EXPERIMENTAL AND IN-SITU PHYSICAL PROPERTIES MEASUREMENTS FROM A SEISMOGENIC ZONE IN A DEEP SOUTH AFRICAN MINE

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Summary

Physical properties of sixty-six cylindrical core specimens from three boreholes are presented and compared with downhole physical property data. To investigate the source of seismic reflectivity observed on the 2D legacy seismic data, we computed synthetic seismograms for adjacent rock units using downhole petrophysical data. The experimental measurements show that the metasediments exhibit lower bulk densities and seismic velocities than the metabasalts and intrusive specimens. The porosity was found to be less than 2% for all the samples. No clear trends emerge when the Poisson's ratio is plotted against the P-wave velocities and porosities of the samples. The calculated reflection coefficients show that several strong reflectors can be identified using seismic reflection methods. The computed reflection coefficients and synthetic seismograms revealed strong reflections that were not identified using the calculated reflection coefficients. Successful correlations are carried out between the synthetic seismic data and lithological logs enabling us to correlate the stratigraphic sequence drilled in the boreholes to the seismic reflections observed on the legacy 2D reflection seismic data. Our experimental results show that the intrusives characterised by low velocities and high densities could potentially be the host structures of the ML5.5 Orkney earthquake.

Experimental and in-situ physical properties measurements from a seismogenic zone in a deep South African mine

Introduction

Since the 1990s, South Africa has experienced several sizeable earthquakes occurring in mining regions at depths ranging between 2 km and 4 km below the surface. These consist of the Welkom (M_L 4.2) and Stilfontein (M_L 5.3) earthquakes, which occurred in 1990 and 2005, respectively. The occurrence of these seismic events resulted in the destruction of mine infrastructure and some cases the death of miners. More recently, the 2014 M_L 5.5 earthquake, which occurred in the Orkney mining district, in the Witwatersrand Basin, is the largest event to occur in a mining region in South Africa (Figure 1). Although mining-related seismic events are common in South Africa (M_L<2), the large magnitude and shallow hypocentral depth (~5 km) of this earthquake raise concern for future large events occurring at active mining levels and their potential to negatively affect mining operations. Additionally, the physical properties of the rocks around the active rupture zone are not well understood because no boreholes had been drilled at depths in and around the aftershock zone. Therefore, no meaningful correlations of the lithological units with physical properties obtained from experimental and in-situ measurements have been done.

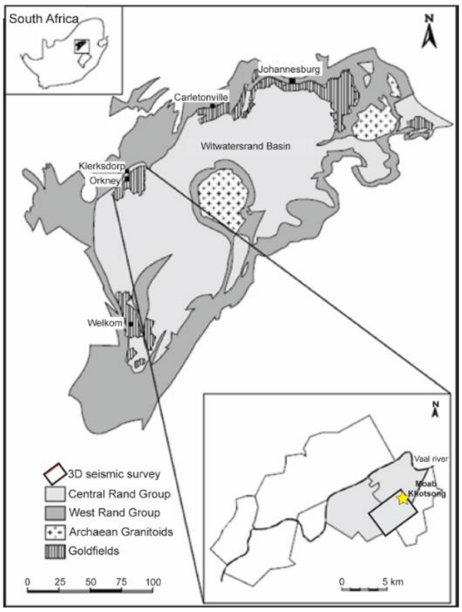

Figure 1 *A simplified geological map showing the location of the study area with respect to the Witwatersrand Basin (Catuneanu and Biddulph, 2001). The black box shows the location of the 1996 Moab 3D seismic survey, which covers the Moab Khotsong gold mine. The star symbol shows the location of the 2014 Orkney M_L 5.5 seismic event.*

The integration of reflection seismic data with experimental measurements of samples from actual survey sites, velocity and density information obtained from downhole measurements and results from acoustic impedance and reflection coefficient calculations, can be interpreted to constrain subsurface rock properties and the location of strategic horizons and structures. Here, we determine the physical properties of a selection of drill core specimens and correlate the experimental results with downhole measurements. We calculate the acoustic impedance and reflection coefficients between adjacent rock units in the aftershock zone and create synthetic seismograms using the sonic and density data.

Legacy 2D reflection seismic data

The 2D arbitrary seismic profile used in this study was extracted from the legacy 1996 Moab 3D seismic survey (Figure 1). The data were acquired using a vibroseis source and 10 Hz geophones, at 50 m source and receiver spacing (Manzi et al., 2019a). A record length of 6 s and sampling interval of 2 ms were used, while the recording was made using a linear sweep: 24 s, 10–90 Hz (Manzi et al., 2019a). The data are characterized by a dominant frequency of 65 Hz, which provides approximately 92 m dominant wavelength (λ) by using an average P-wave velocity of 6000 m/s (Manzi et al., 2019b).

ICDP drilling – Moab Khotsong mine drilling

The ICDP-DSeis drill site was located at the deepest mining horizon at Moab Khotsong mine, at mining level 95L, ~3 km depth (Figure 2). The location of the drill site at the deepest mining horizon was to increase the chances of intersecting the upper fringe of the aftershock zone several metres below. Hole A was drilled 35°-45° downward to intersect the aftershock zone and attained a total length of ~800 m. Hole A deviated from its planned trajectory, to eventually run sub-parallel and at ~100 m from the aftershock zone (Ogasawara et al., 2019). The deviation of hole A led to the drilling of hole B, which attained a total length of ~700 m, to intersect the uppermost part of the M_L 5.5 aftershock zone (Ogasawara et al., 2019). Significant core was lost when hole B intercepted the aftershock zone. To recover additional aftershock zone material, a deviation hole (hole C) was drilled ~544 m from the collar of hole B with a deviation of ~2°-3° (Ogasawara et al., 2019).

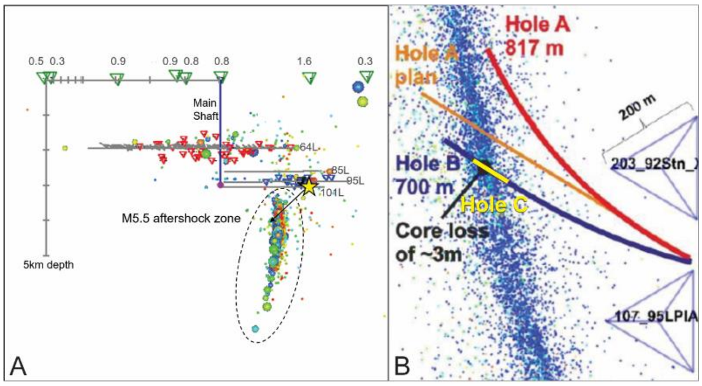

Figure 2 *Underground location of the aftershocks of the 2014 Orkney* M_L *5.5 seismic event. In a) the location of mine infrastructure and in-mine network of accelerometers and geophones. In b) plan view of the aftershocks, mining levels and boreholes A, B and C (Ogasawara et al., 2019).*

Methods and Results

Experimental and in-situ physical rock property measurements

Sixty-six rock specimens were collected from the three boreholes drilled into the 2014 M_L 5.5 Orkney earthquake aftershock zone. The types of specimens comprised cores of metasedimentary, metabasalt and intrusive rocks. Experimental physical properties such as density, porosity, Poisson's ratio and P- and S-wave velocity were measured for all the rock specimens to characterise the physical properties of the aftershock zone. In-situ physical properties, such as the sonic velocity and density were measured in all three boreholes.

Density

Figure 3a shows that the metasediments have the lowest mean density compared to the metabasalts and intrusives, while the intrusives have the highest mean density. Although no obvious trend is observed between density and depth, Figure 3a clearly shows that specimens from similar lithological units have similar densities, across the three boreholes. Therefore, the density is controlled by the mineral composition of the rocks.

Seismic velocity

Measured velocity results show that the metasediment specimens have mean P- and S-wave velocities of 5715 m/s and 3475 m/s, respectively while the metabasalts and intrusives have mean P- and S-wave velocities of 6108 m/s and 3566 m/s and 6425 m/s and 3798 m/s, respectively (Figure 3b and c). When the density of all the specimens is compared with the corresponding P-wave velocity a slight trend of positive correlation is observed. However, it is noted that two intrusive specimens (from the same unit) in hole B and hole C show unusually low P-wave velocities (5399 m/s and 5720 m/s) while showing the highest densities values (3.04 g/cm^3 and 3.09 g/cm^3). This variance is not observed for the same intrusive unit in hole A. Additionally, the trend of positive correlation is not explicit for densities and corresponding S-wave velocities perhaps due to analytical challenges.

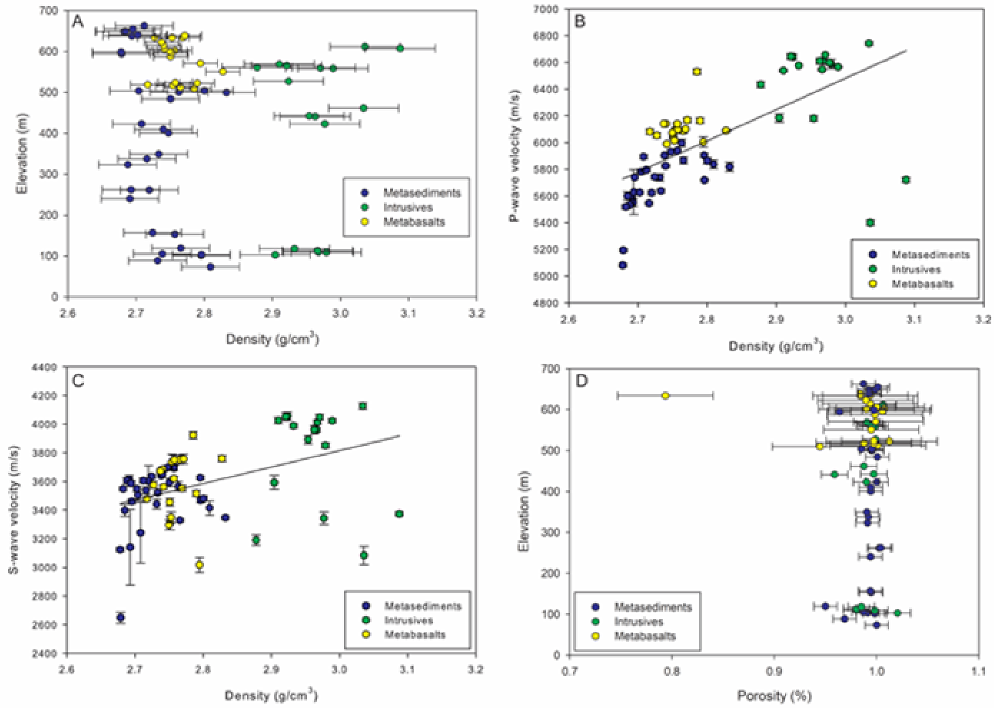

Figure 3 *a) Variation of the density of rock specimens with elevation. b) Relationship between P-wave velocity with density. c) Relationship between S-wave velocity with density. d) Variation of the porosity of rock specimens with elevation.*

Porosity and Poisson's ratio

Figure 3d shows the disparity of porosity with depth in all the rock specimens. The porosity is less than 2% for all the samples with little variation evident across the three boreholes. The low porosity obtained is characteristic of hard crystalline rocks. The low porosity of the metasediments indicates the presence of well-interlocking mineral grains that reduce the connectivity of the pores. The Poisson's ratio ranges from 0.13 to 0.28 for the metasediments, 0.17 to 0.34 for the intrusives and 0.19 to 0.33 for the metabasalts. The lower Poisson's ratio of the metasediments compared to the intrusives and metabasalts might be the result of high quartz content in the rocks. The higher Poisson's ratio exhibited by the intrusives may be associated with increased plagioclase content. The considerable variation in Poisson's ratio of the metabasalt specimens may be the result of the presence of vesicles and amygdales in the samples.

Geophysical borehole-logging

Density and sonic borehole logging were conducted in holes A, B and C to provide stratigraphic correlation across the boreholes, calibrate seismic data sets and correlate lithologies (Figure 4). P- and S-wave velocities obtained from downhole logging show good correlation with experimental measurements. The measured seismic velocity results across the three boreholes exhibit considerable variation and a slight increase with increasing depth.

Synthetic seismograms

Synthetic seismograms were created from the density and sonic log data obtained from the three boreholes to compare with the 2D legacy seismic data (Figure 4). The legacy data are characterised by a 60 Hz dominant frequency and a 4 ms sampling interval. The use of the 1 ms sampling rate produced a smoother wavelet trace and provided excellent correlation when compared with the impedance logs, reflection coefficients, wavelet log and the vertical seismic sections.

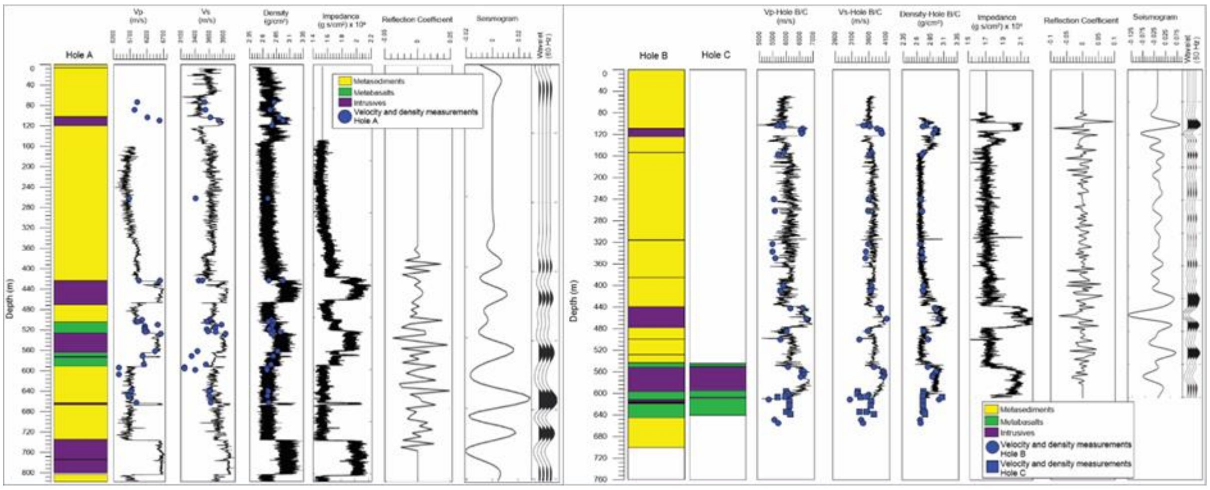

Figure 4 *Physical properties from experimental and downhole logging measurements (boreholes A, B and C) including the synthetic seismograms showing strong reflectors.*

Conclusions

Physical properties of sixty-six cylindrical core specimens from three boreholes are presented and compared with downhole physical property data. To investigate the source of seismic reflectivity observed on the 2D legacy seismic data, we computed synthetic seismograms for adjacent rock units using downhole petrophysical data and compared them with seismic reflections from the reflection seismic profile. Our results reveal that samples dominated by quartz, are associated with low seismic velocities compared to samples that are deficient in quartz. Although the metabasalt specimens exhibit higher P-wave velocities compared with the metasediments, slight overlaps in S-wave velocities and densities between these units are noted. The intrusive specimens exhibit the highest densities and seismic velocities, due to the presence of mafic minerals. Notably, relatively low seismic velocities are observed in one of the intrusive units across the boreholes. This may be attributed to the abundance of sericite. No trends emerge during the analysis of the porosity and S-wave velocity data. No clear trends emerge when the Poisson's ratio is plotted against the P-wave velocities of the samples. The experimentally derived properties agree with the downhole logging data obtained in the three boreholes. The calculated reflection coefficients (≥0.06) show that several strong reflectors can be identified using seismic reflection methods. The computed reflection coefficients and synthetic seismograms revealed strong reflections that were not identified using the calculated reflection coefficients. The strong reflections were not identified, owing to core loss in certain rock units. Our experimental results show that the intrusives characterised by low velocities and high densities could potentially be the host structures of the M_L5.5 Orkney earthquake.

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