CAN MINE TREMORS BE PREDICTED? OBSERVATIONAL STUDIES OF EARTHQUAKE NUCLEATION, TRIGGERING AND RUPTURE IN SOUTH AFRICAN MINES

R J Durrheim[1,2,3] and Hiroshi Ogasawara[1,4]
[1]JST-JICA Science and Technology Research Partnership for Sustainable Development (SATREPS)
[2]CSIR Centre for Mining Innovation, South Africa
[3]University of the Witwatersrand, South Africa
[4]Ritsumeikan University, Japan

Abstract

Mining-induced earthquakes pose a risk to workers in deep mines, while natural earthquakes pose a risk to people living close to plate boundaries and even in stable continental regions. A five-year ca. US$3 million Japan-SA collaborative project "Observational studies to mitigate seismic risks in mines" was launched in August 2010. The project has three main aims: (1) to learn more about earthquake preparation and triggering mechanisms by deploying arrays of sensitive instruments in mines where mining-related stresses are likely to induce significant seismic activity; (2) to learn more about earthquake rupture and damage phenomena by deploying strong ground motion sensors close to potential rupture zones and on the walls of stopes; and (3) to upgrade the South African national surface seismic network in the mining districts. Acoustic emission sensors, accelerometers, strainmeters, and controlled seismic sources are being installed at sites in Ezulwini, Moab-Khotsong and Driefontein gold mines to monitor the deformation of the rock mass, the accumulation of damage during the earthquake preparation phase, and dynamic stress as the rupture front propagates. These data will be integrated with measurements of stress, stope closure, stope strong motion, and seismic data recorded by the mine-wide network. Here we describe the design of experiments that seek to identify reliable precursors of damaging seismic events.

1. Introduction

Earthquakes, and the tsunamis and landslides they trigger, pose a serious risk to people living close to plate boundaries, and a lesser but still significant risk to inhabitants of stable continental regions where destructive earthquakes are rare and preparedness is often low. Recent earthquakes that have caused enormous human and economic losses include the M7.0 Haiti earthquake of 12 January 2010 and the M9.0 Great East Japan earthquake and tsunami of 11 March 2011. The scientific study of earthquake source mechanisms commenced about a century ago, stimulated by the development of seismographs and the occurrence of devastating earthquakes such as the 1891 M8.0 great earthquake in central Japan and the 1906 M7.7 San Francisco earthquake in the USA (Koto, 1893; Agnew, 2002). Since then, many efforts have been made to predict the time and place of earthquakes with sufficient accuracy and reliability to make it feasible to evacuate vulnerable structures and sites (e.g. Simpson and Richards, 1981; Mogi, 1985; Wyss, 1991; National Academy of Science, 1996). However, reliable prediction has not been accomplished. Consequently, efforts to mitigate earthquake risk have focused on probabilistic seismic hazard assessments and zoning, the formulation and enforcement of codes governing the construction and retrofitting of buildings, and the development of monitoring networks to provide Earthquake Early Warning (Japan) and Tsunami Warning following potentially dangerous events.

The Committee on the Science of Earthquakes (National Academy of Science, 2003) concluded *"the science of earthquakes, like the science of many other complex natural systems, is still in its juvenile stages of exploration and discovery. No available theory adequately describes the dynamical interactions among faults or the basic features of rupture nucleation, propagation, and arrest. On short time scales (hours to days), no method for event-specific earthquake prediction has yet demonstrated skill at a statistically reliable level; indeed the chaotic nature of brittle deformation may imply that useful short-term prediction cannot be achieved, even with substantial improvements in the ability to predict precursory signals".* However, the Committee went on to say *"Near-field observations before and during large earthquakes are too few and too limited, however, to rule out categorically the feasibility of short-term earthquake prediction".* Efforts to gain knowledge and develop technologies to predict earthquakes have continued. A notable current initiative is the Collaboratory for the Study of Earthquake Predictability (CSEP), led by the Southern California Earthquake Centre. CSEP has established testing methodologies and testing centres in Japan, New Zealand, Switzerland and the USA (CSEP, 2012). The project we report on here is another example of an effort to make near-field observations to investigate the feasibility of earthquake prediction.

Seismicity poses a serious risk to workers in deep and overstressed mines, such as the deep gold mines in the Witwatersrand basin of South Africa. A 5-year Japan—South Africa collaborative project (~US$3 million) entitled *"Observational studies to mitigate seismic risks in mines"* was launched in August 2010 to address these risks (Ogasawara et al., 2009a; Durrheim et al., 2010). The project has three main aims (Figure 1):

- To learn more about earthquake preparation and triggering mechanisms by deploying arrays of sensitive sensors within rock volumes where mining is likely to induce seismic activity.
- To learn more about earthquake rupture and rockburst damage phenomena by deploying robust strong ground motion sensors close to potential fault zones and on stope hangingwalls.
- To upgrade the surface national seismic network in the mining districts.

The project draws on over a century of South African and Japanese research experience with respect to mining-related and tectonic earthquakes, respectively (e.g. Utsu, 2003; Durrheim, 2010; Durrheim et al., 2010). Japanese experience and technology was adapted and applied to the mining environment, notably:

- Laboratory techniques to detect rock fracturing at the onset of rock mass instability; and
- Exceptionally sensitive sensors, which were originally developed to monitor crustal deformation and natural earthquakes.

The knowledge gained during the course of the project and the new infrastructure installed will improve seismic hazard assessment methods in mines and mitigate the risk of rockbursts. It is also anticipated that new knowledge of earthquake physics will mitigate the risks posed by tectonic earthquakes. In this paper we focus on the design of experiments that seek to identify reliable precursors of damaging seismic events.

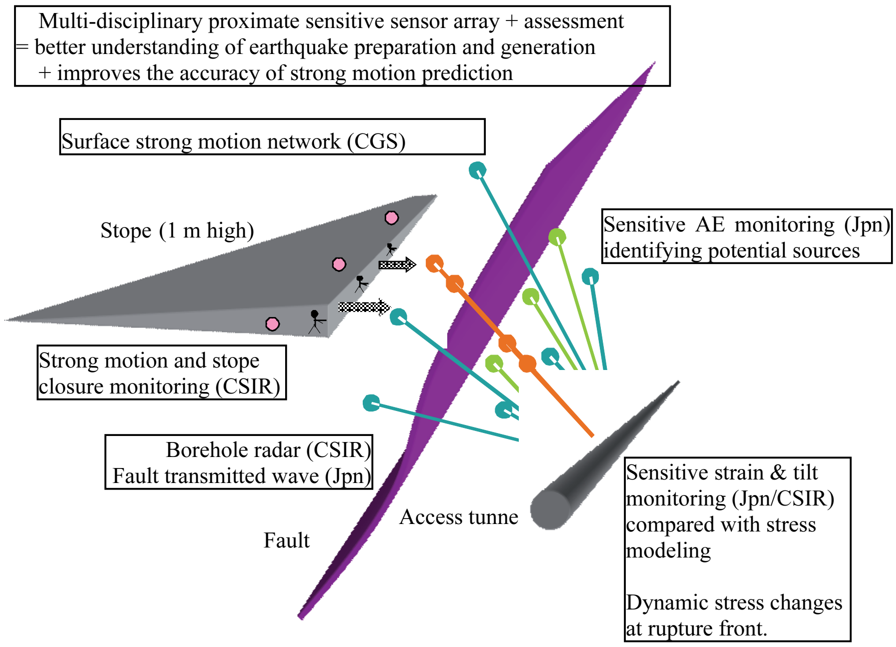

Figure 1. Schematic illustration of the research design. Jpn: Japanese researchers, CSIR: Council for Scientific and Industrial Research, CGS: Council for GeoScience

2. Precursors of seismic events

The scientific method is a systematic approach to solving problems and gaining knowledge. It is not the only approach to solving problems, or always the fastest, but it is the surest (Scholes, 2003). The first step in the research process is the formulation of key questions that help to probe the essence of the problem. Key questions may be expressed as hypotheses that lead to testable predictions. Our key questions are:

1. Are there phenomena that can be used to provide a warning that a seismic event is imminent?
2. What ground motion does a seismic event cause, both in the solid rock and on walls of an excavation?

It is standard practice to investigate the mechanical properties of rocks by loading a specimen in a testing machine until it fails. Deformation and damage processes are monitored by strain gauges and acoustic emission sensors. While the rock mass in a mine or plate boundary is undoubtedly far more heterogeneous than a small specimen of intact rock, laboratory tests are believed to provide insights into the phenomena that precede mine tremors and earthquakes (e.g. Jaeger and Cook, 1979; Durrheim and Labrie, 2007a and 2007b). Prior to failure, the density of microcracks increases in the incipient rupture zone and the mode of deformation changes from linear elastic to non-linear inelastic. It has been postulated that similar phenomena occur in large volumes of rock prior to mine tremors, and analogous behaviour has indeed been observed, e.g. seismicity associated with large seismic events in the Western Holdings No. 6 shaft pillar (Mendecki, 1997). Laboratory, mine and crustal studies have shown that seismological phenomena scale over many orders of magnitude (e.g. Aki, 1967; Gibowicz and Kijko, 1994; Sellers et al., 2003). Boettcher and McGarr (2009) report the seismicity recorded by dense sensor array deployed in TauTona mine show no breakdown in Gutenberg-Richter scaling to M_W -3.7. Kwiatek et al. (2010) extended the observations down to M_W -4.4 in Mponeng mine. These observations provide evidence of small nucleation zones and imply that earthquake processes in a mine can readily be scaled both to laboratory experiments and to natural faults.

We hypothesize that there are measurable changes in some or all of the following physical parameters that can be used to predict the time and location of mining-induced ruptures: stress, strain rate, tilt rate, acoustic emission rate, seismic source parameters, electromagnetic emission rate, and microcrack density. Sensor networks are being established as shown in Table 1 (Durrheim et al., 2012). These hypotheses are not novel. For example, Weiss (1938) proposed eight premonitory phenomena that could be monitored in Witwatersrand mines, including changes in the velocity of "artificial" seismic waves, changes in the natural frequency of pillars, and disturbances of the electrical field. Here we review past attempts to observe precursory phenomena in South African mines, as these studies provide the baseline for our present experiment. We hope that the new arrays of state-of-the-art instruments will reveal precursory phenomena that have hitherto been obscured by noise, as well as co-seismic rupture phenomena that have never before been observed in the near-field.

2.1. Stress-induced seismic velocity changes

Laboratory tests have established that seismic velocities in rock change with stress (e.g. Christensen and Stanley, 2003). However, it has proven difficult to measure this phenomenon in mines. Following the occurrence of an $M_L 3\frac{3}{4}$ mine tremor, McGarr (1974) analysed the travel times of body waves traversing the source region produced by other favourably-located tremors. No changes exceeding the sensitivity threshold of 2 per cent were detected. Maxwell and Young (1996) used seismic tomography to delineate a region of increased velocity (1-2 per cent) associated with mining-induced stresses in a stabilizing pillar. Lynch (2010) attempted to replicate in mines the extremely precise measurements of wave velocity that were made at the San Andreas Fault Observatory at Depth using a repeatable source (Niu et al., 2008), and reported that velocity changes of up to 0.04 per cent were detected over a path of 137 m, which were interpreted to arise from stress changes associated with undercut blasting.

An array has been deployed at the Ezulwini site in order to monitor any changes in seismic transmission properties near the target fault e.g. seismic velocity, Q (Kawakata et al., 2011). A piezoelectric transmitter was installed about 20 m from the fault, and 3-component accelerometers were installed in a line straddling the fault at distances of 7 m, 27 m and 30 m from the transmitter. Signals are transmitted every 0.05 s for 10 minutes each day, and recorded at 400 kHz.

Table 1. Summary of the SATREPS experimental sites as at 31 January 2012
*** installation not yet completed, # not yet procured**

Gold Mine Name	**Ezulwini**	**Moab Khotsong**	**Driefontein**
Owner	First Uranium	Anglogold Ashanti	Gold Fields
Ore body at experimental site	Several reef packages 10s of metres thick	Single thin tabular reef (<2 m), many faults	Single thin tabular reef (<2 m), few faults
Mining scenario	Extraction of shaft pillar, 400 m dia.	Extensive scattered mining	Sequential grid mining
Depth	About 1 km	About 3 km	About 3 km
Concern	Instability of faults in the shaft pillar	Instability of large faults	Instability of dip pillar
Fault characteristics	Fault gouge a few 10s of cm thick	Fault zone a few 10s of m thick	Fault gouge a few cm thick
Applicability of research to mining	Final stage mining e.g. shaft pillars	Mining in highly faulted districts	Sequential grid mining at depth
Japanese Contributions			
Acoustic emission	A few tens of sensors	A few tens of sensors*	-
Strain	2 strainmeters	3 strainmeters*	3 strainmeters
Velocity & attenuation	1 Tx, 3 Rx	2 Tx, 3 Rx*	-
Rupture dynamic stress	3 instruments near fault	-	4 instruments near fault
Slow fault slip	1 sensor	2 sensors*	
Stress	Planned	Completed	Planned
South African Contributions			
Borehole radar	-	Survey completed	-
Tilt	-	2 tilt meters#	2 tilt meters#
Stope closure	-	1 set#	1 set#
Stope ground motion	-	1 set accelerometers#	1 set accelerometers#
Surface ground motion	JICA network*	New network*	JICA network*
Status on 31 January 2012	Underground installation almost completed	80% drilling and 20% installation completed	Japanese installation completed

2.2. Strain

Sacks-Evertson dilatometers were deployed in a deep mine by McGarr et al. (1982). Co-seismic strain steps were recorded and well accounted for by dislocation theory, but no precursory strain exceeding 10^{-8} was detected in the 10 s preceding the seismic events. Very sensitive borehole strainmeters (Ishii et al., 1997) have been installed by SeeSA (Ogasawara et al. 2009b). Continuous 25-40 Hz monitoring allowed us to clearly see the details of the accumulation of mining-associated strain, followed by earthquake-associated strain release and relaxation corresponding to ~10 MPa stress change (Ogasawara et al., 2005). The largest event occurring close to the strainmeter was an M_w2.9 event in February 2003. Frequent non-seismic slow strain changes were noted, some being accompanied by clear forerunners (Naoi et al., 2006). Much clearer forerunners were seen in the Pretorius fault zone at Mponeng mine. Two strainmeters near to the slow events showed that they were caused by slip in the fault zones (Yasutake et al., 2008). In the SATREPS project, we will compare strain data with tilt, AE and stress modelling.

2.3. Tilt

Measurements of tilt made at a depth of 3.2 km near an advancing face in East Rand Proprietary Mine showed continuous changes in tilt related to the enlargement of the excavation, step changes in tilt caused by mine tremors, and unexplained episodes of anomalous tilts (McGarr and Green, 1975). More recently, tiltmeters integrated with seismic sensors were installed at two sites in Mponeng gold mine (Spottiswoode and Milev, 2006; Milev and Spottiswoode, 2005, 2008a, 2008b). It was found that the rates of coseismic tilt and aseismic tilt, as well as seismicity recorded by the mine seismic network, are approximately constant until blasting time. The rates of coseismic and aseismic tilt increased rapidly during blasting time (19h30 to 21h00). The tilt changes associated with the M_w1.9 seismic event at Mponeng on 27 December 2010 are shown in Figure 2. The event produced pronounced after-tilt, which is most probably the result of deformation associated with the aftershock sequence, but could also be the result of aseismic expansion of the area of aftershock activity.

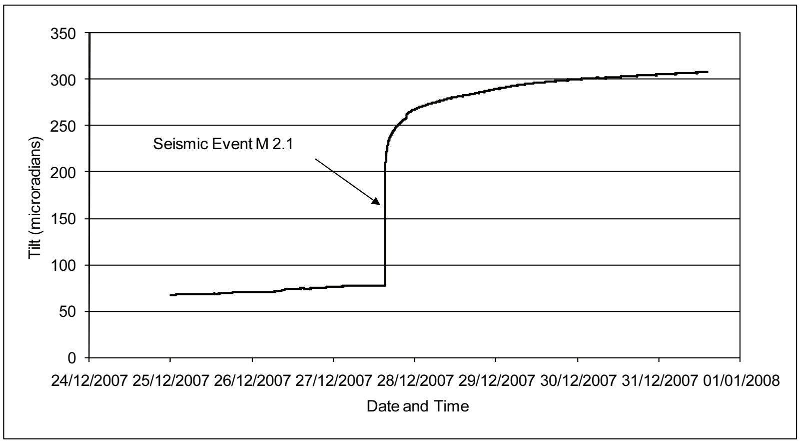

Figure 2. Tilt associated with the M_w1.9 (M2.1) event on 27 December 2007 at Mponeng mine

2.3.1. Acoustic emissions

The Rockburst Research Project, jointly sponsored by the Chamber of Mines and Anglo American Corporation, was initiated in 1977 at Western Deep Levels mine (Brink, 1980; Brink and O'Connor, 1984). This system utilized four tri-axial accelerometers to monitor micro-seismic events. The inter-station spacing was 100-200 m, the response limit of the accelerometers was 10 kHz, and the sampling frequency 5 kHz. Brink and Mountfort (1984) reported that four events (M_L=0.3, 0.4, 1.5 and 2.5) were predictable in hindsight, and expressed the opinion that men could have been withdrawn prior to the events without losing more than one shift, concluding that it was possible to "predict rock bursts with confidence". This prompted a major expansion of the project, with the objective of developing a "real time monitoring system" capable of timely predictions. A pilot project was initiated in 1980. A micro-seismic network consisting of five tri-axial accelerometers was installed to monitor events in the magnitude range $-4<M_L<0$ in a 1 km longwall and a mine-wide 24 tri-axial geophone network was installed to monitor all events with $M_L >0$, but reliable prediction remained elusive.

The JAGUARS team (JApanese-German Underground Acoustic emission Research in South africa) deployed a network of eight acoustic emission (AE) sensors 3300 m below surface in the Mponeng gold mine (Nakatani et al., 2008). The AE sensors had a response limit of 250 kHz and recorded at sampling frequency of 500 kHz. AE activity in a major gabbroic dyke within the quartzite host rock was monitored. The network recorded an M_w1.9 event on 27 December 2007 and some 21,000 aftershocks (Figure 3).

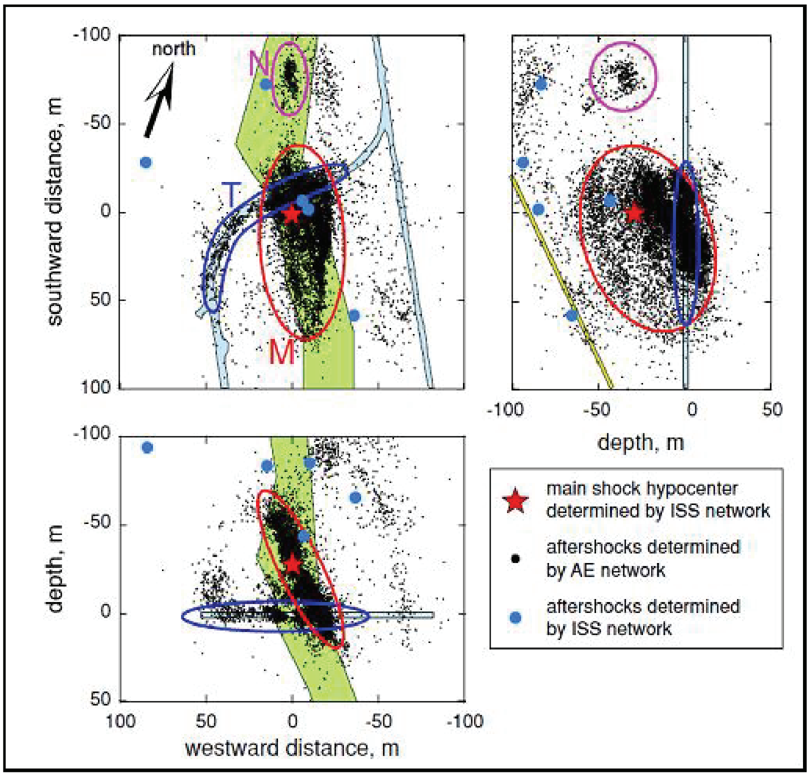

Figure 3. Hypocenters of 21,000 well-located AE events (small dots) in the first 150 h after the M_w1.9 earthquake on 27 December 2007 (Yabe et al., 2009)

In the same period the mine-wide geophone network, with a magnitude detection threshold of approximately M_w-0.5, detected only 9 events in the same area. Naoi et al. (2011) delineated much finer details. The accurately located fault plane allowed us to evaluate stress and strength (Hofmann et al. 2012). More sensitive and accurate monitoring may allow us to investigate seismic parameter changes in greater detail. The JAGUARS array consisted of only eight AE sensors, whereas the SATREPS arrays consist of a few tens of AE sensors at two mines. We expect to obtain far more detailed descriptions in time and space of the pre-, co- and post-seismic fracture processes.

2.3.2. Seismic source parameters

A survey of seismic hazard assessment (SHA) and rockburst risk management practice in South African mines was conducted by Durrheim et al. (2007). It was found that the location of potentially damaging events was available within minutes of their occurrence and used to direct the mine's response, e.g. launching of rescue operations. Many schemes had been devised to identify periods of increased risk. The detection of anomalous short-term seismicity patterns prior to some large seismic events, such as an M_L4 event that occurred on the Trough structure at Mponeng Mine near Carletonville in 1994 (Mendecki, 1997), had raised hope that the success rate of short-term SHA could be improved. However, it was found that reliable and accurate rockburst prediction remained an elusive goal. Nevertheless, SHA was routinely done on the spatial scale of a stope and on the time scale of a day. It was standard practice on mines serviced by ISSI to track cumulative apparent volume, seismic Schmidt number, energy index and activity rate (Van Aswegen, 2005). While it was generally agreed by the research team that reliable rockburst prediction was a difficult and distant goal, the team was of the opinion that effective short-term hazard assessment was achievable.

Spottiswoode (2010) analysed seismic data from five mines (four gold, one platinum) representing a range of deep mining methods, and investigated whether there was any change in the event rate or character prior to large events. The seismic events in this study were recorded on mine-wide networks, and thus the number of foreshocks associated with any one event was relatively small. This difficulty was overcome by stacking events, a technique that has worked well in analysing aftershock statistics (Kgarume et al., 2009, 2010). However, Spottiswoode (2010) did not find a statistically significant difference in foreshock statistics, concluding that short-term prediction on was not feasible on the basis of seismicity rate alone.

2.3.3. Electromagnetic emissions

Nesbitt (1994) investigated the emission and propagation of electromagnetic energy from stressed quartzite rock in a deep mine. While EM emissions are reliably observed in a laboratory setting, significant difficulties were encountered in the real-life noisy situation. Nevertheless Nesbitt (1994) was able to show that EM radiation accompanied blasting activity and one mine tremor, but was unable to demonstrate that EM radiation accompanied other mine tremors, although it is possible that the emitted signals were obscured by noise.

2.3.4. Microcrack density

During the 1980s, researchers at the University of the Witswatersrand investigated phenomena such as the polarization and attenuation of seismic waves in the vicinity of the stope (Cichowicz and Green 1989, Cichowicz et al. 1988, 1990). The early part of the coda P wave was found to be associated with scattering close to the source, raising the hope that this feature could be used to predict rockbursts.

3. Key engineering questions

Engineering is often defined as the practical application of science. The key engineering questions we seek to answer are:

1. Are current in-stope support elements and systems optimally designed to withstand seismic shaking?
2. Are there lessons to be learned from earthquake engineering technologies?

Over the last two decades several new support technologies have been introduced in South African mines, such as prestressed elongates, roofbolts and nets. Durrheim (2012) identifies several characteristics of seismically-induced ground motion that are not taken explicitly into account in the functional specifications for support design (multi-cyclic shaking, shear motion between the hanging- and footwall, transient tensile forces, and structural resonances), reviews investigations of rockburst damage to evaluate the significance of these phenomena, and proposes functional specifications for rockburst resistant in-stope support. In this study we aim to make new in-stope observations to validate or extend past observations. We will also attempt to measure dynamic stresses within metres of the rupture plane. Similar phenomena affect surface structures exposed to earthquake-induced shaking, and earthquake engineers have developed a range of solutions to mitigate damage. We will investigate whether these solutions can be adapted to underground support systems.

4. Implications for the mitigation of seismic risk in Japan

The Japan Headquarters for Earthquake Research Promotion (JHERP) is a special governmental organization established by law after the 1995 Kobe earthquake. It was originally attached to the Prime Minister's office, but is now part of the Ministry of Education, Culture, Sports, Science and Technology. JHERP (2011) published an assessment of earthquake hazard on 11 January 2011, exactly two months before the M9 Great East Japan earthquake (Figure 4). A crucial part of the assessment procedure is the definition of fault segments along the plate boundary. The hypocentre of the M9 earthquake was in the Miyagi-ken-Oki segment (smaller black star), where the probability of occurrence of an M7.5 earthquake within 30 years had been assessed as 99 per cent, which was the highest of any segment. Thus the forecast would have been a complete success had the rupture stopped after several tens of seconds. However, the rupture extended into adjacent segments, two to the south and one to the north (smaller open stars). The largest fault slip was ~50m over a strike length of ~100 km, indicated by the location of bigger black star in the segment Sanriku-oki to Boso-oki. The process lasted for several minutes, and produced a far larger earthquake than was anticipated. The forecasted probability was based on the historical records. For example, in the section of Miyagi-ken-Oki (a smaller black star), the probability calculation was based upon six M7 earthquakes that occurred over several centuries with an average recurrence period of 37.1 year. Nobody anticipated a M9.0 earthquake.

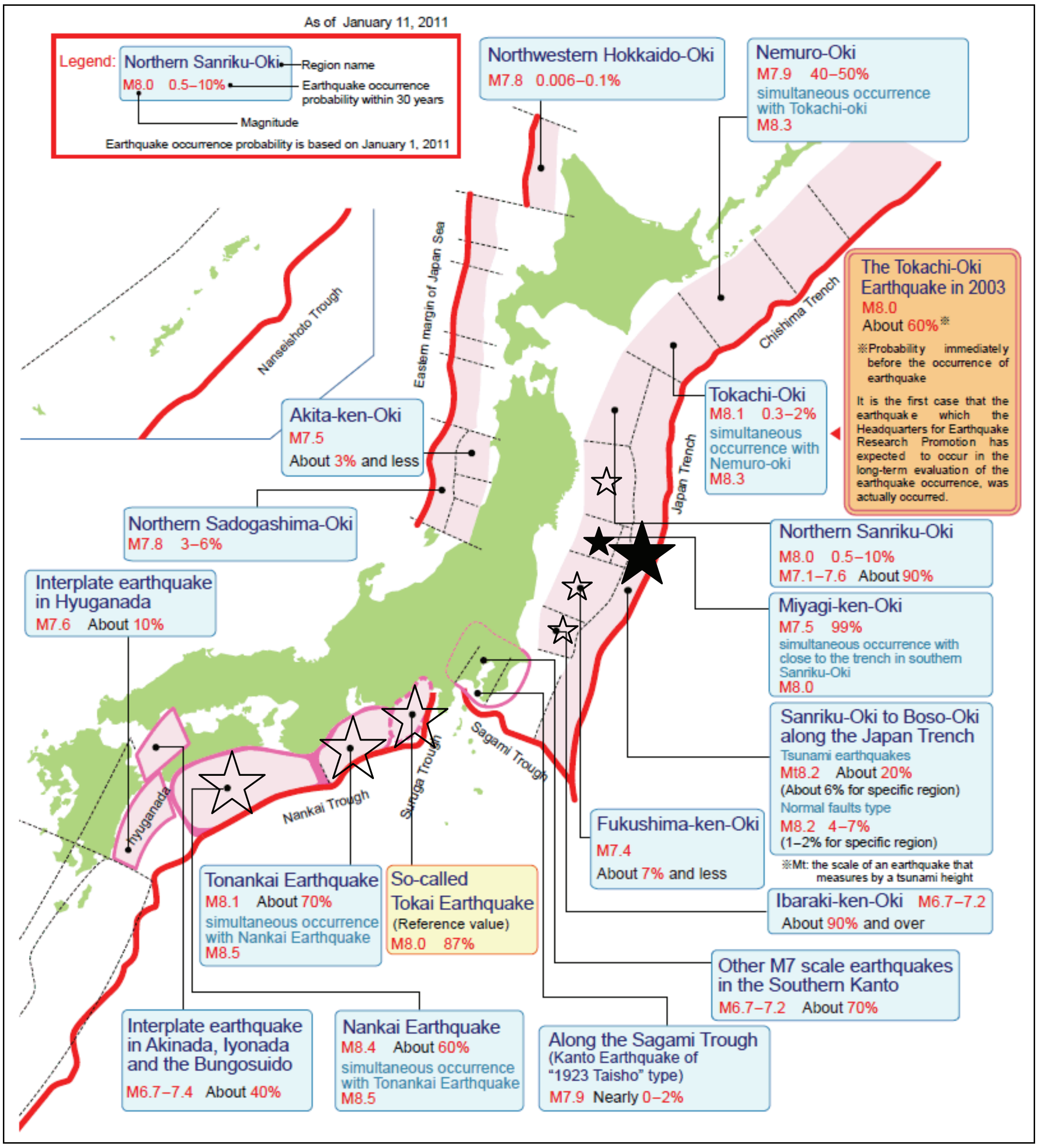

Figure 4. Thirty-year earthquake occurrence probability for Japan (JHERP, 2011)

ORPPC (2011) summarized the reasoning behind the hazard assessment as follows:

- No M>9 earthquake has occurred at a plate boundary with ~100-million-year old or older oceanic plate anywhere on Earth since instrumental monitoring of seismicity commenced about a century ago. The Pacific plate near the Japan Trench is the oldest oceanic plate in the world. It was concluded the plate coupling in the Japan Trench was likely to be weak and that the segment lacked the potential to host an M>8 earthquake.

- Dense seismic and geodetic networks were deployed on Japanese islands in the 1990s, and since then have yielded evidence of significant aseismic slips. It was concluded that the aseismic slip could have relieved the stress significantly; reducing the maximum credible size of earthquakes in eastern Japan. Strong coupling was likely to be confined to the limited number of segments that have hosted M≈8 earthquakes in the last century.
- The segment marked by a bigger black star (Sanriku-Oki to Boso-Oki) has exhibited relatively low levels of seismic activity, which was thought to be attributed to weak coupling at the plate boundary. In contrast, the large segments along the Nankai Trough in Western Japan (large open stars in Figure 4) have also been less seismically active in recent decades, but are believed to be strongly coupled at the plate boundary.
- Since the 1990s GPS monitoring and repeated small earthquakes indicate that there might be strong coupling in far off-shore segments (larger black star in Figure 4). However, these segments are too remote to be delineated with confidence.

Exhaustive seismological research has taken place following the M9 event (e.g. the special issue of Earth, Planets and Space, vol. 63, no.7, pp. 511-902). Kato et al. (2012) found significant foreshock activity prior to the M9 earthquake, suggesting migration of slow slip towards the hypocenter. However, even if the foreshock sequence had been recognised, it is unlikely that the size or time of the event would have been predicted. The Japanese on-land seismological and geodetic networks are the densest in the world. However, they are unable to characterize segmentation and coupling along the off-shore plate boundary adequately. One solution is to deploy an ocean-bottom geodetic and seismic network. However, the recurrence period of great earthquakes is a century or more, so it will take decades before seismic hazard assessments can be improved. The experiment in South African gold mines has the potential to provide Japanese seismologists with new insights into earthquake physics in a far shorter period.

5. Conclusions

Past efforts to identify reliable precursors of damaging tremors in South African mines and great earthquakes in Japan have failed to produce convincing results. This may be due to limitations in the sensitivity and resolution of past observations. We hope to remedy this by monitoring deformation and rupture with unprecedented detail at research sites in three deep gold mines. We recognize that our hypotheses may be falsified, and that none of the phenomena we have identified will produce precursory signals that can be used to issue short-term warnings of damaging seismic events in the brittle hard rock environment. While this would be a disappointing outcome, it will force us to improve our monitoring and analysis technologies, and seek to identify new phenomena that may provide a warning of an imminent seismic event. At the very least we expect to gain new insights into the physics of earthquake preparation and rupture, and will continue to pursue engineering solutions to mitigate the rockburst risk.

Acknowledgements

The Japanese - South African collaborative research project would have been impossible without the assistance of Anglogold Ashanti, First Uranium, Gold Fields of South Africa and companies providing mine seismology technology and services, and the SATREPS team of researchers. The Japanese activities have been partly supported by the Japan Science Promotion Society grant in aid, by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan (No. 21224012), under its Observation and Research Program for Prediction of Earthquakes and Volcanic Eruptions, and by Ritsumeikan University and Tohoku University. The South African activities have been partly supported by the Council for Scientific and Industrial Research, the Council for Geoscience, and Department of Science and Technology through the South African Research Chairs Initiative, and the University of the Witwatersrand.

References

Agnew, D.C. (2002). History of Seismology. In *International Handbook of Earthquake and Engineering Seismology*, vol. 81A, pp. 3-11, Academic Press, Amsterdam.

Aki, K. (1967). Scaling law of seismic spectrum, *J. Geophys. Res.*, Vol. 72, 1217-1231.

Boettcher, M.S., McGarr, A. & Johnston, M. (2009). Extension of Gutenburg-Richter distribution to Mw -1.3, no lower end in sight. *Geophys. Res. Lett.*, vol. 36, L10307, doi:10.1029/2009GL038080.

Brink, A.v.Z. (1980). Rock burst prediction research in South African gold mines. In *Proceedings of the Second Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials*, The Pennsylvania State University, 13-15 November 1978. H.R Hardy Jr. and F. W. Leighton (eds), pp. 95-107, Trans Tech Publications, Clausthal.

Brink, A.v.Z. & O'Connor, D. (1984). Rock prediction research – development of a practical early-warning system. In *Proceedings of the Third Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials*, The Pennsylvania State University, 5-7 October 1981. H.R Hardy Jnr. and F. W. Leighton (eds), pp. 269-282. Trans Tech Publications, Clausthal.

Brink, A.v.Z. & Mountford, P.I. (1984). Feasibility studies on the prediction of rockbursts at Western Deep Levels. *Proceedings of the First International Symposium on Rockbursts and Seismicity in Mines*. N.C. Gay and E.H. Wainwright (eds), SAIMM Symposium Series No. 6, pp. 317-325. Johannesburg: South African Institute of Mining Metallurgy.

Christensen, N.I. & Stanley, D. (2003). Seismic velocities and densities of rocks. In *International Handbook of Earthquake and Engineering Seismology*, vol. 81B, pp. 1587-1594, Academic Press, Amsterdam.

Cichowicz, A. & Green, R.W.E. (1989). Changes in the early part of the seismic coda due to localized scatterers: the estimation of Q in a stope environment. *Pure Appl. Geophys*., vol. 129, 497-511.

Cichowicz, A. Green, R.W.E. & Brink, A.v.Z. (1988). Coda polarization properties of high frequency microseismic events. *Bull. Seismol. Soc. Am*., vol. 78, 1297-1318.

Cichowicz, A. Green, R.W.E., Brink, A.v.Z., Grobler, P. & Mountford, P.I. (1990). The space and time variation of micro-event parameters occurring in front of an active stope. In *Proceedings of the Second International Symposium on Rockbursts and Seismicity in Mines*. C. Fairhurst (ed.), pp.171-175. Rotterdam: A. Balkema.

CSEP (2012). Collaboratory for the Study of Earthquake Predictability, http://www.cseptesting.org, downloaded 11 February 2012.

Durrheim, R.J. (2010). Mitigating the rockburst risk in the deep hard rock South African mines: 100 years of research, in *Extracting the Science: a century of mining research*, J. Brune (ed), Society for Mining, Metallurgy, and Exploration, Inc., pp. 156–171.

Durrheim, R.J. (2012). Functional specifications for in-stope support based on seismic and rockburst observations in South African mines. *Proceedings of the Sixth International Seminar on Deep and High Stress Mining*, 28-30 March 2012, Perth, Australia, Australian Centre for Geomechanics, in press.

Durrheim, R.J. & Labrie, D. (2007a). Data-Driven Simulation of the Rock Mass Response to Mining - Part 1: Laboratory Experiments using Nepean Sandstone Models, Chapter 34 in *Challenges in Deep and High Stress Mining*, Y. Potvin, J. Hadjigeorgiou and D. Stacey (eds), Australian Centre for Geomechanics, pp. 293-304.

Durrheim, R.J. & Labrie, D. (2007b). Data-Driven Simulation of the Rockmass Response to Mining - Part 2: Numerical Modelling of the "Room and Pillar" Experiment, Chapter 35 in *Challenges in Deep and High Stress Mining*, Y. Potvin, J. Hadjigeorgiou and D. Stacey (ed), Australian Centre for Geomechanics, pp. 305-313.

Durrheim, R.J., Cichowicz, A., Ebrahim-Trollope, R., Essrich, F. Goldbach, O., Linzer, L.M., Spottiswoode, S.M. & Stankiewicz, T. (2007). Guidelines, Standards and Best Practice for Seismic Hazard Assessment and Rockburst Risk Management in South African Mines, *Proceedings of the Fourth International Seminar on Deep and High Stress Mining*, 7-9 November 2007, Perth Australia, Y. Potvin (editor), Australian Centre for Geomechanics, pp. 249-261.

Durrheim, R.J., Ogasawara, H., Nakatani, M., Yabe, Y., Milev, A. Cichowicz, A., Kawakata, H., Moriya, H. & the JST-JICA SA research group (2010). Observational Study to Mitigate Seismic Risks in Mines: a new Japanese - South African collaborative project, *Proceedings of the Fifth International Seminar on Deep and High Stress Mining*, M. Van Sint Jan and Y. Potvin (eds), 6-8 October 2010, Santiago, Chile, Australian Centre for Geomechanics, ISBN 978-0-9806154-5-6, pp. 215-225.

Durrheim, R.J., Ogasawara, H., Nakatani, M., Yabe, Y., Kawakata, H., Naoi, M., Ward, A.K., Murphy, S., Wienand, J, Lenegan, P., Milev, A.M., Murakami, O., Yoshimitsu, N., Kgarume, T., Cichowicz, A. & the JST-JICA SA research group (2012). Establishment of SATREPS experimental sites in South African gold mines to monitor phenomena associated with earthquake nucleation and rupture, *Proceedings of the Sixth International Seminar on Deep and High Stress Mining*, 28-30 March 2012, Perth, Australia, Australian Centre for Geomechanics, in press.

Gibowicz, S.J. & Kijko, A. (1994). *An Introduction to Mining Seismology*. Academic Press, Amsterdam, 396 pp.

Hofmann, G., Ogasawara, H., Katsura, T. & Roberts D. (2012). An attempt to constrain the stress and strength of a dyke that accommodated an M_L2.1 seismic event, this volume.

Ishii, H., Yamauchi, T. & Kusumoto, F. (1997). Development of high sensitivity bore hole strain meters and application for rock mechanics and earthquake prediction study. *Rock Stress*, AA Balkema, Rotterdam, pp. 253–258.

JHERP (2011), *Headquarters for Earthquake Research Promotion.* Viewed 19 November 2011, http://www.jishin.go.jp/main/index-e.html.

Jaeger, J.C. & Cook, N.G.W. (1979). *Fundamentals of Rock Mechanics*, 3rd edition, Chapman & Hall, London, 513 pp.

Kato, K., Obara, K., Igarashi, T., Tsuruoka, H., Nkagaichi, S. & Hirata, N. (2012). Propagation of slow slip leading up to the 2011 Mw 9.0 Tohoku-oki earthquake. *Science*, DOI: 10.1126/science.1215141.

Kawakata, H., Yoshimitsu, N., Nakatani, M., Philipp, J., Doi, I., Naoi, M., Ward, T., Visser, V., Morema, G., Khambule, S., Masakale, T., Milev, A., Durrheim, R.J., Ribeiro, L., Ward, M. & Ogasawara, H. (2011). Monitoring transmitted waves across a fault with a high potential for mining induced earthquakes – the Ezulwini gold mine in South Africa, Abstract S31C-2257, AGU 2011 Fall Meeting, 5–9 December 2011, San Francisco, U.S.A.

Kgarume, T.E., Spottiswoode, S.M. & Durrheim, R.J. (2010). Statistical properties of mine tremor aftershocks, *Pure Appl. Geop*., vol. 167, 107-117,

Koto, B. (1893). On the cause of the Great Earthquake in central Japan. J. Coll. Sci. Imp. Univ. 5 (pt 4), 294-353 (now available online Koto, B. (1990), Neo-tectonics; on the cause of the Great Earthquake in Central Japan, 1891. Terra Nova, 2: 301–305. doi: 10.1111/j.1365-3121.1990.tb00080.x).

Kwiatek, G., Plenkers, K., Nakatani, M., Yabe, Y., Dresen, G. & the JAGUARS-Group (2010), Frequency-magnitude characteristics down to magnitude -4.4 for induced seismicity recorded at Mponeng gold mine, South Africa, *Bull. Seism. Soc. Am*., vol. 100, 1165-1173, doi: 10.1785/0120090277.

Lynch, R.A. (2010). Passive and active seismic monitoring in mines. Presented at the *Fifth International Seminar on Deep and High Stress Mining,* 6-8 October 2010, Santiago, Chile (unpublished).

Maxwell, S.C. & Young, R.P. (1996). Seismic imaging of rock mass responses to excavation, *Int. J. Rock Mech. Min. Sci*., vol. 33, 713–724.

McGarr, A. (1974). Earthquake prediction: absence of a precursive change in seismic velocities before a tremor of magnitude of 3¾. *Science*, vol. 185, 1047-1049.

McGarr, A. & Green, R.W.E. (1975). Measurement of tilt in a deep-level gold mine and its relationship to mining and seismicity. *Geophys. J. R. astr. Soc*., vol. 43, 327-345.

McGarr, A., Sacks, I.S., Linde, A.T., Spottiswoode, S.M. & Green, R.W.E. (1982). Co-seismic and other short-term strain changes recorded with Sacks-Evertson strainmeters in a deep mine. *Geophys. J. R. astr. Soc*., vol. 70, 717-740.

Mendecki, A. (ed.) (1997). *Seismic Monitoring in Mines*. Chapman & Hall, London, 262 pp.

Milev, A.M. & Spottiswoode S.M. (2005). Strong ground motion and site response in deep South African mines. *J. of S. Afr. Inst. Min. Metall*., vol. 105, 515-525.

Milev, A.M. & Spottiswoode S.M. (2008a). Rock Mass Deformation Around Deep Level Mining Excavations by Quasi-static and Dynamic Measurements. Abstracts, 2008 SSA Annual Meeting, Santa Fe NM, USA.

Milev, A.M. & Spottiswoode S.M. (2008b). Strong Ground Motion and Site Response Recorded Underground in Deep Level Gold Mines in South Africa. Abstracts, 2008 SSA Annual Meeting, Santa Fe NM, USA.

Mogi, K. (1985). *Earthquake Prediction*, Academic Press, Japan, 355 pp.

Nakatani, M., Yabe, Y., Philipp, J., Morema, G., Stanchits, S., Dresen, G. & the JAGUARS group, (2008). Acoustic emission measurements in a deep gold mine in South Africa – Project overview and some typical waveforms, Abstract Seism. Soc. Am., 2008 annual meeting (Santa Fe, New Mexico). *Seismol. Res. Lett.*, vol. 79, 311.

Naoi, M., Ogasawara, H., Takeuchi, J., Yamamoto, A., Shimoda, N., Morishita, K., Ishii, H., Nakao, S., van Aswegen, G., Mendecki, A.J., Lenegan, P., Ebrahim-Trollope, R. and Iio, Y. (2006). Small slow-strain steps and their forerunners observed in gold mine in South Africa. *Geophys.l Res. Lett.*, vol.33, L12304, doi: 10.1029/2006GL026507.

Naoi, M., Nakatani, M., Yabe, Y., Kwiatek, G., Igarashi, T. & Plenkers, K.. (2011). Twenty thousand aftershocks of a very small (M2) earthquake and their relation to the mainshock rupture and geological structures. *Bull. Seismol. Soc. Amer.*, 101(5): 2399-2407, doi:10.1785/0120100346.

National Academy of Science (1996). *Earthquake Prediction: the Scientific Challenge*. Proceeding of a colloquium held on 10-11 February 1995 in Irvine, California, U.S.A. The National Academies Press, Washington, D.C., Proc. Natl. Acad. Sci., USA, vol. 93, April 1996.

National Academy of Science (2003). *Living on an Active Earth. Perspectives on Earthquake Science.* The National Academies Press, Washington, D.C., 418 pp.

Nesbitt, A.C. (1994). *Investigation of the emission and propagation of electromagnetic energy from stressed quartzite rock underground.* M.Sc. Thesis, University of the Witwatersrand, Johannesburg, South Africa.

Niu, F., Silver, P.G., Daley, T.M., Cheng, X. and & Majer, W.L. (2008). Preseismic velocity changes observed from active source monitoring at the Parkfield SAFOD drill site. *Nature,* vol. 454, 204-208, doi:10.1038/nature07111.

Ogasawara, H., Yanagidani, T. & Ando, M. (ed.) (2002) *Seismogenic Process Monitoring*, Balkema, Rotterdam, 414 pp.

Ogasawara, H., Takeuchi, J., Shimoda, N., Ishii, H., Nakao, S., van Aswegen, G., Mendecki, A.J., Cichowicz, A. Ebrahim-Trollope, R., Kawakata, H., Iio, Y., Ohkura, T., Ando, M. and the Research Group for Semi-controlled Earthquake-generation Experiments in South African deep gold mines. (2005). High-resolution strain monitoring during M~2 events in a South African deep gold mine in close proximity to hypocentres, in *Proceedings 6th International Symposium on Rockburst and Seismicity in Mines*, Y. Potvin and M. Hudyma (eds), Australian Centre for Geomechanics, pp. 385–391.

Ogasawara, H., Durrheim, R.J., Nakatani, M., Yabe, Y., Milev, A., Cichowicz, A., Kawakata, H. & Moriya, H. (2009a). JST-JICA SA research group, a Japanese - South African collaboration to mitigate seismic risks in deep gold mines, *Proceedings of First Hard Rock Safe Safety Conference*, J. Van der Westhuizen (ed.), 28-30 September 2009, Sun City, South Africa, South African Institute of Mining and Metallurgy, pp. 115-134.

Ogasawara, H., Kawakata, H., Ishii, M., Nakatani, M., Yabe, Y., Iio, Y. and the Research Group for the Semi-controlled Earthquake-generation Experiments at deep gold mines, South Africa (SeeSA) (2009b) The Semi-controlled Earthquake-generation Experiments at Deep Gold Mines, South Africa – Monitoring at the proximity to elucidate seismogenic process, *Journal of Japanese Seismological Society,* Ser. 2 (61), pp. S563–S573 (in Japanese with English abstract).

ORPPC (2011), Observational Research Program Promotion Committee, Earthquake Volcano Division, Geodesy Sub-committee, Advisory Committee of Science, Technology and Academy, Japanese Ministry of Education, Culture, Sports, Science and Technology. *2010 Annual Report on Observational Research Program for Prediction of Earthquake and Volcanic Eruption*, 205 pp (in Japanese).

Sellers, E., Kataka, M.O. & Linzer, L. (2003). Source parameters of acoustic emission sources and scaling with mining induced seismicity. *J. Geophys. Res*., 108 (B9), 2418, doi:10.1029/2001JB000670.

Scholes, R.J. (2003). *Good Research Guide*. 2nd edition. CSIR, Pretoria, 18 pp.

Simpson, D.W. & Richards, P.G. (eds) (1981). *Earthquake Prediction. An International Review*. Maurice Ewing Series 4, American Geophysical Union, Washington D.C., 680 pp.

Spottiswoode, S.M. & Milev, A.M. (2006). A study of mine stability using records of ground tilting. *Proceedings of the 41st US Symposium on Rock Mechanics*, ARMA (American Rock Mechanics Association). Paper Number 06-1168.

Spottiswoode, S.M. (2010). Mine seismicity: prediction or forecasting? *J. S. Afr. Inst. Min. Metall.*, vol. 110, 11-20.

Utsu, T. (2003). Centennial Report of Japan. Part 2. Historical development of Seismology in Japan. *International Handbook of Earthquake & Engineering Seismology,* Part B, W. Lee, P. Jennings, C. Kisslinger and H. Kanamori (eds), Academic Press, Chapter 79.33, pp.1-19.

Van Aswegen, G. (2005). Routine seismic hazard assessment in some South African mines, *Proceedings of the Sixth International Symposium on Rockbursts & Seismicity in Mines*, Y. Potvin and M. Hudyma (eds), Australian Centre for Geomechanics, pp. 437-444.

Weiss, O. (1938). The theory of rockbursts and the possibilities of geophysical methods in predicting rockbursts on the producing mines of the Witwatersrand. *Jnl. Chem., Met. Min. Soc. S.A*., vol. 38 (July 1937 – Jun 1938), 273-328.

Wyss, M. (ed.) (1991). *Evaluation of proposed Earthquake precursors, conducted 1989/90 by the IASPEI Sub-commission on Earthquake Prediction*, American Geophysical Union, Washington, D.C., 94 pp.

Yasutake, G., Ogasawara, H., Kawakata, H., Naoi, M. and The Research Group for SeeSA, (2008), Slow strain-steps observed in a potential M2 source area at a 2.9 km depth, Mponeng gold mine, South Africa (2), *ASC-SSJ*, 26 Nov 2008, Tsukuba.

Authors CVs

Raymond John Durrheim, *South African Research Chair in Exploration, Earthquake & Mining Seismology,* CSIR Centre for Mining Innovation & University of the Witwatersrand

Ray Durrheim graduated from the Universities of Stellenbosch (BSc), Pretoria (MSc) and the Witwatersrand (BScHons, PhD). He started his career as an exploration geophysicist with General Mining, after which he took up teaching and research positions at Wits University and CSIR. He was manager of the DeepMine collaborative research programme from 1998-2002. In 2007 he was awarded the South African Research Chair in Exploration, Earthquake and Mining Seismology. He is currently a PI of the Japanese-South African collaborative project "Observational studies to mitigate seismic risks in mines" and co-director of the AfricaArray research and capacity-building programme.

Hiroshi Ogasawara, *Professor*, Ritsumeikan University

Hiroshi Ogasawara started his career as an associate professor of Ritsumeikan University in 1989, and was appointed professor in 2002. He is interested in the rock mass response associated with seismic events, stress modelling and in-situ stress measurement. In the 1980s and early 1990s, he deployed a multidisciplinary array to monitor the rock mass response associated with flooding-induced seismicity in an abandoned silver mine in Japan. He visited the Bernard Price Institute at Wits University and the USGS Menlo Park as a visiting researcher in 1994. Since then he has visited South African many times (7 times in 2011) to monitor rock mass deformation at eleven gold mines. He is currently Chief Advisor of the Japanese-South African collaborative 5-year project "Observational studies to mitigate seismic risks in mines" and also a PI of a 5-year project "Multidisciplinary monitoring of preparation and generation of earthquakes at M2 sources in South African gold mines".