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Emplacement of Some Mafic-Ultramafic Plutonic Suite in South Africa: *Exploration Target Implication*

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Abstract
The Rustenberg Layered Suite (RLS) is one of three plutonic suites of the Bushveld Igneous Complex. The RLS is of great interest because it contains one of the richest Platinum Group Metals on earth. In addition, it has a significant academic interest based on its petrogenesis. The three-dimensional structure and geometry of the Rustenburg Layered Suite (RLS) in the Bushveld Complex was until recently speculative. Recent articles provide a realistic 3D geological model of the RLS based on geophysical data, borehole logs and field mapping reports. Visualisation of 3D models, grid models, fence diagrams and layer stacked maps coupled with regional scale of study afford good insight into the RLS geometry and thereby provide a better understanding and enhanced thorough interpretation of geological relationships and associated structural features. This paper presents the summary of the overall regional geologic features within the RLS in relation to current topics such as the continuity between the eastern and western Bushveld, at depth and the feeder sites.

Keywords: *Rustenburg Layered Suite; geometry;structures;Bushveld Complex.*

Introduction

The Bushveld Igneous Complex (BIC) of South Africa has an area extent of about 65,000 km^2 (Cawthorn and Webb, 2001). The BIC holds the world's largest deposit of Platinum group metals (Vermaak, 1995; Barnes et. al. 2 004; Naldrett 2009). The Bushveld Igneous Complex consists of three suites of plutonic rocks, namely the mafic-ultramafic Rustenburg Layered Suite (SACS, 1980), the Rashoop Granophyre Suite and the Lebowa Granite Suite (Von Gruenewaldt et al., 1989). There are also coeval satellite intrusions, including the Malopo Farm Complex in Botswana.

Research on the geology of the Bushveld Complex has been ongoing for more than one century and over this period, a large body of knowledge about the parental magma source; origin of layering, emplacement geometry, structure and evolutionary issues has been acquired. These have continuously improved our understanding of the Complex (Hunter, 1976), both academically and commercially. Despite the increase in knowledge, researchers have not been able to reach an agreement on many of these issues such as the origin of Layering, magma source, emplacement geometry and overall structure and evolution. One key challenge is how to unravel the subsurface geometry of the entire area since field-based studies could not adequately describe the geometry due to incompleteness of outcrop exposures and limited availability of geophysical data. Several researchers such as Hayes et al. (2018) exploited the melt extraction in classifying the RLS layers; Scoon and Costin (2018) investigated the geochemistry and morphology of magmatic reaction chromite stringers in classifying the emplacement of the layered suite; Mitchell et al., 2019 examined the partial melting of host norite-anorthosite cumulates to decipher the evolution of magma chambers; Robb and Mungall (2020) applied heat flow simulation method to investigate the emplacement of the Rustenburg layered Suite. The geometry is important for a better understanding of the structural evolution, emplacement history, layering and depth relationship between the various limbs. It will also add to the knowledge about distribution of the mineral bearing zones (Wang et.al., 2015) and geological settings. The purpose of this paper is to summarize the overall regional geologic features and highlight some of these salient geologic issues for future exploration.

Subsurface data cannot be directly assessed except through boreholes, tunnels and geophysical survey. Borehole log data are very valuable and provide direct observation of structural and lithologic information to centimetre detail; they also provide clear descriptions of how rocks are spatially laid down. Advances in geological data processing techniques and software development coupled with 3D visualization techniques for borehole data have improved the understanding of subsurface phenomena that allow easy correlation, accurate feature detection and better morphological investigation. A 3D map is the representation of geologic units and structures seen as actual (x, y, z). A geologic 3D map is defined within two surfaces corresponding to the layer's top and bottom. Although such maps can be constructed from seismic data, they are difficult to acquire in areas of rough topography. 3D modeling of geological entities and integration of geophysical datasets offers new perception in mineral exploration mapping.

Geological Setting

The BIC intruded into the Transvaal basin about ca. 2.056-8 Ga (Harmer and Armstrong, 2000; Walraven et. al. 1990; Barton et. al., 1994; Zeh et al., 2014, Wabo et al., 2016) as intrusive sills (Cawthorn, 2012) before undergoing subsidence. The Transvaal basin is situated in the northern parts of the Kaapvaal craton which is the best preserved and oldest continental crust (Youssof et. al., 2013).

The Bushveld Igneous Complex is made up of upper felsic rocks which includes; the Lebowa Granite Suite, Rashoop, Granophyre Suite and Rooiberg Group directly overlaying basal mafic to ultra-mafic rocks known as the (RLS). The RLS host layers that are economically exploited for Platinum group metals, chromium and vanadium. The RLS outcrops within the major compartments or limbs of the Bushveld Igneous Complex (as indicated in Figure 1 below) and are laterally continuous. A summary of the downhole lithologic description, grouping and stratigraphic order based on SACS (1980) is given in Table 1. Major marker horizons that were clearly identified in the logs were utilized in grouping the lithologies into stratigraphic units (these include- the Pyroxenite Marker, Giant Mottled Anorthosite layer, Bastard Merensky Reef, the Merensky Reef, UG2 and UG1 layers, etc.). The stratigraphic classification was based on SACS, (1980) classification scheme and on the work of Coertze (1974), Cameron (1978), Eales et al. (1993) Teigler and Eales (1992), Barnes and Maier (2004) and several unpublished mine reports on RLS and the BIC. A stratigraphic and lithology type table derived from lithological grouping is presented in Table 1 below.

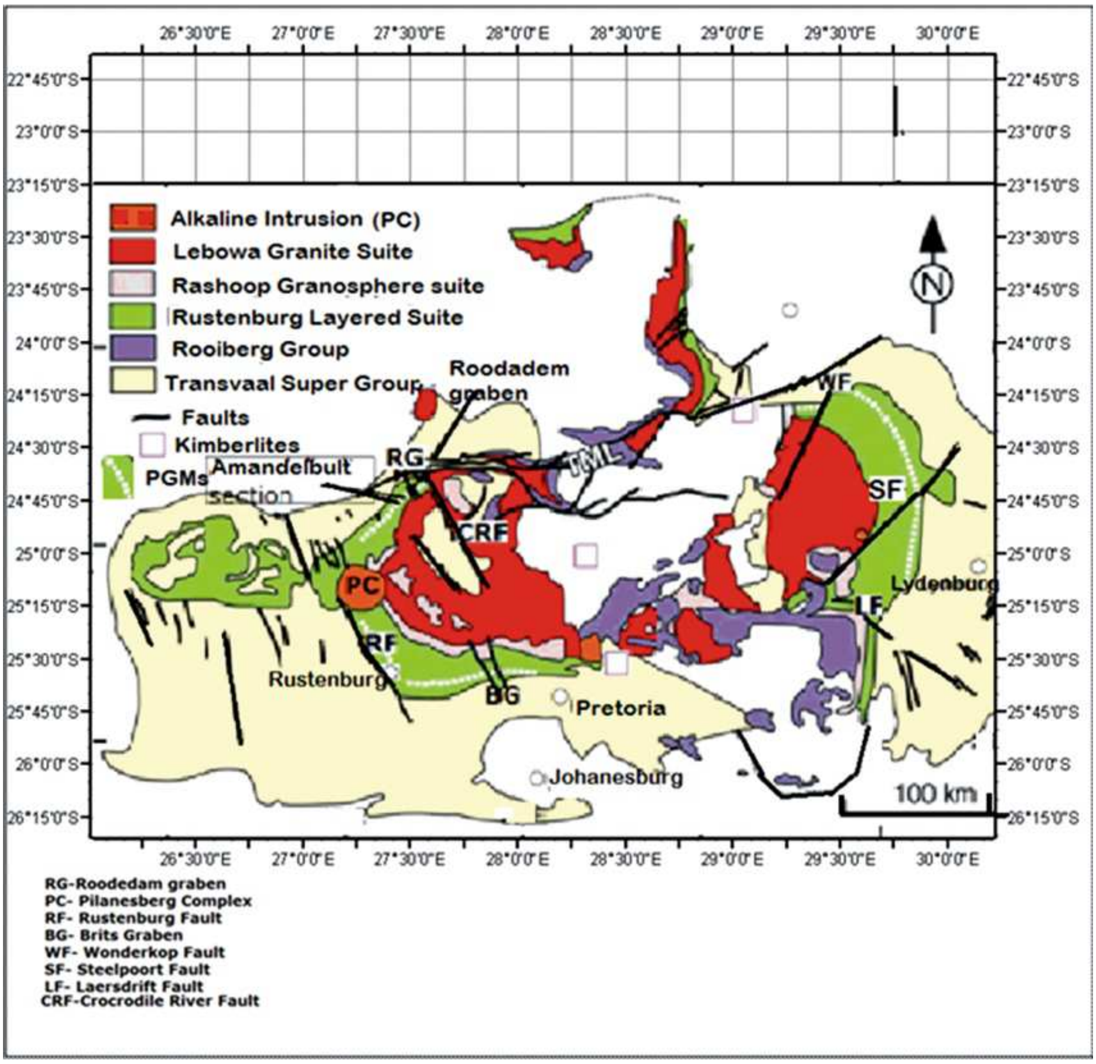

Fig. 1: Geological map of the Bushveld Complex with the major faults Cawthorn et al. 2006

Table 1: Borehole downhole lithostratigraphic description

S/N	Name	Description	G-Value (stratigraphic order)
1	Overburden	Mostly soil, sand, clay or percussion drilled section	1
2	Post Bushveld (RLS)	Mostly Pilanesberg Complex rocks, Bushveld Granites and Granophyres	2
3	Upper Zone	Magnetite layers occurring mostly with gabbro/ anorthosite	3
4	Main Zone	Gabbro, norites, anorthosite, pyroxenite	4
5	Bastard Merensky Reef	Pyroxenitic with thin basal chromite and slightly pegmatoidal	5
6	Bastard Merensky Footwall (BMR)	Lithologies occurring between the BMR and the MR	6
7	Merensky Reef (MR)	Pyroxenitic lithology marked by thin or slightly disseminated chromite stringers and mineralized with PGM	7
8	Merensky Footwall unit (MR FW)	Lithologies occurring between the MR and the UG2 (when the Pseudo Reef is absent)	8
9	Platreef	pyroxenitic lithologies with platinum-group element (PGE)	9
10	Platreef footwall	Metasediments, granites (unclassified), Archaean granites and gneisses.	10
11	Pseudo Reef		11
12	Pseudo Reef Footwall	Lithologies occurring between the Pseudo reef and the UG2	12
13	UG2	chromitite layers	13
14	UG2 Footwall	Lithologies occurring between theUG2 and UG1	14
15	UG1	Chromitite layers	15
16	UG1 Footwall Unit	Lithologies occurring between theUG2 and UG1	16
17	Middle Group Chromitite (MG)	chromitite layers with pyroxenites (MG4-MG0)	17
18	Middle Group Chromitite FW	Lithologies occurring between the MG and LG	18
19	Lower Group Chromitite (LG)	chromitite, harzburgite, pyroxenite (LG7-LG1)	19
20	Lower Group Chromitite FW	Lithologies occurring between the LG1 and Lower zone	20
21	Lower Zone	Pyroxenite, harzburgite and dunite.	21
22	Marginal Zone	Mostly norite	22
23	Pre-Bushveld/Transvaal Supergroup	Metasediments belonging to the Pretoria Group/ Transvaal Supergroup	23
24	Archaean Granite	Archaean granites and gneisses	24

Tectonic Control on the Emplacement of the Bushveld Complex

The Bushveld Complex appears to have intruded into the centre of the Transvaal Basin along an ENE axis, which is parallel to the long axis of the Transvaal Basin. The Transvaal Basin consists of a suit of both clastic and chemical sedimentary rocks with volcanic rocks, attaining a thickness of up to 12 km. Emplacement of the Bushveld rocks was controlled by reactivation along major pre-Bushveld lineaments such as the Thabazimbi- Murchison, Barberton lineaments, the Melinda, Rustenburg and Steelpoort Faults, which represent zones of weakness within the Kaapvaal craton (Du Plessis and Walraven, 1990). The emplacement of the BC explored essentially the NNW and ENE trending structures which are said to have formed during pre-Bushveld tectonic development of the Kaapvaal Craton. The ENE-WSW trend coincides with the depositional axis of the Transvaal basin and it is oriented parallel to Thabazimbi-Murchison Lineament, which is an Archaean greenstone belt/suture (Hunter, 1975). The NE-SW trend is described as a major compression, which, resulted from the collision of the Kaapvaal Craton with the Zimbabwe Craton during Bushveld emplacement (Holzer et al., 1999). Thus, the RLS was possibly emplaced under compression conditions, within a foreland setting (Hunter 1976; Sharpe and Snyman, 1980; Hatton and Sharpe 1988; Hatton and Von Gruenewaldt, 1987). Transvaal Supergroup inliers such as the Marble Hall and Denniton and Crocodile River domes indicate a major pre-Bushveld regional deformation pattern disrupted by Bushveld Complex emplacement (Hartzer, 1995). While one school of thought proposed a single intrusion centre for Bushveld rocks others suggest multiple intrusions along suture zones (Maier et al., 2013; Naldrett, 2009).

Methodology

Subsurface geological data were used to create the three-dimensional images presented in this paper were sourced from the Council of Geosciences, Pretoria, South Africa. Over 1200 borehole records were used to create a subsurface database covering all the limbs of the Bushveld Complex. The data used were limited to those that fully transect two or more zones of the RLS. However, the maximum borehole depth under consideration in this study is limited to about 3000 km due to limitations of available borehole data. Search for borehole data was initiated by digitizing the available record on the digital map of the area in the Arc Map 10.1 environment for easy geographic search of boreholes and in order to get a visual understanding of the spatial distribution.

Regrouping of the litho/stratigraphic units was carried out based on previous studies (Table 1). Information on existing record includes: the map number, farm name, borehole ID, location and orientation information were entered into an Excel spreadsheet and reformatted for entry into RockWorks® 2015, the software package used to model and create three-dimensional images of the subsurface stratigraphy. This is to ensure accurate and reliable representation of the models.

Results

The Subsurface Geometry of the BIC

The geometry of the RLS can be described as layers of multiple sills (Figures 2, 3, 4 and 5) with roof and floor morphology modified by pre-, syn- and post-depositional structures. Pre-Bushveld structures may have determined the initial emplacement geometries of these sill intrusions along; pre-Bushveld faults, the Rustenburg fault (Bumby et al. 1998; Bamisaiye et al., (2017)) and host and graben structures (Teigler et al., 1996; Bamisaiye et al., 2017). Syn-Bushveld structures primarily include cyclic lateral layering of RLS rocks. Post-Bushveld structures primarily include both extensional and compressional faulting related to Namaqua-Natal Orogeny, with both thrusting and normal displacement and tilting of strata due to isostatic readjustment.

The regional stress conditions at the time of emplacement of the RLS supported the emplacement along both NNW and ENE trending and pre-existing regional structures. The actual roof geometry of the RLS is sub-parallel except for the inward dipping of the rims coupled with some doming which clearly shows up on the models presented in this study. This relatively flat morphology might be parallel to the layering of the original sub-horizontal nature of the roof area while pre- and syn-Bushveld folding modified the Main Zone and other basal portion of the layered suite.

General gentle dips (which vary between 5°-21°) and thickening of the mafic-ultramafic igneous layering towards the intrusion centre, especially along the Western and Eastern Limbs of the BC. However, layer thickening towards the intrusion centre - as observed on the 3D models (Figure 4 and 5) and from inverse correlation of structure and thickness in most parts of the Bushveld Complex, is better explained as syn-Bushveld structures. Syn-emplacement subsidence probably allowed both tilting of layer dips along the exposed margins/limbs as well as layer thickening, due to (1) vertical accumulation of crystals from a thicker central part of the magma chamber (2) convective density currents (as envisaged by many for the much smaller Skaergaard intrusion) and/or (3) possible down-slope cumulate slumping.

Connectivity Between the Eastern and Western BIC

Studies before now pointed out that surface geology suggests a simple dipping sheet model, from the outer edges of the Bushveld Complex (or rather RLS) towards its centre. However, the detailed three-dimensional modelling here shows this to be a surficial feature and that at depth much greater complexity is involved. It is also sensibly argued that much of the RLS was probably intruded as sheet-like and sill-like magma masses and that subsequent subsidence was responsible for current dips and that this was a long-lived process influenced strongly by a number of factors including pre-Bushveld geometry of floor rocks and overall tectonic stresses (compressional and tensional) on the Kaapvaal craton and how different stress sets (especially NNW and ENE) interacted. As a result, the present-day geometry observed at depth contains many faults, quite common graben structures, domes and diapiric structures, some basin-shaped features and all of this inherent structural and tectonic complexity reflects, in a broad sense, the interaction of pre-, syn- and post-Bushveld features. The interpreted geometry of stratigraphic intervals of the RLS in this study suggests discontinuous east-west horizontal to sub-horizontal stacked sill emplacement of the Bushveld Complex (Figures 2). The layer stacked model shows an enlarged mass at the surface and near subsurface that thins downwards. The present geometry is indicative of a massive or repeated injection close to the surface and a strong post depositional east-west oriented extensional force possibly responsible for lateral spread of the magma close to the surface. North – South extensional force may not be as strong, but rather dominated by strike-slip tectonics especially between the northern and the southern Bushveld mass. The strike-slip tectonics are post-depositional. The geometry, however, has less lateral spread downwards (with pockets) indicating a discontinuous Eastern and Western single mass at depth. This geometry is unique

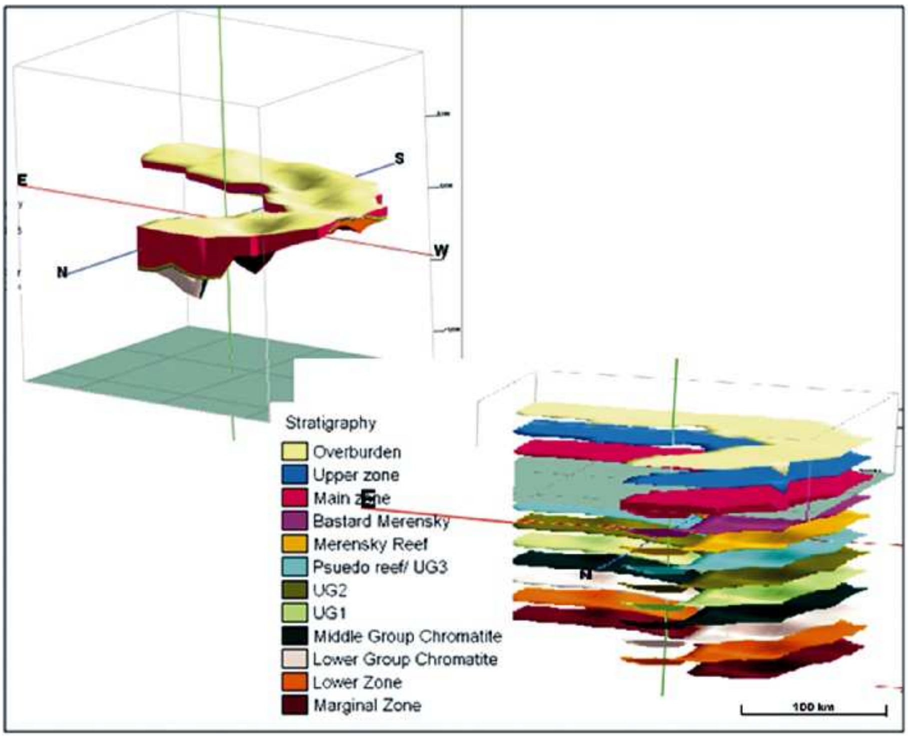

Fig. 2: Expanded flat stratigraphic layers (left) and the 3D stratigraphic model (right) of the Western limb which spans through a distance of 239 km in the Western Bushveld Complex. The Far-Western Bushveld area is exempted from this model

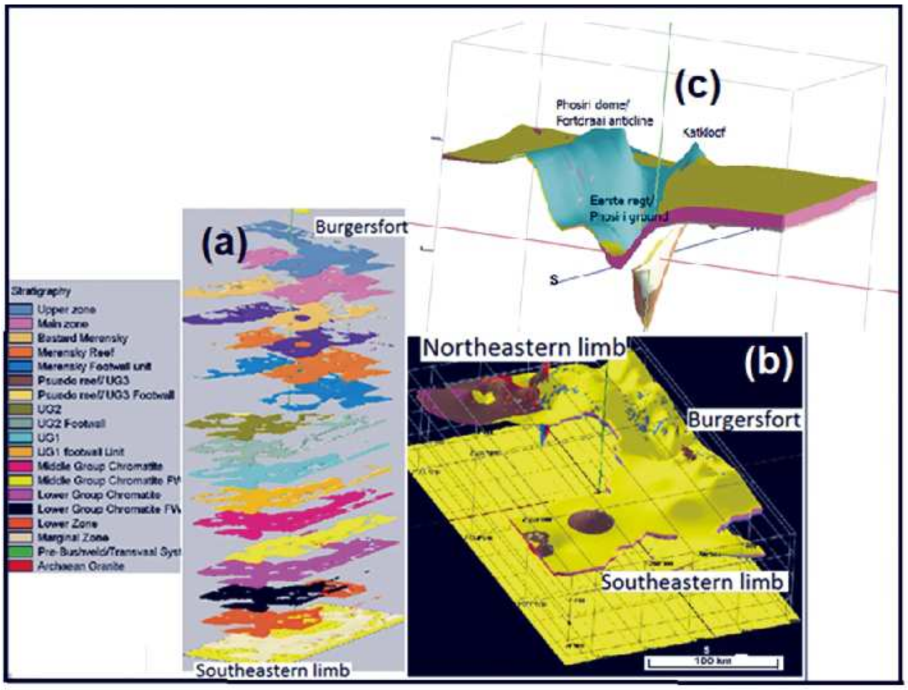

Fig. 3: Expanded flat stratigraphic layers (left) and the 3D stratigraphic model (right) of the eastern limb covers a distance of about 250 km with the exception of the southeastern/Bethal section was omitted due to lack of data. (c) shows the 3D model of the Northeastern Bushveld (vertical exaggeration 10)

because of its lateral spread close, to the surface and more than 2 km downward spread in places. It should however be noted that at depth the lateral spread reduced to pockets of isolated thin layers in places.

Differential Magma Movement and Magma Feeders

Formation of layered igneous suites such as the RLS might likely conform to rotation of maximum principal

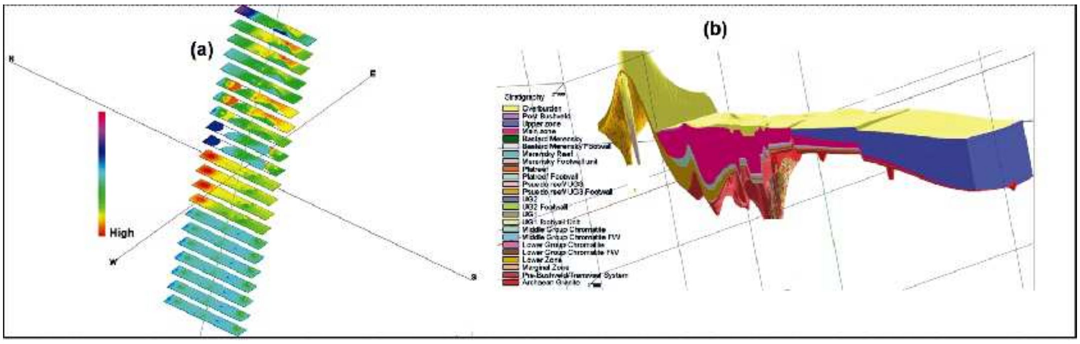

Fig. 4: Expanded coloured structure contor map of each stratigraphic layers (from overburden to Archaean granite) with 2000 m equal seperation, vertical exaggeration of 2.45x and scale of 1.1 inch to 100 km (left) and the 3D stratigraphic model with 15x vertical exergeration and scale of 3 inch to 100 km (right) of the Potgietersrus section has a total distance of 100 km and maximum width of 12 km at the centre of the Northern Bushveld Complex. The Villa Nora section (not captured in the 3D model) outcrop covers an approximated distance of about 39 km with a width of approximately 36 km.

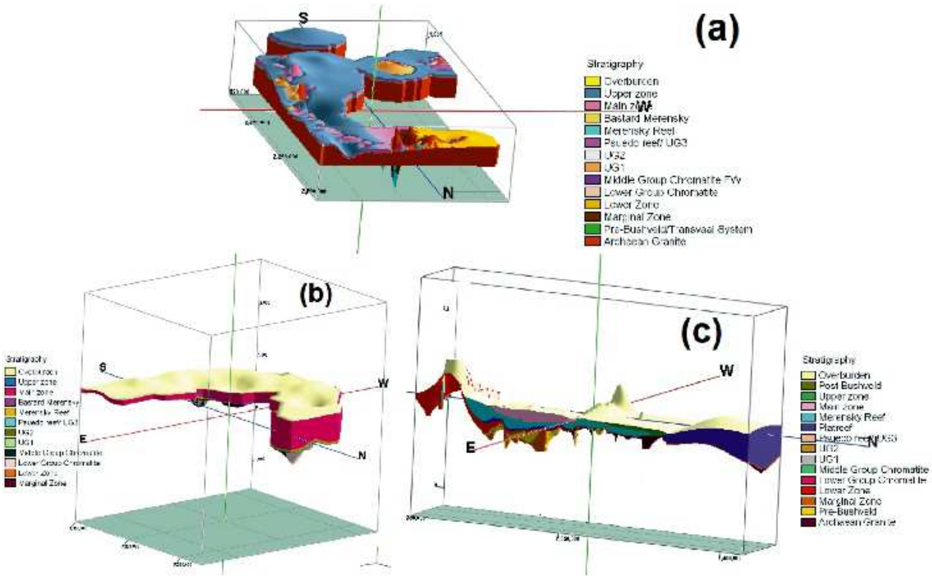

Fig. 5: The RLS is thick along deep-rooted valley systems that were scoured into pre-Bushveld rocks or the Transvaal sequence in which it is emplaced

compressive stress σ_1 from vertical to horizontal according to (Burchardt, 2009), the principal stress at this point is vertical while the other two stress tensors will be horizontal and the magnitude of differential stress is minimal. Sills or sheet intrusion was thus formed when the magma pressure exceeded the vertical stress during upward migration of magma towards the surface. Horizontal to sub horizontal layering occur along lithologic boundaries and surface of unconformity. Example of this is the Bushveld Complex, emplaced at the boundary between the Pretoria Group of the Transvaal Supergroup and overlying Monzonitic residual roof rock and the Rooiberg Group as described (Table 1).

Discussion and Conclusions

The research contribution to global geological science is in providing something totally new: a digital data base for the three-dimensional nature of the RLS; this new data set has been critically evaluated against existing literature and genetic models presented to date for the RLS and Bushveld Complex as a whole.

The result shows remarkable conformity with some of the previous field studies and geophysical (seismic) investigation. Effective representation of the regional and local scale structures was also achieved. It elucidates structures and geometries of the stratigraphic units within the RLS that were hitherto poorly defined. This paper reviewed the major structural trends which coincides with tectonic events in the Kaapvaal craton. The 3D models also helped in understanding the regional structural develomental stages, useful for better analysis and interpretaion. Some anomalously thick zones, interpreted to be likely magma feeder sites, which are essential exploration targets were also identified and classified. It highlights that some of the structures are basement controlled and pre-Bushveld, while a few are post-Bushveld. Features revealing the presence of thrust tectonics within the complex were also highlighted. The surface geometry of the RLS is almost flat except for the inward dipping of the rims coupled with some doming which clearly shows up on the models Figures 5 and 6. This relatively flat morphology (Figures 2 to 6) might be parallel to the layering of the original sub-horizontal roof area while, pre- and syn-Bushveld folding modified the Main Zone and other basal portion of the layered suite (Sharpe and Snyman 1980). The various analyses and interpretations of borehole data compare favourably with available 3D seismic interpretations.

Identification of thickening trends in each unit of the RLS proves to be significant for future exploration (Figures 3, 4 and 5). Most of the synformal structures identified in these models coincide with the site of thick mineralization (Bamisaiye, et al. 2016b) especially at Tweefontein in the Northern sector where the synformal structure dips strongly to the SW (this was also reported by Nex (2005)) and the Grasvally structure that dips to the NW, (also reported by Armitage (2011)).

A Section of ′evolved roof Zone′ recently described by Cawthorn (2012) as missing from the currently accepted stratigraphic section is shown in table 1. The review provides new 3D insights into the structure and kinematic evolution of the RLS.

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