In-mine Underground Tunnel Seismic Experiment, using High-resolution Reflection Seismic Method at Maseve Mine, Rustenburg, South Africa.

Introduction

Modern mineral exploration relies on the application of advanced, contemporary geophysical techniques to narrow down the search for orebody deposits and mine development (Malehmir et al. 2017; Manzi et al. 2020). The seismic method has long been recognized as an effective tool for studying the subsurface for a variety of applications, such as mineral and hydrocarbon exploration, engineering problems, geotechnical evaluations, environmental studies, hydrogeological investigations, seismic risk assessment, and archaeology (Brodic et al. 2017; Manzi et al. 2020). The reflection seismic method is undoubtedly an effective geophysical technique for detailed and reliable imaging of any complex subsurface geological structures (Malehmir et al. 2017; Manzi et al. 2020). The past few years have witnessed an increase in interest of in-mine seismic applications, which employ specific combinations of seismic acquisition, processing, and interpretation techniques in hard-rock and deep mining environments to improve the imaging of the orebodies (Manzi et al. 2020). Malehmir et al [2017] has deployed high-density receiver and source arrays to improve the acquisition seismic bandwidth using broadband sources. Brodic et al [2017] and others have also conducted surface-tunnel-seismic surveys using a three-component (3C) microelectro-mechanical (MEMS-based) seismic landstreamer, coupled with wireless seismic recorders. The combination of these innovative approaches can nurture new ideas on how the in-mine infrastructures (shafts, tunnels, boreholes, and drifts) can be utilized to design seismic experiments that may provide fresh insights into structural imaging of the subsurface geology.

The mining industry is constantly confronted with challenges not only to develop novel approaches in mining increasingly deep mineral deposits but also to do so in a cost-effective manner. The key to achieving these goals begins with a good understanding of the subsurface geological characteristics and proper geometry of the orebody and of any unexpected anomalous geological features ahead of the mining face to optimise extraction and mine safely. This research interest prompted the Council for Scientific and Industrial Research (CSIR) through the Mandela mining precinct and the University of the Witwatersrand to conduct in-mine seismic acquisition experiments in South African mines for the Advance Orebody knowledge (AOK) programme. The experiment involved both passive (surface) and active (surface and underground tunnel) data acquisitions. In this paper, we restrict our focus to the in-mine underground active seismic experiments. These surveys were conducted to map the down-dipping Merensky Reef (MR) development and the UG2 package, both high-grade platinum ore deposits, and to inform the expansion of the mine’s development. The study area is located within the Western Lobe of the Bushveld Complex (BC), which is ~ 38 km NW of Rustenburg Town and ~ 10 km south of the Pilanesberg Alkaline Complex in the North West Province, South Africa (Figure 1a). The BC is known as the largest host of Platinum Group Metals (PGMs), vanadium and chromium commodities in the world (Figure 1). The Complex has been mined for numerous decades for its precious metals and it plays a key role in the economy of South Africa.

Methodology

This study employs high resolution shallow reflection seismic imaging. The main advantage of the reflection seismic is to delineate the geometry of the subsurface structures in greater details and deeper penetration depth. The ability of any geological boundary to produce a significant reflection signature depends wholly on the reflection coefficient (Rc) between these two geological units. Hence, a geological interface can only generate a significant reflection event if the Rc at the boundary is at least 6% (0.06). In this project, the Merensky-UG2 contact and UG2 package are the primary targets. Complex geological structures (faults, dyke swarms, IRUP and potholes) posed a great concern for full exploitation of these economic reefs (Figure 1a, c and d).
The Merensky and UG2 reefs have estimated average velocities of 6400 – 7000 m/s and density values of 2.9 g/cm³ and 4.8 g/cm³, respectively (Campbell 2011). The reflection events across the Critical zone are expected at the interface between the low density anorthosite (2.78 g/cm³), which host the Merensky Reef (MR) and the higher density pyroxenite (3.15 g/cm³) hosting the UG2. Generally, the Critical Zone is characterised by alternating sub-horizontal strata of anorthosites and norites, and the ultramafic pyroxenites and chromitites, which include the targeted UG2 pyroxenite-chromitite package that is approximately 15 – 100 m below the MR. The strong seismic reflections in this zone are the result of changes in density (~ 15%) rather than velocity. The estimated acoustic impedance contrast within this Critical zone could range from 0.02–0.07 Rc, of which the UG2 pyroxenite-chromitite package is expected to exhibit the highest Rc.

Figure 1: (a) The geology of the Bushveld complex showing the three major lobes and the three main suites of the BC (Modified after Campbell [2011]). (b) South African map outline indicating the location of the Bushveld Complex. (c) Magnetic intensity map showing some magnetic signatures of the BC. Note the east – west lineaments (evidence of dyke swarms) that form closure compartments in the area (d) Stratigraphy of the zones in the Rustenburg Layered Suite and the location of the Merensky Reef. The Rustenburg Layered Suite is estimated to be ~8 km long and the Merensky Reef (enlargement in the d) occurs in the Upper Critical Zone.

Data acquisition, processing and interpretation

Seven lines were acquired with the stated objective in mind, of which two are presented here. Line-1 was acquired along the strike direction of the MR, which runs perpendicular to the in-mine reference pillar, and Line 3 was conducted along the tunnel-face adjacent to the reference pillar, which cuts across the MR in up-dip direction. The line 3 acquisition involves 1 m inter-station spacing of different receiver type (4.5 Hz and 14 Hz resonance frequency) while Line 1 was acquired with 5 m separation 24 stations landstreamer system connected with 4.5 Hz geophones. The data were acquired
~ 550 m below the surface using 10 kg sledgehammer source and 24 stations landstreamer system connected with 4.5 and 100 Hz geophones.

The coherent events at 15 - 25 ms and 90 - 120 ms in the shot gathers (Figure 2a,b) are the expected reflections from the UG2 pyroxenite-chromitite contact and the interbedded chromitite seams, respectively. Based on the employed acquisition parameters (shot and receiver spacing of 2-5 and 1-5, respectively), the CMP spacing will be 0.5 - 1.25 m since the shots were taking in between the receivers. The resolution of the data was estimated using the average interval velocity of the Critical zone (6500 m/s) and the dominant frequency (F_D = 300 Hz) of the raw shot gathers. Moreover, we used the conventional radius of the Fresnel zone calculation (F_z = 0.5V_a (T_o/F_D) ^{1/2}, where T_o is the initial interval two-way time of the reflected event to approximate the average horizontal resolvable feature of the seismic data. The smallest resolvable feature with respect to the reflectors at 20 and 105 ms T_o are estimated at 27 m and 60 m width. Therefore, the horizontal sampling above 105 ms (two-way time) is approximately 54 - 60 points per Fresnel zone. In addition, the vertical resolution of the data can be approximated using 1/4 dominant wavelength criterion (λ_D = V_a/F_D). By applying the average P-wave velocity and dominant frequency, the λ_D of the seismic data is ~ 21 m, which shows that the best vertical resolvable feature in the data would be ~ 4 m thick.

The processing workflow includes geometry setup; trace edits and normalizations; frequency and velocity bandpass filtering; deconvolution before stacking; standard CMP analyses; stacking; migration; time-depth conversion and time-varying bandpass filter after migration (Figure 2 and 3). All traces and shots were meticulously placed in their correct positions during geometry setup. Traces were normalized with respect to the maximum amplitude of the entire shot gather and dead traces were removed. Since the velocity variation within the Critical zone is small, we used constant velocity of 6500 m/s that best flattens the reflection hyperbolas for NMO, brute stacking, Migration and time-depth conversion. Furthermore, adequate static correction and full velocity analysis would be performed using Globe Claritas software and the final velocity model will be used for stacking and to obtain the results.

Figure 2: The preliminary processing workflow of Line 1; (a) the seismic raw shot gathers, (b) Result after application of trace editing, trace normalization, AGC, frequency and velocity bandpass filters. Note, CV (yellow arrow) is a possible reflection emanating from chromitite seam. (c) Frequency spectra before and after bandpass filters, respectively. (d) Locations of Line 1 and 3 on X Y coordinate system. (e)Fold distribution along line 1, where the colour bands represent the number of traces per bin (white is 0 and red is 24). (f) Elevation profile along Line-1, the floating datum is set at
536 m. (g) Brute stack time section of Line 1. Note the coherent reflectors (CV) and pothole feature on UG2.

Figure 3: (a) The brute stacked time section of Line 3. (b) Depth converted section using constant average velocity of 6500 m/s. (c) Coloured scale of depth section as in (b).

Conclusion

The preliminary conclusion of this research is based on the successful underground tunnel seismic data acquisition, preliminary data processing and inferred interpretation. Further data processing for all seven lines are currently ongoing. The initial data analysis revealed different seismic events on the shot gathers: P- and S-wave, and SV-wave arrivals with evidence of strong airwaves and likely reflection events. The estimated first arrival P-wave velocity ranges from 6250 – 7000 m/s. The coherent reflected events were interpreted as UG2 pyroxenite-chromitite contact and interbedded chromitite seams within the UG2 package. The depth to the top of UG2 ranges from 30 – 50 m. This study thus highlights the benefits of employing high-resolution shallow reflection seismic methods for possible underground mineral exploration and optimum resource exploitation.

Acknowledgments

Appreciation goes to the Council for Scientific and Industrial Research (CSIR) through Mandela Mining Precinct, South Africa and the University of the Witwatersrand (Seismic Research Centre) for the sponsorship and support. Thanks to GeoLink, OpenGround Resource Pty and Engineering & Exploration Geophysical Services CC for equipment support and the Wits Geophysics Research Team.

Reference


