Mining seismicity in the Witwatersrand Basin: monitoring, mechanisms and mitigation strategies in perspective

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Abstract: The Kaapvaal Craton in South Africa hosts one of the largest gold placer deposits in the world. Mining in the Witwatersrand Basin here has been the source of about one third to one half of the gold ever produced in the world. Gold was discovered in the Johannesburg area in 1886 and after 120 years of continuous operation, mining is currently approaching depths of 4 000 m. In spite of the challenges and risks that the industry has had to deal with including rock temperature, ventilation and water, one of the most feared hazards in the basin has been the threat from the ongoing occurrence of seismicity and rockbursts. The problem first manifested itself by way of the occurrence of tremors roughly twenty years after the commencement of mining operations. This paper traces the history of the approach to rockbursts and seismicity during the 120 year history of mining in the basin. It portrays a picture of the mining seismicity in terms of monitoring phases, mechanisms and mitigation strategies. The work of research organizations over the years is highlighted with a brief mention of current regulation strategies on the part of the mining inspectorate.

Key words: Witwatersrand Basin; monitoring; mechanisms; mitigation; prevention; protection; prediction

1 Introduction

Mining is the arduous task that mankind has allotted himself for the extraction of elements from the crustal regions of the planet. These elements, such as minerals, metals and fossil fuels, have in fact been so discretely placed by earth processes and geological agents over earth time history, that in order to retrieve them, miners must sometimes negotiate unfamiliar environments that present new risks. Coal miners face the threat of methane explosions and wind blasts and as mining edges deeper below surface, the risk of "rockbursts" becomes apparent. Mining it could be said, remains one of mankind's oldest and most dangerous pursuits (Ortlepp, 2005).

Historically, gold has been one of the most sought after precious metals for jewellery and coinage. It is estimated that between one third to half of total global gold production (165 000 tons) has come from one of the world's largest sedimentary deposits located at the southern tip of Africa, i.e. the Witwatersrand Basin (Handley, 2004). In spite of the ongoing seismicity and numerous other hazards,

mining in this deposit has continued for 120 years and is currently approaching depths of 4 000 m.

This paper is an attempt to review the seismicity in the basin from the perspective of its history. In view of the vast developments that have accompanied both the mining along with global and mining seismology over the 120 year history, the survey cannot claim completeness. The back analysis has sought to highlight the major components of this development and the authors are of the opinion that is best done using three basic categories. The mine seismology in the basin is therefore presented in terms of the monitoring, mechanisms and mitigation strategies. A brief overview of the geology and mining in the basin is first provided as a background to this three tier review. Some reference is also made concerning the research bodies that have provided the pivotal role needed in formulating mitigation strategies by turning data into knowledge. Mention is also made of the recently adopted government strategy of regulating the industry through legislation.

2 Geology and the Witwatersrand Basin

The study of geology may well date back to the period around 370 BC when Theophratus (see

Wikipedia), a Greek successor of Aristotle, apparently wrote his work on stones ("Peri Lithon"). Regardless of the concern for dates, what geology has taught us is that the occurrence of minerals and noble metals on planet earth lies scattered throughout its 4.5 Ga geological history.

The world wide occurrence of gold is essentially restricted to two types of deposits. Primary deposits, which are of a hydrothermal or chemical nature, generally occur in igneous and/or metamorphic terrains such as granite complexes and ancient "greenstone belts". Secondary deposits that are sedimentary in nature have the primary deposits as their immediate sources. Deposits that have accumulated in this way through weathering and mechanical concentration and which contain valuable heavy minerals are called placers.

In South Africa, the 2.8 Ga Witwatersrand Basin on the Kaapvaal Craton comprises one of the world's largest gold placer deposits. This elliptical basin stretches over an arc of roughly 400 km traversing across the Free State, North West and Gauteng provinces in South Africa as shown in Fig. 1. Most of the basin is covered by younger sedimentary and volcanic rocks such as those making up the Ventersdorp and Karoo Supergroups. Mining here in this basin has attracted, and continues to attract worldwide attention.
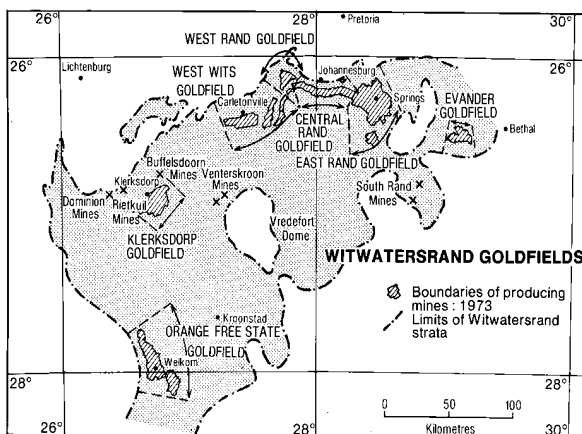

Fig. 1 Location of goldfields within the Witwatersrand Basin (1973) with limits of Witwatersrand strata (Pretorius, 1975).

The gold in this basin occurs in the coarse grained conglomerates forming the upper portions of the "Witwatersrand Supergroup" that hosts roughly 7 000 m of sedimentation. It is found here in association with uranium, quartz, carbon seams, phyllosilicates and pyrite. The mineralization of the Witwatersrand reefs is extensive and a total of

seventy ore minerals, including diamonds, have been documented from the Witwatersrand conglomerates (Feather and Koen, 1975).

The Witwatersrand rocks and the gold contained in them have always entertained much debate as to their origin. Pretorius (1975) has noted one of the accounts of the beginnings of the Witwatersrand goldfields that clarify this debate, i.e. "*that the main reef group of gold bearing conglomerates was stumbled across on a Sunday morning, that there was general agreement by the Wednesday afternoon as to the discovery's being of unprecedented significance, and that by the Saturday evening a violent controversy was well under way as to what had been found.*" Skinner and Merewether (1986) also made the point that, "*Everyone agrees that the host rocks are clastic sedimentary rocks. No such agreement exists as to the origin of the gold contained in the sediments, nor how it came to be emplaced there.*" These latter authors go on to explain that the debate has also been expanded to include the more complex metasomatic and hydrothermal alteration effects and the general consensus seems to be that the geological discussion has continued on ad nauseam.

Following the discovery of the gold bearing conglomerates in 1886 on the Central Rand, extensive and continued exploration in and around the basin led to further discoveries of this precious metal: on the East Rand in 1914, the West Rand and Klerksdorp in 1937, the Orange Free State in 1946 and the Kinross area in 1955 (Durrheim, 2010). Although the last two decades have seen a surge in the price of gold, the emerging financial pressures, turbulent global markets and mounting political pressure on the home front continue to threaten the sustained extraction of gold from this unique deposit. In certain quarters, there have also been the suggestions that the resources in the Witwatersrand goldfields are now 95% exhausted and that production rate will fall permanently below 100 tons per year and that, "*the glory days of South African gold mining appear to have arrived finally at an ignominious end*" (Hartnady, 2009).

3   Mining: following the gold, looking for grade

The continued extraction of gold over a period of 120 years from the supracrustal rocks of the

Kaapvaal Craton now sees mining approaching depths of 4 000 m. At this depth, the natural rock temperatures of about 50 °C and virgin vertical rock pressures of the order of 100 MPa provide an indication of the enormity of the challenges and hazards facing mining.

The story of gold mining in South Africa has been a tale of chasing the "banket" into the earth along the variable dips and strikes and where the spatial extraction has been governed to a large extent by mineral grades. The main reef conglomerate was termed "banket" because of its resemblance, when oxidized, to the Dutch sweet of that name consisting of almonds and brown sugar.

It's a race that has progressed from surface trenches to shafts, tunnels and stopes, as portrayed in Fig. 2. The reefs themselves are accessed through an infrastructure of off reef drives and cross-cuts that are linked to vertical and/or inclined service shaft systems giving the overall layout of a mine shown in Fig. 3.

(a) Driefontein gold mine, 2011.

(b) Drilling a stope face underground in the Free State gold field.

(c) West Rand Consolidated Mines Ltd., 1932 (Watermeyer and Hoffenberg, 1932).

(d) Surface trenches in the Johannesburg area (Jeppe, 1946a).

Fig. 2 From surface to underground, 100 years of mining.
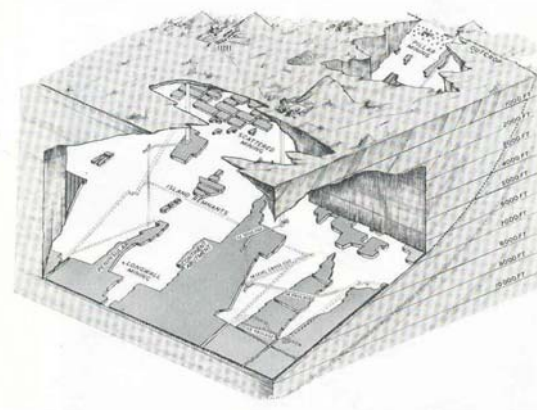
Fig. 3 Layout of a gold mine (Cook et al., 1966).

The statistics relating to the production of gold in South Africa portray both the immensity of the operations and the declining trend in recent years. At the height of gold production in 1970, the industry produced 1 000 tons of gold with a work force of 416 000 people. This came from the extraction of 28 km^2 of tabular ore body at an average stoping width of approximately 1 m. In 1985, production fell to 620 tons with a workforce of 477 000 people. By 2003, the decline in gold production from South Africa was well evident with total production amounting to 320 tons from a labour force of 183 000. In 2010, the production and employment had declined further to 191 tons and 157 000, respectively. In 1985, the reported fatality rate was 0.27 per 1 000 people employed and in 2003 that had improved to 0.20 per 1 000 employees (Ortlepp, 2005). Given the use of normalized accident statistics, the end result may be influenced by independent variation of variables used in the numerator, denominator or both.

The gold bearing reefs in the Witwatersrand Basin are tabular and most are mined at widths of about 1 m. The working environment is harsh. Mining faces are generally advanced by conventional drill-and-blast method mostly in the strike direction. This process over the large distances that are involved results in

the creation of large mined out spans. As mining activities in the basin migrated to increased depths along with these wide spans, the rockburst problem began to manifest itself both on surface and underground. The incidence of these dynamic failures is such that they affect both the safety of the working environment and the productivity of the mining process. It is a problem that has been facing the industry now for 100 years. The toll has seemingly always been high and Dr Simmons (1961) wrote that, "*Thirty-six thousand men have been killed in accidents on the gold mines since the beginning of the century.*" In the same source, he quoted an annual death toll on the South African mines of around 800 using Chamber of Mines annual reports as his reference. Gold mining operations and regions within the basin have suffered damage to both surface and underground structures over the years as a result of the seismic activity that has accompanied mining efforts here (Fig. 4).

(a) Slabbing of tunnel sidewall at 9 000 ft (2 743 m) below surface at Robinson Deep Mine, 1957 (Leeman, 1959).

(b) Damage in tunnel at 2 000 m below surface following M_L=4.2 event at West Driefontein Gold Mine, 1983.

(c) Surface damage in Stilfontein after M_L=5.1 event in March 2005 (Durrheim, 2010).

(d) Collapse of block of flats in Welkom following M_L = 5.2 tremor in 1976 (Durrheim, 2010).

Fig. 4 Damage on surface and underground in the Witwatersrand Basin.

The industry historically does not have a proud safety record, but the mining sector, however, must create and maintain a safe and healthy working environment. The full impact of the risks facing the industry are portrayed in past accident and labour statistic graphs depicted in Fig. 5, a figure taken from Handley (2004), showing the number of fatalities and employment figures since 1887. The graph taken from Jeppe (1946a) and shown in Fig. 6 (1906–1942) has been chosen to show the relative breakdown in contributing causes in death rate, up to 1942 at least. The dashed line superimposed on Fig. 6 shows that the fall of ground category has remained a consistent contributor to the death rate over this early period. While other accident classes showed effective decreases, fall of ground contributions proportionately increased from about one third to half of the contributing causes to the death rate by 1942. These figures would also at the time have included seismic related fatalities. The seismic accidents are linked to the dynamic falls of ground associated with seismic events and no distinction appears to have been made between gravity and seismically related falls during this early period.

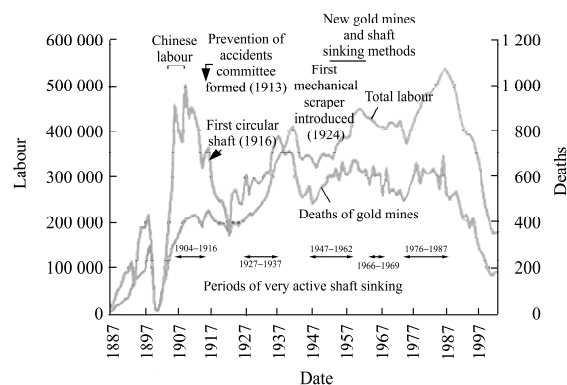Accidents statistics for 2010 reveal that 38 percent of all fatal accidents for the year were rock related,

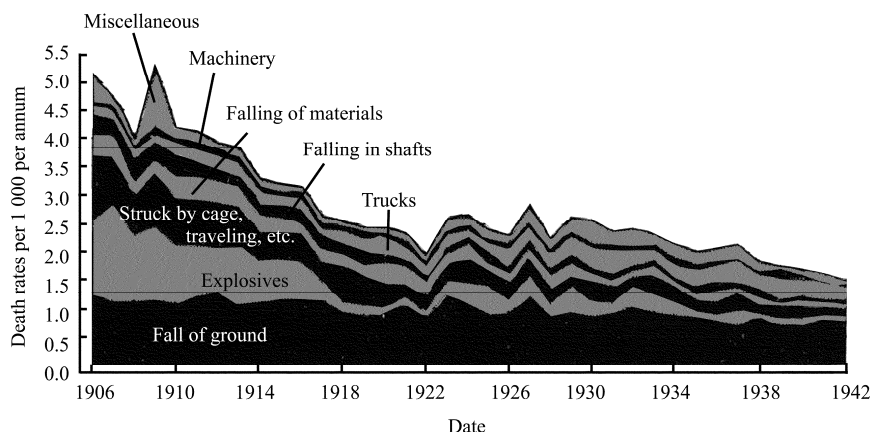**Fig. 5** Industry deaths and labour statistics (Handley, 2004).

Fig. 6 Accident death rates per 1 000 per annum (1906–1942) allocated under causes from Witwatersrand gold mines (Jeppe, 1946b).

i.e. rockfalls and rockbursts (D. Adams Pers. Communication). This appears to be in line with the trend depicted in Fig. 6.

The means by which the risk of seismicity in the basin has been ameliorated over the long period of mining is due to continued efforts in three key areas. These are (1) seismic monitoring, (2) understanding event mechanisms and (3) application of affective mitigation strategies. Consideration to these three areas in the context of their history will therefore be provided in the sections that follow.

4 Seismic monitoring: from astronomers to mine seismologists

The rockburst or tremor problem began to manifest itself roughly twenty years after the commencement of mining (Gane et al., 1946) and this brought panic and a fear of some possibly impending disaster in and around the village at Ophirton (Wood, 1913a). The first key feature concerning the tremors and one that was foremost in the minds of the early pioneers seemed to be the need for monitoring. This interest may also have been linked to concerns from a growing band of earthquake scientists abroad, particularly from Europe, with their focus on the crust of Africa as noted in the early writings of Wood (1913b).

A second key feature in the history of the tremors is the absence of seismologists in the early days. The pioneering work was carried out by astronomers like Wood working at the Union Observatory with the seismologists appearing much later as a result of technical and professional circumstances. This we learn from Wood himself speaking at one of the early technical meetings in 1920: "*Some years ago I took a*

considerable interest in the question of the origin of the earth tremors on the Witwatersrand—more than I am able to do now, when my time is more occupied with the problem of movements among the stars than movements underground here" (Cazalet, 1920).

The need for monitoring, however, has not only remained in place since the early days in the basin but has intensified to meet the ongoing requirements of the industry. At first this involved information about the location of the tremors, which in the early stages was completely unavailable. Once this had been provided, there was the need to move towards providing a quicker location for the tremors. This aspect received renewed impetus in the later years during the digital revolution and the period when seismic networks were motivated as management systems that would assist with rescue operations from the safety point of view. One of the strongest needs in monitoring, however, has always been connected to the question of location accuracy. Although this was originally a research requirement, it also became just as important once the systems started out in their new management role. Today the quest for improved location accuracy still continues, reinforcing the vital need for this action in combating rockbursts problems. The efforts to provide location details with an accuracy related to source size are highly relevant and form the basis of best practice of mining seismology in South Africa as documented in the "Handbook on Rock Engineering Practice" (Mendecki et al., 1999).

All of these aspects of monitoring are evident when examining the monitoring history in the basin. Monitoring has always been a key component of the efforts used to combat the rockburst problem. It was and always will be driven by the need to understand the causes and mechanisms of the tremors or
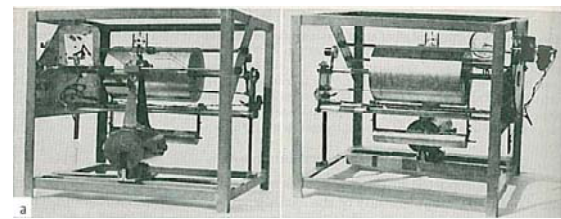
seismicity and formed the vital ingredient for the research and mitigation strategies that followed. Seven phases have been identified from the long 100 year history along with some speculation as to the form that future monitoring will take. Some consideration has also been given to the issue of objectives in view of both the informal and formal goals that have been attached to monitoring throughout the past.

4.1 The early years: questionnaires and human perceptions (1900 to 1908)

The early monitoring of tremors has been linked to the village at Ophirton, but this might not have been the only interest. As early as 1905, there was also a keen interest from earth scientists abroad inquiring about the global occurrences of large earthquakes, particularly in Africa (IASPEI, 2002). The Transvaal Meteorological Department undertook a request from the "Kaiserliche Haupstation fur Erdbebenforschung", the first seismological institute for Germany in Strasbourg, to collect information relating to seismic disturbances over the Transvaal Province using printed question postcards (Wood, 1913a). This typifies the early qualitative phase or approach to monitoring (information gathering) that by its nature was subject to human perceptions. It is, however, not too dissimilar to the methodologies on which early intensity scales (Rossi-Forrel) were based. Even some of the later work on the rockburst problem compiled by Cook et al. (1966) was based on the request for rockburst information by means of questionnaires.

4.2 The instrument phase: from questionnaires to seismograms (1908 to 1938)

The next phase of monitoring was driven by the need to understand more about the mine tremors. Two surface seismographs (Wiechert type) were installed at the Union Observatory and at Ophirton. A good account of the instrument was provided by Cazalet (1920). These instruments as shown in Fig. 7, according to Wood (1913a), eliminated the disadvantage of personal perceptions from the monitoring process: "*These instruments have the great advantage that whatever evidence they give of an earth-disturbance is free from any personal factor.*" They were therefore also able to provide reliable trends determining the increased rate of occurrence with time and assisted in determining that the tremors were related to mining. This was based

(a) Wiechert seismograph.

Horizontal   Inverted   Torsion

(b) Principles of seismograph pendulums.

Fig. 7 Wiechert seismograph (Gane et al., 1946) and principles of seismograph pendulums (Richter, 1958).

on the sharp "kicks" (Wood, 1913b) that characterized the nature of the close tremors compared to the more distant earthquakes recorded by these seismographs.

The instrument however had several shortcomings. No locations or source azimuths relative to the seismograph were possible from the single station recordings, and intensities could only be provided in terms of some indication of the recorded amplitudes from each waveform. In many cases, the seismograms provided good estimates of the distances to earthquakes felt elsewhere in South Africa, such as at Koffiefontein in the Orange Free State on 21 October 1910, where the epicentral distance 563 km (350 miles) corresponded well with the estimated location obtained from observational intensity data using the Rossi-Forrel scale (Fig. 8).
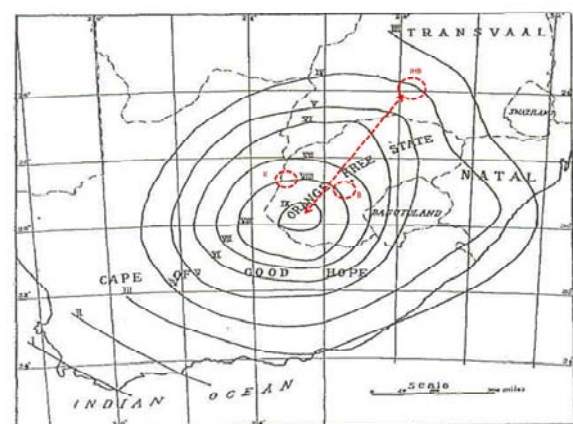
Fig. 8 The Rossi-Forrel plot from the earthquake on 20 February 1912 showing positions of Johannesburg (JHB), Bloemfontein (B) and Kimberley (K) relative to supposed epicentre at Koffiefontein (350 km) (Wood, 1914).

It was clear that Wood (1913a) himself also recognized the inadequacies of the monitoring using single stations insofar as locations were concerned: "*If there were several seismographs placed in a circle around Johannesburg it might be possible to point to the direction of the origin.*" In doing so he was undoubtedly pointing to the next phase of monitoring that would be required. The publication by Gane (1939) provided an analysis of information from this instrument up to 1937. Gane himself also made mention of "*a more intensive experimental study that was in progress at the Bernard Price Institute*" at the time of his study marking a possible end to the instrument phase at this time and a move towards the development of surface systems or networks.
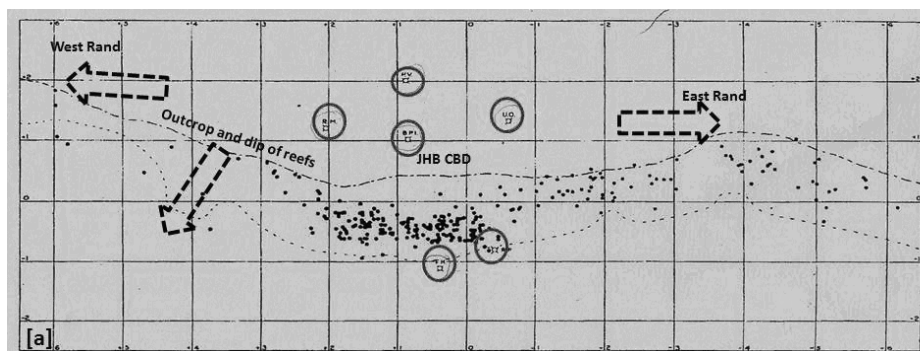
4.3 Move to seismograph networks and common real-time triggering (1938 to 1953)

The shortcomings recognized during the instrument phase culminated in the development of a network of five surface stations distributed around the Johannesburg area that was developed by scientists working out of the Bernard Price Institute (BPI). The system provided time resolution to about 0.1 second with sampling rates of the order of 20 cycles per second. The technology has been described by Gane et al. (1946) and the system provided the first locations for tremors (Fig. 9) around the Central Rand area. Locations were performed by means of the string analogue technique on account of the large amount of time required for analytical based computations.

Estimates of magnitude were based on the relationships provided through the work at the time of Gutenberg and Richter (1942). The calculated figure of energy for large tremors 10^{18} J based on this theory was larger than expected and ruled out the possibility of an origin from simple gravity related falls of ground. The system still suffered from problems relating to epicentral directions as well as from various localized surface site affects.

The BPI system underwent an upgrade during the late 1940s that provided the first real time triggering of a monitoring network at surface. This has been outlined by Gane et al. (1949) and involved the use of a trigger station closer to the source of the tremors providing synchronised triggering of the recording process for the first time. Improved timing from the

(a) Tremor epicenters (Gane, 1939).

(b) Photo of Witwatersrand showing outcrop (dotted black line) of reef in Central Rand area (Jeppe, 1946a).

Fig. 9 Seismic locations of tremors from BPI surface sites (circles).

trigger site also introduced enhanced resolution down to 5 milliseconds with a corresponding accuracy in the locations of 75 m. Gane et al. (1949) reported that false triggering of the sites was a problem with this system. In addition to the triggering feature, automatic magnification control was introduced at the remote sites and a method of frequency modulating a subcarrier, appropriate for transmitting very low frequency signals, was introduced. This made it possible for all the recording to be done at BPI, heralding the first centralized real time surface monitoring network in the basin. It was to be a while before these principles could be applied and extended to the underground environment at individual mines.

4.4 Systems move underground (1953 to 1970)

By 1948 it was realized that attempts to solve the rockburst problem were inadequate. This resulted in a new research drive to understand the rock mass with the idea that the locations of seismic events around the working faces could provide better understanding of the extent of the fracture zone surrounding the underground excavations. This resulted in the establishment of two underground monitoring systems at East Rand Proprietary Mines (ERPM) in 1961 (Cook et al., 1966) and Harmony Mine in the Free State in 1964 (Joughin, 1966). The systems took on a whole new look (Joughin, 1966). Importantly, for the first time, instruments were placed underground close to mine workings.

Recordings from the underground transducers were continuously captured onto magnetic tape with a storage capacity of about 24 hours. On surface the tapes were played back and trigger circuits selected seismic signals on the tapes for transcription onto a photographic record. This was achieved by means of an oscillograph (Hall-Sears 24 channel galvanometer type). The frequency response of the recording system was limited to a range of 15 to 150 Hz. Although the systems were not real time, they provided important information that was used in the landmark research. Although the systems were installed underground on mines, control of the systems seemed to remain in the hands of the research organizations.

4.5 Real time goes underground (1970 to 1990)

During the 1970s, the objective of monitoring appeared to change towards the operation of seismic systems as management tools that could assist with the rescue operations and safety procedures following rockbursts. This, in addition to the promising signs of prediction (Heunis, 1976) that were being developed at the time, resulted in the introduction of real time monitoring systems on a mine wide basis. Underground arrays of geophones were linked to surface computers via extensive cable networks. Essentially, the systems combined the aspects of triggering and association of seismogram signals that had been applied to systems operating on surface in the late 1940s. Processing was originally done using string analogue techniques, but with the advance in computer technology around this time, software algorithms (Eccles and Ryder, 1984) and applications became available resulting in both the ease and increased capacity of processing. A growing number of mines acquired seismic systems and the full progression has been outlined by Durrheim (2010). This phase also saw the birth of the mine seismologist and although the research organizations were very active from the perspective of data analysis, the systems and monitoring eventually became fully owned mine networks.

4.6 The full digital three-dimensional age and routine quantitative monitoring (1990 onwards)

The real time seismic monitoring underwent a further transition in the 1990s that involved the move to quantitative seismic data. The quantitative description of a seismic event required that apart from its timing and location, it could be described by two independent source parameters determined reliably, i.e. seismic moment (inelastic deformation) and either radiated seismic energy or stress drop (Mendecki, 2001). The systems migrated from mini-computers and became desktop based. The advances in processing power, data storage, digital processing and communication even over this phase have added leaps to the capacity and performance of the systems in terms of meeting these quantitative requirements (Fig. 10).

In South Africa, the move to fully digital systems was powered by Integrated Seismic Systems International (ISSI), now operating as the Institute of Mine Seismology (IMS) that remains a global leader in the field of mine seismology.

The change to digital systems has seen a large increase in the event monitoring across the Witwatersrand compared with previous years. Today gold mines within the basin are monitored by a total of 25 systems comprising about 430 underground sites. The number of events detected gives an indication of just how technology has added to the
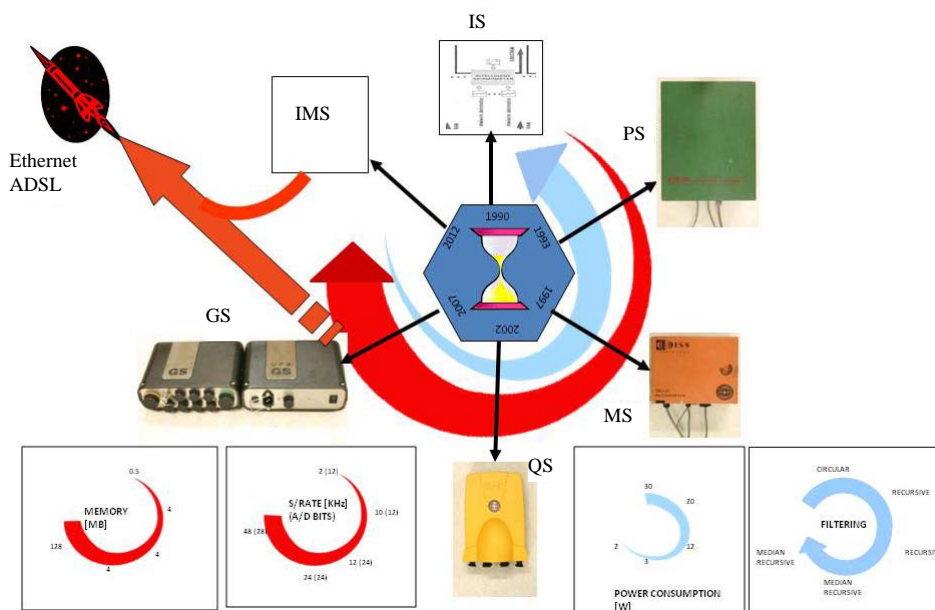
Fig. 10 Changes in monitoring technology from 1990 to 2012.

ability to monitor the tremors on the Witwatersrand. A total of 15 000 events were recorded during the period 1911 to 1937 by the first surface seismic system. It has been estimated that at present about 125 000 events per month are located on the gold mine operations in the basin (Goldbach, 2012). In certain places this figure has even been exceeded. Within the densely spaced network that operated at the Great Noligwa Mine in the Klerksdorp area in 2001, 250 000 events per month were recorded and processed (Durrheim et al., 2006). The change in monitoring capacity from way back in 1920 has therefore not been linear (Fig. 11). The trends here have been estimated in terms of three parameters, i.e. number of events processed per month, number of operating systems and the optimal sampling rates employed during the various phases.

4.7 Future monitoring developments

Further phases of monitoring will undoubtedly continue into the future as they have done in the past, driven in the same way by the need for greater understanding through research. Since mine seismology has followed the path of global seismology closely as portrayed in Fig. 11, consideration from Ben-Menahem's conclusion to his concise history of seismology (Ben-Menahem, 1995) might provide some indication of the way monitoring will go: "*Seismology has reached a stage where its lofty goals cannot be pursued by seismologists alone. Unless we launch a concentrated interdisciplinary research effort, we shall always be surprised by the next major earthquake.*" Future monitoring phases for mine seismology in South Africa are likely to involve two vital aspects: (1) higher resolution monitoring in site-specific areas along with the demand for more accurate automatic processing of waveforms without any loss in accuracy, and (2) the integration of seismic data with other (interdisciplinary) variables, i.e. acoustic emissions, more detailed blasting information and any applicable physically related data such as stope closure.

4.8 A note on monitoring objectives

Looking back over the full history of gold mining, the first clear objectives relating to seismic monitoring appear to be those outlined by de Jongh and Klokow (1982), who advocated rescue and safety as their immediate objective, with medium and long term goals related to mine planning and research functions, respectively. Mendecki et al. (1999) proposed seismic monitoring as a means of quantifying and controlling exposure to seismicity through several objectives including location, prevention, control, warnings and back analysis. While the objectives described above are in accord with current day goals, the desire for immediate locations at this time had become the most pressing motivation for monitoring systems. This represents a break with the objectives prior to 1970, when research and interpretation aspects seemed to
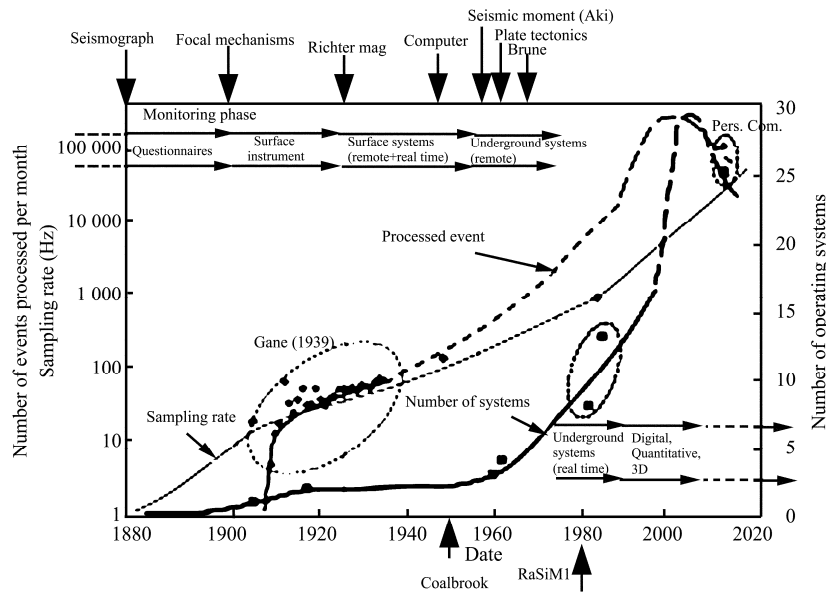
Fig. 11 Development of systems and processed events in Witwatersrand Basin together with processing phases and global seismology time line.

be the major goals of seismic monitoring. This change in priority may be linked to the South Africa's worst mining disaster at Coalbrook in 1960, in which 435 mine workers perished after a massive pillar collapse in a coal mine (van der Merwe, 2006).

5 Understanding mechanisms: the road to mitigation

The history of seismology can probably be traced back to over 4 000 years ago when man started reacting to the phenomena of earthquakes and providing explanations as to the mechanisms. A good account of the history of mainstream seismology has been outlined by Ben-Menahem (1995).

In South Africa, when the occurrence of earth tremors started, it seems that there was little doubt from the researchers that the phenomenon was linked to local mining operations. Wood (1913a) outlined some of the reasoning along with comparisons of similar instances of tremors abroad. He concluded that they were due to slippages of rock rendered unstable by mining and water pumping operations and were more frequent in the vicinity of faults. The early opinion of the tremors however varied and the following paragraphs capture the early thinking on the causes or mechanisms along with the progression to present day understanding.

5.1 Early thinking

The early concern about the possible consequences of the tremors resulted in investigations by two separately appointed commissions, i.e. the Ophirton Earth Tremors Committee (1908) and the Witwatersrand Earth Tremors Committee (1916). The following summary on the early theories has been derived for purposes of continuity and has been based largely on the contents of the reports from these two committees.

5.1.1 *The single blow theory*

This interpretation arose as a result of the apparent sharp "kicks", steep rises in amplitude on the seismogram, that were observed on the needles of the Weichert seismograph for the local tremors (Wood, 1913b). The explanation was that a single impact had occurred underground due to disturbances in equilibrium from the mining. This appears to have been an incorrect interpretation that arose as a result of the limited response of the seismograph that effectively masked the close separation of the "P" and "S" phases at the short distances involved.

5.1.2 *Natural causes*

The belief was that the tremors were related to the causes of local earthquakes recorded within the Southern Africa region at the time and that they were therefore related to normal crustal processes. Local earthquakes reported at the time included among others, Koffiefontein on 20 February 1912 and the Northern Zoutpansberg district on 5 August 1909 (Wood, 1913b).

5.1.3 *Seasonal influences and weather changes*

Interpretations based on these external influences were derived from perceptions of diurnal and

seasonal changes of temperature and humidity (Shocks were apparently more numerous in winter than in summer and also four times more frequent during the night than the day). They were also linked to theories of drainage systems in and around Johannesburg that produced a drying out process in the underlying strata leading to their supposed collapse. Periodicities of various influences were analyzed in detail by Gane (1939) who found that the strongest influence was probably due to blasting.

5.1.4 *Vibration from rock crushing batteries*

The tremors were thought to be related to the crushing activity of the stamp mills or batteries that formed part of the ore processing function. The subsequent vibrations of the plant equipment were thought to cause a loosening of the strata especially along weaker fault planes. This was thought to be exaggerated if the batteries happened to start working in a synchronous manner.

5.1.5 *Distant volcanic activity*

The belief of volcanic influences was based on reports of experiences elsewhere in the world, e.g. the cessation of seismicity in a tin mine in Tasmania was correlated with an earthquake in Malaysia and a volcanic eruption in New Zealand. Similar patterns were postulated for seismic activity in the Johannesburg area, but never materialized. In defense of this belief it must be remembered that the full nature of plate tectonic processes and the spatial extent of the individual plate boundaries was unknown at the time.

5.1.6 *Pumping operations*

Pumping operations removed large amounts of water from the mines. It was felt that this, together with the volume of rock removed by mining, weakened the support of the rock mass and allowed slippages to occur, thereby allowing the rock to adjust to a position of increased stability (Wood, 1913a). The early researchers however had the role of water reversed in terms of what we now know concerning pore water pressures. Early beliefs were based on the thinking that the removal of water from the rock mass resulted in a weakening effect. This is opposite to what is observed in current day mines with flooding and the filling of dam reservoirs (Goldbach, 2009; Brandt, 2001).

5.1.7 *Faulting*

There appears to be little documented on the role of faulting in the early days of the investigating committees. Wood (1913a) recognized that together with pumping, faulting played a role in the origin of the tremors. Pumping subdivided the ground into smaller sections or blocks that were then further subdivided and weakened by faulting. The early thinkers recognized the fact that the presence of faulting was somehow connected to the tremors without being able to identify the actual role that faulting played.

5.1.8 *Pillars*

The belief that the tremors were linked to the failure of pillars seems to have been strong and was certainly the view supported by the Witwatersrand Earth Tremors Committee. There appears to have been an alternate viewpoint that the tremors were linked to failures in the hangingwall zone (tension) and that the pillar failures were a result of over strain following the tensional failures. Knowledge of the location of the seismic events through monitoring was needed to clarify this and in fact only transpired later in the early 1960s.

5.1.9 *Falls of hangingwall*

Theories of the tremors being due to falls of ground appeared to be based on the belief that the disturbances were due to large amounts of rock hitting the footwall of the stopes. This would occasion vibration in the adjacent strata which would then be transmitted to the surface. There was little evidence to corroborate this and the theory was rejected by the investigating committee in 1908. A fall of hangingwall (2 500 tons) had taken place at the Robinson deep mine during the middle of August 1908 but apparently not the slightest shock was felt in connection with this incident.

5.1.10 *Blasting operations*

The effect of blasting as a cause of the tremors arose a result of the fact that blasting, originally taking place between the hours of 11 p.m. and 12 midnight (Ophirton Earth Tremors Committee, 1908), could be heard on surface in the stillness of the night. Most people seemed to agree at the time that the resulted vibrations were so slight that no damage could ensue from the process. It appeared as if the shocks that were being complained about were of an entirely different nature and severity. The link with blasting operations came from the work of Cazalet (1920) along with Gane (1939), Wood (1913a, 1913b) and Stokes (1936) who highlighted the sharp rise in the diurnal distribution after 2 p.m. There were also properties of the event time series which were absent on Sundays and that were noticed about an hour early on Saturdays. This laid the grounds for belief in a strong correlation between blasting processes and the origin of the tremors.

5.2 The effect of multi-reef mining

The original mining in the Central Rand goldfield involved stoping on three reefs that were in close proximity to one another (Main Reef, Main Reef Leader And South Reef). Copies of plans from Jeppe (1946b) show the stoped out areas on this Main Reef group (plans B, C, D). Although the detailed layouts are not visible from the scale of these plots, it is highly likely that the mining of the different reefs, separated by 10's of metres, would have involved over and understoping of solid pillars and remnants. If the pillars were not superimposed, a fact that is highly likely during these early mining days, then the multi-reef sequencing could have led to the creation of large shear stress components that would have contributed to higher than expected energy releases for the shallow depths involved at the time. From current day knowledge of relatively closely spaced reef layouts, the multi-reef mining at the time may have been a factor that compounded the problem of supposedly single reef pillar failures.

5.3 Domes and fracture zones

Following on from the early theories, the effort to understand mechanisms became integrated with the theories of strata movement and generally new developments in rock mechanics in the 1960s. Denkhaus (1965) provided a review of the relevant strata movement theories grouping them into three broad categories, i.e. dome, trough and continuum theories. The dome and trough theories (Fig. 12) dealt with the limits for zones of differential movement and consequent fracturing in the hangingwall, but did not quantify the magnitude of the movements. Continuum theory, treating the earth as a continuous body bounded by the surface in which the excavation is contained, seeks to provide the actual displacement from a given stress field in rock, with given properties.

This opened up the way for the application of elastic theory to rock mechanics and the process received immense benefit from the seismic data that was monitored in the underground environment around the excavations.

Although the three categories of strata movement theory appeared to contradict or diverge from one another, as Denkhaus (1965) noted the three were really modifications of one universal theory. The dome theory may well have had its origin in the thinking of the early researchers who favoured the location of the tremors in the hangingwall, which they held to be in tension. Nevertheless, the period
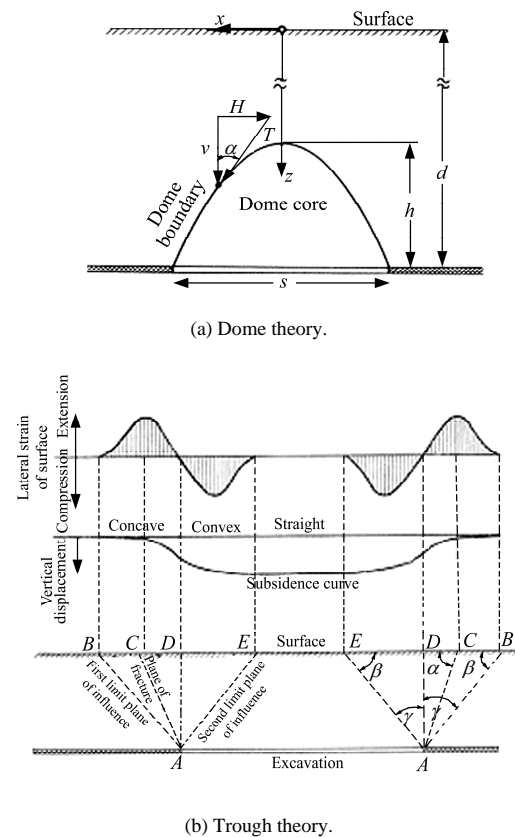

(a) Dome theory.

(b) Trough theory.

Fig. 12 Dome and trough theories of strata movement (Denkhaus, 1965).

1961–1963 saw the fading of the dome theory. In its place came the thinking concerned with a small fracture zone around the excavations. The use of the seismic location of rockbursts was instrumental in leading up to this change in thinking in that: (1) it provided more accurate locations for the foci of the failures and (2) the seismic data gave a quantified determination of the radiated energy and also provided some information of the movements at the source of the ruptures.

The input from the seismic data came as a result of the underground monitoring instituted through the Transvaal and Orange Free State Chamber of Mines and carried out at ERPM and Harmony Mine as previously outlined. The network at ERPM recorded activity around a single longwall while the system at Harmony Mine had the advantage of monitoring activity across the whole mine, largely as a result of the much smaller mining span. It was mainly as a result of this work that Cook et al. (1966) were able to realize that events occurred close to the working faces and that many more seismic events were recorded than manifestations of rockbursts. This is a problem that in all likelihood is linked to the inadequate recording of data and one which still persists up to today.

The results of all this work seemed to give new impetus to the ongoing industry research. Hoek (1965) showed that rock was generally elastic up to the point of fracture and that modified Griffith theory seemed adequate at explaining rock strength and failure. Ortlepp and Nicoll (1965) were able to show that movements in the rock mass were adequately provided by elastic theory.

5.4 First motions and moment tensors

The early pioneering work on earthquake mechanisms goes back to around 1891 when the Japanese geologist Bunjiiro Koto linked faults to earthquakes (Richter, 1958). In 1906, after the San Francisco earthquake, Henry Reid postulated the elastic rebound theory as an explanation for the apparently sudden and uncontrollable forces in the earth's crust. Later work by Prof. Shida of Kyoto University laid the groundwork for first motion studies with the discovery of compression and tension segments in the radiation pattern of seismic waveforms (Kasahara, 1981).

In South Africa, the pioneering focal mechanism work in mine seismology can be attributed to Gane et al. (1953) who examined cataseismic movements (i.e. first movement downwards) in the surface waveforms from the BPI system and postulated movements into mined out areas. This was followed later by the analysis from Joughin (1966) who proposed a method of failure involving volumetric collapses. The analysis was based on the first motions of seismograms recorded from the system at Harmony Mine. He ascribed the collapses to growth in the fracture zone along with sudden failures of rock around the excavations.

The growth in knowledge concerning mechanisms derived from first motion and moment tensor studies is reflected in the proceedings of the series of International Symposia on Rockbursts and Seismicity in Mines (RaSiM) over the years since 1982. Several authors at the first symposium presented first motion studies showing that mining related events were of a shear type and that geological structures were associated with the source of such events (Fernandez and van der Heever, 1984; Gay et. al., 1984; Potgieter and Roering, 1984; Rorke and Roering, 1984; Spottiswoode, 1984). Of particular significance is the study by Gay et al. (1984) who concluded that some of the larger events in the Klerksdorp area were associated with apparently seismically active and hazardous structures. They

suggested that the mining induced energy could not account for any significant part of the total energy released during the large events. It seemed, according to the authors, that some other source of energy would have to have been associated with their occurrence.

Wong and McGarr (1988) presented cases that provided evidence for mechanisms other than pure shear. McGarr (2005) also divided mining induced earthquakes into three categories involving pure shear and combinations of deviatoric and implosional or explosional volumetric components.

First motion and moment tensor analyses continue to be applied to mining events today with many algorithms (Andersen and Spottiswoode, 2001), but continue to show varying ratios of deviatoric and volumetric components in the source mechanisms of mining related events.

5.5 Dynamic brittle shears

A novel mechanism was proposed by Ortlepp and Steele (1973). They advocated a concept that directed attention not only to failure on pre-existing discontinuities, but also to solid intact rock. As they have stated, "*Our concept of a rockburst requires the occurrence of a fault like displacement along a suddenly created fracture plane, or along some suitably orientated geological discontinuity.*" Large volumes and areas of rock were envisaged in the process similar to natural earthquakes, but with displacements of the order of centimeters.

5.6 Summary

As with monitoring technology and practice, the final chapter on source mechanisms has yet to be written. The models described almost 20 years ago in the Chamber of Mines Industry Guide (1988) summarized research thinking, and probably still provide an adequate description of the mechanism of mining-related seismic events. Seismic events require some form of unstable equilibrium, along with a sufficient amount of change in that state, to produce dynamic rock failure. Furthermore, a triggering process or mechanism is required. Events themselves can probably still be categorized into two divisions:

(1) "Crush type" events that occur close to mining faces and within small pillars and generally have $M_L < 2$.

(2) "Shear type" events, which generally locate further away from the reef horizons, and involve ruptures on planes of weakness and/or intact rock.

The excess shear stress (ESS) criterion developed by Ryder (1988) may relate more to the shear type of events, while the energy release rate (ERR) parameter from the work of Salamon (1974), used in the design of mining layouts, probably relates more to the crush type of events closer to the mining faces. There has also been some debate in the industry in recent decades on the classification of events into classes labeled as type "A" (blasting related type) and type "B" (geological shear type) (Richardson and Jordan, 2001).

6 Mitigation

In view of their immense proportions, large natural earthquakes need to be treated according to the concept of a "disaster management cycle". The disaster cycle carries both risk and crisis management sectors (Fig. 13). Mitigation forms part of the risk management section in that it attempts to lessen the effects of any impending future disaster. Not every mining seismic event can be classified as a disaster, but in principle and in view of its purpose aimed at lessening the severity from the occurrence any impending hazard, mitigation principles apply equally to earthquakes and mining events. Mendecki and Lotter (2011) have outlined some of the essential differences between natural earthquakes and mining-related seismicity, with the realization that the driving forces in mines can be controlled, while tectonic forces cannot. This then, if true, must form the basis of any mitigation strategies against mining-induced seismicity. The mining process must also recognize, however, that mining in underground environments creates perturbations in existing stress fields making the onset of seismicity inevitable as mentioned by de Jongh and Klokow (1982).

Fig. 13 The disaster management cycle showing crisis and risk management sections.

With the realization that the mining seismic environment can be controlled to a certain extent, how should appropriate mitigation strategies be constructed in terms of effective risk management? The approach adopted by the DEEPMINE collaborative research program in South Africa (Mendecki and Lotter, 2011) is considered as an useful framework and will form the basis of the current review, i.e. prevention, protection and prediction strategies.

6.1 Prevention

6.1.1 *Strategies from the past*

The recommendations of the Witwatersrand Earth Tremors Committee in 1915 were not too different from current day mitigation techniques insofar as prevention strategies were concerned. The committee considered a total of 21 concepts under the heading of "remedial measures" (Witwatersrand Earth Tremors Committee, 1916: items 71–91) which have been categorized for the purpose of this paper according to the 5 classes tabulated below (Table 1). Most of the recommendations (61%) related in some way to the issue of pillars.

6.1.2 *Current strategies—DEEPMINE*

The methods considered under the DEEPMINE research program probably best reflect the current day overall approach to prevention. These include the use of geophysical methods such as borehole radar to map geological structures ahead of mining, and the selection of appropriate mining layouts. The design and planning of mining layouts (e.g. Vieira and Durrheim, 2001) probably forms the most important part of prevention strategies today. Mining parameters relating to prevention strategies include the concepts of ERR, ESS, average pillar stress (APS), and rockwall condition factor (RCF). In addition, layouts considered in the reduction of overall energy from mining include longwall layouts with strike pillars, sequential grid breast mining, sequential grid down-dip mining, and closely-spaced

Table 1 Breakdown/classification (with referenced paragraphs) of remedial measures highlighted by 1915 commission.

Category	Count	Ratio (%)	Paragraph reference
Mine design	3	14	71, 72, 79
Pillars	13	61	73, 74, 75, 76, 77, 78, 80, 81, 82, 83, 85, 87, 88
Mineral resources	1	4	88
Financial implications	1	4	88
Mining license	2	9	89, 90
Support (sand filling)	1	4	84

dip pillar mining. Importantly, all of these concepts of mine design and layout were outputs of research programs. The analysis provided by Klokow et al. (2003) is an example of the use of various seismic parameters derived from quantitative seismic monitoring that have been used in the assessment of a theoretically designed mining layout.

6.1.3 The importance of research

The pattern that runs through the history of mining in the Witwatersrand Basin is one of a centralized research function, providing the input to mining operations. Initially this involved the analytical work of Wood, Gane and Cazalet, but included the later work of Cook, Joughin and Salamon working under the Chamber of Mines Research Organisation. At present, this function is largely administered by Safety in Mines Research Advisory Committee (SIMRAC) with input from additional organizations such as the Council for Scientific and Industrial Research (CSIR) Centre for Mining Innovation, the Council for Geoscience and the universities. The collaborative DEEPMINE project, aimed at investigating the viability of mining down to depths of 5 km, has provided much input of various aspects of deep level mining. It was a partnership between the industry and various research organizations. In terms of seismic monitoring, the DEEPMINE study tied in well with the objective, defined by Mendecki (2001), of reducing seismicity without retarding the mining process. In this regard, several seismic-related parameters were developed and used to assess mining layouts. The overriding conclusion throughout the history of mining is that seismic monitoring systems provide the key data necessary for effective mitigation strategies to be implemented.

6.2 Protection

In the realm of mining seismicity, mitigation strategies must also include the objective of providing protection to the workers in an underground environment. In the case of the tabular reefs of the Witwatersrand Basin, this includes the tunnel and stopping excavations, along with the shaft working environments.

The design of support is one of the most difficult problems in rock engineering. The issue of seismicity complicates the picture even further in view of the dynamic forces that need to be accommodated in the support structures and designs. The main function of stope support is to prevent the separation of rock and the consequent loosening of fractured rock over the working area immediately behind the face. In the

case of tunnels, it is the separation around the sidewalls and hangingwall or skin of the excavations that must be prevented (Ortlepp, 1978). In this regard, the input from seismic data and monitoring systems is concerned mainly with the provision of estimates of ground velocity and acceleration experienced as a result of the surrounding seismicity. Some of the more familiar relationships involving magnitude, seismic moment and peak ground velocity have been outlined in the applications presented by McGarr (1984). Support designs for rockbursting conditions today are based on a maximum ground velocity of 2 to 3 m/s.

Estimates of the shape and size of the seismic source region in mine seismology from current monitoring systems are still based on the theory provided by Brune (1970) that involves the radius of a circular crack. There are probably adequate grounds for accepting that the mining environment presents significant deviation from this simple model. The circular symmetry around the event hypocentre and the application of this theory to mining scenarios should therefore be questioned, as noted by Spottiswoode (2001). It is out of this framework that current mining research efforts guided by the Institute of Mine Seismology (Mendecki and Lotter, 2011) appear to be moving. These it is hoped will lead to more realistic and accurate estimates of ground excitation and the development of support systems that will ultimately provide greater protection for underground workers and mining excavations.

6.3 Prediction

Niels Bohr (1885–1962) probably said it best when he spoke about prediction, "*Prediction is very difficult, especially about the future.*" This probably ties in well with the claims by Richter that, "*Cranks and amateurs frequently claim to predict earthquakes. They deceive themselves and to some extent the public because it is not generally known how frequent earthquakes are*" (Richter, 1958). Fifty years later, Richter's profound statement still applies, "*Prediction of earthquakes in any precise sense is not now possible. Any hope of such prediction looks toward a distant future.*"

6.3.1 Prediction in mine seismology

Investigations into the prediction of rockbursts can be traced back to 1938. The work of Weiss (1937) outlined the use of geophysical methods as a means of moving towards prediction in South Africa. The

thinking that prediction of bursts was linked to increases in the microseismic activity rates appears in discussions at a symposium on "Rockbursts" held at a New York Meeting of the American Institute of Mining and Metallurgical Engineers in 1941 (Bucky, 1945).

The founding base of the prediction of rockbursts, however, must surely lie with the work of Obert and Duvall (1957) who proposed the use of natural subaudible noises in rock as an indicator for the occurrence of rockbursts. This was the basis of the work that started in South Africa during the early 1970s which led to the establishment of a rockburst project in 1973 at Western Deep Levels Gold Mine, and funded jointly by Anglo American and the Chamber of Mines. This culminated in the installation of an accelerometer network. The back analysis of the recorded event activity from this network revealed the possibility of using the event rates for the prediction of larger damaging events as reported by Brink and O'Conner (1983). This work was expanded and when Cichowicz et al. (1988) reported on the analysis of source parameters for the microseismicity from this system. They reported that the relationship between seismic moment and corner frequency did not seem to support constant stress drop events. They reported that the higher stress drop events were seemingly confined to intact rock beyond the fracture zone and that these would be more suitable for prediction purposes.

6.3.2 *Prediction—a new direction*

It was at about this time that developments in South Africa and in the area of prediction took a new turn. The research work under the SIMRAC took a step towards concentrating on the nucleation phase of instabilities (Spottiswoode, 1997). This was based on the principles emerging from the real time quantitative monitoring in operation during this period. The research work under the SIMRAC banner appeared to move towards the possibility of establishing the concepts of Alert, Alarm and Scram as the phases of monitoring leading up to impending instabilities and rockbursts. The microseismic monitoring had been centralized and combined with the macro networks and this research phase in the SIMRAC was directed largely at the detection and build up of source regions and nucleation processes.

6.3.3 *The move to seismic hazard and risk assessments*

There was little success with the Alert, Alarm, Scram approach (Spottiswoode, 1997) and in 1997, it

appeared that the earthquake fraternity was in fact moving away from and abandoning the hope of ever achieving successful predictions. This was highlighted by a discussion meeting held in London in 1996 under the title: "Earthquakes: Thinking about the unpredictable".

Following the transfer into 2000, it seemed the role of the research work in South Africa then moved in the direction of seismic hazard assessment strategies. This was highlighted by the work of the SIMRAC project (Brink et al., 2000) that studied techniques used to quantify the potential for rock mass instability. The emphasis from a monitoring perspective also appeared to shift to the role of daily hazard assessments linked to the management of risk (long, medium and short terms) in mines for management purposes. The typical methodologies employed at numerous gold mines as well as platinum mines in South Africa have been outlined by van Aswegen (2005) and a typical example of such short term reporting is highlighted in Fig. 14.

6.3.4 *Integration of mine seismicity and numerical modeling*

The last decade has seen a move towards the use of numerical modeling in attempts to forecast theseismic response from mining. Strategies appear to be concentrating on the integration of the numerical results with seismic data, but in a way the efforts are leading to the development of a form of "pseudo prediction" for rockbursts. Modeling in rock engineering became important with the move to the continuum theories of strata movement and they provided a means of visualizing the fields of abstract quantities like stress.

Researchers in South Africa recognized the link between the rockburst problem and elastic theory with the realization that beyond the fracture zone was an area where the rock behaved elastically. This ultimately led to the establishment of the resistance analogue and the ability to calculate the theoretical values of stress around and on a plane containing the boundaries of mining layouts. This, together with the rapid development of similar model building procedures outside the mining industry, is essentially the foundation upon which numerical modeling procedures and computer applications in the mining industry today have been developed. The net result has been the birth of numerical procedures applicable to mining that include: finite difference, finite element, distinct element, fictitious stress, displacement discontinuity and direct boundary element methods
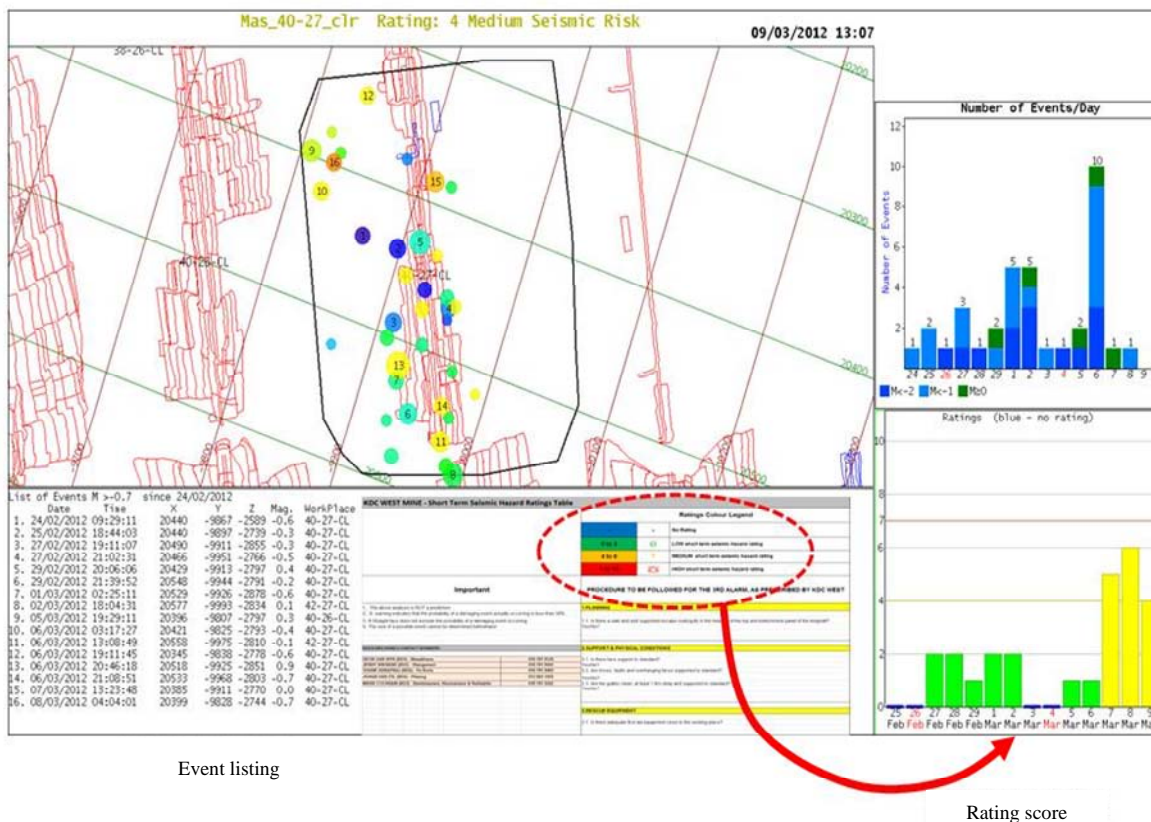
Event listing

Rating score

Fig. 14 Format for short term hazard assessment reports (Gold Fields).

(SIMRAC, 1999). Computer packages housing these methods include MinSim, BESOL, MINAP, DIGS, Map3D, FLAC, UDEC and ELFEN, all of which have contributed towards a greater understanding of the stress distribution around mining excavations.

While most of these facilities originally assisted with the understanding of general static stress problems in mining, it has been the efforts to try to integrate the results from the world of modeling with those of the monitored seismicity that have received attention during the last decade. There is perhaps the realization that both these disciplines, along with the attempts at pseudo prediction, provide an incomplete picture of the response of the rock mass to mining. This area of research—integration may fill the gap that appears to be needed in developing an interdisciplinary approach to the area of mine design as pointed out by Spottiswoode (Brune, 1970). This is still a vastly new developing field that up to now has involved the work of numerous researchers including McGarr and Wiebols (1977), Ryder (1988), and Wiles et al. (2001), and there are many issues in this area that still need to be overcome.

6.3.5 Interdisciplinary developments from the earthquake world

That there may well have to be paradigm shifts in the road to prediction is a fact that is reinforced by the recent work of Grant et al. (2011) related to the occurrence of crustal earthquakes. They have proposed a method whereby charged particles in rock under stress may well result in electronic changes in the atmosphere and the environment that could go some way towards explaining strange animal behaviour that is noticeable in some cases before earthquakes. Should this be the case then mine seismology may have to look for equivalent analogies in monitoring that involve non-seismic variables.

6.3.6 Priorities and lessons from DEEPMINE

As a final word on the prediction story, it may be necessary to pull a leaf from out of the findings of the DEEPMINE project conclusions that throws some light onto the possible priority of the prevention, protection and prediction strategies. "*Seismic management strategies should be based on prevention and protection rather than on prediction.*"

7 Regulation

The South African, mining industry is regulated under the Mine Health and Safety Act (Act No. 29 of 1996). The basis of the regulation is more towards a self regulatory model rather than being prescriptive purely on account of the variable conditions encountered across the mines. The guidelines from the Department of Mineral Resources (DMR) require the mines to operate under "Codes of Practice" where necessary and have included guidelines for codes to combat rockfall and rockburst accidents. The codes are expected to cover rock engineering strategies as well as the objectives and use of seismic monitoring systems.

In South Africa, the question of mine safety has come under the spotlight of late and the inspectorate of the DMR has resorted to temporary mine closure following accidents and incidents on the mines. The Section 54 stoppages are accused of costing the South African economy 500 million US dollars through the loss of 300 000 nonfatal precious metal ounces of production (Creamer, 2012a). The mining industry has questioned the approach with Tito Mboweni, former South African Reserve Bank governor and chairperson of AngloGold Ashanti, accusing the department of "*regulating the industry to death*" through an approach he labeled as "*sledgehammer*" (Creamer, 2012b). The confrontation has intensified with the recent involvement of Labour Court action (20 March 2012) that has seen the DMR being given a deadline to review Section 54 of the Health and Safety Act. In the light of the controversy, it seems that some sort of win-win situation is required and a model of responsive regulation, which may be an alternative for consideration, has been outlined by Durrheim (2001).

8 Research efforts

Throughout the history of mining in the Witwatersrand Basin, an important aspect has been the ongoing research work that has been provided by associated organizations (Durrheim, 2010). Whether these have been private, government or academic organizations, they have, together over the years, supported the major research endeavours that were necessary for the advance in knowledge about the rockburst problem. The main players in the game

have undoubtedly been the Chamber of Mines, through its many name changes and subsidiary research laboratories and organizations such as the Chamber of Mines Research Organization (COMRO), the Council for Scientific and Industrial Research, which merged with COMRO in 1993 to form CSIR Miningtek, and the University of the Witwatersrand through the Bernard Price Institute and the Department of Geophysics. Together these bodies supported the vital function of rockburst research through the various research endeavours. An important player however was added in 1990. The SIMRAC was established in terms of the Minerals Act (50) in 1991. The SIMRAC had the responsibility to identify research areas, imposed levies on mines to fund the research. From 1991 to 2004, more than 250 million Rand was spent on rock related research. The organizations also supported the role of knowledge dissemination through various conferences, publications and feedback sessions. Many of the key parameters used today in the mitigation of rockburst related problems were established at one or other time through the generally centralized programs carried out by these organizations.

The current situation in South Africa is one where the research efforts are dwindling and although some of these role players still exist, they have shrunk in size along with the available financial resources. In the paper dealing with the progress since the Coalbrook disaster, van der Merwe (2006) paints a bleak picture of the research situation in the country with particular reference to coal. He attributes the change to the period when voluntary funding of research ceased along with the introduction of a statutory research levy. This resulted in a dilution of expert input and the initiation of a collapse from 2003 onwards.

Insofar as mining seismology is concerned, there is no current fundamental seismic research being conducted by any of these organizations. Recent developments since 2011 have however culminated in a seismic research drive initiated and coordinated by "Institute of Mine Seismology (IMS)". IMS is an organization that was established through the closure of ISSI at the end of 2010. IMS has set up the initiative whereby participating members, patrons, to support the research drive through funding. In return, patrons have a say in the program governing fundamental seismic research, while also having the opportunity to propose applied research projects applicable to their own mining situations and which are then researched by the complement of highly skilled researchers based at IMS. The patronage is

now entering its second year and is currently supported by the three major mining houses in South Africa (AngloGold Ashanti, Harmony and Gold Fields) along with other partners from across the globe.

In addition to the research venture coordinated by IMS, Japanese researchers have been involved in South Africa since 1995 where they have been monitoring the earthquake generation process in close proximity to hypocenters. Their work has been largely concerned with strain changes as forerunners of seismic events (Yasutake et al., 2008). In 2010, a new 5 year 3.5 million US dollars project entitled "Observational study to mitigate seismic risks in mines" was launched (Durrheim et al., 2012). Research sites have been established at three deep gold mines: Moab Khotsong (AngloGold Ashanti), Kloof Driefontein Complex (Gold Fields), and Ezulwini (First Gold).

9 Conclusions

In South Africa, there is an industry that has supplied the world with about half of the gold that has ever been mined—about 50 000 tons of gold over the last 120 years. Extraction of the gold has been accomplished in the face of numerous challenges of which the rockburst problem remains the most feared and least understood. Mining continued to progress to deeper horizons and to spread out along the Witwatersrand Basin and as the tremors continued so the panic started. Yet the early pioneers of mining seemed to accept the challenge that had started to hamper them with something of a balanced view. The documentation from the early report of the Witwatersrand Earth Tremors Committee in 1915 shows that there was a sound feeling that the show had to go on and that, in their view, sustainability would be dictated in the end by economic viability and safety. Paragraphs 89 and 90 of their report in the section entitled "The means of preventing the tremors" portray their standpoint at the time on the question of the tremors or rockbursts as highlighted in the bullet points below. It is not clear if this was their view on the tremors in general or if it conveyed their feeling more specifically toward the issues of surface damage:

(1) "*89. Objects of mining. It must be remembered that mining operations are not carried out with a view to avoiding shocks in neighbouring towns or dwellings. Mining is concerned with the extraction of ore with the maximum amount of profit and the least risk to life and health, and, although shocks may be unpleasant and even give rise to a sense of alarm for the safety of life and property, the taking of steps to avoid them does not primarily constitute one of the objects of mining.*"

(2) "*90. Damage caused by shocks does not warrant drastic changes. The underground effects of rockbursts are far more serious than those felt on surface, and it is for this reason mainly that steps should be taken to prevent them. If the prevention of shocks in Johannesburg entailed the bringing into force of mining methods which would greatly increase the cost of mining, the small and problematical amount of damage done to buildings and the alarm felt by the inhabitants would be insufficient grounds on which to base the enforcement of such methods. When, however, as the Committee has shown, a modification of existing practice should result not only in greater safety and economy on the mines, but also diminishing the frequency and severity of shocks, it may reasonably be expected of the mines that such steps should be taken.*"

How do the proposed strategies of the early pioneers, reflected in the above clauses, compare with the bigger picture through time in the Witwatersrand Basin? Today the strategy toward the seismically related hazards appears to be structured according to three basic principles, i.e. monitoring, mechanisms and mitigation.

9.1 Monitoring

The process of gaining knowledge was always driven by the function of monitoring. At first this was slow, but it was accelerated with the revolution that brought computer technology to the fore. In this regard, mining seismology generally paralleled the developments seen in global seismology. Monitoring has and will always ensure the elimination of bias that can be introduced through human perceptions. Monitoring also involved recording of seismograms from only 6 surface sites for a period of nearly half a century of mining. It has grown today into a function that involves 25 systems using about 450 underground sites across the mines, through which about 125 000 events are processed and recorded every month. Monitoring will also have to continue into the future if knowledge is to continue simply because the more we know about the rockburst problem, the more there is to know.

9.2 Research

The knowledge gained from the data produced by monitoring came by way of interpretation through research. Initially both the monitoring and interpretation of the data were included under the research umbrella. This appeared to change when individual mine systems were motivated as management tools, largely from the perspective of safety. There was a brief time before this change when the research facilities operated with special project initiatives that were based on the mines. This may have been the time that the industry made its most significant advance into the realm of prediction at least. This phase also operated under the principle of smaller and dedicated higher resolution monitoring areas.

9.3 Mitigation

The control over the rockburst problem that has seen the industry advance to depths approaching 4 km has been achieved through the application of key design and operation concepts developed through the research phases. The mitigation strategies basically involve the three separate phases of prevention, protection and prediction. The greatest advance in these three areas has involved strategies in areas of prevention and protection. While the realm of prediction cannot be ignored, it may have to involve paradigm shifts in terms of the approach to the data that is monitored and collected in future. Solutions may not necessarily be purely confined to the seismic field alone. As in the case of recent findings in the area of earthquake prediction, the problem may in fact involve principles from other disciplines and departments. The road to prediction may well involve the integration of other data variables. This has probably been initiated with the recent moves in the last decade to compare and integrate numerical modeling results with seismic data. The process may well have started but the hope that Richter spoke of may have to involve accelerated extensions with related variables into other fields.

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