Drilling into Seismogenic zone in South African gold mines

D1019 | EGU2020-12094 | Highlight

The seismogenic zones of M2.0-5.5 earthquakes successfully recovered in deep South African gold mines: the outcomes and the follow-up plan

The M5.5 seismogenic zone, one of DSeis's targets, is >100 times smaller than plate boundaries. Another target, **the seismogenic zone ahead of mining faces** is further several 10s of times smaller than the M5.5 seismogenic zone. However, dense near-field seismic monitoring had probed them in detail during 2010-15, which, DSeis accomplished the drilling and the recovery of invaluable fragile samples during 2017-2019 despite the sudden announcements of mine closures or sales.

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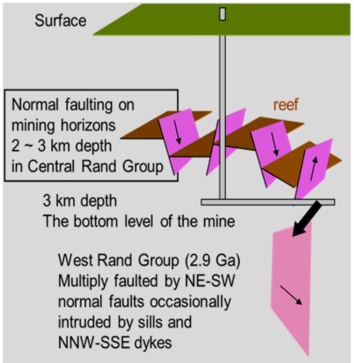
Drilling targets and plan (2007 Mw2.2, 2014 M3.5 and M5.5;

ruptures ahead of thin tabular stopes; EGU2016, EGU 2017, or http://www.seismo.ethz.ch/export/sites/sedsite/research-andteaching/.galleries/pdf_schatzalp/1_Schatzalp2017_Ogasawara.pdf)



This display briefly summarizes the following.

Preliminary results since EGU2019:

Drilling: e.g. Ogasawara et al. (Deep Mining 2019);
Fault material: e.g. Hirono et al. (JpGU 2019, 2020);
Stress measurements: e.g. Yabe et al. (Deep Mining 2019, AGU2019, EGU2020);
Seismic processing: Dinske et al. (2019 EGU); Mori et al. (2019 SSA);
Seismic reflection interpretation: Noda (2020);
Water, gas, and geomicrobiology: Wiersberg et al. (2019 EGU and AGU), Onstott et al. (2019; this display slide 10), Nisson et al. (2019 AGU; slide 11).

A workshop?: it is very critical to summarize and disseminate our outcomes at Kochi Core Center in front of the DSeis core.

Acknowledgements. Finance: ICDP, JPPS, NSF, DFG, NRF, JST-JICA SATREPS, MEXT, Ritsumeikan Univ.
Facilitation: ICDP, AngloGold Ashanti, Harmony Gold, Sibanye Stillwater.

Drilling into Seismogenic zone in South African gold mines

Mainly rotary drilling with ~30m core drilling from surface (SAFOD), while 1.6km full-core drilling from 2.9km depth (DSeis)

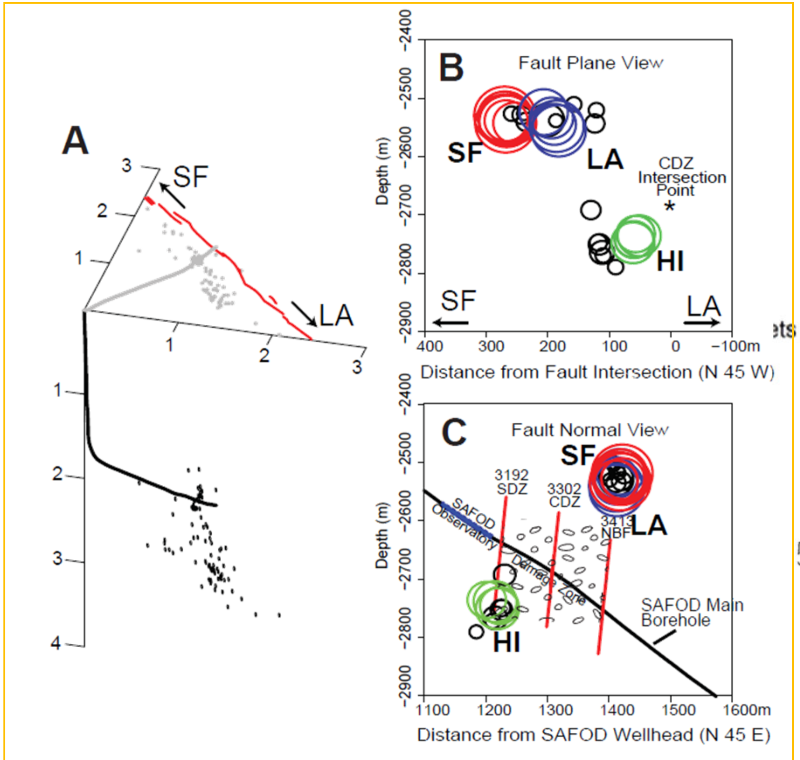


Figure 2. Zoback, M., Hickman, S., Ellsworth, W., and the SAFOD Science Team: Scientific Drilling Into the San Andreas Fault Zone – An Overview of SAFOD's First Five Years, Sci. Dril., 11, 14–28, https://doi.org/10.2204/iodp.sd.11.02.2011, 2011. CC BY 3.0.

▽: CGS's 17 surface strong motion meters. ▽ ▽: AGA 46 underground 4.5Hz geophones
▽: SATREPS 3 underground strainmeters. AngloGold Ashanti (AGA) in-mine seismic data.
★ Ogasawar et al. (2012) measured $s_v > s_{Hmax} > s_{hmin}$ by overcoring.

Seismic information courtesy of Council for Geoscience (CGS) and AngloGold Ashanti (AGA)

Mori et al. (2019 SSA) could invert the <10Hz component of the main shock seismograms to model a finite fault. Higher frequency component was too incoherent to explain. Dinske et al. (2019 EGU) could back-project the mainshock seismograms to illustrate southward rupture propagation and analyze aftershocks compared with mining induced seismicity statistically.

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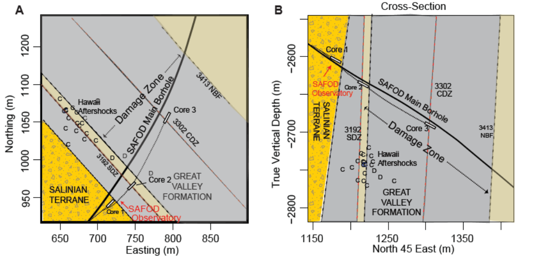
Drilling into Seismogenic zone in South African gold mines

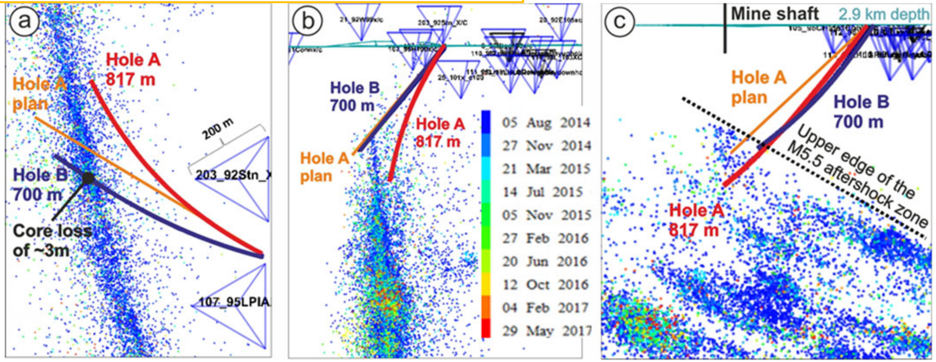
Drilling, downhole logging, installing packer, and monitoring water and gas

M5.5



SAFOD (after Figure 5; Zoback et al. 2011 CC BY 3.0; small boxes: cored sections; others: rotary-drilling)

Successfully minimized borehole instability by drilling in a tension quadrant of the M5.5 sinistral faulting in line with the expected maximum principal stress.



Plan view | M5.5 fault-parallel | M5.5 fault-normal

Full-core drilling in both Holes A and B recovered Roodepoort, Crown, and Babrosco formations (meta- siltstone, quartzite and andesitic basalt) as well as altered dolerite sills and a few m thin dyke, where hypersaline brine was encountered and a packer was installed. Holes B and C (sidetrack; not shown here) intersected an altered lamprophyre dyke, the 2014 M5.5 capable structure, with core-loss and water-loss.

▽: CGS's 17 surface strong motion meters. ▽ ▽: AGA 46 underground 4.5Hz geophones
▽: SATREPS 3 underground strainmeters. AngloGold Ashanti (AGA) in-mine seismic data.
★ Ogasawar et al. (2012) measured $s_v > s_{Hmax} > s_{hmin}$ by overcoring.
Seismic information courtesy of Council for Geoscience (CGS) and AngloGold Ashanti (AGA)

EGU2020-12094 SSP1.4 14pm 5 May Ogasawara et al.

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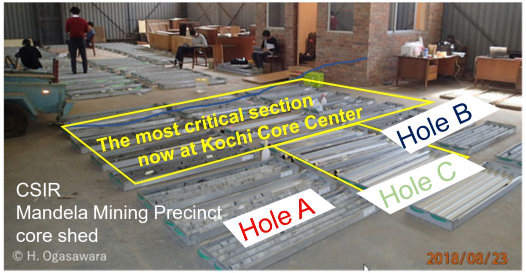
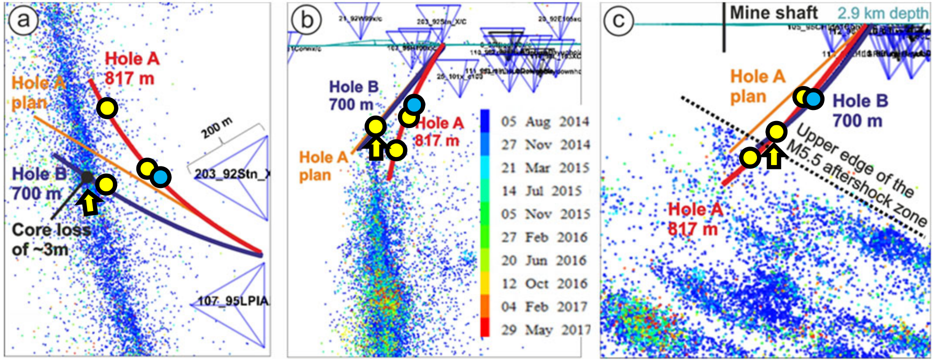
Drilling into Seismogenic zone in South African gold mines

Footprints of DSeis at Moab Khotsong



Successfully minimized borehole instability by drilling in a tension quadrant of the M5.5 sinistral faulting in line with the expected maximum principal stress.



- Higher differential stress was measured (Yabe et al. 2019; EGU 2020).
- Hypersaline brine (10MPa with tidal fluctuation) (Nisson et al. 2019; slide 11)
- Altered lamprophyre dyke was intersected (Hirono et al. 2020 JpGU)

EGU2016

2016: 31 Aug: ICDP approved DSeis full drilling.

2017:

EGU2017

1 Jun: started from 2.9km depth **Hole A** (6m HX casing with 817m NQ2 wire-line full-core drilling);

2 Oct: terminated at 817m from the collar;

4 Nov: started **Hole B** (12m HX casing with 700m NQ2).

2018:

26 Feb: **Hole B** intersected the rupture zone (3m double-tube; core-loss; water-loss);

19 Mar: Terminated **Hole B** at 700m;

EGU2018

24 Apr: **Hole C** (**Hole B** sidetrack; not shown here; 1.5m triple tube) started;

22 Jun: completed **Hole C** 96m;

Aug: **Onstott** and his team as well as **GFZ** team installed water and gas monitoring system.

From Aug: **Ziegler** and **Wits Univ.** team started scanning unrolled optical images for all the 1.6 km core at **CSIR** Mandela Mining Pricinct.

2019:

Apr: completed the unrolled scan;

EGU2019

10 September: Critical cores arrived at **Kochi Core Center** (KCC);

December: completed XRD, XRF, MSCL, X-ray scan.

2020 or 2021: Workshop at KCC?

EGU2020

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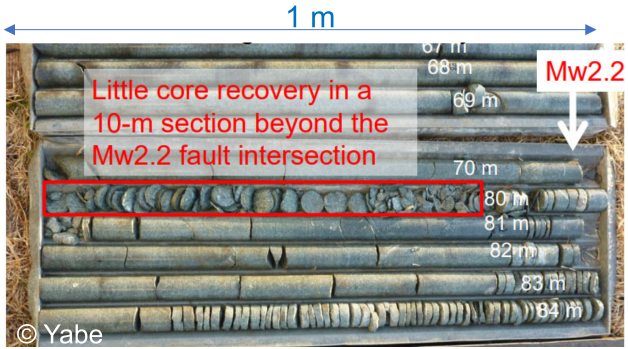
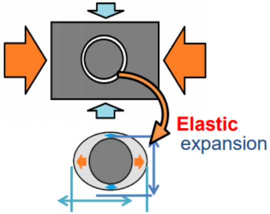
Drilling into Seismogenic zone in South African gold mines

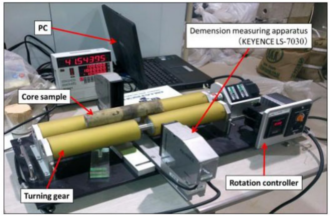
Additional measurements in 2019 with Non-destructive core stress measurements: Diametrical Core Deformation Analysis (DCDA; Funato and Ito, 2017: doi: 10.1016/j.ijrmms.2016.11.002)

- **Principle**
  - Drilling bit cut out cores circularly, followed by non-co-axial elastic expansion in a drilling tube.
  - Measure the variation of shade of the core during being rotated.
- **Measurement resolution: about 0.2 mm in a core diameter (several μstrain for a ~ϕ50mm core)**.
- **Advantage**
  - Only cores longer than 10 and several cm is needed.
  - Several minutes for a measurement in lab.
  - Integrating borehole breakout, we can constrain other stress component.
  - Portable measurement system as a check-in luggage for flight.
- **The other seismogenic zones we have applied**
  - Mw2.2 seismogenic zone at 3.4 km depth at Mponeng mine
  - M3.5 seismogenic zone at 3.4 km depth at Savuka mine



A photo of the core recovered from drilling into the hypocenter of the 2007 Mw2.2 earthquake at 3.4 km depth at Mponeng mine by Yasuo Yabe. The condition of the ground was not suitable for conventional stress measurement methods. Yabe et al. (Deep Mining 2019 doi: 10.36487/ACG_rep/1952_30_Yabe) successfully constrained 3D stress by integrating DCDA, DRA, borehole breakout and core discing.





Measurement system owned by Funato

References: doi:10.36487/ACG_rep/1410_06_Ogasawara, http://www.seismo.ethz.ch/export/sites/sedsite/research-and-teaching/.galleries/pdf_schatzalp/1_Schatzalp2017_Ogasawara.pdf, Yabe et al. (2015; 10.1002/2014JB011680), 10.36487/ACG_rep/1952_30_Yabe

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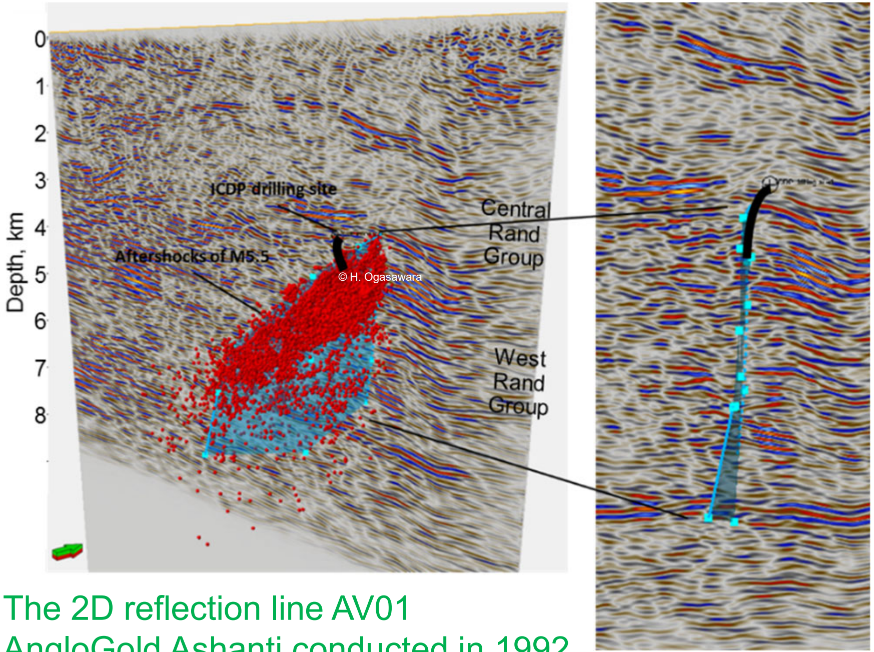
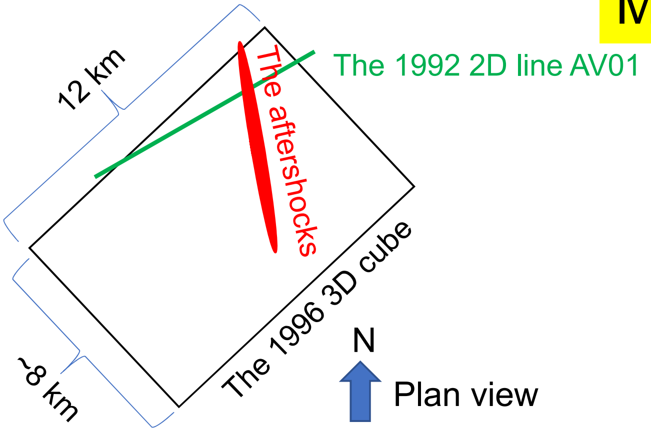
Facilitation: ICDP, AngloGold Ashanti, Harmony Gold, Sibanye Stillwater.

Re-interpretation of legacy seismic reflection data

M5.5



The 2D reflection line AV01 AngloGold Ashanti conducted in 1992.



The 1992 2D seismic reflection data didn't resolve complicated 3D structure although it showed the M5.5 ruptured throughout the West Rand Group (Ogasawara Jr. et al. 2017 AGU; Ogasawara et al. 2019 Deep Mining)

Linzer et al and Manzi et al. (2018) found the 1996 3D cube data that we can still re-interpret, which covered much wider area. Noda (2020) and Ogasawara et al. (2020 JpGU) reinterpreted and found

1. The 2D section of the 3D seismic reflection image was significantly different from those shown in the left figure.
2. The 3D strong reflectors coincided with the sills mapped on the mine's tunnel and DSeis holes intersected, in good agreement with the impedance contrast confirmed in downhole logging in DSeis holes.
3. Some of the reflectors were truncated at the aftershock pane, which suggested the aftershock plane was located at some geological boundary.
4. Such disruption could be traced up to the Transvaal supergroup, near surface.

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Drilling into Seismogenic zone in South African gold mines

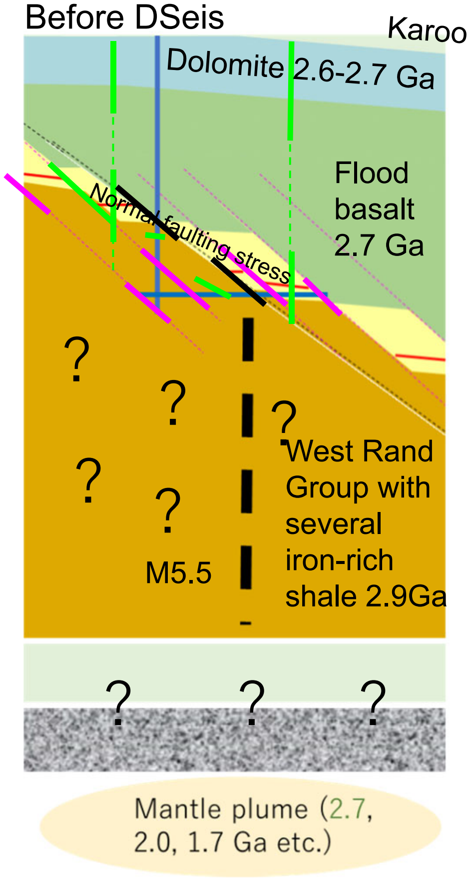
Before DSeis

Well known in Central Rand G

- **Reefs**, **faults**, **dykes**, and etc. intersected by **mine shaft, tunnels, and stopes**;
- Normal-faulting stress.
- **Intrusives** feeding Ventersdorp and younger intrusives;

The unknown

- Why sinistral M5.5?
- Why in **West Rand group**?
- What structure hosted it?
- Water-rock interaction?
- Deep life?

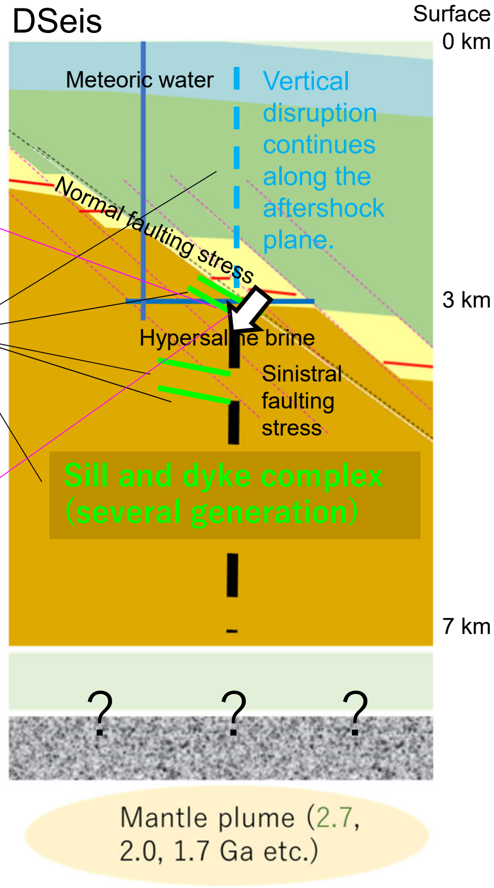


DSeis Drilling intersected dolerite sills, and **lamprophyre dyke**

Geochemical analysis talc and others typically seen at lamprophyre dykes.

3D reflection data Some of the reflectors were at the sills the mine geologists mapped underground.

Hypersaline brine with DOC (similar to those found at Kidd Creek mine or to be found on Mars?) and abiogenic gas found at intrusives (see Slides 10, 11 in this display).



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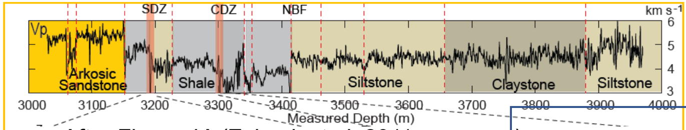
Schematic comparison between DSeis (right) and SAFOD (Left; Zoback et al. 2011)



After Figure 4A (Zoback et al. 2011; CC BY 3.0)

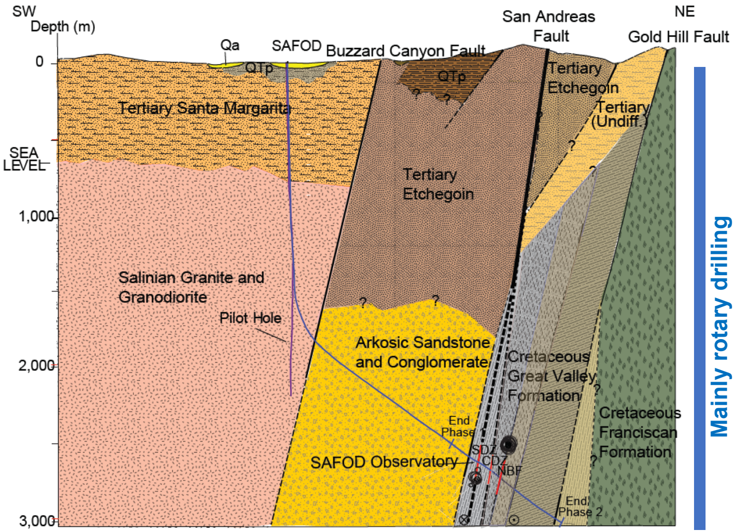
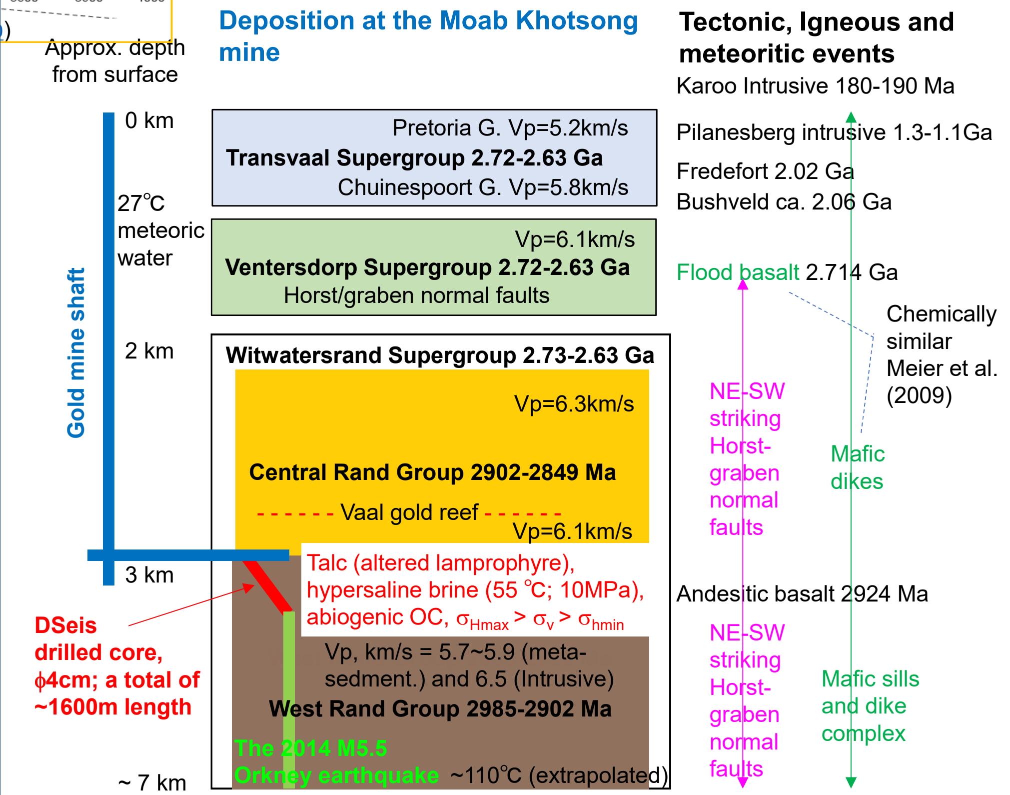


Figure 3. Zoback, M., Hickman, S., Ellsworth, W., and the SAFOD Science Team: Scientific Drilling Into the San Andreas Fault Zone – An Overview of SAFOD's First Five Years, Sci. Dril., 11, 14–28, https://doi.org/10.2204/iodp.sd.11.02.2011, 2011. CC BY 3.0.

A creeping section on the San Andreas fault, a transform plate boundary with subduction of paleo-ridge-structure



Geology data after Frimmel (2002), Dankert and Hein (2020), and the mine. Data of fault material, water, and velocity after Hirono et al. (2020), Onstott et al. (2019 Slide 10) as well as Nisson et al. (2019 Slide 11), and Ogasawara (2018).

Acknowledgements. Finance: ICDP, JPPS, NSF, DFG, NRF, JST-JICA SATREPS, MEXT, Ritsumeikan Univ.
Facilitation: ICDP, AngloGold Ashanti, Harmony Gold, Sibanye Stillwater.

Might it be possible to say DSeis' drilling rig was at a paleo **continental** rift zone corresponding to here??? Let's organize a workshop to discuss cores recovered, stress, seismic processing, altered mantle material, hypersaline water with much DOC, and additional downhole work in existing holes.

A rare invaluable access to the seismogenic zone.

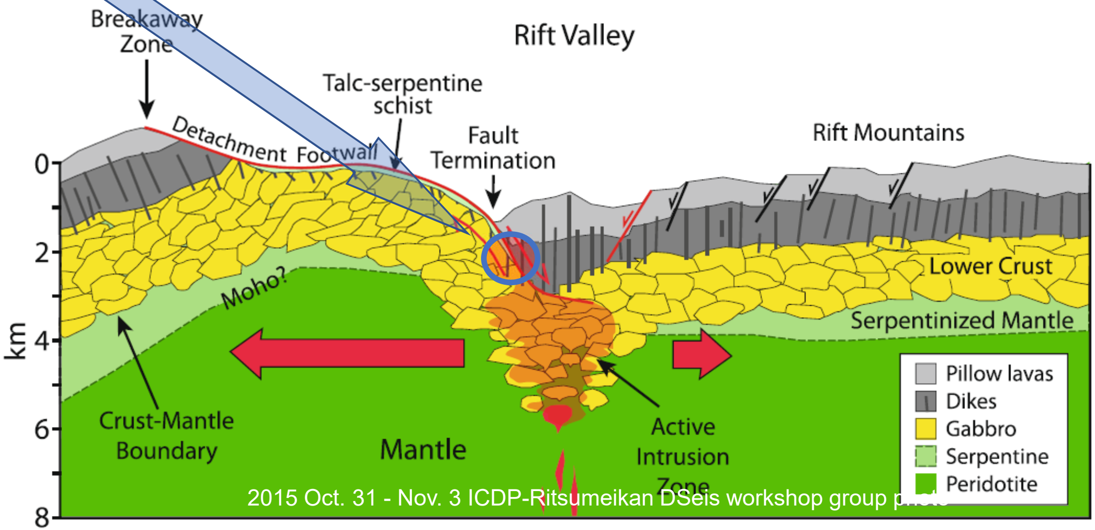


Fig. 1 Cartoon showing formation of an oceanic core complex on a non-conservative "plutonic growth fault," also known as an oceanic detachment fault. Red arrows show spreading asymmetry similar to that documented at Atlantis Bank due to fault capture causing the majority of newly accreted crust to spread to the left in the figure. Talc-serpentine schist (~ 1 m thick) is exaggerated for graphical purposes and is shown intruding along the active detachment fault between the upper crust and the gabbro laterally from where it crosses into mantle peridotite near the transform or a ridge discontinuity

Henry J. B. Dick , Astri J. S. Kvassnes, Paul T. Robinson, Christopher J. MacLeod and Hajimu Kinoshita. ***The Atlantis Bank Gabbro Massif, Southwest Indian Ridge.*** Progress in Earth and Planetary Science (2019) 6:64 https://doi.org/10.1186/s40645-019-0307-9

Acknowledgements. Finance: ICDP, JPPS, NSF, DFG, NRF, JST-JICA SATREPS, MEXT, Ritsumeikan Univ.
Facilitation: ICDP, AngloGold Ashanti, Harmony Gold, Sibanye Stillwater.

Onstott et al. (2019) Abstract, Mars Extant Life: What's Next? (LPI Contrib. No. 2108)

- Earth's deep subsurface is perhaps the closest analogue for the study of Martian habitability, owing to the hypothesized similarity of each planet's subsurface geology and the irrelevance of atmospheric or radiative factors. As such, terrestrial subsurface lithoautotrophic microbial ecosystems (SLiMEs) are a promising area of astrobiological study. Hypersaline subsurface ecosystems are of special interest because of their likely occurrence on present day Mars [1]. During the formation of the cryosphere the fractional crystallization of ground water will form a residual brine. On Earth, salt-saturated brines are mostly associated with Phanerozoic salt deposits and saline ground waters and brines hosted in Precambrian crystalline rocks [2]. At Kidd Creek mine in Canada, brines discovered in ore deposits have been isolated from the surface for billions of years [3] in a setting with a relatively low thermal history (<100° C) for the past 2 billion years. Such brines provide terrestrial analogues to the past and present Martian subsurface, and potentially provide clues as to whether subsurface abiotic organosynthesis reactions lead to the emergence of life.
- In early 2018 we discovered a brine reservoir in the Archean Kaapvaal Craton of South Africa. Samples were collected of high temperature brine from 3.0 to 3.1 km underground in the Moab Khotsong gold mine, South Africa (26.98° S, 26.78° E). The host shale, quartzite, conglomerate, and amygdaloidal lava are referred to as the West Rand Group (a part of the Witwatersrand Supergroup), and were deposited between 3.1 to 2.9 Ga and intruded by 2.7 Ga mafic sills. The brines are associated with the contact zones between the mafic intrusions and host rock and occur between 2.55 km to 3.4 km below ground. Brine temperatures range from 48 to 55ºC and pressures are over 100 bars.
- One sample collected at 3 km depth exhibited high concentrations of Cl^- (4.3 M), Na^+ (1.3 M), and Ca^{2+} (1.5 M), with minor amounts of sulfate (0.8 mM), nitrate (14 μM), total Fe (2.8 mM), Mg (5.3 mM), acetate (30 μM), and formate (198 μM). Another sample at 3.1 kmbls contained high level of Cl- (4.2M), lower concentration of sulfate (0.2 mM), nitrate (7.4 μM), but much greater acetate (259 μM), and formate (684 μM) concentrations. A gas sample collected at 3.1 km was mainly CH_4 (62 vol-%), followed by He (16 vol- %), N_2 (15 vol-%), H_2 (4.8 vol-%), Ar (1.6 vol-%), and higher hydrocarbon gases including alkylsulfides. The carbon isotope signatures of CH_4 and higher hydrocarbon gases suggest an abiogenic gas source produced by water–rock reactions. Epifluorescence microscopy and SEM imaging revealed microbial cells in one borehole at 104 cells/mL. This is noteworthy given the energetic tax imposed by high salinity environments. Moab Khotsong is the only location where subsurface brines have been encountered in the Witwatersrand Basin. The composition of these brines suggests they have likely been isolated from the surface since the Proterozoic, providing a terrestrial analogue to the Martian subsurface. Furthermore, the discovery of living biomass from such hypersaline, deep, and presumably old water, extends the abiotic fringe and could provide clues to the limits of habitable subsurface environments on Mars.

Acknowledgements. Finance: ICDP, JPPS, NSF, DFG, NRF, JST-JICA SATREPS, MEXT, Ritsumeikan Univ.
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Nisson et al. (2019) Abiotic (Prebiotic?) Organic Chemistry in a Potentially Ancient Hypersaline Brine: New Insights on the Limits of Microbial Life Inhabiting 3.1 km Deep Fracture Fluid in South Africa. Abstract, AGU Fall meeting B11K-2202

- Deep subsurface fracture fluid environments are often saline and are associated with elevated temperatures relative to the surface. Consequently, inhabiting microbial life is expected to have adapted to the significant physical and energetic constraints of these environments. As these conditions may be similar to those imposed by subsurface **Martian** environments, characterization of **hypersaline** subsurface habitats may aid in the **search for life** under analogous conditions. The recent discovery of **near saturated brines** 3 km below land surface in the South African gold mine, Moab Khotsong (26.98 S, 26.78 E), presents an opportunity to characterize microbial life in potentially ancient brines hosted within the 3.1-2.9 Ga Witswatersrand Supergroup. To enhance our understanding of how subsurface habitability changes with increasing abiotic constraints, we collected **fracture fluid samples** between 1.2-3.1 km depth from Moab Khotsong.

- Fluid temperature and salinity increased with depth, ranging from **26.7-55° C** and **3-240 ppt**, respectively, with pressures >100 bars at deeper levels. Isotopic signatures for **δ2H/δ18O** of the deeper brines plot **far from the global meteoric water** line consistent with removal of water by low temperature clay formation reactions. Gas composition by GC-MS revealed a predominance of methane and ethane within **C1-5 hydrocarbon** compounds, but **a lack of C6+ hydrocarbons**, also suggestive of fluid derived from a more abiotic end member. The gases contained a suite of odorous C2-5 alkyl sulfides that may be sustained by **thermochemical sulfate reduction**; however, this is inconsistent with **the paucity of H2S**. The δ2H and δ13C values for C2-3 hydrocarbons relative to that of methane suggest their production dominantly occurs via **abiogenic polymerization** from **water-rock interactions**. Initial metagenomic analysis revealed similar lithoautotrophic communities between shallower fluid and the deep brines, with the latter containing **a higher relative abundance of halophiles and thermophiles.** These preliminary results suggest fluids, whose chemical composition has been long affected by water-rock interaction, do impose constraints strong enough to alter microbial composition and functionality within the subsurface, and may lend insight to habitability of the Martian subsurface.

Acknowledgements. Finance: ICDP, JPPS, NSF, DFG, NRF, JST-JICA SATREPS, MEXT, Ritsumeikan Univ.
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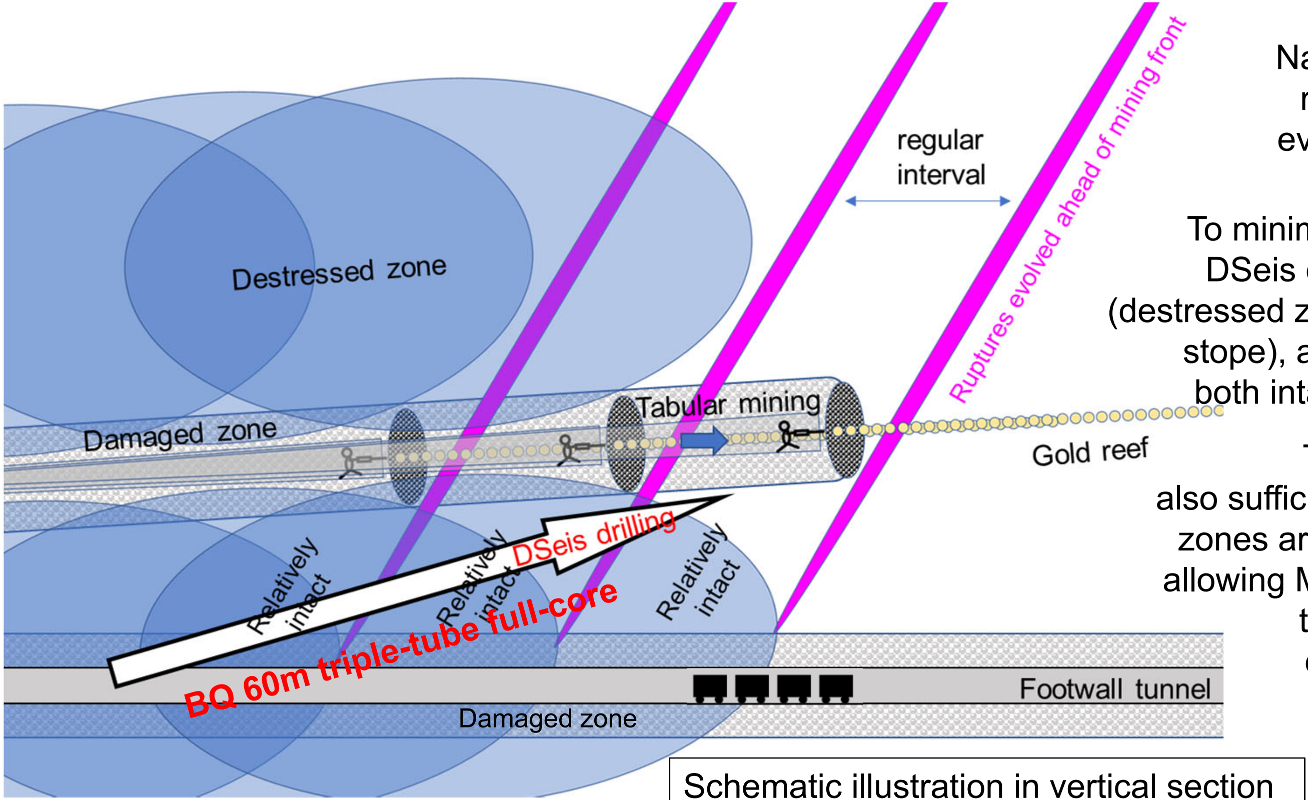
DSeis accomplished recovering intact country rock and fault material (gouge and breccia). Mngadi et al. (2019 AGU) found interesting frictional characteristics.

On mining horizon



Schematic illustration in vertical section

With a dense AE network Naoi et al. (2015) elucidated the ruptures with a regular interval evolved ahead of the advancing mining faces.

To minimize drilling-induced damage, DSeis drilled a hole in stress shade (destressed zone below the tabular mining stope), accomplishing the recovery of both intact country rock and ruptures

The recovered samples were also sufficiently away from the damage zones around the stope or the tunnel, allowing Mngadi et al. (2019 AGU; see the next slide) to look into the difference between rock-rock friction and naturally generated fault material.

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Mndadi et al. (2019) The effect of gouge formation on fault propagation along underground brittle shear fractures. Abstract, AGU Fall meeting, NH11D-0805

- Mining at deep and high-stress levels induces stress fracturing around and ahead of the mining stope, with the Ortlepp shears occurring tens of meters ahead of the mining front. These brittle shear fractures are particularly prone to large damaging seismic events Mw1-4. Moriya et al. (2015) and co-workers used acoustic emissions (AEs) down to Mw -5 to delineate these brittle shear fractures, several tens of meters across, and reveal that they resemble "Ortlepp shears".
- ICDP DSeis allowed us to drill and recover the ruptured rock mass from the remnant shaft pillar at 1 km depth, at Cooke 4 gold mine, South Africa. The mine used to be subjected to vertical stress as large as those of virgin ground comparable to depths of ~3-4 km. **To minimise drilling-induced damage**, we recovered the ruptured rock mass after the mine completed overstoping, relieving stress in the rock mass almost entirely. We used **a 1.5m-long triple-tube core-barrel with metal split spoons to maximise recovery** of **rock volume with the fractures recently formed including fragile breccia and fault gouge** (commonly referred to as 'rock flour' in South African gold mines).
- We present physical observations of recovered core samples, recent rupture surfaces, rock and gouge chemistry, and slip-friction-experiments **at low-to-high velocity (~1.0 mms-1 to 1200 mms-**1), typical of underground Ortlepp shears and tectonic earthquakes. The recovered competent and brittle host rocks are quartzite, pebbly quartzite, argillaceous quartzite and conglomerate, which form part of the lower Elsburg Individuals members of the Central Rand, Witwatersrand Basin, which is the world's biggest gold deposit. These host rocks are mainly composed of quartz (62.2 – 96.2 wt%) and muscovite (2.9 – 37.6 wt%), while mapped brittle shear fractures are primarily characterised by fault gouge-rock powder, rock fragments and angular rough rupture surfaces. The fault gouge rock powder and rock fragments also contain predominantly quartz and muscovite minerals, similar to host rocks.
- At high slip velocities (~400mms-1 - 1200mms-1) friction experiments reveal that:
  - (a) friction is significantly lower at steady-state;
  - (b) the steady-state friction coefficients approaches 0.26; and
  - (c) friction is highly dependent on velocity.
- Remarkably, **the gouge samples** and **the rock-to-rock samples** showed **a difference in the weakening behavior** at **intermediate to high slip velocities**. The rock-to-rock experiments revealed **an unexpected sudden decrease at lower slip velocities** compared to gouge experiments, in the process generating larger than expected volumes of rock powder for competent quartz-rocks. We, therefore, propose that the rate of gouge formation may control fault rupture propagation processes along underground brittle shear fractures. If the fault gouge rock powder is formed quickly, strengthening of the fault (or brittle shear fracture) may occur, and temporarily prevents the weakening process at low to high slip velocities (~10 - 100mms-1). However, if there is initially very little to no fault gouge rock powder during fault propagation, fault frictional strength will weaken faster. Here we suggest that we can predict brittle shear fracture rupture propagation process along an underground brittle shear fracture from conducting low, intermediate to high-velocity friction experiments of both the gouge and rock on rock experiments. These findings should have important implications for the rupture propagation processes along the shear zones.

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DSeis team wishes to get together again soon

2015 Oct. 31 - Nov. 3 ICDP-Ritsumeikan DSeis workshop group photo

2018

A photo by Wiersberg

2018

In 2019 at Kochi Core Center. Left: micro-focus CT, right: a photo during medical X-ray CT scanning.

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