The state-of-the-art in 3D orebody modelling: a case study of KDC East gold mine, South Africa

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ABSTRACT

The state-of-the-art in 3D modelling of the structurally complex orebody begins with (1) 3D seismic imaging, (2) horizon picking, (3) data conditioning, (4) fault detection, (5) fault-horizon projection, (6) data integration, and (7) statistical analysis. A variety of 3D seismic imaging and interpretation techniques have played an integral part in improving the quality of the orebody modelling for deep mineral mining industries. This paper presents the world-class model of the VCR orebody across KDC East gold mines (Witwatersrand Basin) as derived from the 3D seismic reflection data, underground geological mapping, and exploration boreholes. The re-processing of the 1994 seismic data using advanced seismic imaging algorithms, such as Kirchhoff prestack time migration (KPSTM), has increased the signal-to-noise (S/N) ratio of the data. The technique has proven to be effective in imaging the steeply horizons and structures (e.g., faults, dikes) in the areas characterized by major lateral velocity variations (such as the Witwatersrand Basin), compared to finite-difference poststack migration (PSDM).

The seismic attributes such as dip, dip-azimuth and edge detection have been successfully applied in delineating complex structural architectures, such as multiple fault bifurcations, intersecting and cross-cutting faults that cannot be interpreted using conventional picking on seismic sections. Consequently, these complex structures and their geometries were modeled and projected to the VCR horizon using the advanced modelling techniques derived from Non-Uniform Rational B-spline (NURBS). The computed compartment maps from the integrated data have resolved orebody compartment sizes below the dominant seismic wavelength (~124 m). Using these different techniques, a geologically reasonable 3D structural orebody model was developed. The model could be used for future mine planning and designs.

Key words: Witwatersrand Basin, 3D seismic imaging, seismic attributes, compartmentalization, orebody.

INTRODUCTION

The geologically complex Kloof-Driefontein Complex (KDC) East of South Africa hosts one of the richest gold orebodies in the Witwatersrand Basin, the Ventersdorp Contact Reef (VCR, ~1.5 m in thickness). The complex geometry of the VCR, the increase in mining depth, and inherit structural complexity of the mine make it difficult to place shafts and support infrastructure, or to operate the mines safely. This means that there are an increasing number of technical challenges in exploration and optimizing new resources, with rising costs and reduced effective mine designs.

3D SEISMICS

In the late 1980s, the 3D seismic reflection technique became the core geophysical tool for Witwatersrand gold mines, being used to delineate gold-bearing reefs, faults, dikes and folds. In 2003, Gold Fields Ltd.

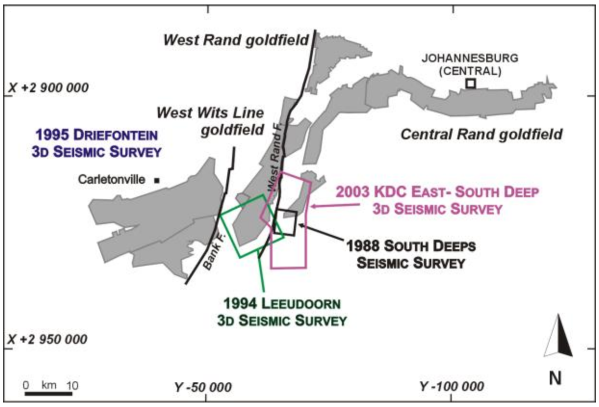

Figure 1. Location of the Kloof-Driefontein (KDC) East and South Deep seismic surveys (after Gibson et al., 2000).

conducted a high-resolution 3D seismic reflection survey (which overlaid the 1994 Leeudoorn survey), targeting the down-dip portion of the auriferous VCR in the KDC East (Fig. 1). Its application made the prediction of hazards along drilling trajectory possible. It facilitated optimum planning of drilling targets while mitigating risks.

Recent developments in a multitude of processing and interpretation techniques have motivated the re-processing and interpretation of the old 3D seismic datasets. In this paper, we present an innovative workflow for creating a world-class model of the orebody. The workflow includes the state-of-the-art in (1) 3D seismic imaging, (2) horizon picking, (3) data conditioning, (4) fault detection, (5) fault-horizon projection, (6) data integration, and (7) fault statistical analysis.

3D SEISMIC IMAGING

Prestack time migration

3D seismic imaging (or migration) is the most important step in the seismic processing workflow. Migration suppresses noise in the data and move seismic reflections to their true positions, and thus produces the best possible image of the surface. Today, a variety of migration techniques are implemented in the software packages for imaging complex structures or steeply dipping stratigraphy. These migration techniques are applied either in time or depth domain, pre-or post-stack.

To increase the signal-to-noise (S/N) ratio of the data, the 1994 Leeudoorn data was re-processed using Kirchhoff prestack time migration (KPSTM) technique. PSTM is a process by which each trace is migrated before stacking the common offset gathers. Kirchhoff migration is a non-recursive method that is based on Green’s function theory and on an integral solution of the wave equation (Yilmaz, 2001). The major advantages of the Kirchhoff prestack time migration (KPSTM) over other methods (e.g., finite-difference, diffraction summation) are its ability to compensate for amplitude due to spherical divergence or spreading factor, obliquity, and wavelet shaping factors (distortions of amplitude and phase during wavefront propagation) before stacking (Yilmaz, 2001).

The application of KPSTM to 1994 Leeudoorn data improved the imaging of the VCR, faults and stratigraphy when compared to the conventional poststack finite difference depth migration technique originally applied to the data (Fig. 2a, b). In addition, the technique has proven itself to handle lateral velocity variations, and thus allowing imaging of steeply dipping and overturned structures (e.g., synclines, anticlines). This is extraordinary evidence that the Kirchhoff migration is a superior imaging technique, especially in structurally complex areas.

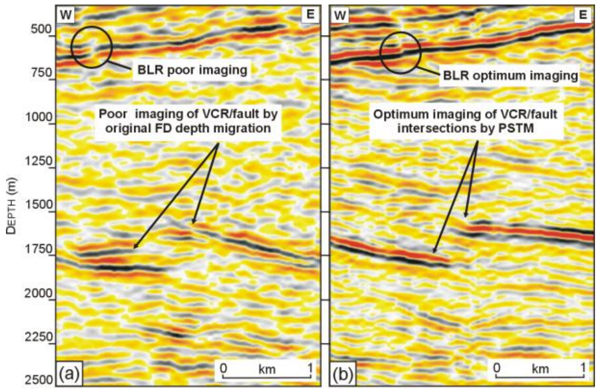

Figure 2: Depth-converted (amplitude display) seismic sections from 1994 Leeudoorn data. (a) The 3D poststack finite difference depth migrated (PSDM) section. (b) The 3D prestack Kirchhoff time migrated (PSTM) section.

SEISMIC INTERPREATION

The traditional seismic interpretation begins with the picking and tracking of outstandingly clear, strong and laterally consistent seismic horizons on migrated seismic sections at wide and short line spacing. The horizons and faults are picked along inline and crossline of the seismic sections. However faults with throws less than less the quarter dominant seismic wavelength (~25 m throw) cannot be detected through conventional interpretation, but may be detected through attribute analysis.

Data conditioning

After picking the VCR horizon data points in seismic sections (Fig. 3a, b), and prior to the computation of the seismic attributes, the data was smoothed using post-fault interpolation smoothing filters such as mean, median and bi-harmonic smoothing filters. The mean and median filters have the ability to enhance subtle laterally continuous events by effectively de-noising low S/N ratio areas in the VCR horizon image. While increasing the S/N ratio, the arithmetic mean and median filters tend to smooth both the noise and edges (faults), and extremely smear and distort the edges by shifting their positions. This problem was solved by using a bi-harmonic filter.

The bi-harmornic filter suppresses random noise and enhances the continuity of events while preserving acuity of the edges (faults) (Fig. 3c). The filter also enhances the detecting of subtle faults and filters the isolated horizon noise introduced by autopicking, and thus minimizing unrealistic fault geometries. It separates the gross structural configurations (long wavelength) from faults and dykes (short wavelength), and eliminate errors resulting from false complex geometries created by conventional picking around faults.

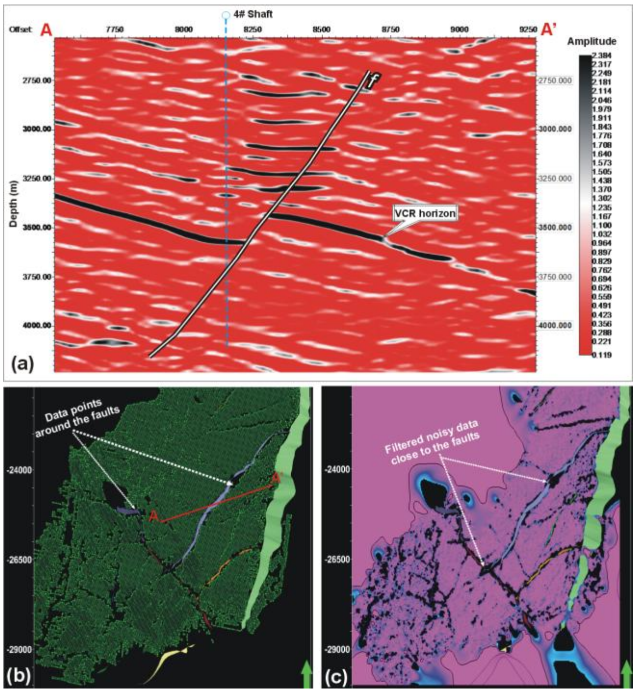

Figure 2. (a) Seismic section (amplitude display) across KDC East mine. (b) Manually picked and autotracked seismic horizon data points with low S/N ratio. (c) Smoothed horizon by a bi-harmonic smoothing filter.

Horizon-based seismic attributes

Seismic attributes have played an integral part in improving the quality and efficiency of fault detection in 3D seismic interpretations. Dip magnitude and dip-azimuth, introduced by Rijks and Jauffred (1991), have been found to be very useful in the detection of faults that fall below seismic vertical resolution limit. In simple form, dip and dip-azimuth are defined as the magnitude (or amount of inclination of a horizon) and the direction of the time gradient computed at each sample trace of the interpreted horizon grid, respectively. The dip attribute can only detect a fault when its dip angle is noticeably different from that of the horizon. Conversely, a dip-azimuth can only detect a fault whose dip direction is distinctly opposite to that of the layers (Manzi et al., 2012b). To overcome the problem of differences in detectability, we computed the edge detection attribute to the bi-harmonic smoothed VCR horizon.

The edge detection attribute is basically a combination of dip and azimuth variations that are normalized to the local noise of the picked horizon grid (Manzi et al., 2012a). This attribute, when displayed in suitable colour bars, highlighted subtle faults and complex fault architectures such as fault connectivity, fault continuity, multiple fault bifurcations and crosscutting relationship between fault systems (Fig. 4). Such small details and complexity were not detected by dip, dip-azimuth and conventional interpretations in the seismic vertical sections (**Figure 4**).

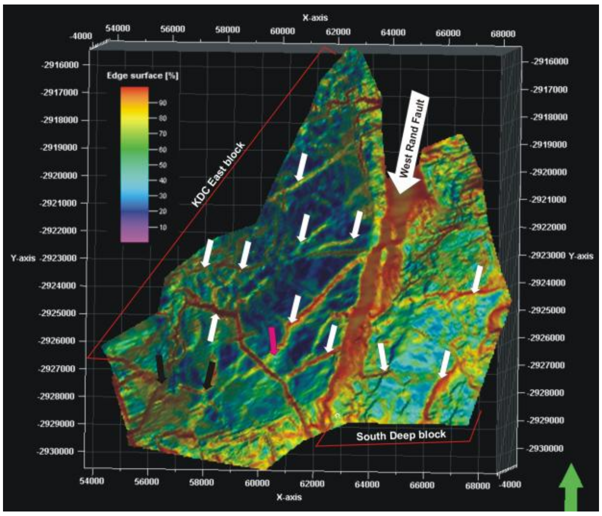

Figure 4. 3D visualization of the VCR edge detection attributes through KDC East and South Deep surveys. Map shows optimum imaging of faults cross-cutting relationships (indicated by black arrows) and faults bifurcations (indicated by dark pink arrows). The West Rand Fault is the major structure separating KDC East and South Deep gold mines.

DATA INTERGRATION

Even with a very good edge detection technique, features such as thin dikes, near-vertical faults, and subtle faults with offset as low as 1-2 m cannot be detected because they are well below seismic resolution limit. Thus an orebody model derived solely from seismic data may under-estimate the size-frequency distribution of faults and spacing of faults that offset the orebody within mineable blocks. To avoid this, the seismic model and geological mapping model were integrated (incorporating dikes and faults) and computed the spacing of faults or compartment maps (Fig. 5 a, b).

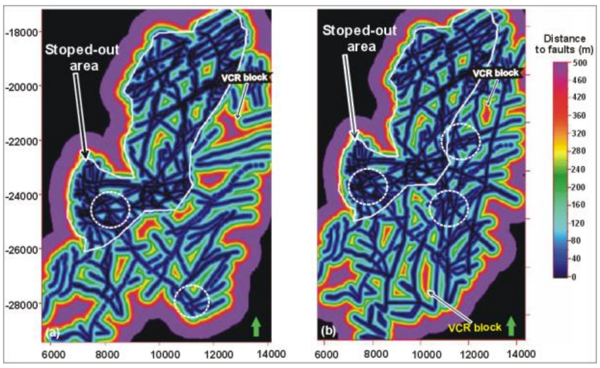

Figure 5. (a) VCR Compartment size maps derived from seismically defined faults. (b) Compartment size maps derived from the integration of seismically defined faults and underground mapped faults and dykes. White dotted circles represent zones of

mining risks.

The results show that the seismic data predict overly large unfaulted compartments (150-500 m), indicating that the technique under-estimated the number of dikes that offset the orebody (Fig. 5a). On the other hand, the integrated data model even resolved the small compartment block sizes (50-500 m) that are even below the horizontal seismic resolution limit (124 m) (Fig 5b).

MODELLING

The structural complex architectures (such as cross-cutting and antithetic faults, fault and dykes juxtapositions, and fault multiple bifurcations) that characterized the VCR orebody were interpolated and projected into the VCR seismic horizon using an advanced modelling technique (derived from Non-Uniform Rational B-Splines (NURBS)) (Foley, 1994). The NURBS-based modelling technique provided a great flexibility in moving the 'fault sticks' (3D fault and dike surfaces) through their 'pillars' (edges of fault sticks) into their true appropriate positions in the VCR horizon (Fig. 6a, b). In contrast, conventional modelling techniques create 3D horizon-fault curve geometries that are jagged, since they cannot model curving, intersecting and cross-cutting faults.

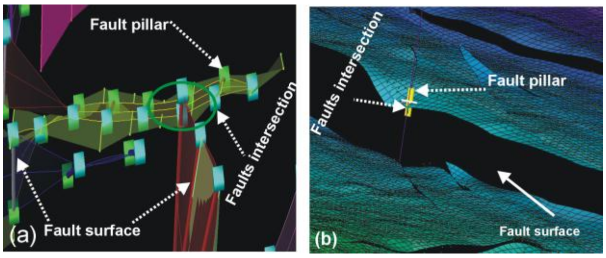

Figure 6. Modelled fault surfaces and fault pillars) using NURBS-based modelling technique.

Finally, the structurally complex orebody model developed was transferred into mine software packages for future mine planning and design (Fig. 7).

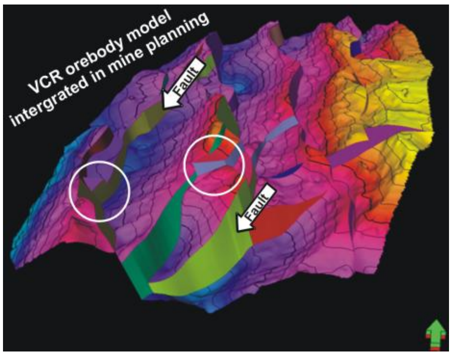

Figure 7. 3D structural orebody model in mine software packages (e.g. AutoCAD).

CONCLUSIONS

This paper has presented the state-of-the art approach used to develop a world-class structural model of the Ventersdorp Contact Reef orebody at KDC East gold mine. The use of Kirchhoff prestack time migration technique in the processing workflow significantly improved the signal-to-noise ratio of the old data, thus improving the imaging of steeply dipping horizons and structures (faults and dikes). Careful analysis of the data conditioning techniques (e.g., mean, median and biharmonic filtering operators) and horizon-based seismic attributes (e.g., dip, azimuth and edge detection) have enhanced the detection of complex structural architectures and subtle features that offset the orebody by throws as small as 10 m. The newly invented NURBS-based modelling technique in the modelling software packages has enabled the projection of complex fault architectures in the orebody model, and thus minimizing risks associated with deep underground gold mining.

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