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M.Sc. Thesis Proposal suggested to the ICDP DSeis Project

Characterisation of fractures, lithology and stress state along boreholes drilled at a deep South African gold mine using core and geophysical logs

Project Framework

At the Moab Khotsong gold mine from AngloGold Ashanti at Orkney, south of Klerksdorp (North West Province, South Africa) a M5.5 earthquake took place on 5th August 2014. The M5.5 earthquake and its aftershocks, which are still ongoing, locate between 3.5 km and 7 km below ground surface with left-lateral strike-slip faulting mechanisms on an unknown geological structure striking NNW-SSE and dipping nearly vertically. Thus, the upper edge of the activated fault is only some hundred meters below the nearest mine workings at 3 km depth.

Mining-induced alteration of the state of stress and the causes of mine seismicity in general are hot topics that warrant research in South Africa's deep mines (e.g., Durrheim 2010, Hofmann et al. 2013, van Aswegen 2013, and Ogasawara et al. 2015, and references cited therein). Within the frame of the proposed ICDP project *Drilling into seismogenic zones of M2.0 – M5.5 earthquakes in deep South African gold mines* (DSeis; Ogasawara et al. 2015) several long boreholes will be drilled downwards from the mining level depth at about 3 km below ground and fully cored with double- and/or triple-tube core barrels. The proposed boreholes aim at penetrating the M5.5 seismic source zone. Manifold seismic and borehole analyses are planned and aim at characterising and investigating the earthquake's source zone and the geological setting (lithology, stress state, etc.) in order to understand the origin and the processes that led to the Orkney earthquake. In addition, the characterisation of the lithology, rock mass fractures (joints and faults), and the stress state within and surrounding deep ore bodies is an important part in the geological assessment and hazard assessment of deep South African gold mines. The obtained datasets will help to constrain geological and geomechanical models necessary for better understanding of the seismicity recorded at Orkney.

Lithological and fracture data can be derived from oriented cores and borehole logs (e.g., Ziegler et al. 2015; Figure 1). Since deep and unsupported boreholes are prone to borehole collapse relatively soon after drilling (e.g., due to stress-induced and structurally-controlled borehole closure) core logging is essential and at best can be complemented with data from a geophysical borehole logging campaign (including borehole geometry, spectral gamma, porosity, density, p- and s-wave velocity logging etc.) carried out immediately after the borehole has been drilled. Stress state data can come from various sources and scales, such as local *in situ* stress measurements (e.g., utilising hydraulic fracturing and overcoring techniques carried out in boreholes), analyses of borehole logs (e.g., borehole breakouts and induced tensile fractures), measurements on cores (see, e.g., summary by Zang and Stephansson 2010), and fault plane solutions at larger scales. The primary stress measurement techniques suggested at the Moab Khotsong mine will be overcoring utilising the Compact Conical-ended Borehole Overcoring technique (CCBO; e.g., Ogasawara et al. 2014)

in short upwards-drilled boreholes and stress measurements on cores utilising the Diametrical Core Deformation Analysis (DCDA; e.g., Funato et al. 2012, Ito et al. 2013) derived from long downwards-drilled boreholes. In order to reduce stress-induced borehole breakouts (and core disking) the borehole trajectories will be optimized (i.e., boreholes will be aligned based on the best estimate of the local stress orientation in order to reduce differential stresses perpendicular to the borehole axes). Despite the expected low stress-induced damage of cores and boreholes, it is advantageous to complement rock stress estimations (see above) with *in situ* stress inferred from analyses of borehole logs (borehole breakouts and induced tensile fractures; Figure 2 left) and rock cores (e.g., disking and petal fractures; Figure 2 right) if applicable. If distinct stress-induced core damage or borehole sections with low core recovery are observed, then stress estimates obtained from measurements carried out on only intact core sections may deliver an incomplete picture of the stresses acting in the penetrated rock mass.

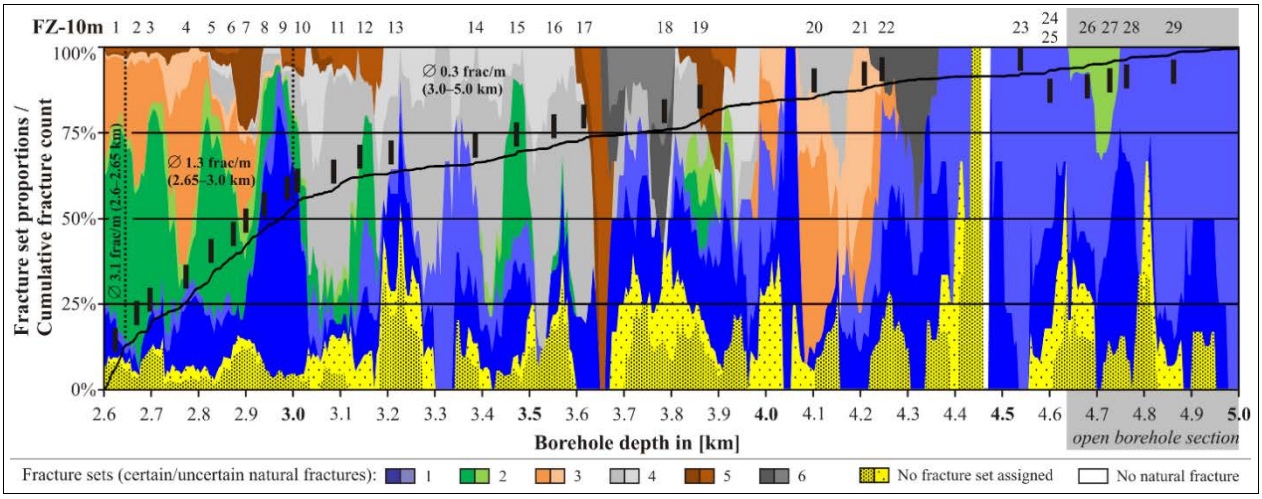

Figure 1: Example of a fracture dataset obtained from the analysis of a 2.4 km long ultrasonic image log run in the Basel-1 petrothermal borehole, which penetrates the crystalline basement of Northern Switzerland (Ziegler et al. 2015). Fracture set disposition and cumulated fracture count versus depth are shown. Calculation of fracture set proportions was done using a 50 m long sliding window. Black bars indicate the locations of zones of high fracture frequency (FZ-10m); some of these zones may indicate fault zones.

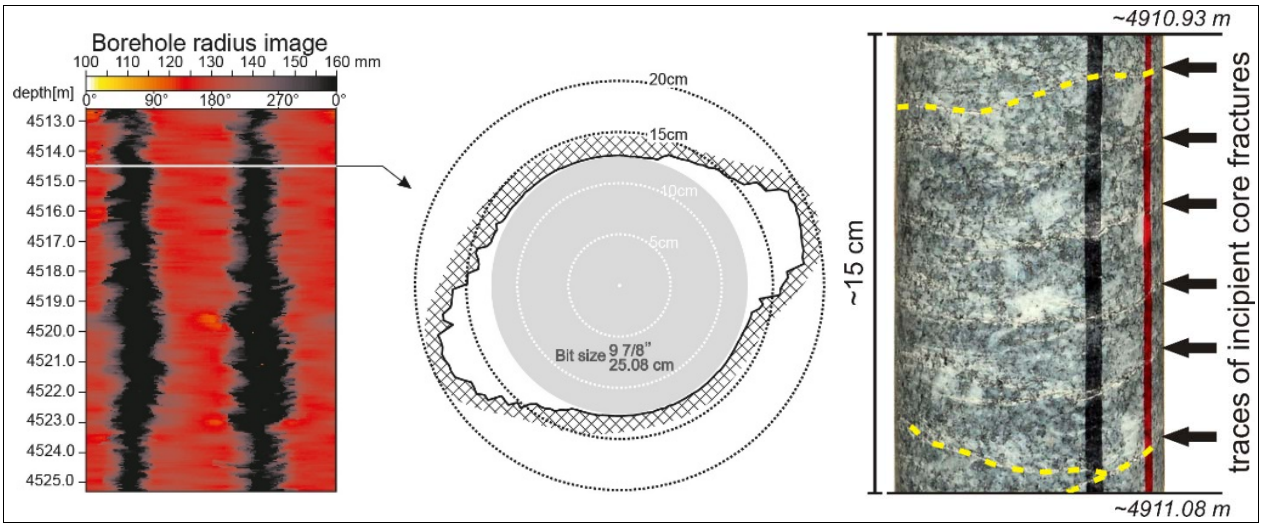

Figure 2: left: Example of borehole breakouts (BB) in the 5 km deep Basel-1 well identified from a borehole geometry log (Valley and Evans, 2009). The borehole cross-section shows two opposing BB used for determination of the SHmax orientation, which strikes perpendicular with respect to an axes fitted through the BB. right: Example of incipient fractures in the Basel-1 core (photo: Ziegler). The core was obtained from about 4.9 km depth below rig floor. Core disking fractures are indicators of high stress magnitudes. Their shape and spacing may be indicative of the orientation and magnitude of SHmax.

Thesis Goals

This thesis aims at investigating 1) lithology, 2) fault architecture, 3) natural fracture sets, and 4) possible rock stress indicators (borehole breakouts and drilling-induced tensile fractures from borehole logs, and disking fractures in cores) along the intended borehole(s) using core logging and interpretation of borehole geophysical logs. Special emphasis will lie on the identification of faults and characterisation of fault architecture and lithology.

The work load described here is tentative and can be reduced depending on the obtained data and the detail of the analyses, and/or shared with other project partners with common interests. The core analyses carried out in this thesis will help identifying intact core pieces that will be used for follow-up rock mechanical analyses, not part of this thesis.

Proposed Methods

First, we will log cores from (selected) boreholes at Moab Khotsong gold mine. This work will most probably be carried out together with a mine geologist and other project partners. The focus of the logging lies on lithological and structural logging (host rock, dyke, and fault rock composition) and core fracture set characterisation (fracture type, orientation, infill, mineralisation/alteration, roughness, spacing, sets, and stress-induced core fractures). Special emphasis will be put on the characterisation of joints and fault rocks. We will select intact and faulted core samples from different formations for rock mechanical analyses (rock strength, deformability characteristics etc.) to be carried out at the Engineering Geology rock laboratory at ETH Zurich (a second MSc proposal and not part of this thesis) and mineralogical analyses of the selected cores utilising, e.g., light microscopy and XRD analyses (optional).

Second, we will analyse available geophysical logs run in the borehole(s)[1]. The borehole geometry might be investigated using a calliper sonde or an acoustic televiewer sonde. Such data will allow us to determine natural and drilling-induced fractures cutting the borehole, and to identify and characterise borehole breakout locations and geometries at the borehole wall. Geophysical borehole logs will be analysed using Wellcad© (Advanced Logic Technology) and IGOR Pro© (WaveMetrics). Fracture data will be processed with Dips© (RockScience). If available, we will investigate additional logs such as spectral and/or total gamma logs, and characterise faults and fault zones using porosity, density, and acoustic logs.

Finally, the obtained datasets from core and geophysical logging will be compared. All analysis carried out in this MSc thesis are non-destructive, except where core will be taken for mineralogical and rock mechanical analyses after full documentation.

Required Student Skills

We are looking for a student with a background in earth sciences and interested in rock mechanics. The candidate should have good computer skills and willingness to work with a multi-disciplinary team of international researchers and mining geologists. The candidate should have the motivation to spend a few weeks in a deep mine in South Africa.

[1] Borehole geophysical logging sondes have not yet been selected. The logging company might analyse some of the raw data.

MSc Thesis Research Schedule

Month	1*	2	3	4	5	6	7	8
Task (this thesis)	Proposal		Main thesis					
Geological data and further literature review								
Core logging (lithology, fractures)**								
Selection of core samples								
MSc thesis proposal writing								
Natural fracture analysis from borehole geophysical logs								
Borehole breakout and drilling-induced fracture analysis								
Petrographic analysis of selected core (thin sections, XRD)***								
Analysis of spectral/total gamma data								
Core and well-log data comparison								
MSc thesis writing and scientific article preparation								

* MSc thesis at ETH usually start with a proposal in December and last 8 months, field work (core logging etc.) can be carried out earlier
** in collaboration with a mine geologist, the geology department of AngloGold Ashanti, and other project partners
*** optional, likely within the frame of a follow-up proposal on rock (and fracture) mechanical testing

Thesis Supervisors

- Dr. Martin Ziegler (Engineering Geology, ETH Zurich, Switzerland)
- Prof. Simon Löw (Chair Engineering Geology, ETH Zurich, Switzerland)

Co-Referee / Local partners

- Dr. Gerrie van Aswegen (Seismologist; Institute of Mine Seismology, Stellenbosch, South Africa)
- Gerhard Hofmann (Seismologist; AngloGold Ashanti, South Africa)
- Andre Belbin (Geologist; AngloGold Ashanti, South Africa)

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