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Multidisciplinary Monitoring of the Entire Life Span of an Earthquake in South African Gold Mines

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The Research Group for Semi-Controlled Earthquake-Generation Experiments in South African Deep Gold Mines

Since 1992, the authors attempted to monitor stress, its build-up and strength at M>~2 hypocentres in South African deep gold mines. In the second field experiment, the authors successfully monitored the entire strain history within a hundred metres from the hypocentres, associated with a few seismic events with M>2. However, there were no close strong-motion meters available to locate asperities; only a single strainmeter was available, so the authors were not able to locate the strain-change source; no in situ stress measurements were carried out at the site, and no information was available to constrain strength. In order to address these deficiencies, from 2003 to 2004, the authors deployed new experimental instrument arrays at fault bracket/stabilising pillars. Multiple strainmeters, arrays of strong ground-motion meters, sensitive thermometers to monitor seismic heat generation, and fault displacement meters were installed. Successful monitoring began, but the authors learnt that they had to develop instruments for much quicker drilling and installation, especially at highly stressed pillars adjacent to mining operations.

1 INTRODUCTION

After the 1995 Kobe earthquake, which caused more than 6,000 fatalities, dense nationwide arrays of strong-ground-motion meters, highly sensitive seismometers and GPS were deployed in Japan, in order to monitor earthquake-generation processes in detail. One of the principal results of this monitoring was discovering the role of asperities and the role of the surrounding area, both before and after large events (e.g. Iio et al., 2003). However, the interaction of asperities or initiation of rupture are still not fully understood, because hypocentres are too distant to observe in detail even with sensitive, low-noise instruments that are in place for years, even with a high-resolution recording system. The stress and strength at the hypocentre are still fundamental parameters that have never been monitored directly. In addition, large events occur too infrequently to allow us to learn about them within a short time period.

However, in order to monitor frequent seismic events, we can most closely approach hypocentral areas in deep mines. Although stress is well controlled during mining (e.g. Ryder and Jager, 1999, 2002), not enough direct, high-resolution monitoring of stress, and its build-up and strength, has been done in hypocentral areas of potentially hazardous seismic events. However, with sensitive, low-noise, stable instruments for monitoring natural earthquakes, pioneering work was done by the group headed by Art McGarr in the 1970s - 80s (e.g. McGarr et al., 1982). With a modern, higher-resolution recording system, the Research Group for Semi-controlled Earthquake-generation Experiments in South African deep gold mines has attempted to monitor earthquakes since 1992 (Nicolaysen, 1992; Iio and Fukao 1992; Iio, 1995; Sumitomo, 1998; Ogasawara et al., 2001, 2002). ISS International Ltd. has helpfully collaborated in high-resolution monitoring as well as seismic monitoring (e.g. Mendecki, 1993, 1997).

Recently, this group has successfully used a sensitive strainmeter to monitor interesting strain changes within a hypocentral area (e.g. Takeuchi et al. 2003; Ogasawara et al., 2005). However, there were no nearby strong-motion meters available to locate asperities; only a single strainmeter was available, which was not sufficient to locate the strain-change source; no in situ stress measurements were carried out at the site.

In order to address these deficiencies, from 2003 to 2004 we deployed two new experimental instrument arrays at fault bracket/stabilising pillars in the Tau Tona and Mponeng gold mines, South Africa. Heat generation associated with seismic events can be effective in constraining fault strength. Our study also attempted to monitor temperature change.

We had difficulties drilling in a highly stressed stabilising pillar with both sides mined, and we describe this below. Next, we describe how drilling and instrument deployment went smoothly at a planned fault bracket pillar with only a mined waste slot. We also mention the necessity of developing instruments for much quicker drilling and installation.

2 EXPERIMENTAL SITE AT A FAULT STABILISING PILLAR WITH BOTH SIDES BEING MINED

2.1 Site Description

One of our new experimental sites was located at a fault-stabilising pillar about 2.9 km deep in the Tau Tona mine (Figure 1). The following characteristics occur around this site:

- The gold reef dips southeastward at an angle of about 20 degree (see two dipping plates in Figure 1, in which the solid and mined portions are represented by a mottled pattern and black, respectively).

- Two normal faults dip northwestward, intersecting the gold reef with a total throw of about 40-50 m (two light-grey planes in Figure 1).

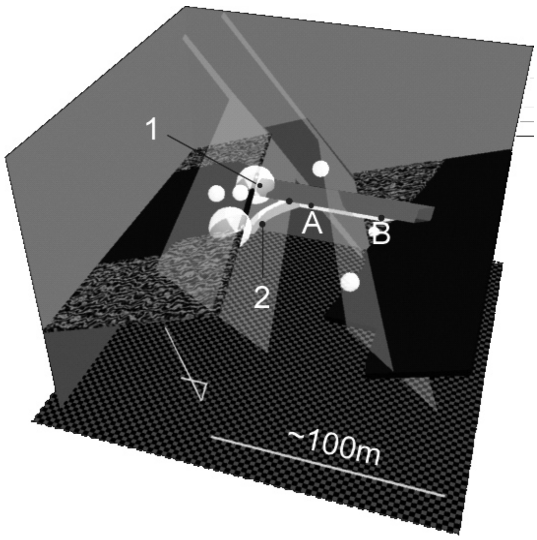

FIG. 1 Simplified schematic illustration representing 3D configuration of gold reef intersected by two faults (light grey). Access tunnel (white) is capped with a waste slot (dark grey), forming a so-called T-shaped slot. See details in text

- The eastern fault was sufficiently exposed at the intersection of a tunnel and a waste slot (Points 1 and 2 in Figure 1), and characterised by a ~30 cm thick, coarsely fractured zone. Both sides of the zone were laminated with finely-fractured flakes less than 1 cm thick, suggesting fresh fracturing. Slight water seepage was evident locally. The western fault was not exposed well, but was definitely located at the T-shaped slot.
- A so-called T-shaped slot, consisting of a tunnel capped by a wider waste-slot about 1 m thick and 15 m wide (in Figure 1, a white, horizontal prism and a medium-grey, narrow plate laid horizontally on the prism), was excavated across two faults.
- A gold reef on the northwestern side of the bracket pillar had previously been mined.
- Figure 1 shows the situation in August 2003. Full-scale mining of the gold reef on the southeastern side of the pillar began at the end of 2002, and advanced toward the northeast. An M2 event occurred in March 2003 and another in August 2003 (southern and northern larger spheres in Figure 1, respectively) and another occurred in October 2003 (not shown in Figure 1).
- The country rock is quartzite with a typical Young's modulus of ~70 GPa.

Any information on stress and strength in the above situation is very crucial for understanding an earthquake source and for effective and safe mining. So, two cubbies (small chambers 2.5 m high x 3 m wide x 5 m deep) were excavated by blasting (A and B in Figure 1) for drilling space. Our original plan was to drill several holes 15-30 m long, in order to install two strainmeters to monitor shear and normal strain changes on the fault, to install multiple strong ground-motion meters to locate asperities, and to carry out stress measurement beforehand.

2.2 *In situ* Stress Measurement

In addition to continuous monitoring of strain change as we have done at the second experimental site (Ogasawara et al., 2005), we tried to measure stress beforehand: direct measurement with overcoring (2.2.1) and indirect measurement with a borehole camera and cores (2.2.2).

2.2.1 Overcoring with an intelligent, recoverable Ishii strain meter

We used an intelligent Ishii strainmeter (Figure 2), which has an A/D converter, a microprocessor, memory and rechargeable batteries (e.g. Yamauchi et al., 2000). It enables wireless overcoring even in a deep, vertical borehole, 1 km being the deepest one known (e.g. Matsumoto et al. 2000, Ishii et al. 1997, 2002). We specially designed this strainmeter to be installed in a BX hole (60 mm diameter), and it has eight components to enable us to measure three-dimensional stress by a single overcoring. The power consumption of the strain cell is very low and we can schedule operation of the measurement system, enabling monitoring for a long period. Therefore, if we leave a recovered core for a while with the strain-cell inside, we can monitor inelastic expansion. In addition, pressure calibration is easily done if we put the recovered core into a pressure vessel. No underground wire connection is needed. Everything except installation and overcoring can be done on the surface.

Figure 3 schematically illustrates the installation and overcoring procedure. The strain cell is inserted in a BX hole (60 mm diameter) with grout (Figure 3a and b). After the grout has set, the hole is reamed to a diameter of 114 mm (4 9/16 size), followed by overcoring with a double-core-tube barrel. Although we had difficulty in drilling the shallower part, we successfully drilled a BX hole 15 m long. The core for the last few metres had no disking. With a borehole camera,

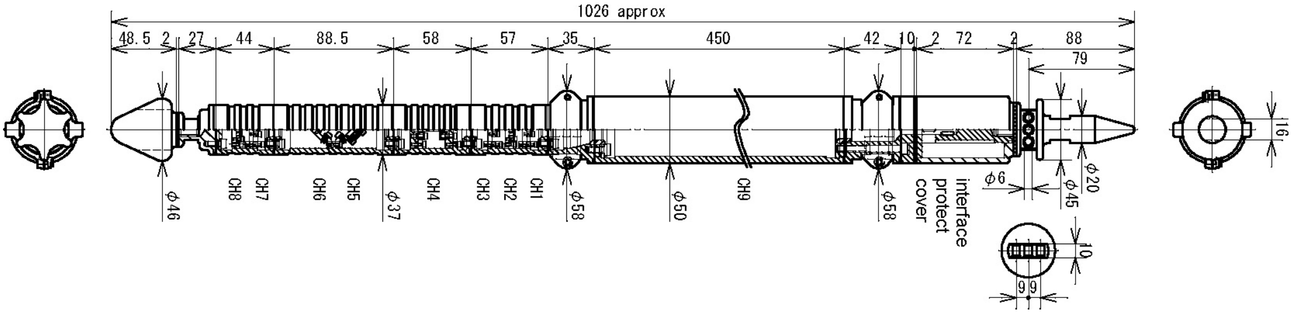

FIG. 2 An 8-component intelligent Ishii strainmeter (FS-4022, Makome Corp. Japan). Chs. 1-3: borehole-normal components, Ch. 4: borehole-parallel component, Chs.5 & 6: borehole-oblique components, Chs. 7-8: same as Chs.1&2 for redundancy. Ch.9: quartz thermometer. The strainmeter has an A/D converter, a microprocessor, memory and rechargeable batteries, enabling wireless overcoring

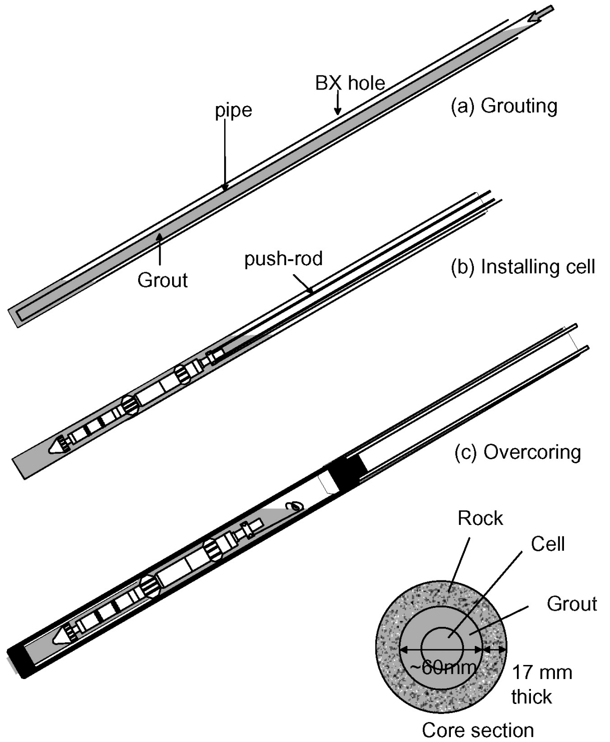

FIG. 3 Schematic illustration of installation and overcoring procedures for an intelligent, recoverable Ishii strainmeter

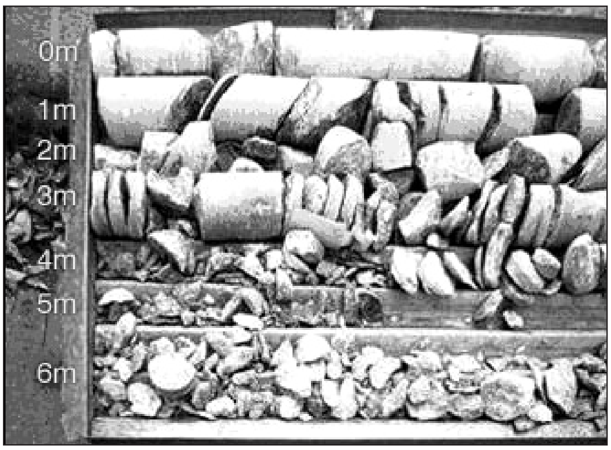

FIG. 4 An example of highly fractured BX core

we confirmed that there was no borehole breakout in the last few metres. We installed a strainmeter at a depth of 15 m in late June 2003.

2.2.2 Fracturing from high stress and difficulty in drilling

Generally, the highest stress is located several metres from the tip of a thin, tabular cavity (e.g. Jager and Ryder 1999, 2002). Thus, we had serious fracturing at a depth of several metres from the edge of the T-shaped slot. Figure 4 shows typical examples of a BX drill core. With an increase in stress, the core was disked (~3 m deep in Figure 4) and eventually crushed (4 - 6 m deep in Figure 4). At a depth of 6 - 7 m, borehole breakout enlarged hole diameter considerably (dashed circle in Figure 5), which made accurate reaming or overcoring difficult. We tried to repair the hole, but eventually gave up overcoring in November 2003.

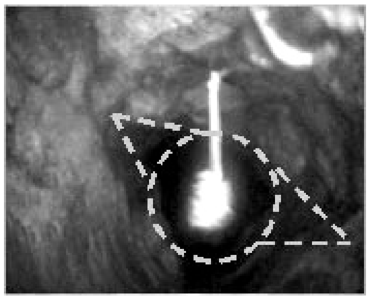

FIG. 5 Typical borehole camera image at a depth of 6 - 7 m. Original hole and break out are indicated by dashed grey circle and lines. White string with mass is a vertical marker

2.2.3 Indirect stress measurement

We successfully recovered a core at the depth of interest and tried to monitor 'anelastic strain recovery' (ASR method; e.g. Amadei and Stephansson, 1997). However, no significant ASR was observed, possibly because of the relatively low porosity of quartzite.

We also tried the 'differential strain curve analysis' method (DSCA; e.g. Amadei and Stephansson, 1997), but failed. When a sample was subjected to hydrostatic pressure, the dominant orientation of microcrack closure was borehole-parallel. Evidently the closure direction was controlled by invisible cracks of core-disking origin.

Both sides of the borehole wall were wedged (see dashed line wedges in Figure 5) by borehole breakout (e.g. Amadei and Stephansson, 1997). This suggests a direction of maximum principal stress oblique to the fault plane. From June to August 2003, we observed that the extent of borehole breakout increased along with the advance of mining on the southeastern side of the pillar. Two M>2 events took place in August and October 2003 within 100 m of the borehole. Therefore, repeated observations of an open hole might be the best method to learn about stress states under very high-stress conditions.

2.3 Final Monitoring Configuration

Despite difficulties in drilling, we successfully installed strong-ground-motion meters at a depth of 10 m in two cubbies (A and B in Figure 1), and a strain meter at a depth of 7 m in Cubby A.

3 EXPERIMENTAL SITE AT A PLANNED FAULT-BRACKET PILLAR WITH ONLY A WASTE SLOT BEING MINED

In contrast to the above-mentioned experimental site that had conditions of considerable stress, an experimental site 2.9 km deep in the Mponeng mine was affected little by a concentration of high stress. This site was located at a planned fault-bracket pillar. Figure 6 schematically illustrates the three-dimensional configuration of tunnels, the gold reef and the Pretorius fault zone. Only a waste slot about 50 m wide was excavated along the gold reef to protect the crosscut tunnel. Our target area, indicated by a square in Figure 6, is characterised by a dense, existing geophone array surrounding the site.

3.1 Target Area with a Distinctive Weak Plane

In the target area, eleven holes 5 – 30 m long were drilled smoothly, because stress was not yet seriously concentrated. Figure 7 illustrates the configuration of boreholes and our target weak plane. Our site was located within the Pretorius fault zone, which is several tens of metres wide and consists

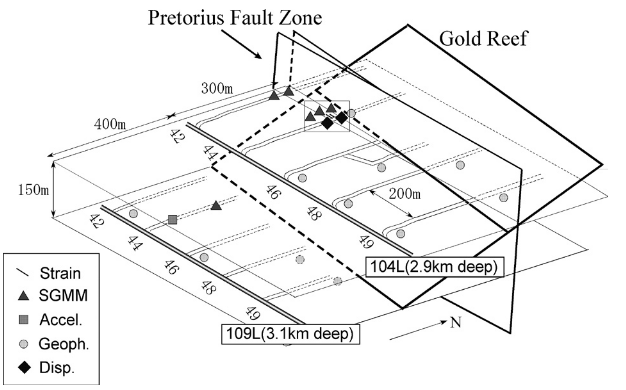

FIG. 6 Three-dimensional configuration of tunnels, gold reef and the Pretorius fault zones. A small square: our target is located near an intersection of the 104/44 crosscut tunnel and the fault

of complex geology in the country rock (basaltic lava on the hangingwall and quartzite on the foot wall), along with fragmented patches and fill-ups with cataclasite. We located many weak planes on the sidewall of the tunnel: e.g. K, A1 and M are major ones in Figure 7. Among these, we have identified a single continuous weak plane (dotted grey line in Figure 7), which bounds the southern end of the fault zone at this locality (Kita et al., 2004). This scenario is suggested by the following observations of the cores and tunnel wall, and by borehole camera records (Nakatani et al., 2004):

- A narrow (2-20 cm), severely damaged zone (stars in Figure 7) on the borehole wall was recognised in all of the five holes penetrating through this plane. Rock material was lost from the borehole wall at these damage zones.
- This damage was found to be restricted to a fairly flat plane extending from a 20 cm-thick shear zone exhumed on the tunnel wall (labelled M).
- Core material recovered from this plane, as well as from plane M exhumed in the tunnel, is weak (friable).

South of this boundary there is a single lithology consisting of basaltic lava, while the lithology to the north of this boundary is complex, including 2.0 to 300 cm thick layers of quartzite, cataclasite, and lava, in variable sequences.

3.2 Direct Measurement of Frictional Heating by Earthquake Slip (Nakatani *et al.*, 2004)

3.2.1 Experimental design

The site provided us a rare opportunity to install thermometers to monitor the frictional heat of a forthcoming earthquake. Heat conduction in rocks is very slow; it takes a week for the temperature 1 m from the heat source (slip plane) to reach a peak, followed by much slower cooling. The slower the change is, the more difficult becomes the separation from background noise and instrument drift. Time to peak values increases with the square of the source's distance.

Assuming a 2 cm slip at a 50 MPa frictional resistance, the magnitude of the temperature rise is about 0.15 K. The magnitude is proportional to generated heat and inversely proportional to source distance.

Taken together with the time-to-peak value mentioned above, difficulty increases with the cube of source distance. We have set our target value of heating equivalent to a 2 cm slip at 5 MPa, so that we can detect the heat signature even if the fault friction is much lower than laboratory values (Byerlee, 1978), as has sometimes been proposed

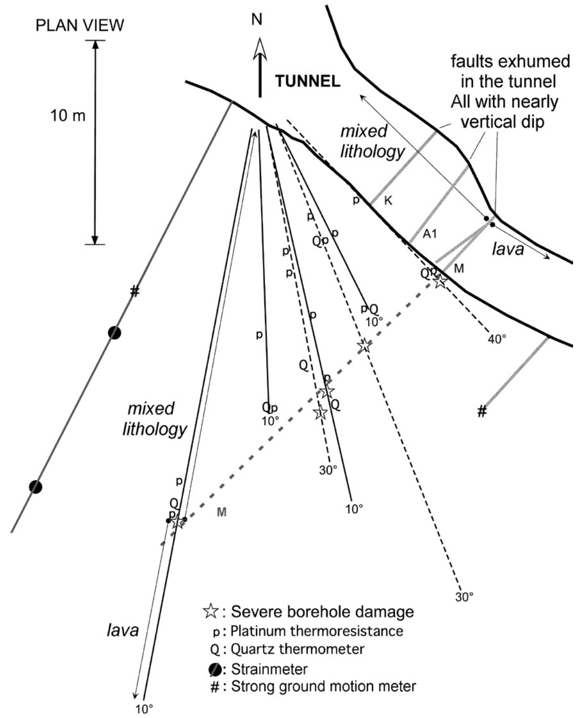

FIG. 7 A plan view map illustrating configuration of boreholes, with locations of sensors and relevant geological features (Modified from Nakatani *et al.*, 2004)

FIG. 8 An example of drill core from a strainmeter hole (a line with solid circles in Figure 7) at Mponeng mine

(e.g. Lachenbach and Sass, 1980). We estimate that sensors must be installed within a metre of the fault to achieve this, and our installation was successful.

3.2.2 Sensor layout

Two types of sensors have been installed as shown in Figure 7. Many were placed to cover a significant extent (15m x 6m) of the discrete weak plane mentioned above, in order to check the uniformity of frictional heating. Some were laid close to two possible minor slip planes (K and A1) in case slip occurred along them. Records obtained so far indicate a slow cooling (0 to 6 mK/day), presumably due to tunnel development (two years ago) and air conditioning following it. The trend of this long-term cooling is linear and is easy to remove from our results, so that we are likely to detect temperature rises of the extent discussed earlier.

3.3 Strain, Fault Displacement and Strong-Motion Monitoring

Figure 8 shows the BX core from a strainmeter hole (a line with two solid circles in Figure 7). In contrast to highly fractured core at Tau Tona, the core exhibited little fracture. We successfully installed two strainmeters (solid circles in Figure 7) at depths of 13 m and 25 m, with which we monitored shear and normal strains in the fault zone. Figure 9 shows an example of strain recordings with two seismic events and blasting-induced drift that lasted for a 30-s period on the order of 10^{-7}. As these were recorded clearly with the multiple strainmeter, we can confidently discuss them in detail. Fault-displacement meters were installed at K and M in Figure 7. Two strong-motion meters were installed as shown by # in Figure 7. With these instruments we can monitor the entire life span of an earthquake.

4 PRACTICAL STRATEGY

Figure 10 shows seismicity within cubes 500 m on a side and centred on strainmeters in the Tau Tona and Mponeng mines. We started drilling in May 2003 at Tau Tona and in June 2003 at Mponeng, finishing the former in November 2003 and the latter in February 2004. After installation, monitoring was begun in March 2003 at both mines.

Meanwhile, significant seismicity, such as reported in our second experimental field, occurred at the Tau Tona mine. An M > 2 event with a large strain step occur in October 2003. The fundamental modification in stress state by the event could not be monitored, because monitoring had not been started. In contrast to the Tau Tona mine, significant seismicity has not yet started near our sites at Mponeng. A large strain step was expected with a smaller event in October 2003, but it was not a large event that thoroughly disturbed the stress state. A larger event is still anticipated, and will be monitored with our dense array. The difference in the two mines was simply due to the speed and difficulty in drilling, which was dependent on the stress level. Even with the better conditions at Mponeng, however, our installation procedure was not quick enough.

In order to quantitatively monitor rockmass behaviour, quick drilling and installation are crucial to keep up with fast stress changes attending mining in South African gold mines. The instruments we imported from Japan were originally designed for long-term stability rather than for

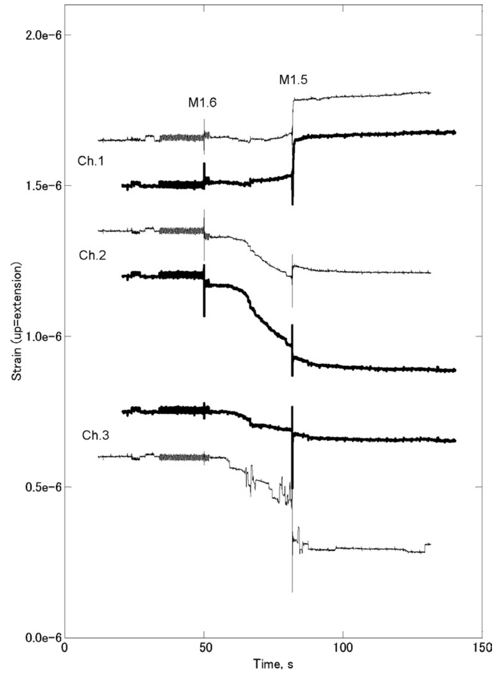

FIG. 9 An example of strain recordings for a two-minute period (12 Mar 2004) at Mponeng

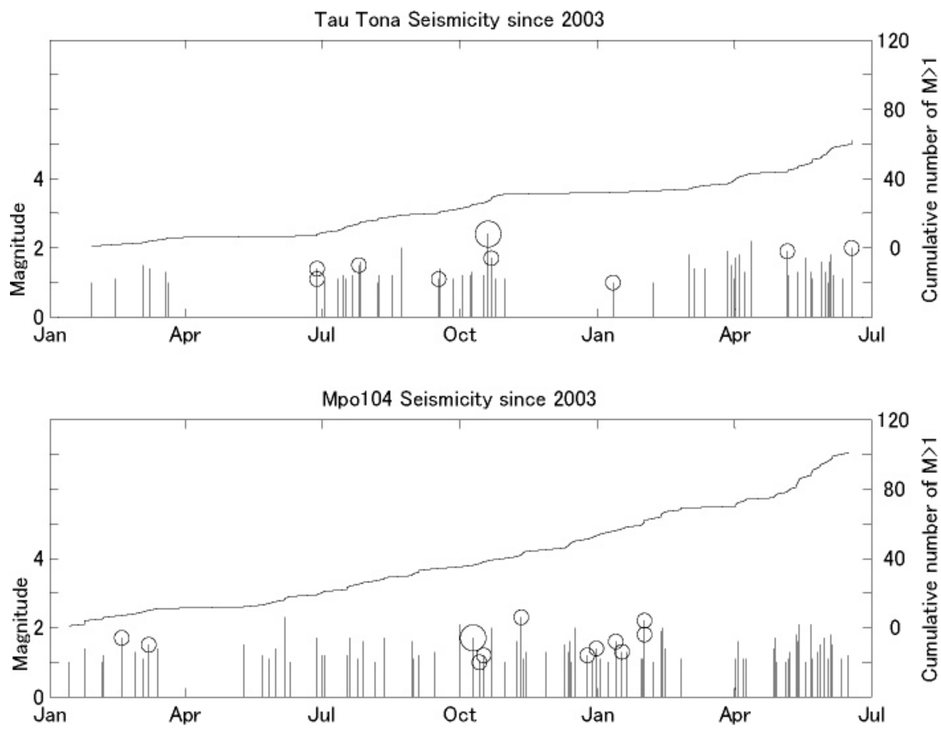

FIG. 10 Comparison with seismicity and monitoring preparation. Line: cumulative number of M>1 in a volume of 500m x 500m x 500m centred on our strainmeter. Bar: magnitude. Larger and smaller circles: events with expected strain step > about 10^{-4} and about 10^{-5} at our site, respectively

quick drilling and installation. In consequence, we must thoroughly redesign every instrument and installation procedure for easier, smaller-diameter drilling, including easier interfaces for power-supply and data communication. Such instrumentation will ultimately result in practical, quantitative monitoring in deeper gold mining.

5 CONCLUDING REMARKS

Though we had difficulty in drilling at a site under very high-stress conditions, and considerable delay ensued, we successfully deployed an ideal, dense array for multidisciplinary monitoring of the entire life span of an earthquake.

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