Enhanced geological modelling of the Upper Elsburg reefs and VCR to optimize mechanized mine planning at South Deep Gold Mine

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Synopsis

South Deep Gold Mine, owned by Gold Fields Ltd., is situated near Westonaria in the Gauteng Province of South Africa and mines the conglomerate bands of the Upper Elsburg reefs (Mondeor Conglomerate Formation) of the Witwatersrand Supergroup and the Ventersdorp Contact Reef (VCR) of the Ventersdorp Supergroup. The stoping and underground developments are mechanized. The Upper Elsburg reefs are mined by a variety of mining methods, including mechanized drift and fill, modified drift and bench, longhole stoping, and low-profile mining. Optimal mine design and scheduling for deep-level mechanized mining are complex, and success is highly dependent on detailed, robust, and accurate geological and geostatistical models.

Geological structures significantly influence the sedimentological characteristics, distribution, and preservation of the Upper Elsburg reefs and VCR. Accordingly, particular emphasis is placed on the generation of a mine-scale structural model that accommodates the relationships between the older north-trending fault systems (West Rand and Panvlakte faults) and younger east-trending dextral wrench faults. Results from underground mapping, borehole intersections, and high-resolution three-dimensional seismic data have been integrated to produce coherent three-dimensional geological models.

The Upper Elsburg reefs suboutcrop against the VCR and comprise an easterly diverging clastic wedge, thickening from the suboutcrop position, to approximately 130 m at the mine's eastern boundary. The Upper Elsburg reefs are characterized by conglomerate and quartzite bands forming multiple, stacked, upward-fining unconformity-bounded couplets. Palaeocurrent directions are dominantly from west-northwest to east-southeast, indicating that the more proximal deposits are preserved close to the suboutcrop, with distal facies to the east.

Sedimentological modelling is applied to individual stratigraphic units and caters for facies definition. This is achieved through channel width (CW) kriging and fitting of type sections to borehole and mapping data. Homogenous geological geozones for each stratigraphic unit are thus defined within individual structural blocks on the basis of those sedimentological parameters that have been found to have a positive spatial correlation to gold concentration. These geozones then serve as constraints to the evaluation of the orebody.

This contribution presents a summary of the modelling processes that are currently applied in the development of high-confidence, timeously produced geological models that are essential input for mineral resource estimation and mechanized mine planning and scheduling.

Keywords

Witwatersrand Basin, West Rand Goldfield, South Deep Gold Mine, Upper Elsburg reefs, VCR, geological modelling, mine planning and scheduling, gold distribution, channel width.

Introduction

Location

South Deep Gold Mine is located some 40 km southwest of Johannesburg near the town of Westonaria. It is accessed via the N12 highway between Johannesburg and Kimberley and the R28 route between Randfontein and Vereeniging. Geologically, the mine is situated in the West Rand Goldfield on the northwestern limb of the Witwatersrand Basin (Figure 1).

This contribution aims at detailing the geological modelling approach as recently developed and refined at South Deep Gold Mine. Accurate and timeous geological modelling is of prime importance to resource estimation, mine planning, and scheduling, and the mining methods are therefore also detailed.

Geological background

The macro-structure of the West Rand area is characterized by older north-trending faults (West Rand and Panvlakte) and younger east-trending dextral wrench faults (Waterpan and Wrench; Figure 2). This faulting has resulted in the development of structural blocks dominated by the West Rand (or Witpoortjie) and Panvlakte Horst blocks that are superimposed over broad folding associated with the southeast-plunging West Rand Syncline. The northern limb of the syncline dips towards the south-southwest, and the southern limb to the east-northeast.

Although some of the later dykes strike in an easterly direction, intrusives are dominantly north-trending Ventersdorp, Bushveld, and Pilanesberg age dykes. The geological structure plays a significant role in determining the sedimentological characteristics and the distribution and preservation of

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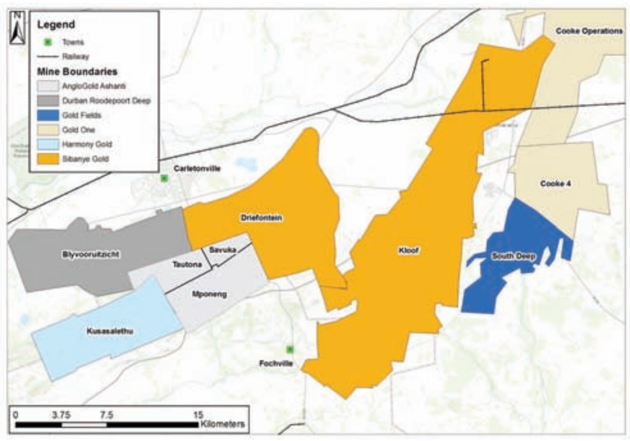

Figure 1—Locality plan of South Deep Gold Mine

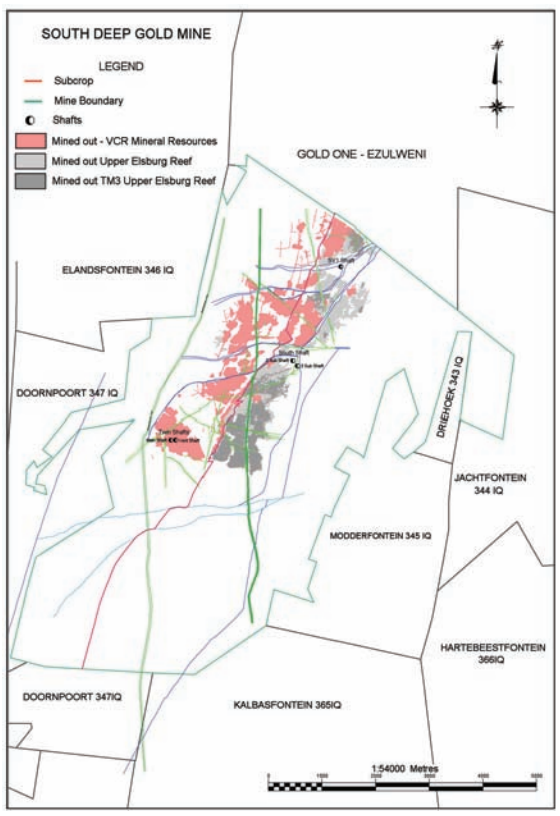

Figure 2—Major structures in the South Deep mining area. Dykes are in dark green, faults in blue

the auriferous reefs. Accordingly, the geological and resultant grade models must take cognisance of the position, displacement, and fault relationships by defining zonal boundaries that correlate with these structures as well as other geological variables.

On surface, the mine lease area comprises an undulating topography where the bedrock is largely covered by residual soils and alluvium. Outcrops are dominated by rocks belonging to the Pretoria Group of the Transvaal Supergroup that have a regional dip towards the south at less than 10 degrees. Poorly exposed outliers of younger rocks (Karoo Supergroup) have been observed in the northern portion of the lease area.

The youngest Transvaal strata are interbedded andesitic lava and tuff of the Hekpoort Formation that outcrop to the south of the mine infrastructure. They attain a maximum thickness of 260 m and are underlain by up to 550 m of quartzite and interbedded shale of the Timeball Hill Formation. These sediments are best exposed on the east-trending ridges that dominate the northern portion of the mine lease.

The Pretoria Group rocks are underlain by a 1 300 m thick sequence of sediments, predominantly dolomite and chert, belonging to the Malmani Subgroup of the Chuniespoort Group, which forms the basal unit of the Transvaal Supergroup. The lowermost 20 m of the

Chuniespoort Group is occupied by the Black Reef Quartzite Formation.

Below the sediments of the Transvaal Supergroup is a 1 500 m thick sequence of basaltic lava belonging to the Klipriviersberg Group of the Ventersdorp Supergroup. These rocks, in turn, form the hangingwall of the gold-bearing reefs (Figure 3).

The Ventersdorp Contact Reef (VCR) marks the contact between the Central Rand Group sediments and the Klipriviersberg lava and is deposited on a major regional unconformity.

Within the mine lease area, the VCR is best developed west of the Upper Elsburg suboutcrop. The Upper Elsburg Individuals and Massives, which are comprised of conglomerate with interbedded quartzite, form part of the Waterpan and Modderfontein Members that constitute the upper portion of the Mondeor Conglomerate Formation, Turffontein Subgroup (SACS, 1980; Figure 4). It is these auriferous conglomerate units that are the main mining target at South Deep. The Upper Elsburg reefs occur as a clastic wedge composed of 15 units with a rotational onlap and a disconformity between each unit. The clastic wedge diverges from the suboutcrop against the VCR in the central portion of the mining rights area to a maximum vertical thickness of approximately 130 m at the eastern boundary (Figure 4). The suboutcrop against the VCR trends at a bearing of approximately N23°E, forming a divergent clastic wedge at approximately right angles to the suboutcrop.

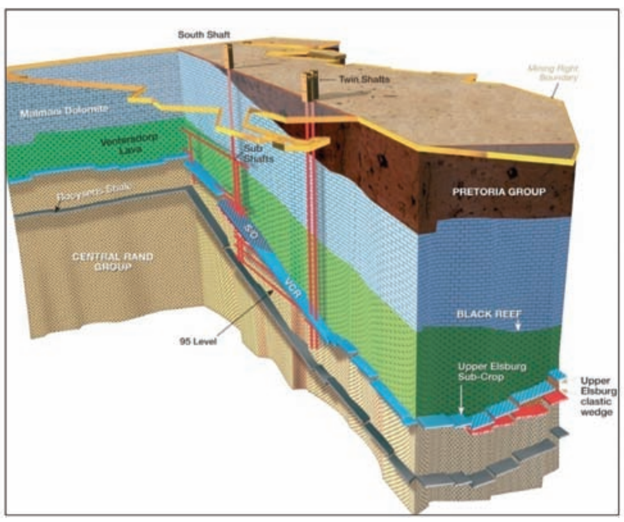

Figure 3—Schematic isometric diagram illustrating the stratigraphic sequence at South Deep Gold Mine (Gold Fields Ltd, 2011)

Mining methods

South Deep has evolved into a fully mechanized mining operation with the last conventional mining taking place in early 2008. Mining currently takes place up to 2 700 m below the surface. Currently, three mining methods are utilized to supply ore to the plant.

Drift and bench mining

Drifts are linked to drift accesses and advance at 3.7 m per blast during the primary drift mining phase. Bench accesses are mined from the opposite direction at a lower elevation (Figure 5). Benches are mined by drilling vertical blast-holes and cleaned through remote loading. Finally, when a bench is mined out, it is backfilled and the neighbouring drifts and benches are accessed and mined.

Longhole stoping

Top and bottom drives are mined to access the longhole stope (Figure 6). A slot raise is developed between the top and bottom accesses to create a free-breaking face. The slot is approximately 15 m in height, equal to the width of the planned longhole stope. Blast-holes emulating a fan are drilled from either the top or bottom access. These blast-holes are usually referred to as a ring, and typically three rings are blasted at one time, delivering approximately 4 060 t of rock per blast. After cleaning through remote loading, further rings are blasted until the entire stope is extracted.

Destress mining

Stope access drives are mined from the main access drive (Figure 7). Out of the stope access drives, stoping drives are mined sequentially and then backfilled. Upon completion of backfilling the stoping drive, the stoping access drive is advanced to access the next stoping drive.

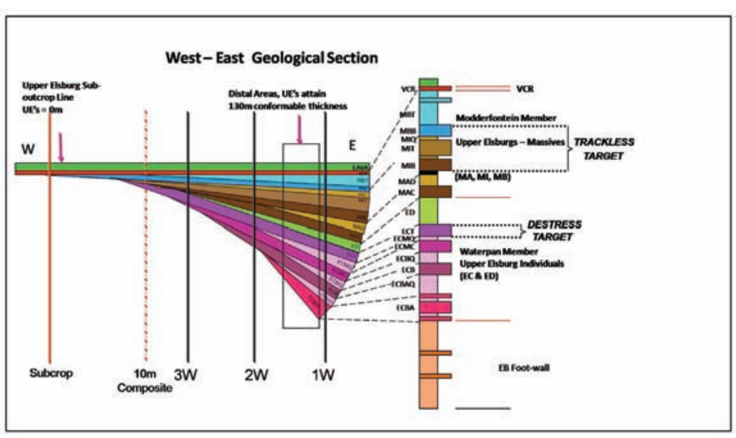

Figure 4—Schematic section through the 15 Upper Elsburg reefs and VCR at South Deep

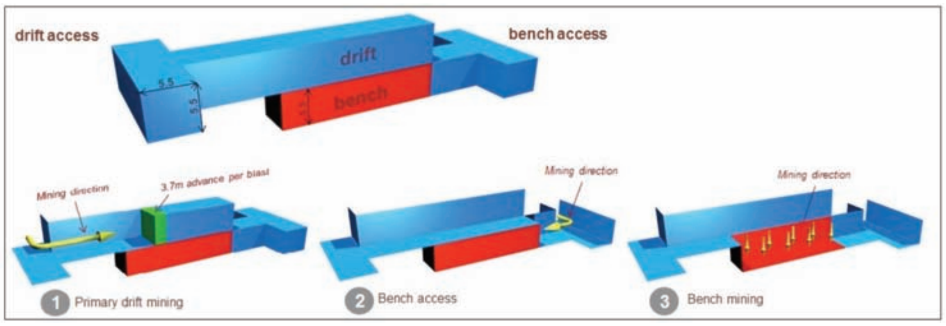

Figure 5—Sequence of mining and mining direction during drift and bench mining (Gold Fields Ltd, 2011)

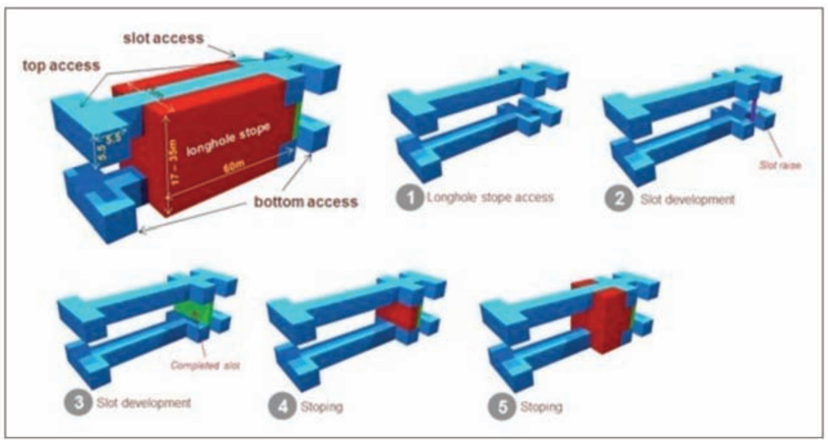

Figure 6—Sequence of mining and stope development during longhole stoping (Gold Fields Ltd. 2011)

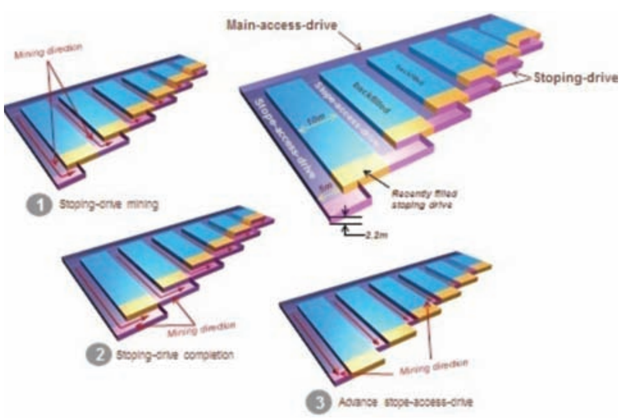

Figure 7—Sequence of mining and stope development during destress mining (Gold Fields Ltd. 2011)

The orebody has a shallow dip of between 15° and 20° towards the south. This dip is steeper than the maximum inclination at which mechanized mining can take place, therefore destress mining is done horizontally. Drift and bench mining cannot take place at an apparent dip of more than 8°, thus this mining method is used only in areas where selective mining is viable. Due to the scale of these mining methods, no attempt is made to separate the quartzites from the gold-bearing conglomerates. All extracted material (ore and waste) is sent to the plant for processing.

Domaining

It is recognized that there is a strong correlation between sedimentological parameters and gold distribution within the Upper Elsburg and VCR sediments. Sedimentological data is captured in both exploration and grade control drilling programmes and includes parameters that have been found to correlate closely with grade distribution. These are, in order of precedence: channel width (CW, in metres), percentage conglomerate (%), and average clast size (millimetres). Modelling considers both the proximal/distal relationship and channel morphology within a specific unit. Higher grades are associated with proximal rudaceous phases, while lower grades occur distally.

Spatial plots of grade and sedimentary data are employed to define homogenous areas for each parameter within a defined structural block and unit. The first step is to produce a plot of the raw data to create a reference point for future processing. All raw data is obtained from validated borehole logs and assays. Histograms and cumulative frequency plots of the raw data determine the optimal intervals for the generation of gridded, classed data plots and contour plans. These are ultimately utilized to define homogenous area boundaries (Figure 8).

These individual parameter boundaries are then overlain to define overall geological facies boundaries within a block. The geological facies in each block are then compared to those in other blocks and, where facies with similar characteristics

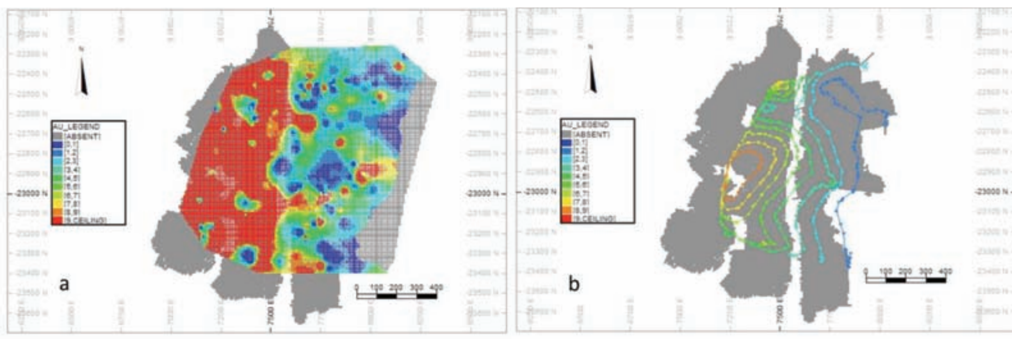

Figure 8—(a) Class plot of gridded Au values (MBB Reef), and (b) contour plot of Au values (MAC Reef). Current mining areas are in grey as shown in Figure 2

are identified, they are amalgamated to produce an overall geozone with a unique grade and sedimentary signature. Within each geozone, grades are assumed to be homogenous, and interpreted to be a realization of the stationarity random function (Duke and Hanna, 2001). When reconciled, a close resemblance between geozone estimates and actual reef characteristics, including grades, is encountered.

All estimation is confined within the boundaries of the defined geozones ('hard boundary'). 'Soft' boundaries are drawn as a perimeter around the hard bundaries and have been introduced to facilitate estimation along the edge of a geozone where insufficient data is available within the defined search radius. The use of soft boundaries is applied only where a geological relationship exists with the adjacent geozone, i.e. where geological evidence suggests that the boundary in question coincides with a gradual transition between geological environments, such as proximal/distal relationships.

The soft boundary of a geozone will incorporate the samples of the transition zone, i.e. the area between the hard and soft boundaries (Figure 9). The incorporation of additional data improves the confidence of the estimate.

In the absence of geological continuity across a geozone boundary (i.e. where samples at close proximity to each other are deemed unrelated), such samples will be excluded by the hard boundary and have no influence on the estimation. Typically this occurs where geozones are separated by faults that are known to have a significant lateral displacement (Figure 9).

Prior to estimation, histograms and trend plots are generated to indicate any modality or drift in the data that new borehole intersections may have introduced into the geozone (Figure 10).

Further improvements to the stationarity of geozones are achieved by evaluating various corridors of consistent length and width along the area of interest. Comparison of the statistical characteristics of each corridor reveals, whether geozones are appropriately defined or if further refinement is required (Figure 11).

Geological modelling

Geological modelling history

A seismic survey of the mine lease area was conducted in the late 1980s. The information obtained from the seismic survey points formed the basis for the evolution of the early three-dimensional (3D) geological models. At the time, it was general knowledge that the orebody comprised the Upper Elsburg reefs as well as the VCR, which unconformably overlies the Upper Elsburg reefs. Since the early 2000s the Upper Elsburg reefs have been modelled as four major sedimentological and stratigraphic units. The VCR lava contact represents the seismic datum. Close to the suboutcrop these four units, predominantly composed of juxtaposed conglomerate, were modelled as one unit, and termed the 'Shore Line Composite' (SLC). These models considered bottom and top contact surfaces intersected by faults, to a resolution of 2 m.

In 2004, a second seismic survey was commissioned owing to vast improvements in data acquisition and processing. The survey results were utilized together with drilling and mapping information to develop an enhanced geological model. The four initial major sedimentary units were further defined and subdivided into first seven and later sixteen 3D-modelled units, with the seismic data locating the contact between the VCR and Ventersdorp lavas.

In 2008/09, the seismic data of the 2004 seismic survey was re-processed and integrated with the geological models. Notably, up to this stage, the 3D modelling consisted mainly of seismic survey interpretations, underground mapping, and straight-lining between successive borehole intersections. It is noted that the earlier modelling packages were not as flexible and user-friendly in constructing 3D geological models currently available software.

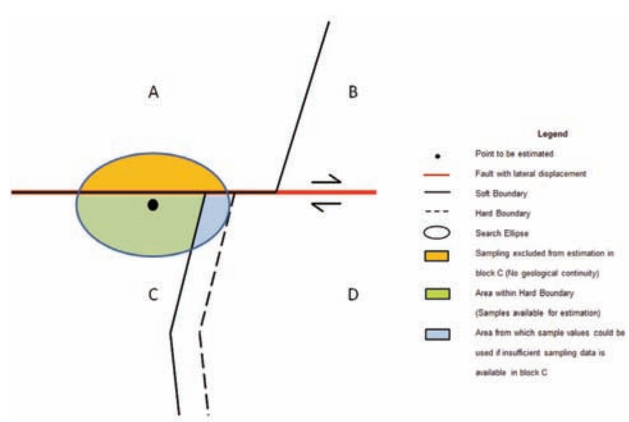

Figure 9—Schematic plan depicting 'hard' and 'soft' boundaries and their relevance for estimation of geozone 'C'

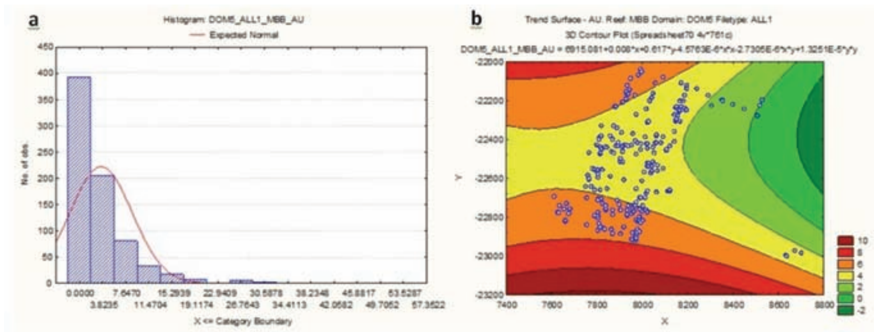

Figure 10—(a) Example of a histogram for the MBB Reef (Au g/t), and (b) trend plot for the MBB Reef (Au g/t)

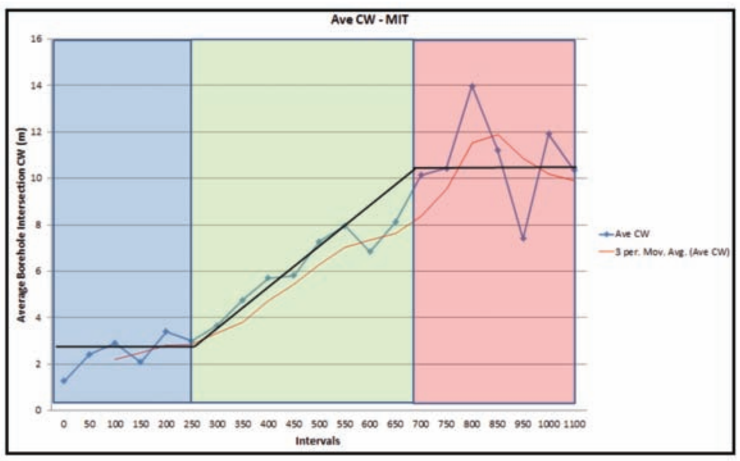

Figure 11—Representation of CW stationarity valuation showing two stationary geozones (blue and red) as well as a gradational unit (green)

During 2010, the limitation of straight-lining between borehole intersections became evident from irregularities between observed and modelled data. Available data revealed that the clastic wedge does not always diverge to the east at a constant rate due to reactivation of syn-depositional faults. In certain localities, the divergence ratio is greater than in other areas, while towards the east, the Upper Elsburg reefs reach a maximum thickness of approximately 130 m and the units become sub-parallel and conformable to each other.

These observations triggered the introduction of type sections, based on palinspastic reconstructions at regular intervals throughout the orebody. The sections were linked to the actual borehole intersections to obtain correct CW values for localized areas. These sections formed the basis of a representative depositional model, yielding robust CW values to be used during geological modelling and estimation.

The newly established methodology for CW estimation, detailed in the following section, ensures that different users will obtain identical results, with a full audit trail compliant with all reporting codes that enhances the transparency of the geological model construction process. Figure 12 provides a graphic illustration of the evolution of the South Deep geological models.

Current geological modelling procedures

Channel width estimation

Earlier methods used at South Deep were dependent, to some extent, on the users' experience and frame of reference. Therefore, the geological model was susceptible to subjectivity. This was mostly due to the limitations of digital terrain modelling software packages available in the geoscience environment at the time. As described previously, South Deep's mine planning procedure is highly dependent on accurate and robust, fully 3D resource models, which in turn are explicitly a function of the quality and accuracy of the geological model.

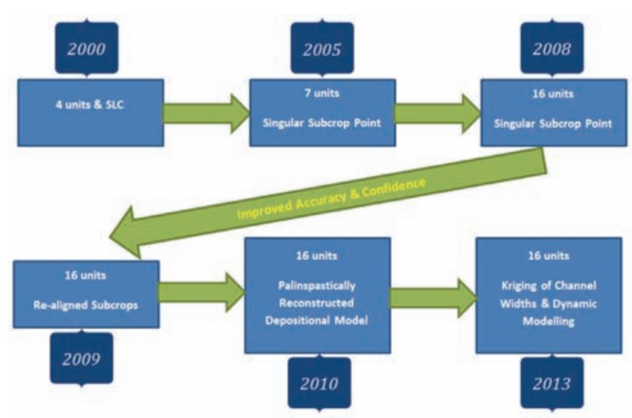

Figure 12—Graphic representation of the evolution of the South Deep geological model illustrating the increase in accuracy as well as confidence

To mitigate the subjectivity of geological modelling processes, emphasis has been placed on the estimation of the CW. Currently, uneconomic quartzitic units become thicker towards the east, while the mature conglomeratic units are more consistent in CW throughout the mine lease boundary (Figure 13).

The variograms for quartzite and conglomerate CWs perpendicular to the suboutcrop with the VCR are detailed in Figures 14a and b. In modelling the variograms and constructing the variogram contours, a specific unit of the respective lithology (quartzite or conglomerate) was selected that was representative of the deposit as a whole. The anisotropic variogram model for the conglomerate units indicates a range exceeding 800 m perpendicular to the suboutcrop, while the quartzite shows a range of 400 m.

From the variograms it can be determined that CW is mostly continuous in the suboutcrop direction (N23°E) with ranges in excess of 400 m in any direction. However, various wrench faults occur throughout the orebody, offsetting the clastic wedge in a dextral direction with lateral movement of 80 m to 300 m. Due to the character of the divergent clastic wedge, CWs across these wrench faults are not conformable. To mitigate the influence of the wrench faults and the easterly trend in CW, the search ellipse has been set to two and four grade-control drillhole spacings (30 x 30 m) in an east-west and north-south direction (N23°E), respectively.

Due to the unavailability of drilling platforms, the 30 x 30 m drilling grid is not achieved in all of the current mine areas. Consequently, CW estimation is not achieved over the entire lease area. Therefore, a further limiting factor is applied during the kriging of CWs. If more than seven full-reef validated intersections are utilized in the estimation, the estimated value is considered valid. If not, then the CW attribute is obtained from the relevant depositional model, as described in the previous section. Due to all the constraints and limits put on the estimation of the CW, the best estimator to apply is ordinary kriging.

The CWs are then added as an attribute to a point file; from there the points are draped onto a wireframe surface of a reef unit. Once these points conform to the surface, they are translated by the CW value to the elevation where the following reef unit would be encountered. The digital terrain model obtained from the estimated locations is then further integrated with the actual drillhole intersections.

Stratigraphic sequence modelling of CW

In addition to kriging, stratigraphic sequence modelling, known at the mine as the type section method, is also applied

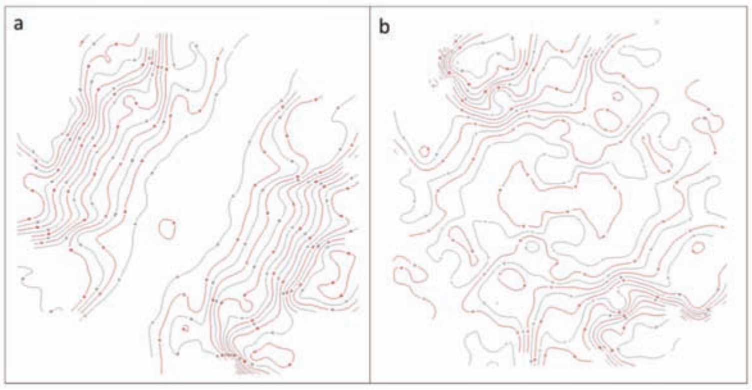

Figure 13—Variogram contours of (a) quartzitic units illustrating a clear continuation direction parallel to suboutcrop, and (b) mature conglomeratic units illustrating a more isotropic example with some continuation experienced in the suboutcrop direction

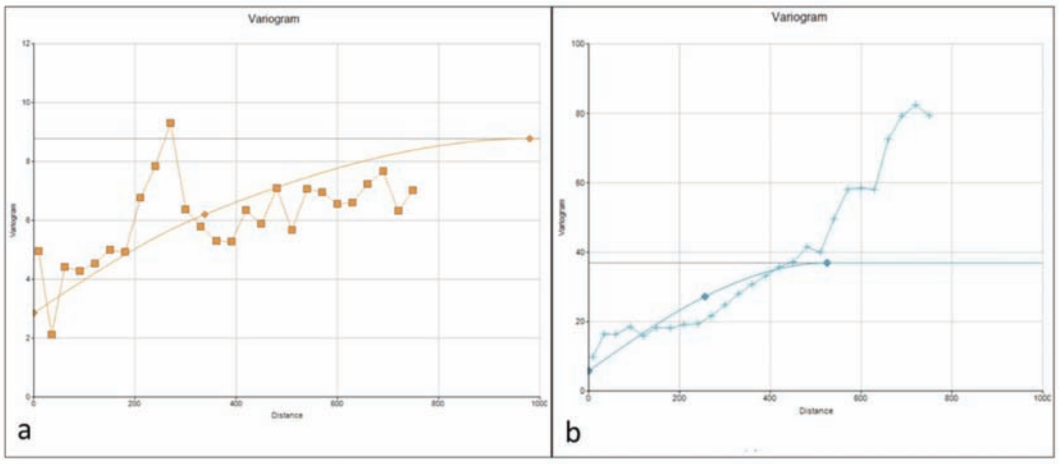

Figure 14—Variogram models of (a) conglomeratic unit perpendicular to suboutcrop yielding ranges of more than 800 m, and (b) quartzitic unit perpendicular to suboutcrop showing ranges of more than 400 m

to determine CW. Of the two methods, kriging yields a more accurate result and is preferred. However, owing to the scarcity of data in new mining areas, kriging estimation in these areas must be conducted with caution. Type sections of stratigraphic sequences are constructed for these areas and utilized in CW determination.

Stratigraphic sequence modelling entails the construction of palinspastic sections (Figure 15) conforming to borehole intersections. This results in a local CW model (Figure 16) for areas with insufficient data. These CWs are then utilized in the stratigraphic sequence modelling.

The importance of CW is highlighted when considering that eight conglomerate bands, intercalated by quartzite units, are mined. Thus an error of a few metres at the top of the stratigraphic sequence will propagate down and have an adverse effect on the spatial position of the lower conglomerate bands.

Once the thicknesses between stratigraphic surfaces have been modelled, mapping data, boreholes, seismic points, and isopach plots are integrated to create the final stratigraphic surface. Quality assurance and quality control techniques include visual checks on sections of the stratigraphy, as well as percentage borehole honouring analysis.

Future development of geological models

Previous geological modelling methods employed at South Deep were effective for building robust and accurate geological models, but were time-consuming. However, by applying the estimation techniques discussed above, utilizing modern and improved software, there will be significant staff and time reductions.

The new software – which is a proprietary software package and therefore not described – has the advantage that all data used is dynamic. Boreholes and mapping data are continually updated to refine the geological models of the sixteen stratigraphic surfaces (Figure 4). Updates are characterized by minimal turnaround times, resulting in the latest geological model being constantly available. The importance of regularly updated geological models to mining and mine planning are obvious.

Presently, only areas with current mining activity are dynamically built and are thus kept up to date as new information becomes available. Areas where mining occurred in the past will be converted from a digital terrain format into the dynamic format on a project basis.

Conclusions

Mechanized mining requires a high-confidence design throughout the planning and scheduling phase to limit off-reef mining. A reliable mine design is underpinned by up-to-date grade-tonnage models, which in turn are supported by accurate geological models. To achieve this, South Deep Mine implemented various innovations, including channel width (CW) estimation and dynamic and stratigraphic sequence modelling. These are accompanied by rigorous quality assurance and quality control processes. As a result, updated

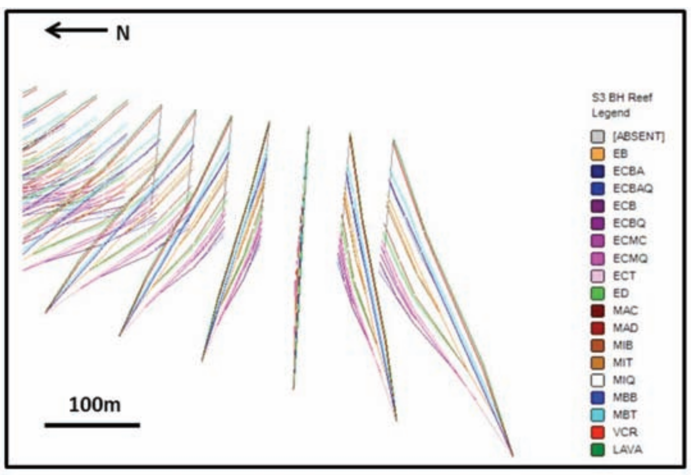

Figure 15—Palinspastic type sections created for CW determination

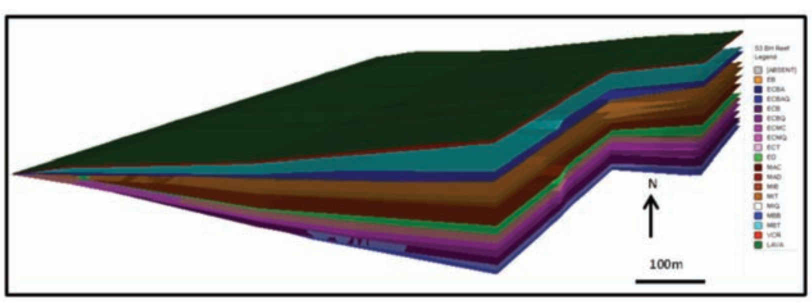

Figure 16 – Representative depositional model of South Deep

geological and grade control models are continuously produced, facilitating accurate and optimal mine planning, design and extraction of the orebody.

Given the multi-reef nature and structural complexities of the orebodies, geological modelling at South Deep Mine has progressively improved over the years. The implementation of the CW estimation process through kriging has also provided the mine with an auditable geological modelling process. Kriging of reef thicknesses is fundamental to the geological modelling, and as more drill-hole and mapping data becomes available, the construction of type sections and consequently stratigraphic sequence modelling will be converted into an estimated model.

A highly detailed geological model of the sixteen individual reef units enables resource estimation and consequently mining to be conducted at higher confidence levels.

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