

# Observational studies to mitigate seismic risks in mines — a new Japanese–South African collaborative research project

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## Abstract

*Mining-induced earthquakes pose a risk to workers in deep, South African mines, while natural earthquakes pose a risk to people living close to plate boundaries. We introduce a five year Japanese–South African collaborative project entitled ‘Observational studies to mitigate seismic risks in mines’ that commenced in 2010. The project, which seeks to develop human and instrumental capacity in South Africa, will build on previous studies carried out by Japanese and South African seismologists in deep gold mines. The project has five major work streams: (i) determination of rock properties; (ii) sensitive close monitoring; (iii) seismic hazard assessment methods; (iv) strong ground motion monitoring; and (v) upgrading of the South African National Seismological Network in the mining districts. Some aspects of the study will also cast light on the mechanisms that generate tectonic earthquakes.*

## 1 Introduction

Mining-induced earthquakes pose a serious risk to workers in deep mines in South Africa, while natural earthquakes pose a serious risk to people living in Japan and other regions that are close to plate boundaries. We introduce a five year ~US\$3 million project entitled ‘Observational studies to mitigate seismic risks in mines’ that seeks to address these risks. The project has three main aims:

1. To learn more about earthquake generation mechanisms through near-source monitoring 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 project is carried out under the auspices of the Science and Technology Research Partnership for Sustainable Development (SATREPS) program ‘Countermeasures towards Global Issues through Science and Technology Research Partnership’. SATREPS is a joint initiative of JST (Japan Science and Technology Agency) and JICA (Japan International Cooperation Agency), and aims to acquire new knowledge to tackle global issues like environment and climate change, infectious diseases, water shortages, natural disasters, and bio-resources. The agreement between the Japanese and South African governments was concluded in February 2010, and preliminary work has begun.

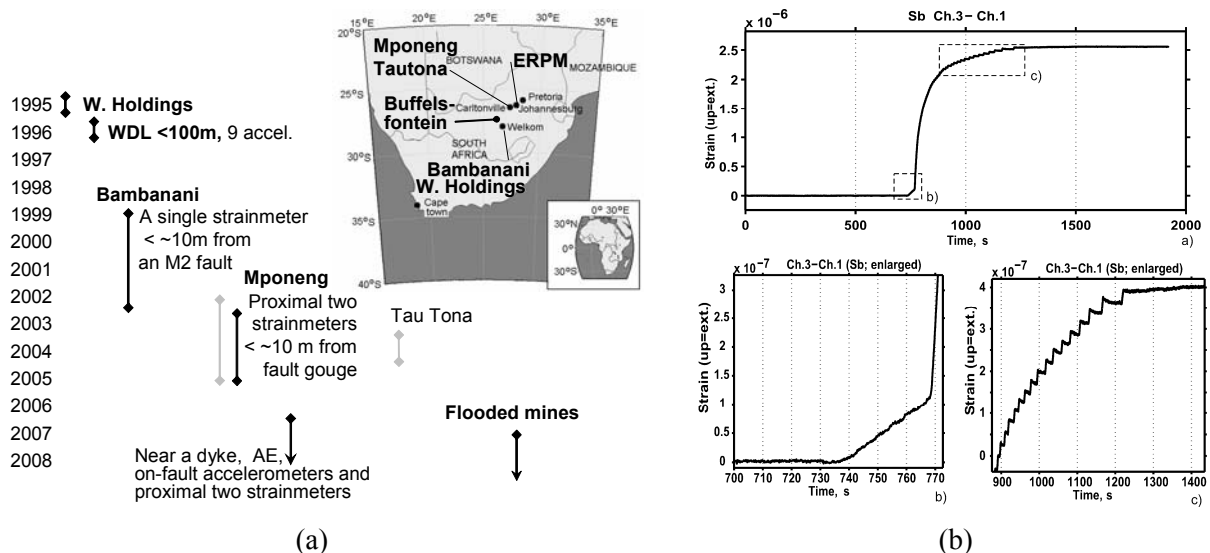
## 2 Previous Japanese research in South African mines

Japan is an earthquake-prone country, having an event of a magnitude greater than 7 usually every year. 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 US\$150 billion. A future M8 earthquake may cause even greater losses. Consequently, there have been strong demands to predict earthquakes and mitigate seismic risks in Japan. Following the Kobe earthquake, very dense seismic and GPS networks were deployed throughout Japan (station spacing typically a few tens of kilometres) to record the spatio-temporal variation of seismicity and the rupture process of every large event. However, the hypocenters are too deep (typically 10–20 km) for the details of the earthquake preparation and generation processes to be seen. Thus Japanese scientists have been seeking for opportunities to have a closer look at these processes, and some of this work has been done in the deep gold mines of South Africa. The new SATREPS project builds on previous studies carried out by Japanese and South African seismologists in deep gold mines. The most significant experiments and results are summarised below. The South African National Seismograph Network (SANSN) is also described as it is an integral part of the new project.

### 2.1 SeeSA

In 1991, the late Professor Louis Nicolaysen of 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 (IASPEI). After the proposal was endorsed by IASPEI, Prof. Nicolaysen visited Japan to solicit support from the Japanese Seismological Society (Nicolaysen, 1992). Since then, a Japanese – South African cooperative research program has monitored 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)’.

The first pilot experiment was performed at Western Holdings mine in 1995 (Figure 1a). A very sensitive borehole strainmeter (Ishii et al., 1997) able to detect fine details of rock mass deformation and record large, sudden changes associated with large events was installed (Ogasawara et al., 2002; Van Aswegen and Laas, 2003). The rock mass deformation was correlated with seismicity monitored by the Integrated Seismic System (Mendecki, 1997). A 200 m array of nine triaxial accelerometers installed in boreholes drilled from a footwall tunnel revealed that the rupture processes of  $M_L=0\sim 1$  earthquakes were as complex as natural great earthquakes, and that the stress drop and energy efficiency were similar (Yamada et al., 2005, 2007).

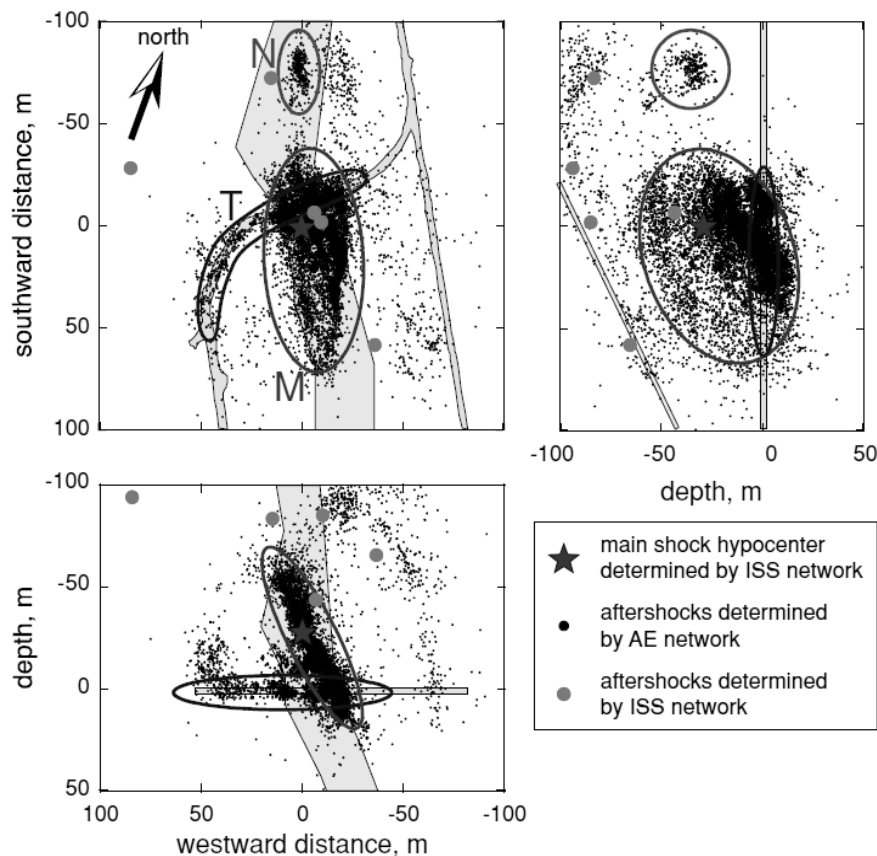


**Figure 1** (a) Semi-controlled earthquake-generation experiments in deep South African gold mines up to 2008 (after Ogasawara et al., 2009); (b) slow strain changes with a clear forerunner (735 s to 765 s) observed at the Pretorius fault zone, Mponeng mine (after Ogasawara et al., 2009; data after Yasutake et al., 2008)

A sensitive Ishii strainmeter installed in a fault loss at Bambanani mine successfully tracked rock mass deformation (Ogasawara et al., 2005) and clearly showed the accumulation of mining-associated strain, followed by earthquake-associated strain release and relaxation corresponding to  $\sim 10$  MPa stress change. The largest event occurring close to the strainmeter was an  $M_w 2.9$  event in February 2003. Frequent non-seismic slow strain changes were noted, some being accompanied by clear forerunners (Naoui et al., 2006). Much clearer forerunners were seen in the Pretorius fault zone at Mponeng mine (Figure 1b). Two strainmeters near to the slow events showed that they were caused by slip in the fault zones (Yasutake et al., 2008). However, the mine-wide seismic system was not sensitive enough to delineate the source fault of those major events, limiting the investigation.

## 2.2 JAGUARS – acoustic emission monitoring

The Japanese – German (GeoForschungsZentrum and GMuG) – South African (CSIR) cooperative project is referred to as JAGUARS (Japanese–German Underground Acoustic emission Research in South Africa). A small network (approx. 40 m span) of eight acoustic emission (AE) sensors covering a frequency range up to 200 kHz was deployed 3,300 m below surface in the Mponeng gold mine (Nakatani et al., 2008). The site monitors AE activity in a major gabbroic dyke within the quartzite host rock, about 90 m from mining operations. High-frequency waveforms with components greater than 100 kHz, were successfully observed for events with hypocentral distance of up to 50 m, many of which occurred in pristine rock outside the damage zones caused by various mining activities. The network recorded an  $M_w 1.9$  event on 27 December 2007 (Figure 2).

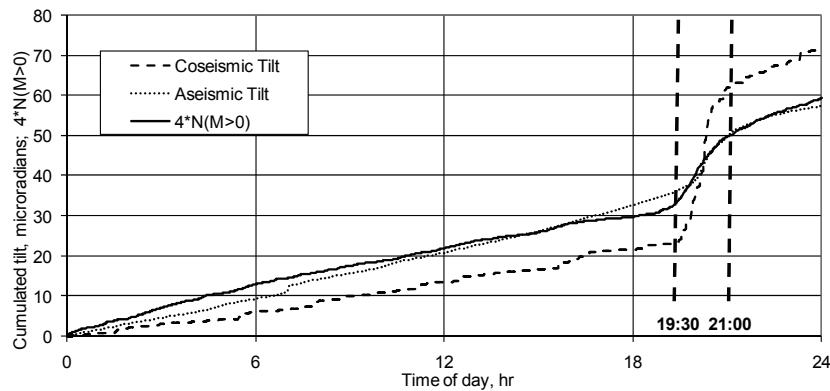


**Figure 2** Hypocenters of well-located AE events (small dots) in the first 150 h after the  $M_w 1.9$  earthquake on 27 December 2007 (Yabe et al., 2009). The hypocenter of the  $M_w 1.9$  and aftershocks located by the mine-wide network in the 150 h are shown by a star and large filled circles, respectively. Horizontal and vertical distances are referenced to the epicentre of the mainshock and ceiling of the access tunnel (3,264 m deep), respectively. The dyke strikes roughly north-south and is intersected by the tunnel. The gold reef is 50–100 m above the tunnel

In the 150 hours following the event, more than 21,000 aftershocks were located within 100 m of the network (Yabe et al., 2008). In the same period the mine-wide geophone network, with a magnitude detection threshold of approximately  $M_w$ -0.5, detected only nine events in the same area. Seismic velocities were determined using in situ ultrasonic transmission tests using shot points spread along a borehole spanning a distance of about 50 m, measuring fairly high velocities indicative of good rock quality. The acoustic emission system successfully delineated a fault near the Pink and Green dyke that was the source of the  $M_w$ 1.9 event. Mining-induced temporal changes in strain were also successfully tracked, showing that the dyke was approaching failure (Katsura et al., 2008).

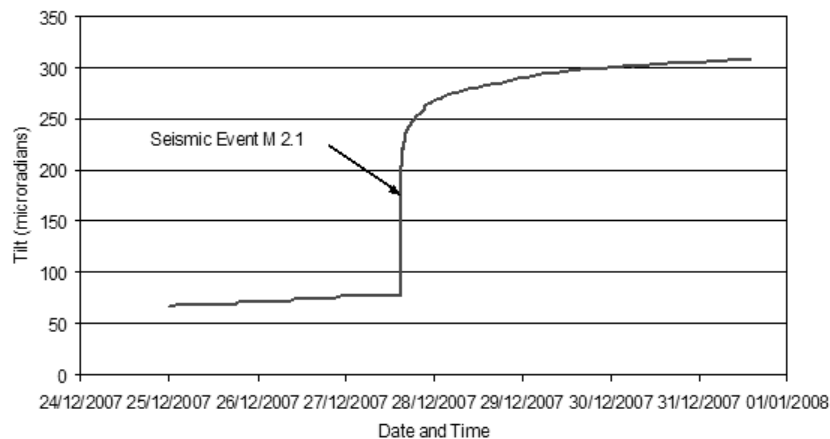
### 2.3 CSIR – monitoring of coseismic and aseismic deformation due to mining

Two underground sites in Mponeng gold mine were instrumented by CSIR with tilt-meters integrated with seismic monitors (one was the JAGUARS site described above). Both the rate of tilt and the ground motion, were analysed in order to understand the behaviour of the rock mass around deep level mining (Spottiswoode and Milev, 2006; Milev and Spottiswoode, 2005, 2008a, 2008b). 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. Coseismic and aseismic tilt showed rapid increase during the blasting time and the subsequent flurry of seismic activity (Figure 3).



**Figure 3** Distribution of coseismic and aseismic tilt during the day at Mponeng mine

The tilt changes associated with the  $M_w$ 1.9 seismic event at Mponeng on 27 December 2010 are shown in Figure 4. The event has well pronounced after-tilt, which is most probably the result of the aftershock sequence, but could also be the result of aseismic expansion of the source.

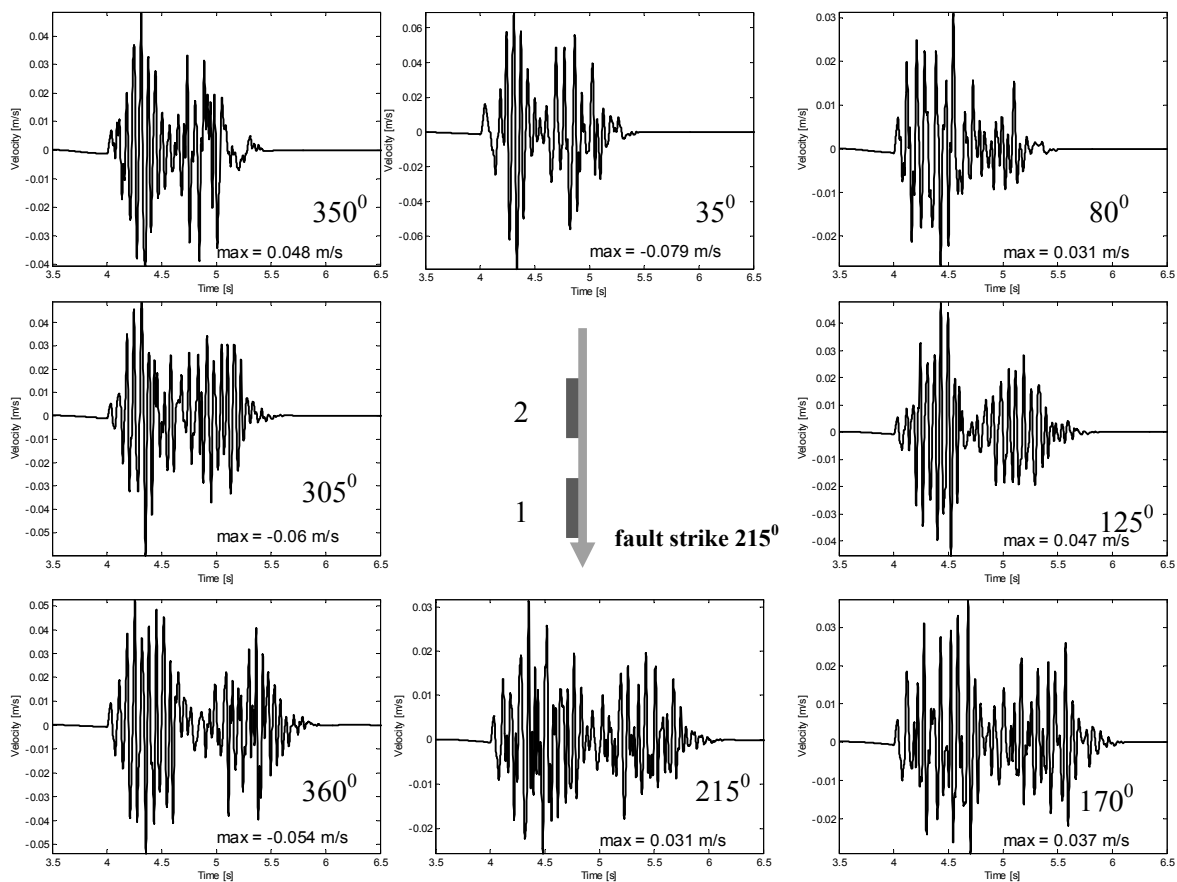


**Figure 4** Tilt associated with the  $M_w$ 1.9 ( $M2.1$ ) event on 27 December 2007 at Mponeng mine

## 2.4 Council for Geoscience – surface monitoring of mining-related seismicity

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. Presently, the SANSN consists of 23 stations that communicate triggered and continuous data to the CGS offices in Pretoria, where analysis is undertaken daily to identify seismic events. The current distribution of seismic stations of the SANSN limits the lower magnitude detection threshold to  $M_L = 2.0$ . Results of data processing are disseminated to government agencies and the international scientific community via seismological bulletins (e.g. Saunders, 2009). The CGS also supports projects that contribute towards a better understanding of the mechanisms of damaging seismic events located in the mining districts (e.g. Cichowicz, 2005).

On 9 March 2005, an  $M_L 5.3$  earthquake in the Klerksdorp mining district caused considerable damage to property in the town of Stilfontein and led to the temporary closure of the mine. Unfortunately, there were no surface seismic stations near the town. A method for modelling strong ground motion in the near field was developed by Cichowicz (2007, 2008, 2009) and Cichowicz et al. (2008, 2009). A point source model was deemed unsuitable for near-field ground motion prediction as the fault geometry, heterogeneity of slip on the fault plane, and directivity can influence the ground motion. An extended seismic source model was preferred. This requires that a large fault be 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 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 surface ground motion caused by the Stilfontein  $M_L 5.3$  earthquake at the source-site distance of 5 km is shown in Figure 5. A model with two asperities predicts much larger PGA, PGV and amplitude of response spectra than a simple point source model.



**Figure 5** Velocity of ground motion predicted at a distance of 5 km from the epicentre on a hard rock surface. The station azimuth is displayed next to each synthetic seismogram. The fault strike was  $215^\circ$ . The positions of two asperities are marked with bold lines

### 3 SATREPS – observational studies to mitigate seismic risks in mines

Building on previous studies of mine-related seismicity reviewed above, the new SATREPS project aims to upgrade the schemes of seismic hazard assessment in deep mines. Experiments are planned Moab-Khotsong, Mponeng, Driefontein and Ezulwini mines. Five major outputs have been defined.

#### 3.1 Output 1 – rock properties in the seismic source region

Knowledge of the mechanical properties of rocks comprising the earthquake source region and its surroundings are indispensable prerequisites for the project. For examples, the elastic constants are necessary to evaluate stress change from the observed rock deformation, and the elastic wave velocity to accurately locate seismic events. The stress–strain behaviour, changes in micro-fracturing activity, and physical properties prior to the ultimate fracture of rock samples collected from the source region should give fundamental information for understanding the preparation process of the earthquake. In addition, heterogeneity of the rock properties must be probed because it may control the preparation and generation of earthquakes. The detailed mapping of fractures and geology is also a fundamental component of the investigation, as they may have a significant influence on earthquake preparation and strong motion generation.

We intend to map the rock mass and collect rock samples to probe mechanical properties in both the impending seismic sources and surrounding host rock. Measurements of basic parameters (elastic constants, fracture strength and elastic wave velocities) will be made in both South Africa and Japan, while more advanced experiments (temporal changes in the micro-fracturing activity and the physical properties during fracture process) will be conducted in Japan. Typically it takes about a year to mine a 100 m span. As the face approaches a geologically weak plane (e.g. a fault or dyke), several M2 earthquakes are likely to be induced. Drilling and the collection of rock samples will be done in several phases:

- In 2010, a program of exploratory drilling will attempt to delineate the fault zones that the mining face will approach in 2012–13. We have examined the five year mining plan to identify experimental sites where the seismicity is expected to peak in 2012–13, and drilling has commenced. Additional holes will be drilled (in 2011) to install sensors so that they will cover the region of the impending source three-dimensionally.
- Following the series of seismic events, additional holes will be drilled to collect rock samples and map fractures associated with the events.
- If the seismic fault is clearly defined, we will seek to exhume a section of the fault for a detailed examination, something that is impossible for natural great earthquakes.

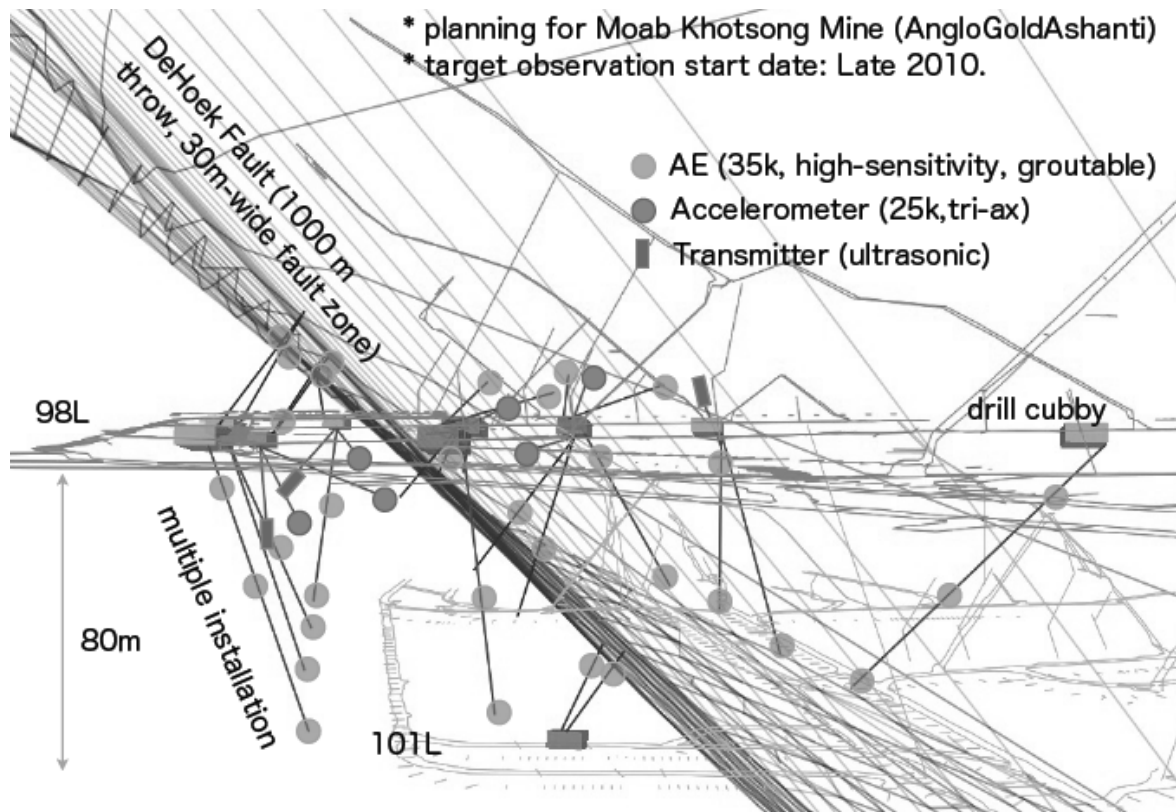
#### 3.2 Output 2 – sensitive close monitoring

We seek to investigate the preparation processes preceding earthquakes, and especially the occurrence of forerunners. However, quasi-static stress changes and high-frequency seismic waves decay very rapidly with distance. Consequently, arrays of instruments designed to monitor subtle change associated with preparation of earthquakes must be installed as close as possible to the likely source region. Several types of sensitive instruments will be used to monitor the rock mass.

- *Micro-fracturing* that accompanies the development of the fracture plane can be detected and located with an acoustic emission (AE) monitoring system. A >100 kHz AE array will be deployed to detect centimetre-scale micro-fractures in a 100 m diameter volume that encompasses the target earthquake fault (Figure 6). Micro-fracturing activity down to sizes of about several centimetres. Each AE is automatically located and the locations transmitted to the surface via internet for near real-time monitoring, while the waveforms are stored in the on-site PC for further detailed analysis.
- *Quasi-static episodic deformation* of the rock mass can also be monitored with sensitive strain meters and tilt meters. Strain and tilt will be sampled at a frequency of 50 Hz to see the detail of aseismic episodic events and their forerunners. Data will be transmitted to surface to reveal, in near real-time, how the impending earthquake source is loaded and how stress is released by seismic events. Aseismic events can be detected by long-period seismometers.

- *Stope closure* will also be monitored to provide additional information on stress redistribution near earthquake sources and the deterioration of the rock mass surrounding excavations, which could make the excavation prone to damage when subjected to violent shaking.

As noted above, boreholes are being drilled at several mine sites to locate the faults.



**Figure 6** Monitoring instrumentation planned for Moab Khotsong Mine, Klerksdorp gold field

### 3.3 Output 3 – seismic hazard assessment

Routine mine-wide seismic monitoring, with typical station interval of about 500 m, provides valuable data sets to assess seismic hazard. Typically a hundred  $M > -1$  events per day occur within a  $1 \text{ km}^2$  area. ISS International Ltd has introduced a method of assessing rock mass instability based on variations in stress and strain-related seismic parameters (Van Aswegen, 2005). It is routinely used in some South African mines as a hazard assessment scheme. Some modest success has been achieved. We will rigorously test seismic hazard assessment methods currently used in South African mines. We will also apply the stress inversion method that was recently used by Japanese seismologists to delineate the fine detail of stress distribution (e.g. Kato et al., 2006).

### 3.4 Output 4 – strong ground motion

The evolution of fault rupture has not yet been monitored in situ at scales greater than the centimetre dimension of a laboratory rock sample. Consequently, it is not known how rupture evolves or how strong ground motion is generated in great tectonic earthquakes. Because of the lack of the knowledge, we neither know if we can detect the preparation phase of a great earthquake, nor accurately predict strong ground motion generated by a great earthquake (Milev and Spottiswoode, 2005; 2008a, 2008b). Mineworkers are exposed to the risk of strong motion and associated fall of ground by seismic events. There are two main strategies to mitigate the seismic risk: (i) to reduce the number and size of seismic events through optimal mine planning; (ii) to reinforce and support the rock mass so that it does not unravel when exposed to violent shaking. In order to improve mine design strategies and the effectiveness of support elements and systems, we have to clarify the geometrical attenuation of strong motion and the site amplification factor at the stope.

The main components of the study are:

1. **On-fault monitoring:** small networks, several tens of meters in extent, will be deployed very near to faults that have the potential to produce  $M > 2$  earthquakes and a rupture exceeding 100 m. Accelerometers and high-capacity strain meters will be used to measure strong ground motion and dynamic stress changes.
2. **In-stope monitoring:** several strong motion meters powered by dry-cell batteries will be installed in stopes.
3. **Attenuation and site effects:** strong ground motion is most violent in the near field, i.e. within one fault length from a source fault, which is several tens of meters for a typical mine rockburst caused by an  $M \sim 2$  event. However, a typical mine-wide seismic network can only locate the source with an accuracy of a few tens of meters. Consequently, the empirical relationship between hypocentral distance and strong motion is not well defined. However, micro-fracture monitoring locates sources very accurately, which will improve estimates of the geometrical and intrinsic attenuation. We will also compare strong motion at the site and source to investigate the site amplification factor. Improved measurements of attenuation and site amplification will contribute to efforts to design mining layouts and support systems.
4. **Scaling law:** we will compare the monitored dynamic stress change and fault slip with existing lab-experimental results to clarify the scaling relationship in dynamic rupture process. We collect data for the event with magnitudes ranging from 0 to 2 or above. With these data, we attempt to get an answer to the question “does fracture energy increase with the magnitude of seismic events?”

### 3.5 Output 5 – upgrading the SANSN in the mining districts

Large earthquakes ( $M > 4.0$ ) occur several times a year in mining districts and sometimes cause damage to surface structures. However, these important earthquakes are inadequately recorded by both the sparse SANSN and mining networks, which are equipped mainly with 4.5 Hz geophones that are unable to record the long-period signal below 0.3 sec generated by large earthquakes. This limits an accurate evaluation of the faulting process of such big earthquakes. However, the mechanisms of large seismic events provide insight into local tectonics, allowing a better understanding of the stress regime. Furthermore, the software currently used by the CGS to analyse seismograms, though widely used throughout the world, does not automatically pick phases or locate events. Consequently the CGS is unable to respond rapidly to requests for information following an earthquake.

Several major technical developments are planned:

1. A cluster of strong ground motion stations will be deployed on the surface, most likely in the Far West Rand goldfield. The cluster of strong ground motion seismic stations will greatly contribute to identification of seismically active features in the mining district and to the development of a methodology to estimate damage at the surface. It will also provide standardised magnitude estimation in the mining district and facilitate basic analyses, such as focal mechanism determination and stress field analysis.
2. A modern Data Centre will be established in the Council for Geoscience (CGS) headquarters in Pretoria. At present, the CGS analysts manually process about 20 events per day. The upgraded seismic software will be able to process automatically up to 1,000 events per day, and display them on the CGS website in near-real time.
3. Development and validation of a parametric model that will be capable of predicting strong ground motion for hazard assessment and rapid estimates of strong ground motion following a large earthquake. Probabilistic seismic hazard assessment indicate that earthquakes as large as  $M 5.5$  could occur in the mining districts (Shapira et al., 1989). However, it is unlikely that ground motion caused by earthquakes with  $M$  much greater than 4 will be observed in the course of the experiment. Therefore, extrapolation techniques will have to be used to predict strong ground motion caused by very large events. Such a parametric model is controlled by seismic source properties, ray path attenuation and near surface effects. The output from the results of Output 4 and the underground



mining network will provide seismic source parameters for calibration/validation of the strong ground motion parametric model.

The Data Centre and the cluster of stations will be a very significant step towards the extension of the SANSN into all mining districts. The ultimate goal of the Data Centre and monitoring will be the prediction of strong ground motion in near-real time in all towns surrounding mining districts (radius 100 km). The recipients of ground motion prediction will be the Disaster Management Centre in Gauteng Province and, most importantly, the public. All the above hardware and software assets will be incorporated into the South African National Seismograph Network (SANSN) so running costs and maintenance will become a responsibility of the SANSN.

The first temporary seismic stations equipped with strong ground motion sensors (Surface Triaxial Force balance Accelerometer) will be installed in 2010. In 2011 the temporary stations will be upgraded to permanent seismic stations. Near-real time seismic information and dissemination starts in 2011, when temporary stations become operational. Starting from 2012, after sufficient data has been accumulated, ground motion caused by earthquakes of magnitudes between 1 to 4 will be used to estimate attenuation parameters, geometrical spreading and near surface effects. To meet the needs of the earthquake engineering community, the parametric model should take into account some commonly used site classification schemes.

## 4 Conclusion

The new SATREPS project ‘Observational studies to mitigate seismic risks in mines’ is a project that will provide the springboard for new levels of collaboration between Japanese and South African seismologists. It addresses important issues. Knowledge of earthquake nucleation, rupture and strong ground motion in the near field will be gained that can be used to mitigate the risks of tectonic earthquakes in Japan. The knowledge will be directly applicable to deep hard rock mining in South Africa. It may be used to upgrade seismic hazard assessment schemes in mines and on the surface, improve mining layouts and support systems. In addition, there will be a focus on building both instrumental and human capacity in South Africa.

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