This pdf file contains:

- **p. 1-5**: a preliminary translation of J-DESC News, which will be published in Japanese soon, on **the DSeis-PROTEA meeting, held at the University of the Witwatersrand, Johannesburg, from 22 to 24 January**.
- **p. 6**: a copy of our **poster presented at ICDP 25+ conference in July 2023**.

Yabe and Ogasawara will also report on some of the DSeis results and PROTEA perspectives during EGU 2024 on 16 April 2024.

EGU24-3723 Yabe et al.

EGU24-14233 Ogasawara et al.

Yabe, Ogasawara, Kieft, Castillo and Fujita will report at JpGU 2024. A follow-up meeting is planned for 3 June 2024 at the Ritsumeikan Campus in Tokyo.

A new window to study seismogenic zones and deep life opened by scientific drilling at a deep South African gold mine

Yasuo Yabe (Tohoku Univ.) and Hiroshi Ogasawara (Ritsumeikan Univ.)

A research meeting was held to report on the results of the ICDP DSeis (Drilling into seismogenic zones of M2.0-M5.5 earthquakes in deep South Africa gold mines) project. This project has completed full core drilling from a depth of 2.9 km into the upper margin of the aftershock zone of the 2014 Orkney M5.5 earthquake, followed by studies in seismogenic zone and deep life. Based on the results, its successor, PROTEA (Probing the heart of an earthquake and life in the deep subsurface), was proposed. A total of 64 participants from seven countries (Photo 1) met at the University of the Witwatersrand (Johannesburg, South Africa) from 22 to 24 January for lively discussions both in person and online.

Johannesburg, where the research meeting was held, is located at the northern end of the 300 km by 150 km Witwatersrand Basin, which extends from east-northeast to west-southwest, and the DSeis project drill site is on the northwestern margin of this basin.

The drill site (Photo 2) is located at a depth of 2.9 km in marine and terrestrial sedimentary hard rock formations with a thickness of several kilometers that were deposited on a granitic basement between 2.9 and 2.8 billion years ago. The uppermost part of the sedimentary sequence hosts economic gold reefs in conglomerate; 2.7 billion years ago, a northeast-southwest trending rift zone developed with supercontinental break-up and was overlain by flood lava. Two billion years ago, in addition to new igneous activity, the oldest and largest known meteorite impact (the Vredefort impact) disturbed the basin structure. The most significant geological event after this was the igneous activity during the Gondwana continental break-up.

After World War II, gold deposits were found 2-3 km underground in the northern and western margins of the basin. An M5.5 earthquake occurred on 5 August 2014 in the Orkney area, approximately 160 km south-west of Johannesburg. Data analysis from the South African National Seismic Network (strong-motion meters on surface) and the mine's underground seismic networks indicate that the hypocenter of this earthquake was deeper than the Moab Khotsong mine workings above, and that the seismic focal mechanism solution was a NNW-SSE strike-slip fault, as opposed to a mine-induced earthquake (NE-SW normal faulting for larger events). There is also a clear gap between the upper end of the aftershock activity and the induced seismicity around the mining horizons, although the upper end of the aftershock activity is only a few hundred meters below the deepest tunnel of the mine (depth about 3 km). The rupture of the mainshock extended to a depth of 7 km. The Orkney earthquake is therefore considered to be a tectonic earthquake. As in many large earthquakes, we can see segregation among large slip zones, strong-motion generating zones and aftershock zones. The seismic focal mechanism solution for the aftershocks also suggested a change in stress regime with depth. Re-analysis of 3D seismic reflection data acquired prior to the mine development revealed a number of reflection surfaces in the aftershock zone that may represent intrusive rocks.

Critical samples from the upper margin of the aftershock zone and the Onstott dike were selected from a total of approximately 1.6 km of core samples and analyzed in a joint project between ETH Zurich, University of the Witwatersrand, Osaka University, , Hiroshima University, Tohoku University, Ritsumeikan University, Kyoto University and the International Research Institute for Marine Cores, Kochi University. In addition, geomicrobiologists from the USA and South Africa studied the hypersaline brine in the Onstott Dike. As a result, we found the following:

(1) A larger number of aftershocks are located parallel to the intersections of sills crosscut by the lamprophyre dike formed by partial melting of the upper mantle beneath a continent. These are metamorphosed and hydrothermally altered under temperature and pressure conditions similar to those at the base of the seismogenic depth interval beneath the Japanese islands. The crosscut sills and sedimentary hard rock formations, which dip ~20 degrees to the south-east, have different chemical and mineral compositions, resulting in parallel bands with variable rheology.

(2) Shear stresses determined from the elliptical cross-sectional profiles of the core samples show significant spatial variation, being high near the Hole A hypersaline brine and almost zero near the aftershock zone.

(3) The upper margin of the aftershock zone is an altered, talc- and biotite-rich basic intrusive rock (the lamprophyre dike). The friction coefficient under wet conditions is low (0.2-0.3). The frictional properties are velocity-strengthening such that seismic slip (unstable fault slip) cannot occur, but localized unstable slip (aftershock activity) can occur if after-slip is present.

(4) The brine has a near-saturated concentration (24 wt%, Na-Ca-Cl), a temperature of 54 ° C and a pressure of 10 MPa. Based on isotopic ratios of noble gases, it is estimated that it has been isolated from the outside environment for 1.2 billion years. During the isolation over a very long geological time period, H_2O have been decomposed by radiation from the decay of radioactive atoms, resulting in high salinity concentrations.

(5) A low density (about 100 cells/ml), microbial population containing archaea and eubacteria was detected in the brine veins. The microbial community included halophilic eubacteria and their parasitic viruses.

(6) Redox substances such as H2 and NO3 are dissolved in the brine, and short-chain carbohydrates of abionic origin, such as kerogen radiolysis, are also abundant.

PROTEA will attempt 1,800 m of drilling to investigate the physical properties and stress fields in the large slip and strong motion generating zones of the mainshock that were not reached by the DSeis project (Fig. 1). In addition, several boreholes will be drilled to extensively explore the brine fissure to further investigate the subsurface biosphere. PROTEA's preliminary proposal was submitted to the ICDP in January 2024 and we hope that more people will join us to strengthen the plan for the ICDP workshop in 2025 and the drilling proposal in January 2026. We would be grateful if you could help us.

Acknowledgements: the costs of organizing the DSeis-PROTEA meeting were supported by Ritsumeikan University. We would like to thank Professor Raymond Durrheim and all the staff and students of the University of the Witwatersrand for their efforts in facilitating the meeting.

Photo 1: A group photo during the DSeis-PROTEA meeting

Photo 2: DSeis's drilling site at a depth of 2.9 km at the Moab Khotsong mine (Photo by Ogasawara)

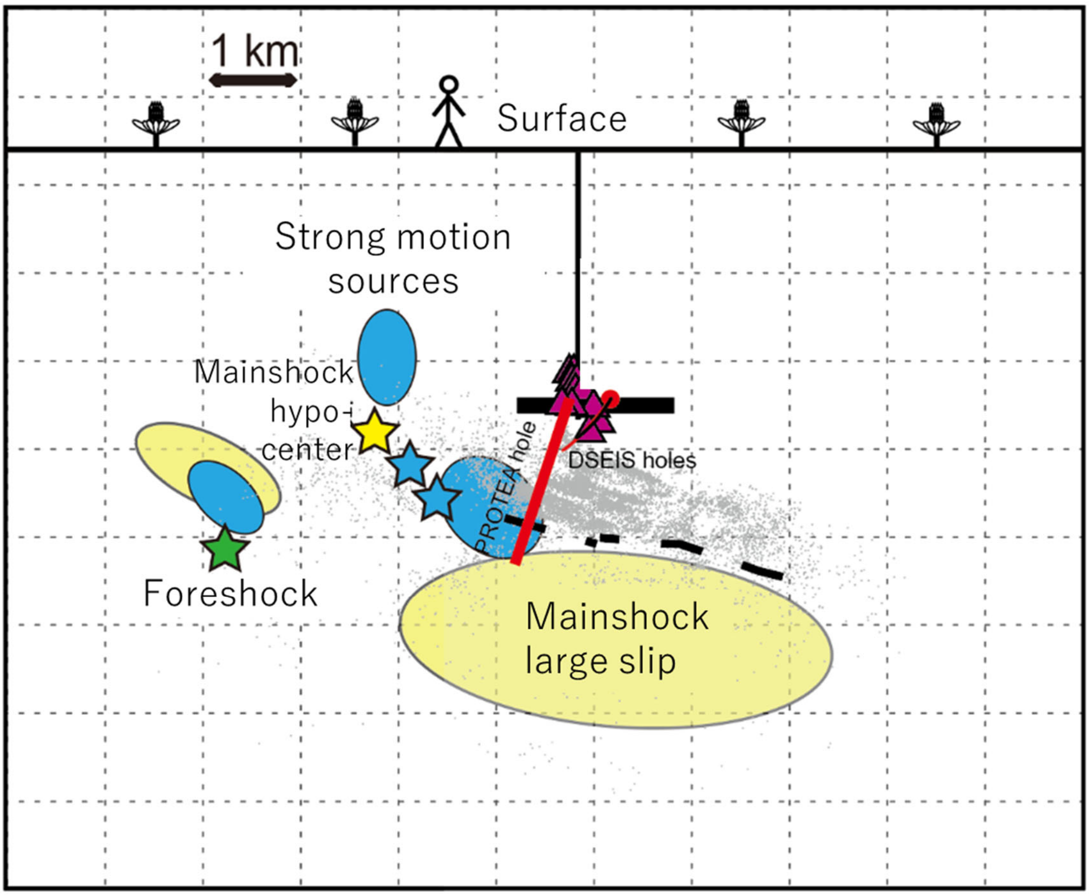


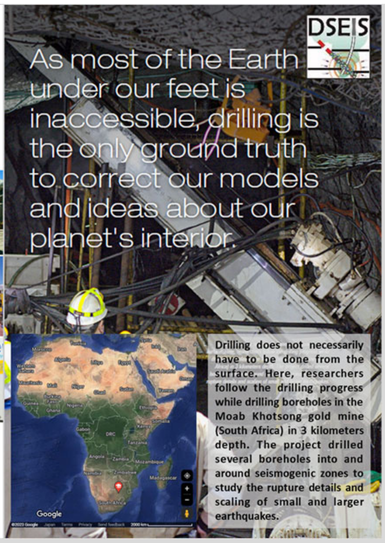
Figure 1: Schematics representing the configuration of the DSeis and PROTEA boreholes (the red thin and thick lines, respectively) and the potential drill targets in a vertical section parallel to the fault plane of the 2014 Orkney M5.5 earthquake. The vertical shaft and horizontal tunnel take us to the drill sites at a depth of 2.9 km from the surface and at a distance of ~ 2 km from the vertical shaft. Small grey dots: the aftershocks of the 2014 Orkney M5.5 earthquake. Purple triangles: the hypersaline brine sites. The green, yellow and blue stars represent the locations of the hypocenters for the foreshock, mainshock and large phases during mainshock, respectively. The ellipsoids in cream represent the area of large fault slip (>70mm) during the mainshock. The ellipsoids in light blue represent the areas of strong motion generated during the mainshock. To invert the spatio-temporal evolution of the mainshock rupture, we have to take into account the complicated 3D seismic velocity field. We will be discussing this very carefully in the forthcoming meetings.

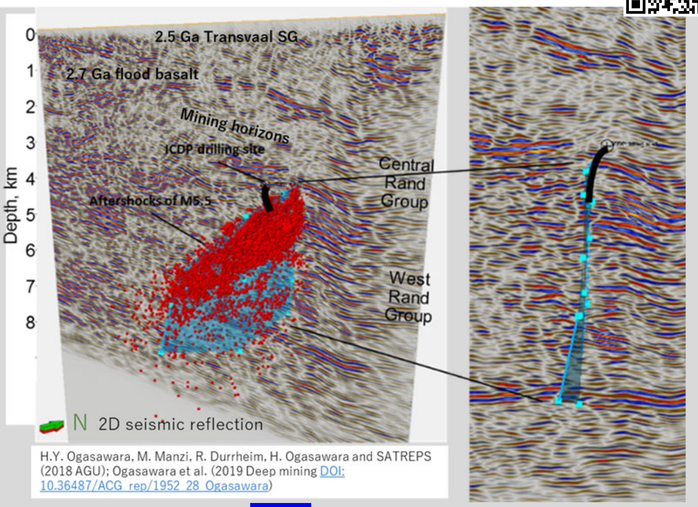
DSeis: Drilling into Seismogenic zones in South African gold mines

Discoveries in earthquake science and deep life.

H. Ogasawara (Ritsumeikan Univ.) and the DSeis team

Modified after "p.1-2, Thrill to Drill"





The Moab Khotsong mine Hole B intersected the aftershock zone; lamprophyre dyke, fault breccia and gouge was recovered.

DSeis milestones

2014 The Orkney M5.5 quake occurred below the mining horizon. It had a strike-slip mechanism, which is unusual for mining-related events. This M5.5 and the other M2~3 seismogenic zones were well located by numerous aftershocks with dense seismic networks.
2016 ICDP approved DSeis.
2017-2018 Drilling started underground at 2.9 km depth. Hole A intersected the 2.9 Ga West Rand Group with Onstott dyke. Hole C sidetracked Hole B. A total of 1.6 km-long continuous NQ core recovery; down hole logging; core stress measurements.
2019 Non-destructive core investigation at KCC; 50 cut discs investigated by XRD, XRF, SEM, frictional test. U-tube system installation; sampling of hypersaline brine.

2020 COVID; no on-site work or core work.
2021 Resume work at KCC in Nov. (XRF core-scan, EPMA, Vp, core stress meas.).

2022-3 Several papers (right QR codes). Further downhole logging. SEM-EDS at Kyoto Univ.
2023 March: frictional experiments; underground visit.
2023 June: New U-tube system installed.

Future
Follow-up journal papers
ICDP operational report
Uncased holes still available to reach the exciting spots.
Preparation to release ICDP data.

Moab Khotsong mine drilling, down hole logging, core physical property

Ogasawara et al. (2019)

Nkosi et al. (2022)

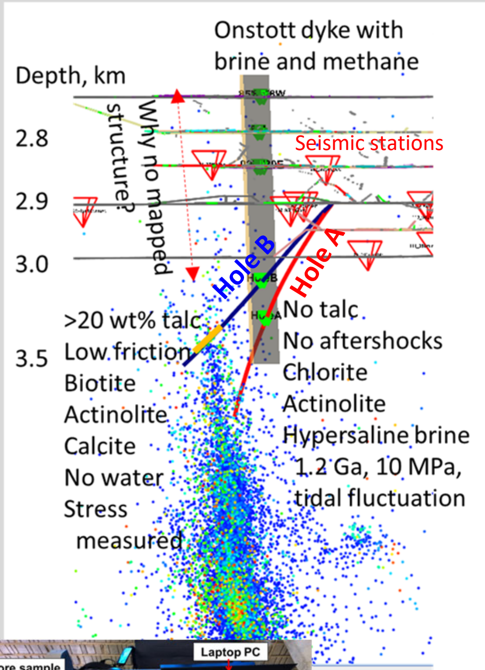
All relevant outputs

Miyamoto et al. (2022)

Seismogenic zones on mine horizons

Mngadi et al. (2021) on fault gauge recovered

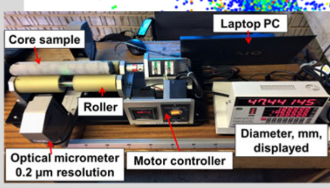
Yabe et al. (2022) on core stress measurements.



Onstott (1955-2021) and his team installed a U-tube system to periodically sample water from Hole A, discovering ancient hypersaline brine summarized in the following two papers.

Nisson et al. (2023)

Warr et al. (2022)



Core ellipticity measurement system to estimate shear stress Funato and Ito (2017) developed.

Surprising and significant discoveries were made in the DSeis holes that penetrated the upper fringe of the M5.5 aftershock zone:

(1) Presence of talc, as well as mineral assemblages expected in the middle crust (Miyamoto et al., 2022; Oba et al. JpGU 2022; Yabe et al. JpGU 2023; Ogasawara et al. JpGU 2023);
(2) Significant spatial variation of stress in the seismogenic zone (Mima et al., JpGU 2022; Yabe et al. 2022);
(3) Aftershocks "streaks" associated with dykes and sills intruded into 2.9 Ga sediments (Suzuki et al., JpGU 2022);
(4) >1 Ga hypersaline brine, potentially an analog of a habitable Martian environment (Warr et al. 2022; Nisson et al., 2023), due to radiolysis of water and silicate weathering.

Acknowledgements: Moab Khotsong mine, Harmony Gold, AngloGold Ashanti, ICDP, JST-JICA SATREPS, JSPS (Kakenhi, Core-to-Core, Int. Bilateral), MEXT Japan, US NSF, NASA, German DFG, SA NRF, CSIR, CGS, Wits. Univ. Ritsumeikan Univ., MaCRI (Kochi Core Center; KCC), Kochi Univ., Kyoto Univ., Hiroshima Univ., NIPR, the SA and Japanese geotechnical firms.