990s, there has also been a major change in components and systems available for local support. Rapid-yielding hydraulic props have been largely replaced by pre-stressed yielding elongates. Roofbolting of the face area and areal support systems such as nets and thin spray-on liners have been evaluated, and all show potential. A methodology to design support systems has been expanded (Daehnke *et al.*, 2001).

The borehole radar technique has been developed to detect hazardous structures between raise lines in environments, such as the VCR or Merensky Reef, where favourable electrical property contrasts exist between the footwall rocks and the overlying lavas (Du Pisani and Vogt, 2003 and 2004). Small faults and other changes in topography are accurately positioned, giving prior warning of oncoming changes in mining conditions. Terraces and slopes in the VCR are mapped, facilitating planning of the optimal extraction of the gold within the block. Potholes can be detected on the Merensky Reef prior to stoping, thus facilitating the planning of stope layouts.

The extraction of remnants is likely to become an increasingly important issue on the many gold mines approaching the ends of their lives. Techniques to mine them safely are critically needed. Local high-sensitivity seismic networks are sometimes installed to monitor 'hot-spots' and diagnose problems.

The cleaning stage of the mining cycle is particularly risky as face area support is often difficult to install following the blast and may inhibit scraping or water-jetting operations. Two emerging technologies may provide solutions: remotely controlled LHDs, originally developed to clear minefields in combat zones, and roofbolting (Roberts *et al.*, 2004). Recent unpublished research indicates that roofbolting across faults inhibits fallout due to repeated seismic shaking (personal communication, Dr E. Sellers, CSIR Mining Technology, 2004), as well as joints, dykes and fractures (personal communication, L. Gardner, Impala Platinum, 2005).

Rock-breaking technologies

Numerous rock-breaking technologies have been tested in the past decade, either to remove workers from the hazardous zone or to enable round-the-clock and seven-days-a-week mining. These technologies range from incremental improvements to the conventional drill-and-blast method (rigs, jigs and remote controls) and long-hole drilling methods, to fully mechanized narrow reef mining systems, and low energy explosives and propellants. In gold mining, perhaps the most significant advance in the field of rock-breaking in the past decade has been the thorough field-testing and widespread implementation of preconditioning in areas prone to facebursting (Toper *et al.*, 2003).

One of the advantages of the drill-and-blast method is that most mining-induced seismicity takes place at the time of the blast when the face is rapidly advanced and the stress redistributed. Typically 60 per cent or more of the potentially damaging seismic events occur during the period that the mine is evacuated for blasting. It has been argued that continuous mining will actually induce significantly less seismicity per unit area mined than drill-and-blast, as the perturbation of stress is far more gradual. Other researchers have argued that the level of seismicity is independent of the mining method, and consequently continuous mining will result in a greater hazard, as the same number of events will be distributed randomly through the working shifts. Investigations into the effect of the mining method on seismicity in Witwatersrand mines indicated that the overall seismic hazard, which is dominated by the larger seismic events, is independent of the rock-breaking process (Durrheim, 2001). It is not possible to make a general statement concerning seismic risk, as the exposure of workers to rockbursts and other contingent risks (e.g. loss of equipment, delays of production) depend on the details of each mining method.

Conclusions

Mining-induced seismicity is an inevitable consequence of mining at depth. While the relationship between seismic energy release and rockburst hazard is not simple, studies indicate that seismic energy release is considerably less in Bushveld Complex mines than Witwatersrand Basin mines operating at similar depths. While being alert to important differences in geology, *in situ* stress, mining layouts and methods, there are many opportunities to transfer hard-won knowledge and technologies.

The last decade has seen the widespread implementation of a range of technologies (Table II), with another wave in the field-testing phase. This paper has highlighted technological solutions to the rockburst problem, but there is also room for substantial progress in the fields of training, supervision and work organization before the benefits of these technologies is exhausted. Techniques to identify hazardous structures ahead of mining, such as 3D surface reflection seismics, systems for mine-wide seismic monitoring, and borehole radar are useful in both the Witwatersrand Basin and Bushveld Complex. The drive to introduce mechanized rock-cutting machinery is far stronger in the Bushveld Complex, as mining conditions tend to be

Comparative seismology of the Witwatersrand Basin and Bushveld Complex

easier and the potential life of many mines extend far into the future. Should these technologies prove to be successful, there could well be opportunities to transfer them to Witwatersrand Basin mines.

Statistics show that injuries and fatalities are greater in the face area than any other area in Witwatersrand Basin and Bushveld Complex mines. There are several reasons for this: workers spend much of their time in the stope face area; it requires great discipline to keep support up to standard while meeting the demands of drilling, blasting and cleaning; the peak ground velocities are higher; and the unsupported span tends to be larger. There could be two ways to address this: install full-time on-the-face support that does not hinder tasks such as drilling and cleaning such as rockbolts; or reduce the exposure of workers through greater mechanization and remote control of equipment.

We believe that continued technical research is necessary for our gold and platinum mining industries to remain competitive and we have to strive for continuous incremental improvement, while looking for the quantum changes that can revolutionize industries. The danger posed by icebergs to transatlantic travel was not solved by building stronger ships, but by the development of the airliner!

Acknowledgements

SIMRAC is thanked for permission to publish the work conducted as part of project SIM 040206 (A holistic assessment of SIMRAC rock-related research). Tony Jager, Gokhan Güler and Dr Ewan Sellers (all of CSIR), Les Gardner (Impala Platinum) and an anonymous reviewer are thanked for their thoughtful reviews.

References

- BRINK, A.V.Z., ROBERTS, M.K.C., and SPOTTISWOODE, S.M. Further assessment of seismic hazard/risk in the Bushveld Complex platinum mines and the implication for regional and local support design. Final Report, Project GAP 821, Safety in Mines Advisory Committee, Johannesburg, South Africa, 2002. 42 pp.
- COOK, N.G.W., HOEK, E., PRETORIUS, J.P.G., ORTLEPP, W.D., and SALAMON, M.D.G. Rock mechanics applied to the study of rockbursts. *Journal of the South African Institute of Mining and Metallurgy*, May 1966, pp. 436–714.
- DAEHNKE, A., VAN ZYL, M., and ROBERTS, M.C.K. Review and application of stope support design criteria. *Journal of the South African Institute of Mining and Metallurgy*, 2001, vol. 101, pp. 135–164.
- DU PISANI, P. and VOGT, D. Borehole Radar Delineation of the Ventersdorp Contact Reef in Three Dimensions, *Exploration Geophysics*, 2004, vol. 35, pp. 278–282.
- DU PISANI, P. and VOGT, D. Radar frequency electrical properties of rocks associated with the VCR, UG2 and Merensky orebodies, *Proceedings of the 8th SAGA Biennial Technical Meeting and Exhibition*, 2003, South African Geophysical Association.
- DURRHEIM, R.J. Management of mining-induced seismicity in ultra-deep South African gold mines, *Proceedings 5th International Symposium on Rockbursts & Seismicity in Mines*, Van Aswegen, G. Durrheim, R.J. and Ortlepp, W. D. (eds.), The South African Institute of Mining and Metallurgy, 2001, Symposium Series S27, pp. 213–219.
- DURRHEIM, R.J., SPOTTISWOODE, S.M., JAGER, A.J., and VAN DER MERWE, A.J. Seismic monitoring of pillar system performance in Bushveld Complex platinum mines. *Proceedings of the 1st Southern African Rock Engineering Symposium*, Johannesburg, South Africa. Gürtunca, R.G. and Hagan, T.O. (eds.). South African National Group on Rock Engineering, 1997, pp. 515–521.
- GAY, N.C., DURRHEIM, R.J., SPOTTISWOODE, S.M., and VAN DER MERWE, A.J. Effect of geology, *in situ* stress and mining methods on seismicity in Southern African gold and platinum mines. *Proceedings of the International Congress of Rock Mechanics*, Tokyo, Japan. Fujii, T. (ed.). International Society for Rock Mechanics, 1995, vol. 3, pp. 1321–1325.
- HAILE, A.T. and JAGER, A.J. Rock mass condition, behaviour and seismicity in mines of the Bushveld igneous complex, SIMRAC Report GAP 027, Department of Mineral and Energy Affairs, South Africa, 1995.
- MANGANYE, J., GRODNER, M., and SCHWEITZER, J. Geotechnical catalogue for ultra-deep Witwatersrand mining, DeepMine Final Report, task 2.4.1, 2001.
- MCGARR, A. Observations constraining near-source ground motion estimated from locally recorded seismograms, *Journal of Geophysical Research*, 1991, vol. 96, pp. 16495–16508.
- MILEV, A.M., SPOTTISWOODE, S.M., MURPHY, S.K., and GEYSER, D. Site response and strong ground motion, recorded underground, during mine-induced seismic events. *Proceedings of the 10th Congress of the International Society for Rock Mechanics*, Johannesburg, South Africa. The South African Institute of Mining and Metallurgy, 2003, Symposium Series S33, pp. 817–828.
- PRETORIUS, C.C., MULLER, M.R., LARROQUE, M., and WILKINS, C. A review of 16 years of hardrock seismics on the Kaapvaal Craton, *Hardrock Seismic Exploration*, Eaton, D., Salisbury, M. and Milkereit, B. (eds.), Developments in Geophysics Series, SEG, Houston. 2003, pp. 247–268.
- ROBERTS, M.K.C., LAMOS R.A. and MURPHY, S.K. The application of short rockbolts in ultradeep tabular stoping. *International Journal of Rock Mechanics and Mining Sciences*, 2004. vol. 41, issue 3, p. 544.
- ROBERTS, M.K.C. and SCHWEITZER, J.K. Geotechnical Areas associated with the Ventersdorp Contact Reef, Witwatersrand Basin, South Africa. *Journal of the South African Institute of Mining and Metallurgy*, 1999, vol. 99, pp. 157–166.
- ROBERTS, D.P., ROBERTS M.K.C., and JAGER A.J. Alternative support systems for mechanised stopes. *Proceedings of the International Platinum Conference*, Sun City, South Africa. The South African Institute of Mining and Metallurgy, 2004, Symposium Series S38, pp. 77–82.
- SCHWEITZER, J.K. and JOHNSON, R.A. Geotechnical classification of deep and ultra-deep Witwatersrand mining areas. *Mineralium Deposita*, 1997, vol. 32, pp. 335–348.
- STEVENSON, F., HIGGS R.M.A., and DURRHEIM R.J. Seismic imaging of precious and base metal deposits in southern Africa, *Hardrock Seismic Exploration*, Eaton, D., Salisbury, M. and Milkereit, B. (eds.), Developments in Geophysics Series, SEG, Houston, 2003, pp. 141–156.
- TOPER, A.Z., JANSE VAN RENSBURG, A., and NOBLE, B. Preconditioning Guidelines. Safety in Mines Advisory Committee, Johannesburg, South Africa, 2003. 11 pp.
- TRICKETT, J.-C., DÜWEKE, W.A., and KOCK, S. Three-dimensional reflection seismics: worth its weight in platinum. *Proceedings of the International Platinum Conference*, Sun City, South Africa. The South African Institute of Mining and Metallurgy, 2004, Symposium Series S38, pp. 257–263.
- VIEIRA, F.M.C.C., DIERING, D.H., and DURRHEIM, R.J. Methods to mine the ultra-deep tabular gold-bearing reefs of the Witwatersrand Basin, South Africa. *Underground Mining Methods: Engineering Fundamentals and International Case Studies*, Hustrulid, W.A. and Bullock, R.L. (eds.), Society for Mining, Metallurgy, and Exploration, Inc., 2001, pp. 691–704. ♦