A JAPANESE - SOUTH AFRICAN COLLABORATION TO MITIGATE SEISMIC RISKS IN DEEP GOLD MINES

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ABSTRACT

Mining-induced seismicity poses a hazard to workers in deep South African mines, while natural earthquakes pose a hazard to people living in Japan and other regions of the world that are close to plate boundaries. We introduce a 5-year Japanese-South African collaborative project entitled *"Observational study to mitigate seismic risks in mines"*. The principal investigators are H. Ogasawara (Japan) and RJ Durrheim (South Africa). The project will build on previous studies carried out by Japanese seismologists in South African mines, and will develop human and instrumental capacity in South Africa. This knowledge will contribute to efforts to upgrade schemes to assess seismic hazard and to mitigate the seismic risks in deep mines. The knowledge is also relevant to the study of the mechanisms that generate tectonic earthquakes. The project was conditionally approved in April 2009 by the Japan Science and Technology Agency (JST), an external agency of the Ministry of Education, Culture, Sports, Science and Technology, and the Japan International Cooperation Agency (JICA), an external agency of the Ministry of Foreign Affairs. It is anticipated that the agreement between the Japanese and South African governments will be concluded by the end of the 2009 financial year and that research work will commence in 2010.

1 Introduction

Mining-induced seismicity poses a serious risk to workers in deep mines in South Africa, as do natural earthquakes to people living in Japan and other regions of the world that are close to plate boundaries. We introduce a 5-year Japanese-South African collaborative project entitled *"Observational study to mitigate seismic risks in mines"*. The project will build on previous studies carried out by Japanese and South African seismologists and rock engineers in deep South African gold mines. These studies are described in this paper, together with the proposed new project. The project has three main aims:

(1) To learn more about earthquake generation mechanisms through monitoring in close proximity to the seismic source in South African gold mines. This knowledge will contribute to efforts to upgrade schemes of seismic hazard assessment and to limit and mitigate the seismic risks in deep and highly stressed mines and in areas vulnerable to natural earthquakes.

(2) To develop human and technical capacity in South Africa.

(3) To upgrade the South African national seismic network.

The Japanese members of the research group are from Ritsumeikan, Tokyo, Tohoku, Kyoto and Kagoshima universities and the Japanese Institute of Advanced Industrial Science and Technology, Tono Research Institute of Earthquake Science. The South African members are from the Council for Scientific and Industrial Research (CSIR), Council for Geoscience (CGS), the University of the Witwatersrand, as well as practitioners from gold mining companies. The principal investigators are H. Ogasawara (Japan) and RJ Durrheim (South Africa).

The project is carried out under the auspices of the JST-JICA program *"Countermeasures towards Global Issues through Science and Technology Research Partnership",* which was launched in the 2008 financial year. JST and JICA are acronyms for the Japan Science and Technology Agency and the Japan International Cooperation Agency, respectively. JST is an external agency of the Ministry of Education, Culture, Sports, Science and Technology. JST mainly promotes educational and research activities in science and technology domestically, but tries to find opportunities for international promotion. JICA is an external agency of the Ministry of Foreign Affairs. It is primarily oriented towards diplomacy, but is also trying to find an opportunity of the diplomacy in science and technology. In the 2008 financial year, JST and JICA launched the above-mentioned joint program. It aspires to acquire new knowledge to tackle global issues like environment/climate change, infections diseases, water shortage, natural disasters, and bio-resources. In the 2009 financial year, 21 projects that tackle global issues were conditionally approved, six for African countries. Our project is one of two projects to be carried out in South Africa. The program encourages the application of the acquired knowledge in society. Our goal is to advance our understanding of the earthquake generation process, and to use this knowledge to mitigate seismic risks, not only in South African mines, but also in Japan and elsewhere in the world.

2   Background

Japan is an earthquake-prone country, having an M>7 event every year, on average. About 10 per cent of seismic events over the world take place in and around the 378×10^3 km^2 country (c.f. 1229×10^3 km^2 for South Africa). For example, in 1995 the Kobe earthquake (M_w=6.9) caused more than 6 400 fatalities, damaged more than 64 000 houses, and caused economic losses amounting to about ZAR10^{12}. An impending M8 earthquake, expected to occur around 2030, may cause an even greater disaster. Consequently, there have been strong demands to predict and mitigate seismic risks in Japan. Following the 1995 Kobe earthquake, very dense seismic and GPS networks (station spacing typically a few tens of kilometres) have been deployed to

delineate in much finer detail the earthquake-prone geology and spatio-temporal variation of seismicity and rupture process of every large event. Yet, hypocenters are too deep (typically 10-20 km) to see the details of earthquake preparation and generation processes. Japanese scientists have been seeking for opportunities to have a closer look at these processes.

In 1991, Prof. Nicolaysen of the BPI at the University of the Witwatersrand submitted a proposal *"Semi-controlled experiment on seismic events"* to the International Association of Seismology and Physics of the Earth's Interior (1991). After it was endorsed by IASPEI, Prof. Nicolaysen visited Japan to promote the proposal to Japanese Seismological Society (Nicolaysen, 1992). Since then, Japanese-South African cooperative research (Figure 1) has been monitoring the earthquake generation process in great detail in close proximity to hypocenters (e.g. Ogasawara et al., 2002, 2009). The project has been referred to as *"The Semi-controlled earthquake-generation experiments at deep gold mines, South Africa (SeeSA)"*. ISS International Ltd has greatly assisted the project.
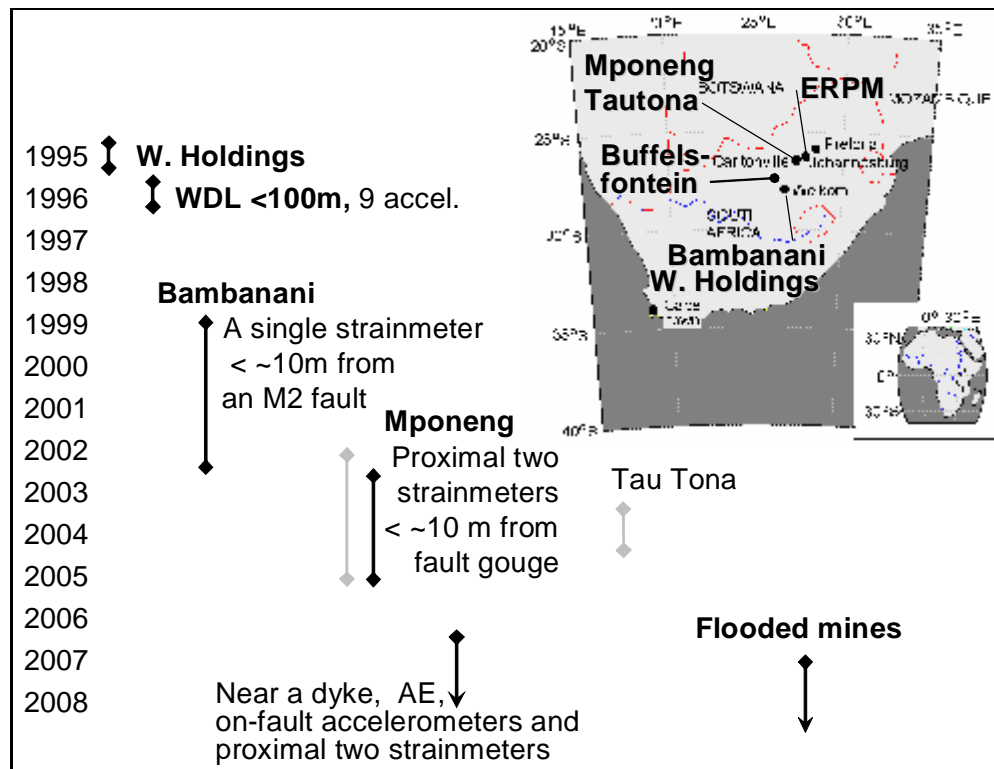

Figure 1. Semi-controlled earthquake-generation experiments at deep gold mines to 2008 (after Ogasawara et al., 2009). Periods of monitoring are shown by vertical lines. Arrows indicate on-going projects. WDL: Western Deep Levels South Mine (currently Mponeng), where an array of 9 triaxial accelerometers was deployed within 100 m of potential seismicity. Flooded mines: ERPM and Buffelsfontein. The new JST-JICA project accommodates bigger experiments at Moab Khotsong and Driefontein mines and smaller experiments in some other mines.

A pilot experiment was performed at Western Holdings mine in 1995. A very sensitive borehole strainmeter (Ishii, 1997) was able to detect fine details of rock mass deformation and record large, sudden changes associated with large events (Ogasawara et al., 2002; Van Aswegen and Laas, 2003). We found it to be of significant value to compare the rock mass deformation with seismicity monitored by the Integrated Seismic System (Mendecki, 1997). A 200 m array of nine borehole triaxial accelerometers installed along a footwall haulage revealed that the rupture process of M_L=0~1 earthquakes were as complex as natural great earthquakes and that the stress drop and energy efficiency were almost the same (Yamada et al., 2005, 2007).

At Bambanani mine, a sensitive Ishii strainmeter installed in a fault loss successfully tracked rock mass deformation (Figure 2 and Ogasawara et al., 2005). We could clearly see mining-associated-accumulation and earthquake-associated-release in strain, followed by relaxation corresponding to ~ 10 MPa stress change. The largest event closest to the strainmeter was M_w2.9 on the fault in February 2003, when the Sigma 1 parallel component (Ch.1 in Figure 2) showed an increase in stress (went down in Figure 2). The increased stress was finally released by an M_w2.0 event that occurred two months later in April 2003 at nearby dyke. We felt these data should be used to assess rock mass stress evolution during significant seismicity, by comparing with stress modelling. The data were continuously recorded with a frequency of 25 Hz. Frequent non-seismic slow strain changes were noted (connected dots in Figure 2; Yamamoto, 2008), some being accompanied by clear forerunners (Naoi et al., 2006).
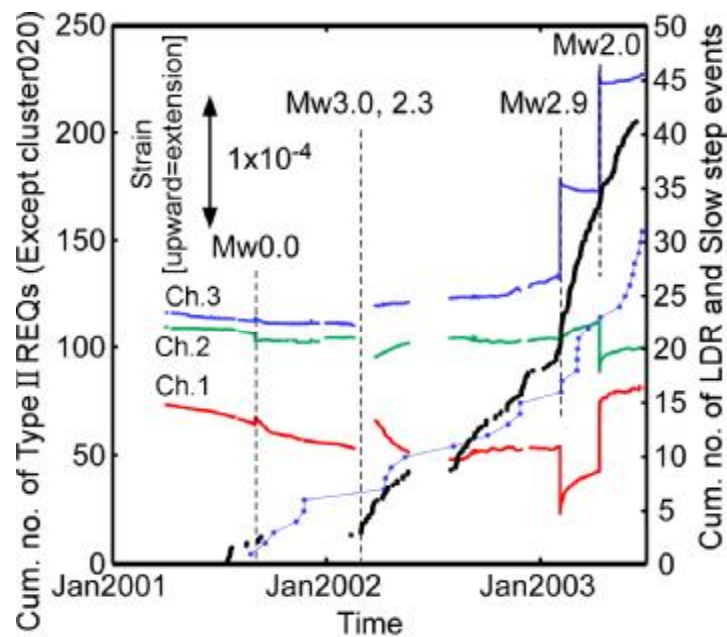

Figure 2. Strain change recorded over a 3-year period at a fault loss in the Bambanani mine. Connected-dots: cumulative number of slow events. Thick line: cumulative number of repeating earthquakes close to the Mw2.9 event in February 2003 (after Ogasawara et al. 2009, data from Ogasawara et al. 2005, Naoi et al. 2006, and Yamamoto 2008).

Much clearer forerunners were seen at Pretorius fault zones at Mponeng mine (Figure 3). Two strainmeters near to the slow events showed that they were caused by slip on the distinctive fracture zones in the fault zones (Yasutake et al., 2008). However, the mine's seismic monitoring was not sensitive enough to delineate the source fault of those major events, limiting the investigation. The problem was solved by the project described in the next section.
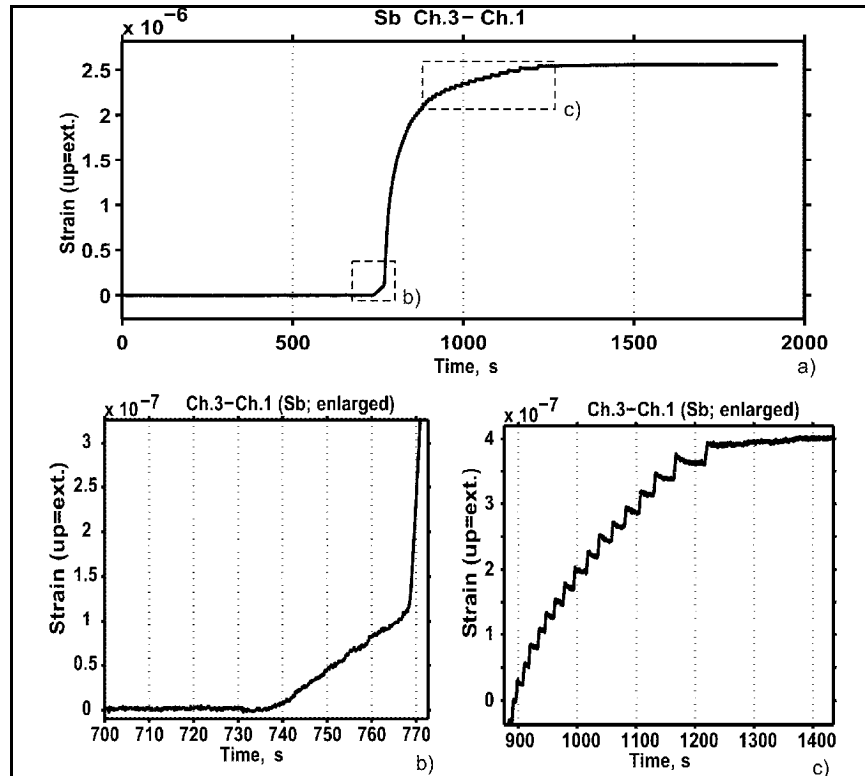

Figure 3. An example of slow strain changes with clear forerunner after 735 s (b)
observed at the Pretorius fault zone, Mponeng mine (after Ogasawara
et al., 2009; data after Yasutake et al., 2006).

3   JAGUARS AE monitoring of dyke failure, Mponeng

Nakatani et al. (2008) deployed a small network (approx. 40 m span) of eight acoustic emission (AE) sensors covering a frequency range up to 200 kHz in a seismically active hard rock pillar at 3300 m below surface in the Mponeng gold mine, South Africa (Figure 4). The site is located at the contact of a major gabbroic dyke within quartzite host rock at about 90 m from nearby mining cavities. It was Japanese–German-South African international cooperative project and referred to as JAGUARS (JApanese-German Underground Acoustic emission Research in South africa). GeoForschungsZentrum (GFZ; German Research Centre for Geoscience) Potsdam and GMuG joined the project from Germany, and CSIR joined from South Africa.
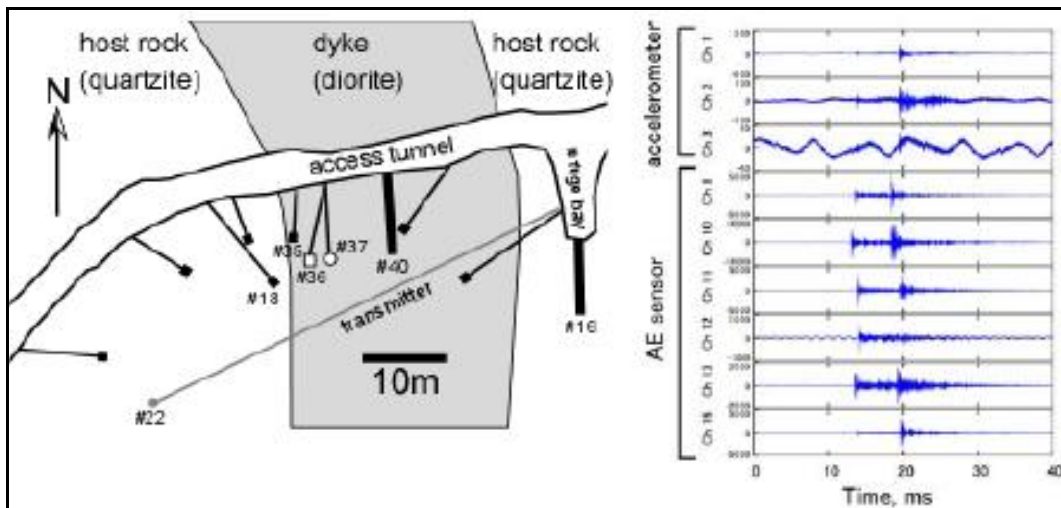
Figure 4. (Left) Plan view of the geology and mining configuration around the site at Mponeng Mine. Tunnels shown are at 116L (tunnel floor at z = -3543.5 m, datum is 275.8 m above shaft collar). Geological features (dykes) are shown in horizontal positions measured at the reef level. The tabular reef dips 26.5 deg toward SSE. Solid square: AE sensor, white square and circle: 25kHz accelerometer and hydrophone, respectively, thick lines: boreholes with Ishii borehole strainmeter near the bottoms. (Right) examples of wave forms. AE sensors picked up a huge number of events that were not detected by the accelerometer.

This was the first implementation of a high-frequency AE network at seismogenic depth in hard rock formations monitoring AE and microseismic events at frequencies > 10 kHz. High-frequency waveforms with > 100 kHz components were successfully observed for events with hypocentral distance of up to 50 m, many of which occurred in pristine rock formation outside the damage zones by various mining activities. Lower-frequency events were recorded as well, the observation window overlapping the mine's routine monitoring up to 2 kHz (Figure 4).

The network recorded an M_w 1.9 (M_L 2.1) event in close proximity. In the 150 hours following the event, more than 21,000 aftershocks were located within 100 m of the network (Yabe et al. 2008; Philipp, 2008). For the same period the mine's geophone network, with a magnitude detection threshold of approx. M_w -0.5, detected only 9 events in the same area, demonstrating a huge gain in detectability of microearthquakes. We determined seismic velocities using in-situ ultrasonic transmission tests within the frequency range of the observation band of our network (1 kHz - 180 kHz), using shot points spread along a borehole spanning a distance of about 50 m (see a gray longest line in Figure 4 indicating the transmission hole). Fairly high velocities for the local rock types have been concluded, indicating good quality of rocks there. The acoustic emission system picked up several thousand times more events than the mine's seismic network near the 116/45 crosscut at Mponeng, successfully delineating a fault near the Pink and Green dyke that was the source of the M_L 2.1 event (Figure 4). Mining-induced temporal changes in strain were also successfully tracked, showing that the dyke was approaching failure (Katsura et al. 2008).

4   Monitoring of quasi-static and dynamic deformations due to mining

Two underground sites in Mponeng gold mine in South Africa were instrumented by CSIR with tilt-meters integrated with seismic monitors. Both the rate of tilt, defined as quasi-static deformations, and the ground motion, defined as dynamic deformations, were analysed in order to understand the rock mass behaviour around deep level mining (Spottiswoode and Milev, 2006; Milev and Spottiswoode, 2005, 2008a, 2008b). Figure 5 illustrates the distribution of coseismic and aseismic tilt during the time of the day. It was found that the rate of coseismic and aseismic tilt, as well as seismicity recorded by the mine seismic network, are approximately constant until the daily blasting time, which takes place from about 19:30 until shortly before 21:00. During the blasting time and the subsequent seismic events the coseismic and aseismic tilt shows rapid increase.
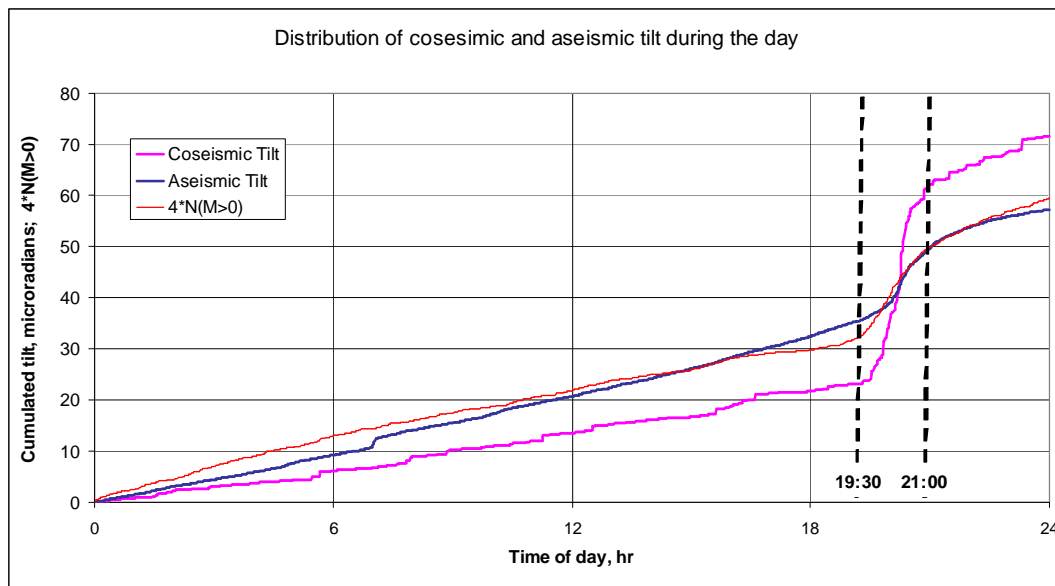

Figure 5.   Distribution of coseismic and aseismic tilt during the day at Mponeng mine

The tilt rate before and after a seismic event was also studied. It is interesting to note that lack of after-tilt was found for smaller co-seismic tilt steps (e.g. no change in the tilt visible between 0.1and 100 microradians after a seismic event). An example of the tilt rates before, during, and after a normal 'fast' seismic event is shown in Figure 6. In most cases there was no after-tilt.

Much of the quasi-static deformation, however, occurs independently of the seismic events and blasting and was described as 'slow' or aseismic events. Figure 7 illustrates slow aseismic deformations or so called "slow" seismic events.
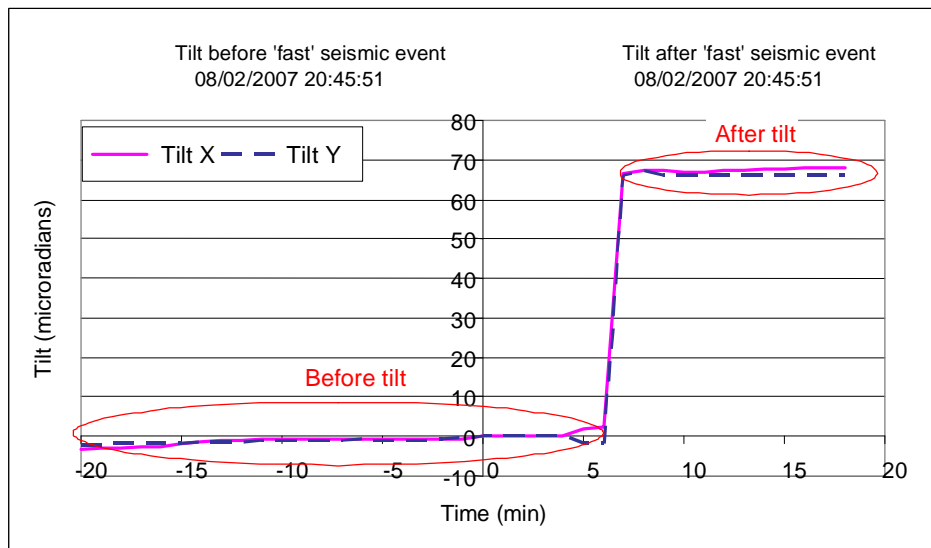
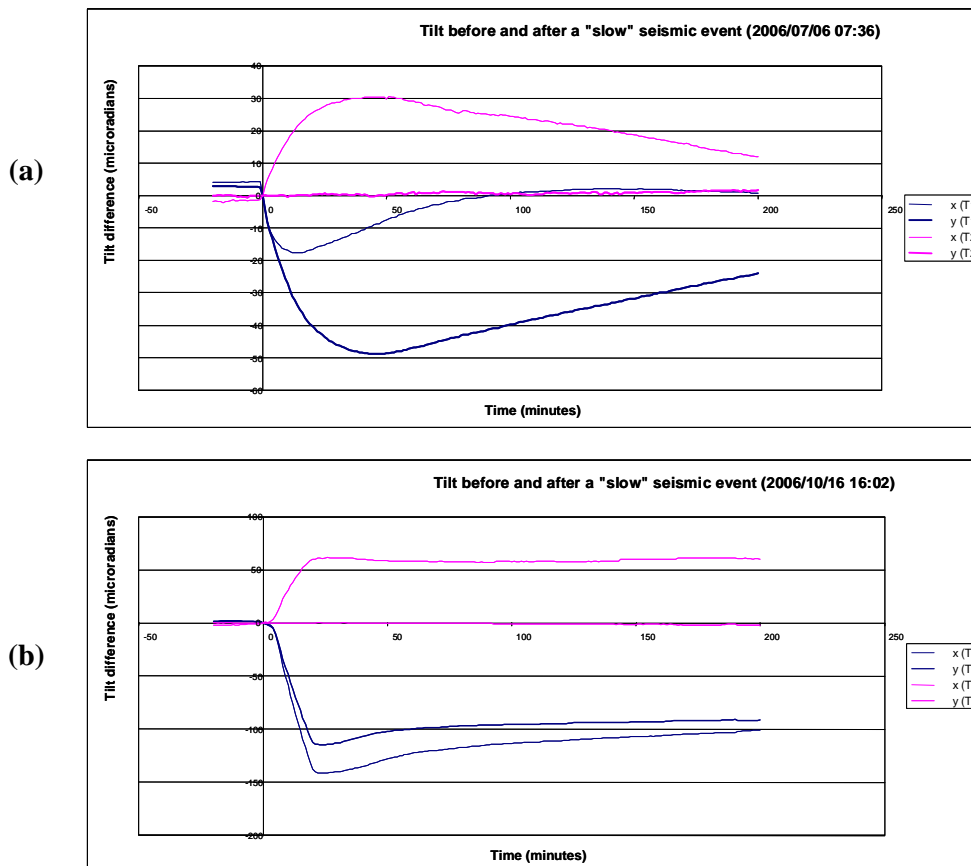**Figure 6.** **Tilt during the "fast" seismic event**

Figure 7. **Examples of "slow" seismic events**

The tilt changes associated with an $M_w1.9$ ($M_L2.1$) seismic event are shown in Figure 8. It is interesting to notice that the event has well pronounced after-tilt, which is most probably the result of the aftershock sequence following the event. The distribution of the tilt changes associated with $M_L2.1$ event are shown in Figure 9. Three populations of tilt jumps can be identified: (i) small tilt jumps representing the Gaussian noise, (ii) intermediate size tilt jumps interpreted to be aseismic tilt changes, and (iii) the coseismic tilt changes.
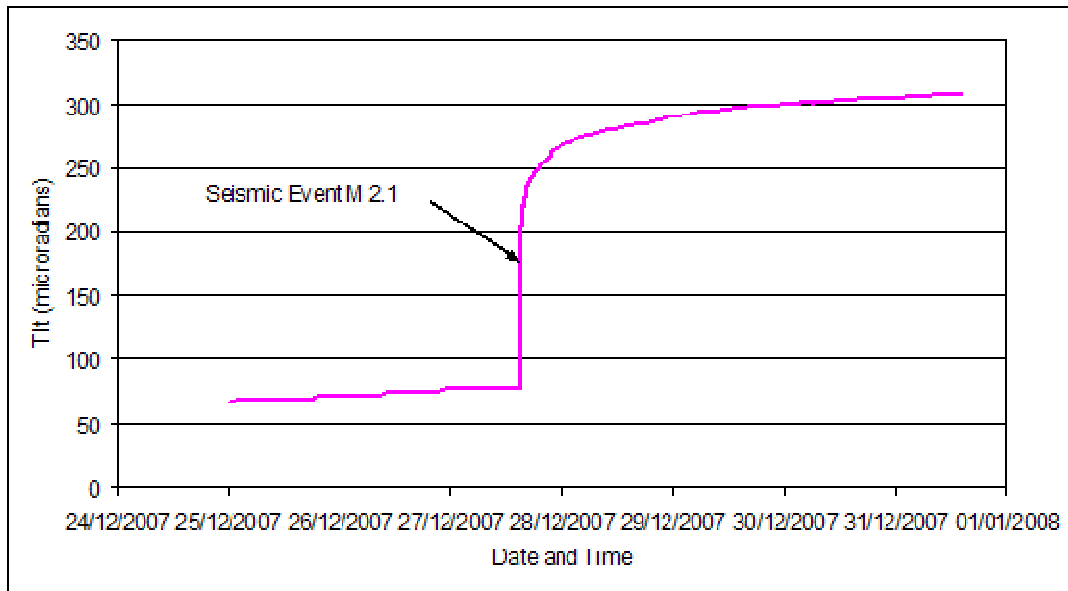

Figure 8.   Tilt associated with $M_L2.1$ event on 12/27/2007 located close to the research site at 116 level, Mponeng mine
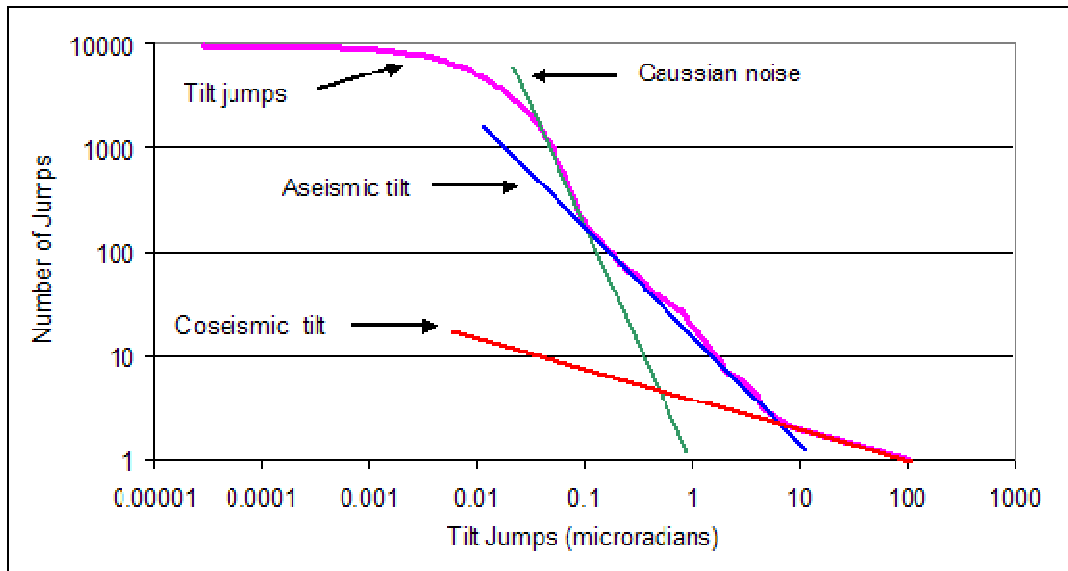

Figure 9.   Interpretation of tilt changes associated with $M_L2.1$ event on 27 December 2007 at Mponeng mine

5   Monitoring of seismicity in the mining districts by a cluster of surface seismic stations

5.1 Motivation

Seismic monitoring objectives are to locate seismic events as quickly and accurately as possible. The South African National Seismograph Network (SANSN) is a regional seismograph network that records seismic activity throughout South Africa and large seismic events in southern Africa. Figure 10 illustrates the layout of the network. The SANSN is equipped with low-frequency instrumentation appropriate for the recording of large events. Stations of the SANSN were upgraded during 2006 to meet international standards. Presently, the SANSN consists of 23 stations that communicate triggered and continuous data to the Silverton offices of the Council for Geoscience (CGS), where analysis is undertaken daily to identify seismic events. Results of data processing are disseminated to agencies of Government and the International Scientific Community via quarterly seismological bulletins (Saunders, 2009). The CGS also acts as a repository for waveform data recorded by the stations of the SANSN, which can be used by future generations of scientists to re-evaluate findings. Progress in waveform data capture over the past four years has lead to waveform data being kept as continuous records at 20 samples per second. The current distribution of seismic stations of the SANSN limits the lower magnitude detection threshold to approximately Richter Magnitude value of about 2.0. The analysis software used by the CGS, though widely used throughout the world, does not facilitate an automatic phase picker and location which results in the CGS unable to respond to an earthquake within a short period of time.
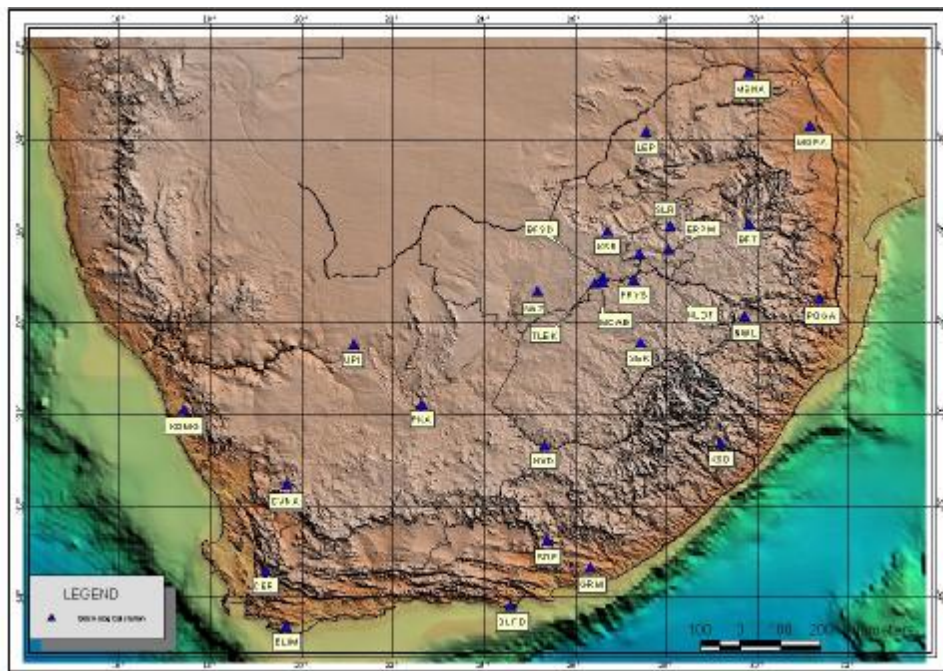

Figure 10. Geographical distribution of stations comprising the South African National Seismograph Network.

Figure 11 shows the map of seismicity of Southern Africa. It should be noted that more than 95 per cent of the total seismicity comes from the mining districts. The error in location reported by the CGS for mining activity is relatively large, and is a function of the number of stations that recorded the event, the accuracy of the P-wave arrivals picking as well as the precision of the velocity model. Eight SANSN stations are currently deployed near the gold and platinum mining areas. The location error is of the order 1 to 10 km. Consequently the CGS is only able to identify the district in which large events occur, and not the particular mine.
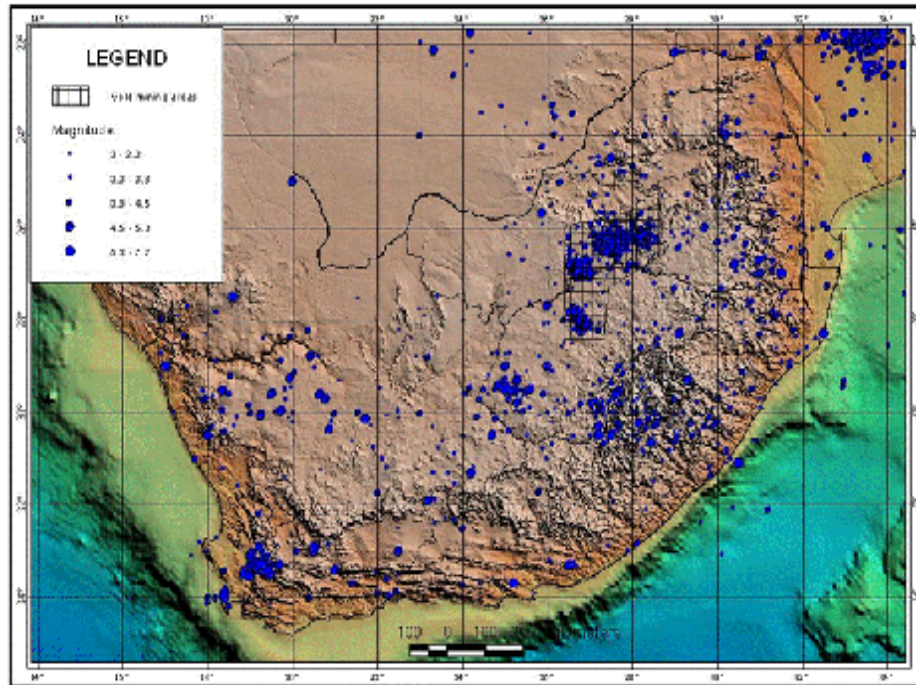

Figure 11. Seismicity of Southern Africa. Note that more than 95% of the total seismicity comes from mining districts.

All seismically active mines operating in gold mining districts are equipped with seismic networks. Well-designed seismic networks are capable to identify seismic-prone structures. The location determined by the mine network is accurate to within a few tens of meters due to the density of the seismic stations that are located at different depths surrounding seismic event (Cichowicz, 2005). The velocity model of the mine networks can be accurately determined since the network covers a small area of almost uniform geological structure. Mining networks are equipped with a combination of 4.5 Hz and 14 Hz geophones which are suitable for locating small, high frequency seismic events and for estimating seismic source parameters of these events. However, sensors used by the mines are not suitable to record low-frequency seismic signals that are necessary for analyzing the source parameters of large seismic events (Figure 12). Furthermore, the magnitude scales that are used by the different mining houses to calculate the size of seismic events are not always correlated with each other or with the Richter Magnitude used by the CGS.
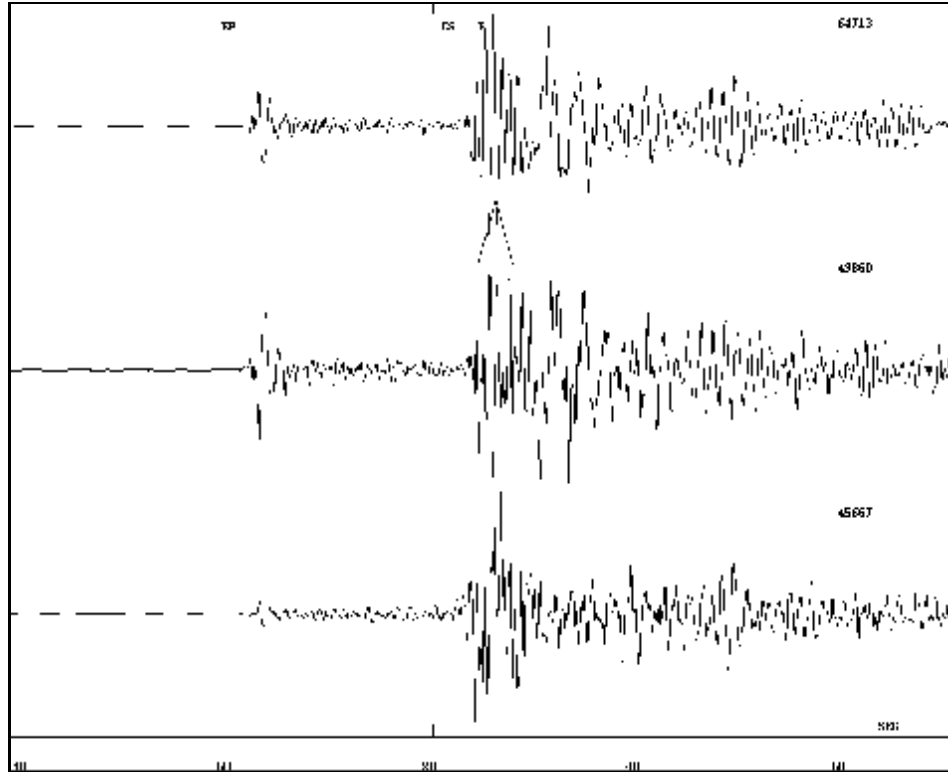
Figure 12. A seismogram of the Stilfontein earthquake (M5.3, 9 March 2005) recorded by the SANSN station (Senekal) at a distance between source and station of 180 km. The seismogram is shown in the frequency range from 0.033 Hz to 2 Hz.

Mining companies and the research organisations affiliated with them focus mainly on safety issues in the stope area and the research of large seismic events in mining districts is not their main focus. However, mechanisms of large seismic events provide insight into local tectonics, allowing a better understanding of the stress regime of our crust. Additionally, it is vital to understand the risks associated with possible ground motion, which occurs in close proximity to the seismic source. The CGS supports projects that contribute towards a better understanding of the mechanisms of damaging seismic events located in the mining districts (Cichowicz 2007, 2008, 2009, Cichowicz et al. 2008, 2009). On 9 March 2005 the Stilfontein earthquake caused a temporary closure of the mine, which was an economic disaster for the whole town owing to job losses. A better understanding of the tectonics of the area will prolong the economic life of the mine.

The question arises, what type of a ground motion caused the damage observed on the surface? Unfortunately, during the Stilfontein earthquake, there was no seismic station on the surface near the town. Therefore, a comparison of prediction of ground motion with observation can not be performed. Different approaches have been developed to simulate strong ground motion. A method for modelling strong ground motion should be able to simulate a source-space time evolution and wave propagation from a fault to

the receiver. If the scenario earthquake is in the near field, a point source model is not suitable for ground motion prediction. The fault geometry, heterogeneity of slip on the fault plane, and directivity can influence the ground motion in the far and near field. Simulation of an extended seismic source requires that a large fault is divided into sub-faults and each sub-fault is considered as a small point source. The waveform of a small event is time-delayed, scaled, and summed to simulate the ground motion of a large earthquake. The earthquake source is represented as a set of point sources with a source time function. The source time function of the simulated earthquake is represented as a linear combination of the source time function of the sub-events. This approach enables the inclusion of directivity into simulation of the process.

Simulation of the ground motion caused by the Stilfontein M5.3 earthquake at the surface at the source-site distance of 5 km is presented on Figure 13. A model with two asperities predicts much larger peak ground acceleration (PGA), peak ground velocity (PGV), and amplitude of response spectra than the simple point source model. The most important parameters of strong ground motion prediction are sizes of asperities and the asperities static stress drop.
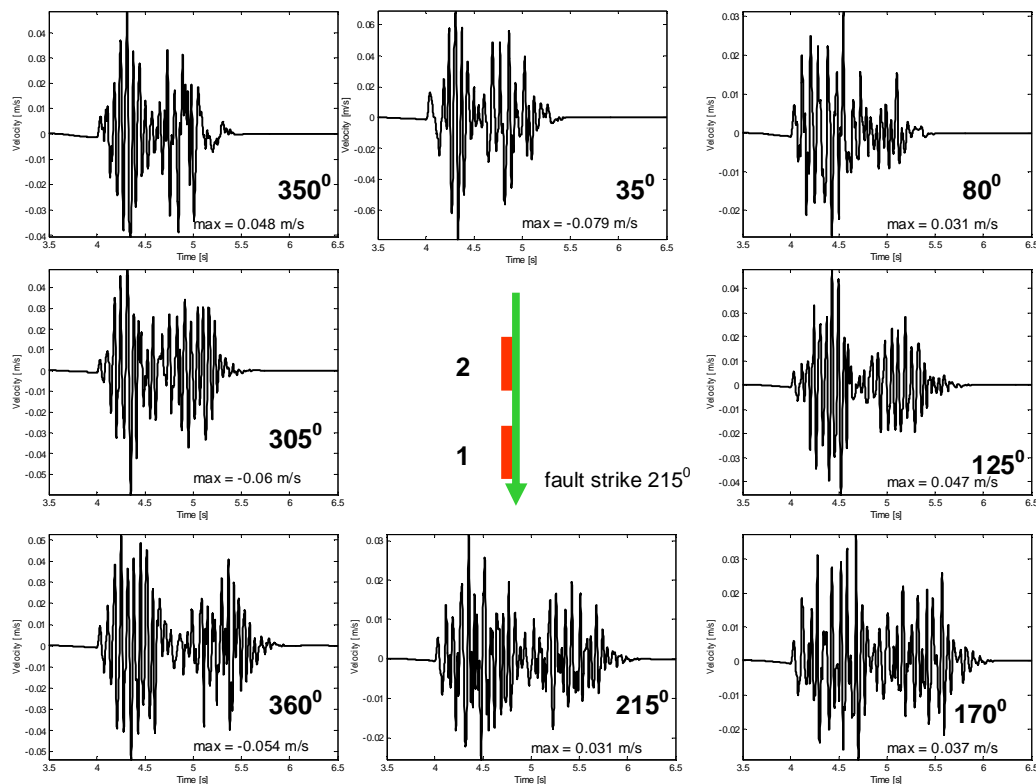

Figure 13. Velocity of ground motion predicted at a distance of 5 km from the epicentre on a hard rock surface. The fault strike, 215° (green arrow) and station's azimuth are displayed next to the waveform. The positions of two asperities are marked with red lines.

5.2 Objectives of surface monitoring

This component of the project has two objectives: firstly, to install a cluster of several seismic stations on the surface in one of the mining districts, most likely in the West Rand and Far West Rand; and secondly, to upgrade the software in order to be able to automatically process larger volumes of data, perhaps several thousands of waveforms per day from the current level of only a few hundred per day. This will enhance the Seismological Bulletin with information relevant to the mining industry.

What is the likely threshold sensitivity that will be provided by the cluster of new seismic stations? The answer to this question can be provided by analyzing the data from the research project conducted by the CGS in the Klerksdorp district. Three strong ground motion sensors were installed in the Klerksdorp district in 2008. Figure 14 shows a range of values of magnitudes recorded in the mining district at different distances. The most important is the low end of magnitude for the different distances. The detailed inspection of Figure 14 reveals that the threshold is magnitude 1.0 for a distance range from 2.5 km to 30 km.
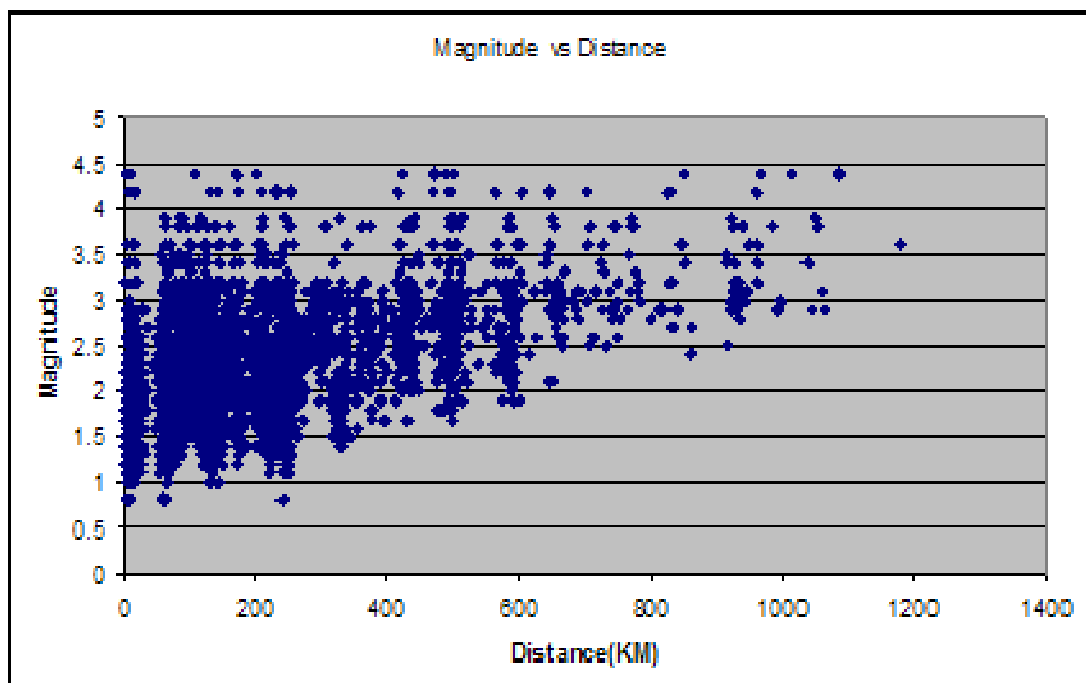

Figure 14. Magnitude versus distance for seismic events recorded in the mining districts by the SANSN network from 2008/05 to 2008/12. The distances range from 3 km to about 70 km and are only available due to the installation of three temporary stations for research purposes, while the permanent SANSN stations monitor mining related events from a minimum distance from the seismic source of about 70 km.

The cluster of strong ground motion seismic stations will greatly contribute to:
- Improvement of the accuracy of location of mining events.
- Identification of seismically active features in the mining district.
- Facilitate a basic analysis, such as focal mechanism determination and regional stress field analysis.
- Development of methodology for detailed analysis of the largest recorded events in mining districts using both inversion and modelling techniques.
- Development of methodology to estimate damage at the surface, which is a function of the fault geometry and the slip direction, complexity of the seismic source, local geology and the distance between source and surface infrastructure.
- Provide standardized magnitude estimation in the mining district.
- Provide seismic information to mine closure and water management projects.

The intelligent use of seismic methods and its full integration with rock engineering and mining geology will add value by identifying of hazardous features in mines.

6   Proposed JST-JICA project

Building on previous studies reviewed above, the project ultimately aims to upgrade the schemes of seismic monitoring and risk assessment in deep mines. A dense array of instruments will be deployed to monitor the response of the rock mass to mining and to any seismic events that may occur. We hope to record the entire life span of several earthquakes with source regions greater than 100 m in extent (i.e. with local magnitude $M_L=2$ and greater).

The main components of the project are:
(1) A highly sensitive microfracture monitoring system will be installed in the area of high seismic potential to identify the source fault of impending earthquakes.
(2) The mining-induced stress field will be tracked using numerical modelling and sensitive strain/tilt observations (e.g. Spottiswoode and Milev, 2006), compared with stope closure meter (e.g. Malan et al., 2003). These observations may also pick up precursory activities of the fault.
(3) Near-fault dynamic stress will be monitored during the mainshock rupture to improve the assessment of strong shake, with which the strong shake at the disaster site is also monitored to compare (e.g. Milev et al., 2003).
(4) Aftershocks will be also analyzed to microfracture level to delineate the mainshock rupture in detail, which is a prerequisite to assess postseismic rock stability in terms of stress redistribution by the mainshock.
(5) The South African National Seismograph Network (SANSN) will be upgraded, enabling quicker processing of seismic information in the mining district where research project will install a cluster of surface seismic stations.
(6) Better assessment of strong ground motion on surface by damaging mine related seismic events.
(7) Field observations of the seismic source and the collection and laboratory analysis of rock samples.

7   Concluding remarks

The project was conditionally approved in April 2009 by JST and JICA. The grant for the 5-year project is worth approximately US$3 million. These funds may only be used for equipment and 5-year running costs. The cost for permanent research employee must be recovered from other sources. It is anticipated that the agreement between the Japanese and South African governments will be concluded by the end of the 2009 financial year.

In the previous study, the grant covered only a very limited range of our research activities. However, in addition to the JST-JICA fund, Japanese researchers receive other grants from the Japanese Society for the Promotion of Science (comparable to South African National Research Foundation) and a 5-year program to promote the observational research to predict earthquakes and volcanic eruptions by the Japanese Ministry of Education, Culture, Sports, Science and Technology that can be used in parallel. With the grants, we will be able to upgrade our activity, eventually resulting in social benefit for both countries.

8   Acknowledgements

9   References

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