Stress state in the upper margin of the aftershock zone of the 2014 Orkney earthquake (M5.5), South Africa, estimated from analyses of drill cores and borehole breakouts of ICDP-DSeis drillings

Yasuo Yabe1, Makoto Kanematsu2, Mitsuya Higashi2, Ryogo Tadokoro2, Shunsuke Yoshida2, Kosuke Sugimura3, Hiroshi Ogawara3, Takashi Ito3, Akio Funato4, Martine Ziegler5, Bennie Liebenberg6, Bryan Watson1, Siyadnda Mngadi8, Musa Manzi8, and Raymond Durrheim8

1Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, Sendai, Japan (yasuo.yabe.e2@tohoku.ac.jp)
2Faculty of Science and Engineering, Ritsumeikan University, Kusatsu, Japan
3Institute of Fluid Science, Tohoku University, Sendai, Japan
4Fukada Geological Institute, Tokyo, Japan
5ETH Zurich, Zurich, Swiss
6ICDP-DSeis, Orkney, South Africa
7School of Mining Engineering, University of the Witwatersrand, Johannesburg, South Africa
8School of Geoscience, University of the Witwatersrand, Johannesburg, South Africa

The 2014 Orkney earthquake (M5.5) occurred below the Moab Khotsong gold mine in South Africa. The shallowest aftershocks were located only several hundred meters below the deepest level of the mine. Two boreholes (Holes A (817 m) and B (700 m)) were drilled toward the upper margin of the aftershock zone from a specially excavated chamber at 2.9 km depth by the ICDP-DSeis project. Hole A deflected from the aftershock zone, while Hole B intersected it. Hole C was branched from Hole B to recover more samples from the aftershock zone. Except for the intersection in Hole B, the drill core recovery was ~100%. In-hole geophysical logging, including the surveys of the borehole wall geometry were carried out along the entire length of Hole A, while they could be done only as far as the intersection with the aftershock zone in Hole B due to hole closure. Hole C was not logged.

The focal mechanism solutions of mining induced earthquakes shallower than 3 km are usually of the normal faulting type, while those of the Orkney earthquake and its aftershocks deeper than 3.5 km have a strike-slip signature. In this study, we applied the Deformation Rate Analysis (DRA) and the Diametrical Core Deformation Analysis (DCDA) techniques to rock cores recovered from Holes A, B and C to explore the depth variation in the stress state that would cause the depth variation in the faulting regime. In the DRA, a cyclic loading is applied to a sub-sample cut from a drill core to determine the normal stress in the loading direction from hystereses of the stress-strain curve. We determined the normal stresses in 9 directions at each depth to recover the principal stress state redundantly. However, because it takes much time for sub-sample preparations and loading, we applied this technique only at 3 depths in Hole A. With the DCDA, the
differential stress in the plane normal to a borehole is evaluated from the ellipsoidal cross-sectional shape of the rock cores. Though only the differential stress can be measured by the DCDA, it takes only several minutes for measurement at each depth. We evaluated the differential stress as densely as every several meters along Holes A, B and C.

Rock cores of Hole A were oriented by comparing joints and veins identified on the borehole wall optical-televiewer images and in the cores. Thus, the stress orientations in the plane normal to Hole A can be determined as the orientation of the maximum and the minimum core diameter. The stress orientation is obtained also from the breakout of borehole wall identified by the acoustic televiewer. Further, by combining the differential stress magnitude evaluated by the DCDA and the width of the breakout, magnitudes of the maximum and the minimum compression are estimated. We introduce the depth variations in the stress state along Holes A, B and C, as well as those of in-hole logging data to discuss spatial heterogeneity of stresses in the source region of the Orkney earthquake.