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The Ventersdorp Contact Reef model in the Kloof Gold Mine as derived from 3D seismics, geological mapping and exploration borehole datasets

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ABSTRACT

A model of the Ventersdorp Contact Reef (VCR) orebody at Kloof Gold Mine was derived by integrating 3D reflection seismic data with information derived from underground mine mapping and exploration drilling. The study incorporated the depth-converted prestack time migrated (PSTM) seismic cube, the mine geomodel, faults and dikes mapped in excavations, mine development infrastructure, and intersections of the VCR by surface and underground exploration drilling. The 3D seismic data provide an accurate geometric model of the VCR orebody and its offsets. The underground mapping datasets help to define minor faults and dikes that are below seismic resolution limits. The integration of the these datasets allowed (1) for better mapping of fault architectures and distributions within the lease area, (2) definition of the likely zones of difficult ground conditions around seismically imaged dikes and faults, and (3) better predictions of the number and spacing of faults that offset the VCR within minable blocks. The model is useful in mitigating both economic and safety risks of deep mining.

1. Introduction

The Archean Witwatersrand Basin of South Africa has been the world's largest known gold deposit since its discovery in 1886. Almost 60 kt of gold has been mined, with a retained reserve estimated at 35 kt gold [1]. Gold occurs in conglomerate units known as reefs, which vary in thickness from 10 cm to 5 m. Gold mining in several goldfields takes place at depths ranging from about 500 m to 4500 m below surface [1–4].

Initially orebody models were based on geological mapping, exploration drilling, and interpretation of gravity and magnetic data [5–8]. However, these techniques lacked the resolution and areal coverage needed to generate robust geological models of deep ore bodies [8,9]. In the late 1980s, the 3D reflection seismic method became the core tool for final stage exploration and feasibility studies [10].

The application of 3D seismic techniques in the Witwatersrand gold mines has been reported by Gibson et al. [4], Pretorius et al. [6,7], and Malehmir et al. [10,11], among others. A multitude of processing, interpretation and structural modeling techniques have been developed in recent decades, making it worthwhile to re-process, interpret and model old 3D seismic datasets. By using these techniques, it is now possible to generate a state-of-the-art 3D orebody model that unravels structural complexities such as intersecting and cross-cutting faults. However, the 3D seismic technique, like any other geophysical prospecting technique, has its specific limitations [12].

Firstly, many seismically-derived horizon models suffer from major depth misties when correlated with the borehole controls. This is commonly the result of inaccurate velocity fields that are used for migration (either pre- or post-stack) and the conversion of travel times to depth during processing. In structurally complex areas such as the Witwatersrand Basin, lateral velocity variations make the velocity analysis a challenging task [13]. This is because seismically-derived models are fundamentally developed from the seismic travel time data that has been corrected for depth using complex velocity fields. A constructed geological model is therefore dependent on how well the velocity fields have been approximated at various seismic processing stages. Furthermore, the velocity fields for migration and subsequent time-to-depth conversion processes are, in turn, dependent on the number and distribution of boreholes. A variety of techniques have been proposed to improve velocity analysis in complex areas during prestack migration processing stages [13,14]. Unfortunately, apart

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from the reprocessing of the datasets, there is currently little that can be done to correct for the large uncertainties of depth misties between seismic horizon models and borehole controls, especially when the inaccurate seismic velocity field has been used for migration and subsequent time-to-depth conversion.

Secondly, the resolution of fault imaging is primarily a function of the dominant frequency and the signal-to-noise ratio (S/N) of the field data. The seismically-derived ore horizon models are also dependent in the S/N of the picked seismic horizons. Faults have a number of effects, almost always undesirable, on underground gold mining. These effects include: (1) physical displacement of gold-bearing reefs that may make the reefs impractical to mine, (2) reducing the stability of the mining hangingwall in underground workings, and (3) they may act as conduits for ingress of water and flammable gas into underground workings. Faults have their origin and evolution in a range of processes such as compression and extension. It is important to effectively recognize faults in the seismic data and determine their orientation and amount of vertical displacement (throw). This type of information can assist in (1) the unraveling the fault generation mechanisms and timing, (2) mitigating the risk of falls of ground or rockbursts ahead of mining. Furthermore, faults can exhibit complex structural architectures such as multi-fault segments that bound orebody blocks, multiple bifurcations from a single plane to form a branched fault array, and late faults that crosscut and offset fault systems. These features have significant impact on mine development. Failing to identify fault (and dike) arrays is risky in terms of mine planning and design.

In studies by Manzi et al. [15,16], various seismic interpretation techniques, including edge detection attribute analysis, were used to image faults with throws as small as 10 m. However, Gibson et al. [4], Manzi et al. [15,16], and [17] showed that regardless of the quality of the seismic data, there are always smaller faults that offset the orebody that cannot be imaged, and have a significant impact on mine development. Even with a very good 3D seismic survey design, state-of-art processing and interpretation capabilities, features such as thin dikes, near-vertical faults, subtle faults with offset as low as 1–2 m and which displace the gold-bearing reef by more than the stoping height, cannot be directly imaged by seismics because they are well below seismic resolution limit. For example, seismic data with dominant frequency of 50 Hz and high S/N can resolve faults with throws as small as 5–10 m, while seismic data with low S/N can only resolve faults with throws of 25–30 m.

Thirdly, structural imaging and fault horizon models derived solely from seismic data depend on factors such as the 3D seismic survey design, the skills and experience of seismic processor and interpreter; and the time given to perform the interpretation. Therefore, taking a 3D geological model constructed from seismic data only as a true and final geological model may be inaccurate. Faced with a wide range of uncertainties, it is necessary to incorporate other models based on, for example, datasets such as underground mapping and exploration boreholes. Quality geological mapping data, in particular, is extremely useful when attempting to model faults and dikes that fall below seismic resolution limits.

In this study we derive the model of the Ventersdorp Contact Reef (VCR) orebody in Kloof Gold Mine, by integrating 3D seismics, geological mapping and exploration borehole datasets. To generate a robust orebody model we, (1) minimize the impact of depth misties in the seismic defined VCR ore horizon through the application of a depth-error gridding method, and (2) correct for lateral mis-positioning of structures in the seismic model by testing errors between seismic amplitude and underground infrastructures such as shafts and excavations.

Importantly, given that a prolonged period of mining and associated mine mapping has occurred across a large area of the Kloof Gold Mine, we extend studies by [18] in using 3D seismics to interpret the stoped-out areas adjacent to development areas. By doing so, we are able to assess and estimate how many of the seismically invisible structures are likely to be present in development areas and use these data to enhance a geological model of the VCR orebody. To achieve this goal, we determine and then apply a series of fault statistics from well-mapped structures immediate to the area of interest. These statistics include measuring the size-frequency distribution of faults (mainly normal faults), computation of fault attributes (e.g. dip), fault spacing, fault throw (vertical component of the displacement) and fault heave (horizontal component of the displacement) for various geometries across the study area. These statistics are important when attempting to define likely face advancement rates, scheduling and ultimately bulk production rates and tonnages. They also help define the zones around the seismically-imaged structures where difficult ground conditions are expected, and predict the number and spacing of faults that offset the orebody within minable blocks. This type of statistical analysis is undertaken for the first time in the Witwatersrand Basin.

In the past two decades, it has become clear that there are well-defined fractal relationships between fault throw and the size-frequency distribution of faults [19,20]. These values vary greatly between different suites and the age of structures. The historic geological mapping data from Kloof Gold Mine provide a superb database from which to derive these statistics.

2. Kloof gold mine

2.1. Mining history and prospects

The Kloof Gold Mine is owned and operated by Sibanye Gold (subsidiary of Gold Fields Limited). The mine is the product of an amalgamation that took place in April 2000 of the Libanon, Kloof, Leeudoorn and Venterspost mines under Gold Fields Limited, and forms the western part of the Kloof–Driefontein Complex (KDC). Prior to the amalgamation, the Kloof Gold Mine operated as a separate entity and was granted a lease to mine down-dip of the Libanon mine at depths between 2.5 and 3.7 km.

Kloof Gold Mine is a critical asset of Sibanye Gold. Of its 83 million ounce resource base, approximately 29 million ounces are situated below current shaft depths. The 3D seismic survey explores these areas, which are critical to ensuring long-term sustainability beyond 2021.

Geographically, the Kloof Gold Mine is located in the West Wits Line goldfield of the Witwatersrand Basin, 65 km southwest of the city of Johannesburg (Fig. 1). The major portion of the mining lease area is situated in the West Wits Line goldfield, but the northerly portion straddles the boundary of the West Rand goldfield (see Fig. 1). Four gold-bearing reefs are exploited, namely the Ventersdorp Contact Reef (VCR), Kloof Reef (KR), Libanon Reef (LR) and Middelvlei Reef (MR). The VCR represents 93% of the reserve portfolio, while 4% comes from MR and 3% from the KR and LR collectively. The VCR is one of the richest ore horizons in the Witwatersrand Basin goldfields.

The mining area in Kloof comprises five producing shafts that mine varied contributions from remnant pillars and virgin reefs. The Kloof Gold Mine has an estimated reserve of 44.1 Mt for a Life of Mine (LoM) head-grade of 13.9 g/t gold. These are planned for depletion by 2021 at an average production rate of 170,000 t/month. The deepest mining level of the orebody is at 3.347 km below surface and the total gold production is averaged at 1667 kg/month at an average yield grade of 6.0 g/t.