Characteristics of Fault Rocks Within the Aftershock Cloud of the 2014 Orkney Earthquake (M5.5) Beneath the Moab Khotson Gold Mine, South Africa

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Abstract Cores recovered during the International Continental Scientific Drilling Program project “Drilling into Seismogenic zones of M2.0 to M5.5 earthquakes in deep South African Gold Mines” include fault breccia from within the aftershock cloud of the 2014 Orkney earthquake (M5.5). The breccia and surrounding intrusive rocks, probably lamprophyres rich in talc, biotite, calcite, and amphibole, had high magnetic susceptibilities owing to the presence of magnetite. All of these characteristics can be attributed to fluid-related alteration. Both the breccia and the lamprophyres had low friction coefficients and showed evidence of velocity strengthening, which is inconsistent with the occurrence of earthquakes. Variable amounts of talc, biotite, calcite, and amphibole within the lamprophyres might have produced complex frictional properties and spatial heterogeneity of fault stability. The altered lamprophyres may be the host rocks of the 2014 Orkney earthquake, but frictional complexity may have governed the magnitudes of the main- and aftershocks and their distributions.

Plain Language Summary Drilling into seismogenic zones is an important scientific endeavor, not only to advance our understanding of the mechanisms of earthquakes, but also to provide information that will improve the resilience of humankind to these deadly hazards. The International Continental Scientific Drilling Program supported deep drilling into the aftershock region of the 2014 Orkney earthquake (M5.5) and successfully recovered samples of faulted rock material from about 3.3 km depth by drilling from a depth of about 3 km in a South African gold mine. The samples were intensely sheared and rich in talc, which is a weak mineral with a very low friction coefficient. The fault zone probably developed within this talc-rich rock, which would indicate that the earthquake was closely related to a pre-existing weak geological structure. However, other minerals in the fault rocks might also have influenced the spatial heterogeneity of fault stability and earthquake generation.

1. Introduction

The 2014 Orkney earthquake (M5.5) occurred on 5 August 2014 below the Moab Khotson gold mine near Orkney, southwest of Johannesburg, South Africa (Figure 1a; Midzi et al., 2015). The mainshock and aftershocks were clearly recorded at the surface by strong-motion meters operated by the South African Council for Geoscience (Manzunzu et al., 2017; Midzi et al., 2015) and by in-mine geophones and strainmeters (Ogasawara et al., 2017, 2019). Analysis of the seismograms revealed that the hypocenter was 4.7 km below the surface and identified a distinct NNW–SSE striking vertical planar aftershock cloud 3.5–7.0 km below the ground surface (Figure 1b). The strike-slip focal mechanism differs from the mechanisms generally associated with mining-induced seismicity but is consistent with the regional stress field associated with the East African rift system (Manzunzu et al., 2017). The hypocenter was considerably deeper than those of typical of mining-induced
earthquakes (2–3 km below the surface; Ogasawara et al., 2017). Therefore, the mainshock and aftershocks of the 2014 Orkney earthquake might be in response to the regional tectonic stress field.

Although core samples have been recovered from various active faults by numerous drilling projects such as the San Andreas Fault Observatory at Depth project (Zoback et al., 2011) and the Taiwan Chelungpu Fault Drilling project (Ma et al., 2006), to our knowledge, none of those wells reached the seismogenic depths at which regular earthquakes nucleate. Historically, deep mines close to earthquake hypocenters have provided rare opportunities to drill into the focal areas of earthquakes and recover seismogenic fault materials (Durrheim, 2015). Several such wells were recently drilled under the “Drilling into Seismogenic zones of M2.0–5.5 earthquakes in deep South African Gold Mines (DSeis)” project, which commenced in June 2017 and concluded in July 2018. DSeis was supported by the International Continental Scientific Drilling Program (ICDP). The main goals of DSeis were to characterize the in situ stress fields and rocks in and around seismogenic faults and, in particular, to understand the process and mechanism of the 2014 Orkney earthquake (Ogasawara et al., 2017; Voosen, 2017).

Hole A at Moab Khotsong (collared at 2.9 km depth with 817 m drilled length) failed to reach the aftershock cloud of the Orkney earthquake because the borehole deviated from its planned trajectory and ran roughly parallel to the cloud. However, Hole B (drilled length, 700 m) intersected the cloud (Figure 1c), after which it transected a 3.2-m zone of non-recovery of core (hereafter, core-loss zone), loss of drilling fluid, and recovery of clearly damaged core fragments. The spatial relationship of the damaged core zone with the aftershock cloud suggests that it corresponds to the source fault of the 2014 Orkney earthquake (Figure 1c; Ogasawara et al., 2019). The DSeis onsite team undertook post-drilling core logging, downhole logging, and core curation, as documented by Ogasawara et al. (2019) and Nkosi et al. (2022). Except for the core-loss zone, continuous core samples were successfully recovered from Hole B. Subsamples for the analyses of this study were taken from the Hole B cores at downhole distances between 530 and 660 m below the drill collar (hereafter, all core positions are downhole distances).

The core and fault-related samples from Hole B were the first to be retrieved from within the aftershock cloud of a $M > 5$ natural tectonic earthquake and provide a rare opportunity to improve our understanding of the nucleation processes of seismic events. In this paper, we present a preliminary data set from the recovered core samples and discuss the relationship between the generation of the 2014 Orkney earthquake and the damaged zone.

2. Materials

2.1. Overview of Geology at the Mine Site

The Moab Khotsong gold mine exploits the Vaal Reef, a gold-bearing quartz-pebble conglomerate in the Central Rand Group of the Witwatersrand Supergroup (Figure 1a; Catuneanu & Biddulph, 2001; Dankert & Hein, 2010; Frimmel & Minter, 2002). The deepest formations exposed in the Moab Khotsong mine include the uppermost formations of the underlying West Rand Group (Ogasawara et al., 2017), dated at 2.9 Ga (Tucker et al., 2016). Hole B core samples include strata from the Roodepoort, Crown, and Babrosco Formations of the Jeppstown Subgroup of the West Rand Group (Figure 1d). The Roodepoort Formation (Fm.) in Hole B is composed mainly of metasiltstone and quartzite, whereas the Babrosco Fm. is composed of quartzite. The Crown Fm. consists of an Archaean flood basalt dated at 2.914 ± 8 Ma (Armstrong et al., 1991). The above-mentioned sedimentary formations are metamorphosed and intruded by several generations of sills that are sub-parallel to the bedding, and dikes that dip at high angles (Meier et al., 2009). The oldest inclusions in the intrusive rocks are associated with the activity of the Ventersdorp Large Igneous Province (2.7 Ga; e.g., Ernst, 2014).

2.2. Fault-Related Samples From Hole B

Samples that represent the upper and lower fault zones (UFZ and LFZ, respectively; Figure 1e) were recovered from damaged zones in Hole B at 616 and 619 m, which were classified as fault breccias (Figures 1f and 1g). The core-loss zone was just above the UFZ at 613–616 m (Figure 1e). Fifty subsamples, representative of each lithology present and the UFZ and LFZ, were collected. Fractures were mapped on the Hole B core samples, and the frequency (number of fractures per 1-m core) were determined.
3. Methods

3.1. Determination of Mineral Assemblages, Major Elements Analysis, Microscopic Observation, and Rock Porosity and Density Measurements

X-ray diffraction (XRD) spectra of the 50 subsamples from the Hole B core were obtained with an X’Pert PRO MPD spectrometer (Spectris PANalytical). The samples were blended with α-alumina (20 wt.%) as an internal standard and mounted on XRD glass holders by the side-load method to minimize preferred alignment of the phyllosilicates. The weight percent contents of the constituent minerals were determined using the RockJock Program (Eberl, 2003), which fits stored integrated XRD patterns of standard minerals.

Thirteen samples of representative lithology and structure were selected from the 50 subsamples. Their major element concentrations were measured with an X-ray fluorescence spectrometer (MagiX PRO, Spectris) by the conventional glass bead method.
Thin sections were prepared from the intrusive rock of the Crown Fm. (at 610.94 m), the UFZ and LFZ, and were inspected under an optical microscope and a scanning electron microscope (SEM; JSM-7600F, JEOL) operating at an acceleration voltage of 15 kV.

Porosity and density of the 50 subsamples were obtained: Dry and wet mass were measured with a precision of ±0.0001 g on an electronic balance, and dry volume was determined with a helium-displacement pycnometer (Pentapyc 5200e, Quantachrome) with a nominal precision of ±0.01 cm³.

3.2. Friction Experiments

Friction coefficients were determined for five powdered samples (less than about <100 μm grain size) of metabasalt (549.55 m), intrusive rock (600.40 m), intrusive rock near the fault zones (619.10 m), quartzite (651.88 m), and the UFZ by using a double direct shear device as described by Kawamoto and Shimamoto (1998). Powdered samples (2 g) were placed between a pair of gabbro blocks (each 50 × 40 × 20 mm) with roughened surfaces (80) to prevent slippage. The initial thickness of each sample was 1.0–1.5 mm and the maximum shear displacement of the apparatus was 20 mm. We used slip velocities of 0.3, 3, and 33 μm s⁻¹ and a normal stress of 40 MPa in our experiments, which were conducted at room temperature and humidity. The velocity dependence of friction, expressed as a − b = Δμ/Δln V, where μ₀ is the steady-state friction coefficient and V is the slip rate, was evaluated by the method of den Hartog et al. (2012). The value of a − b is an important parameter for determining whether frictional instability is likely to occur (e.g., Dieterich, 1978, 1979; Ruina, 1983).

3.3. Magnetic Mineral Analysis

Magnetic susceptibilities of all 50 subsamples were measured at room temperature with a MFK1-FA Kappabridge (AGICO). Low-temperature isothermal remanent magnetization (IRM) was imparted by cooling the samples from room temperature to 10 K in a 3-T magnetic field. The loss of IRM was monitored at ~1.5 K intervals during heating of the samples to 300 K in a zero magnetic field using a MPMS-XL (Quantum Design). Thermomagnetic analyses were done with a NMB-89 thermobalance (Natsuhara Giken). The samples were heated to 700°C and then cooled to room temperature at 10°C min⁻¹ in a magnetic field of 0.3 T in air at atmospheric pressure. Changes in the induced magnetization were monitored at 5-s intervals.

4. Results

High densities of fractures were observed in the Crown Fm., especially in and around the two fault zones and in the metabasalt just below them (Figures 1d and 2). Porosities were slightly elevated (by up to 4%) in two samples from the intrusive rock (612.80 m) close to the core-loss zone and in the UFZ (Figure 2). Magnetic susceptibilities of the intrusive rocks close to the core-loss zone and in both fault zones were in the range 3.0 × 10⁻² to 2.6 × 10⁻² (S1 unit), higher than those of all other strata (<2.6 × 10⁻²) except for the metabasalt at 597.16 m (1.5 × 10⁻²).

The mineral assemblages of the fault zones and their surrounding intrusive rocks (610.94–619.10 m) were characterized by low quartz and feldspar contents and high amphibole, biotite, talc, and calcite contents. There were also lower SiO₂, Al₂O₃, and Na₂O contents and higher Fe₂O₃, MgO, and CaO contents within the same downhole range (Figure S1 in Supporting Information S1; raw data summarized in Table S1 in Supporting Information S1).

There were clear positive correlations in Al₂O₃–SiO₂, quartz–SiO₂, feldspar–Al₂O₃, and plagioclase–Na₂O plots, but negative correlations in Fe₂O₃–SiO₂, MnO–SiO₂, MgO–SiO₂, and CaO–SiO₂ plots (Figures S2 and S3 in Supporting Information S1). An isocon diagram of the average compositions of surrounding intrusive rocks versus those of fault rocks showed higher CaO content within the fault rocks (Figure S4 in Supporting Information S1). Comparison of the mineralogy of the two fault zones with the surrounding intrusive rocks revealed that the biotite and amphibole contents of the UFZ were slightly lower than those of the LFZ and the intrusive rocks (Figure 2). However, within the two fault zones and the surrounding intrusive rocks, the weight percentages of these minerals varied (e.g., low talc contents were detected in samples of intrusive rocks at 610.94 and 611.25 m).

Microscopic examination of the intrusive rock of the Crown Fm. (610.94 m) showed it to be composed of fine-grained amphibole, biotite, augite, phengite, chlorite, and calcite and to have a hydrothermally altered lamprophyric texture (Figure 3a). In contrast, the UFZ included a high proportion of submicron-scale grains, together representing a localized shear zone (Figure 3b) in which the ultrafine grains were mainly talc and calcite.
with abundant biotite. Shear foliations were evident in SEM images of both the UFZ and LFZ (Figures 3c and 3d, respectively).

When our friction experiments reached about 16-mm displacement, the friction coefficients for the metabasalt (549.55 m), intrusive rock (600.40 m), and quartzite (651.88 m) had reached steady state at frictional coefficients between about 0.70 and 0.75, whereas those for both the UFZ and intrusive rock just below the LFZ (619.10 m) were about 0.65 at 16-mm displacement (Figure 4). All samples showed a rapid rise of friction coefficient just after slip commenced. The coefficient then transitioned after 1–2 mm of slip either to a steady increase or a plateau, which we attributed to shear-induced hardening, probably a result of progressive crushing and dissemination (gouge formation) during the experiments (den Hartog et al., 2012). The $a - b$ values of the metabasalt (549.55 m), intrusive rock (600.40 m), and quartzite (651.88 m) were 0.000, whereas positive $a - b$ values were obtained for the UFZ (0.003) and the intrusive rock at 619.10 m (0.004), just below the LFZ. The $a - b$ values of all samples at all step changes are summarized in Table S2 in Supporting Information S1.

Thermal demagnetization curves for low-temperature IRM in the UFZ, LFZ, and the intrusive rock just below the LFZ (619.10 m) showed remanence loss with increasing temperature (Figure 5a). In particular, both the LFZ and the intrusive rock showed sharp decreases of magnetization at about 120 K, probably caused by the Verwey
transition of magnetite (Dunlop & Özdemir, 1997). The thermomagnetic curves for these intervals also showed losses of magnetization at about 580°C (Figure 5b), which corresponds to the Curie temperature of magnetite (Dunlop & Özdemir, 1997). These losses of magnetization were more remarkable in the LFZ and intrusive rock than in the UFZ.

5. Discussion and Conclusions

The cored metasediments that we examined from the Roodepoort and Babroocks Fms. (Figure 1d) preserved their original compositions and sedimentary structures (e.g., lamination). However, the metabasalts in the Crown Fm. had lost their original compositions; igneous minerals were replaced by plagioclase, quartz, and chlorite. Similar alteration has been reported by Armstrong et al. (1991), who noted that the basalts were strongly altered with the original mineralogy totally replaced by a low greenschist-grade assemblage.

The intrusive rocks that enclose the fault zones and the core-loss zone within the Crown Fm. (610.94–619.10 m) showed high amphibole, biotite, talc, and calcite contents. Such biotite-amphibole-rich intrusive rocks with high-potassium mafic compositions are characteristic of lamprophyres, which occur primarily as dikes, lopoliths, laccoliths, and small intrusions (e.g., Rock & Groves, 1988); talc and calcite are presumably formed by secondary hydrothermal alteration or metamorphism (e.g., Moore & Rymer, 2007). We attribute the low friction coefficient of the intrusive rocks to their high talc content, which is among the weakest of all minerals (e.g., Moore & Lockner, 2008, 2011). The high magnetic susceptibilities of the
rocks that enclose the fault zones and the surrounding intrusive rocks might be a response to magnetite that was not detected in XRD patterns, although the presence of magnetite is suggested by their losses of magnetization at about 120 K and 580°C. Magnetite is known to occur as a product of reaction and alteration in lamprophyres (e.g., Rogers & Longshore, 1960).

The distinctly damaged zones of the UFZ and LFZ have previously been interpreted to correspond to the source fault of the 2014 Orkney earthquake on the basis of their spatial relationship with its aftershocks (Figure 1c; Ogasawara et al., 2019). The fault breccias of the UFZ and LFZ are characterized by shear foliations, high talc contents, and low friction coefficients. In contrast to the LFZ and the lamprophyre close to the fault zone (619.10 m), the UFZ does not show distinctive losses of magnetization at ∼120 K and ∼580°C, implying it has undergone magnetite alteration due to low-temperature oxidation (Dunlop & Özdemir, 1997). Furthermore, the biotite, hosting magnetite, and amphibole contents in the UFZ were slightly lower than those of the LFZ. Therefore we consider that of these rocks, the UFZ has undergone the most intense alteration.

We consider the high talc contents (up to 29.8 wt.%) in both the fault zones and their surrounding altered lamprophyres to be the most important outcome of our study of the Hole B core samples. Talc is well known as a frictionally weak mineral (Chen et al., 2017; Giorgetti et al., 2015; Moore & Lockner, 2008, 2011) and has been observed worldwide in active faults, for example, in the San Andreas Fault (Moore & Rymer, 2007). When the talc contents of mixtures of talc with quartz (Moore & Lockner, 2011) or calcite (Giorgetti et al., 2015) exceed 15 wt.%, there is a dramatic decrease of friction coefficient. Therefore, the fault zones of recent earthquakes below the Moab Khotsong gold mine might have developed selectively within highly altered lamprophyre of relatively low shear strength.

However, talc has been shown to have positive $a - b$ values in both dry and water-saturated environments over wide ranges of temperature, pressure, and slip velocity (Chen et al., 2017; Giorgetti et al., 2015; Moore & Lockner, 2008). The $a - b$ values we determined for the UFZ and the altered lamprophyre (619.10 m) were positive. Such positive values indicate stabilization of fault slip during an earthquake (e.g., Dieterich, 1978, 1979; Ruina, 1983), so the positive value we obtained for the UFZ is inconsistent with the occurrence of the 2014 Orkney earthquake and its aftershocks.

Here, we focus on the mineral assemblages within the lamprophyres that enclose the fault zones. Their main minerals are amphibole, biotite, talc, and calcite, but the weight percentages of these varied among samples. For example, one lamprophyre sample (610.94 m) had amphibole, biotite, talc, and calcite contents of 45.0, 32.3, 2.6, and 5.0 wt.%, respectively, whereas in another lamprophyre sample (612.20 m) their contents were 26.5, 19.2, 29.8, and 7.8 wt.%, respectively (Table S1 in Supporting Information S1). Clearly, there were large variations along the borehole of the ratios of the minerals within the altered lamprophyres enclosing the fault zones; these variations likely extend locally in three dimensions.
Laboratory experiments by Fagereng and Ikari (2020) showed that $a - b$ values for amphibole assemblages in fault rocks are randomly positive and negative at slip velocities of 0.1–30 μm s$^{-1}$ under 10 MPa normal stress at room temperature. Experiments by Scruggs and Tullis (1998) yielded negative $a - b$ values for biotite at slip velocities of 0.001–10 μm s$^{-1}$ under 25 MPa normal stress at room temperature. In contrast, Carpenter et al. (2016) obtained positive $a - b$ values for calcite at slip velocities of 0.1–1,000 μm s$^{-1}$ under 10 MPa normal stress at room temperature. The large differences in these experimentally derived $a - b$ values suggest that trends of fault stability can be complex for earthquakes generated in altered lamprophyres. These contrasting results also provide a new insight that fault rock minerals other than talc can govern whether or not earthquake nucleation and rupture propagation occur, and can also constrain fault stability. However, to improve our understanding of the stability of faults in altered lamprophyre, more friction experiments are needed using not only cored lamprophyre samples but also synthetic materials in which the weight ratios of the amphibole, biotite, talc, and calcite end members are well controlled. Further investigation of both the degree of hydrothermal alteration in natural lamprophyres and its spatial distribution is also important for correlations of fault rocks with seismic activity.

**Data Availability Statement**

Raw data of physical properties constitutive minerals and constitutive major elements of the Hole B subsamples and of our friction experiments and magnetic mineral analyses are available online at [https://doi.org/10.5061/dryad.547d7wmb7](https://doi.org/10.5061/dryad.547d7wmb7).

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