IS WS in Davos on 11-13 March 2015

Stress and strength at seismic event hypocenters in deep South African gold mines and the M5.5 Orkney Earthquake

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In the SATREPS 5-year project “Observational studies in South African mines to mitigate seismic risks” under the Japanese and South African MoU, we measured stress beyond previous limit in South African gold mines (Fig.2). With calibrated initial stress, we successfully estimated stress in seismogenic zones (Fig.3).

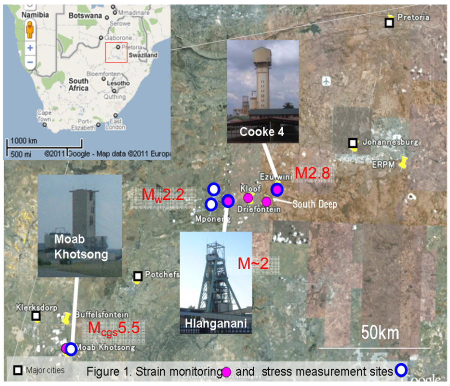


Fig. 1. An index map of our research sites. In the recent several years, multidisciplinary seismic monitoring was going on at six gold mines whose largest depth of mining is 3.4 km from surface. Yabe et al. (Keynote lecture in this workshop) reported on our activity at Mponeng and Cooke 4 (Ezulwini) mines. On 5 August 2014, Mcgs5.5 took place in Klerksdorp area, which called for an ICDP workshop.

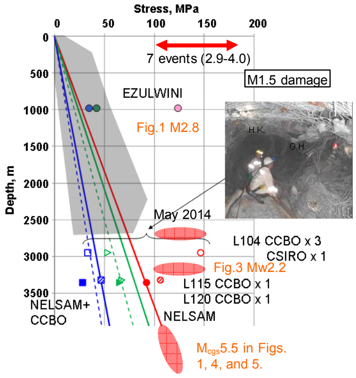


Fig. 2. Stress measurements beyond previous limit (gray zone). Red, green, blue: measured σ_1, σ_2, and σ_3. Red arrow: the range of σ_1 Hofmann et al. (2013) estimated for M2.9-4.0 seven events. Note that the measured σ_1 (circles) and the σ_1 estimated at the M_{cgs}5.5 fault is in the same range.

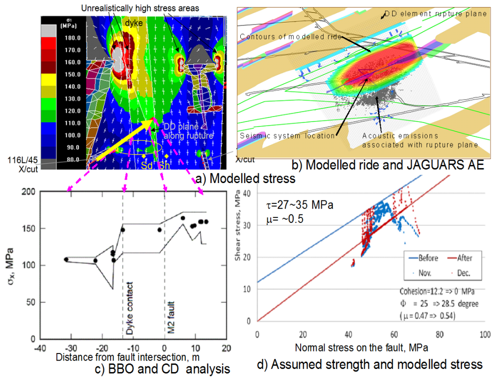
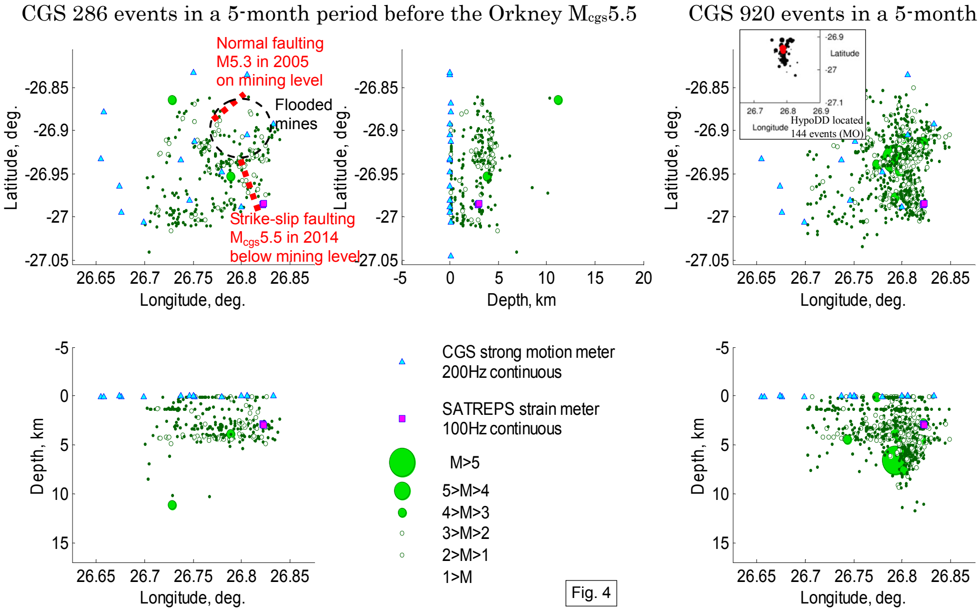
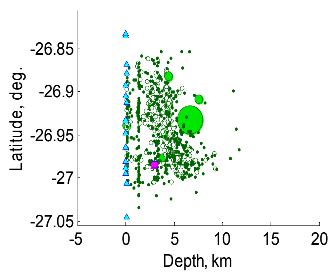


Fig.3. A Mw2.2 event in 2007 at Mponeng mine and associated research. a) Stress modelling by Hofmann et al. (2012), drilling into the Mw2.2 hypocenter by Yabe et al. (2013). b) Reproduction of fault slip by stress modelling by Hofmann et al (2012) and JAGUARS Mw2.2 AE aftershocks (Nakatani et al. 2008; Yabe et al. 2009; keynote in this WS). c) Stress estimation by Yabe et al. (2013). d) Stress estimation by Hofmann et al. (2012) and Ogasawara et al. (2013). Drilling direction was not suitable for overcoring stress measurements or better core recovery.

A M_{cgs}5.5, the largest event in South African mining area, took place on 5 Aug 2014 near Orkney, and also near one of our main SATREPS observational sites. This event was very different in several aspects from typical mining-induced earthquake, as shown or described below. CGS surface strong motion meters (▲ in Fig. 4) were installed in 2010. Preliminary velocity structure is used for the location in Fig.4, which shifts mining induced earthquakes deeper probably (from 2-3 km depths to 1–4 km depths). Automatic P- and S-wave arrival picking algorithms (Horiuchi et al. 2011) was used, which picked arrivals of the M5.5 initial phase P and main phase S (Fig.6 inset), causing larger located depth for the M_{cgs}5.5 in Figs.4 and 6). Figure 7 and HypoDD relocation revealed that the main rupture (5.0km depth) followed the initial rupture (M~3 at 4.8km depth)

CGS 286 events in a 5-month period before the Orkney M_{cgs}5.5 CGS 920 events in a 5-month period after the Orkney M_{cgs}5.5





Typical mining induced events (e.g. 2005 M5.3):
Normal faulting.
NE-SW strike.
On mining level.

The M_{cgs}5.5 event on 5 Aug .2014.
Strike slip.
NNW-SSE strike almost parallel to σ_{Hmax} direction.
Below mining.

Question:
Tectonic? Mining-induced?
Future seismic hazard?

Sharp planar aftershocks are seen only in the area to **the south of the mainshock** hypocenter.

The M_{cgs}5.5 also activated **seismicity in the flooded mines** (2-3 km depth) to the **north of the M_{cgs}5.5** hypocenter.

SATREPS 3strainmeters at 2.8 and 2.9 km depths (100Hz continuous) and in-mine 4.5Hz-geophone network (2-3 depths; 6kHz A/D; event trigger recording) are to be integrated.

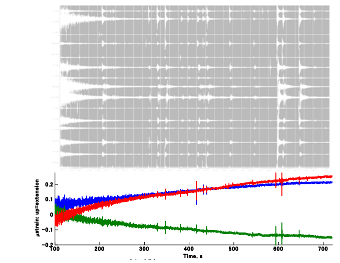


Fig. 5. Surface CGS strong motion (upper) and 2.9km-depth SATREPS strainmeter (lower) seismograms in 10 minutes following the M_{cgs}5.5.

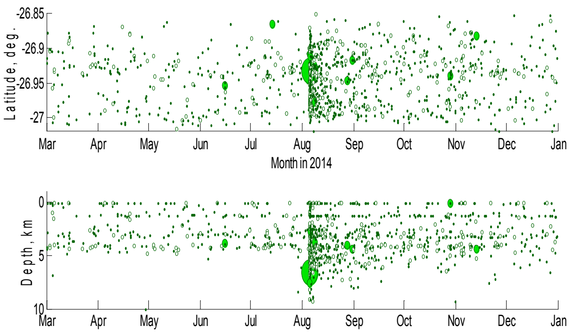


Fig. 6. Time-latitude (upper) and time-depth (lower) plots of .1206 CGS events.

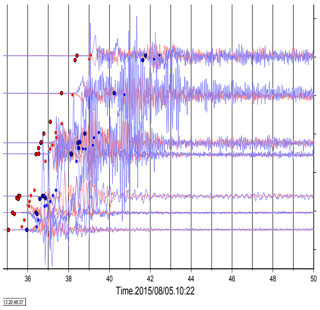
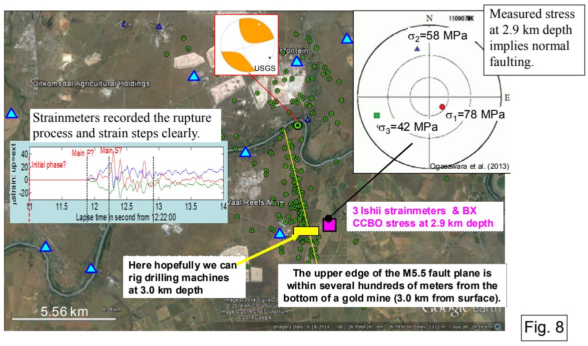


Fig. 7. M~3 Initial and main phases in CGS strong motion recordings (by MO).

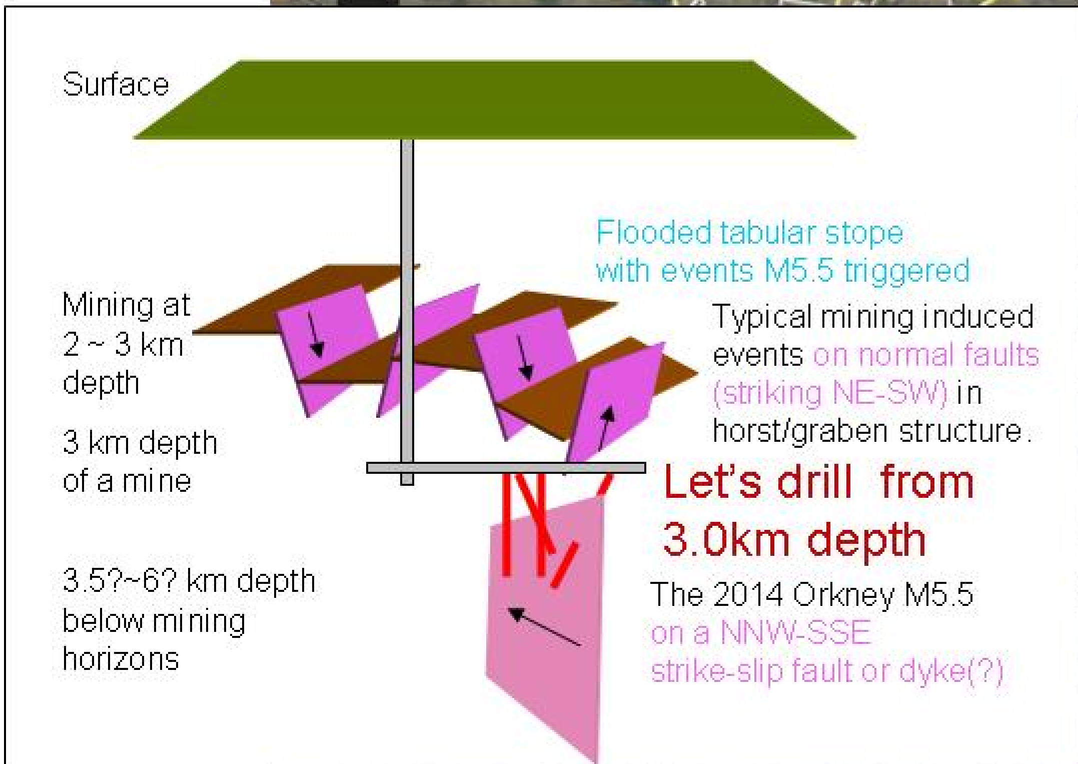


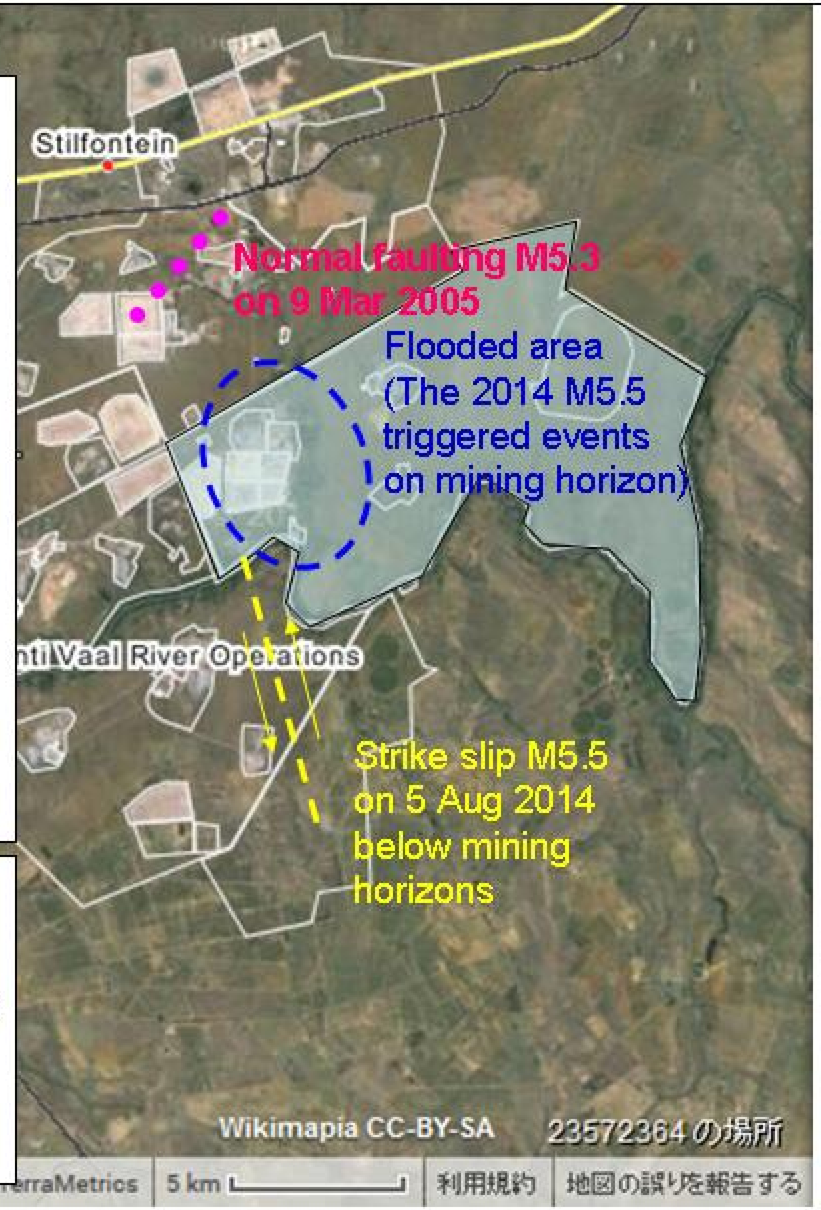
This is a **rare opportunity that we may be able to drill holes from 3km depth**, a bottom level of a mine. The M_{cgs}5.5 didn’t cause serious damage on mining levels because the event was significantly deeper. It’ll be very interesting to probe geology, mechanical property, in-situ stress, and pore pressure around the fault in the holes. Post-drilling monitoring with strainmeters, pore pressure sensors, and geophones will allow us to discuss loading and strength recovery of the faults. Some of us and specialists of deep-hole drilling and monitoring have submitted an ICDP workshop proposal to discuss in depth scientific objectives and drilling strategy. We hope the proposal will be approved to let us show some update at the workshop (hopefully in South Africa in September). Please let me know if you are interested in participation of the workshop. We will keep you updated.

We thank the late Gilbert Morema, Raymond Vermeulen, Thabang Masakale, Johan Oelofse, and mine employees for their kind, consistent assistance.

Reference: Ogasawara et al. (ARMA2014; DeepMining 2014), Nakatani et al. (SRL2008), Yabe et al. (EPS2009; RS2013), Hofmann et al. (SHIRMS2012, RS2013).

Let's hope ICDP workshop is approved to discuss scientific objectives and the best strategy of drilling from 3.0km depth





1972 M4.7	1982 M4.6	1984 M4.1	1996 M4.2
1973 M4.8	1983 M5.1	1986 M4.8	1997 M4.4
1977 M5.2	1983 M4.3	1987 M4.9	1997 M3.8
1978 M4.5	1983 M4.0	1987 M4.5	1997 M4.0
1980 M4.9	1983 M4.0	1988 M4.3	2001 M4.2
1981 M4.8	1984 M5.0	1988 M4.4	2004 M4.9
1981 M4.9	1984 M4.8	1989 M4.4	2005 M5.3

Geophone only before 2010

2010 DMR CGS strong motion meters

SATREPS

2014 M5.5

ICDP Workshop Proposal submitted to ICDP on 15 January 2015

Title: Drilling into seismogenic zones of M2.0 – M5.5 earthquakes in deep South African gold mines (DSeis)

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Keywords: Earthquake physics, seismogenic zone, 3D stress tensor, Orkney M5.5
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Abstract

Several times a year, mining-induced earthquakes with magnitudes equal to or larger than 2 take place only a few tens of meters away from active workings in South African gold mines at depths of up to 3.4 km. The largest event recorded around mining region, a M5.5 earthquake, took place near Orkney, South Africa on 5 August 2014, with the upper edge of the activated fault being only some hundred meters below the nearest mine workings (3.0 km depth). This is one of the rare events for which detailed seismological data are available, both from surface and underground seismometers and strainmeters, allowing for a detailed seismological analysis and comparison with in-situ observed data. Therefore, this earthquake calls for rapid response drilling to investigate the physics of seismic source zones. Such project will have a significantly better spatial coverage (including nuclei of ruptures, strong motion sources, asperities, and rupture edges) than drilling in seismogenic zones of natural large earthquakes and will be possible with a lower risk and at much smaller costs.

In seismogenic zones in a critical state of stress, it is difficult to delineate local spatial variation in both directions and magnitudes of principal stresses (3D full stress tensor) reliably. However, we have overcome this problem. We are able to numerically model stress better than before, enabling us to orientate boreholes so that the chance of stress-induced damage is minimized, and enabling us to measure 3D full stress tensor successively reliably even when stresses are as large as those expected in seismogenic zones. Better recovery of cores with less stress-induced damage is also feasible. These will allow us to address a key scientific question in earthquake physics, namely the stress and strength in seismogenic zones, which have remained elusive.

We propose to hold a 4-day workshop to plan scientific drilling into the very recently activated fault zone near Orkney, South Africa to obtain for the first time 3D in situ stress tensor measurements. The meeting will serve to clarify key scientific objectives of the project; to discuss technical feasibility and best strategy of drilling, identify best possible drill sites; discuss logging, stress measurements, and monitoring; and review on-going and previous seismological projects in South African gold mines and in other related research. We intend to invite researchers from several disciplines and several countries. The workshop will be held in South Africa (Witwatersrand basin) in the third quarter of 2015.

Scientific Objectives

Our aim is to study earthquake physics in the seismogenic zone of M2 – M5.5 earthquake with better spatial coverage. We also aim to understand how well the real stress states are reproduced by seismological analysis and numerical stress modelling. M2 seismogenic zones, probably dry, within tens of meters from mine workings are different in rupture size and drilling distance and difficulty from the M5.5 seismogenic zone, potentially wet. These combined efforts will inform us scale dependency and complement of the M5.5 study and its strategy. Furthermore, our planned work will include:

(1) DIRECT MEASUREMENT of the 3D FULL STRESS TENSOR in boreholes that have been orientated to minimize the chance of stress-induced damage.

(2) INTEGRATED STRESS ANALYSIS of hydro-fracturing and other information that we will compare with the results obtained through direct measurements, borehole logging and core investigation.

(3) ANALYSIS of AVAILABLE SEISMIC DATA to delineate co- and post-seismic rupture processes, strong motion sources, stress inversion, spatio-temporal variation of stress drop, Coulomb failure stress, b-value, and pore pressure to compare with the results of drilling and measurements.

(4) TESTING of HYOPOTHETICAL SOURCE MECHANISMS that explain why the M5.5 event took place at a depth significantly larger than the mining horizon with a faulting mechanism different from nearby mining induced events.

(5) INSTALLATION of SENSORS CLOSE to the M5.5 FAULT to monitor seismicity, and spatio-temporal changes in strain, pore pressure, and velocity structure. These measurements will enable us to determine background rates and investigate fault-healing effects and sources of stress perturbations.