

# The Risks to Miners, Mines, and the Public posed by Large Seismic Events in the Gold Mining Districts of South Africa

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## ABSTRACT

A magnitude 5.3 seismic event occurred on 9 March 2005 in the Klerksdorp district of South Africa. The event and aftershocks shook the nearby town of Stilfontein, causing serious damage to several buildings and minor injuries to 58 people. At a nearby deep gold mine, two mineworkers lost their lives and 3200 mineworkers were evacuated under difficult circumstances. The Chief Inspector of Mines initiated an investigation into the risks to miners, mines and the public arising from seismicity in gold mining districts. It was found that the seismic event on 9 March 2005 could be ascribed to past mining, and that 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 even after mine closure. Placement of slimes in old mining workings is unlikely to reduce risks significantly. Seismic monitoring should continue after mine closure, and the seismic hazard should be taken into account when the future use of mining land is considered. Seismic events are likely to be triggered as mines are allowed to flood. It is possible that a seismic event could cause movement on a fault transecting a water plug and/or water barrier pillar, open up a fluid pathway, and allow flow of water into populated mine workings. While it is unlikely that such an occurrence would become an uncontrollable inrush, the consequences could be disastrous and the risk must be seriously addressed. However, the risk of a seismic event on one mine causing serious damage in a neighbouring mine is considered small because major infrastructure such as shafts are usually located at least a kilometre from mine boundaries, and there is generally good cooperation between neighbouring mines with respect to mine planning and blasting schedules. The national and local monitoring networks, operated by the Council for Geoscience and mining companies, respectively, are on a par with those installed in seismically active mining districts elsewhere in the world. However, steps should be taken to improve the quality of seismic monitoring and to ensure continuity, especially as mines change hands. A range of technologies is available to mitigate the risks of underground damage resulting from large seismic events. However, if there has already been extensive mining near geological features that could host large seismic events, any further mining adjacent to the structure must be carefully planned. The Klerksdorp and Free State gold mining districts are incorporating the risks of seismicity in their disaster management plans, and Johannesburg is urged to do likewise. Some buildings are considered vulnerable to damage by large seismic events, posing safety and financial risks. It is recommended that an earthquake engineer inspect the building stock and review the content and enforcement of building codes. Appropriate training should be provided to all members of emergency services, and drills should be practised regularly at public buildings to avoid panic should a large seismic event occur.

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## 1 INTRODUCTION

A seismic event with a local magnitude  $M_L=5.3$  occurred at 12h15 on 9 March 2005 at DRDGold's North West Operations, Northwest Province, South Africa. The event and its aftershocks shook the nearby town of Stilfontein, causing serious damage to some buildings (Figure 1). Shattered glass and dislodged masonry caused minor injuries to 58 people. Three schools, two commercial properties, three blocks of flats, the civic centre and 25 houses suffered major damage. The direct cost of the damage to buildings in Stilfontein is estimated at R20 to R30 million.



Figure 1. Damage in Stilfontein caused by the  $M_L=5.3$  tremor on 9 March 2005

At the mine, two mineworkers lost their lives, and 3200 mineworkers were evacuated from the workings under difficult circumstances. The No. 5 Shaft and its infrastructure suffered severe damage, effectively halting mining operations in that section of the mining complex. The mine went into liquidation shortly afterwards, and some 6500 mineworkers lost their jobs. Approximately R500 million was claimed from insurers for damage to mine infrastructure and loss of production.

The events on 9 March 2005 raised some wider questions. For example:

- Is the technology available to cope adequately with large seismic events in the current situation of remnant mining, deeper mines, and mining within large mined-out areas?
- Are current approaches to mine planning, design, monitoring, and management appropriate and adequate?
- Does mining, past and present, trigger or induce large seismic events? Will it continue to do so in the future?
- Can the effect of seismicity on mining towns and communities be limited and, if so, how?

Furthermore, other developments pertinent to the DRD situation and elsewhere raised an additional concern; namely, the relationship between mine water and seismicity.

In response to these concerns and in consultation with her principals at the Department of Minerals and Energy, the Chief Inspector of Mines, Ms May Hermanus, commissioned an investigation to assess the risks to miners, mines and the public arising from seismicity in mining areas, with particular reference to gold mines, remnant mining, pillar mining and mining districts in which mines are largely mined out or where flooding is occurring. The investigation team was instructed

to draw on current knowledge and expertise to arrive at conclusions, make recommendations, and identify further research needs. While there was considerable discussion and debate between team members, it did not attempt to achieve complete unanimity on all points. The main report was endorsed by all team members, and represents a consensus view.

## **2 MINING AND SEISMICITY IN SOUTH AFRICA**

Gold was discovered near present-day Johannesburg in 1886, and earth tremors and rockbursts were already a cause of concern to mining communities as early as the first decade of the 20th century. 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). At that time, there were no seismograph recordings that could be used to determine the magnitude of these earliest seismic events with any kind of scientific correctness. Following a recommendation of the 1908 Committee, a seismograph was installed at the Union Observatory in Johannesburg in 1910. Another seismograph was installed in Ophirton, but was moved to Boksburg in 1913, where shocks were beginning to be felt. It was only 50 years later that reliable seismic monitoring networks were established.

As the gold mining industry expanded and the severity of the problem increased, further committees were appointed in 1915, 1924, and 1964. From early on there was recognition of the need to distinguish between natural earthquakes and mining-related seismic disturbances. 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.” It was concluded, “the shocks have their origin in mining operations”, and “while it may be expected that severer shocks than any that have yet been felt will occur in Johannesburg, their violence will not be sufficiently great to justify the apprehension of any disastrous effects” (Anon, 1915).

The 1924 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 committee extended its enquiries as far afield as Canada, USA, and even India, where large “area rockbursts” were believed to be associated with major faulting in the Kolar goldfield in Mysore State. The report of the 1924 committee makes many recommendations about general mining policy, protection of travelling ways, and the stoping out of remnants.

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). The time was considered opportune 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 committee’s recommendations were based on a considerable body of research and practical observations. The necessity for carrying out further research was noted.

Superficially, the key issues addressed by the current investigation do not differ greatly from the issues addressed by the 1908, 1915, 1924 and 1964 committees. However, much has changed in the past four decades. The South African gold mining industry is mature and declining: production has been falling at an average rate of four per cent per annum for the past three decades. Only 342 tons

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of gold were mined in 2004, compared to 1000 tons in 1970. New problems are faced as mines approach the ends of their lives, cease operation, and workings are flooded. Meanwhile, many of the cities and towns in the gold mining districts have grown, and several seismic events with magnitudes exceeding 5 have caused damage to residential, commercial, and civic buildings in these towns. In addition, a great deal of rock mechanics and seismological research has been conducted since 1964. Much of it is reported in the proceedings of the six quadrennial *Rockbursts and Seismicity in Mines Symposia* held since 1982 and reviewed by Ortlepp (2005). Nevertheless, South Africa remains the world's top gold producer, the gold mines directly employ over 100,000 workers, and gold remains a significant source of foreign exchange. It is clearly in the national interest to ensure that the gold mines continue to generate these benefits as long as possible without posing unacceptable risks to mineworkers and the public.

Large seismic events causing serious damage to surface and/or mine infrastructure first occurred in the Free State region in the 1970s. An  $M_L=5.2$  seismic event caused a six-storey apartment block to collapse in Welkom in December 1976 (Figure 2). Fortunately, it was possible to evacuate the building before it collapsed. This event first evoked the idea of a natural earthquake being the ultimate cause. For example, Dr Piet Pienaar, consulting geologist for Anglo American Corporation, was reported in the press to have said that the "Welkom earth tremor was almost certainly the result of geological phenomena and not caused by mining activities" (*The Friend*, 10 December 1976), and a report by foreign geotechnical consultants allowed this explanation to gain acceptance (W.D. Ortlepp, pers. comm.).



Figure 2. Damage to an apartment block in Welkom caused by a  $M_L=5.2$  tremor on 8 December 1976



The media again used the term “earthquake” in 1989 when the “second Welkom earthquake” caused minor but widespread damage on surface. However, observed displacements on the President Brand fault in a nearby mine demonstrated that the origin of the earthquake was indeed close to mine workings (Figure 3). Another notable event that caused significant damage to surface buildings and mine infrastructure in the Free State region occurred in 1999, and became known as the “Matjabeng earthquake”. It was similarly associated with conspicuous movement and some damage on a large fault (the Dagbreek), which extended across kilometres of contiguous mining.

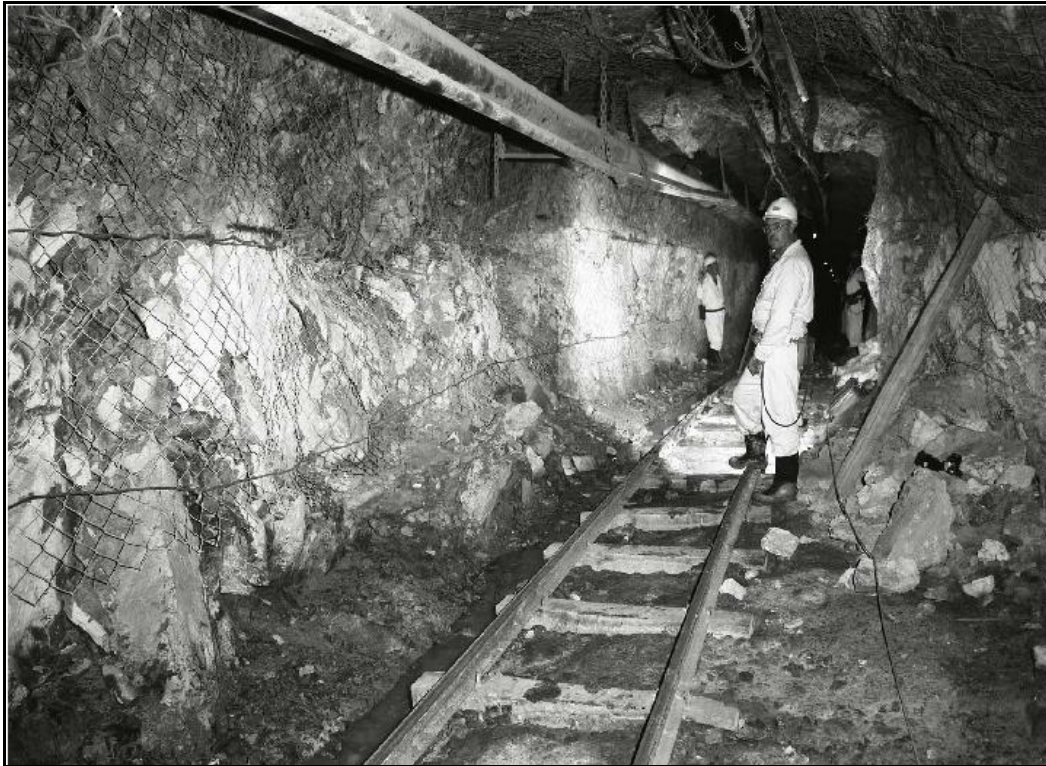


Figure 3. Fault slip caused by a mining-related seismic event observed in a tunnel. Fresh dip-slip displacements of up to 0.37 m were found along the President Brand fault following a  $M_L=4.7$  mining-related earthquake that occurred at a hypocentral depth of 1800 m on 25/01/1989 in the Free State goldfield (Ortlepp, 1997: 69). Note the offset in the grade line opposite the miner in the foreground. Photograph W.D. Ortlepp.

A catalogue of damaging seismic events that have occurred in South Africa since 1900 was compiled by the investigation team by searching the seismological bulletins of the Council for Geoscience, scientific publications, mining company records, and newspaper articles (Durrheim et al., 2006). The catalogue is not claimed to be complete or exhaustive, but is believed to list most mining-related events that have caused significant damage to buildings on the surface, or caused serious damage to mine infrastructure such as shafts or winding machinery that could have endangered many lives. In the 15-year period 1991-2005, the Council for Geoscience recorded 113 seismic events with  $M_L>4$  in the gold mining districts of South Africa (see Table 1). However, only about 30 of these events are listed in the catalogue, which indicates that many events with  $M_L>4$  do not cause significant damage to surface structures. However, the March 2005 event in Stilfontein, which led to this investigation, was preceded by at least 14 large events in the Klerksdorp mining district in the previous 32 years that caused significant damage to surface buildings, or serious damage to important mine infrastructure that might have resulted in catastrophic loss of life.

An important parameter in the estimation of seismic hazard is the maximum magnitude ( $M_{max}$ ), yet it is one of the more contentious as it is most likely a size of earthquake that has not yet occurred in the region under study.  $M_{max}$  for natural and mining-related earthquakes in southern Africa has been estimated to be in the order of 7.5 and 5.5, respectively (Shapira et al., 1989). A value of  $M_{max}$  not exceeding 5.5 for mining-related events is supported by the data in Table 1, if the approximation  $M_{max} \approx M_L(\text{largest recorded event}) + [M_L(\text{largest recorded event}) - M_L(\text{second largest recorded event})]$  (Dunn, 2005) is applied.

Table 1. Large seismic events in the gold mining districts, 1/1/1991 to 31/12/2005  
(Source: Council for Geoscience, 2006)

	East Rand	Far West Rand	Klerksdorp	Free State
Number of events with $4 \leq M_L < 5$	2	27	68	16
Number of events with $M_L \geq 5$	0	0	2	2
Magnitude of largest event	4.1	4.7	5.3	5.1
Magnitude of 2 <sup>nd</sup> largest event	4.0	4.6	5.0	5.1

### 3 INVESTIGATION PROCESS

The investigation was officially announced on 18 October 2005, following the release of the report on the inquiry into the seismic event of 9 March 2005 (Department of Minerals and Energy, 2005). Interested and affected parties were invited to bring their concerns and relevant information to the attention of the Investigating Team, and hearings were held in the gold mining districts during November and December 2005. The interviews were recorded and transcribed, and interviewees were given the opportunity to correct and amend the transcripts to ensure that their views were accurately and comprehensively captured. The transcripts are not included in the final report, but rather served as aide-memoirs for interviewees who made written submissions, and for members of the investigation team to use in formulating their findings. Further discussions with interested and affected parties took place in January 2006, when the two Californian members of the investigation team visited South Africa. Submissions were received from representatives of the following parties.

- Gold mining companies: AngloGold Ashanti, Gold Fields, Harmony, Simmer and Jack, President Steyn, and South Deep made oral submissions. AngloGold Ashanti, Gold Fields, and Harmony supplemented their oral submissions with written submissions, and DRDGold made a written submission.
- Labour organisations: The National Union of Mineworkers, Solidarity, and United Association of South Africa made oral submissions.
- Department of Minerals and Energy: Principal and senior inspectors from the Free State, Northwest and Gauteng regions made oral submissions.
- Tertiary educational institutions: Prof. Huw Phillips, head of the Mining Engineering Department at the University of the Witwatersrand made an oral submission, while Prof. Nielen van der Merwe, head of the Mining Engineering Department at Pretoria University was a member of the investigation team.

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- Mine seismology researchers and consultants: Both oral and written submissions were made.
- Disaster management authorities in local and district municipalities: Oral submissions were made by officials in the Free State, Klerksdorp and Gauteng regions.
- Risk management, business continuity and disaster recovery specialists: Representatives of financial institutions with infrastructure in the Johannesburg CBD made oral submissions.
- In addition, several independent consultants and equipment manufacturers made oral and/or written submissions.

## **4 FINDINGS AND RECOMMENDATIONS**

The nine questions posed by the Chief Inspector of Mines in the investigation team's terms of reference form the basis of this section. Each question is stated, followed by the investigation team's findings and recommendations, as well as a short summary of supporting evidence and a discussion of relevant issues. The full report (Durrheim *et al.*, 2006) includes the terms of reference of the investigation, a catalogue of large seismic events in South Africa since 1900, details of the investigations team's activities, the reports by team members, and written submissions by interested and affected parties.

### **4.1 Cause of the 9 March 2005 event**

**Question 1:** Can the seismic events that occurred on 9 March 2005 at DRDGold's North West Operations be ascribed to mining; i.e. did mining past and/or present trigger the seismic events?

**Findings:** The magnitude 5.3 event and its aftershocks can be ascribed to past mining. The event was caused by rejuvenated slippage on an existing major fault, with the extensive mining activities in the region contributing most of the strain energy. The chance of these events being solely due to natural forces is considered to be extremely small.

**Recommendations:** Some insurance policies only cover damage due to natural seismic events and exclude damage caused by mining-induced events. Consequently, disputes concerning the cause of seismic events arise between insurance companies and property owners and business owners following damaging events such as the one of 9 March 2005. It is recommended that the terms and conditions of insurance policies are reviewed in the light of scientific evidence that most seismic events in gold mining districts, large and small, are mining-related.

**Discussion:** The finding that the seismic events on 9 March 2005 are mining-related is based on both statistical and mechanistic considerations. It is incontrovertible that deep mining causes the rocks surrounding excavations to deform, and that the strained rock mass sometimes fails suddenly, either along a pre-existing weakness or by initiating a new rupture, causing the surrounding rock to shake violently. Everyone who made submissions on this point agreed that most of the seismic events observed in the gold mining districts could be ascribed to mining. However, opinions differed regarding the contribution of natural forces, particularly when the larger magnitude events (greater than magnitude 4, say) were considered. These large events invariably take place along pre-existing geological weaknesses, and sometimes may occur several hundreds of metres away from mining activity.

The southern African region is relatively stable from the point of view of natural crustal seismicity, as it is remote from the boundaries of tectonic plates. Nevertheless, seismic events violent enough to cause damage to surface structures occasionally occur. The magnitude 6.3 and 7.5 earthquakes that occurred in the Western Cape (September 1969) and in central Mozambique (February 2006), respectively, are examples of such events. However, statistical analysis demonstrates that the

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number of potentially damaging seismic events is far greater in gold mining regions than in surrounding regions. In his report to the investigation, Dr Kijko showed that the number of events exceeding magnitude 3 in the Klerksdorp mining region exceeds the average for South Africa outside gold mining districts by a factor of 700 (Durrheim *et al.*, 2006). Dr Kijko used a threshold of 3 for statistical purposes, as very few events with magnitudes exceeding 4 have been recorded outside the gold mining areas. There is no known difference in geology or natural stress field between the gold mining districts and adjacent regions that can account for this.

Studies have also shown that the extent of mining close to large faults in the Klerksdorp and Free State districts can account for the displacement and slip area required to produce events exceeding magnitude 5 (Brummer and Rorke, 1990.). In these districts, unmined and highly stressed fault-loss areas may extend for distances as great as 10 kilometres.

Events with a similar magnitude have occurred before in the gold mining districts, and hence the event of 9 March 2005 cannot be considered “totally anomalous”, as claimed by a witness at the Inquiry (Department of Minerals and Energy, 2005). For example, magnitude 5.2 events occurred in the Free State and Klerksdorp gold mining districts in 1976 and 1977, respectively. It is interesting to note that an analysis of seismicity in the Klerksdorp region indicated a recurrence time for magnitude 5 events of about 20 years (Gibowicz and Kijko, 1994: 334-335), though it must be noted that changes in mine production affect recurrence times, as the amount of seismic energy released is approximately proportional to the amount of rock that is mined (Gay *et al.*, 1995).

Mine seismologists distinguish between induced and triggered events: an event is “induced” if mining activity is considered to have provided most of the energy that is involved in the event, and “triggered” if the energy contributed by the mining activity is small but sufficient to create instability. Many studies have shown that sufficient energy is provided by mining operations to induce seismic events. In his submission, Dr Spottiswoode showed that extensive mining induces stresses considered to be capable of triggering seismic events at considerable distances from excavations (Durrheim *et al.*, 2006). Furthermore, Dr McGarr has shown that the dewatering of the rock mass during mining operations will tend to stabilise faults that might have been close to failure (Durrheim *et al.*, 2006). The Earth’s crust is normally saturated with water, and the fluid pressure opposes the gravitational and tectonic forces that clamp and stabilise faults. Hence, the dewatering of the rock mass, all other things being equal, will increase the stability of the faults. As parts of the crust may have a low porosity and/or permeability, the strengthening effect of dewatering is difficult to quantify for a particular feature without detailed studies of the properties of the fault zone.

Information submitted to the inquiry held to determine the cause of the seismic event of 9 March 2005 showed that the main seismic event was located within a few tens of metres of the No. 5 Shaft Fault and the reef horizon. The reef in this region had been extensively mined in the past. The shaft pillar that was being mined in the year prior to the seismic event was more than two kilometres away from the focus of the  $M_L=5.3$  event. The stress perturbation due to the shaft pillar mining would have been relatively small at the focus of the seismic event. Thus the extensive mining carried out more than a decade prior to the event was probably the major influence causing the event.

Much of the debate concerning the contribution of natural forces and mining to large seismic events seems to be driven by concerns regarding liability and compensation, rather than by scientific inquiry.

#### **4.2 Likelihood that large seismic events will recur**

**Question 2.** What are the probabilities of repeat occurrences in the same or other mining districts, especially where the mines are mature and large areas are mined out?



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**Findings:** Seismic events will continue to occur in the gold mining districts as long as mining continues. Seismicity will decrease as production diminishes, and will slowly reduce to the background levels when mining ceases. There are distinct differences between the mining districts with respect to the maximum magnitude of events. The Klerksdorp and Free State districts tend to experience larger events than the East, Central, West and Far West Rand. These differences are ascribed to differences in geological structure and mining layouts. Events with magnitudes exceeding 4 may cause some damage to buildings on the surface, while events with magnitudes exceeding 5 may cause serious damage. At current production rates, an event that exceeds magnitude 5 is likely to occur in the Free State or Klerksdorp district every twenty years or thirty years, on average. It is considered unlikely that events with magnitudes exceeding 5.5 will occur in the gold mining districts (Shapira *et al.*, 1989)

**Recommendations:** Seismic monitoring should continue after mine closure to determine when seismicity has reached background levels. The seismic hazard should be taken into account when considering the future use of mining land and the building codes applicable to any structures. Research should be undertaken to identify and delineate the most hazardous geological structures.

**Discussion:** Many studies have shown that seismic energy release is roughly proportional to the volume of mining, though this relationship may differ between regions, mines, and reefs. No unusual change in this relationship has been noted as mines reach the end of their lives. The narrow subhorizontal stopes created by gold mining tend to close due to creep effects in the rock mass, allowing the stress that has been induced by mining to dissipate slowly. It is, however, necessary to take special precautions if highly stressed remnants are to be mined, especially if they are intersected by faults and dykes. Planning to remove clamping or bracket pillars alongside major faults must be particularly conservative. The onus should be on the mine owner to demonstrate there are good reasons to believe that the risk is, in fact, low.

### **4.3 Seismic risks posed by the flooding of mines**

**Question 3:** What are the effects of flooding and the corresponding rising water levels on the stability of faults and other geological features?

**Findings:** If a fault is permeable to fluids, flooding can increase the pore fluid pressure on its surfaces, diminishing the effective stress clamping the fault, and decreasing its stability. Consequently, seismic events are likely to be triggered as the water level rises in mines that have been closed and allowed to flood. Seismicity will decrease once the water table stabilises. It is considered unlikely that any event triggered by a rising water table will have a greater magnitude than the events that occurred during mining.

**Recommendations:** Further research should be conducted into the relationship between seismicity and flooding. The possibility that rising and/or fluctuating water levels may trigger seismic events must be taken into account when the future use of mine land is considered, as well as in building codes applicable to any structures.

**Discussion:** The pumping of water from depth is costly, and thus there is a strong incentive for mines to be allowed to flood once the ore reserve has been exhausted. There is a concern that the flooding may trigger seismicity. Observations of mine flooding in Canada, India, Japan, Poland, and the partial flooding of Stilfontein, South Deep, and ERPM mines in South Africa, show that this is indeed the case. These observations have been supplemented by a theoretical analysis carried out by Dr McGarr (Durrheim *et al.*, 2006). These studies indicate that the flooding-induced seismic events are unlikely to have larger magnitudes than events that occurred during mining, and are likely to cease once the water table stabilises. However, this is a topic that merits further research, and monitoring of seismicity and water levels is recommended.

**Question 4:** What are the effects of seismicity on inter-mine water plugs and water barrier pillars?

**Findings:** It is possible that a seismic event could cause movement on a fault surface transecting a water plug and/or water barrier pillar, open up a fluid pathway, and allow flow of water into populated mine workings. While it is unlikely that such an occurrence would become an uncontrollable inrush, the consequences could be disastrous and so the risk must be seriously addressed.

**Recommendations:** If the flooding of old workings adjacent to current operations is being contemplated, a thorough survey of the mining geometry and geology must be conducted to ensure that the integrity of the rock mass comprising the water barrier pillar is not compromised, a risk assessment must be performed, water plugs must be designed according to internationally acceptable standards, seismicity and water flow must be monitored. Depending on the outcome of the risk assessment, water doors may be constructed and extra pumping capacity provided. Evacuation plans should be formulated and emergency drills conducted regularly.

**Discussion:** As noted above, the rise in water level on one side of a water barrier pillar is likely to be accompanied by an episode of seismicity. South Deep mine was faced with the possibility of a water-filled compartment with a 1500 m head being created up dip of its mining operations. The risk assessment and action plan implemented by South Deep should be used as a benchmark for any other mine facing a similar situation.

#### **4.4 Risk to neighbouring mines posed by large seismic events**

**Question 5:** What are the seismic damage risks to neighbouring mines in areas in which mines are mature?

**Findings:** The risk of a seismic event on a mine causing damage to underground workings on a neighbouring mine depends on the distance between the focus of the event and vulnerable areas on the adjacent mines. There is some risk to mine workings within a kilometre or so of the mine boundary if a fault or dyke with a history of seismic activity transects the mining properties. The risk is not considered high because major infrastructure such as shafts are usually located a kilometre or more from mine boundaries and there is generally good cooperation between neighbouring mines with respect to mine planning and blasting schedules.

#### **4.5 Capability to manage the risks posed by large seismic events**

**Question 6:** What is the adequacy of current technology, monitoring, and communication methods in managing current risks?

**Findings:** A range of technologies, ranging from stoping layout and sequencing strategies to local support methods, is available to mitigate the risks of underground damage resulting from large seismic events.

- Stope and tunnel support systems cannot guarantee the safety of workers within a few tens of metres of the source region of a large seismic event. Thus, if an area has already been extensively mined near any geological features that could host a large seismic event, any further mining of remnants or pillars adjacent to the structure must be cautiously considered and carefully planned.
- There is no technology anywhere in the world that is able to predict the time of occurrence of seismic events. The Council for Geoscience operates the South African National Seismic Network (SANSN) that monitors seismicity on a regional scale, while mines operate local monitoring systems. Both systems are considered useful and comparable with those installed in seismically active mining districts elsewhere in the world. However, steps should be taken to improve the quality and ensure the continuity of seismic monitoring, especially as mines change hands or close.

- The decline in seismological expertise on mines, at universities, and in research organisations during the past decade is a cause for concern.

#### **Recommendations:**

- Additional SANSN stations should be established in each mining district to provide adequate seismic coverage. SANSN locations can be improved by using current mine data to improve velocity models.
- Mine seismic monitoring systems and practice should be improved. For example: sensors able to determine accurately the source parameters of large events should be added; measures should be taken to prevent the loss of seismograms following power outages that large events often cause; the standard of maintenance should be improved; and seismic hazard assessment procedures should consider spatial dimensions and time scales appropriate for the occurrence of large seismic events.
- It is crucial that knowledge and technology continue to be developed through research work, accompanied by effective implementation and enforcement.

#### **Discussion:**

Stope and tunnel support. It was noted that most mines have failed to implement the best of available support technologies for both stoping and tunnel development. In an endeavour to save immediate working costs, some mines have reverted to previously discarded support practices even where the latest understanding may deem safety to be compromised. It should be emphasised, however, that such deviations from best practice would have little or no influence on overall mine stability and the incidence of very large seismic events. The consequences of these practices are greater damage to mine workings should a seismic event occur.

South African National Seismological Network (SANSN). SANSN stations are distributed equally over South Africa. Consequently, stations located several hundreds of kilometres away are used to determine focal locations. The regional coverage is important for monitoring natural seismicity and to enable comparison with the mining districts. However, only events with magnitudes exceeding 2 are reliably recorded, and it is often impossible to locate the foci of these events with a better accuracy than 5 km. While the mining district in which the event occurred can usually be indicated, it is difficult to determine the mine and impossible to identify the part of the mine or geological structure.

Mine seismic networks. All rockburst-prone mines have seismic networks that are useful for locating events, initiating rescue efforts, evaluating mining methods, and assessing seismic hazard. However, several shortcomings were identified:

- Only high frequency geophones are used. Consequently, the magnitude of large events cannot be accurately determined, as these large events radiate much of their ground motion at lower frequencies, leading to underestimates of  $M_L$ .
- Sometimes critical recordings of large events are lost as a result of power failure. It is recommended that mine networks be synchronised with Universal Time, which will make it far easier to use data from adjacent mines in order to locate an event. Secondly, it is desirable to provide an uninterrupted power supply that will prevent data loss.
- Some mines have been lax in maintaining their seismic network, with the result that the quality of seismograms is poor.
- Some mines have failed to recalculate the seismic parameters of past events following the introduction of new software, with the result that there are discontinuities in the histories.

Consequently it is difficult to assess trends and hazard. In some instances, seismic archives have been lost. This is a problem when mines have changed hands or closed.

- The spatial dimensions and time scales used to assess seismic hazard are sometimes unsuitable to determine the likelihood of occurrence of large seismic events.

**Expertise.** In the past decade there has been a serious decrease in high-level seismological and rock engineering expertise in South Africa. Practitioners have retired, emigrated, or changed occupation. Funding for research, which has not been generous in the past, has further diminished in recent years. The need for fundamental research into the source mechanisms of large seismic events and the damage mechanism of rockbursts is particularly urgent.

**Question 7:** Will the placement of slimes and other mining discards underground alleviate the situation?

**Findings:** There is no merit in placing slimes or backfill in areas that have been mined out in the past for the purposes of reducing the risks of large seismic events, as much closure as already taken place. The placement of slimes or backfill should be motivated by the need to provide local stability for current mining operations or for the disposal of surface waste.

**Recommendations:** Stabilising pillars may also be used to control seismicity, and should be considered in any mining strategy. More research of a fundamental nature is required to improve the understanding of how bracket pillars affect the source mechanism of large seismic events.

**Discussion:** There are several reasons the placement of slimes or backfill in old mine workings is not regarded as a worthwhile endeavour:

- Some stress has already been regenerated through total closure;
- It would be extremely difficult to ensure significant filling; and
- It could make any future mining (e.g. stabilising pillars, low-grade ore) more difficult, thereby sterilising remaining ore resources.

The use of stabilising pillars to limit the amount of closure and to clamp geological structures should be carefully considered when mining occurs in the vicinity of potentially hazardous geological structures.

#### **4.6 Vulnerability of infrastructure and readiness for disaster**

**Question 8:** What are the implications for disaster management in mining districts in which seismic risk exists?

**Findings:** Disaster management officials in the district municipalities that cover the Klerksdorp and Free State gold mining districts are incorporating the risks of seismicity in their disaster management plans. However, this does not appear to be the case for the Johannesburg Metropolitan Municipality.

**Recommendations:** Johannesburg officials are urged to include seismic hazard in their disaster management planning. Appropriate training should be provided to all members of emergency services, and drills should be practised regularly at all public buildings (schools, hospitals, offices, etc.) so that panic can be avoided in the should a seismic event occur. There is considerable scope to improve the seismic hazard assessment process and emergency response, and a comprehensive set of recommendations is provided in the report.

**Question 9:** What are the risks to existing surface structures and infrastructure near major geological structures in mining districts? What precautions or restrictions should be applied to these?

**In Proceedings of the Third International Seminar on Deep and High Stress Mining, 2-4 October 2006, Quebec City, CANADA, J Hadjigeorgiou and M Grenon (editors), Université Laval, Canada.**

**Findings:** Some buildings in gold mining districts are considered to be vulnerable to damage, and even collapse during seismic events, posing safety and financial risks. There are simple, relatively inexpensive measures that could limit damage and the risk of injury. Major financial institutions in the Johannesburg Central Business District (CBD) are concerned that disruptions to services even for a few hours following a seismic event could affect business continuity and cause losses, and are considering moving critical operations out of the CBD.

**Recommendations:** An experienced earthquake engineer should be contracted to inspect the building stock and review the content and enforcement of building codes. Officials from Johannesburg Metropolitan Municipality should meet with members of the CBD Seismic Interest Group to discuss concerns and develop strategies.

## **CONCLUSIONS**

Large seismic events with local magnitudes as up to 5.5 are likely to shake the gold mining districts of South Africa as long as deep level mining continues, and for several years after mining ceases as the rock mass gradually stabilises. Although it is unlikely that these events will cause large-scale destruction in nearby towns, the large events are capable of causing damage to buildings and infrastructure, and injuries to people. It is prudent to enforce appropriate building codes should any new structures be built near deep mines. It is recommended that a survey to public buildings such as schools or hospitals be conducted to determine if any reinforcement or modification is required. Furthermore, emergency response and disaster management agencies should include mining-related earthquakes in their response plans.

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