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3D Reflection Seismics for Deep Platinum Exploration in the Bushveld Complex, South Africa

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Summary

Seismic methods have become, and will continue to be, an important tool to help unravel structures hosting mineral deposits at great depth. This work demonstrates how the reflection seismic method (mainly 3D seismics) has been successfully used to explore some of the world's largest platinum deposits and map the gross structural architecture that controlled the formation of these ore bodies, support mine planning and contribute to safety. A case study from the Bushveld Complex in South Africa is presented, demonstrating the importance of advanced 3D seismic attributes for high-resolution structural mapping.

Introduction

The platinum deposits of South Africa are associated with the ~2.06 Ga Bushveld Complex (Figure 1a, b), which is widely known as the world's largest igneous complex with an estimated minimum area of 64,000 km^2 (Cawthorn, 1999). The potential of the Bushveld Complex for hosting platinum has been known since the early 20th Century, with the first economically significant platinum deposit being discovered in 1924. The platinum is associated with a sequence of rocks known as the Rustenberg Layered Suite (2055.91±0.26 Ma; Cawthorn, 1999) with the bulk of the deposits hosted within the Critical Zone (Figure 1c). This is principally comprised of orthopyroxenites and chromitites within the Lower Critical Zone with the appearance of norites and anorthosites within the Upper Critical Zone. The economic resources, platinum-group elements (PGEs), chromium and vanadium, are found in stratiform horizons, referred to in mining terminology as 'reefs'.

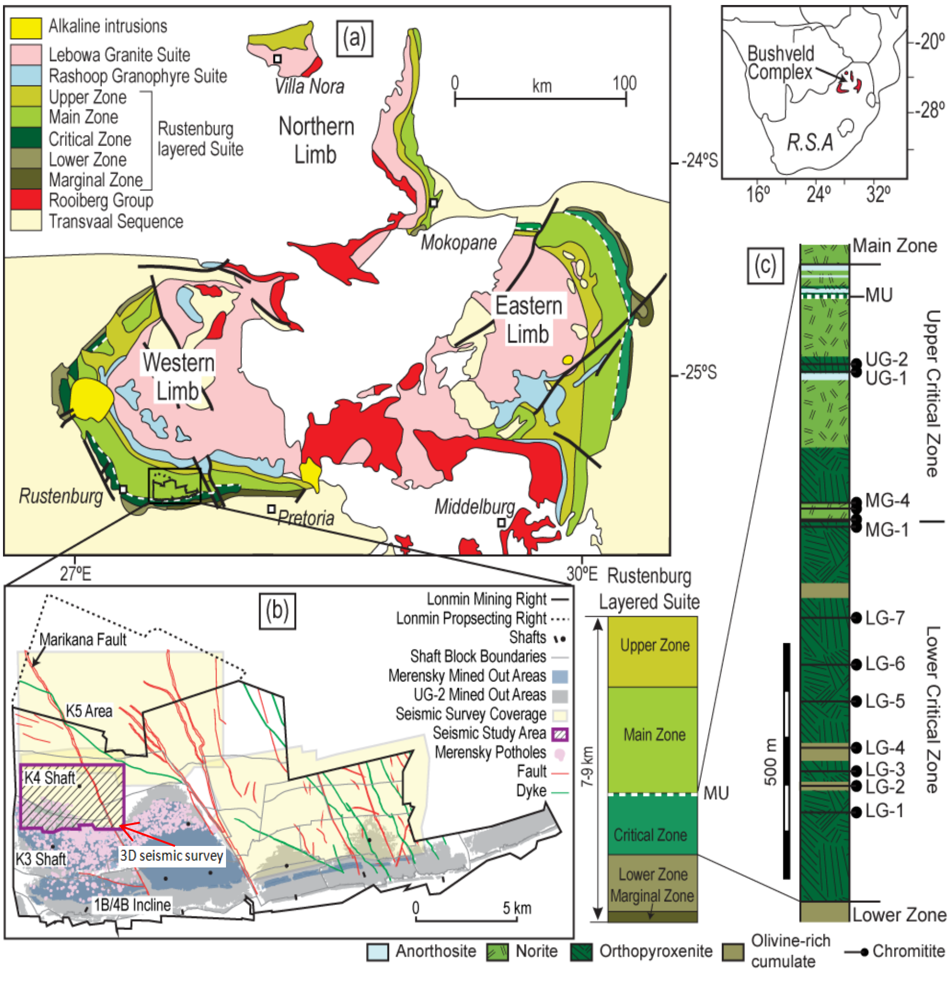

Figure 1 *Map of the Bushveld Complex showing the location of the Lonmin Marikana mine (modified from Cawthorn, 1999). (b) Map of the Lonmin Marikana mining site showing the locations of: the study area in the K3 shaft; the overlapping seismic study area; workings on the UG-2 (grey) and Merensky (blue) Units and known Merensky potholes (pink) in the worked areas. (c) Schematic stratigraphic column of the Critical Zone indicating the locations of the chromitites and the Merensky Unit (MU).*

Exploitation of these resources is affected by geological complexities, which include faults, dykes and more complex structures such as iron-rich ultramafic pegmatite (IRUP) bodies and potholes. Large-scale faults (throw >25 m, Figure 1b) are well constrained by surface and underground mapping, while dykes (Figure 1b) or IRUP bodies can be distinguished from their surface expressions, underground mapping and magnetic signatures (Hoffman and Plumb, 2014). Potholes are transgressive features where one of the typically stratiform units cuts down into the underlying units, so that the ore body lies at a lower stratigraphic level than expected, developing circular or ovoid pits. Determination of pothole locations ahead of mining is currently unreliable, and statistical models are used for mine planning purposes. These geological features, combined, are estimated to result in geological losses, on average, of 15% for the UG-2 Unit and 14% for the Merensky Unit in the Marikana region, with up to 30% losses in spatially restricted areas. Thus, additional tools beyond exploration drilling and geological mapping are required to adequately characterize the ore bodies during the mine developments. This work demonstrates how 3D seismic methods and 3D seismic attributes have been used to explore for deep platinum-bearing horizons and map the gross structural architecture that control the formation of these deposits, focusing on a case study from the Bushveld Complex in South Africa.

3D seismic survey

In 1999 the Karee mine conducted a high-resolution 3D reflection seismic survey (Figure 1b) for mine planning and deep mineral exploration purposes (e.g., Malehmir et al., 2018). The details about the acquisition and processing of the data are discussed by Larroque et al. (2002). The main objective of the 3D seismic survey was to delineate the Merensky and UG-2 reefs (at ~ 500 – 2500 m below surface), and to image faults, potholes and fracture zones critical for geotechnical planning of the mine. The dominant frequency obtained during 3D seismic acquisition over the Karee region is 65 Hz, and 6000 m/s was a good mean velocity value observed during the processing of the data providing a dominant wavelength of about 90 m.

The Merensky and UG-2 reefs rarely exceed 2 m in thickness and are too thin to be directly resolved by surface reflection seismics. Instead, it is the interface between their hangingwall and footwall rooks that is imaged due to large acoustic impedance (product of the bulk density × seismic velocity) contrasts and significant reflection coefficients (RC ≥ 6 %) at these interfaces. Figure 2 shows Karee mine 3D seismic volume, providing successful seismic imaging of the Merensky reef (MR), UG-2 chromitite reef and faults.

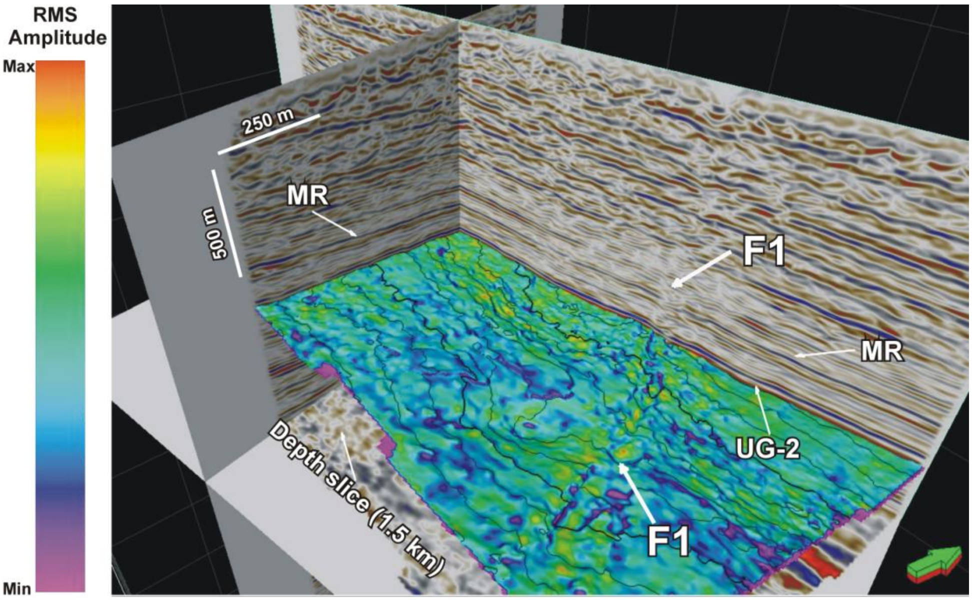

Figure 2 *3D visualization of the 3D seismic volume showing the successful imaging of the Merensky Reef (MR), chromitite (UG-2) and its associated seismically mapped fault on the Root Meant Square (RMS) amplitude attribute display.*

The MR is characterized by a strong seismic response, but is less prominent than the UG-2 reef, due to a lesser acoustic impedance contrast between the feldspathic orthopyroxenites (~6400 m/s seismic velocity and a ~2900 kg/m^3 density) and the less dense anorthosites and leuconorites (~5700 m/s seismic velocity and 2700 kg/m^3 density). The UG-2, on the other hand, exhibits a strong seismic reflection character due to a major acoustic impedance contrast between the dense chromitite (~6400 m/s velocity and density up to 4800 kg/m^3) and the less dense pyroxenite, norite or anorthosite (~5700 m/s velocity and densities between 2700 and 2900 kg/m^3). Therefore, the large acoustic impedance contrast is controlled by the bulk density variations within the target strata, rather than by seismic velocity, as there is no significant contrast in the seismic velocities. Continuity of both the UG-2 and Merensky Reef horizons is confirmed by the seismic data, although both display variations in their strike and dip across the study area (Figure 2). The most dominant feature imaged by the seismic data in the area is the Marikana Fault (F1), which is a north-northwest trending, normal fault (~ 500 max throw) that steeply dips at ~75–80 degrees to the west. The depth positions and apparent dips of the Marikana Fault have been confirmed by underground mapping and drilling. The identification of F1 and its variations in dip angles and vertical throws is important, as it is likely to cause weak ground conditions during mining. In addition, the constraints on fault orientations and timing of activity across the mining areas are significant and will need to be studied and be factored into future mine planning and development.

Edge detection attributes indicate the occurrence of randomly distributed elliptical potholes (Figure 3a). Integration of these attributes with underground observations (Figure 3b) confirms that many metre-scale geological features are present and contribute to the complexity of the area. This allows for the interpretation of seismically small-scale faults from subtle offsets of the reflectors and for association of potholes with faults (Figure 3c,d), despite their apparent random distribution (Figure 3a).

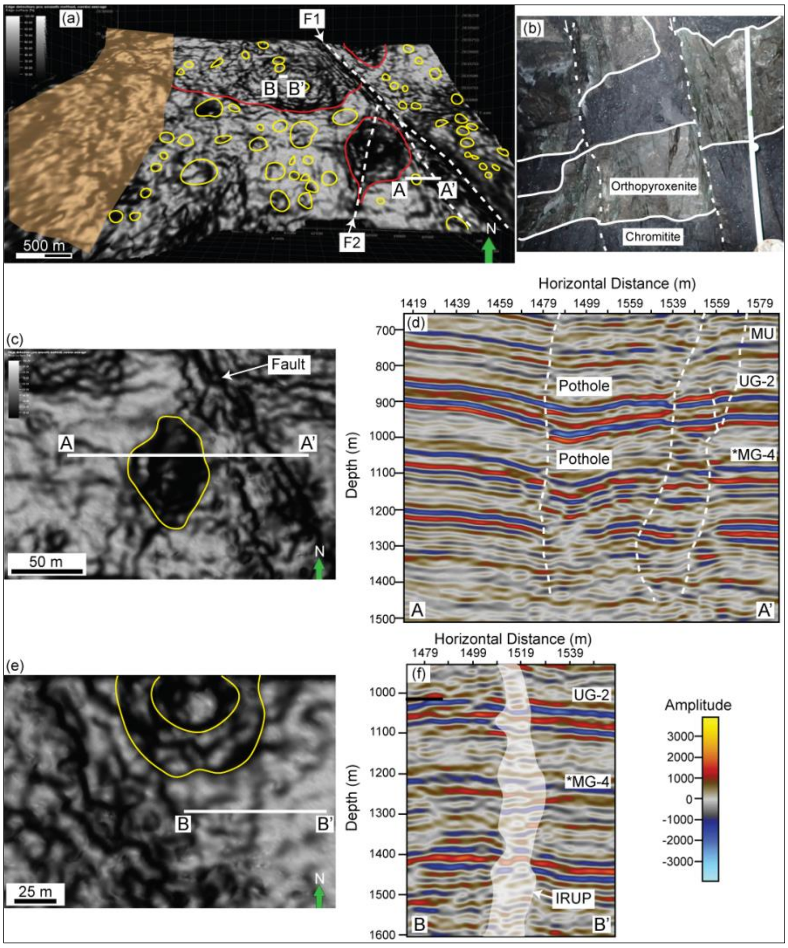

Figure 3 *Interpreted edge detection map computed for the UG-2 horizon combining dip and dip azimuth attributes. Elliptical structures, interpreted as potholes, are outlined in yellow; large-scale (>500 m diameter) depressions are outlined in red; faults (F1, Marikana Fault, and F2) are marked by dashed white lines. Note the left hand side of the area (shaded in orange) has not been interpreted due to a lower signal-to-noise ratio at the edge of the survey. Location of seismic area is shown in*

Figure 8. (b) Underground exposure of UG-2 Unit affected by brittle faults (dashed lines), scale bar is 1 m in length. (c) Enlarged area marked by A-A' in (a) with central pothole outlined in yellow. (d) Seismic section from line A-A' indicates both UG-2 and interpreted MG-4 horizons are potholed, in association with faulting. (e) Enlarged area marked by B-B' in (a) with complex pothole outlined in yellow. (f) Seismic section from line B-B' with IRUP pipe structure.

The third principal geological complexity in the study area is the IRUP bodies. While their near surface expressions are visible in magnetic data, bodies at depth are not visible using the magnetic method. At depth, IRUPs can be detected within the seismic data as they result in scattering of the acoustic energy, so can be recognised from diffuse portions of the reflectors. Pipe-like IRUP bodies are interpreted in the region from the seismic sections, but are not expressed in the attribute analysis (Figure 3e,f). This indicates that comprehensive analysis of the 3D seismic data is important for detecting all the geological complexity within the ore bodies and is vital for any mine planning purposes.

Conclusions

A case study from the Bushveld Complex demonstrates the impact of a high-resolution 3D seismic survey on the development program of a platinum mine, and shows that reflection seismology can play an important role in determining the structural position of thin, layered ore bodies and image potholes and faults. In the Bushveld Complex, the data have also been used to study the mechanisms by which the potholes are developed, possibly providing some insights in unravelling complex magmatic processes. The techniques applied within this study are not only of interest to the academic community, but also for the mining community. This is because they can benefit planning operations by providing a better estimation of the resources and inform in the siting of the sinking of future shafts. Thus, any future mine development plans should take the described structural parameters into account when assessing the potential of their licence areas.

Acknowledgements

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