Mitigating the risk of rockbursts in the deep hard rock mines of South Africa: 
100 years of research

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ABSTRACT: South Africa hosts two of the world’s richest ore bodies, the gold-bearing conglomerates of the Witwatersrand Basin and the platinum-bearing pyroxenites of the Bushveld Complex. Both ore bodies extend to depths of several kilometers. Gold was discovered near present-day Johannesburg in 1886. Mining-induced seismicity and its hazardous manifestation, rockbursting, were first encountered in the early 1900s when extensive stopes reached depths of several hundred meters. A committee, appointed in 1908 to investigate the cause of the tremors, recommended that seismographs be installed, and scientific observations began in 1910. Research was carried out in an ad hoc way until a mining research laboratory was established in 1964. Since then, research addressing the risks of deep hard rock mining has mostly been conducted under the auspices of the Chamber of Mines Research Organization, the Mine Health and Safety Council, and several collaborative research programs. Research work to mitigate the rockburst risk has focused on three main areas: (i) development of macro-layouts (e.g. sequential grid) and regional support (e.g. backfilling) to control the release of seismic energy through the geometry and sequence of mining; (ii) development of support units and systems (e.g. rapid-yielding hydraulic props, pre-stressed elongates) to limit rockburst damage; and (iii) mine seismology, which seeks to develop techniques to continually assess the seismic hazard and control seismic activity (e.g. through the rate of mining). Implementation of these technologies, together with improvements in training, work organization and regulation, have reduced fatality rates and made it possible to mine successfully at depths exceeding 3.5 kilometers.

RISKS POSED BY ROCKBURSTS

The gold-bearing strata of the Witwatersrand Basin, which crop out near present-day Johannesburg, have produced almost one-third of the gold ever mined (Handley 2004). The Central Rand goldfield was discovered in 1886. Mining-induced seismicity and its hazardous manifestation, rockbursts, were first encountered in the early 1900s when extensive stopes, supported solely by small reef pillars, reached depths of several hundred meters. Gold-bearing conglomerates were found buried beneath younger strata in the East Rand district in 1914, the Far West Rand and Klerksdorp districts in 1937, the Orange Free State in 1946, and the Kinross district in 1955. The dipping conglomerate “reefs” were found to persist to depths of several kilometers. Rockbursts have remained one of the most serious and least understood problems facing deep mining operations, claiming the lives of thousands of mine workers. Despite many technical advances, rockbursts continue to pose a significant risk (Figure 1).
As the South African gold mining industry expanded and the severity of rockbursts increased, the authorities appointed several committees to investigate the problem.

- In 1908, minor damage in a village near Johannesburg led to the appointment of a committee, chaired by the Government Mining Engineer, to “inquire into and report on the origin and effect of the earth tremors experienced in the village of Ophirton”. The 1908 Ophirton Earth Tremors Committee found that “under the great weight of the superincumbent mass of rock … the pillars are severely strained; that ultimately they partly give way suddenly, and that this relief of strain produces a vibration in the rock which is transmitted to the surface in the form of a more or less severe tremor or shock” (Anon 1915). The 1908 Committee recommended that the support pillars should be replaced by waste packs.

- The 1915 Witwatersrand Earth Tremors Committee was asked to “investigate and report on: (a) the occurrence and origin of the earth tremors experienced at Johannesburg and elsewhere along the Witwatersrand; (b) the effect of the tremors upon underground workings and on buildings and other structures on the surface; (c) the means of preventing the tremors.” The 1915 Committee concluded that “the shocks have their origin in mining operations”, and “while it may be expected that severer shocks than any that have yet been felt will occur in Johannesburg, their violence will not be sufficiently great to justify the apprehension of any disastrous effects” (Anon 1915).

- The 1924 Witwatersrand Rock Burst Committee was appointed “to investigate and report upon the occurrence and control of rock bursts in mines and the safety measures to be adopted to prevent accidents and loss of life resulting therefrom” (Anon 1924). The 1924 Committee made many recommendations concerning general mining policy, protection of travelling ways, and the stoping out of remnants.

- The 1964 Rock Burst Committee was mandated to “study the question of rockbursts and to revise the recommendations of the Witwatersrand Rock Burst Committee (1924)” (Anon 1964). It was considered opportune to conduct a new investigation as “not only had mining depths in excess of 11,000 feet below surface been reached on the Witwatersrand, but the rockburst danger had also revealed itself in the newer mining areas of the Far West Rand, Klerksdorp and the Orange Free State”. The recommendations of the 1964 Committee were based on a considerable body of research and practical observations. The necessity for carrying out further research was noted.

South Africa’s gold production peaked at 1000 t in 1970, while employment on gold mines peaked at 500,000 in the latter half of the 1980s. Mines reached depths exceeding 3.5 km, the greatest mining depths in the world by far. However, rockbursts continued to claim scores of lives each year. Mining-related seismic events first caused serious damage to surface structures in the Free State district when an $M_L=5.2$ seismic event damaged a six-storey apartment block in Welkom on 8 December 1976, which was fortunately evacuated before it collapsed (Figure 2).
Figure 2. Apartment block in Welkom destroyed by an $M_L=5.2$ tremor on 8 December 1976 (photograph 'The Star')
The largest mining-related seismic event recorded in South Africa occurred in the Klerksdorp district on 9 March 2005. The $M_L=5.3$ main shock and aftershocks shook the nearby town of Stilfontein, causing serious damage to several buildings (Figure 3) and minor injuries to 58 people. No. 5 Shaft at DRDGold’s Northwest Operations suffered severe damage, two mineworkers lost their lives, and 3200 mine workers were evacuated under difficult circumstances. The event prompted the Chief Inspector of Mines to appoint an Expert Panel to investigate some wider concerns regarding the risks posed by gold mining, including:

- Does mining, past and present, trigger or induce large seismic events and will it continue to do so in the future?
- Are the technologies available to manage seismicity adequate in the current situation of remnant mining, deeper mines, and mining within large mined-out areas?
- Are current approaches to planning, design, monitoring, and management appropriate and adequate?

Superficially, the issues were similar to those addressed by the earlier committees. However, much had changed since 1964. The South African gold mining industry was mature and production had been falling for the past three decades (only 255 t of gold was mined in 2007, compared with 1000 t in 1970). New problems were faced as mines approached the end of their lives, ceased operation, and were allowed to flood. Many of the cities and towns in the gold mining districts had grown, and several seismic events with $M_L>5$ had caused damage to residential, commercial, and civic buildings. In addition, a great deal of rock mechanics and seismological research had been conducted.

![Figure 3. Buildings in Stilfontein damaged by a $M_L=5.3$ tremor on 9 March 2005 (photograph R.J. Durrheim)](image)

The Expert Panel (Durrheim et al. 2006) concluded that the $M_L=5.3$ seismic event was the result of extensive mining that had taken place over several decades. Seismic events will continue to occur in the gold mining districts as long as deep-level mining takes place, and are likely to persist for some time after mine closure, especially while they flood. Regional and in-mine monitoring networks were found to be on a par with those installed in seismically-active mining districts elsewhere in the world, although measures to improve the quality and continuity of seismic monitoring were recommended, particularly when mines change ownership. A range of technologies available to mitigate the risks of large seismic events was identified, although it was noted that particular care should be taken when mining close to geological features that could host large seismic events.
The Bushveld Complex is the world’s largest resource of platinum group elements. Seismicity only became a source of concern in the 1990s when mining depths approached 1 km. Knowledge and experience gained in gold mines is being adapted and applied in an endeavour to prevent rockbursting becoming a serious problem.
RESEARCH ORGANIZATIONS

The history of private, government and academic organizations that played a prominent role in rockburst research work is briefly summarized in this section so as not to interrupt the research narrative.

The Witwatersrand Chamber of Mines was formed in 1889, only three years after the discovery of gold. It changed its name several times as the mining industry expanded and political structures evolved: to the Chamber of Mines of the South African Republic in 1896, the Transvaal Chamber of Mines in 1900, the Transvaal and Orange Free State Chamber of Mines in 1953, and finally to the Chamber of Mines of South Africa in 1967. The Coalbrook Colliery disaster, in which 435 men died, occurred in January 1960. It is the worst accident in South African mining history. The official enquiry found that there was no scientific basis for the design of pillars in coal mines, and highlighted the need for systematic research. Consequently the Transvaal and Orange Free State Chamber of Mines established a Mining Research Laboratory (later renamed the Chamber of Mines Research Organization, COMRO), to address issues such as pillar design in coal mines and the threats to the gold mining industry of increasing depth and working costs and a stagnant gold price. It was funded on a cooperative basis by the six major mining houses operating in South Africa at that time. By 1986 COMRO employed nearly 700 people, although restructuring in the early 1990s led to the closure of several divisions, a reduction in the staff complement, and finally a merger with the CSIR in 1993.

The Council for Scientific and Industrial Research (CSIR) was founded in 1945. Rock mechanics research was carried out in the National Mechanical Engineering Institute (NMERI). As noted above, COMRO merged with the CSIR in 1993, and the CSIR Division of Mining Technology (Miningtek) was formed with a staff complement of about 250. However, support for mining research continued to decline. The CSIR Centre for Mining Innovation was constituted in 2009, with a research staff complement of about 40.

The University of the Witwatersrand, founded in 1922, has its origins in the South African School of Mines, which was established in Kimberley in 1896 and transferred to Johannesburg as the Transvaal Technical Institute in 1904, becoming the Transvaal University College in 1906, and the South African School of Mines and Technology in 1910. The Bernard Price Institute for Geophysical Research (BPI) was founded in 1936. Bernard Price was an electrical engineer and founder of the Victoria Falls and Transvaal Power Company. Gold mines were a major customer, but power failures owing to electrical storms were a recurrent problem. The BPI initially carried out research in two main fields: thunderstorm, atmospheric and lightning phenomena; and geophysical investigations for which the Witwatersrand was particularly suitable, such as the seismic waves generated by mining-related earth tremors. Researchers at the BPI played a leading role in establishing the discipline of mine seismology. The Department of Geophysics, founded in 1955, complemented the research activities of the BPI and became the base for mine seismology research work after the closure of the BPI in 2003.

The South African National Seismological Network (SANSN), operated by the Council for Geoscience (formerly the South African Geological Survey), was established in 1971. The SANSN monitors the entire country, and presently consists of 23 stations. The earthquake catalogue is complete above local magnitude 2. More than 90 per cent of the located events occur within the gold and platinum mining districts. Eight of the SANSN stations are deployed near these districts, yielding a location error of 1 to 10 km in these regions. Studies of seismic activity have shown that the southern African sub-continent is a tectonically stable intra-plate region, characterized by a relatively low level of natural activity (Brandt et al. 2005).

ISS International Ltd. (ISSI), a company specializing in technologies to monitor and model the rock mass response to mining, was founded in 1990. Directed by Aleksander Mendecki, it has become a world leader in mine seismology technology, with more than 100 systems installed worldwide. ISSI has conducted many research projects for mining companies, SIMRAC and collaborative research programs.

RESEARCH ENDEAVOURS

In this section we chronicle the research work that has been carried out over the last century to determine the cause and mitigate the effects of rockbursts in the deep hard rock mines of South Africa

First surface seismographs (1910)
The first investigation into the causes of mine tremors was conducted in 1908 by the Ophirton Earth Tremors Committee. Based on the recommendations of the 1908 Committee, two seismographs were installed in 1910, one at the Union Observatory in Johannesburg and the other in the village of Ophirton. Seismograms recorded by the 200 kg Wiechert horizontal seismograph at the Union Observatory were analyzed by Wood (1913, 1914), who concluded that the source of the tremors was close to Johannesburg and probably on the Witwatersrand itself. The Ophirton seismograph was moved to Boksburg in 1913, where tremors were beginning to be felt. Philip Gane of the BPI analyzed the diurnal distribution of nearly 15,000 events, and found that their incidence peaked at blasting times (Gane 1939). An analysis of more that 29,000 mine tremors recorded in the period 1938–1949 produced similar results (Finsen 1950, cited by Cook 1976).

First surface seismograph network (1939)
Fatalities due to rockbursts in gold mines remained a serious concern, and in 1938 the Chemical, Mining and Metallurgical Society of South Africa convened a Scientific Discussion Meeting where the need for rigorous scientific research into the fundamental mechanics of rockbursts was recognized. An array of seismographs covering the northern rim of the Witwatersrand Basin was deployed in 1939 by researchers at the newly established BPI. Data were transmitted by radio to a central point, where continuous 24-hour registration coupled with an ingenious device that triggered distant seismographs allowed all the larger mining-related events to be located accurately in space and time (Gane et al. 1953). It was shown that the epicenters of tremors were confined to areas that had recently been mined.

Initiation of coordinated research (1953) and the first underground seismograph network (1961)
By 1948 it had become apparent that isolated and purely practical attempts to solve the rockburst problem were inadequate. The mining methods advocated to minimize rockbursts were subject to compromise and contradiction. For example, the recommended support methods ranged from filling the stopes with waste as solidly as possible, to complete caving of worked-out areas.

In 1953 the Transvaal and Orange Free State Chamber of Mines sought the aid of scientists at the CSIR and the University of the Witwatersrand (particularly the BPI), and assumed sponsorship of all rockburst investigations. The achievements of the program are summarized in a landmark paper by Cook et al. (1966). In retrospect, three overlapping phases can be discerned:

1. Observations of a largely empirical nature, e.g. observations of the pattern of fracturing in laboratory tests and underground, in situ measurements of stress, statistical relationship between mining variables and rockbursts, and networks for seismic monitoring and development of seismic location techniques. The first underground network was installed at East Rand Proprietary Mines (ERPM, see Cook 1963, 1964 and 1976) in 1961 to monitor a kilometer of working face at a depth of 2.5 km (Figures 4, 5 and 6). A similar nine-seismometer network was established at Harmony mine in the Free State goldfields in 1964 (Joughin, 1966). A portable high-resolution seismic network was also used to study de-stressing blasts at ERPM.

2. Attempts to attribute rational significance to the documented experience, e.g. analytical studies based on elastic theory, development of analogue techniques for solving the elastic response of complicated mine outlines.

3. Formulation of a rockburst mechanism. It was postulated that the rock mass was divided into two domains: a region of continuous rock remote from the excavation where behaviour is elastic and predictable, and a region close to the excavation where the behaviour is non-elastic. The transition from the elastic to the non-elastic region involves fracture and the release of energy. A final phase of controlled underground experiments was proposed to test the hypothesized rockburst mechanism and to vary the mining parameters to minimize the effects of rockbursts.
Figure 4. Anatomy of a typical deep Witwatersrand Basin gold mine (a pictorial view of ERPM from Cook et al., 1966)
Figure 5. Delay-time analogue computer used to find focus of seismic events (from Cook et al., 1966)

Figure 6a. Plan (1000 ft grid) of F longwall East and G longwall West, ERPM, and foci of 445 seismic events. (Cook et al., 1966)

Figure 6b. Dip section of F longwall East, ERPM, and foci of located seismic events (Cook et al., 1966)
The Mining Research Laboratory of the Transvaal and Orange Free State Chamber of Mines (founded in 1964 and renamed the Chamber of Mines Research Organization, COMRO) assumed responsibility for rockburst research, which focused on three main areas:

1. **Mine layout**, aimed at minimizing the effect of rock pressure at the design stage. The MINSIM computer program was one of the outstanding research products. Upgraded versions of the boundary element elastic code are still widely used.

2. **Support units and systems**, aimed at reducing falls of ground and the extent of rockburst damage. Rapid-yielding hydraulic props, developed by 1970, were a breakthrough in the support of stopes exposed to seismic activity. Backfilling was another major theme.

3. **Rockburst control**, which was concerned with developing instruments to monitor seismicity and engineering techniques to control the rockburst risk.

COMRO’s contribution to various projects over the next three decades is described below.

**Regional and research seismic networks in the 1970s**

**Klerksdorp Regional Seismic Network**: The increasing level of damage and injuries due to rockbursts in the Klerksdorp mining district led to the establishment of a permanent seismic network in 1971 as a joint venture between the Chamber of Mines and the four mining companies in the area (Van der Heever 1984). Only four seismometers were initially installed, which proved to be too few for accurate locations as the area monitored was about 200 km². By 1982 the network consisted of 32 stations. In addition, an 18-station micro-network was installed to monitor a seismically hyperactive area of 0.1 km². Underground communication was by means of electrical cables up to 10 km long, while surface communication was by radio rather than by wire (Scheepers 1984).

**Western Deep Levels and the Rockburst Research Project**: The first attempt to monitor seismicity at Western Deep Levels mine was in 1965, when a network of surface and underground seismometers was established. The network operated consistently for two periods, March 1966 through February 1967, and January 1969 through May 1969 (Seaton and Hallbauer 1971). A new seismic monitoring system was developed at Western Deep Levels in 1974, and in 1977 the Rockburst Research Project, jointly sponsored by the Chamber of Mines and Anglo American Corporation, was initiated. This system utilized four tri-axial accelerometers to monitor micro-seismic events. Such monitoring could only occur between 20h00 to 6h00 owing to noise from rock drills and blasting. Data was recorded on magnetic tape, which was brought to the surface for playback. In 1979, cables were installed to enable data to be transmitted to the surface where digitizing, processing and storage on digital magnetic tape took place. Brink and Mountfort (1984) reported that four events (Mₘ=0.3, 0.4, 1.5 and 2.5) were predictable in hindsight, and that men could have been withdrawn prior to the events without losing more than one shift, and expressed the opinion that it was possible to “predict rock bursts with confidence”. This prompted a major expansion of the project, with the objective of developing a “real time monitoring system” capable of timely predictions. A pilot project was initiated in 1980. A micro-seismic network consisting of five tri-axial accelerometers was installed to monitor events in the magnitude range -4<Mₘ<0 in a 1 km longwall, and a mine-wide 24 tri-axial geophone network was installed to monitor all events with Mₘ>0.

**Source mechanism studies**: From 1969 to 1979 the BPI team of Art McGarr, Steve Spottiswoode, Rod Green and Nick Gay contributed significantly to the emerging discipline of mine seismology (e.g. McGarr 1971; Spottiswoode and McGarr 1975; McGarr et al. 1975; Gay and Ortlepp 1979 and McGarr et al. 1981). The magnitudes of the stresses driving violent failure and the dimensions of the ruptures in the rock were determined for the first time. It was found that the source mechanism of many mining-induced tremors is similar to the mechanism of shallow natural earthquakes.

**Doornfontein research networks**: During the late 1970s, COMRO installed two research networks at Doornfontein mine (Pattrick, 1984): a 200 m array consisting of 19 geophones to monitor trials of a mechanical non-explosive mining machine; and a 2 km array consisting of 13 geophones to monitor seismic events in a larger area of about 2 km². Data were recorded on two 24-hour magnetic tapes that were played back and digitized in a surface laboratory. In 1981, a 12-channel 20 m array was installed to monitor the non-violent sub-audible fracturing ahead of advancing stopes. All of these networks were temporary, and operated for periods of a few months to a few years.
Routine in-mine monitoring (1978 onwards)
The first fully mine-owned and -staffed seismic network was installed at Blyvooruitzicht Mine in 1978 (Spottiswoode 1984). In 1982 the Gold Fields group established a network on its mines in the Far West Rand region. The collapse of an apartment block in Welkom following an $M_s=5.2$ event on 8 December 1976 prompted Anglo American to install a permanent regional seismic network on its mines in the Free State district. By April 1980, 24 geophones were installed covering an area of about 300 km$^2$, yielding a location accuracy of 300 m in plan and 500 m in depth (Lawrence, 1984).

Quantitative seismology (1990 onwards)
The success achieved during the 1970s and 1980s of using seismology to better understand the source mechanisms of mining-related seismic events led to improvements in mine layouts and support design. Mine seismology moved from the realm of pure research to become a practical and indispensable tool for production purposes. By the early 1990s, real-time seismic monitoring using digital networks had become the standard within deep gold mines. The primary objectives were: (i) rapid response to rockbursts to limit the loss of life, (ii) assessment of the seismic hazard, (iii) back analysis of large and/or damaging seismic events, and (iv) research to improve knowledge of the rockbursting phenomena and support experimental development of technologies to mitigate the risk.

SIMRAC (1991 onwards)
The Safety in Mines Research Advisory Committee (SIMRAC) was established in terms of the Minerals Act (Act 50 of 1991) with the principal objective of advising the Mine Health and Safety Council (MHSC) on the determination of the safety risk on mines and the need for research. SIMRAC has the responsibility to identify research projects, impose a levy on mines to fund such research, conclude agreements for carrying out such projects with research organizations, monitor project progress, and communicate the results of research to all parties concerned. SIMRAC identified rockbursts and rockfalls as serious safety hazards, particularly in gold mines. From 1991 to 2004, more than R250 million was spent on rock-related research, representing some 500 man-years of effort. This large body of work, mostly carried out by CSIR Miningtek and ISSI, is briefly summarized below. For a more comprehensive reviews see Adams and Van der Heever (2001) and Durrheim et al. (2005).

1. Basic scientific research
   This was conducted to determine the properties and behavior of the rock mass and the engineering materials that are used to stabilize and support it.
   • Rock properties and rock mass behavior: Research work involved field and laboratory investigations and numerical simulations. Advanced computer codes, such as WAVE (simulation of wave propagation and the elastodynamic interactions between faults and stopes) and DIGS (simulation of large-scale assemblies of interacting cracks), were developed and used to improve the fundamental understanding of rock failure mechanisms (Napier et al. 1995, 1998 and 2002).
   • Mine seismology: Techniques were developed to analyze seismograms and seismicity patterns. Early work concentrated on the quantitative description of the seismic source and seismicity (e.g. Mendecki et al. 1996), with attention subsequently being given to the rockburst damage mechanism (e.g. Durrheim et al. 1998). Attempts were made to predict seismic events, but the success rate was not high enough to be used to withdraw crews on a routine basis (De Beer 2000). The focus then turned to the management of risk through the continuous assessment of the seismic hazard, the creation of rockburst-resistant excavations through optimum layouts and support systems, and the integration of seismic observations with numerical modeling to achieve better simulations of rock mass behavior (e.g. Mendecki et al. 2001).

2. Engineering research
   This was conducted to produce practical methodologies and technologies to improve safety.
   • Layouts and design criteria: There was a major change in layout philosophy in deep gold mines in the early 1990s - the favored orientation of stabilizing pillars changed from strike to dip, as the pre-development of tunnels allowed hazardous structures to be detected and bracket pillars to be planned prior to stoping (Vieira et al. 2001). These new layouts were evaluated, as well as other regional support systems such as backfill and bracket pillars. Considerable work went into the development of reliable mine design criteria. The validity of concepts such as Energy Release Rate
(ERR), Excess Shear Stress (ESS) and Volumetric ESS were tested, and the concepts expanded or new concepts introduced (e.g. Generalized ERR, Local Energy Release Density).

- **Support components and systems:** Many new components and systems were evaluated. Pre-stressed yielding elongates and packs made of synthetic materials were widely introduced, while thin spray-on liners were evaluated as a possible replacement for shotcrete. A new methodology to design stope support systems was developed (Roberts et al. 1995) and widely implemented.

- **Mining methods:** Preconditioning was field-tested. It was demonstrated to reduce the hazard of face-bursting and was widely implemented.

3. **Transfer of knowledge and technology.**
   - Reports are available on CD and or may be downloaded from the website [http://www.mhsc.org.za/](http://www.mhsc.org.za/).
   - A small library of Textbooks and Guidelines has been published.
   - Numerous product launches, seminars and workshops have been held.

4. **Implementation**

Several projects sought to support the industry implement research findings and new technologies. For example, problems associated with the use of rapid yielding hydraulic props were investigated (Glisson and Kullmann, 1998), and methods for training underground workers in strata control were developed (Johnson et al., 2000 and 2002).

A study was commissioned to assess the scope, quality, and impact of South African rock-related research in general, and the SIMRAC research program in particular (Durrheim et al. 2005). The review team concluded that SIMRAC had succeeded in identifying the major research needs and had coordinated a comprehensive program of research. In particular, it was found that SIMRAC-sponsored research had contributed to the development of several important new technologies, such as systems for seismic monitoring and analysis, dip-pillar mining layouts, pre-conditioning, and pre-stressed elongates. Furthermore, SIMRAC-sponsored research had also contributed to the work of the collaborative research programs and the formulation of the mandatory "codes of practice to combat rockfall and rockburst accidents". The relatively small impact of the research effort on safety statistics was attributed to the increasing depth of mining, the increasing proportion of remnant and pillar mining, the failure to achieve short-term prediction, the long lead-time for new knowledge to be implemented, and shortcomings in the knowledge and technology transfer process. It was noted that some of the work was of a very high quality, attested by the award of Rocha Medals to four CSIR researchers between 1999 and 2005, viz. Arno Daehnke, Francois Malan, Lindsay Linzer and Mark Hildyard. (Rocha Medals have been awarded annually since 1982 by the International Society of Rock Mechanics for an outstanding PhD thesis. Richard Brummer of COMRO was awarded a Medal in 1990.)


The *DeepMine Collaborative Research Program*, which sought to create the technological and human resources platform to mine gold safely and profitably at depths of 3 to 5 km, was initiated by Güner Gürtunca, Director of CSIR Miningtek, in 1998. The 5-year R66 million program of research was sponsored by AngloGold, Durban Roodepoort Deep, Gold Fields, the Chamber of Mines of South Africa, CSIR, and the Department of Trade and Industry. Research work that directly addressed the rockburst risk, mostly carried out by CSIR Miningtek and ISSI, is briefly reviewed below using the DeepMine research methodology as a framework (for a more comprehensive review see Durrheim 2007).

1. **Define the ultra-deep environment**
   - No new rock types are expected at ultra-depth, although the thicknesses of the various strata are expected to change, and the ore body to become increasingly quartzitic. Although the intensity of fracturing and convergence is expected to increase significantly with depth, the size of the fracture envelope will remain much the same.
   - The relationship between the depth of mining and seismic activity was investigated using data acquired in the Carletonville district, where the same reef has been mined from 150 m to 3400 m below surface. The relationship was not robust enough to make firm predictions about the level of seismicity at ultra-depth.

2. **Establish systems criteria**
3. **Assess if currently available technologies meet the systems criteria**
   - An assessment of the effect of face advance rate on seismicity indicated that the maximum safe mining rate is dependent on the geotechnical area. Slightly higher mining rates may be sustained at ultra-depth without an increase in the hazard of face bursting because time-dependent fracture processes will take place more rapidly.
   - An assessment of the effect of the mining method (e.g. drill and blast, continuous non-explosive rock breaking) on seismicity indicated that the overall seismic hazard, which is dominated by the larger seismic events, is independent of the rock-breaking process.
   - An assessment of seismic prediction capability indicated that while predictions were better than random, this was not sufficiently reliable for implementation as a management tool.
   - Commonly used rockburst-resistant support systems (e.g. yielding timber elongates, or timber packs with rapid yielding hydraulic props, or backfill and rapid yielding hydraulic props) were shown to meet the systems criteria for the support of narrow stope at ultra-depth, although areal coverage would become increasingly important as depth increases.

4. **Conduct research**
   - Fill the knowledge or technology gaps if the ultra-deep environment or systems criteria were not known or the currently available technology did not meet the criteria.
   - Stress was successfully measured at a depth of 3352 m, 700 m deeper than any previous stress measurement in a South African gold mine.
   - A new methodology was developed to estimate the seismic hazard at ultra-depth, based on the concept of Volumetric Energy Release and Potential Damage Area.
   - Borehole radar technology was developed to detect hazardous structures in environments, such as the Venterdorp Contact Reef, where favourable electrical property contrasts exist between the footwall rocks and the overlying lavas (Du Pisani and Vogt 2004). Small faults and other changes in reef topography could be accurately located, giving prior warning of changes in mining conditions.
   - A holistic strategy to manage seismicity was formulated. The proposed strategy had three main components: (i) reduction of seismicity by using geophysical methods to identify seismogenic structures (dykes, faults) ahead of mining, and design the layouts accordingly; (ii) the use of appropriate support systems to create rockburst-resistant excavations; and (iii) the continuous monitoring of seismic hazard. It was concluded that it would be possible to adapt rock engineering technologies (mine layouts, stope and tunnel support systems, etc.) to manage the levels of seismicity expected at ultra-depth, provided there was foreknowledge of potentially seismogenic structures (Durrheim, 2001).

**Semi-controlled earthquake-generation experiments (SeeSA, 1995-present)**
In 1991 Louis Nicolaysen, Director of the BPI, submitted a proposal “Semi-controlled experiment on seismic events” to the International Association of Seismology and Physics of the Earth’s Interior (IASPEI), which was taken up by the Japanese seismological community. Since 1995 Japanese-South African cooperative research projects have been monitoring the earthquake generation process in close proximity to hypocenters (e.g. Ogasawara et al. 2002 and 2009; Yamada et al. 2005 and 2007). Amongst the significant observations were large, sudden changes in strain associated with large events (Ogasawara et al. 2005), and strain forerunners of seismic events (Yasutake et al. 2008).

**KNOWLEDGE DISSEMINATION**
Several landmark publications have documented advances in understanding of the causes of rockbursts and the development of measures to mitigate the risk. The Association of Mine Managers published two volumes (1933 and 1975) containing papers and discussions addressing the rockburst issue. *An Industry Guide to Methods of Ameliorating the Hazards of Rockfall and Rockbursts* (Anon, first edition 1977; second edition 1988) was prepared by COMRO at the request of the Association of Mine Managers. These guides summarized the state of the art of rock engineering in South African tabular hard rock

Several noteworthy conferences addressing the rockburst issue have been held in South Africa. The Association of Mine Managers of South Africa held the Symposium on Strata Control and Rockburst Problems of the South African Goldfields in 1972. The First International Symposium on Rockburst and Seismicity in Mines was held in 1982 and the Fifth Symposium in 2001, the quadrennial symposium becoming the prime international venue for the sharing of rockburst research (see review by Ortlepp, 2005). The Tenth Congress of the International Society of Rock Mechanics and the Second International Seminar on Deep and High Stress Mining were held in Johannesburg in 2003 and 2004, respectively.

Figure 7. Cover of the “Rockfall and Rockburst Guide” (Anon, 1988) showing some of the technologies used to ameliorate the seismic hazards, viz. rapid yielding hydraulic props, timber packs, computer simulations of mine layouts, and backfill.

CONCLUSION

Gold was discovered in 1886 near present-day Johannesburg, and mine tremors soon posed a risk. The first scientific measurements of mining-related seismic events were made with a seismograph in 1910, exactly a century ago. Efforts to understand the causes of mining-related seismicity and to mitigate the effects of rockbursts were first coordinated in the 1950s, when the Chamber of Mines mobilized experts at CSIR and the University of the Witwatersrand to research the phenomena. Over the next half century, COMRO, CSIR, the BPI, ISSI and other research organizations devised new mine layouts, improved
support elements and systems, and developed real-time digital seismic networks to monitor the response of the rockmass to mining (Figure 8). Mining at depth would have been impossible without these advances, and a significant reduction in fatalities and injuries has been achieved.

Not all research efforts have been successful. An obvious means of reducing the rockburst risk would be to reduce the exposure of workers to hazardous conditions in the face area. Numerous rock-breaking technologies have been tested in the past two decades under the auspices of COMRO, CSIR and various collaborative research programs. These range from incremental improvements to the conventional drill-and-blast method (rigs, jigs and remote controls) and long-hole drilling, to fully-mechanized narrow reef mining systems (impact rippers, activated and mini-disc cutters) and low-energy explosives and propellants. While some technical successes were achieved, none of these methods have been implemented on a large scale.

South Africa’s gold production peaked at 1000 tonnes in 1970. Inevitably, ore bodies have been depleted and production has declined to about 250 tonnes, levels that are comparable with the output in the 1920s. Public and private for rockburst research has also reduced, so it is not surprising that the research capacity has declined drastically. COMRO and the BPI have closed, as have laboratories for the testing of rock properties, support elements, and backfill. One positive result is that many researchers have joined the ranks of practitioners and collaborators, aiding the transfer of knowledge.

Figure 8. Example of a modern seismic report sheet used for monthly planning (figure courtesy of ISSI and TauTona gold mine). Short-term hazard assessments are also issued daily.

Nevertheless, there are several very good reasons why the capacity to do research into mining at deep and high-stress conditions should not be lost. Gold continues to make a significant contribution to the South African economy through wages, tax and foreign exchange earnings. Furthermore, it is estimated that South Africa hosts 40 per cent of the world’s gold resource (Chamber of Mines, 2007), much of it in reefs that were below pay limits at the time of mining or that are at ultra-depth. The gold price has climbed
to record levels in recent years, which could make the mining of these resources attractive. The Bushveld Complex hosts almost 90 per cent of the world's platinum group metal resources (Chamber of Mines, 2007), and output has expanded tremendously in recent decades. Mining is already reaching the depths where seismicity poses a risk. The latest published statistics (Chamber of Mines, 2007) report that in 2007 the South African gold and platinum mines employed 169 057 and 186 411 people, respectively, while fatality and injury rates remain higher than international safety benchmarks.

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**BIBLIOGRAPHY**

Chronological list of MSc and PhD theses that address the cause and mitigation of rockbursts in South African mines.


