History of Endeavours to Mitigate the Rockburst Risk in South African Mines

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ABSTRACT: Gold was discovered near present-day Johannesburg in 1886. Mining-induced seismicity was first encountered in the early 1900s when extensive stopes reached depths of several hundred meters. The State appointed committees in 1908, 1915, 1924, 1964 and 2005 to investigate the cause of the tremors and to recommend mitigating measures. The 1908 Committee recommended that seismographs be installed and scientific observations began in 1910. The main mitigating strategies that were developed were: (i) mining layouts and regional support systems (e.g. strike and dip pillar systems, backfill) that controlled the release of seismic energy through the geometry and sequence of mining; (ii) local support units and systems (e.g. rapid-yielding hydraulic props, pre-stressed elongates, yielding tendons) that limited rockburst damage; and (iii) seismic monitoring technology that continually assesses the hazard and the effectiveness of measures to 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 of 4 kilometers.

1. RISKS POSED BY ROCKBURSTS

Gold was discovered in 1886 in quartz pebble conglomerates that crop out near present-day Johannesburg (Figure 1). As mining operations followed the ore body, the dipping "reefs" were found to persist to great depths. Today mining is taking place 4 km below the surface. The conglomerates had been deposited on the rim of an Archean sedimentary basin, which is largely covered by younger strata. The reefs were traced by geological inference and geophysical mapping, and new gold fields were discovered in the East Rand district in 1914, the Far West Rand and Klerksdorp districts in 1937, the Free State in 1946, and the Kinross district in 1955.

Handley, 2004

Cartwright & Cowan, 1978

Figure 1. Early mining near Johannesburg

The Witwatersrand Basin has produced almost one-third of the gold ever mined (Handley 2004), although the human cost has been enormous. 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. In 1961 Dr H Simmons wrote, *"Thirty-six thousand men have been killed in accidents on the gold mines since the beginning of the century"* (Simmons, 1960). In the 2012 report of the Department of

Mineral Resources to the Parliamentary Portfolio Committee, it was stated that 75,000 lives had been lost in mining accidents since 1900. Note that this figure refers to the entire sector, although gold mines are certainly the largest contributor to this toll. About half of the fatalities on gold mines are “rock-related”, divided roughly equally between gravity-driven “falls of ground” and seismically-driven “rockbursts”. Rockbursting remains one of the most serious and least understood problems facing deep mining operations (see Figure 2) and continues to pose a significant risk, despite many technical advances. As the South African gold mining industry expanded and the severity of rockbursts increased, the State appointed various committees to investigate the origins of the tremors and to recommend mitigating measures.

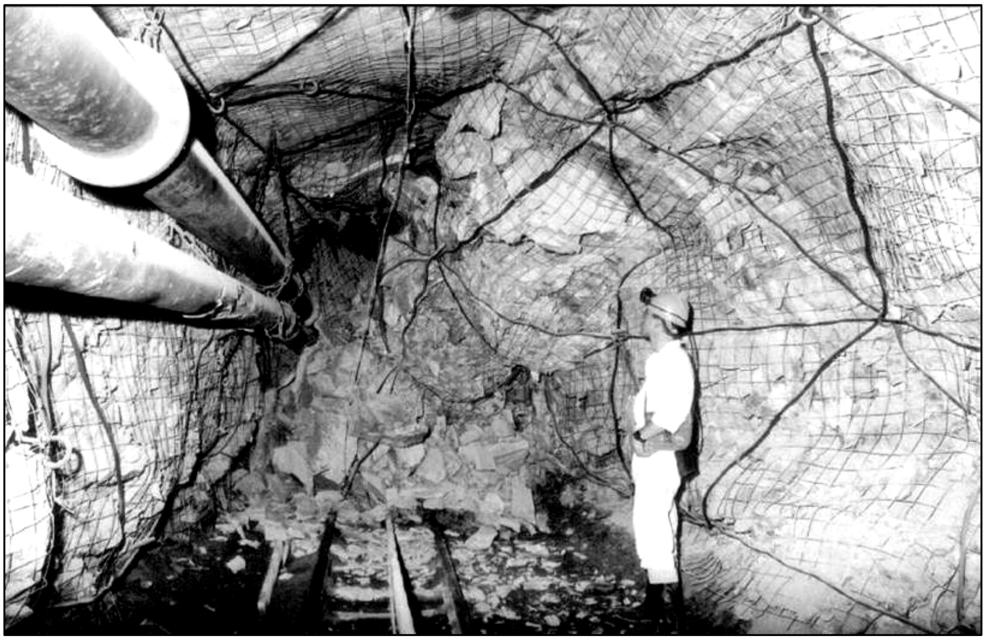


Figure 2. Tunnel in a deep South African gold mine damaged by an M_L=3.6 tremor (photograph W.D. Ortlepp)

1908 Ophirton Earth Tremors Committee: 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 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, and that seismographs should be installed.

1915 Witwatersrand Earth Tremors Committee: The 1915 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).

1924 Witwatersrand Rock Burst Committee: The 1924 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.

1964 Rock Burst Committee: The 1964 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.

2005 Expert Panel: The largest mining-related seismic event ever recorded in South Africa occurred on 9 March 2005 in the Klerksdorp district. The M_L5.3 main shock and aftershocks shook the nearby town of Stilfontein, and caused serious damage to several buildings and minor injuries to 58 people (Figure 3). 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.

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

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: (a) Does mining, past and present, trigger or induce large seismic events and will it continue to do so in the future? (b) Are the technologies available to manage seismicity adequate in the current situation of remnant mining, deeper mines, and mining within large mined-out areas? (c) Are current approaches to planning, design, monitoring, and management appropriate and adequate? Superficially, the issues addressed by the 2005 Panel were similar to those addressed by earlier committees. However, much had changed since 1964. A large gold resource, together with developments in technology that addressed the risks posed by increasing rock stress and temperature, had made mining possible at depths exceeding 3.5 km (the greatest mining depths in the world by far). South Africa's gold production peaked at 1000 t in 1970, and employment on gold mines peaked at 500,000 in the latter half of the 1980s. Since then gold production and employment has declined as the ore body has been mined out. [Only 191 tons of gold was mined in South Africa in 2010, according to the Chamber of Mines (2011b).] New problems arose 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.

The Expert Panel (Durrheim et al. 2006) concluded that the 9 March 2005 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. The Expert Panel noted that a range of technologies were 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.

South Africa is also home to the Bushveld Complex, 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.

2. RESEARCH

Seismology started to emerge as a quantitative science in the last decade of the nineteenth century, and its methods were soon used to investigate mining-related tremors in South Africa. Ben-Menahem (1995), in his concise history of seismology, describes developments in theory (such as continuum mechanics), technology (such as the invention of the mechanical seismograph and digital computer), and observations (such as those produced by the World-wide Standard Seismograph Network, WWSSN) that led to quantum advances in the understanding of earthquakes. Not only has South African mine seismology has drawn on these advances in science and technology, but the deep mines provide a "laboratory" where the physics of earthquakes can be studied at close range, attracting researchers from Europe, Japan and the USA.

2.1 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 opposed by increasing depth and working costs and a stagnant gold price. COMRO was funded on a cooperative basis by the six major mining houses operating in South Africa at that time. In 1986 COMRO employed nearly 700 people. COMRO was restructured in the early 1990s. Several divisions were closed, the staff complement was reduced, and in 1993 it merged with the CSIR.

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 to form the *CSIR Division of Mining Technology* (Miningtek) 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 Geophysics) was founded in 1936. Price was an electrical engineer and the 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. BPI Geophysics was mandated to carry out research in two main fields: thunderstorm, atmospheric and lightning phenomena; and geophysical investigations for which the Witwatersrand was particularly suitable, such as mining-related earth tremors. Researchers at BPI Geophysics played a leading role in establishing the discipline of mine seismology. During World War II, BPI Geophysics became a centre for radar research. The *Department of Geophysics*, founded in 1955, complemented the research activities of BPI Geophysics and became the base for mine seismology research work after its closure in 2003. The University of the Witwatersrand is seeking to revitalize its engagement with the mining industry and working to establish a large-scale world-class institute for mining, minerals and exploration research. The institute will be launched in July 2012.

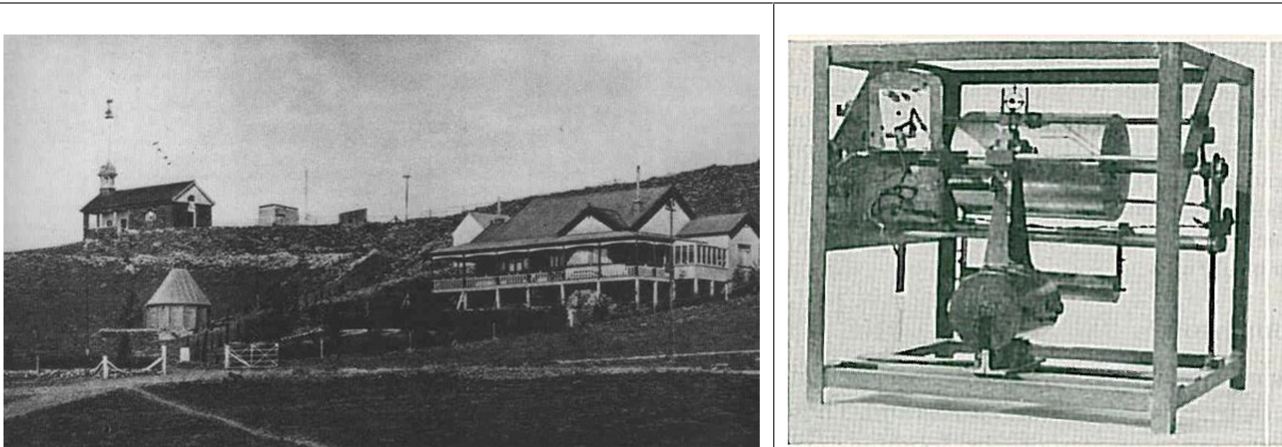
The *South African National Seismological Network* (SANSN), operated by the *Council for Geoscience* (formerly the South African Geological Survey), was established in 1971. The SANSN monitors the entire country, and presently consists of 23 stations. The earthquake catalogue is complete above local magnitude 2. 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). More than 90 per cent of the 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. Since 2010 the CGS has established several local networks to monitor mining-related seismicity in the Central Rand, Far West Rand, and Klerksdorp gold mining regions.

ISS International (ISSI), a company specializing in technologies to monitor and model the rock mass response to mining, was founded in 1990. ISSI 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, as well as a programme of self-funded research. In 2010, the *Institute for Mine Seismology* (IMS) bought the businesses and assets of ISS International and ISS Pacific.

2.2 Research efforts to address the rockburst problem

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

2.2.1 Deployment of the 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 (Figure 4) and the other in the village of Ophirton. Seismograms drawn 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 BPI Geophysics 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).



(a) **(b)**

Figure 4. (a) The Government Meteorological Department in the Johannesburg in 1905, better known as Union Observatory and later named the Republic Observatory (image, Africana Museum) (b) 200 kg Wiechert horizontal component seismograph (Gane et al., 1946, Figure 1)

2.2.2 Deployment of the first surface seismograph network (1939)
In January 1938 Oscar Weiss published a 52 page paper entitled “the theory of rockburst and the possibilities of geophysical methods in predicting rockbursts on the producing mines of the Witwatersrand” (Weiss, 1938). These topics remain the subject of research to this day. 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. The inadequacies of the single station seismograph were recognized, and a network of five seismographs was deployed on the northern rim of the Witwatersrand Basin in 1939 by researchers at the newly established BPI Geophysics. 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. 1946). Epicenters were determined used a “string analogue” technique (Figure 5) rather than by complicated arithmetic, and it was shown that the epicenters of tremors were confined to areas that had recently been mined. Electrostatic seismometers especially designed to meet the criteria for monitoring mine tremors were built at BPI Geophysics (Gane, 1949).

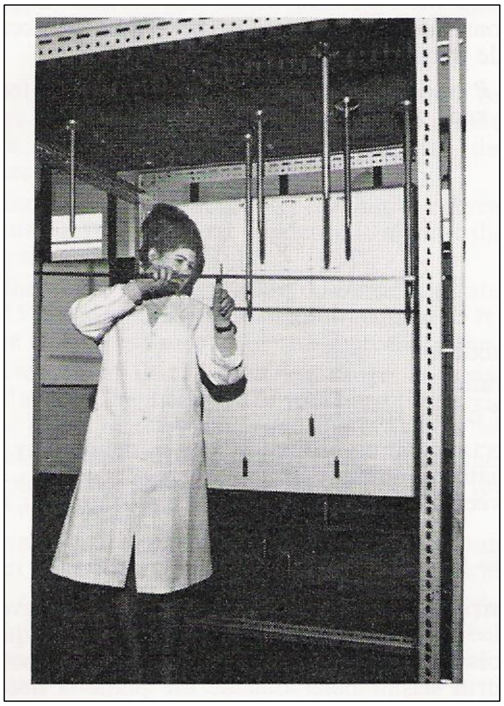


Figure 5. Delay-time analogue computer used to find focus of seismic events (from Cook et al., 1966)

2.2.3 Initiation of coordinated research (1953); deployment of the first underground seismograph network (1961)

The anatomy of a typical deep Witwatersrand mine is shown in Figure 6, showing the change in mining methods from pillar mining at shallow depths, scattered mining at intermediate depths, and longwall mining at great depth.

It had become apparent that isolated and purely practical attempts to solve the rockburst problem were inadequate. The mining methods that were 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 the complete caving of worked-out areas.

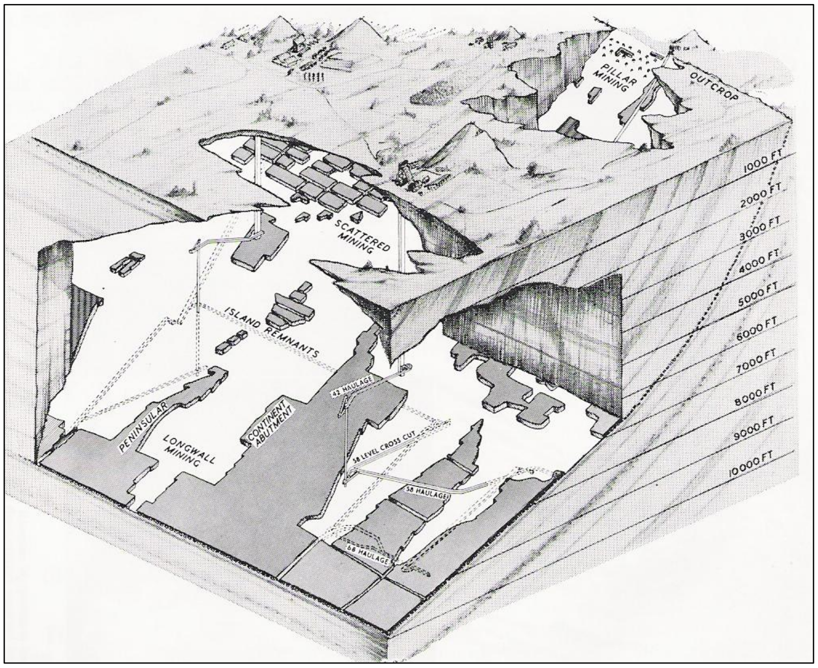


Figure 6. Pictorial representation of East Rand Proprietary Mines (from Cook et al., 1966)

In 1953 the Transvaal and Orange Free State Chamber of Mines enlisted the aid of scientists at the CSIR and the University of the Witwatersrand (particularly BPI Geophysics), 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 of research can be recognized, and a fourth phase was proposed:

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 seismic network was installed at East Rand Proprietary Mines (ERPM) in 1961 to monitor a kilometer of working face at a depth of 2.5 km (Cook 1963, 1964 and 1976). Figure 7 shows the occurrence of seismicity at ERPM. 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.
4. *Controlled underground experiments.* A final phase of research was proposed that involved experiments designed to test the hypothesized rockburst mechanism, and to vary mining parameters in attempts to minimize the effects of rockbursts.

(a) (b)

Figure 7. (a) Plan (1000 ft grid) of F longwall East and G longwall West, ERPM, and the foci of 445 seismic events. (b) Dip section of F longwall East, ERPM, and foci of located seismic events. Figures from 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. In a special 1989 issue of *Mining Survey* to commemorate the centenary of the Chamber of Mines, three focus areas of rockburst research were identified:

1. *Mine layout*, aimed to minimize 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 to reduce 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*, aimed to develop instruments to monitor seismicity and engineering techniques to control the rockburst risk.

2.2.4 Establishment of regional and research seismic networks (1970s onwards)

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). Four seismometers were initially installed. This proved to be too few to provide accurate locations over an area of about 200 km^2. By 1982 the network had been expanded to 32 stations. In addition, an 18-station micro-network was installed to monitor a seismically hyperactive area of 0.1 km^3. 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 made in 1965. A network of surface and underground seismometers was established, which 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 during the working shift. 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 (M_L=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 $-4<M_L<0$ in a 1 km longwall, and a mine-wide 24 tri-axial geophone network was installed to monitor all events with $M_L>0$.

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 km^2. 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.

“Golden decade” of mine seismology at BPI Geophysics (1969-1979)
From 1969 to 1979 the BPI Geophysics 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). Much of this work was carried out at ERPM. 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. This work provided the scientific basis for routine min-mine monitoring.

2.2.5 Routine in-mine monitoring (1978 onwards)

The collapse of an apartment block in Welkom following an M_L=5.2 event in 1976 (Figure 8) 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). The first seismic network that was fully owned and staffed by a mine was installed at Blyvooruitzicht Mine in 1978 (Spottiswoode 1984). In 1982 the Gold Fields group established a seismic network on its mines in the Far West Rand region (Riemer, 1982).

Figure 8. Apartment block in Welkom that collapsed following an M_L=5.2 tremor on 8 December 1976 (The Star)

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. The state-of-the art in the late 1980's is summarized in the COMRO Industry Guide (Figure 9).

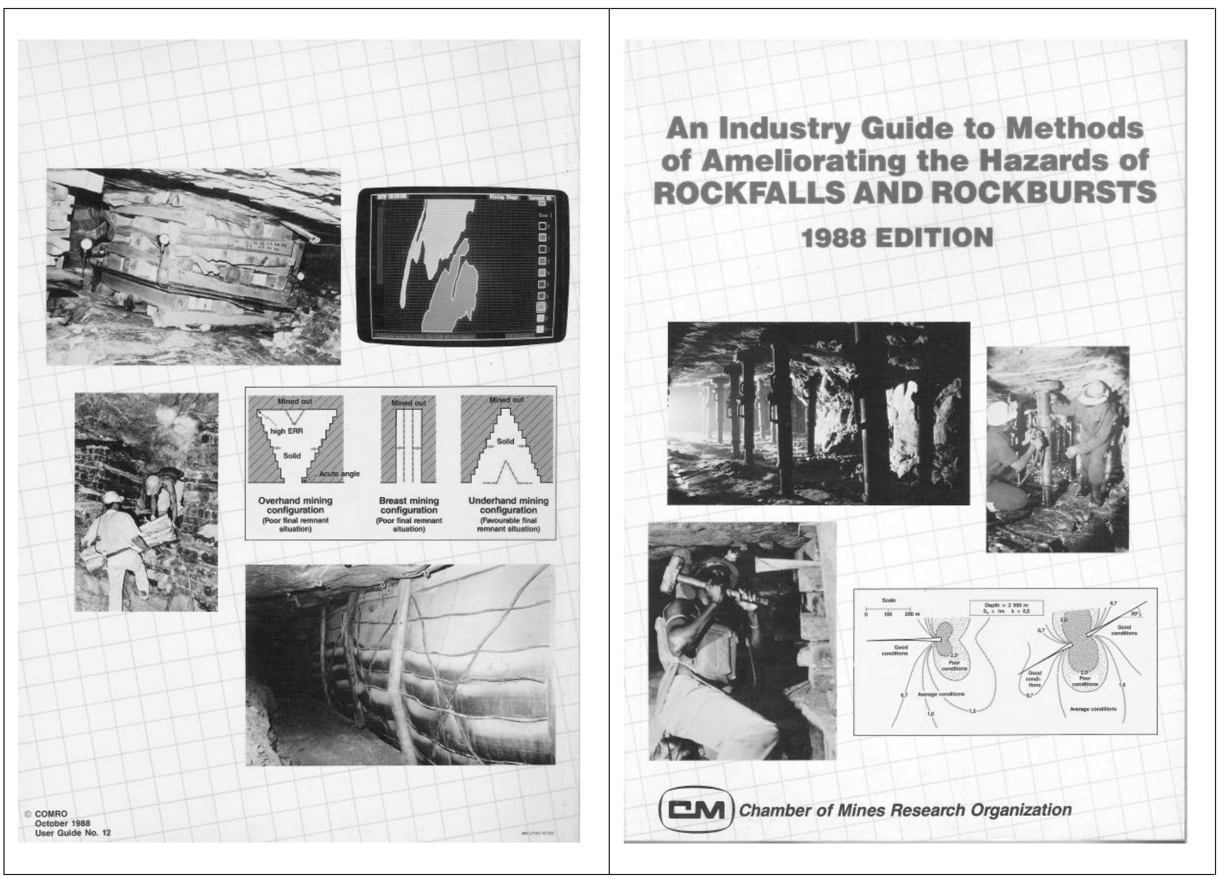


Figure 9. Cover of the COMRO "Rockfall and Rockburst Guide" (Anon, 1988) showing some of the technologies developed to mitigate the risks posed by rockbursts, *viz.* rapid yielding hydraulic props, pre-stressed timber packs, computer simulations of mine layouts, and backfill.

2.2.6 Quantitative seismology (1990 onwards)

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 rockburst phenomena and to support experimental development of technologies to mitigate the risk. Major initiatives are described below

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 comprehensive reviews see Adams and Van der Heever (2001) and Durrheim et al. (2005).

The *DeepMine Collaborative Research Program (1998-2002)*, 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 was mostly carried out by CSIR Miningtek and ISSI. For a comprehensive review see Durrheim (2007).

Semi-controlled experiment on seismic events (SeeSA, 1995-2010). 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, 2009a; Yamada et al. 2005, 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).

JST-JICA Science and Technology Research Partnership for Sustainable Development (SATREPS, 2010 – present) A 5-year Japan—South Africa collaborative project (~US$3 million) entitled "Observational studies to mitigate seismic risks in mines" was launched in August 2010 (Ogasawara et al., 2009b, Durrheim et al., 2010). The project has three main aims: (i) To learn more about earthquake preparation and triggering mechanisms by deploying arrays of sensitive sensors within rock volumes where mining is likely to induce seismic activity.; (ii) To learn more about earthquake rupture and rockburst damage phenomena by deploying robust strong ground motion sensors close to potential fault planes and within mining excavations, and (iii) To upgrade the South African surface national seismic network in the mining districts (Durrheim et al., 2012). To our knowledge this is the most ambitious observational mine-seismology research project ever undertaken in terms of the number of sites and sensor and the scope of research.

3. CONCLUSION

Gold was discovered in 1886 near present-day Johannesburg. As mines deepened, mine tremors posed a risk. The State instituted a committee in 1908 to investigate the cause of the tremors and to recommend measures to mitigate their effects. Research was recommended, and the first scientific measurements of mining-related seismic events were made with a seismograph in 1910. 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. The Chamber of Mines established its own research organization in 1964. Research organizations and practitioners 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. Mining at depth would have been impossible without these advances, and a significant reduction in fatalities and injuries has been achieved.

These efforts have not eliminated the rockburst risk entirely. An obvious means of the risk further is 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 (e.g. 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. Anglogold Ashanti has recently announced the establishment of a technology innovation consortium that seeks to implement alternative and unconventional mining technologies that will reduce the exposure of workers to hazardous environments in deep mines (Cutifani, 2012). An ambitious five-year research programme "Observational studies to mitigate seismic risks in mines" was initiated in 2010. It is funded by the Japanese government, CSIR, Council for Geoscience, Department of Science of Technology, South African Research Chairs Initiative and the University of the Witwatersrand.

South Africa's gold production peaked at 1000 tons in 1970. Inevitably, ore bodies have been depleted and production has declined to under 200 tons, levels that are comparable with the output in the 1920s. Public and private support 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.

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. The latest published statistics (Chamber of Mines, 2011a, 2011b) report that in 2010 the South African gold and platinum mines employed 157 019 and 181 969 people, respectively, while fatality and injury rates remain higher than international safety benchmarks. 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 12 per cent of the world's gold reserves (Chamber of Mines, 2011b), while additional resources are contained 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), output has expanded tremendously in recent decades, and mines are already reaching the depths where seismicity poses a risk.

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