Giving the legacy seismic data the attention they deserve

Musa Manzi[1]*, Alireza Malehmir[2] and Raymond Durrheim[1] discuss the importance of retrieving, recovering, and reprocessing legacy seismic data for mineral exploration.

Introduction

Key minerals may soon be in short supply as shallow mineral deposits are mined-out; therefore exploration for economically feasible deep-seated deposits to sustain a long-term global growth is a great challenge. New deposits are likely to be found using reflection seismic surveys in combination with drilling, field geological mapping and other geophysical methods. Seismic methods have already have contributed significantly to the discovery of some of the world's major mineral deposits (Milkereit et al., 1996; Pretorius et al., 2000; Trickett et al., 2004; Malehmir and Bellefleur, 2009; Malehmir et al., 2012). However, use of the method is not widespread because it is deemed to be expensive. Although improvements in computing capabilities have led to cost reductions, the costs are still beyond exploration budgets of many companies. Thus, mining companies have had little financial ability to acquire new reflection seismic data, and very little governmental support has been available to acquire research seismic surveys for mineral exploration.

Over the last few years, there has been a proliferation of seismic solutions that employ various combinations of equipment, acquisition, and processing techniques, which can be applied in hard rock situations to improve the imaging resolution (Denis et al., 2013). The best acquisition solutions to date have come from the deployment of high-density receiver and source arrays which the extension of the seismic bandwidth to six octaves using broadband sources (Duval, 2012). Another area of seismic research has focused on surface seismic acquisition using three-component (3C) microelectro-mechanical (MEMS-based) seismic landstreamers (Brodic et al., 2015), coupled with wireless seismic recorders, and surface-tunnel-seismic surveys (Brodic et al., 2017). However, numerous difficulties have been encountered, even with these innovative acquisition seismic approaches. Seismic surveys acquired in the mining regions suffer from noise produced by the drilling, blasting and transport of rock and the crushing of ore. Furthermore, in some mining regions the acquisition of new data is not permitted due to new environmental regulations.

In such a fast evolving seismic technological era, legacy reflection seismic data are often regarded by mining companies and geoscientists as inferior compared with the newly acquired data. This paper demonstrates that if the legacy data are properly retrieved, reprocessed, and interpreted using today's standard techniques, they can be of significant value, particularly in the mining regions where no other data are available or the acquisition of new data is difficult and expensive. The development of multitudes of processing algorithms and seismic attributes, in particular, make it worthwhile to reprocess and interpret legacy data to enhance the detection of steeply dipping structures and geological features below the conventional seismic resolution limits (i.e., a quarter of the dominant wavelength), which was not possible with the tools that were available when the data were originally acquired and processed. The new information obtained from the legacy data may benefit future mine planning operations by discovering new ore deposits, providing a better estimation of the resources and information that will help to site and sink future shafts. Thus, any future mineral exploration project could also take the geological information obtained from the reprocessed and interpreted legacy seismic data into account when planning new advanced seismic surveys (Manzi et al., 2018). The latest seismic algorithms are particularly interesting to South Africa's deep mining industry because South Africa has the world's largest hard rock seismic database, which could benefit from new processing techniques and attributes analyses. These techniques could be applied to legacy seismic data to identify areas of interest, improve structural resolution and to locate deeper ore deposits. Seismic attributes, in particular, could be used to identify any subtle geological structures crosscutting these deposits ahead of the mining face that could affect mine planning and safety.

Deep mining and legacy seismic surveys in South Africa

Historically, South Africa has been a leading global supplier of mineral production, and it retains an important role in mining and minerals. The Witwatersrand Basin of South Africa contains the world's largest known accumulation of gold, and has yielded more than a third of the gold ever mined. The basin is known to host substantial resources that may become attractive to exploit in the future, depending on the gold price and technological developments. Furthermore, the Bushveld Complex of South Africa hosts more than 90% of the world's platinum-group metal resources, output has expanded tremendously in recent decades, and mines are already reaching mining depths beyond

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2 km. As gold and platinum mining proceed, some of the ore bodies are found to persist at greater depths (>2 km) beneath the cover rocks, with significant challenges to continue exploration and extraction. Geological problems encountered in mining can include the loss of the deposit, unexpected dykes and faults, rock bursts, rock falls, and intersections of gas and water reservoirs. Even with detailed advanced exploration, mining operations have been affected by many problems, such as gas outbursts, water inundations, dangerous strata conditions, and severe operational problems, that can result in injuries to personnel, as well as major losses of equipment and production.

The challenge of an exploration method is to achieve ever greater resolution in increasingly complex environments and at greater depths. A step in this direction was taken by field trials of high-resolution reflection seismic surveys by the Gold Division of Anglo American Corporation (now AngloGold Ashanti Ltd.), with the aim of reducing geological 'surprises' prior to mining and shaft sinking (Pretorius et al., 2003). Between the 1980s and early 2000s, the Gold Division of Anglo American Corporation and various mining companies acquired a series of 2D seismic data (36,000 km in total length) and more than seven 3D reflection seismic surveys in the Kaapvaal Craton for gold and platinum exploration in South Africa, with special focus in the Witwatersrand Basin and the Bushveld Complex. This is one of the most extensive hard rock seismic exploration programmes in the history of mineral exploration. Some of these legacy data have been donated to Wits Seismic Research Centre of the School of Geosciences, University of the Witwatersrand, for academic and research purposes. The details of these exploration programmes, including the acquisition and processing of these data, are reported by Pretorius et al. (2003).

The quality of some of the legacy seismic data from South Africa is poor when they only been preserved in published in paper copies, and it is difficult to judge existing geological interpretations. Moreover, some of the original data are unrecoverable due to tape deterioration. Therefore, recovering and reprocessing these legacy data become increasingly important for structural interpretation and to predict geological conditions in advance of the mining face. One advantage of analysing the legacy data is that they are less contaminated by noise originating from excavations and mining operations. We show, through case studies from the Witwatersrand Basin and Bushveld Complex in South Africa, that the increased resolution from reprocessing of the legacy data can lead to a better imaging of complex structural architecture that controls gold and platinum mineralisation. In addition, geological information from the reprocessed legacy data can be used to identify areas of interest and optimize acquisition parameters for new advanced seismic surveys.

Reappraisal of legacy seismic data for gold exploration and mine safety

Kloof-South Deep gold mine

The targets of Witwatersrand Basin exploration are the gold- and uranium-bearing quartz pebble conglomerates or 'reefs', which are mainly covered unconformably by the predominantly volcanic Ventersdorp Supergroup; the dolostone, shale, lava, and quartzite formations of the Transvaal Supergroup; and the shale and sandstone formations and coal seams of the Karoo Supergroup. The reefs are approximately 2 m-thick and their reflection coefficient relative to the enclosing quartzites is almost zero (with the exception of the Ventersdorp Contact Reef (VCR), which is interbedded between quartzites and basic lavas). Fortunately, reflections arise from marker horizons above and below the reefs, allowing the geological structure to be mapped (Pretorius et al., 2000; Manzi et al., 2018).

The 3D reflection seismic example from the Kloof and South Deep gold mines of the Witwatersrand Basin represents one of the world's first 3D seismic surveys acquired for mineral exploration. The 1987 South Deep and 1994 Leeudoorn (now Kloof) seismic surveys were acquired, processed and merged to form a single seamless Kloof-South Deep 3D seismic cube by a contractor, which was presented to Gold Fields Ltd in a report. The 1987 South Deep survey was the first 3D seismic survey to be acquired for mineral exploration in South Africa (Campbell and Crotty, 1990). Both 3D seismic surveys were acquired over a known gold deposit (i.e., VCR – Ventersdorp Contact Reef, located between 2 and 3.5 km depth), covering a major fault system (i.e., WRF- West Rand Fault with 1.5 km maximum throw). Figure 1a shows a 1994 seismic section, showing poor imaging of the fault zone and ore body (VCR) characterized by multiple amplitude anomalies. As seen in the original seismic section, the fault zone and ore body cut-off is not well defined. The legacy seismic section is dominated by strong noise, masking important reflections from the ore body. According to an unpublished report, the 1996 data were passed through normal moveout (NMO) and dip moveout DMO corrections, followed by poststack migration using the 3D finite difference algorithm. To improve the quality of the legacy data, we reprocessed the entire seismic volume, focusing on filtering

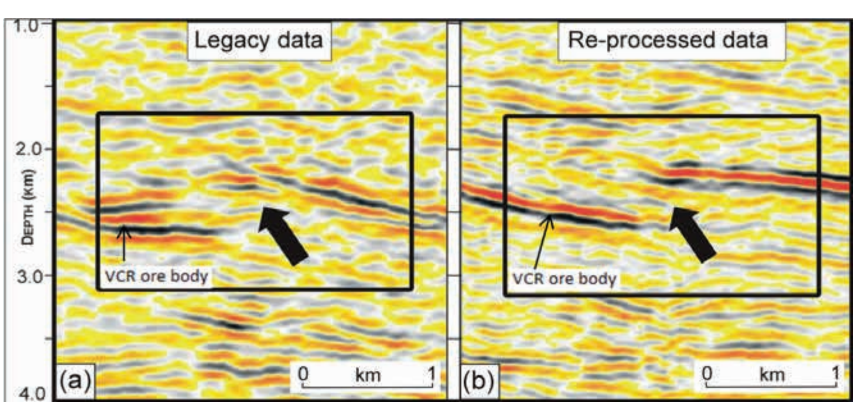

Figure 1 Comparison of legacy conventional data and reprocessed seismic data at Kloof-South Deep mine. (a) Legacy 1994 conventional data set processed through 3D poststack finite difference migration method. (b) Reprocessed seismic data using 3D prestack Kirchhoff time migration. Note that the new imaging algorithms show better resolution relative to the poststack depth migration that was originally applied to the same data, shown in (a). The new image shows better imaging of the fault's offset of the Ventersdorp Contact Reef (VCR) ore body.

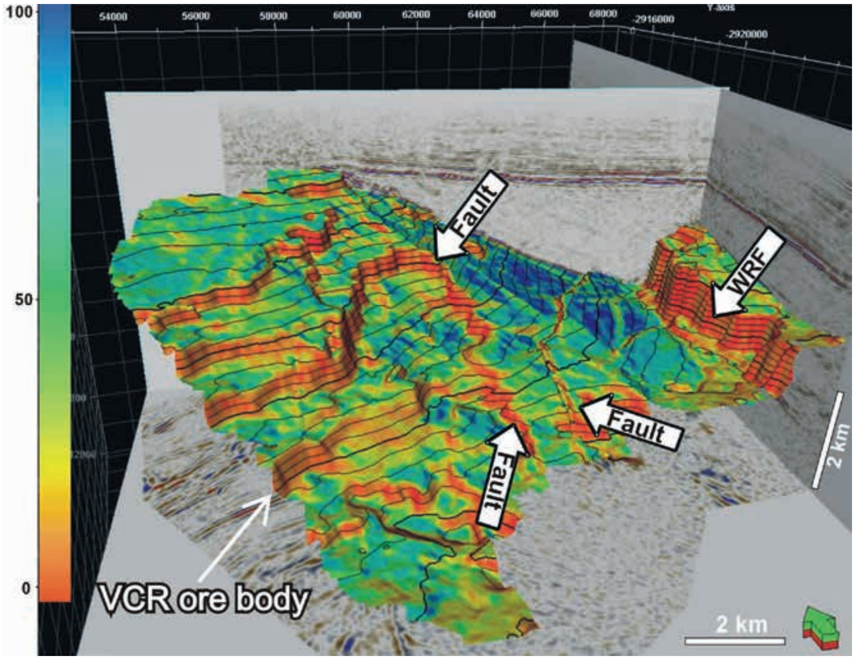

Figure 2 Ventersdorp Contact Reef (VCR) horizon-fault framework for Kloof-South Deep mine defined from the edge-detection seismic attribute (colour bar is given in percentages). The edge-detection attribute shows the successful imaging of faults. The attribute enhances the detection of the faults' continuity, bifurcation, and crosscutting relationships. The edge-attribute map also shows the West Rand Fault (WRF ~2 km maximum throw) that crosscuts the VCR ore body.

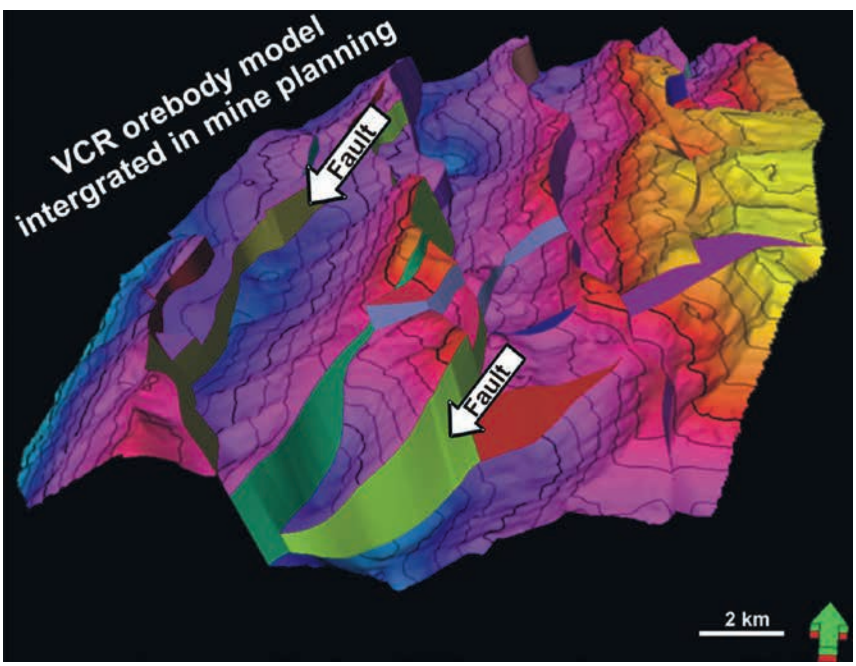

Figure 3 Final Kloof-South Deep ore body model with incorporated seismically mapped faults, which can be integrated into data mine packages for mine planning and design purposes. Note the crosscutting relationship between faults that is often difficult to see through drilling and/or underground mapping (Courtesy of Gold Fields Ltd).

shot gathers, velocity analysis and migration (Manzi et al., 2012a). Figure 2b is the reprocessed seismic section enhancing the fault and the continuity of the ore body more clearly. The application of filters to shot gathers, combined with improved velocity analysis and 3D Kirchhoff prestack time migration (PSTM), improved imaging of the ore body and steeply dipping faults (Manzi et al., 2012a; 2015). This example demonstrates the benefit of reprocessing of legacy seismic data for better delineation of the mineralized zones and steeply dipping faults at great depths.

New developments in 3D seismic attributes have made it possible to extract new information from the legacy seismic surveys (Manzi et al., 2015). The 3D edge-detection seismic attribute, in particular, is good at detecting faults that are not visible on seismic sections, emphasizing the high interconnectivity, bifurcation, and crosscutting relationships between faults that offset the ore body (Figure 2). The edge detection attribute was applied to enhance detection of horsts and anticlines that might bring the ore body to mineable depths; and grabens, synclines and thrust faults that might have preserved the ore body from erosion. Figure 3 is is the structural framework of the VCR ore body developed from the seismic attributes and structural modelling. These results were integrated with geological information to improve the understanding of the current major South Deep ore body model (Manzi et al., 2012b). With some 78 million ounces of resources and 29 million ounces of reserves, South Deep is one of the world's premier gold ore bodies.

Moab Khotsong gold mine

In this example, we show how the reprocessing of the legacy 2D seismic data can optimize the imaging of earthquake-prone

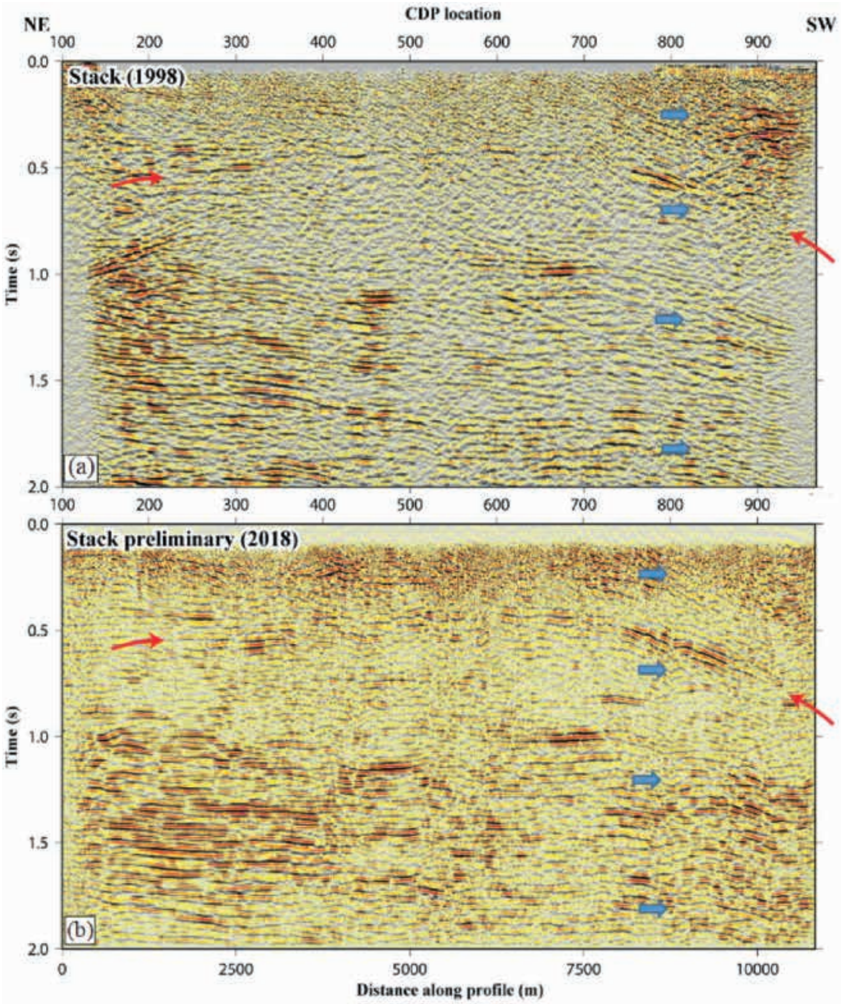

Figure 4 Comparison between (a) legacy stacked section processed in 1998 and (b) reprocessed (only preliminary at this stage) stacked section from the at Moab Khotsong gold mine. Note that the reprocessed section shows higher resolution, and better continuity of the reflections compared to the legacy section. The new section also shows better imaging of the fault's offset (shown by blue arrows) of the reflector (indicated by red arrows) located above the mining level.

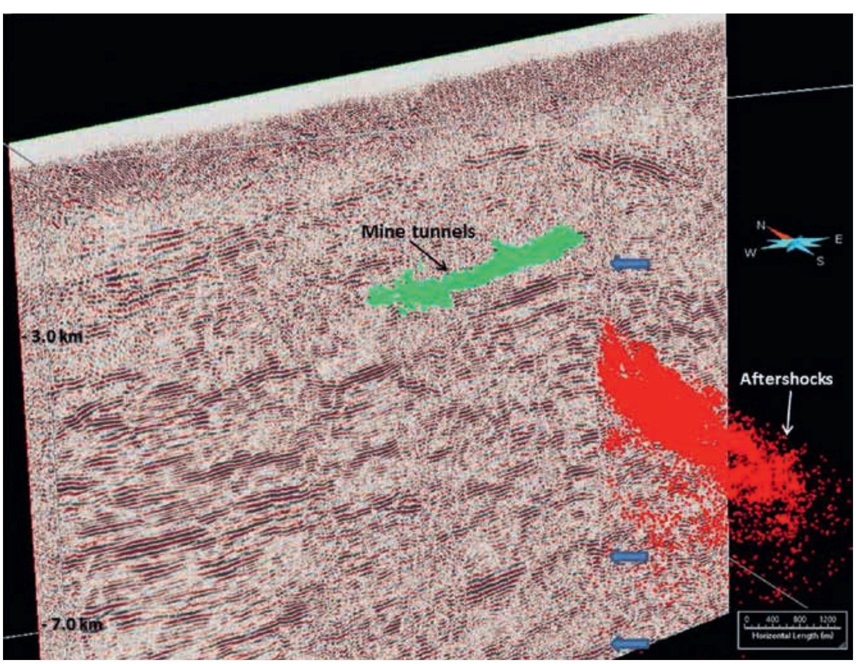

Figure 5 Integration of the reprocessed Moab Khotsong seismic section with aftershocks and mine workings (e.g., tunnels). Note that the reprocessed section shows the imaging of the geological structure (fault or dyke) that may have hosted the 2014 M5.5 earthquake that occurred in the Moab mining region in South Africa. There is strong correlation between the imaged geological structure and aftershock location.

geological structures, thus improving the mine planning and reducing mining risks posed by seismic events. Moab Khotsong mine is located in the Klerksdorp goldfields in the western region of the Witwatersrand Basin. The mine exploits the Vaal Reef ore body (VR~1 m thick) at depths between 2.5 km and 2.9 km below surface (Pretorius et al., 2000). The ore body is about 2 m-thick and does not have a significant acoustic impedance contrast relative to the enclosing quartzites, thus cannot be imaged directly by the reflection seismic method (Pretorius et al., 2003). However, its structure can be mapped by imaging reflective marker horizons above and below it.

In 2014, a seismic event of magnitude 5.5 took place near the Moab Khotsong gold mine. The in-mine dense geophone network and the surface strong motion network elucidated the aftershock zone dipping nearly vertically (Ogasawara et al., 2016). The 2014 M5.5 event and its aftershocks were located between depths of 3.5 and 7 km with a left-lateral strike-slip faulting mechanism on an unknown geological structure. The curiosity around this seismic event triggered our interest to retrieve, reconstruct co-ordinates, acquisition geometry and shot records of an 11km-long north-northeast trending legacy seismic profile cross-cutting the seismogenic zone. The objectives of this project were to (1) evaluate the nature of seismic reflectivity of the structures above and below the ore body, and (2) to image the geological structure that may have been reactivated and hosted the seismic event. The navigation information, which was restored from the available field documentations, such as observer logs, recording sheets and location maps obtained from the company's archives, formed the basis for an accurate reprocessing. The data were acquired using a vibroseis source at 50 m source and receiver spacing. The record length and sampling interval were 6 s and 2 ms, respectively. The recording was made using a linear sweep: 24 s, 10-90 Hz.

Figure 4 compares the legacy stacked section processed in 1998 by a contractor (Figure 4a) and our 2018 reprocessed stacked section (Figure 4b). Most improvement resulted from our prestack processing of gathers, which included time-variant band-pass filtering that increased dominant frequency when compared with the original processing, trace editing, and the application of surgical median filters to attenuate random and coherent noise. A general assessment of the two sections (Figure 4a,b) reveals that the reprocessed section exhibits higher signal-to-noise ratio (S/N) than the 1998 section. For example, the 1998 section exhibits a variable amount of noise in the upper portion of the sections (0-0.4 s), which may be source-generated noise or processing artefacts (Figure 4a). Data quality for the reprocessed section is good at the target level (~ 0.5 s) across the section and moderate at great depths (1.0-2.0 s) due to structural complexities (Figure 4b). Most importantly, the reprocessed section improves the seismic imaging of a steeply dipping structure (indicated by blue arrows) and continuity of a strong seismic reflection with variable dips, located between 0.5 and 0.8 s (shown by red arrows).

In general, the reprocessed results provide great insight into the complex geologic structurer around the M5.5 earthquake source zone. In particular, one of the steeply dipping dykes (indicated by blue arrows), possibly collocated with the steeply dipping fault zone, is imaged and interpreted to have been the locus of the M5.5 rupture due to its correlation with the aftershock locations (Figure 5). Identification of this structure is important for mine safety.

Reappraisal of legacy 3D seismic data for platinum exploration

Karee platinum mine

In this case study we have used seismic attributes, such as RMS amplitude and edge detection attributes, to improve the interpretation quality of the legacy 3D seismic data acquired for platinum exploration in the Bushveld Complex (South Africa). Seismic detection of faults, dykes, potholes and iron-rich ultramafic pegmatitic (IRUPs) bodies is of great importance to the platinum mining industry, as the variable distribution of these structures continues to be disruptive to the extraction of the economic resources from the platinum-bearing horizons (Carr et al., 1994). The legacy 3D seismic data covering the Karee platinum mine were acquired and processed in 1993 by Compagnie Générale de Géophysique (CGG), producing a final prestack time migrated (PSTM) volume that exhibits strong seismic reflectivity for shallow (< 100 m) and deep targets (> 100 m). Unfortunately, the raw data are no longer available for reprocessing of this seismic cube, hence the application of the post-migration seismic attributes to improve interpretation quality. There is also limited information available on the observer's reports on the acquisition and processing workflow conducted by CGG, and, thus, we are unable to provide the full details. The Karee platinum mine exploits two main platinum-group elements (PGE)-, chromium- and vanadium-bearing ore bodies, the massive chromitite layer (UG-2 reef) and Merenskey reef (MR), at depths greater than 500 m below surface (Hunt et al., 2018).

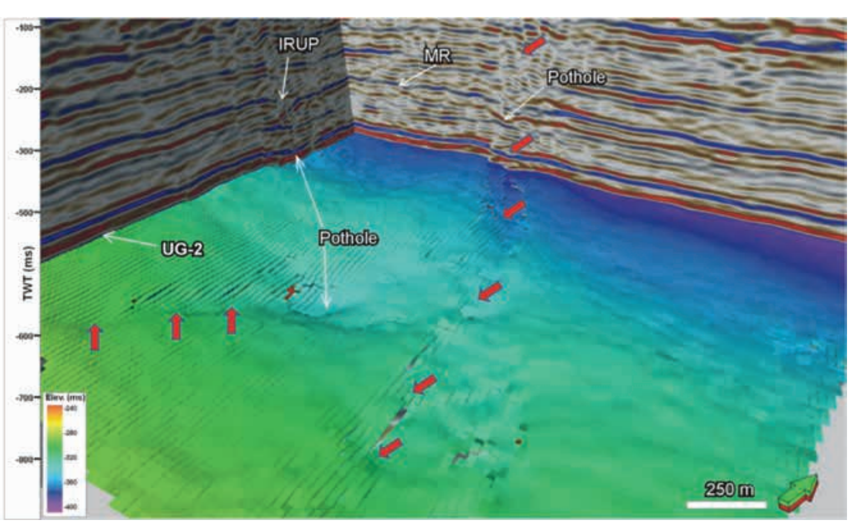

Figure 6 3D visualization of the 3D seismic data from Karee platinum mine. A time elevation map of the UG-2 horizon derived from conventional picking across survey areas, showing potholes and faults (indicated by red arrows) of all strikes and dips. TWT: Two-way travel time.

Figure 6 is an example of the seismic volume, showing the presence of geological structures (e.g., faults, IRUPs, and potholes) that affect the mining economic horizons at depths between 500 m and 2500 m. The time map (Figure 7a) and RMS amplitude map (Figure 7b) of the UG-2 horizon provide a first interpretation-pass indication of faults (indicated by white arrows) and potholes (shown in Figure 7c). Subsequently, edge detection attribute (Figure 8a,b) was computed to detect features that were not easily identified in the legacy time structure map. The edge detection map (Figure 8b) reveals some degree of potholing and faulting that is not observed in other maps (e.g., time structure map and RMS amplitude). For example, the relationship between the northwest-trending fault (F2) and ~ 500-m wide pothole is well defined in the edge detection map (Figure 8b), but not in the other attribute maps.

What also makes the application of the edge detection attribute remarkable is its ability to detect the geometry of a northwest-trending Marikana Fault (MF), shown in Figure 8a,b. For example, the edge detection map shows that MF splits to form a northeast-trending fault (F1), suggesting that the fault is a complex structure (Figure 8b). This structural relationship is important for mining, thus future mine development plans will need to be updated to take the new structural parameters into account. These faults and potholes, if under-sampled (missed), could significantly impede mine development, and their heaves (in the case of normal offset for faults) and their thinning (in the case of reef loss at the centre of the pothole) could translate into a decrease in the volume of the mineable platinum ore body.

Conclusions

Through case studies we have shown that, to get the most out of the legacy data, old files should be converted into new file formats to keep them accessible, readable and usable for future exploration projects. Case studies from the gold and platinum mining regions demonstrate that reprocessing and re-interpretation of the legacy seismic data using modern techniques can significantly improve the quality of the interpretations. In areas that are closed due to stricter environmental regulations, reprocessing of the legacy data may be the only option to obtain improved images of the subsurface. In cases where the raw data are no longer available, the quality of the structural interpretation can be improved by using state-of-the-art seismic attributes.

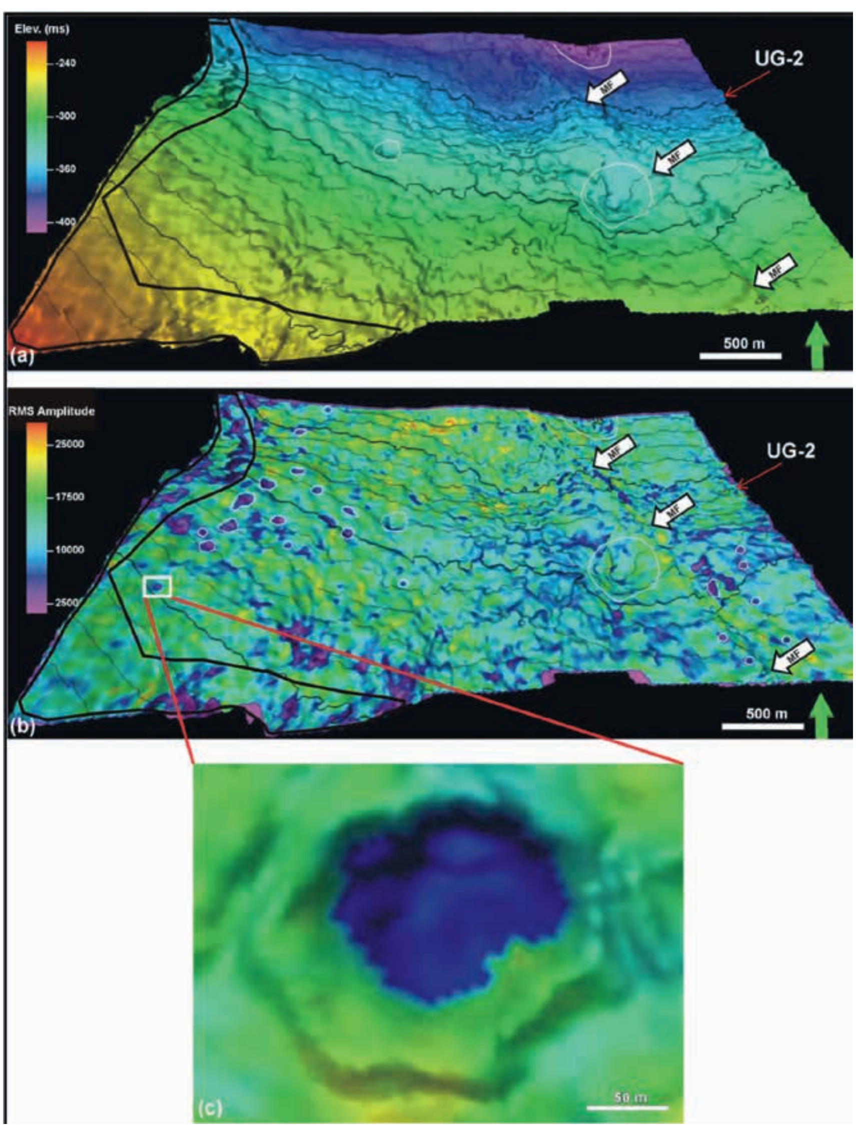

Figure 7 UG-2 maps of the ore body at Karee mine showing imaging of faults before and after the computation of the Root Mean Square (RMS) amplitude attributes. (a) UG-2 time map (gridded) showing imaging of faults (indicated by white arrows) and potholes (highlighted in white) through conventional interpretation. (b) and (c) UG-2 RMS amplitude map showing imaging of the faults (indicated by white arrows) and potholes (highlighted in white), mostly with throws as small as 50 m. MF: Marikana Fault.

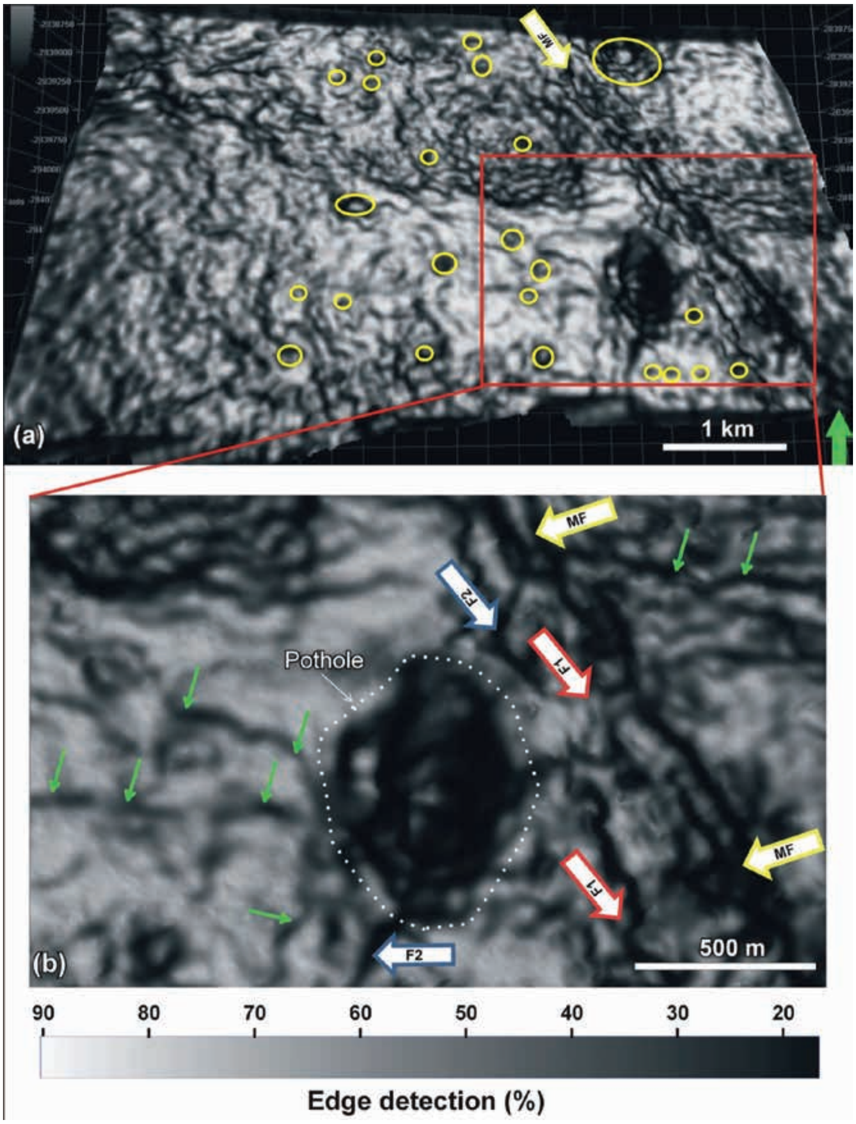

Figure 8 (a) UG-2 edge detection attribute map showing successful imaging of structures (potholes, as indicated by yellow circles or ovals, and faults) at this horizon. The north-northwest trending Marikana Fault (MF) (indicated by yellow/white arrows) is the major structure within the survey area. (b) The MF seems to branch into two fault segments (MF and F1), which was not observed using conventional interpretation. The attribute also shows imaging of a F2 fault cutting through a large pothole (~ 500 m diameter) and subtle faults with throws as small as 10 m (indicated by green arrows). Grey colour strips represent the subtle discrete or sharp edges on the horizon, which can be associated with low throw faults and small diameter potholes.

What made the reprocessing of legacy seismic data from Kloof-South Deep gold mines remarkable was the ability to image the continuity of the ore body and its associated structural architecture. Establishment of the continuation of the ore body may assist the mine in enhancing the resource calculation, financial valuation of the orebody and life-of-mine planning.

The case study from Moab Khotsong gold mine illustrates that reprocessing of the legacy seismic data may image steeply dipping structures (faults and dykes) that may host earthquakes and major risks to mining, especially in deep mine workings. The case study from Bushveld Complex demonstrates that, when no raw pre-stack data are available, the stacked legacy seismic data may benefit from post-stack processing using novel seismic attributes. In this example, the attributes reveal a complicated pattern of faults and potholes affecting the platinum horizons which were not visible on the legacy data. Based on the results presented in this paper, we anticipate that deep-seated mineral deposits may be discovered in the future through the reprocessing and interpretation of the legacy data using latest seismic algorithms.

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