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Three dimensional geometry of the rustenburg layered suite, South Africa

Géométrie tridimensionnelle de la formation de rustenburg, Afrique du Sud

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Abstract:

Recently the use of three-dimensional (3D) models for visualizing the subsurface has gained prominence as an effective tool for resource evaluation and underground studies. The 3D models of the Rustenburg Layered Suite (RLS) in the Bushveld Igneous Complex (BIC) were created to show the boundaries and geometry of each stratigraphic units using geostatistical techniques. Most frequently used data for similar studies are well-logs and seismic data, however for a continous regional scale studies over the entire study area, such data is not available. The use of borehole log data with spatial distribution across the limbs of the BIC provides an exceptional alternative to visualize on a regional scale the structural geometry of the area.This paper therefore, utilized the available borehole log record, field based reports and maps for the modelling. The result shows 3D models that reveals the present day regional geometric relations of RLS units that was inadequately constrained prior to this study.

Résumé:

L'utilisation des modèles tridimensionnels (3D) pour visualiser le sous-sol a pris de l'importance en tant qu'outil efficace pour l'évaluation des ressources et des environnements souterrains. Les modèles 3D de la Formation de Rustenburg (F.R) dans le Complexe Igné de Bushveld (CIB) ont été créés pour déterminer les limites et la géométrie de chacune des unités stratigraphiques à l'aide de techniques géostatistiques. La revue de la littérature mentionne que les données le plus souvent utilisées dans ce genre d'étude sont sismiques. Elles font malheureusement défaut dans un contexte régional comme celui du complexe igné de Bushveld. L'utilisation des données de forages à distribution spatiale dans le complexe de Bushveld offre une alternative exceptionnelle qui permet de visualiser sa géométrie structurale à l'échelle régionale. Cet article utilise les données de forages disponibles, des rapports et des cartes géologiques pour produire un modèle numérique. Le résultat montre que les modèles 3D révèlent l'existence de relations géométriques régionales qui n'apparaissent pas distinctement dans les études antérieures.

Keywords / Mots clés

3-dimension; 3D visualization; Rustenburg Layered Suite; geometry; BushveldComplex.
3Dimension; visualisation 3D;modèles de la formation de Rustenburg; géométrie; complexe Igné de Bushveld.

INTRODUCTION

Previously, subsurface geological estimation of the geometry of rock contacts and other geologic features were for the purpose of reserve and resource estimations from sparse surface outcrop mapping and limited seismic data. However, with recent rapid advancements in computer technology and software development, subsurface rock geometry can be determined accurately through interpolation of sparse borehole log data (Chang and Park, 2004; McCarthy and Graniero, 2006). The geometry of subsurface rock and structural features can be interpreted from visualisation of three-dimensional (3D) block models (Houlding, 1994; Middlemis,2001; Chunxiang *et al*.,2003;Wu, 2004; Chang and Park 2004;Wu *et al*., 2005; Thurmond *et al.*, 2005; McCarthy and Graniero,2006; Zheng *et al.*, 2007; Caumon *et al.*, 2009; Royse *et al.*, 2009), fence diagrams (Van Driel, 1989; Wu, 2004), grid stack (Kessler *et al.,* 2009), structure and isopach contouring methods (Bird, 1988; Van Arsdale, 2000; Tearpock and Bischke, 2002: Groshong, 2006), cross sections and profiles (Pflug *et al*., 1992; Kaufmann and Martin, 2008; Royse *et al.*, 2009).

The Rustenburg Layered Suite (RLS) occurs as sillsat shallow depths between the overlying volcanic mass of Rooiberg felsites and Rashoop Granophyre Suite and the underlying Transvaal Supergroup rocks (Eriksson *et al*., 1995) as presented in figure 1. 3D models at each stratigraphic interval is presented here to enhance the understanding of the geometry of the RLS and to constrain the mode of emplacement on a regional scale. 3D geomery of the rocks can also be used to explain the shape and contact relationship of rocks especially with sub-horizontally layered rocks (Bayer and Dooley, 1990; Jones *et al.,*2008; Houlding, 1994; Rosenberg, 2005; Hogan *et al*., 1998; Améglio and Vigneresse, 1999;Wu *et al*.,2005). While field obsevation alone might not be adequate to model an accurate 3D model (Ameglio and Vigneresse, 1999), due to lack of good outcrop exposures and unavalability of continuous high resolution seismic data across regions. The use of geo-statistical method with ability to quantify or estimate variance and correlation coeficent in borehole log data has proved as a good alternative. Recently, 3D models of intrusion has also been found to be significant in the study of volcanology and hazard management (Auger *et al*., 2001), underground water monitoring (Zhou *et al*., 2007; Kresic, 2006). It also find application in climate change detection (Sheppard, 2005; Koca, 2006; Svensen *et al*., 2007), resouce evaluation (Aarnes *et al*.,2011), mining, in studying magma emplacement and geometry (Gudmundsson *et al.,* 2009; Galindo and Gudmundsson, 2012).

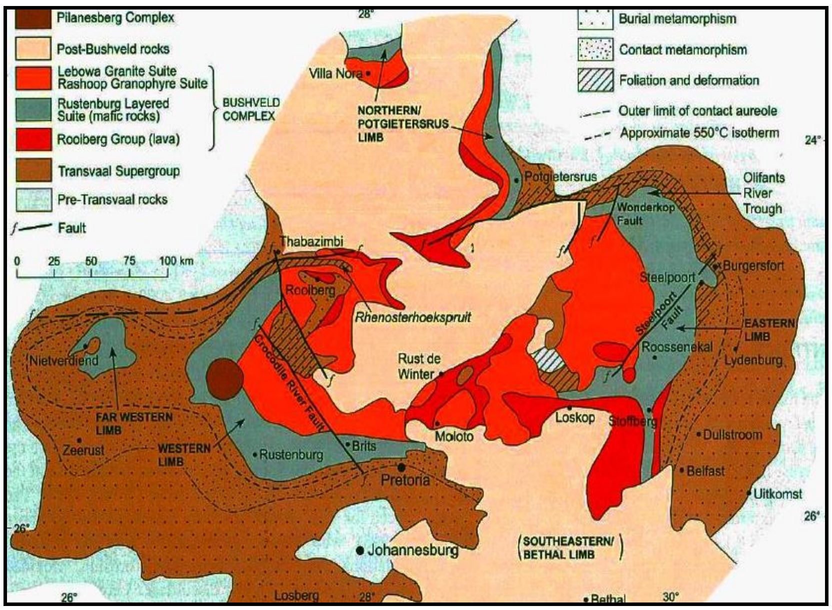

Figure 1: Geological map of the Bushveld Complex with the Rustenburg Layered Suite (RLS) and the Bushveld granites by Cawthorn et al., 2006.

The geometry of the Bushveld Igneous Complex BIC was first described as a lopolith by Hall (1932). Further probing into the geometry revealed funnel-shaped intrusions (Wager and Brown, 1967; Willemse, 1964) while seperate inward dipping sheet model was proposed by De Beer 1987; Du Plessis and Kleywegt, 1987. Gravity modelling by Webb et al. (2004), interpreted the Eastern and Western mafic units as connected sheets that were subsequently deformed. Campbell (2006 and (2009), identified widespread graben structures, floor domes, syn-Bushveld diapirs, and graben collapse structures within the RLS using seismic surveys. Kgaswane et al. (2012) and Cole et al.(2014) reconfirmed continuous sheet model earlier proposed by Cawthorn et al. (1998); Cawthorn and Webb (2001); Webb et al (2004, 2011).

Roberts (1970) proposed sills of horizontal to sub-horizontal geometry that transgresses into underlaying floor rocks. Both geophysical investigation and other studies have been incorporated in describing the geometry of the BIC (Kruger, 2005 and references therein). Major obstacle to this study has been the patchy nature of the investigation. This paper provides a model that substantiates the shape of the BIC at the subsurface with special reference to the RLS.

GEOLOGY

The Bushveld Complex in South Africa is made up of felsic and mafic (layered) rocks which constitute the RLS as indicated on Figure 1. The mafic layered part of the Complex has very poor outcrop exposure.

Its aerial extent, however revealed through drilling and mining. The Bushveld Complex intruded into the Kaapvaal craton some 2.06-2.05 Ga (Walraven et al. 1998, Olsson, 2010) and occupied a total area of about 65 000 km^2. It was emplaced discordantly on the Pretoria Group rocks of Transvaal Supergroup which form the lower contact to the RLS in most places except for few areas where the rocks are directly overlying the Archean floor. The felsic rocks include the Lebowa Granites and the Rashoop Granophyres which forms the roof rock to the RLS the roof rocks to RLS according to recent findings include a monzonic lithology beneath the Rooiberg Group felsites (Cawthorn, 2013) as well as Bushveld Granites in three areas (from borehole data), around Pilanesberg Complex in Western Bushveld, at Belfast, Southeastern Bushveld and in the Northern lobe. The RLS occurs within major compartments of the Bushveld Complex, the far Western Bushveld, the Villa Nora area in the North and more prominently the Western, Eastern and Northern Bushveld limbs. Major lithostratigraphic sub-division of the RLS includes the Marginal Zone, the Lower Zone, the Critical Zone (made up of Lower, Middle and Upper sub-divisions), the Main Zone and the Upper Zone.

METHODS

Borehole data produced by Mining companies from direct observation of cores form the fundamental data on which the 3D models were generated. Over 1,200 borehole data were collected and stochastically filtered to identify anomalous entries while interval maps were generated by first determining the top and basal contact of each unit and by gridding the surface elevation of each stratigraphic unit using Kriging interpolation method in Rockworks 15 environment. The interval maps were later modelled to create 3D surfaces.

Chronological order was defined to specify the time of stratigraphic units within the model while complex geological relationships such as transgressions, on laps and other cross-cutting features were addressed before generating models. Grid models, stratigraphic solid models, isosurfaces fence diagrams, isopachs and isopach stacks, strip logs and surface maps were also generated to enhance the understanding of the subsurface and for interpretation purpose. Several unpublished reports, maps, images, geophysical data and reports were included in the study and interpretation.

3D MODELS OF WESTERN BUSHVELD

The 3D model reveals the geometry of the RLS rocks in Western Bushveld Complex (fig. 2). The figure also shows the elevated rim and the general central dipping nature of the RLS rocks. The Amandelbult section shows down-dipping layering of RLS rocks. Figures 3 and 4 show the geometry of the Western Bushveld compartment as continuous layers.

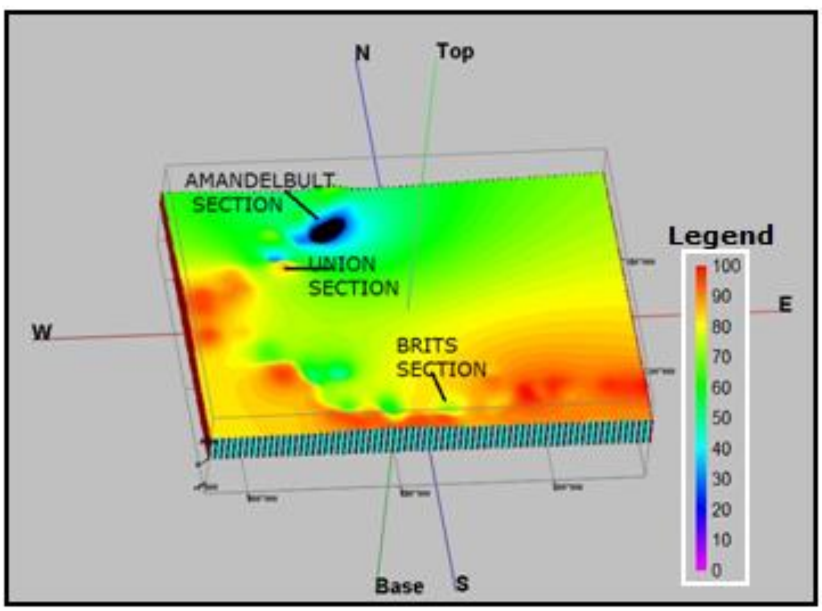

Figure 2: The Main Zone of Western Bushveld display uplifted rim dipping to the centre. Legend shows hot to cold depth intensity. The extreme north-eastern edge is very shallow while the south western edge is uplifted.

3D MODEL OF THE RLS IN THE EASTERN BUSHVELD COMPLEX

The geometry of the Eastern Bushveld Complex as revealed on the 3D model in Figures 5 and 6 shows very rugged topography with a lot of doming especially along the edges and most of the layers dip in the same direction. Doming and faulting structures in the area might be responsible for the exposure of some of the lower units at the surface. These dome are as a result of folding of underlying floor rocks before the emplacement of the RLS (de Waal, 1970; Du Plessis and Walraven, 1990; Hartzer, 1995; Armitage, 2011). 3D models of the Eastern Bushveld RLS rocks in the area reveal that the doming affected the entire RLS stratigraphic units. The central part of the Eastern Bushveld is marked by the presence of valleys, which occur between the northern part and the southern parts.

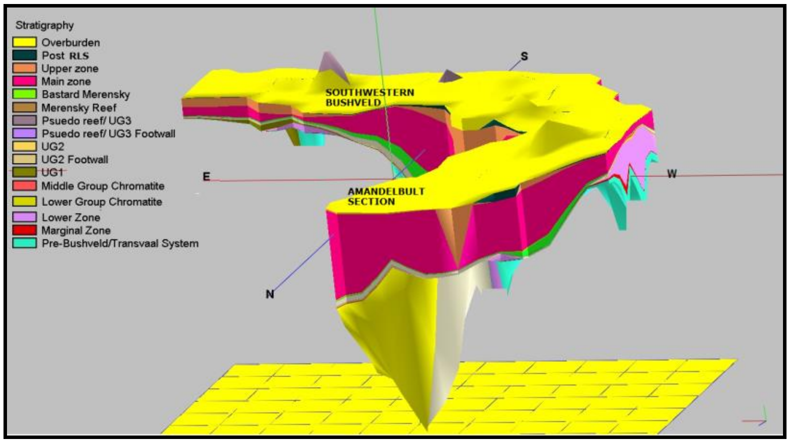

Figure 3: 3D model showing the sill nature of RLS rocks at the surface and the varied nature of the floor geometry of the RLS (Vertical exaggeration -33). The geological interface was modelled as geological boundaries that are parallel or subparallel to each other and exist continuously across the limb.

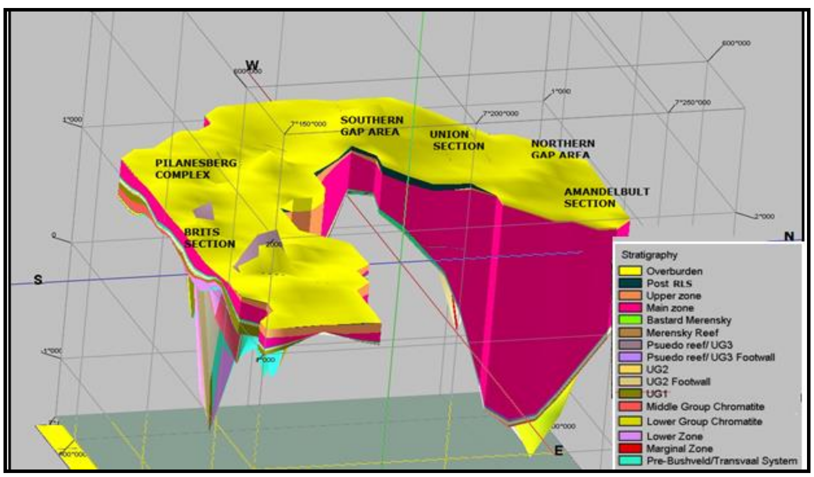

Figure 4: E-W view of the Western Bushveld 3D model showing the sill-like nature of the intrusion (VE-45). Note that the thickness of the layers increases towards the centre especially in the North-east and around the Pilanesberg Complex but thins towards the eastern parts of the Brits Section.

3D MODELS OF THE RLS IN THE NORTHERN LIMB OF THE BUSHVELD COMPLEX

Northward dipping stratigraphic units mark the Northern sector of the Bushveld Complex or Potgietersrus sector. The Upper Zone lithologies thickens northward in this sector, this is enhanced by structural dipping in the same direction. The Upper Zone unit also transgresses northwards down to the Archaean granite floor rock. Thickness of the different stratigraphic units is more pronounced at the central sector, where other structural features (such as horst and graben structures, normal faults, and folds) as indicated in Figures 7 to 9 are also exposed. This sector exhibits more diffuse structural pattern at the subsurface than at the surface. Alternating pair of anticlinal and synclinal structures (with down throw and up throws) are also observed on the models for this sector.

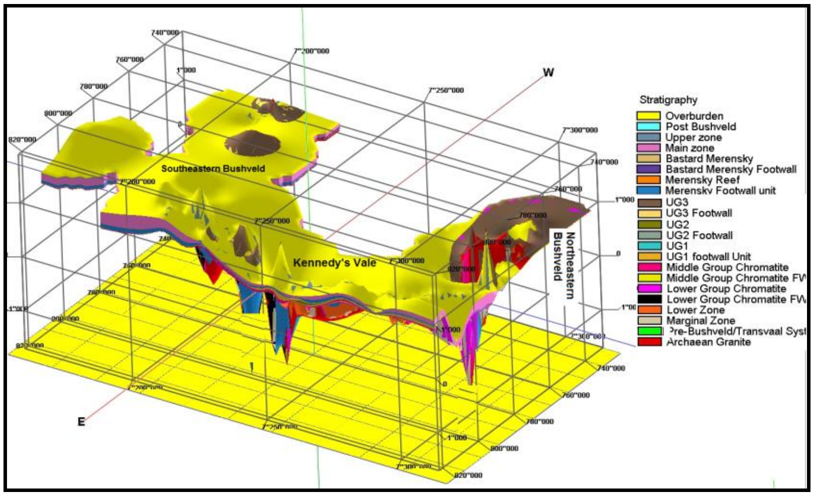

Figure 5: 3D model of the Eastern Bushveld (Vertical Exaggeration is 25)

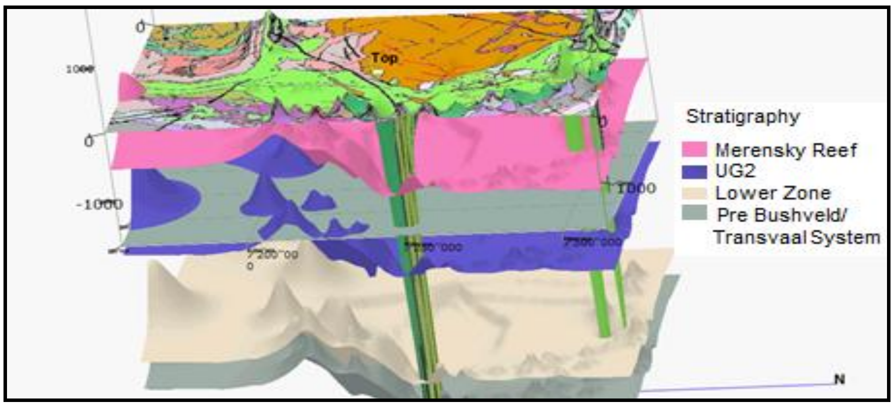

Figure 6: Exploded 3D model of the Eastern Bushveld Complex showing some layers of the RLS with the draped geological map at the top (Stratigraphic index does not apply to draped geological map). Up-doming are more prominent in south-eastern Bushveld and on lower units of RLS (i.e. from the base of the Main Zone downwards) than in north-eastern Bushveld and the upper units of RLS i.e. the Upper Zone unit.

The models also reveal that the RLS in this lobe rests progressively on older rocks from south to north where it directly lies on the Archaean floor confirming the earlier observation by Ashwal *et al*., (2005) and Kinnaird *et al*., (2005). However, the Lower Zone unit at the southern sector of the Northern Bushveld transgressed the overlying RLS rocks and rest directly on the Transvaal rocks.

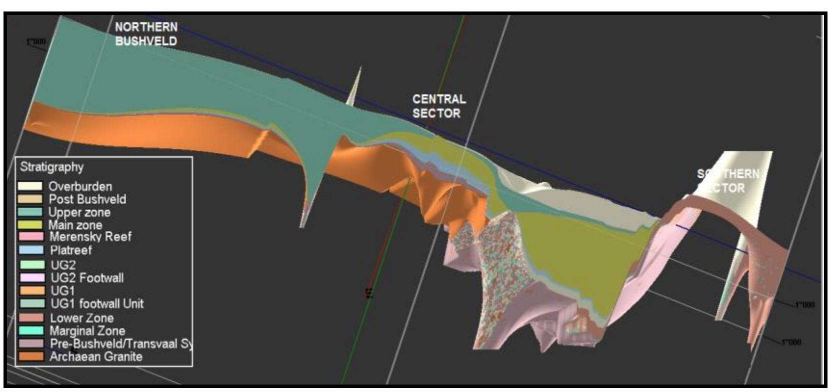

Figure 7: 3D model of the Northern Bushveld.

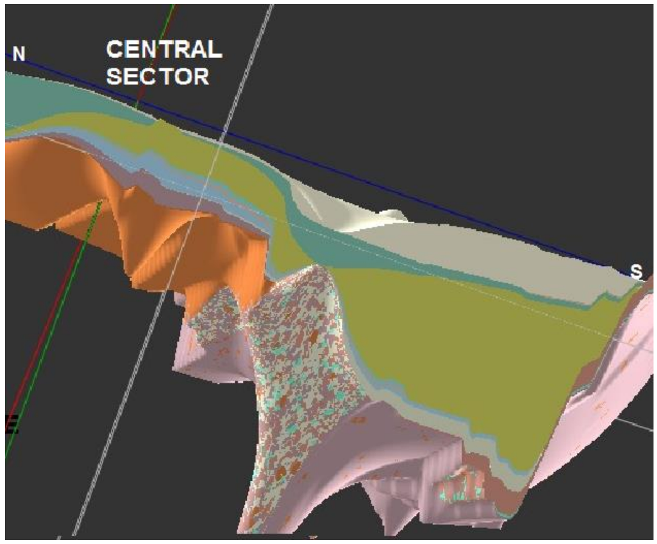

Figure 8: 3D model showing a close-up view of the central sector of the Northern Bushveld. Note the folding and step-like features, which might be due to imbricate staking at the base of this sector.

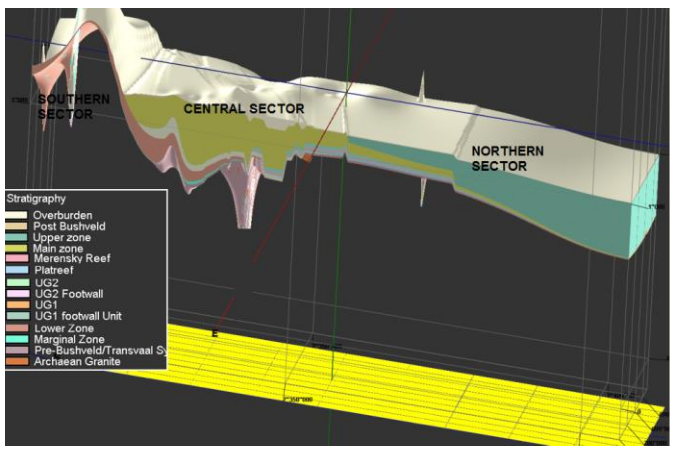

Figure 9: South west view of Northern Bushveld 3D model with borehole logs showing the geometry and the rugged nature of the central part.

3D MODEL OF THE RUSTENBURG LAYERED SUITE ACROSS THE BUSHVELD COMPLEX

Figure 10 shows the 3D model for the Bushveld Complex most of these models reveal strong tectonic control, resulting in elongations that are parallel to the trend of regional structures. A good example of this is the NNW-SSE outcrop elongation parallel to the Rustenburg Fault. Overview of the entire BIC shows that the south eastern part, the Northern limb, and the far western section were structural high areas before the emplacement of the RLS with the south eastern Bushveld floor sloping northwards. The south eastern part must have been the highest part while the extreme edge of the north-western BIC and central part of the Eastern Bushveld occurred as the lowest points before the emplacement of the RLS rocks as indicated in Figure 10. Figure 11 shows the 3D striplog model of some of the borehole logs used in generating the three-dimensional models. Stratigraphic fence diagram drawn across the Western and Eastern limbs of the Bushveld Complex in figure 12 can be interpreted as evidence for continuous sheet model proposed by Cawthorn et al. (1998); Cawthorn and Webb (2001); Webb et al (2004, 2011); Kgaswane et al. (2012) and Cole et al. (2014).

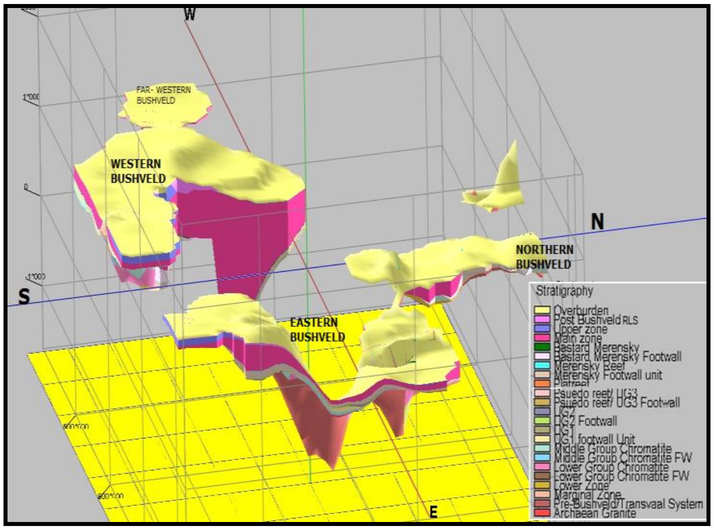

Figure 10: 3D model from the overburden to the floor of the RLS (VE-46).

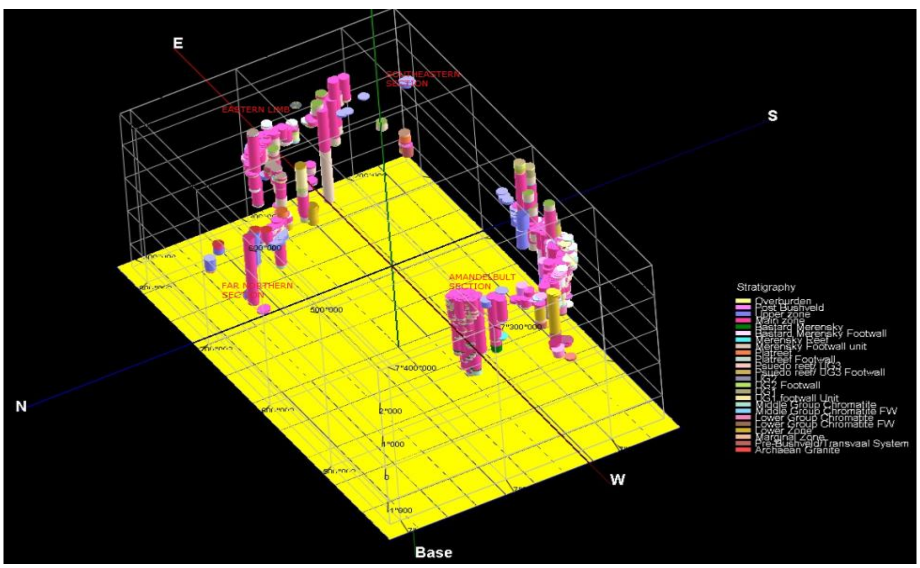

Figure 11: Multi-strip log image of some of the boreholes used for the 3D modelling.

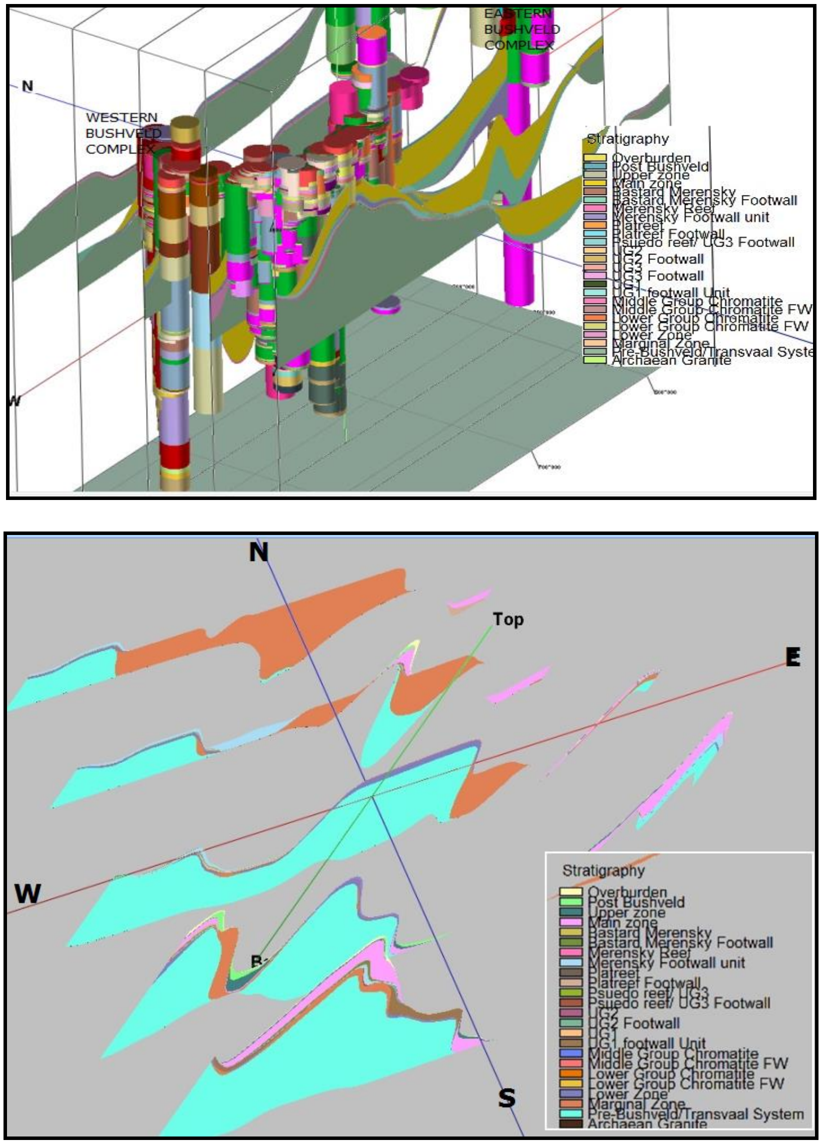

Figure 12: Stratigraphic fence diagrams across Western and Eastern Bushveld Complex with strip logs (up) and without strip log (down).

DISCUSSION

The tremendous down-dipping and step-like layering of RLS rock at the Amandelbult section probably enhanced the volume of magma deposit in the area, and might also signify closeness to the magma source. Step-like layering pattern in this area probably shows evidence for multiple magma injections. Southward dipping of RLS rocks in this area has been reported by Maier *et al*., (2013) to extend over 10 km, and might also indicate direction of magma transport. This structure is most probably pre-Bushveld since the structure and thickness of RLS shows inverse relation. The relationship between the structure in which magma accumulates and thickness of the accumulation is usually inverse if previous structurally-negative areas i.e. low land areas such as synclines and basins form before magma influx and thus receive more magma. However, positive structural areas will receive less influx except if the area has structurally been disturbed by later tectonic activities.

Our 3D model revealed general gentle dipping and thickening towards the center especially in the Western Bushveld and Eastern Bushveld, this can be related to subsidence after deposition according to Gough and Niekerk (1959); Hattingh, (1995). However, the thickening towards the center as indicated on the 3D models and inverse correlation of existing structures and corresponding thickness of RLS rocks in most parts of the Bushveld Complex probably suggest a pre-Bushveld emplacement feature that was probably modified by post-emplacement deformation in some parts. Otherwise the edges of the Complex ought to be thicker than the subsided central section; since dipping to the center should have been accompanied by flattening towards the center.

Area around the Pilanesberg Complex shows subsidence and faulting of the RLS rocks especially at the subsurface while at the surface it reveals a circular geometry. The RLS at Eastern Bushveld is penetrated by floor rock domes believed to have formed by diapirc processes (Uken and Watlkeys, 1997). The progressive transgression of the RLS rocks in the Northern Bushveld reveals increasing northward dipping of underlying Archean floor rocks and corresponding northward thickening of the overlying Upper Zone rocks. This geometry probably resulted from northward sliding of overlying Upper Zone rocks over the floor rocks. Further, southwards, the Upper Zone transgressed underlying RLS rocks to form a horst and graben structure in the central sector. Presence of folds and step-like features in the floor of the central sector probably indicate imbricate staking due to thrusting which Friese, (2004) had reported earlier in the area.

The east-west orientation of the Bushveld southern mass was attributed to tension in the east-west direction, contrary to the elongate northern mass, which was due to compression in the east-west direction (Truter, 1955). Evidence for the east-west elongation is supported by the location of the Far Western Bushveld Complex compartment to the west of Western and Eastern Bushveld Complex compartments (Hunter,1976) as well as variation in magma composition from north to south.

Magma preferential migration pathway and geometry is influenced by crustal compression and extension as well as presence of pre-existing structures (Hodge *et al*., 2012 and references there in). While extension in the crust will allow lateral migration of magma and create obstruction to its upward migration, compression permits upward migration and acts as barrier to lateral migration. Pre-existing structures act as weak zones and pathways through which magma can flow. The regional stress conditions at the time of emplacement of the RLS supported the emplacement along existing NNW and ENE regional trends or weak zones. The two trends can be correlated with tectonic events in the Kaapvaal Craton and also coincide with the trend of weakness during the formation of the Kaapvaal Craton (de Wit et al., 1992).The ENE trend coincides with the depositional axis of the Transvaal basin and it is also oriented parallel to Thabazimbi-Murchison Lineament (Hunter, 1996). The NE-SW trend was described as a major compressional trend (which resulted from the collision of the Kaapvaal Craton with the Zimbabwe Craton) during Bushveld emplacement (Holzer et al., 1999). The geometric pattern on the stratigraphic intervals of the Rustenburg Layered Suite suggest horizontal to sub-horizontal emplacement of the Bushveld Complex (Voordouw et al., 2009).

Sills or sheet intrusions are usually formed when the magma pressure exceed the vertical stress during upward migration of magma towards the surface (Sharpe and Snyman, 1980). Field observation by Valentine and Krogh, (2006) and many other researchers in other parts of the world has revealed that most often, horizontal to sub-horizontal layering occur along lithologic boundaries and surface of unconformity. This can be related to the Bushveld Complex (emplaced at the boundary between the Pretoria Group of the Transvaal Supergroup and overlying Rooiberg Group) as described by Cawthorn *et al*., (2006); and the Karoo Basin as described by Chevallier and Woodford, (1999); Saint-Blanquat *et al*., (2001); Burchardt, (2009) and references there in). Sill emplacement can also occur when the upper layer or the roof layer is more rigid according to Thomson and Hutton (2004) and Kavanagh *et al*., (2006).

CONCLUSION

This paper presents 3D models and other diagrams for geologic visualization and interpretation of the geometry of the RLS. Lateral variation between the upper and lower sections of the RLS with the roof and floor contact was used to describe the geometry relationships. Comparison with available geological and geophysical information produced good correlations. The Model reveals the sill-like nature of the layers in most part of the lobes and the influence of the floor rock structure on the units. This is more obvious wide spread floor rock influence on all the lobes and is probably responsible for the doming, funnel-like geometry in some parts. The RLS in Western Bushveld thickens mostly towards the centre. At the Northern limb, it exhibits central thickening with graben geometry; the southern sector is uplifted while the northern sector dips northwards and transgressed the floor rock.

The doming at the South-eastern Bushveld Complex is more prominent than those at North-eastern Bushveld. Lower Zone rocks, which form a positive structure, dominate the southern sector; this might be related to the presence of the Pretoria-Zebediela anticline. The models can be used in constraining the geometry of the economic units for better mining and engineering planning.

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