Uncovering the southern Bushveld Complex, using reflection seismic and gravity data

S.E. Scheiber-Enslin
School of Geosciences, University of the Witwatersrand, Johannesburg, 2050, South Africa
e-mail: stephanie.scheiber@wits.ac.za: 0000-0003-1966-4651

S.J. Webb
School of Geosciences, University of the Witwatersrand, Johannesburg, 2050, South Africa
e-mail: susan.webb@wits.ac.za

M. Manzi
School of Geosciences, University of the Witwatersrand, Johannesburg, 2050, South Africa
e-mail: musa.manzi@wits.ac.za

Abstract

The Bushveld Complex is well explored at shallow mining levels, but the deeper structures of the complex remain unclear. Geophysical studies have been instrumental in shedding light on these deeper regions, including seismic, gravity, and magnetic studies.

Reflection seismic line DG326 crosses a largely geophysically unstudied part of the Bushveld Complex, over 160 km. The seismic line starts south of the western limb of the complex and ends in the lower part of the eastern limb. The line covers the possible connection between the southern limb of the complex and the western and eastern limbs.

Along the profile (from southwest to northeast), the seismic line crosses outcropping Transvaal Supergroup rocks underlain by Witwatersrand Supergroup rocks; Bushveld granites and granophyres; the large Dennilton Dome and rocks of the Rustenburg Layered Suite. The dome is made up of basement rocks surrounded by Transvaal Supergroup rocks and has brought Rustenburg Layered Suite rocks closer to the surface in the northeast.

Connectivity was investigated between the southern and western limbs, however, poor seismic imaging below a strong shallow continuous reflector makes any conclusion impossible. Connectivity is, however, supported by gravity (~15 mGal high, with a width of around 15 km) and kimberlite data.

Introduction

The Bushveld Complex in South Africa is the largest known layered igneous intrusion with significant economic value. The complex was emplaced between 2055.54 ± 0.27 and 2056.88 ± 0.15 Ma (Mungall et al., 2016; Zeh et al., 2015), and is divided into the western, eastern, northern (Potgietersrus), southern (Bethal), and far western limbs (Figure 1). The eastern and western limbs of the complex have been well studied, while the northern and southern limbs are less so due to access issues and being covered by younger sedimentary rocks. Stratigraphically, the Bushveld Complex is broken into the mafic Rustenburg Layered Suite and acidic Lebowa Granite, Rashoop Granophyre, and Rooiberg Volcanic suites (Figure 1). The Rustenburg Layered Suite in turn is divided into the Upper, Main, Critical, Lower, and Marginal Zones, with the Critical Zone hosting important economic minerals.

Reflection seismic data are an important and well-used exploration tool. In South Africa, these data have been used for exploration in a wide range of geological settings, such as exploring for gold in the Witwatersrand Basin, or platinum and platinum group elements in the Bushveld Complex. The western and eastern limbs of the Bushveld Complex are sparsely imaged by long (>30 km) seismic profiles that show shallow limbs dipping (12 to 20°) toward the centre of the complex (Campbell, 1990, 2011; Odgers, 1998; Odgers et al., 1993; Sargeant, 2001) (Figure 1). Seismic line DG326 was originally shot to explore for extensions of the Witwatersrand Basin. In this study, we now use it to shed light on the subsurface structure in the southwestern parts of the Bushveld Complex.

The limbs of the complex are imaged using magnetic (Figure 2a) and gravity data (Figure 2b). The magnetitite layers of the Upper Zone shows up as a strong magnetic high/low pair outlining the limbs of the complex. The high-density nature of the Bushveld Complex compared to the surrounding sedimentary rocks of the Transvaal Supergroup means it shows up as a high on the Bouguer gravity map. Additional magnetic signatures are due to several dykes and dyke swarms that crosscut the complex.

The connectivity between the western and eastern limb has been supported using gravity modelling, kimberlite xenoliths, and receiver function data (Cole et al., 2021; Kgaswane et al., 2012; Webb et al., 2011; Webb et al., 2004). The connectivity between these limbs and the southern limb is poorly studied. Here we use reflection seismic and gravity data over the southern part of the complex, over seismic line DG326 (Figure 1), to investigate connectivity further.

Geology of the region

The seismic line passes horizontally over rocks ranging in age from Archean (~2.9 Ga) to Permian (~280 Ma) (Figure 3 and Table 1): Section A passes over Transvaal Supergroup rocks that are dipping towards the northeast, and underlain by Witwatersrand Supergroup rocks (0 to 30 km along profile); Section B and C pass over units of the Waterberg Group, and even younger Karoo Supergroup (30 to 87 km along profile); Section D passes over Rooiberg volcanics and Nebo granites of the Bushveld Complex (87 to 110 km along profile); Section E passes over the Dennilton Dome where older basement and Transvaal Supergroup are exposed (110 to 140 km along profile). In this region, the orientation of the profile changes from a northeast strike to southeast. The last section, section F passes over the Rooiberg volcanics, Rashoop Granophyre, and Rustenburg Layered Suite of the Bushveld Complex (140 to 170 km along profile).

The Witwatersrand Supergroup is made up of the Archean West Rand (lower) and Central Rand (upper) Groups. The laterally extensive West Rand Group consists mainly of alternating quartzites and shales, while the Central Rand Group occurs in

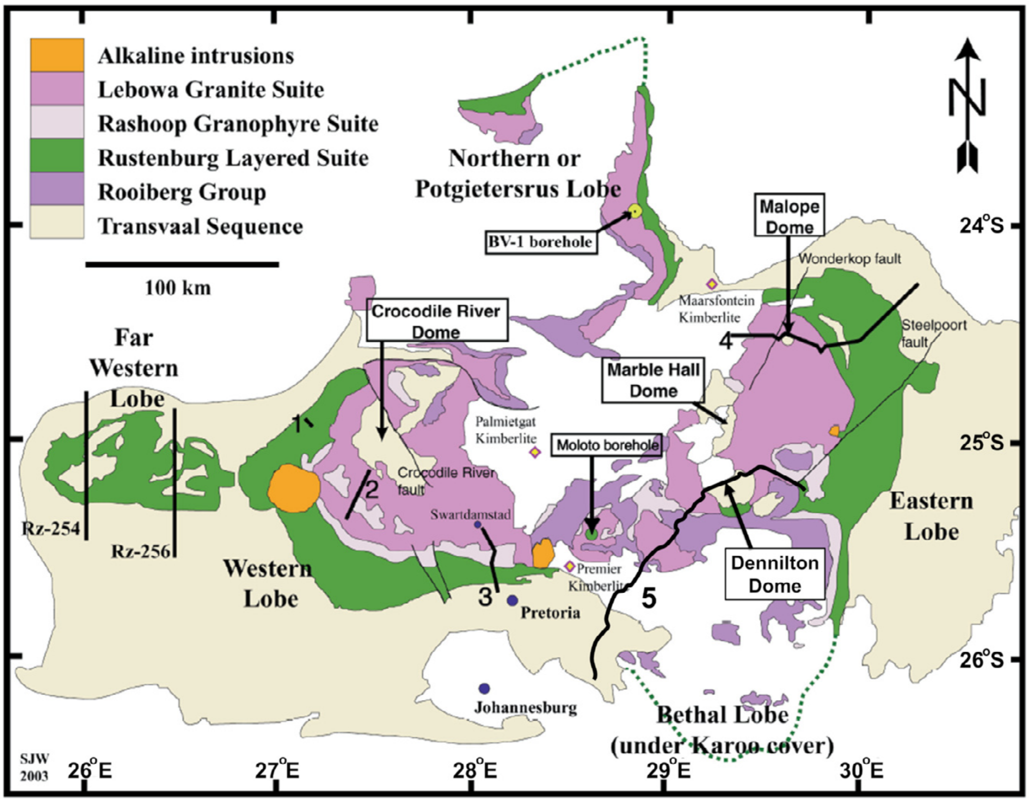

Figure 1. Map of the Bushveld Complex showing the western, far western, eastern, northern (Potgietersrus), and southern (Bethal) limbs (modified from Webb et al. (2004)). Existing long (>30 km) seismic data that sparsely cover the western, far western, and eastern limbs are shown (Lines 1-4, Rz-254 and Rz-256). Seismic line DG326 (Line 5) covers the join between the Bethal limb in the south and the central part of the complex and is investigated in this study. The Dennilton Dome, which lies close to the Steelpoort fault, is imaged by seismic line DG326.

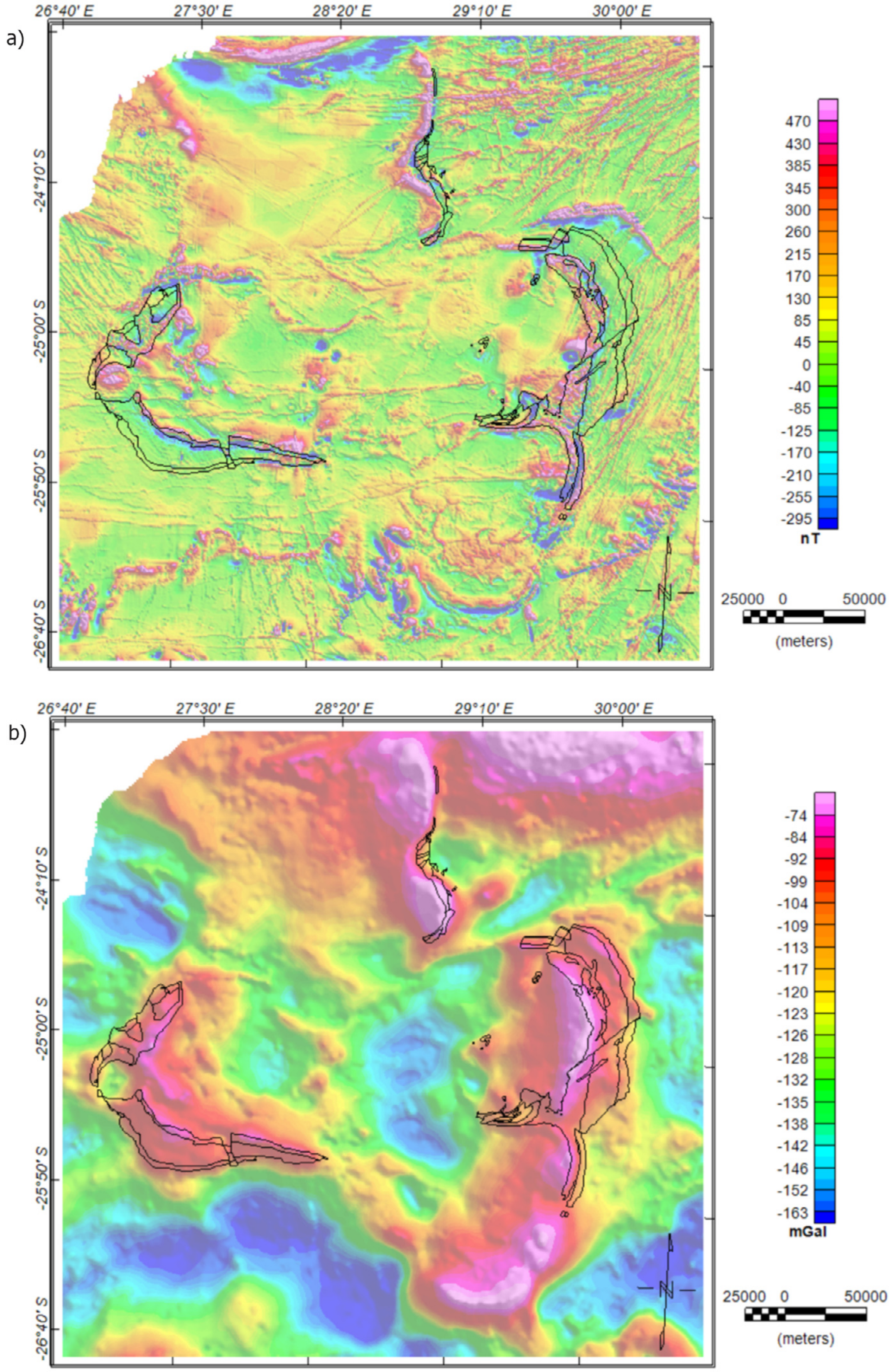

Figure 2. *(**a**) Total magnetic intensity (TMI) and (**b**) Bouguer gravity map of the Bushveld Complex (black outline). Inset map shows the location of the Bushveld Complex (green) in the northeast of South Africa. A strong magnetic anomaly is associated with the Upper Zone of the Rustenburg Layered Suite, and a Bouguer gravity anomaly is associated with the dense rocks of the Rustenburg Layered Suite. These data are freely available from the Council for Geoscience.*

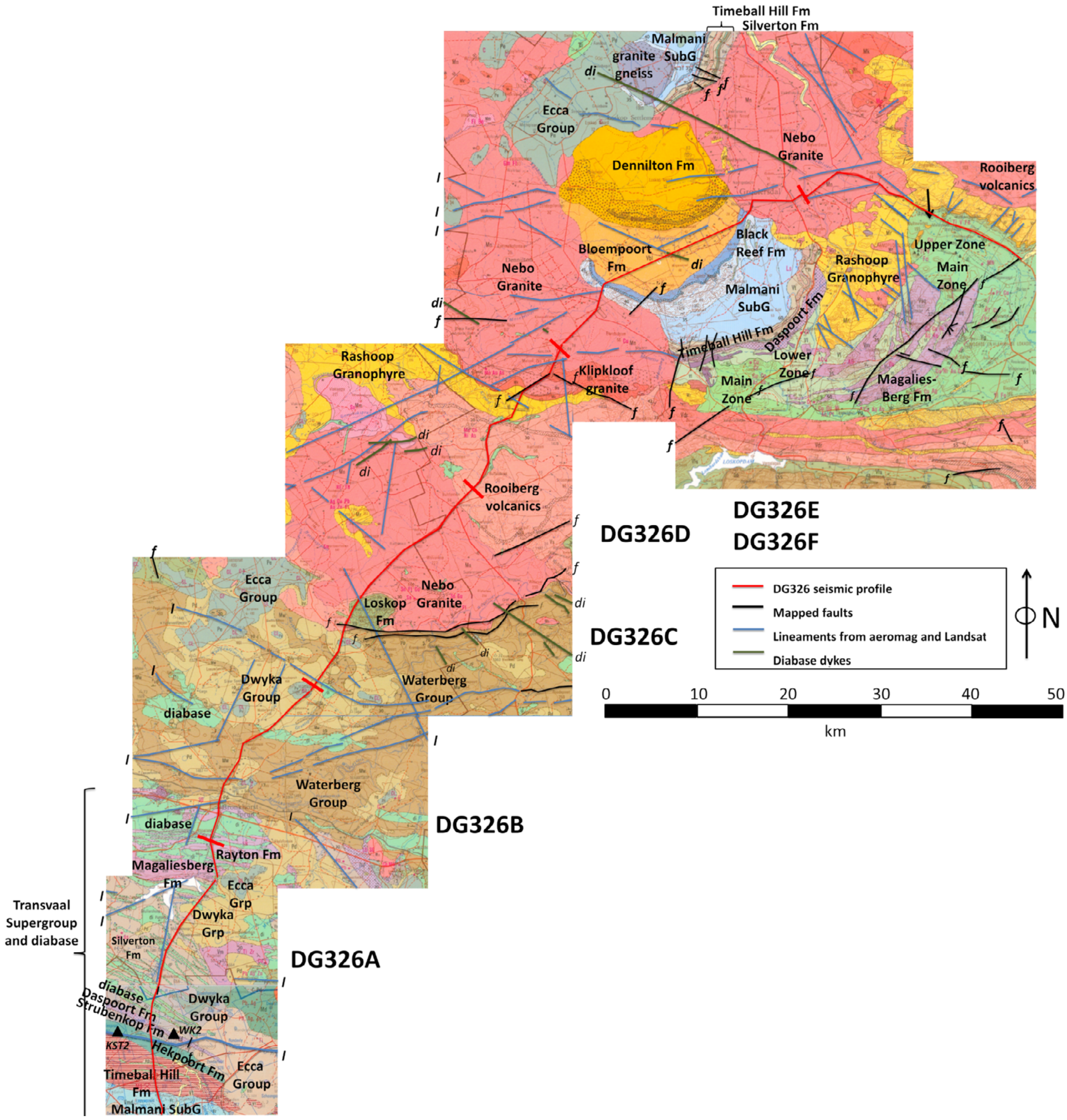

Figure 3. *1:250 000 geology covered by seismic line DG326 (SACS, 1980). The different sections of the line are marked. Boreholes KST2 and WK2 are marked with black triangles in the southwest (Button, 1968).*

pockets and consists mainly of conglomerates and quartzites (McCarthy, 2006). The Central Rand Group is unconformably overlain by volcanics and metasediments of the Ventersdorp Supergroup, which in turn is unconformably overlain by the Transvaal Supergroup. These alternating quartzites and shales of the Central Rand Group provide a strong acoustic impedance contrast that allows for effective imaging with seismic methods.

The Transvaal Supergroup consists of lower chemical sedimentary units of the Chuniespoort Group and upper clastic sediments and volcanic lithologies of the Pretoria Group. The quartzites of the Black Reef Formation lie below the Chuniespoort Group. The rocks of the Transvaal Supergroup show up as a distinctive package of reflectors on seismic data due to strong contrasts in acoustic impendance (Campbell, 1990, 2011; Odgers, 1998; Odgers et al., 1993; Sargeant, 2001).

The Bushveld Complex intruded the Transvaal Supergroup around 2 060 Ma, and therefore in places the Transvaal rocks form the floor and roof rocks of the complex, and outcrop around the boundary of the complex (Cawthorn et al., 2006). The layers of the Transvaal Basin, in general, dip towards the centrally located Bushveld lithologies.

Buchanan (1975) reported on seven boreholes drilled in the Bethal district around the southern limb of the complex. Six of these intersected the complex, which was divided into five

Table 1. Full stratigraphy for outcropping rocks in the study area including the Karoo Supergroup, Waterberg Group, Bushveld Complex, and Transvaal Supergroup. The colour key correlates with that used in seismic interpretations in this study (SACS, 1980). Abbreviations: SG=Supergroup; G=Group; S=Suite; Fm=Formation; Z=Zone; An=Anorthosite; Gn=Gabbronorite; GW=Greywacke; Px=Pyroxenite; Qtzite=Quartzite.

SG/Complex	Grp (G)/Suite (S)	Formation (Fm)/Zone (Z)	Rock units	
	Diabase			
Karoo SG	Ecca G		Sandstone and shales	
	Dwyka G		Tillite	
	Waterberg G	Wilge River Fm	Sandstone, quartzitic in places; conglomerate	
		Loskop Fm	Shale, sandstone, conglomerate; volcanic rocks	
Bushveld Complex	Rooiberg G		Volcanics	
	Rashoop Granophyre S		Granophyre	
	Lebowa Granite S	Klipkloof	Granite	
		Nebo	Granite	
	Rustenburg Layered S	Upper Z (UZ)	Gabbro, an, magnetite	
		Main Z (MZ)	Gn, an, px	
		Critical Z (CZ)	An, px, norite, chromitite	
		Lower Z (LZ)	Dunite, px, harzburgite	
		Marginal Z (Marg)		
Transvaal Supergroup	Pretoria G	Rayton Fm	Qtzite, shale, sub-gw	
		Magaliesberg Fm	Qtzite, minor hornfels	
		Silverton Fm	Shale, carbonaceous in places; hornfels, chert	
		Daspoort Fm	Qtzite	
		Strubenkop Fm	Shale	
		Hekpoort Fm	Volcanic rocks	
		Timeball Hill Fm	Shale, siltstone, conglom in places, qtzite	
	Chuniespoort G	Malmani Subgroup	Dolomite and Chert	
		Black Reef Fm	Qtzite, conglom, shale, dol. limestone and shale	
Witwatersrand Supergroup	Central Rand G			No outcrop
	West Rand G			
	Groblersdal G	Bloempoort Fm	Slate, qtzite Volcanics?	
		Dennilton Fm	Granophyric gneiss, schist and granulite	

zones. Zones 1 to 4 were correlated with the Upper Zone of the Bushveld Complex, while the Lower Zone was correlated with equivalent zones in other parts of the complex. The Main and Critical Zones were shown to be missing in this part of the complex, thought to be due to a separate injection centre in this region. This is suggested by faster cooling and higher oxygen fugacity recorded in rocks in this region compared to the Eastern Bushveld Complex (Buchanan, 1975).

The Waterberg Group was deposited shortly after the intrusion of the Bushveld Complex (Barker et al., 2006). In the study area, the two main stratigraphic units are the Loskop Formation and the Wilge River Formation of the Middelburg Basin. The Wilge River Formation unconformably overlies the Loskop Formation in the study area. The formation consists of sandstones and conglomerates, which dip at approximately 10° towards the centre of the basin. These units are intruded by post-Waterberg microgabbroic thick diabase sills and dykes (northwest and northeast striking).

The Loskop Formation regionally unconformably overlies Rooiberg and Pretoria Group rocks. Rustenburg Layered Suite clasts have been found in the Loskop Formation and Nebo Granites have intruded the Loskop Formation.

Several domes exist within and outside the Bushveld Complex (Clubley-Armstrong and Sharpe, 1979). Smaller domes (<50 km) exist in the Bushveld Complex and are thought to be due to diapirism associated with highs in the underlying Transvaal Supergroup or basement highs (Clubley-Armstrong and Sharpe, 1979; Gerya and Uken, 2003). The Dennilton Dome is one of the largest domes in the complex at ~60 km.

The Dennilton Dome lies at the intersection of an east-northeast and northwest trending anticline associated with the Steelpoort and Laersdrift faults (Figure 1). Clubley-Armstrong and Sharpe (1979) suggest the Dennilton Dome was a pre-existing feature and that the intrusion of the Bushveld Complex and development of the Steelpoort Fault system reactivated the dome “through development of isostatic instability”.

Within the dome, older basement rocks are brought to surface. Younger Transvaal Supergroup rocks around the edges of the dome have also been brought to the surface. There is some debate about the classification of these basement rocks. The 1:250 000 geological map of the region classifies the rocks of the Dennilton Formation (gneiss and felsites) and Bloempoort Formation (sedimentary and volcanics) as the Groblersdal Group (Walraven, 1978). The map shows granite-gneisses further north of the seismic line as part of the Dennilton inlier. Hartzer (1995), however, classifies the gneisses of the Dennilton Formation as being separated from the felsites of the Bloempoort Formation by an unconformity, and therefore classified these as two separate units. Hartzer (1995) also showed that these pre-Black Reef successions extend across the entire Transvaal basin and that the Black Reef in the Dennilton inlier is unusually thick due to thrust faulting. Hartzer (1995) includes the Bloempoort Formation as part of the Transvaal Supergroup. Eriksson et al. (2006) classify the rocks of the Dennilton inlier as consisting of basement rocks, the Bloempoort Group, and Transvaal Supergroup rocks. The Bloempoort Group consists of upward-coarsening cycles of carbonaceous claystone-siltstone and sandstone, with subordinate course-grained clastic rocks, carbonates, and volcanic rocks. The classification from the 1:250 000 map is used here because the map was used when interpreting the seismic line.

In terms of domes outside of the complex, the well-studied Johannesburg Dome is approximately 150 km southwest of the Dennilton Dome, south of the Bushveld Complex. More recent studies by Ormond and Lehmann (2022) conclude that the dome formed because of south- and east-directed fold-and-thrust belts of basement material during sedimentation of the Central Rand Group of the Witwatersrand Supergroup. Several Paleoproterozoic deformation events then affected the structure of the dome and deposition of cover rocks.

Data and methods

Reflection seismics

The 2D reflection seismic profile DG326 is six seconds two-way time (TWT) data (i.e., imaging the upper crust) that was acquired by the Gold Division of Anglo-American Corporation of South Africa (now AngloGold Ashanti Ltd) at the end of 1990. The primary goal of the seismic survey was to map the extent of the Witwatersrand basin in this region. In this study we present the seismic profile, with the objective of understanding the continuity of the Bushveld Complex in this region. The line is divided into six segments (A, B, C, D, E and F), each approximately 20 to 30 km long. The data was acquired along the R42 road north of Delmas and continues towards the northeast along the R25 road (east of Bronkhorstspruit), and then curves towards the southeast on the R33 road (east of Groblersdal).

The setup during data acquisition is shown in Figure 4 and summarised in Appendix Table A1. (Suppplementary data files are archived in the South African Journal of Geology repository (https://doi.org/10.25131/sajg.127.0040.sup-mat)). The survey spectrum has a useful spectrum of between 10 and 50 Hz, and a calculated dominant frequency of 36 Hz. The higher frequency content of the data was used to image shallower upper crustal bodies. The calculated vertical resolution of the data is approximately 50 m (Appendix Table A2), therefore throws on faults and bodies smaller than 50 m will not be imaged on the seismic data. Processing parameters are outlined in Appendix Table A3.

Gravity, Magnetics and Petrophysical Properties

Aeromagnetic data over South Africa were collected by the Council for Geoscience from the 1980s to the late 1990s. The magnetic data were flown at a line spacing of 1 km, with a tie line spacing of 10 km and sample spacing of around 60 m. The flight height for the survey was between 100 to 150 m (Stettler et al., 2000). The final aeromagnetic anomaly was calculated with respect to the normal Earth magnetic field (Intensity: 28 700 nT, Declination: -22.6°, Inclination: -66.1°).

The Bouguer gravity data used in this study form part of the Council for Geoscience regional dataset (Venter et al., 1999), with an average station separation of 14 km. In the Bushveld Complex, coverage is much higher, around 5 km or less, giving us confidence is the anomalies mapped along the seismic line. The gravity data were processed using standard techniques, i.e., drift corrections, latitude corrections (theoretical gravity based IGSN71 and IGF67), free air and Bouguer corrections with a reduction density of 2670 kg/m^3. A plot of Bouguer gravity versus elevation by Webb (2009) shows scatter around an approximate straight line that is relatively well fit using this reduction density.

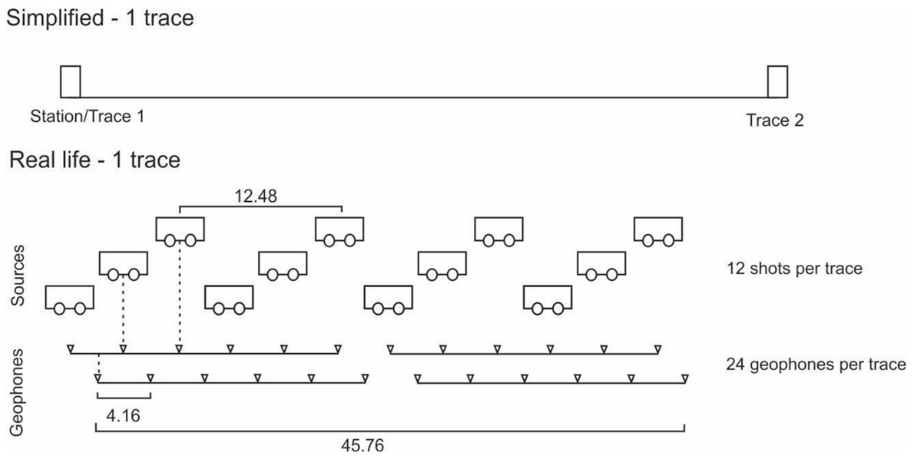

Figure 4. *Survey acquisition procedures for seismic line DG326. Four strings of geophones were used, with six geophones per string, giving a total of 24 geophones per trace. Four vibrator trucks were used per trace, positioned at every fourth geophone (12.5 m between vibrators). Once the sweep (10-60 Hz; 3 sweeps per vibrator; 24 seconds per sweep) was completed, the vibrator would move to the next geophone (4.1 m move up). This layout led to a geophone group spacing/station interval of 50 m and 12 shots per trace. The total line length was 170 km.*

Table 2. Density values (kg/m³) for rock types in the study area (Maré, 2012).

		Average density (kg/m³)	No samples
Post Waterberg Diabase		2900	35
Waterberg Group		2600	45
Bushveld Complex	Felsics	2650	21
	Rustenburg Layered Suite	3050	127
Transvaal Supergroup	Upper Transvaal	2650	29
	Lower Transvaal	2750	72
Witwatersrand Supergroup	West Rand Group	2800	8
	Central Rand Group	2700	16
Greenstone basement		2800	15

Density values of rock types in the study area from the Council for Geoscience Physical Properties Atlas (Maré, 2012) are recorded in Table 2. While no density modelling is carried out in this paper, the densities assist in the interpretation of gravity data over the region.

Seismic data – Results and interpretation

Seismic section DG326 is shown in Figure 5a, with outcropping geology marked above the section, with the seismic characteristics of the section marked in Figure 5b. The section has a vertical exaggeration of 2. Realistically the seismic section should be stretched out over several more pages, and therefore dipping features would not appear as steep.

Transvaal and Witwatersrand Supergroup

Along Section A, the strong layered seismic reflectors correlate with the Transvaal Supergroup on surface (light blue region in Figure 5b). These horizons dip to the northeast from the start of the profile and extend down to two seconds TWT (6.7 km) around 40 km along the profile. These strong reflections are a result of the large acoustic impedance contrast between volcanics, shales and quartzites in the Transvaal Supergroup. The supergroup is cut by several steep thrust faults.

On the seismic section the Transvaal Supergroup unconformably overlies strong layered, dipping reflectors that are deformed (folded and faulted) (red region in Figure 5b). At the start of the profile these layers extend from the surface down to 1.5 seconds TWT. These units were investigated in the 1960s for possible extensions of the Witwatersrand Basin (Button, 1968), and therefore several boreholes cover this region: Boreholes WK2 and KST2 lie between 5 to 10 km along the seismic line and extend to approximately 2.7 to 2.8 km depth (Figure 5a). These boreholes intersect upper Witwatersrand Supergroup below Transvaal Supergroup rocks, and this package is interpreted as such.

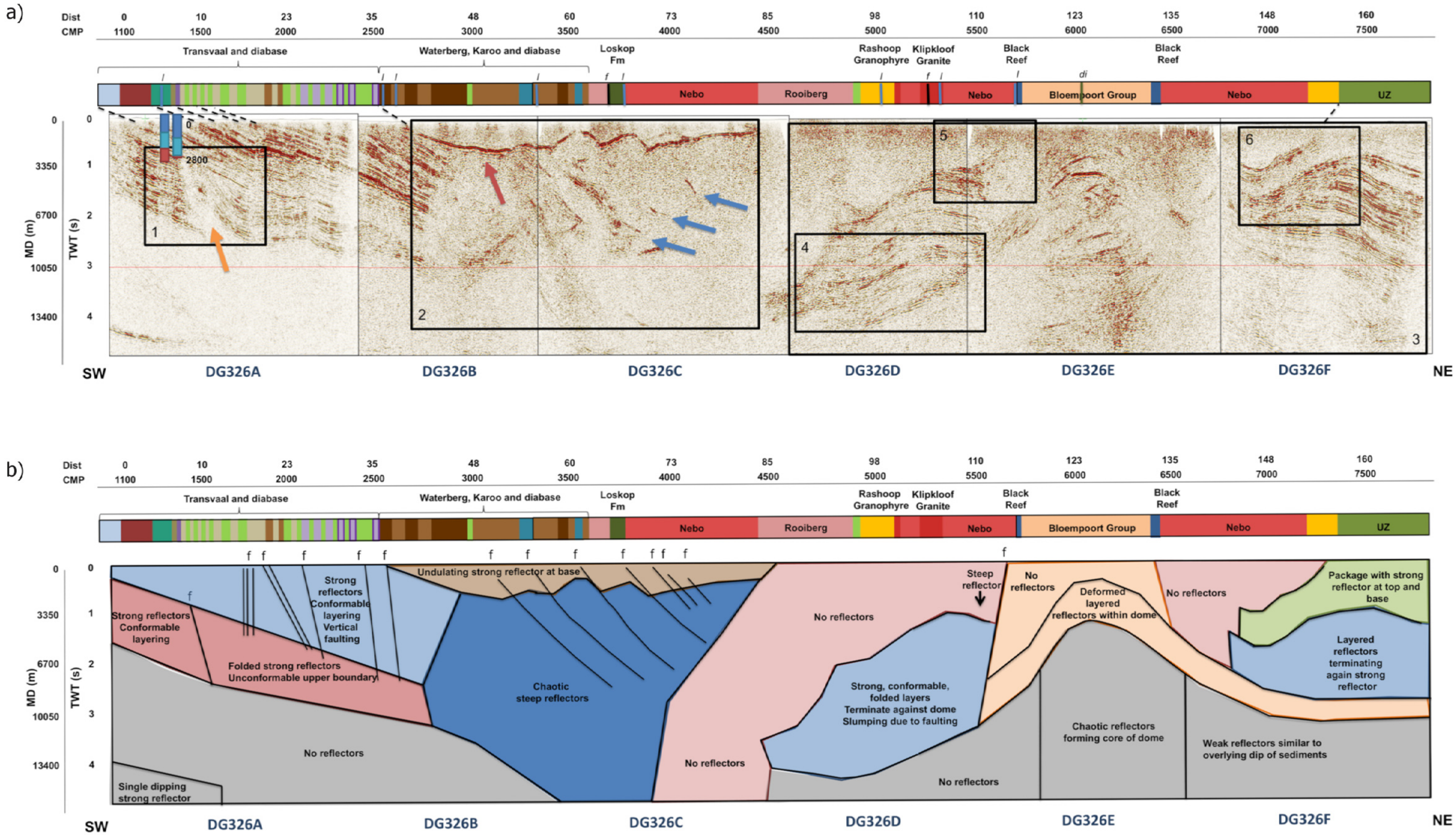

Figure 5. *(**a**) Seismic line DG326 with outcropping geology marked along the top of the section. Boreholes KST2 and WK 2 are shown between 5 and 10 km along the profile (Button, 1968): Pretoria Group=dark blue and Chuniespoort Subgroup=light blue of the Transvaal Supergroup; Upper Witwatersrand Supergroup sediments=red. (**b**) Seismic characteristics of seismic line DG326 are described. Faults are marked on the surface geology as black lines f, while lineaments from geophysical and Landsat data are marked as blue lines l, and diabase dykes are marked with green lines and di. Marked blocks (1-6) will be investigated further in the following sections. Coloured arrows indicate features discussed in the text.*

Below these Witwatersrand rocks is assumed to be basement rocks due to the lack of strong reflectors (grey region in Figure 5b). A strong reflector is, however, evident around four seconds TWT at the start of the profile with a similar apparent dip direction to the Transvaal and Witwatersrand supergroups.

The Witwatersrand Supergroup rocks imaged on Section DG326A appear to be divided by a steep structure (orange arrow in Block 1 in Figure 5a and Figure 6). To the southwest (i.e., left of the orange arrow) the layers are relatively undeformed and dipping to the north, while to the northeast the layers are folded (right of the orange arrow). This steep structure (orange arrow) is investigated further using seismic attributes in Figure 6. Envelope and general spectral decomposition are seismic attributes used to analyse subsurface features by enhancing the information derived from seismic signals. The envelope attribute, also known as instantaneous amplitude, highlights the strength or energy of seismic reflections, helping to identify geological boundaries and discontinuities. Spectral decomposition, on the other hand, breaks down seismic data into its frequency components, allowing for the detection of subtle stratigraphic features. Decisions are based purely on visual inspection of the attributes.

In Figure 6, the envelope attribute applied to the seismic section favours a fault separating the undeformed and folded regions of the Witwatersrand Supergroup (Model 1). The general spectral decomposition attribute in Figure 6 favours a model where there is only folding of the units to the northeast but no fault separating the two regions (Model 2). In this study we favour Model 1, and the steeply dipping feature is assumed to be a fault. The vertical feature correlates with an east-west lineament mapped on surface using aeromagnetic data and/or Landsat data around 7 km along profile. There appears to be no offset along this structure in the overlying Transvaal Supergroup rocks.

Studies have shown that the Witwatersrand basin is cut by several faults, with several phases of deformation (McCarthy, 2006). The first was syn-depositional deformation linked to regional compression linked to deposition of the early Central Rand Group. This deformation led to fragmentation of the

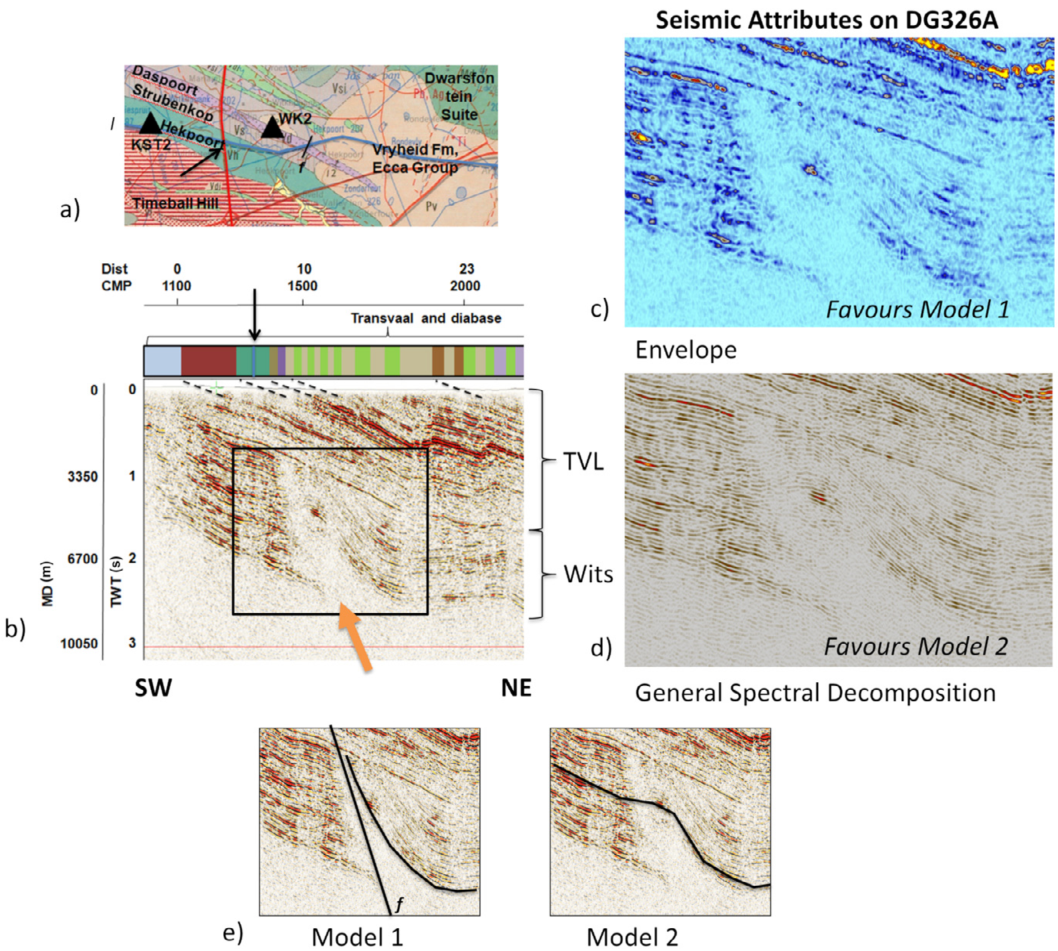

Figure 6. *Investigation of Witwatersrand Supergroup units imaged in Block 1 on seismic section DG326A (in Figure 5a).* ***(a)*** *Geology of the region covered by Block 1. This section of the line passes entirely over Transvaal Supergroup rocks. Red line marks the seismic line and blue line marks an inferred fault (i.e., lineament mapped using geophysical and/or Landsat data), also indicated by a black arrow.* ***(b)*** *Seismic section showing Block 1 (black box). Fault mapped on surface is marked with a black arrow on the outcropping geology. Orange arrow demarcates vertical structure of interest.* ***(c)*** *Envelope attribute and* ***(d)*** *General spectral decomposition seismic attributes applied to the Block 1 seismic section to help interpret the apparent near-vertical feature marked by the orange arrow.* ***(e)*** *Geological models used to explain the feature marked by the orange arrow.*

basin into a number of domains, bounded by discontinuities. Deformation was also characterised by gentle warping or tilting, or thrusting along the margins of the domain towards the basin, "resulting in marginal overfolds and the development of pronounced angular unconformities". The second stage of deformation was during the eruption of the volcanics of the overlying Ventersdorp Supergroup. Relaxation of compressional stress led to reactivation of thrusts as normal faults (McCarthy, 2006). Additional normal faults were also initiated. Post-Transvaal deformation was the third stage of deformation linked to the Vredefort impact structure.

Waterberg Sill and Karoo Supergroup

Along Section B and C (distance of 35 to 85 km) a strong shallow reflector is evident above one seconds TWT (red arrow in block 2 in Figure 5a and Figure 7). The start and end of the reflector correlate with outcropping Waterberg Group rocks. In places the Dwyka Group from the younger Karoo Supergroup outcrops above the strong reflector. This strong reflector is thought to be a post-Waterberg sill that has intruded along the base of the Waterberg rocks. Imaging of the continuation of Transvaal and Witwatersrand supergroup below this strong reflector is not clear. This is most likely due to the sill reflecting a large amount of the energy back to surface. This poor imaging could also be due to sideswiping during collection of the seismic data.

Around 50 km along the profile there is deformation of this strong reflector/sill, resulting in topographic highs. The edges of these topographic highs correlate with chaotic steep reflectors in the underlying units (blue arrows in Figure 5a and Figure 7). Seismic attributes are used to better understand this deformation. This deformation could be caused by updoming (Model 1), but it is more likely the result of faulting (Model 2). Shallow listric faults are mapped on the seismic data and assumed to be the cause, some of which correlate with faults mapped on surface.

Bushveld Felsic Phase

On Section C and D there are no strong reflectors. On surface Nebo Granites, Rashoop Granophyres and Rooiberg volcanics outcrop from approximately 65 km to 110 km (pink region in Figure 5a and Figure 8a). Between 65 km and 82 km, even though Nebo Granites outcrop on surface, the strong reflector of the Waterberg sill is still clearly imaged below the granites on the seismic data (<1 second TWT; red arrow in Figure 5a and Figure 8a).

The poor imaging below the Waterberg sill and the outcropping volcanics and granites make it difficult to determine whether the Transvaal and Witwatersrand supergroups extend

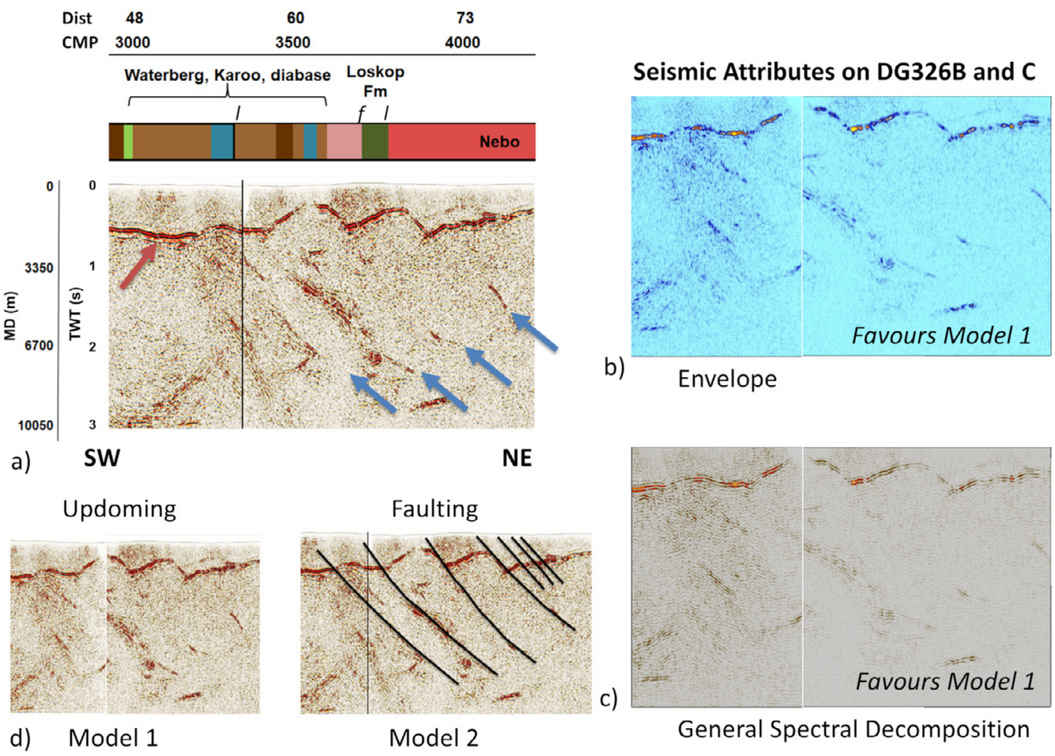

Figure 7. *Investigation of Waterberg and underlying rocks in Block 2 on seismic section DG326B and C (Figure 5a): (**a**) Zoomed-in seismic section: A shallow strong reflector is imaged around one second TWT (red arrow) and assumed to be a sill. Between 50 and 75 km the sill appears to be deformed. The edges of topographic highs in the sill correlate with dipping reflectors at depth (blue arrows). (**b**) Envelope and (**c**) General spectral decomposition attributes are applied to the seismic section. Both attribute images support Model 2 shown in (**d**), i.e., shallow normal listric faulting, instead of deformation due to updoming (Model 1). The faults correlate with steep reflectors in the underlying section, and faults mapped on surface.*

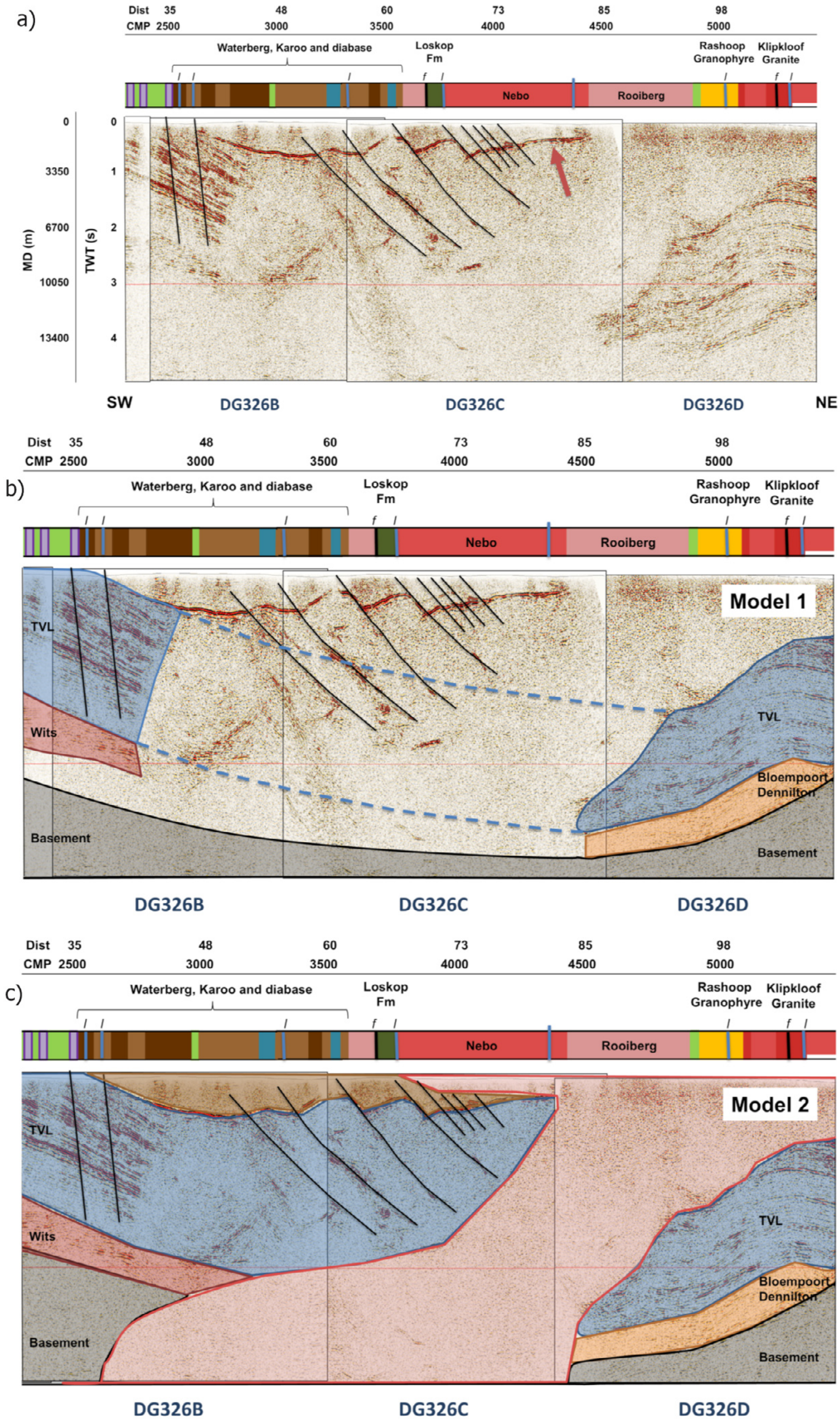

Figure 8. *Investigation of deeper rocks and structures in Block 2 on seismic section DG326B, C and D (in Figure 5a) (**a**) Original seismic section with geology and faults marked above and on the profile. The red arrow indicates continuity of the Waterberg sill. (**b**) In Model 1 it is assumed that the Transvaal Supergroup rocks continue below the strong reflector of the Waterberg Group and the outcropping Nebo Granites, Rooiberg volcanics and Rashoop Granophyres (dashed blue line) but are just not imaged on the seismic data. (**c**) In Model 2 it is assumed that the granites and granophyres disrupt the continuity of the Transvaal and Witwatersrand supergroups. Model 2 is adopted in this study.*

across this region and correlate with reflectors imaged at depth on Section D (light blue region in Figure 8b and c, between 85 to 110 km along profile), or the granites and granophyres intruded and separated the two sections of sedimentary rocks at depth. These two models are investigated in Figure 8. In this study we assume the granites and granophyres intrude across the sediments (Figure 8c).

Dennilton Dome

On Section E the Dennilton Dome is clearly imaged (Block 3, 4 and 5 in Figure 5a). The dome in outcrop is approximately 20 km in diameter, but at depth (>4 seconds TWT; 13 km depth) the dome has a diameter of around 60 km. Dennilton Formation and Bloempoort Formation rocks form the core of the dome and are surrounded by upwarped Transvaal Supergroup rocks, as seen in outcrop. This suggests that, similar to the Johannesburg Dome, the Dennilton Dome was an existing basement high before intrusion of the Bushveld Complex.

Deformation that has occurred on the southwestern slope of the dome is investigated in Figure 9. A large fault is imaged on the southwestern flank of the dome (black line in Figure 9a). The fault is mapped on surface as a lineament using geophysical data and/or Landsat data (black arrow on Figure 9a). The lower

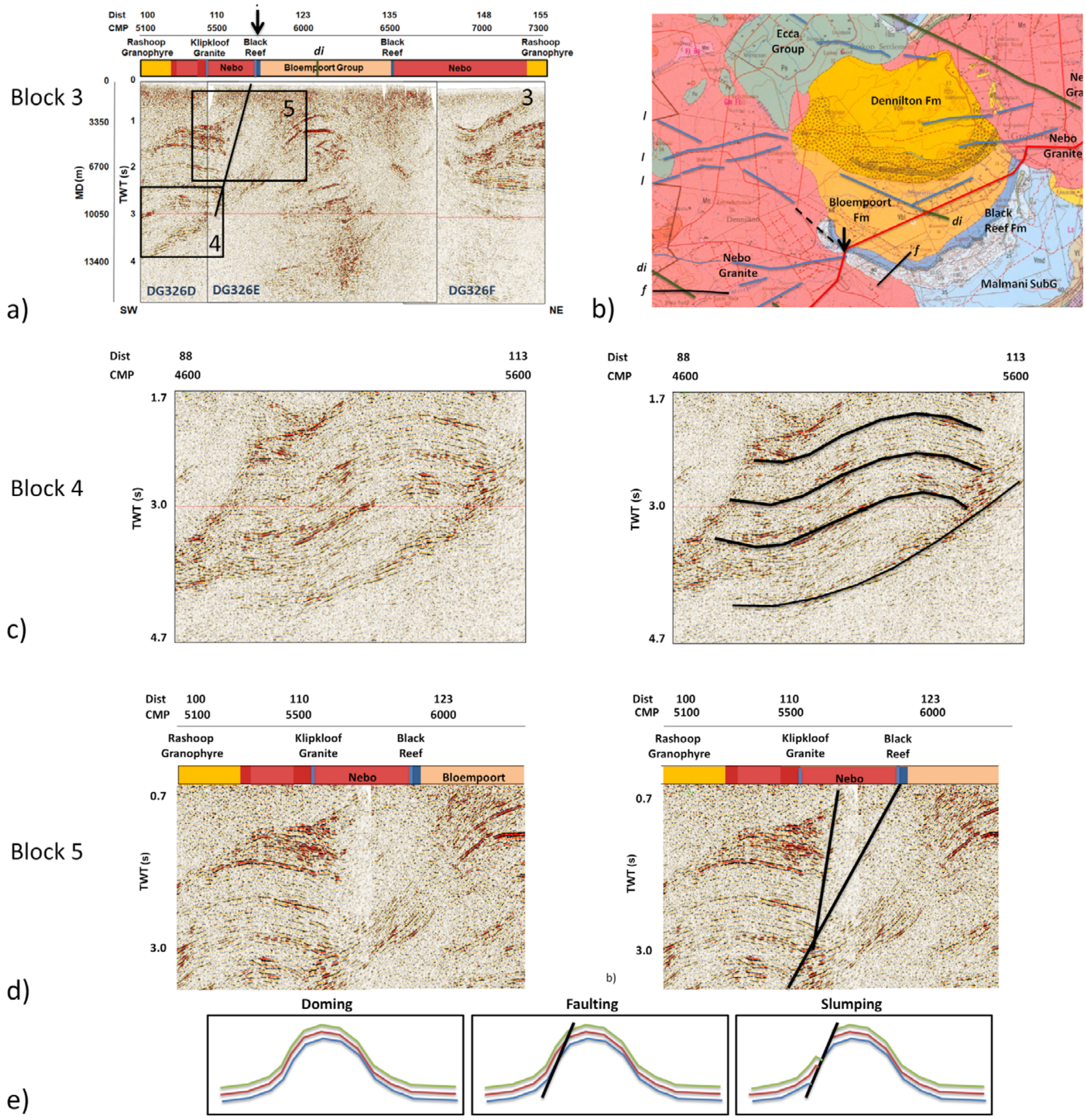

*Figure 9. Investigation of the southwestern flank of the Dennilton Dome on seismic section DG326D (**a**) Seismic section across the entire dome (Block 3 from Figure 5a). Smaller Blocks 4 and 5 are marked. The fault to the southwest affecting the Transvaal Supergroup rocks onlapping onto the dome is marked (black line and arrow). (**b**) Geological map of the dome and seismic line (red line). The black arrow marks a lineament mapped using geophysical and/or Landsat data (blue and black dashed lines) that correlates with the fault mapped on the seismic data in (a) (black line and arrow). (**c**) Block 4: Lower Transvaal Supergroup units onlapping onto Dennilton Dome (original seismic section on the left and interpreted on the right). (**d**) Block 5: Upper Transvaal sediments near the centre of the Dennilton Dome affected by faulting and slumping (original seismic section on the left and interpreted on the right). The process of slumping is shown in (**e**) doming followed by faulting and then slumping of sediments.*

Transvaal Supergroup units are imaged on the seismic data onlapping onto the dome (Block 4 in Figure 5a and Figure 9). The large fault on the southwestern flank of the dome has caused slumping of shallower Transvaal Supergroup sediments off the side of the dome (Block 5 in Figure 5a and Figure 9).

Continuity of Transvaal sediments

The continuity of the Transvaal sediments across the seismic profile is assumed based on similar seismic characteristic and similar package thickness (Figure 10). The seismic reflectors that link with mapped Transvaal sediments on surface (block 1), are assumed to link with the package of strong reflectors on the southwestern flank of the dome (block 2), and at the end of the DG326 profile in the northeast where there is no outcrop (block 3) (Figure 10). It is assumed that the Transvaal sediments were continuous across this line but were disrupted by the rising dome and the intrusion of the acidic phase of the Bushveld Complex.

Rustenburg Layered Suite

Section F is the only section where mafic rocks of the Rustenburg Layered Suite are clearly imaged, and is investigated in Figure 11. The rocks of the eastern limb of the Rustenburg Layered Suite outcrop at the end of the profile, therefore it is assumed the rocks directly below it are Rustenburg Layered Suite (green region in Figure 5b, and Figure 11a).

The strongest known reflections in the Rustenburg Layered Suite are associated with the Critical Zone (CZ). The large acoustic impedance contrasts is due to alternating layers of anorthosites and norites and the ultramafic pyroxenites and chromitites in the CZ (Campbell, 2003; Trickett et al., 2009). From other seismic lines in the Bushveld, namely Line 4 in the northeastern part of the eastern limb (Odgers and du Plessis, 1993; Sargeant, 2001), and Line 3 in the southeastern part of the western limb (Odgers, 1998) (Figure 1), the thickness of the Upper Zone and Main Zone is approximately one second TWT (approximately 3 km). It is therefore assumed that the strong reflections around one second TWT at the end of the profile are due to layering in the CZ. This CZ layering follows a similar pattern to the overlying boundary between the Rustenburg Layered Suite and granites/granophyres (green arrow, Figure 11). The other alternative is that these units are part of the Transvaal Supergroup below.

North of the Dennilton Dome, from around 165 km along profile DG326 to the end of the profile, the rocks of the Bushveld Complex and Transvaal Supergroup are relatively concordant at depth (blue arrow, Figure 11), which is the same relationship as seen on other seismic profiles throughout the complex (Campbell, 2013 and Odgers, 1998). However, on the northeastern side of the dome (148 to 165 km along profile), the Rustenburg Layered Suite rocks cut down into rocks of the Transvaal Supergroup (Block 6 in Figure 5a, and green arrow in Figure 11).

In Figure 11, it can be seen from outcrop that the Transvaal rocks are brought to surface on the northeastern flank of the Dennilton Dome (yellow arrow, Figure 11). At depth around 140 km along the profile (~2 seconds TWT; 6.7 km depth), the Bushveld rocks are shown to be pushed upwards by the dome (green arrow), but at shallower depths it isn't clear if these rocks exist on the flank of the dome or have been replaced by Nebo Granite Suite rocks (red arrow). If economic rocks in the CZ are brought closer to surface, this would have financial implications.

The complete interpretation of seismic line DG326 is shown in Figure 12. Further investigations need to be conducted to see how the rocks of the Bloempoort Group relate at depth to rocks of the Witwatersrand Supergroup. The main features interpreted are above the vertical resolution of 50 m.

Potential field data

From southwest to northeast, seismic line DG326 (Figure 13a) extends from the southern limb of the Bushveld Complex as defined by magnetic data, over several dykes and terminates in the strong magnetic signature of the eastern limb (Figure 13b). On the Bouguer gravity data, seismic line DG326 extends from a gravity high of the southern limb, over a gravity low and terminates in the strong gravity high of the eastern limb (Figure 13c and d).

Future work should involve the creation of a density model to investigate whether denser Rustenburg Layered Suite material is uplifted on the flanks of the Dennilton Dome (black arrows 1 and 2, Figure 13d), and whether this denser material also underlies the southern part of the seismic profile (black arrows 3, Figure 13d). The density values in Table 2 show that the densest material in the area is Rustenburg Layered Suite and post-Waterberg diabase.

Such a model should include Moho depths from the more recent AfricaArray broadband seismic stations. Moho depths for the complex were originally determined during the South African Seismic Experiment in the 1990s, with a station spacing of just over 100 km and approximately 16 stations (Nguuri et al., 2001). These stations were infilled in 2014 by AfricaArray researchers, improving the resolution of the data, with station spacing of under 100 km and approximately 23 stations.

It should be noted that the broad gravity high at the start of the profile (arrow 4 in Figure 13d; 10 to 30 km along the profile in Figure 14c and d) is most likely due to denser Transvaal and Witwatersrand Supergroup rocks at shallower depths compared to the less dense Waterberg and Karoo sediments, and felsic Bushveld rocks further to the northeast.

An existing regional 3D density model over the entire Bushveld Complex (Cole, 2018) shows the continuity of the Rustenburg Layered Suite below the southern part of the seismic profile, however, seismic profile DG326 was not used to constrain this model. This model by Cole (2018) reveals a complex geometry, with 5 to 8 km thick continuous Rustenburg Layered Suite between the western and eastern limbs and in the south-eastern limb. Bushveld granites and younger sediments form a 4 to 7 km-thick cover over the central Rustenburg Layered Suite. The modelling also reveals updomed basement material in the eastern limb. This model was created by joint forward modelling of regional gravity and magnetic data and

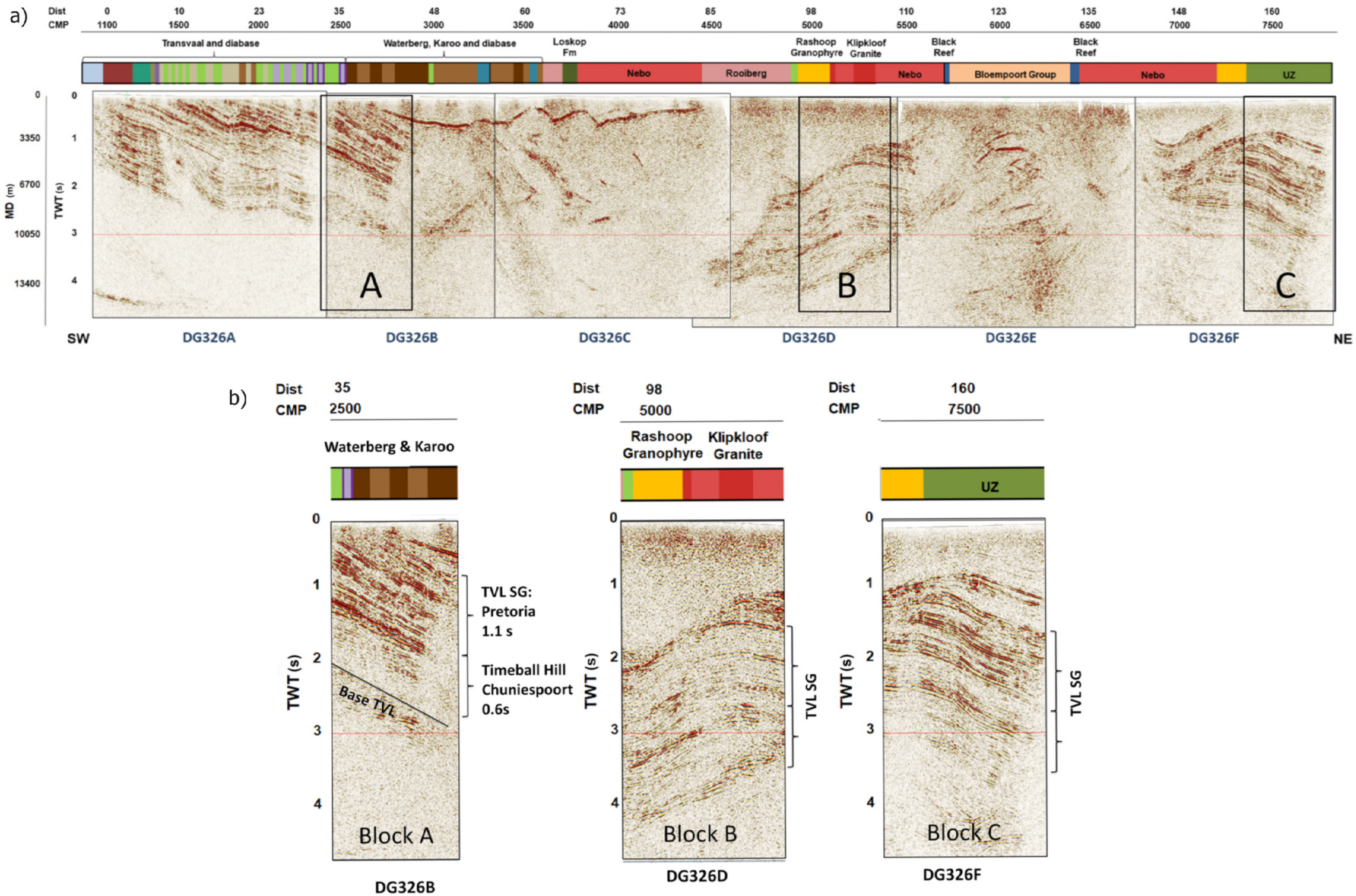

Figure 10. *(**a**) Seismic section DG326, with block A, B and C used to investigate the continuity of Transvaal Supergroup (TVL) units across this profile. (**b**) Zoom in on blocks 1, 2 and 3. At the start of the profile (block 1), Transvaal sediments are interpreted on the seismic section based on outcrop. Around 100 km along profile (block 2), Transvaal sediments are interpreted at depth (1.5 seconds TWT) on the southwestern side of the Dennilton Dome due to their thickness and seismic characteristic, dipping to the southwest. The sedimentary package of the Transvaal Supergroup is around two seconds TWT thick, with strong layered reflectors. Around 160 km along profile (block 3), Transvaal sediments are also interpreted at one second TWT on the northeastern side of the dome dipping to the southeast, with the same characteristics.*

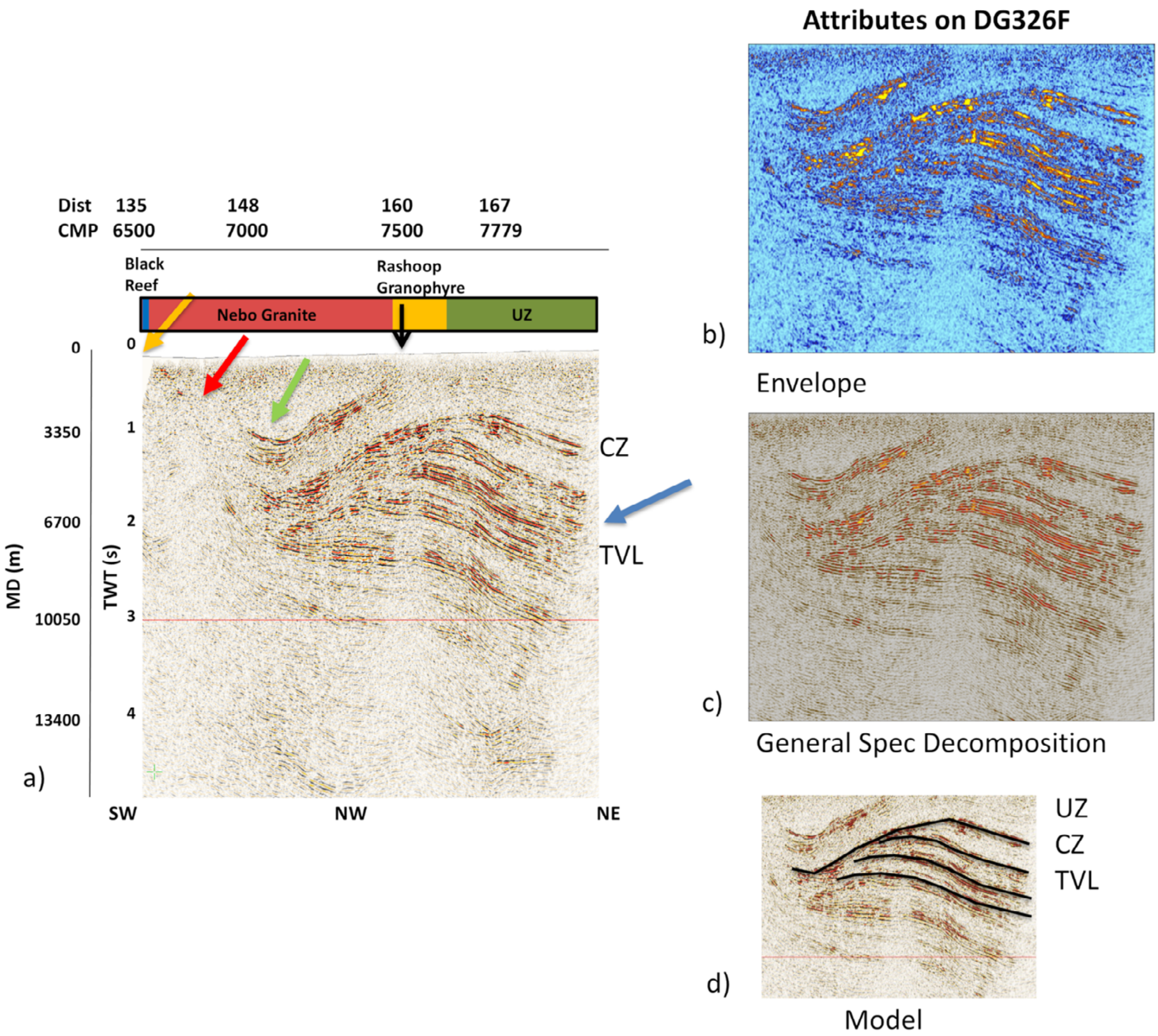

Figure 11. *Investigation of the Rustenburg Layered Suite on seismic section DG326F (Block 6 in Figure 5a): (**a**) Zoomed in seismic section. The strong reflectors of the Critical Zone (CZ) and Transvaal Supergroup (TVL, blue arrow) are marked. (**b**) Envelope and (**c**) General spectral decomposition attribute applied to the seismic section in (a); (**d**) Both attribute images support a model where the Rustenburg Layered Suite rocks (with the lower layer being CZ) cuts down into the rocks of the Transvaal Supergroup just northeast of the Dennilton Dome. The dome brings rocks of the Transvaal Supergroup close to surface (Black Reef Formation, yellow arrow), but it isn't clear if the same is true for the Bushveld Complex rocks (unclear region, red arrow).*

was constrained using published crustal thickness, density, and susceptibility data, geologic mapping, boreholes, and limited seismic reflection data (Campbell, 2011; Odgers, 1998; Odgers et al., 1993; Sargeant, 2001). This 3D density model has led to the proposal that the Bushveld Complex was emplaced as a sill and dipping sheet model (Webb et al., 2019).

Conclusion

The connection between the Western and Eastern Limbs of the Bushveld Complex has previously been shown using gravity modelling and the Palmietgat kimberlite in the centre of the complex (Figure 1). The connection between these two limbs and the southern limb is not as clear, particularly due to younger cover and limited geophysical data. Magnetic and gravity data suggest the eastern limb connecting with the southern limb, but the connection between the western limb and southern limb isn't as clear.

The seismic line DG326 provides a first image of this region between the southern and western limbs. The seismic line passes over Witwatersrand, Transvaal, Waterberg and Karoo rocks in the southwest. The seismic data do not provide evidence of the units at depth in the southwest due to poor seismic imaging. Therefore there is no seismic evidence of a connection between the western and southern limbs of the complex.

However, a high on the Bouguer gravity data could suggest a connection. A connection is supported by borehole data around 40 km to the northwest of the seismic line. The borehole is on the edge of Premier kimberlite and intersects Bushveld rocks, i.e., around 200 m of pyroxenite which is proposed to belong to the CZ (Cawthorn and McKenna, 2006; Figure 1).

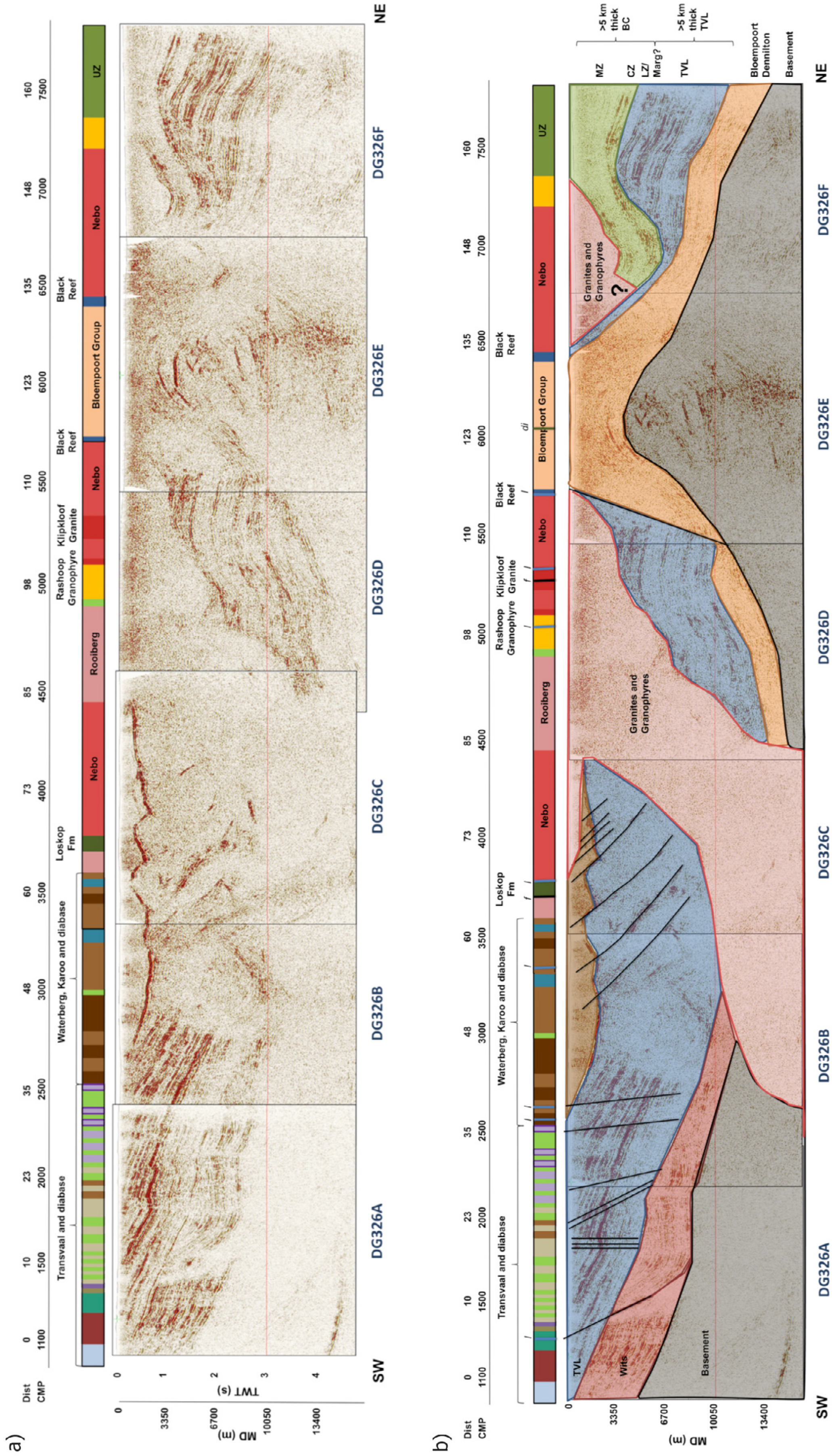

Figure 12. *(**a**) Seismic profile DG326 with outcropping geology marked along the top of the section. (**b**) Interpreted seismic section. See Table 1 for details about rock types.*

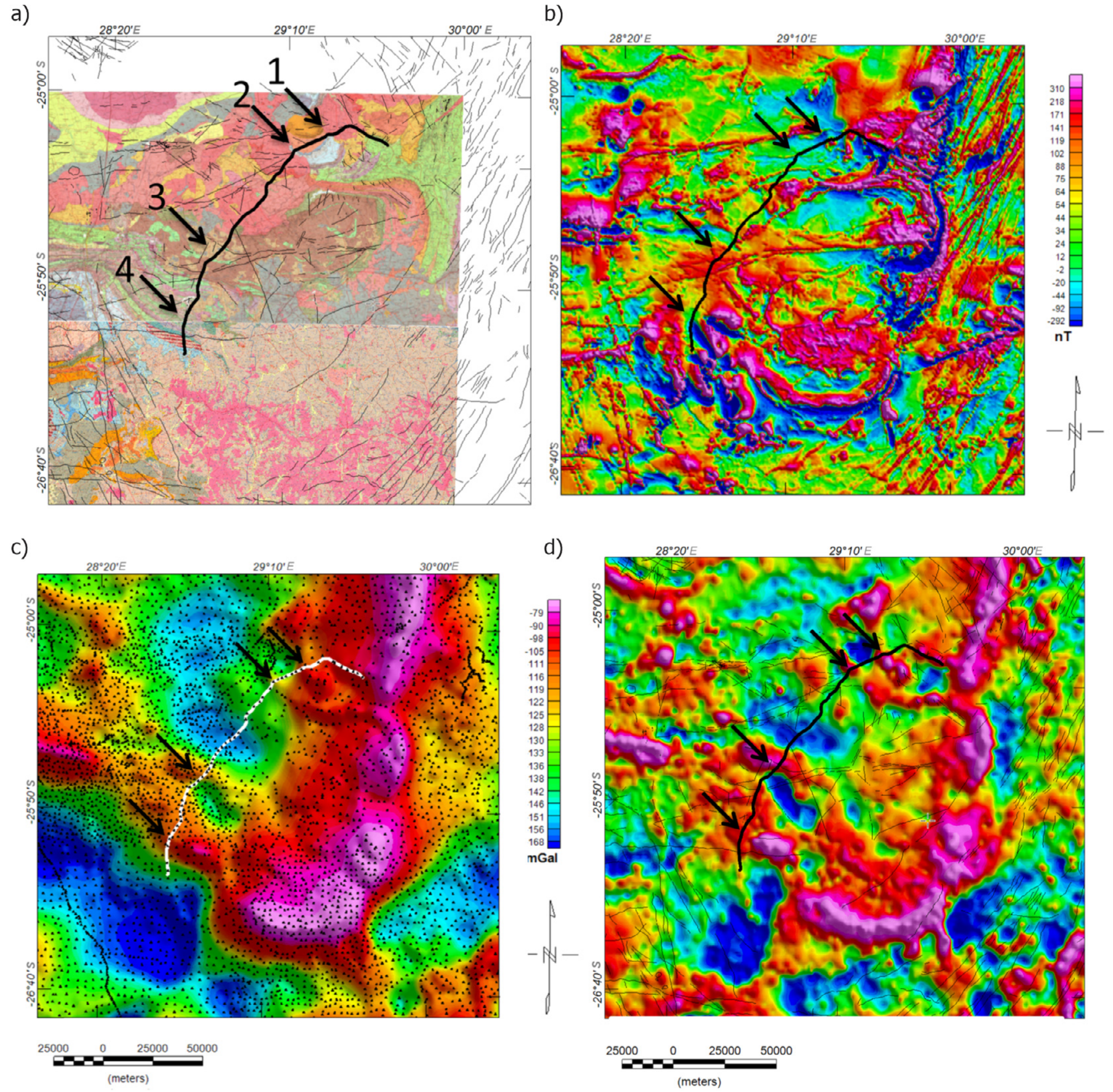

Figure 13. *(**a**) 1:250 000 geological map; (**b**) TMI data; (**c**) Bouguer gravity data with data points marked; (**d**) Vertical derivative of the Bouguer gravity data over seismic line DG326 (black and line). The four thick black arrows indicate the gravity highs to be investigated through modelling in this study. The seismic line is well covered by gravity stations in the south (with station spacings of 5 km or less), except to the north around the Dennilton Done where coverage is less, however there are numerous stations along the seismic line with similar spacing as the south.*

The next step to confirm connectivity would be gravity modelling over seismic line DG326 but would need to include broadband seismic Moho depths from the recent AfricaArray survey. Gravity modelling of the western and eastern limbs has shown that a large-scale accurate model cannot be created without including Moho depths (Webb et al., 2004, 2011, 2019).

In the northeast, the seismic line passes over felsic and mafic rocks of the Bushveld Complex and uplifted basement in the Dennilton Dome. The dome appears to have brought Rustenburg Layered Suite rocks closer to surface in the northeast, but it is unclear if this is shallower than 2.7 km.

Regional seismic lines, such as DG326 in the Bushveld Complex, provide invaluable information about the subsurface structure of large geological bodies. And while the cost of them is prohibitive, they go a long way to advancing understanding. On the other end of the spectrum, South Africa's freely available regional magnetic and gravity datasets should be a first port of call for all geoscientists working locally. While the resolution is not high, these data help with regional understanding of a site. Integration of multiple geoscience datasets in turn will aid in reducing the non-uniqueness of geological models and should be considered best practice.

Acknowledgments

The authors are grateful to the reviewers and editors who helped to improve this manuscript significantly. This project was funded by the University of the Witwatersrand, with software support from IHS Kingdom and Geosoft. We thank Anglo American Corporation of South Africa (now AngloGold Ashanti Ltd) for data access.

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Editorial handling: M.A. Elburg.