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The Value of Seismics in Mineral Exploration and Mine Safety

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Summary

The word “seismics” in the geoscience community is often used synonymously with “oil and gas”, despite its successes in other applications, for example, in mineral exploration, engineering application, mine planning and safety.Over the past few decades, the method has been developed and successfully used for mineral exploration, mine planning, and safety in “hard rock” metallogenic provinces worldwide (e.g., Australia, Europe, Canada, and South Africa), leading to the discovery of giant minerals and metal deposits.However, despite these successes, the method’s capabilities in mining still remains less-known to many geoscientists and some mining companies are still reluctant to use it for “hard rock” exploration and mining.The purpose of this paper is to demonstrate how the reflection seismic method has been successfully used to explore and discover some of the world’s largest mineral and metal deposits that are located deep underground - where exploration drilling is more costly and risky. A wide range of case studies from hard rock environments are covered, for example, from South Africa and Canada.

Introduction

The word "seismics" in the geoscience community is often used synonymously with "oil and gas", despite its successes in other applications, for example, in mineral exploration, engineering application, mine planning and safety. The reflection seismic method has been widely used in the oil industry since the 1960s to locate oil and gas reservoirs in "soft" sedimentary rocks. It is thus a known truth amongst geoscientists that a reflection seismic survey is a key geophysical tool an oil company would use to increase its hydrocarbon's exploration' success, reduce risk and monitor the reservoir through time. Over the past few decades, the method has been developed and successfully used for mineral exploration, mine planning, and safety in "hard rock" metallogenic provinces worldwide (e.g., Australia, Europe, Canada, and South Africa), leading to the discovery of giant minerals and metal deposits. For example, in the last 20 years, Geosciences Australia has acquired numerous regional 2D seismic lines (more than 15,000 km) and a few 3D seismic surveys across the Yilgarn Craton to provide insights into the crustal-scale mineral-bearing fluid pathways and possible source rocks (Urosevic et al., 2005). In addition, hundreds of 2D seismic surveys and tens of 3D seismic surveys have been acquired across the Witwatersrand Basin and the Bushveld Complex to map their structures, as well as delineate the deep-seated gold- or platinum-bearing horizons and other subsurface structures (Manzi et al., 2012). However, despite these successes, the method's capabilities in mining still remains less-known to many geoscientists and some mining companies are still reluctant to use it for "hard rock" exploration and mining. This is primarily due to high cost of seismic surveys versus drilling, particularly 3D seismics, its variable performance in complex structural settings, and in some cases ambiguous interpretation results (mainly 2D seismics). Furthermore, oil-and-gas industry geoscientists tend to have little knowledge of the technique, in terms of its application to mining and other near-surface applications.

With shallow economic mineral deposits becoming increasingly hard to find, the discovery of deep seated giant mineral and metal deposits is needed to sustain long-term global growth. However, this goal is likely to be achieved by using a state-of-the exploration approach involving smart and cost effective seismic designs and acquisitions; as well more advanced re-processing of the legacy seismic data. The reflection seismic method has proven to be the only surface geophysical method that provides a high-resolution image of the subsurface and information about structural and lithological relationships that control mineral deposits at depths. The purpose of this paper is to demonstrate how the reflection seismic method has been successfully used to explore and discover some of the world's largest mineral and metal deposits that are located deep underground - where exploration drilling is more costly and risky. A wide range of case studies from hard rock environments are covered, for example, from South Africa and Canada. We also show how seismic surveys have been used by mining companies to map the gross structural architecture that controlled the formation of mineral deposits, support mine planning, mitigate risks associated with mining-induced seismicity and contribute to safety.

Although 3D seismic surveys are expensive relative to linear 2D seismic surveys, aeromagnetic surveys, and traditional exploration drillings, they offer great advantage for processing and interpretation of the seismic data, thus providing a more detailed understanding of the complex 3D structural networks of the ore body and the tectonics of the area. Generally, 3D seismic surveys are carried out only at previously well-explored sites with known economic ore deposits (such as an existing mining site), where exploration drilling and 2D seismic surveys have already been conducted. The 2D seismic surveys, on the other hand, continue to be used at an initial exploration stage, to map the regional structural framework of the target area and to evaluate the acquisition parameters for a potential follow-up 3D seismic survey. There are, however, many challenges faced in adapting a conventional seismic method that was developed primarily for hydrocarbon exploration to hard rock mineral exploration. These include, but are not limited to, low mapping resolution for shallow and deep targets due to: (1) the low bandwidth of the vibroseis sweeps source used for acquisition, typically four and, at most, five octaves; (2) a low density of source and receiver positions; and (3) a large bin size, shot offset and low nominal fold.

Most mineral deposits have favorable physical properties to be targeted using various geophysical methods, but many of these methods do not have sufficient sensitivity and resolution at great depth (>500 m). The ability of the boundary between two geological entities to generate a strong reflection depends on the contrast in the acoustic impedance (product of velocity and density), the dimensions and geometry of the targets. Furthermore, it is shown in several studies (Malehmir et al., 2012) that the success of the reflection seismic surveys depends on the site conditions (e.g., accessibility, topography, and thickness of the weathered layer) and the geology (e.g., rock properties, steepness of dips, and geological complexities such as tight folding).

3D Seismics for Gold Exploration

The case study from the Kloof and South Deep gold mines in the Witwatersrand Basin in South Africa represents pioneering work that demonstrated the effectiveness of the 3D reflection seismic method for deep gold exploration. Kloof Gold Mine is a well-established intermediate to ultra-deep-level gold mine that is accessed from surface through vertical shaft systems to different depth levels. The deepest mining level of the ore body is at 3.35 km below surface and the total gold production is averaged at 1667 kg/month at an average yield grade of 6.0 g/t. In 1987 and 2003, high-resolution 3D seismic reflection surveys were conducted targeting the gold-bearing horizon in the Kloof and South Deep gold mines. In 2012, these surveys were merged and re-processed as a single entity of final depth-converted prestack time migrated (PSTM) seismic data to produce a single seismic cube. The 3D seismic survey was able image and resolve a previously unknown 250 m wide and 1.0 km long discrete ore body block (VCR) preserved between two fault segments in a major fault zone (West Rand Fault, 2 km maximum throw), which is shown in Figure 1a, b. The identification of the new ore body block was confirmed by underground mapping. Establishment of the continuation of the ore body assisted in improving and enhancing the resource calculation, financial valuation of the ore body, and life-of-mine planning.

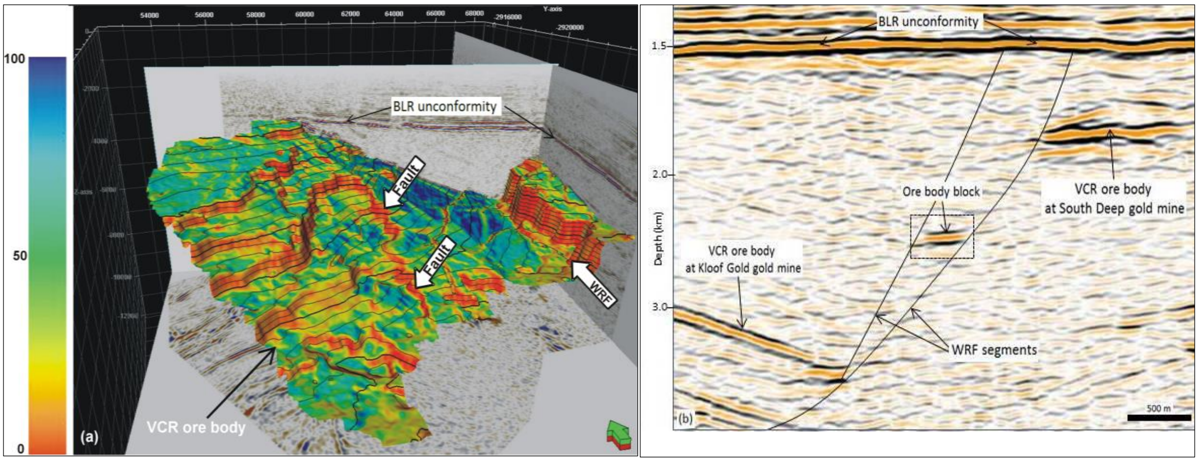

Figure 1 *(a) VCR horizon-fault framework defined from the edge-detection seismic attribute (colour bar is given in percentages). The edge-attribute map also shows the West Rand Fault (WRF ~ 2 km maximum throw) that crosscuts the VCR ore body. (b) Seismic section (amplitude display) across the West Rand Fault (with a throw of 1.5 km in the north of study area) showing a seismically imaged VCR ore body block preserved between segments of the steeply-dipping West Rand Fault. CRG: Central Rand Group; WRG: West Rand Group.*

3D Seismics for Platinum Exploration

Through the case from Karee mine in the Bushveld Complex of South Africa, we show that seismic methods are capable not only of detecting platinum ore bodies associated with thin (<5 m) stratiform rock horizons (known as reefs) at depths below 200 m, but also of helping the mining industry to optimize mine planning in a cost-effective manner. The mine exploits two main PGE-, chromium- and vanadium-bearing ore bodies, the UG-2 and Merenskey reefs (MU), at depths of 1300 m below surface. Exploitation of these resources is affected by geological complexities, which includes faults, dykes and more complex structures such as iron-rich ultramafic pegmatite (IRUP) bodies and potholes. In 1999, the Karee mine conducted a high-resolution 3D reflection seismic survey for mine planning and deep mineral exploration purposes, which was acquired by Compagnie Générale de Géophysique (CGG). The survey successfully delineated the Merensky and UG-2 reefs, as well as faults, IRUPs, potholes and fracture zones critical for geotechnical planning of the mine (Figure 2a-j).

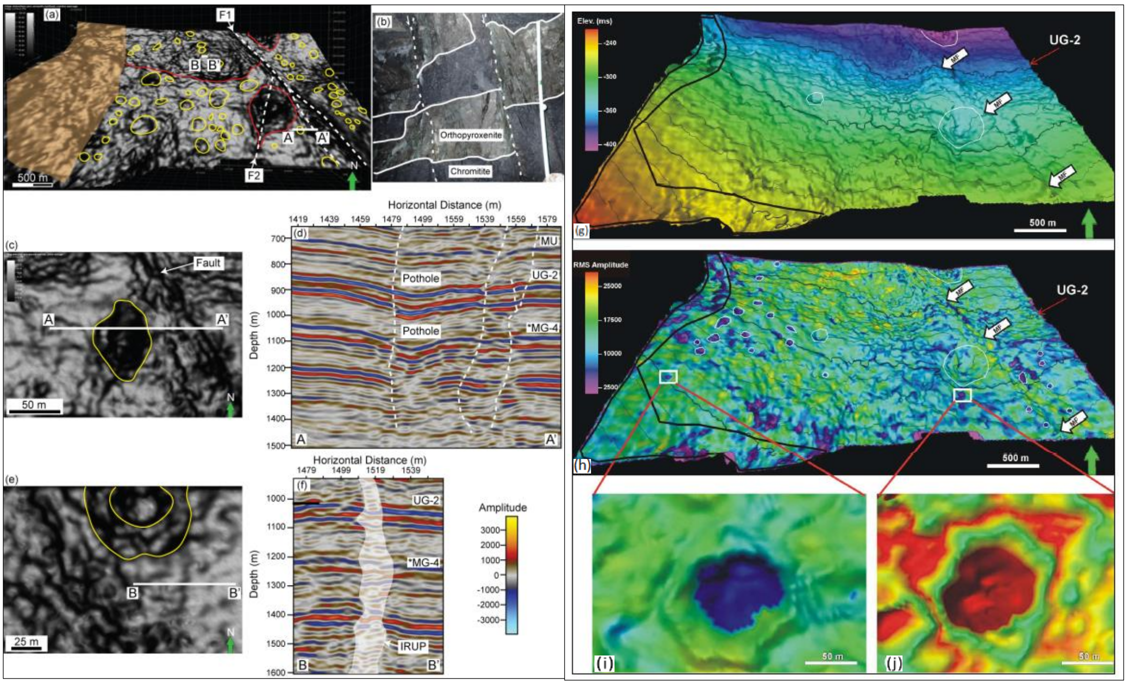

Figure 2 *(a) Interpreted edge-detection map computed for the UG-2 horizon combining dip and dip azimuth attributes. Elliptical structures, interpreted as potholes, are outlined in yellow; large-scale (> 500 m diameter) depressions are outlined in red; faults (F1, Marikana Fault, and F2) are marked by dashed white lines. (b) Underground exposure of UG-2 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. (g) UG-2 time map (gridded) showing imaging of faults (indicated by white arrows) and potholes (highlighted in white) through conventional interpretation. (h), (i) and (j) UG-2 RMS amplitude map showing imaging of the faults.*

3D Seismics for VHMS Exploration

In Canada, Noranda Inc. (now Xstrata) acquired several 3D seismic data for VHMS exploration in the Bathurst and Abitibi mining camps. One of their 3D seismic surveys led to the discovery of a 6–8 Mt massive sulfide lens at a depth of 1.2 km in the Halfmile Lake area (Figure 3;Malehmir and Bellefleur, 2009).

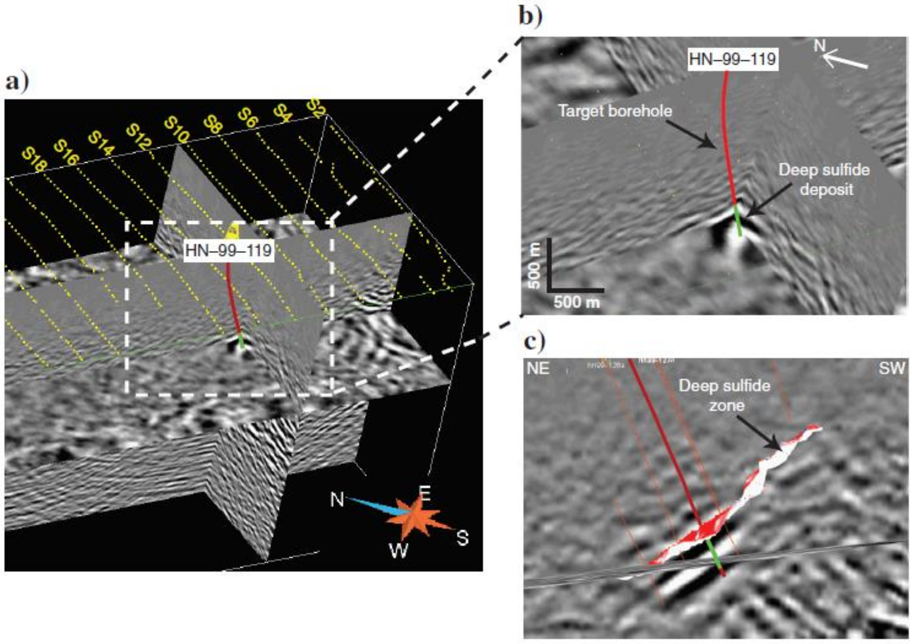

Figure 3 *3D seismic data (a-c) showing high amplitudes in the seismic data correlating with the location of a deep massive sulphide deposit at 1.2 km-depth in the Halfmile Lake area, which was confirmed through drilling of borehole HN-99-119 (Malehmir and Bellefleur, 2009).*

Conclusions

We have illustrated, through case studies from hard rock environments in South Africa and Canada that deep mineral exploration using high-resolution seismic data (mainly 3D) provide high-definition images of structures at great depth for mine planning, designs and safety. The case study from Kloof and South Deep gold mines clearly illustrates the risk in relying on the interpretation derived from non-seismic geophysical data, and the value of re-processing the legacy data for better evaluation of the ore block resources. 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. . The seismic techniques presented in this paper sare not only of interest to the academic community, but also to the mining industries, i.e., they can benefit planning operations by providing better resource estimation, and better-informed siting of future shafts.

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