Petroleum and Coal

Article **Open Access**

Subsurface Structural Features of the Basement Complex and basin architecture of the southwestern main Karoo Basin, South Africa, using Magnetic and Gravity Data Analysis

Zusakhe Nxantsiya[1,2], Oswald Gwavava[2] and Christopher Baiyegunhi[3]

[1] *Council for Geoscience, Private Bag X112, Pretoria 0001, Gauteng Province, South Africa*
[2] *Department of Geology, Faculty of Science and Agriculture, University of Fort Hare, Private Bag X1314, Alice 5700, Eastern Cape Province, South Africa*
[3] *Department of Geology and Mining, School of Physical and Mineral Sciences, University of Limpopo, Private Bag X1106, Sovenga 0727, Limpopo Province, South Africa*

Received October 8, 2021; Accepted March 1, 2022

Abstract

The south-western Karoo Basin is considered to be one of the prospective areas for shale gas exploitation in South Africa. The area is underlain by sources that give rise to interesting geophysical anomalies like the Beattie Magnetic Anomaly (BMA) and the Cape Isostatic Anomaly (CIA). To date, the possible sources of these interesting features are not well understood. In this study, we investigate the source(s) of the anomalies and produce 2½ D gravity models that unravel the basin architecture. The magnetic and gravity slices result shows that shallowest seated signatures are due Karoo dolerite intrusions, which are concentrated in the northern part of the study area. The 2½ D gravity models revealed that the basin deepens to a depth of about 4600 m in the south-western region, near the front of the Cape Fold Belt. The Ecca Group which is the targeted group for shale gas exploration in the Karoo is observed within the depth range of 0–4 km. The model also revealed that the Karoo dolerite intrusions are interconnected at depth and mostly concentrated at the centre of the basin, which will pose a threat to fracturing the Karoo formations for shale gas exploitation.

Keywords*: Magnetic; Gravity; Modelling; Depth slices; Geodynamics; Karoo Basin.*

1. Introduction

The Karoo Basin, particularly the area under investigation is of interest to scientists and resource economists. From the perspective of the latter i.e. the economists, shale gas reserves of the Karoo Basin in South Africa have been estimated to have a potential to positively influence the economic state of the country, more especially in this period of global need for an efficient, clean burning and affordable energy source. From a scientific standpoint, the area is underlained by sources that give rise to distinctive geophysical anomalies like the Beattie Magnetic Anomaly (BMA), Southern Cape Conductive Anomaly (SCCB) and the Cape Isostatic Anomaly (CIA) [1-5]. Ground breaking geophysical studies on the Karoo Basin were first conducted by Beattie during the year 1909 in which a large terrestrial E-W trending magnetic anomaly was revealed and it was later referred to as the BMA. The BMA and SCCB are the largest known anomalies in the southern Karoo Basin [1,5]. These anomalies both occur in the same zone and have an east-west striking direction. The BMA is present on the southern part of South Africa, its signature across the Karoo strata is in a E-W striking direction. However, since the discovery of BMA, its source remains unclear with several hypotheses proposed to account for the causative body of the BMA.

The BMA becomes broader and stronger up to a depth of about 15 km and it could possibly be due to a buried body within the basement [1]. Likewise, the source of BMA was suggested to be exposed supracrustals, migmatites, and shear zones within the underlying Natal thrust terranes [2]. On the other hand, [3] envisaged that the source is a massive ore body confined within the Namaqua Natal Metamorphic Belt (NNMB). However, [6] and [7] attributed the source to be serpentinites that are present on the southern boundary of NNMB. Despite the different proposed hypotheses regarding the source of BMA, they generally locate the causative body within the NNMB. Most importantly, the work carried out by [3] revealed that the source of E-W trending BMA is confined within the NNMB and it was interpreted as a massive/disseminated deformed sulphide-magnetite ore body with metasomatic overprint. This appears to be feasible with newly derived information from seismic reflection data models which indicates that the NNMB continues below the CFB tectonic front [3]. Thus, disputing [6] and [7] that the source of the BMA might be serpentinites that define the southern boundary of NMMB. Seismic models by [3-4] along IyA- 200501 images the BMA at approximately 15 km beneath the surface and characterises thrust faults. These thrust faults are described to have caused duplication of the Cape and Karoo sequences in the south, resulting in the thickness of more than 12 km [8]. The work of [9] sheds a light on the use of borehole and reflection seismic data that the Karoo Basin deepens to as much as 4000 m in the southwest and to at least 5000 m in the south eastern part with sediment thickness between 5500 to 6000 m. The Whitehill Formation, which is the targeted formation for shale gas exploration, occurs between the depth of 3000 and 4000 m in southwest, while in the southeast, it increases more than 5000 m [2]. Moreover, the Karoo Basin has been intruded by a network of dolerite dykes and sills, and these mafic intrusions formed a complex and unique geology in the Karoo, leading to possible difficulties in exploiting the shale gas.

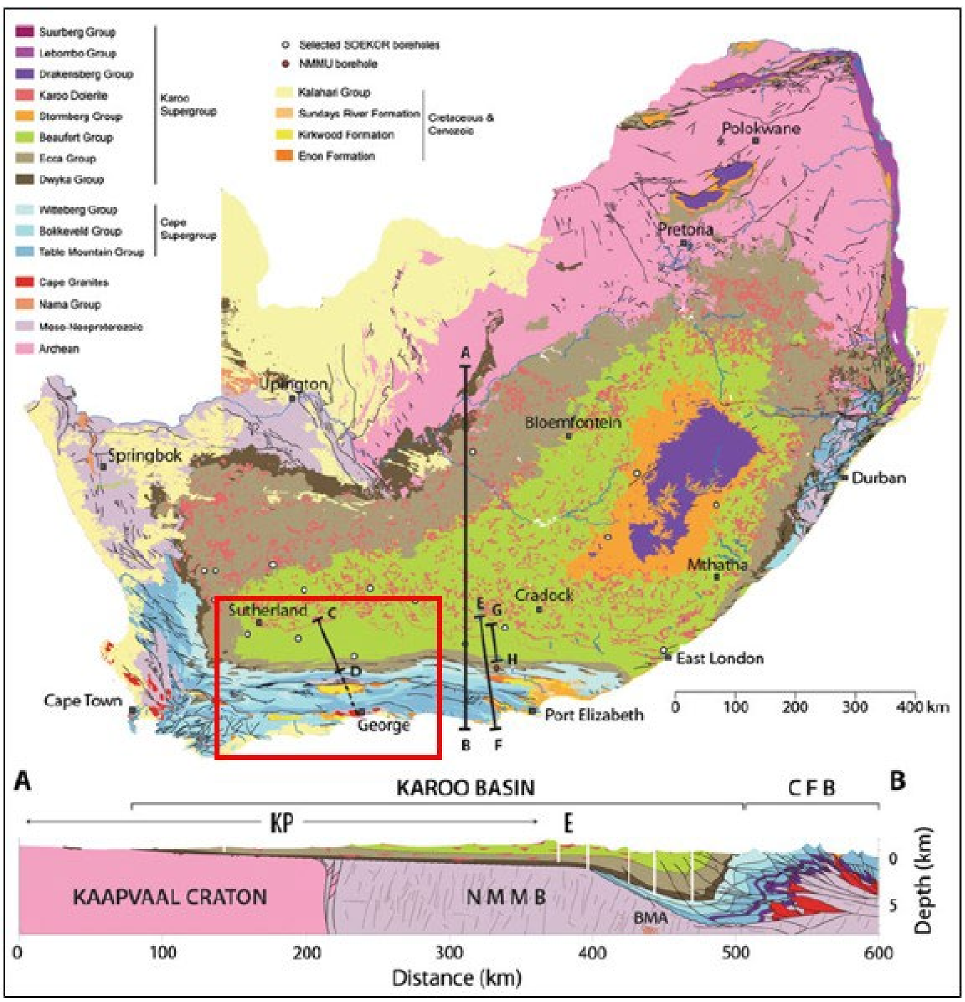


Figure 1. The geological map of South Africa showing the location of geophysical profiles in the Karoo Basin [10]. Note: The red square indicate the boundaries of the study area

The Karoo Basin has been at the centre of research for many years, with various studies ranging from paleontology, sedimentology, structural geology and others have been conducted. However, not much work, if any has been done on mineral evaluation and resource development in the Karoo Basin. The reason being its sedimentary rocks were thought to contain no natural resources that are economically viable in the international market, except for coal deposits. In few instances where minerals are found, they occur in small quantities with low grade quality to be economically extracted. It is believed that, the above is part of the underlying reasons that resulted in researchers having little interest and overlook the geology of the Karoo. This lead to existence of little/less knowledge amongst researchers about the subsurface of the Karoo due to insufficient amount of geophysical data to probe the basin at depth. Also, the source of some magnetic and gravity anomalous signatures within the study area are not known and only few existing models image the subsurface of the main Karoo Basin up to the Moho. Hence, this study is undertaken to investigate the source(s) of magnetic and gravity anomalous signatures within the study area, interconnectivity of the dolerites at depth and produce 2½ D gravity models that will unravel the basin architecture. The area under investigation is estimated at about 90,945 km^2. Geographically, it lies within the latitude of 31° S and 34° 50′ S and extend towards the east from the longitude of 20° E to 24° E (Figure 1), engulfing almost the entire succession of Cape Supergroup and south-western strata of the Karoo Basin in the Western Cape Province of South Africa. In the study area, the rock formations are clearly visible in road cuttings along regional road R61 and national road N1 that links up the towns of Beaufort West and Laingsburg. In this paper, we present the result of magnetic and gravity derivatives, power spectrum, depth slicing and 2½ D gravity models to map the subsurface geology, including shallow and deep seated structures such as dolerite intrusions, faults and folds in the area and ultimately reveal their geometry. Furthermore, we carefully look at the gravity models to see any possible anomalous features that can be linked to the BMA source(s).

2. Geology and stratigraphy

The Cape and Karoo Supergroups record the most significant history of non-marine and marine sedimentation from the Palaeozoic to the Lower Mesozoic period (300 Ma) along the Paleo-Pacific margin of Gondwana [10]. The Cape Supergroup is often referred to as the backbone of the Cape Fold Belt [11]. The Cape Fold Belt (CFB) comprises of Palaeozoic clastic sedimentary rocks of the Cape Supergroup that rests with sharp unconformable contact on the Precambrian Basement rocks and are in turn overlained by the rocks of Karoo Supergroup [12]. The Cape Supergroup to have been deposited during rising and falling of the ocean along a shallow continental-shelf that flanks the southern margin of Gondwana [8,13]. On the other hand, the Karoo Supergroup rocks are considered to be intracratonic thermal sag basin fills [14]. [15] indicated that the tectonic setting of the CFB is controversial and several models which seek to account for its deformation have been proposed. The seismic model by [3] images the CFB as a Jura Mountains with several zones of tectonic collision that developed due to southward subduction [15]. A sinistral strike-slip orogeny was proposed by and to have developed in response to reactivation of the southern margin of NNMB [16-17]. According to [15], there is no existing field evidence such as horizontal lineations to support this model. Seismic and magnetotelluric studies have the source(s) of the BMA to complex remnants of magnetised rocks [2-5]. Thus, disputing the cordillera type retro-arc models that interpret the source of the BMA as a fossil suture zone that formed as the result of collision of a landmass and the Kalahari Shield [15].

The Cape Supergroup is believed to have been deposited in a shallow continental-shelf between the mid-Cambrian to Upper Devonian and rests unconformably on Precambrian metasediments and Cambrian granitic intrusion [8]. The rocks of the Cape Supergroup are present in two areas in Southern Africa. Outcrops believed to belong to this supergroup have been observed in the northeast of Port St. Johns (Msikaba Formation) and also occur between Vanrynsdorp and Fish River, forming the Cape Fold Belt parallel to the coastline [18]. The rock strata of the Cape Supergroup are subdivided into three mapable units based on the age and depositional environment and these include, the Table Mountain, Bokkeveld, and Witteberg

Groups [8,13]. The deltaic Witteberg Group is geologically the youngest unit in the Cape Supergroup dated to have been deposited between Late Devonian to Early Carboniferous [19]. It consists mostly of thin- bedded, reddish grey siltstones and interbedded thin beds of sandstone lying on top of marine Bokkeveld Group [8]. The underlying Bokkeveld Group comprises of black shale, siltstone and olive-grey sandstone units. [20] compared the Bokkeveld Group with the Table Mountain Group and found that the former consist of shale and siltstone that erodes easily and form valleys. The latter has been described by [8] to comprise of a thick sedimentary succession made up of 2000–5000 m thick quartz-rich sandstones and interlayered glacial tillite of the Pakhuis Formation and shale units of the Cederberg Formation towards the top. The Table Mountain Group quartz-rich sandstone underwent metamorphism to form quartzites as a consequence they are resistant and erode to form mountain ranges [20]. The glacial deposits of the Pakhuis and Cederberg Formation marks the glaciation and deglaciation event of Gondwana at about 444 Ma [10]. Detrital zircon dating points the source of Cape Supergroup sediments to the Namaqua Natal Metamorpic Complex and Pan African orogenic belts between 1200–1000 Ma and 650–500 Ma, respectively [15].

The overlying Karoo Supegroup forms the thickest and most complete stratigraphic sequence of several depositories of the Permo-Carboniferous to Jurassic age in the south-western Gondwana [21]. This sedimentary sequence reaches a maximum thickness of up to 5 km in front of the Cape Fold Belt and reflect a variety of palaeo climatic conditions and depositional environments from glacial to marine, deltaic, fluvial and aeolian [22-23]. These palaeo environments reflect a special time in the history of Earth during which the supercontinent Gondwana amalgamated and broke-up at 750–130 Ma [8]. The Karoo Basin records about 100 Ma of sedimentation [24], and it is subdivided stratigraphically into five main major groups with subgroups, formations and members. The basal part of the Karoo is marked by the Late Carboniferous glacial deposits of the Dwyka Group. These glacial Dwyka Group diamictites mark the beginning of deposition in the main Karoo Basin and are overlain conformably by the Permian marine shale, mudrock, sandstone and rhythmite units of the Ecca Group [22]. The Late Permian - Early Triassic Beaufort Group was emplaced on fluvial environment on top of the Ecca Group [22]. Just above the Beaufort Group, the Middle Triassic age Stormberg Group is overlain by the younger Drakensberg Group which is the last set of rocks to be deposited in the Karoo Supergroup. The latter is believed to have formed during Late Triassic to Early Jurassic period (183 Ma) through extrusion of magma along fissures and cracks (Drakensberg lava), thus capping the Karoo sedimentary rock with approximately 1400 m thick layer of basalts [25].

3. Methodology

3.1. Data acquisition and processing

The magnetic data was supplied by the Council for Geoscience South Africa in the form of a gridded magnetic dataset. The report of the Council for Geoscience shows that the airborne geophysical surveys for the acquired data were conducted between the years 1980s and late 1990s using a Piper Navajo (ZS MAR) aircraft with an embedded proton magnetometer (1 nT resolution) to detect and measure magnetic field variations [26]. The surveys were conducted at a flight height between 100–150 m above the sea level with a line spacing of 1,000 m in a north-south direction and tie lines spacing of 10,000 m in a perpendicular direction to the flight lines. The acquired magnetic original space domain grid was prepared for filtering and enhanced using Geosoft Oasis Montaj. Data enhancement involves application of various geophysical filters such as reduction to the pole (RTP), derivative in x, y, z direction, analytical signal, and depth slicing. The results are presented in the form of geophysical maps. The supplied data shows that the study area was covered by data from three different surveys merged together. However, the merging process produced lineaments at the merged boundaries of the data, herein it referred to as "Artefact". This was due to the datasets not being accurately or properly adjusted to same datum. Similarly, the gravity data were also supplied by the Council for Geoscience in a form of xyz data file consisting of a total of 12309 gravity stations. The spacing between individual stations is approximately 1–3 km apart. The gravity data had been reduced to Bouguer gravity values. Depth slicing was calculated on the Bouguer gravity values and the results are also presented in the form of geophysical maps.

3.2. Profiles selection and 2½ D gravity models

Seven gravity profiles were systematically selected to cover the study area. The profiles are roughly equally spaced and positioned in such a way that they cut across the rock strata and geological structures perpendicular (45–90°) to the strike direction across the study area. Six of the profiles were orientated in such a way that they cut across the BMA and SCCB throughout the area. The gravity profiles position and extent on the ground were determined from the geological map of South Africa. Four profiles were oriented in a NE-SW direction, while the other three were positioned in a NNW-SSE direction nearly perpendicular to E-W dyke trends. Seventy-one rock samples were collected in the field from both the Cape and the Karoo sequences and their dry density were determined using Archimede's principle. For each selected gravity profile, 3 models were generated using the minimum, average and maximum density values as well as incorporating well data. Each model was constructed by extracting x, y, Bouguer gravity, and elevation values from several gravity station points along the selected profile into an Excel file and then imported to GM-SYS software. GM-SYS is an extension on Geosoft Oasis Montaj which provides an interface for interactive manipulation of geological bodies and it performs real time calculations of gravity field response, thus enabling the calculated gravity field curve to match the observed gravity curve with a minimum root mean square (RMS) error. The GM SYS software employs the methods of [27-28] and utilizes the algorithms described in [29] to calculate the gravity response. It also allows the model to extend from plus to minus infinity (e.g. ± 30000 km), thus eliminating edge effects. More details on the modelling procedures can be found in [1, 30-31]. The models were constrained using the measured density, thickness from outcrops and borehole data. The densities of both the Cape and Karoo Supergroup rocks measured in the laboratory were used in the modelling, together with those from [31]. The old SOEKOR borehole data within the study area were used together with seismic refraction and magnetotelluric images provided in [4] and [8] along IyA-200501 to constrain the models. The thicknesses and depths were extracted from eight SOEKOR boreholes documented in [2]. The outcrop/thicknesses of various groups were extracted from the geological map of Southern Africa [32]. The Moho depth have been indicated to be between 40–50 [31,33]. To cover the depth envisaged for the Moho by these authors, the depth to the Moho was initially set at 30 km and allowed to vary up to 60 km during the modelling process. This will model to establish the best fit depth for the Moho. The thickness of the modelled dolerite intrusions were estimated from [34-35]. The modelled dolerite sills and dykes were originally set in horizontal and vertical positions, respectively and allowed to vary during the modelling process to have the best fit model. Since a total of 21 models were obtained, only those of the average density values are presented in this paper. The alternative models were used to check the sensitivity of the models with respect to change in layer densities and thicknesses.

4. Results and interpretations

4.1. Magnetic

4.1.1. Reduced to pole

The reduced to pole (RTP) residual magnetic field map of the study area is shown in Figure 2. The acquired data was reduced to the pole (RTP) mainly to remove the effects of magnetic inclination, as well as to allow accuracy in interpreting the location of magnetic sources relative to geologic features. The area under investigation is characterised by numerous patchy high magnetic zones, including the Beattie Magnetic Anomaly (BMA). The BMA is a thin band/ a linear zone of high magnetic intensity, cutting across southern Africa in an east-west trending direction. Around the centre of the map, at Leeu-Gamka, the anomaly separates into two, north and south anomalies that are almost parallel to each other at its western end. This anomaly continues and extends farther to the east and west of the study area. Apart from the BMA, four zones of magnetic highs occur farther north within the study area and these are marked as 2nd and 3rd anomalies on the NE portion of the map, while another two sets of similar nature are marked as 4th and 5th anomalies in the NW part (Figure 2). These anomalies, including the BMA record a maximum magnetic intensity of about 513 nT.

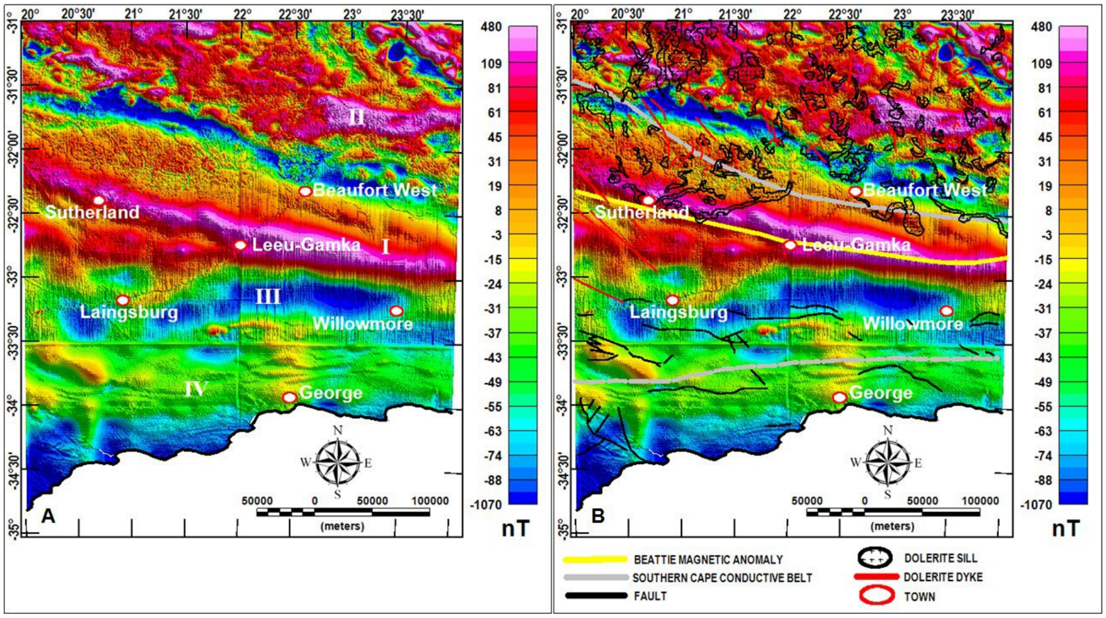


Figure 2. (a) Reduced to pole map of the study area showing magnetic anomalies; (b) Reduced to pole map superimposed on geological features and some selected geophysical features. Note: The numbers in roman figures represent Magnetic domains with the study area and are attributed to, I= Beattie Magnetic Anomaly; II= attributed to Karoo dolerite intrusions; III= Non magnetic sedimentary rocks of the Karoo Basin; IV= correlate with the location of the Cape Fold Belt

4.1.2. Full horizontal magnetic derivative

The Full horizontal derivative filter aids in locating boundaries of anomalous bodies and thus enables estimation of the horizontal extent of such bodies as well. The full horizontal derivative magnetic field map was superimposed on the geologic lineaments (Figure 3). This was done to correlate anomalies with previously mapped geological features [10], such as faults, dolerite dykes and sills. It was observed that most of magnetic bodies are concentrated on the northern part of the map from latitude 32°30′ S upwards, with very few occurring on the southern part including the BMA. Similarly, the signature from the BMA is not clearly visible. This might be caused by the deep location of its causative body. In Figure 3, a narrow, highly magnetic feature is seen starting from Beaufort West passing through Leeu-Gamka, Laingsburg and just above 33°30′ S at the edge of the map towards southwest direction, cutting across the folded Cape Fold Belt. This was overlaid with the national road and railway line map of South Africa and it coincides exactly with the railway line which links Johannesburg and Cape Town. It rather is caused by DC (direct current) railway.

4.1.3. Vertical derivative

The first vertical derivative of the magnetic field within the study area is presented in Figure 4. The first vertical derivative filter suppresses magnetic signatures arising from deep seated magnetic bodies and enhances those which are due to near surface bodies. The map has been overlain on geology, mainly to correlate anomalies with geological features, such as faults, dolerite dykes and sills. It is noted that, most of the magnetic anomalies exhibit ring structures, while others occur as thin lines and these are typical of Karoo dolerite sills and dykes, respectively. Some of the anomalies are in places where they do not coincide with known outcrops and it is inferred that these are due to shallow magnetic bodies that do not outcrop.

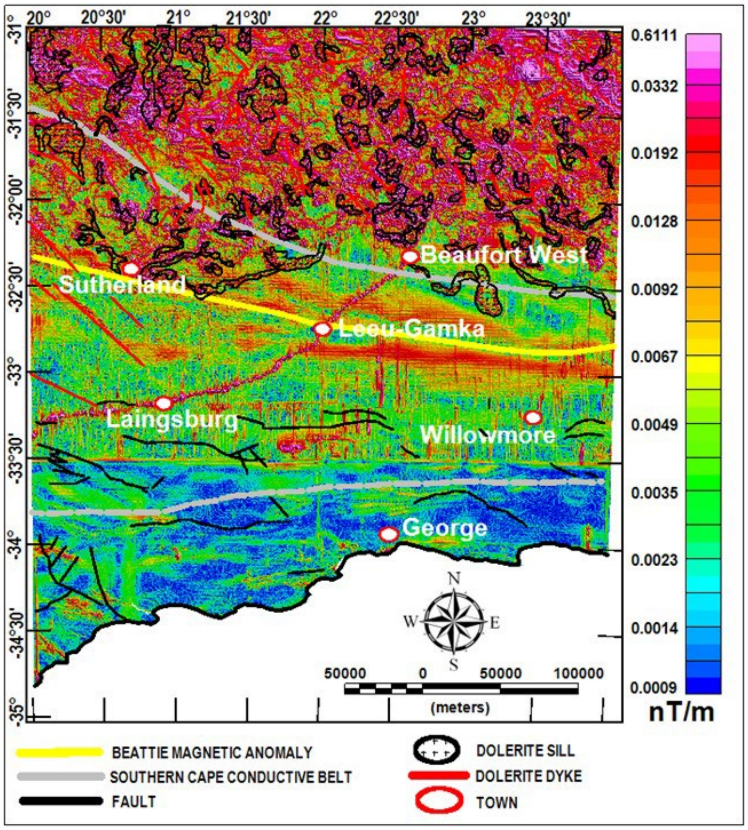


Figure 3. Full horizontal derivative map superimposed on the geological features. Dotted black lines = national roads and railways

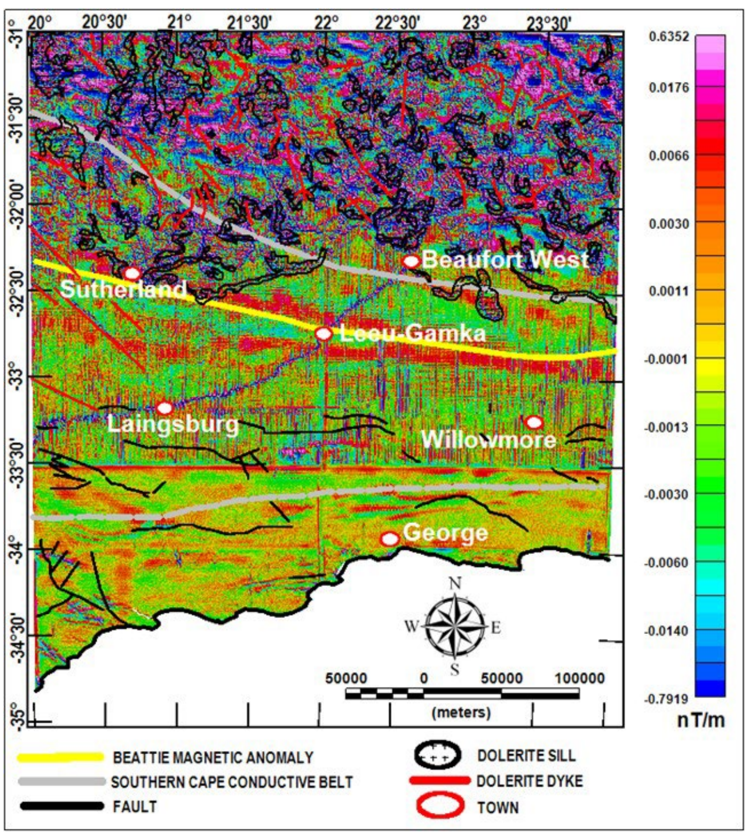


Figure 4. Vertical derivative map superimposed on geological features

4.1.4. Analytical signal

The magnetic analytic signal map of the study area is displayed in Figure 5.

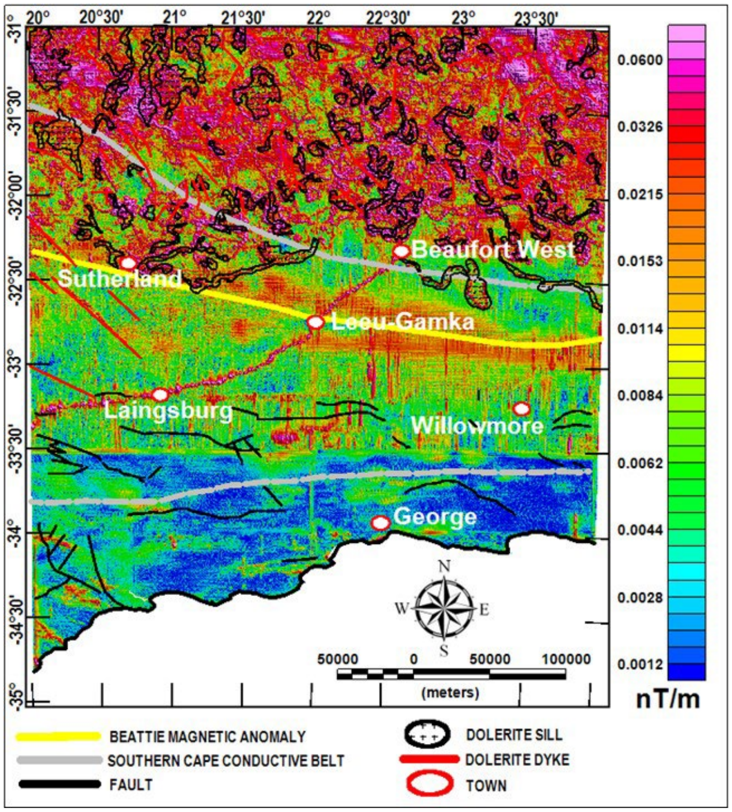


Figure 5. Analytical signal map superimposed on geological features

The analytic signal filter combines both the vertical and horizontal derivatives to delineate the edges/ boundaries of subsurface magnetic bodies. As seen in Figure 5, the northern part of the study area has numerous ring like structures which are inferred to be sills. Several lineaments are seen and these are possibly dykes/ faults. The inferred powerline for the railway line clearly stands out extending from Beaufort West through Leeu-Gamka and Laingsburg. The BMA, although its signature is weak, is seen as a zone of 20–30 km wide on the eastern side before its bifurcation.

4.1.5. Depth slicing

The radial averaged power spectrum of the magnetic data was taken in order to determine the occurrences of magnetic anomalies at various depth levels. A total of five linear segments (depth slices 1–5) were fitted to the curve, the steeper segments represent deeper sources (Depth slices 5 and 4), while the steep to gentle segments (depth slices 3, 2 and 1) represent shallow anomalous sources (Figure 6a). The intensity of magnetic signatures at various depths is shown in Figure 6(b–f). Through depth slicing, magnetic signatures due to near surface bodies were discriminated from those resulting from deep seated anomalous bodies.

Depth slices (1–3) in Figure 6 are populated by numerous narrow anomalies with ring and linear patterns which are inferred to be due to dolerite sills and dykes, respectively. These narrow anomalies are absent on map for deeper depth slices (i.e. ≥ 4308 m; Figure 6e). Signatures resulting from the dykes outcropping on the surface do not occur beyond 4308 m. Therefore, these extends from the surface up to depths of about 4308 m (depth slices 1– 3). The BMA shows weak intensities for the shallow depth slices 1 and 2, and its intensity increases with depth, as shown on depth slice 3. The splitting of the BMA into two near Leeu- Gamka is much clearer on the depth slice 5, at a depth of about 9488 m. This is an indication that its causative body is present deep below the surface. Similar findings are presented by [3] that the source of the BMA might be a deformed sulphide magnetite body occurring at mid crustal depth. A continuous low magnetic zone trending NW-SE borders the northern side of the BMA, whilst its southern edge is bounded by another magnetic low zone that breaks up on the western edge of the map. Some signatures on the northern part of the maps (Figure 6) are less intense on depth slices 1 and 2 and progressively become more intense as well as broaden with deeper depth slices, i.e. depth slices 3–5.

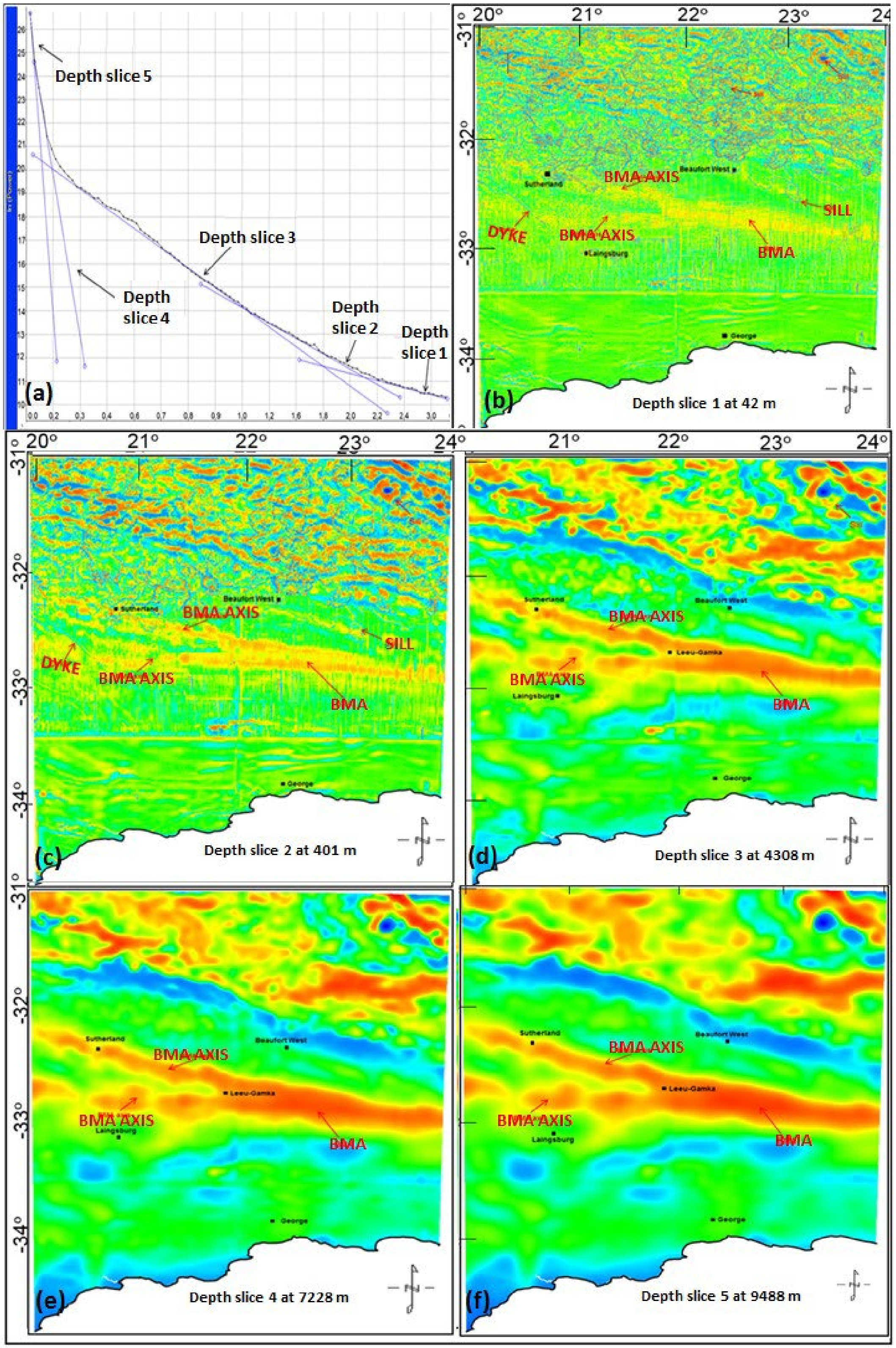


Figure 6. Depth slice showing changes in anomaly features with depth. Note: Depth slices 1 to 5 are at depths 42, 401, 4308, 7288 and 9488 m, respectively

4.2. Gravity

4.2.1. Bouguer gravity anomaly map

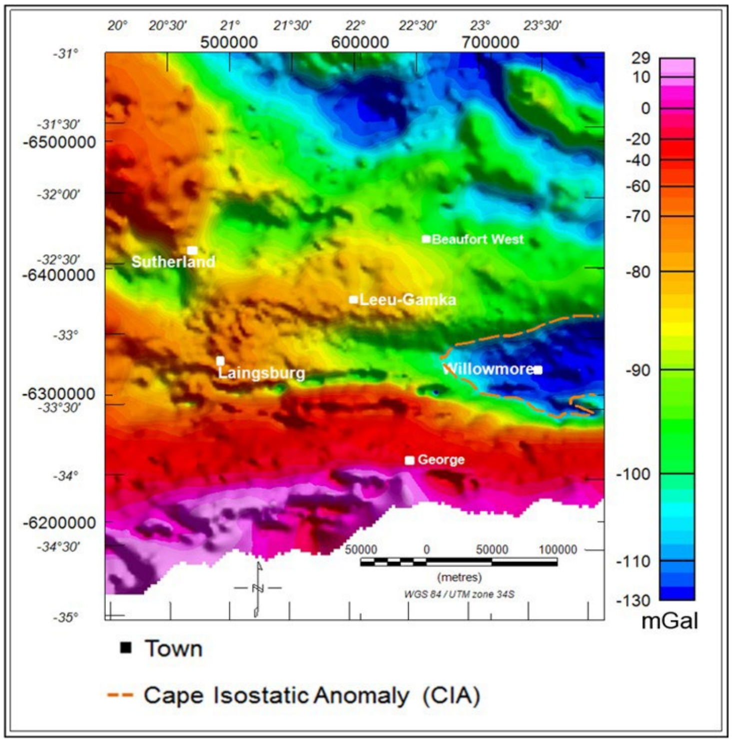


Figure 7. Bouguer gravity map showing gravity highs and lows. Red to yellow colours represent high values and blue colours represent low values

The Bouguer anomaly map of the study area is shown in Figure 7. Several significant zones of anomalous highs and lows are seen to occur within the area. Notably, the Cape Isostatic Anomaly (CIA) which is associated with a gravity low zone that has a lowest value of -130 mGal in the area around Willowmore (WM) and Steytlerville (SV) towns (Figure 8). The CIA continues further to the east of the study area across the Cape Fold Belt. In the southern part of the area, near the coast, an E-W trending, strong gravity high zone of at least 50 km width is seen with its intensity decreasing inland towards the north. Other gravity high zones occur on the north western part of the area. The highest gravity intensity ranges between 0–29 mGal and occurs near the coast along the CFB. This is likely to be the effect of the steeply rising Moho near the coast as shown by seismic refraction data presented by [4]. The seismic refraction images show that the Moho to be between 40–45 km inland and relatively shallow (30 km) towards the coast.

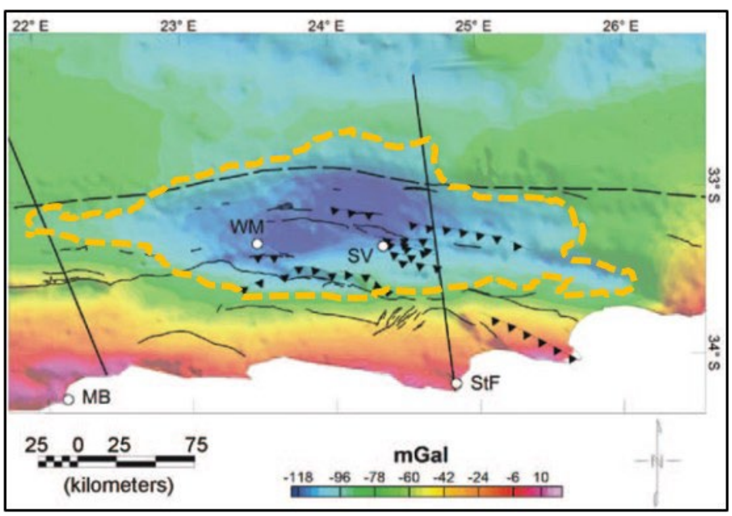
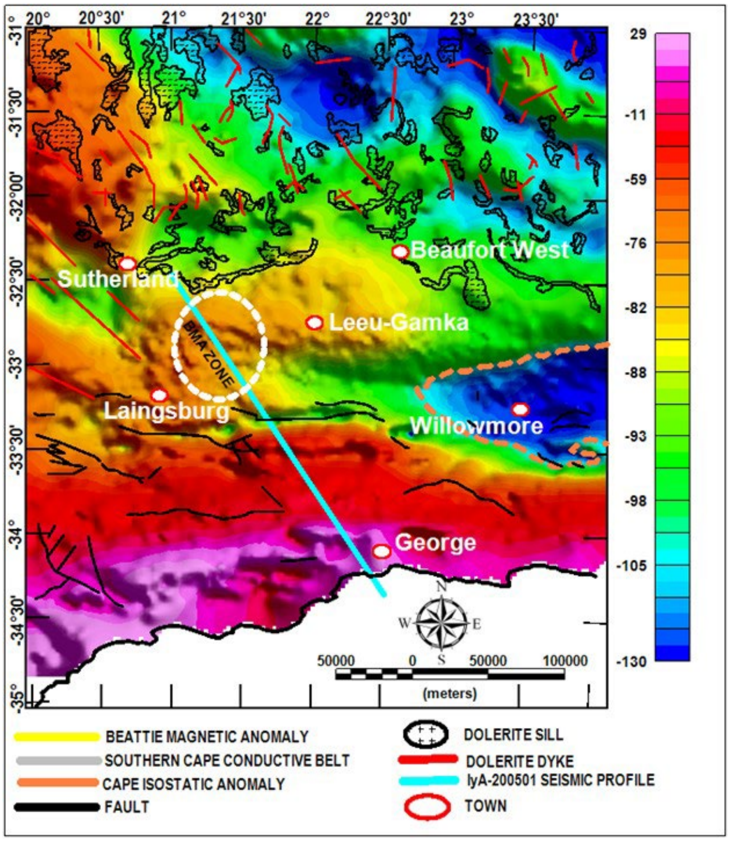


Figure 8. Regional .Bouguer gravity map showing spatial extent of the Cape Isostatic Anomaly [9]. Black vertical solid lines =seismic refraction profiles; black horizontal lines= normal faults; black lines with triangles= thrust faults; black dashed line= approximate northern boundary of the CFB. WM= Willowmore, SV= Steytlerville, MB= Mossel Bay, StF= St Francis Bay

4.2.2. Correlation of geology with Bouguer gravity

Some gravity anomalies viewed on the map (Figure 9) cannot be correlated with any geology on the surface, therefore they are likely to be due to subsurface sources. For example, the gravity anomaly denoted by a white, dotted line circle in Figure 9 correlates with the BMA



surface signature identified by [4] on seismic data along the seismic refraction profile IyA- 200501. The maximum recorded amplitude of gravity high is about 29 mGal. Towards the southern part, near the coast, the 50 km wide east- west trending gravity high coincides with the Cape Fold Belt. This signature continues along the CFB towards the east of the study area for several kilometres.

Figure 9. Bouguer gravity map superimposed on geological lineaments of the southwestern Karoo Basin

4.2.3. Radially averaged power spectrum

Just like the magnetic depth slicing, the radially averaged power spectrum of Bouguer gravity was computed and four linear segments (depth slices 1–4) were initially fitted to the curve to isolate anomaly contributions to a map derived from source bodies in a certain depth range. These four segments correspond to the average depths of 1290, 2430, 7120 and 57300 m (Figure 10). The gravity anomaly that occurs on the northeastern part of the study area (delineated by black dotted line on the depth slice 1 in Figure 10) is seen to be well defined with increased intensity on depth slice 3, but disappeared on depth slice 4. Depth slice 4, which is at a depth of 57300 m shows a strong, E-W trending gravity signature in the order of 29 mGal along the coast and it is likely to be the effect of the mantle rocks. On depth slice 4, two zones of gravity low are seen to occur, the CIA in the southeast and the other in the north. This reveal that the CIA is due to a very deep seated source, possibly low density material. Some of the high frequency anomalies are persistent up to the depth of about 2430 m (depth slice 2).

In addition, other depth slices of Bouguer gravity were computed to resolve the resulting gravity signatures at various depths beneath the sedimentary rocks from about 10 km to about 80 km depth (Figure 11 (a–l)). The generated depth slices revealed the depth spatial distribution of anomalous bodies. The central part of the area is marked by an east-west oriented gravity positive anomaly that is more or less coincident with the BMA axis. In the northeast corner, an oval shaped, positive anomaly exists, as well as along the southern edge of the area running parallel to the coast. The northern edge of the latter is roughly coincident with the southern boundary of the SCCB. Another significant gravity low anomaly (the CIA) is present in the south eastern part of the area around the vicinity of Willowmore town. The depth slice at 9950 m (Figure 10a) shows clearly a zoned gravity signature following the axis of the BMA cutting across the centre of the area from east to west and it bifurcates into two limbs near its western end, with one limb passing through Sutherland and the other passing through Laingsburg (see black solid lines in Figure 10). At this depth the signatures of both the northern and southern limbs appear to be much stronger compared to that of the main signature. The depth of this anomaly correlates well with the depth location of the BMA as interpreted by [33] on seismic image along IyA-200501. Farther down to the depths of 15000 m, 20000 m and 25000 m (Figure 11b–d), the signatures from the limbs still remain stronger, however they seem to be isolated from the main body whose signature becomes weaker.

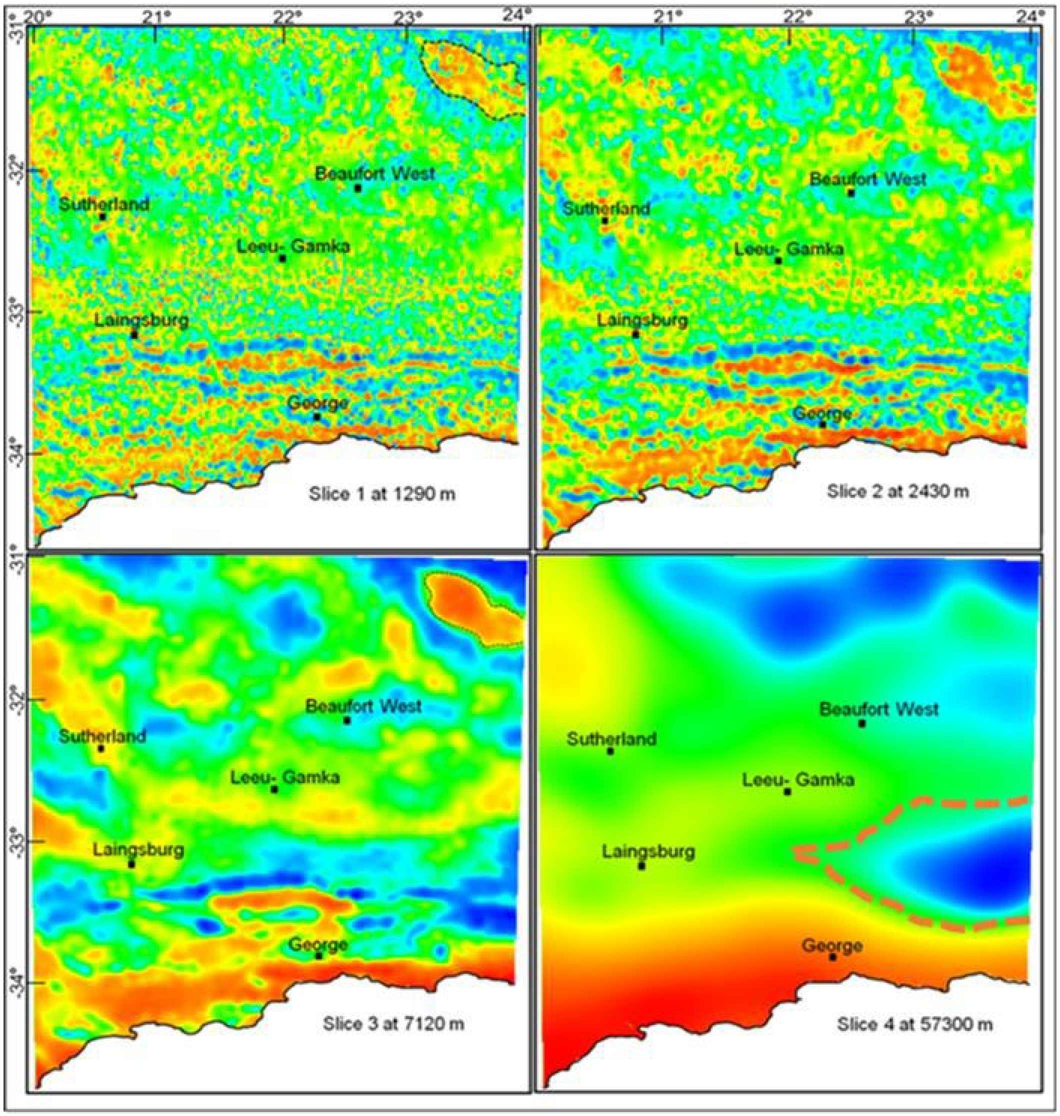


Figure 10. Gravity depth slices showing changes in gravity anomalies with increasing depth. Orange dotted line in depth slice 4 marks the Cape Isostatic Anomaly

At 35,000 m depth (Figure 11e), a positive y- shaped, NE–SW striking signature appears within the zone of the BMA, with the northern limb of the main body starting to show. This anomaly becomes stronger, clearer and complete at depth of 40500 m (Figure 11f). At this depth, the anomaly appears as the mirror image of the BMA, although the point of the birfucation of the BMA occurs about 150 km to the west of the gravity one. However, farther down to 45100 m depth (Figure 11g), the signature from the northern limb fades, thus revealing that the whole y-shaped anomaly is not resulting from a single source body. This body continues to be visible all the way down to the depth of 80200 m as a thick, single, ENE-WSW striking, linear anomaly with its signature becoming weaker (Figure 11h–l). An oval shaped anomalous body of notable intensity is seen on the NE corner of the area (depth slice at 9950 m). The signature gradually disappears with depth up to 45100 m where it is visible as small circular anomaly. Another zone of gravity high is seen on the southern part running parallel to the coast line. On depth slices at 9950 m (Figure 11a), this anomaly appears to result from isolated smaller bodies, some preserving a circular shape while others are linear.

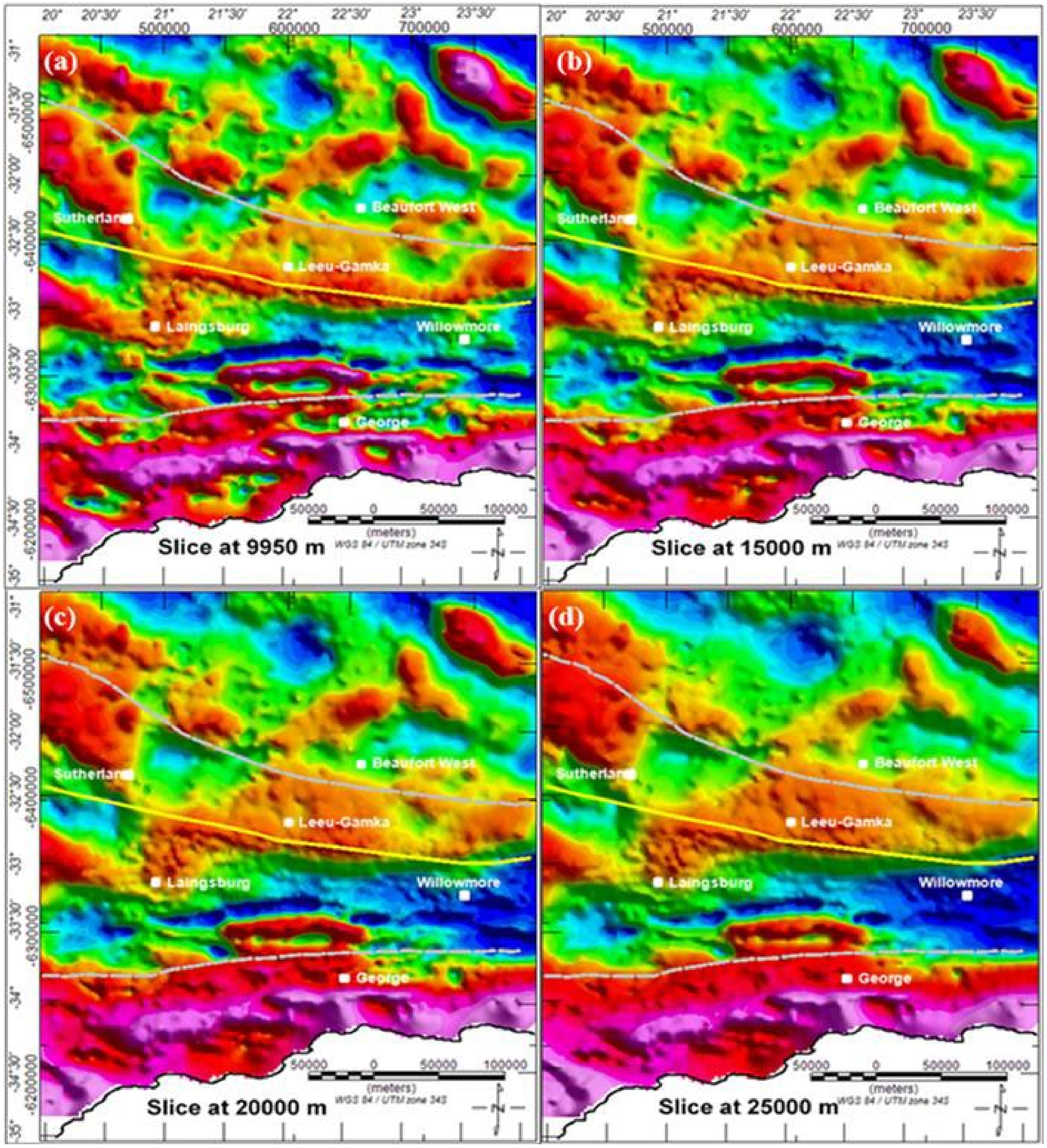


Figure 11. (a–d). Gravity depth slices at 9950, 15000, 20000 and 25000 m. Note: the yellow solid line represent the projected position and the horizontal extent of the BMA. The grey dotted line marks the boundaries of the Southern Cape Conductive Belt. The black solid line represent inferred BMA axis

However, with increasing depth (depth slice at 25000 m; Figure 11d), the anomaly appears to be due to a single body with strong intensity in the centre which becomes relatively weaker towards its boundaries. The southeastern part of the area is marked by a gravity low zone, the CIA. The CIA begins to emerge clearly on the 35000 m depth slice and gradually decreases in size with increasing depth. At this depth (35000 m; Figure 11e), other signatures of similar nature (shape and intensity) becomes visible on the northern part of the area.

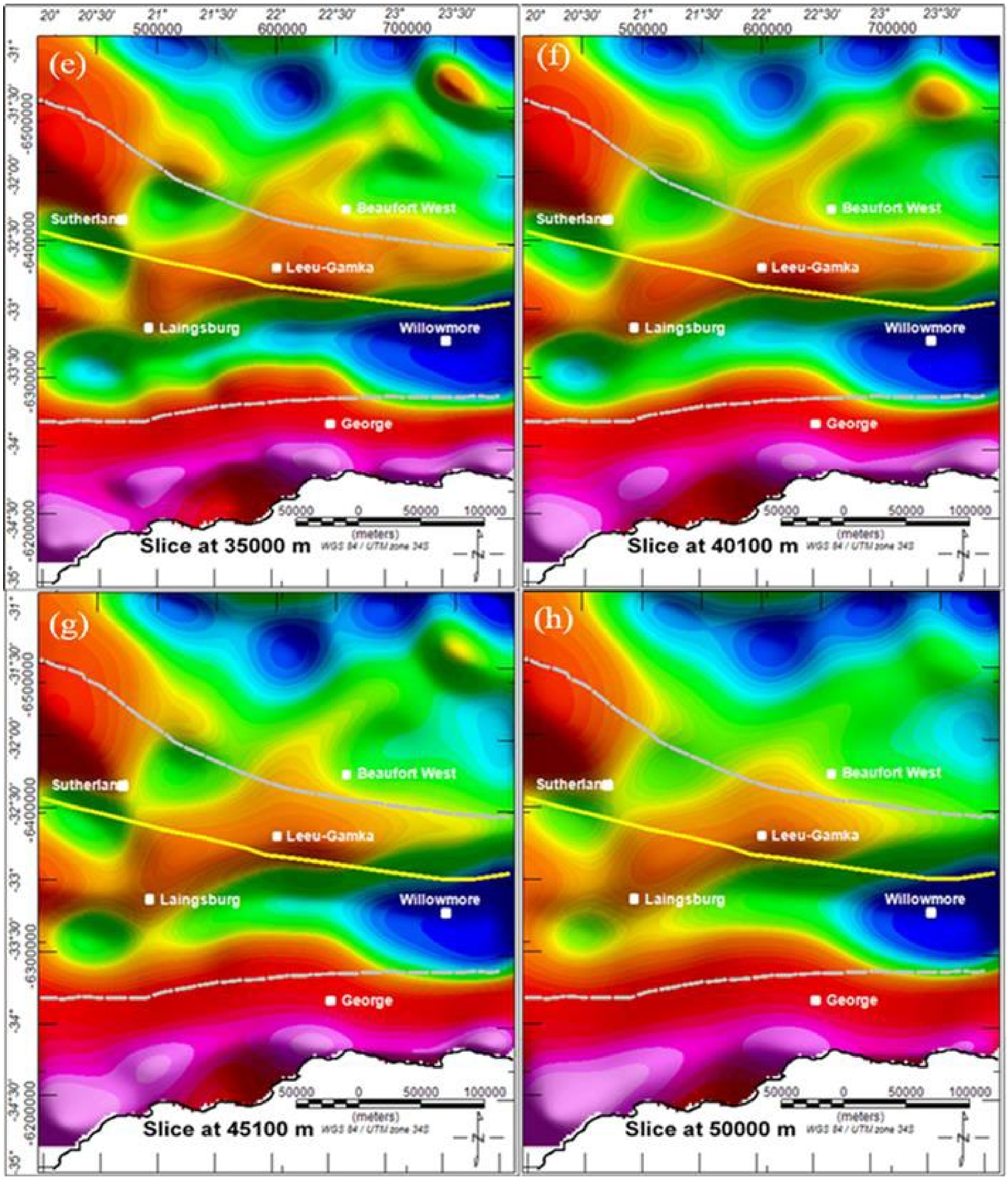


Figure 11. (e–h). Gravity depth slices at 35000, 40100, 45100 and 50000 m. Note: the yellow solid line represent the position and the horizontal extent of the BMA. The grey dotted line marks the boundaries of the Southern Cape Conductive Belt

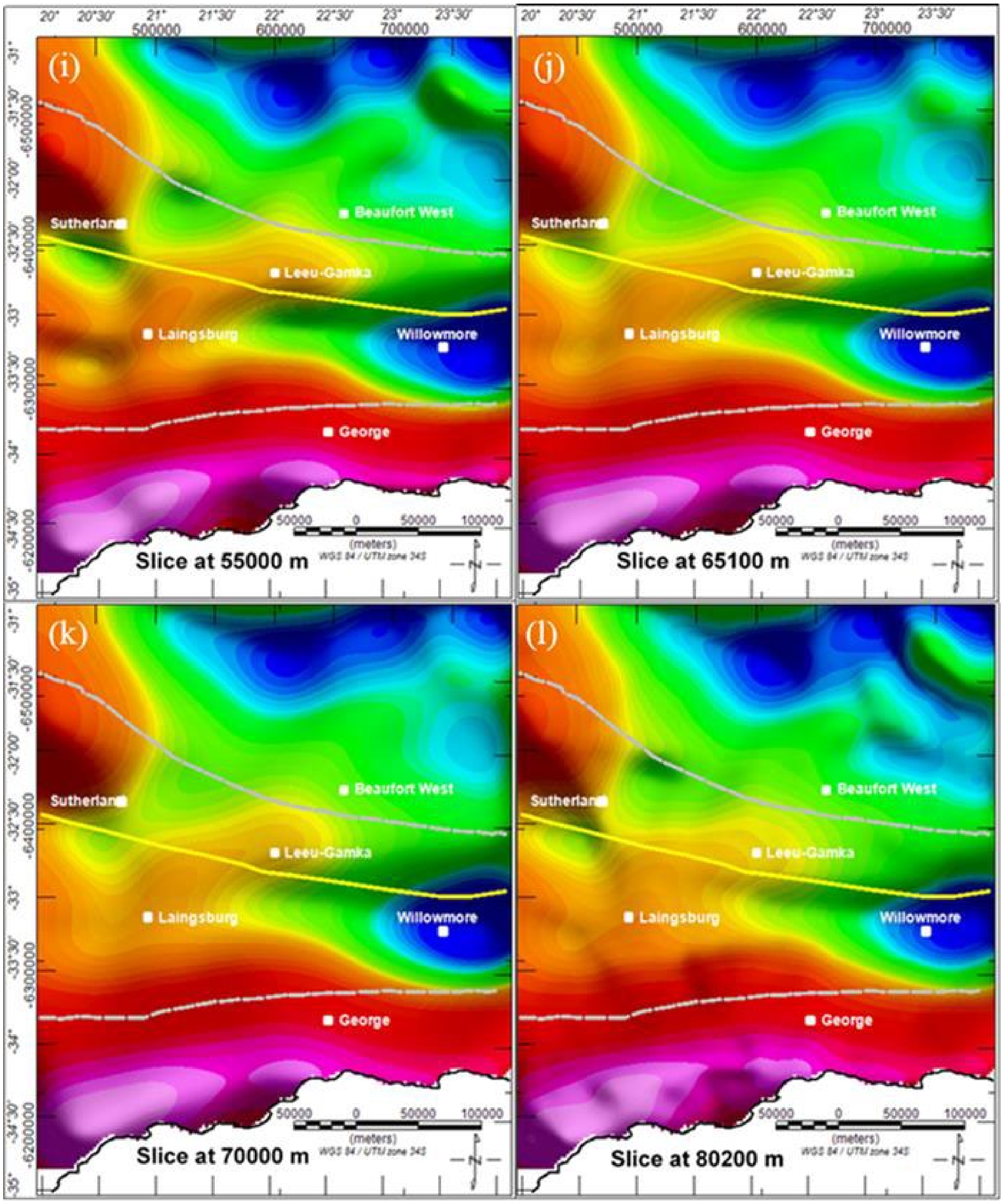


Figure 11 (i–l). Gravity depth slices at 55000, 65100, 70000 and 80200 m. Note: the yellow solid line represent the position and the horizontal extent of the BMA. The grey dotted line marks the boundaries of the Southern Cape Conductive Belt

4.2.4. Gravity power spectrum

The radially averaged power spectrum (Figure 12) was calculated in the wavenumber domain in order to estimate the depth to sources. The approximated depth ($h = \frac{\text{Slope}}{-4\pi}$) of about 0.9 km and up to 24 km were calculated (after subtracting the flight height) from the slope as the average depth to the top of the shallow and deep sources respectively.

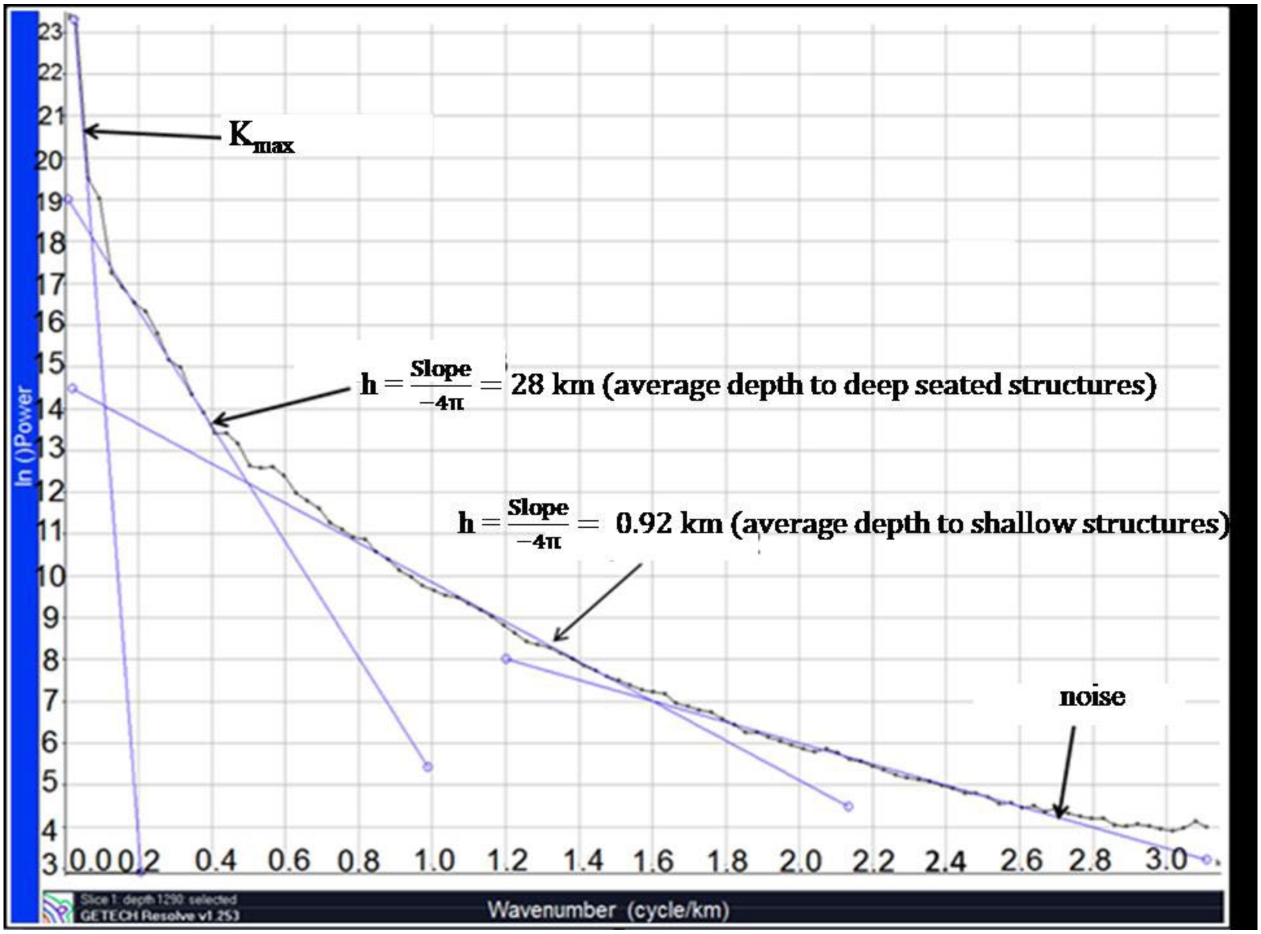


Figure 12. Radially averaged power spectrum of the aeromagnetic data of the study area

4.3. Gravity modelling

The seven selected profiles (A-G) for the gravity modeling are shown in Figure 13. The measured densities of the rock are presented in Table 1.

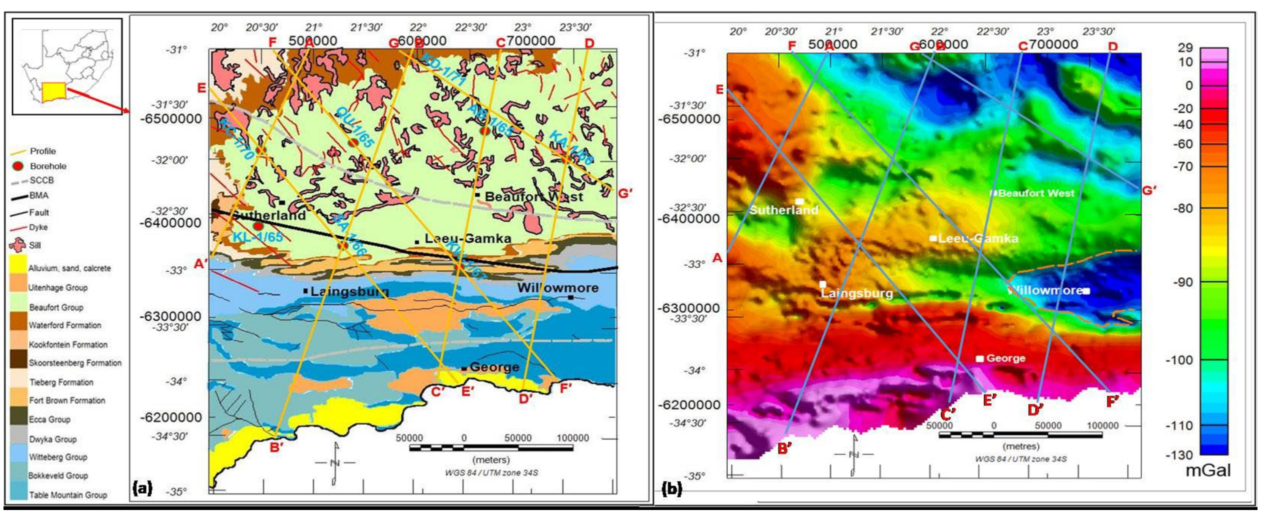


Figure 13. The southwestern Karoo Basin geological map showing the location of gravity profiles and eight SOEKOR boreholes within the study area. The boreholes are indicated by red circles while the gravity profiles are solid yellow lines

4.3.1. Profile A–A' gravity model

The gravity modelling result of profile A–A’ is shown in Figure 14. Profile A–A' extends for approximately 230 km in a NNE-SSW direction and ends about 50 km south of Sutherland town (Figure 13). This region is geologically characterised by a network of dolerite intrusions (sills and dykes) slicing through the Carboniferous sedimentary rocks of the Karoo as well as those of underlying Cape Supergroup. Along profile A–A', the gravity anomaly reaches a maximum and a minimum of about −64 mGal and −102 mGal, respectively. It is evident from the model that the geological formations are sub-parallel to each other with folding, faulting, and intrusions in places. The internal basin architecture displays huge highs and lows, comprising the basement relief (SSW portion of the profiles). Apparently, they are related to the thrust terrane shown in Figure 1. An interpretation of the subsurface model, from the oldest geological formation to youngest reveals that the Cape Supergroup extends to the depths of approximately 12 km below sea level in the south with its top surface occurring approximately at 2 km below sea level on the north. This depth extent is close to the depth of Cape Supergroup shown by the 2007–2010 model of [3]. The Dwyka and Ecca Groups occur between the depths of 0–3 km and both groups show a lateral uniform thickness along the profile with gentle folds in places. The Beaufort Group occurs above sea level. Furthermore, the model predicts that the dolerite intrusions form a network of interconnected dykes and sills in the subsurface and the sills extend laterally for several kilometres below the surface. The Moho is horizontal at a depth of 45 km below sea level.

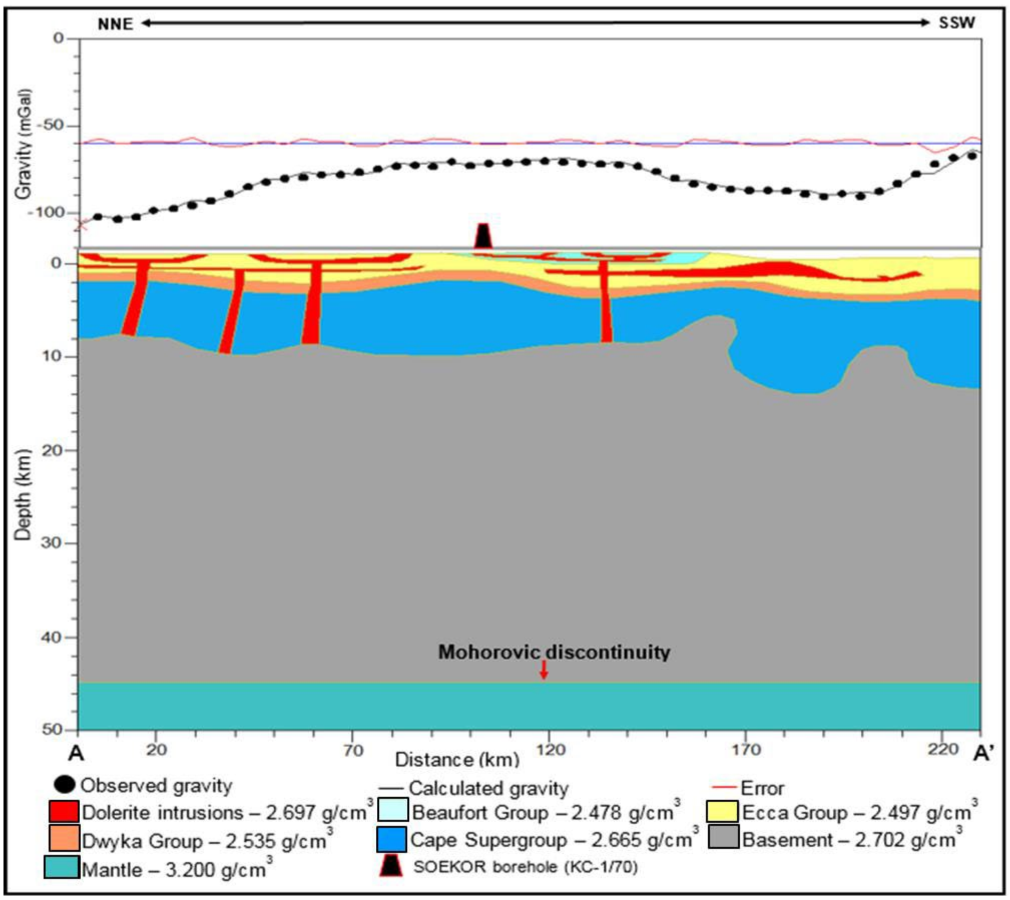


Figure 14. A geological subsurface model along profile A–A'. Vertical Exaggeration (VE) = 3.02. Initial and final Root Mean Square (RMS) error are 87.6 and 1.7, respectively. Note: The Moho was allowed to vary within a depth range of 40–45 km. At borehole KC-1/70, 105 km in SW direction, the base of the Dwyka Group is encountered at 1745 m below the surface

4.3.2. Profile B–B' gravity model

The gravity model along Profile B–B' with gravity values increasing from inland (NNE side) towards the coast (SSW side) is depicted in Figure 15. The maximum recorded gravity is about 15 mGal with the minimum value of around –94 mGal. The model characterises the geology of the Dwyka, Ecca, and Beaufort Group as undulating subhorizontal sedimentary layers with cross- cutting vertical to near vertical and horizontal to near horizontal dolerite intrusions. In this locality the rock layers are seen to occur very shallow towards the north north east end of the profile and this could be due to regional uplift. The Dwyka, Ecca, and Beaufort Group occur within a depth of 2 km from the surface, while the Cape Supergroup reaches a depth of 8 km in the south south west (near the coast). The Moho is horizontal at 45 km depth and shallows to a depth of about 43 km towards the end of the profile that is near the coast.

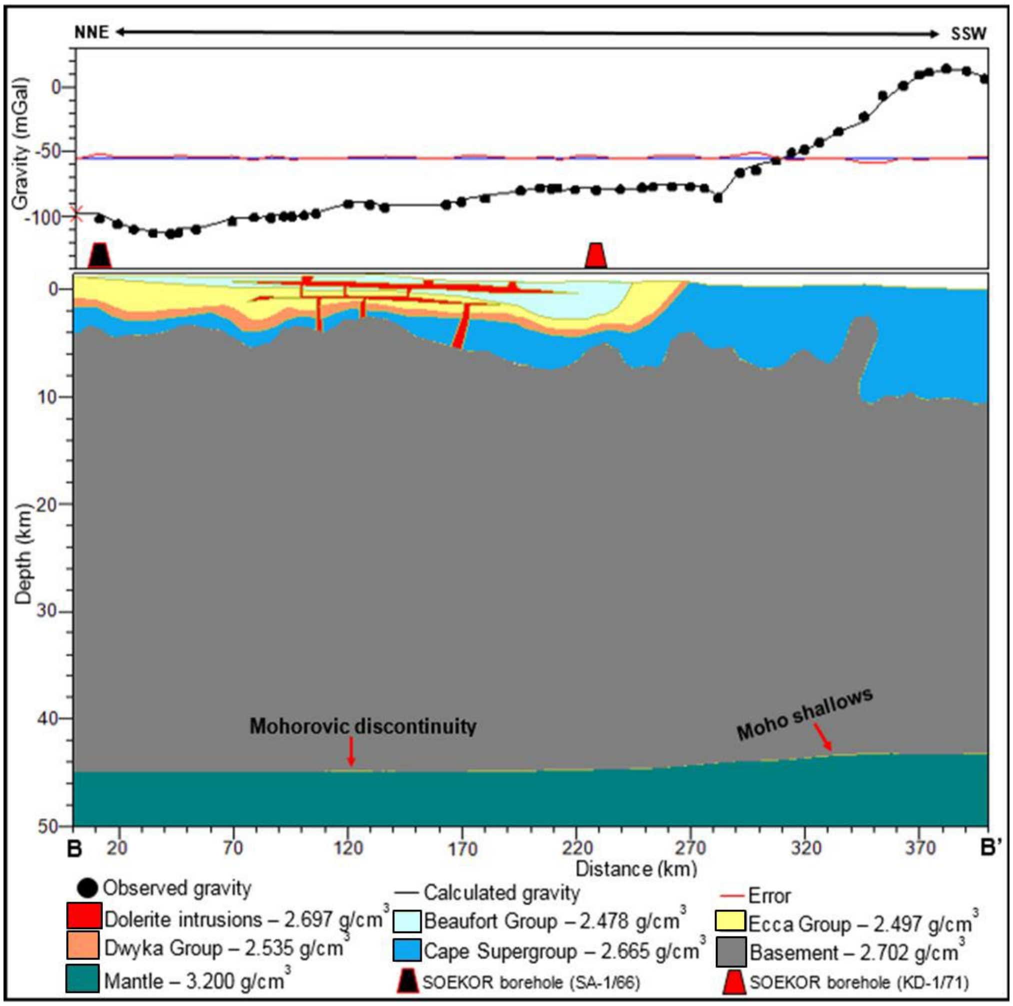


Figure 15. A geological subsurface model along profile B-B'. VE = 3.02. Initial and final RMS error is 81.3 and 1.6, respectively. Note: The Moho was allowed to vary within a depth range of 40–45 km. At borehole KD-1/71, 10 km in SW direction, the base of the Dwyka Group is at 1451 m. While at borehole SA-1/66, 230 km in SW direction Dwyka is encountered at 3572 m and the top of the Whitehill Formation is at 2754 m below the surface

4.3.3. Profile C–C' gravity model

Profile C–C′ is 340 km long in a NNE-SSW direction, running through borehole AB-1/65 and borehole KW-1/67 (Figure 13). It cuts across the entire succession of the Main Karoo Basin, through the BMA, SCCB and Cape Supergroup. The gravity model depicted in Figure 16 shows that the Cape Supergroup have a gradual increase in thickness towards the coast (south), whereas towards the northern extremity of the basin, it has been observed to be relatively thin with a possibility of pinching out further to the north. Along this profile, the Cape Supergroup reaches a depth of approximately 12 km in the south and shallows to a depth between 3 and 4 km in the north. The Dwyka and Ecca Group are encountered at depths between 0 and 3 km from the surface. Both these successions show a thin uniform layering at the centre of the basin and become relatively thick away with folding signs in the south. Such variations in thicknesses, particularly thinning at the centre of the basin could be linked to diagenetic processes, that is, induced compaction by thick sedimentary cover of the Beaufort Group. The Beaufort Group occur as a thick sedimentary sequence at the centre and the latter (centre) has been observed to be the deepest part of the basin. The model also inferred that below the surface, the Karoo dolerites occur as a network of interconnected dykes and sills with some having the same parent feeder dyke. These intrusions, mostly the sills occur as basin like structures (ring/ saucer), while the dykes are commonly associated with faults. The structure of the dolerite intrusions shown by the model is similar to that of [34].

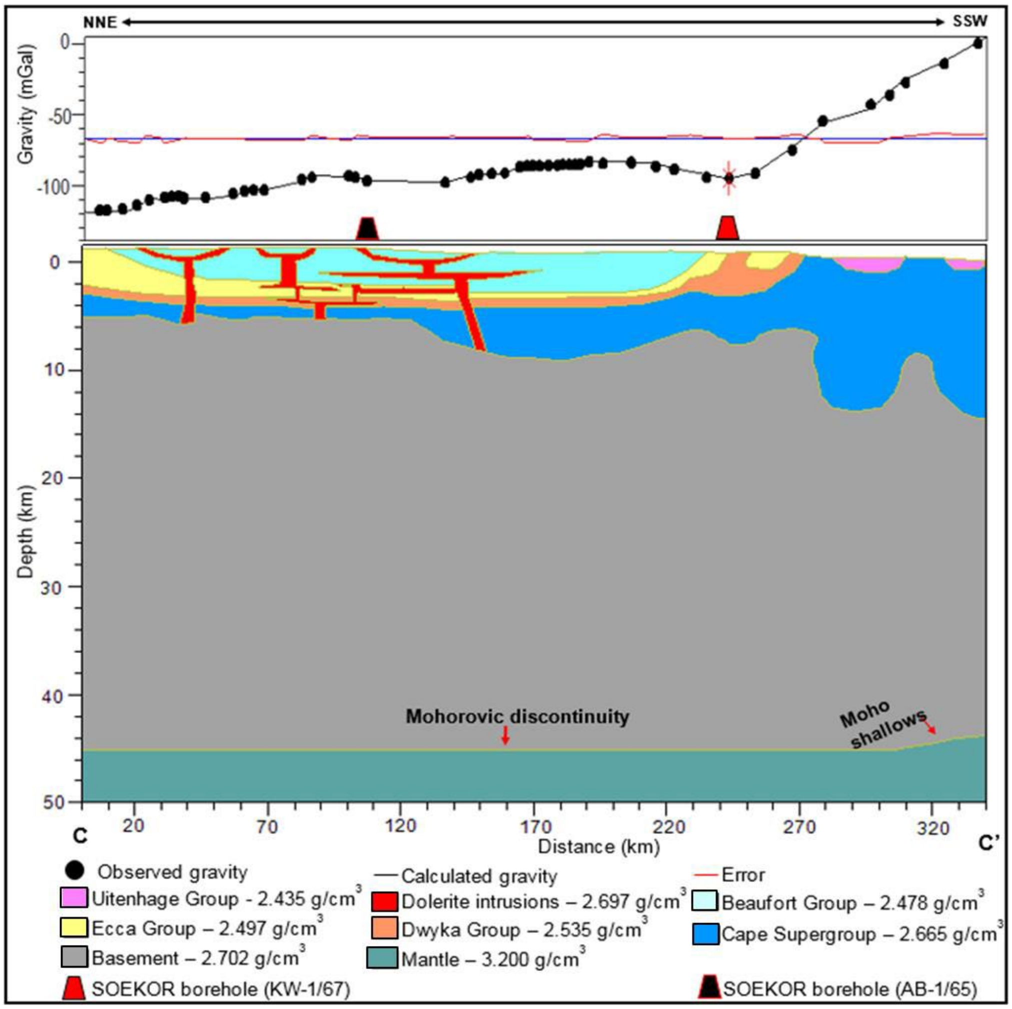


Figure 16. A geological subsurface model along profile C–C'. VE = 3.02. Initial and final RMS error are 73.2 and 1.9 respectively. Note: The Moho was allowed to vary within a depth range of 40–45 km. At borehole AB-1/65, 100 km in SW direction the top of Whitehill Formation is encountered at 2009 m below the surface. While at borehole KW-1/67, 240 SW direction is between 4200–4500 m below the surface

4.3.4. Profile D–D' gravity model

Profile D–D' extends for 345 km in a NNW–SSE orientation, crossing the locations of the BMA and SCCB before ending up at the south coast (Figure 13). The maximum recorded gravity is approximately 0 mGal with a minimum of −127 mGal (Figure 17). The Cape Supergroup reaches a depth of more than 12 km from the surface with its thickness changing from thick in the south to very thin towards the north of the basin (Figure 17). Typical of the Cape Supergroup, tight folding is evident towards the southern part of the basin. The overlying Dwyka and Ecca groups are seen to occur at depths between 0 and 3 km below the surface and both of these groups indicate signs of deformation (folding) at depths. Dolerite intrusions are mostly concentrated at the centre of the basin, specifically piercing through the Beaufort Group at the top, down to the Cape Supergroup. Furthermore, the deepest part of the basin occurs as the synclines.

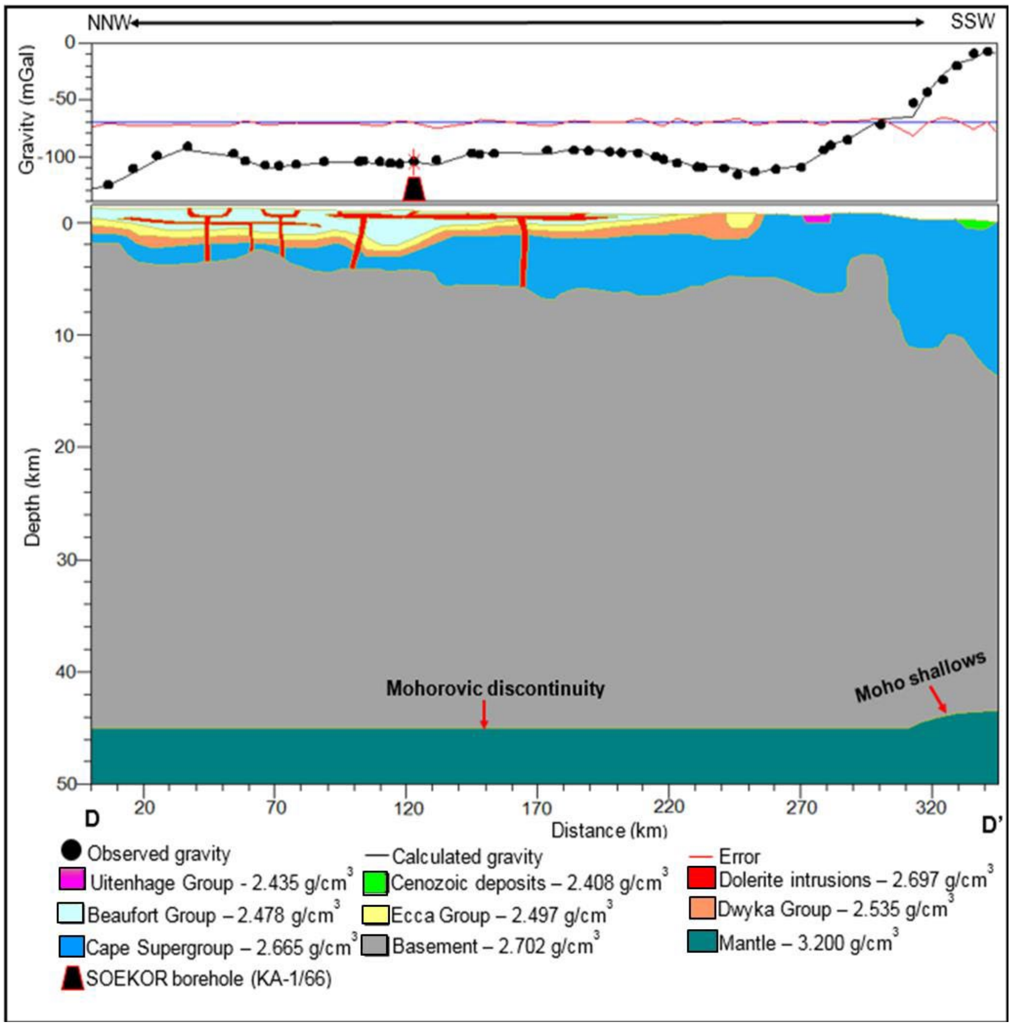


Figure 17. A geological subsurface model along profile D–D'. VE = 4.54. Initial and final RMS error are 59.3 and 1.5 respectively. Note: The Moho was allowed to vary within a depth range of 40–45 km. At borehole KA-1/66, 124 km in SW direction the base of the Dwyka Group is at 2525 m and the top of the Whitehill Formation is not well defined

4.3.5 Profile E-E' gravity model

The gravity model in Figure 18 extends from north of Sutherland to the south of George (Figure 13) and covers a distance of 375 km. The maximum recorded gravity along the profile is 21 mGal with the minimum value at −85 mGal. The model reveals that near the BMA the thickness of the Cape Supergroup changes from thick in the far south to very thin near the BMA and thickens again away from the BMA towards the north.

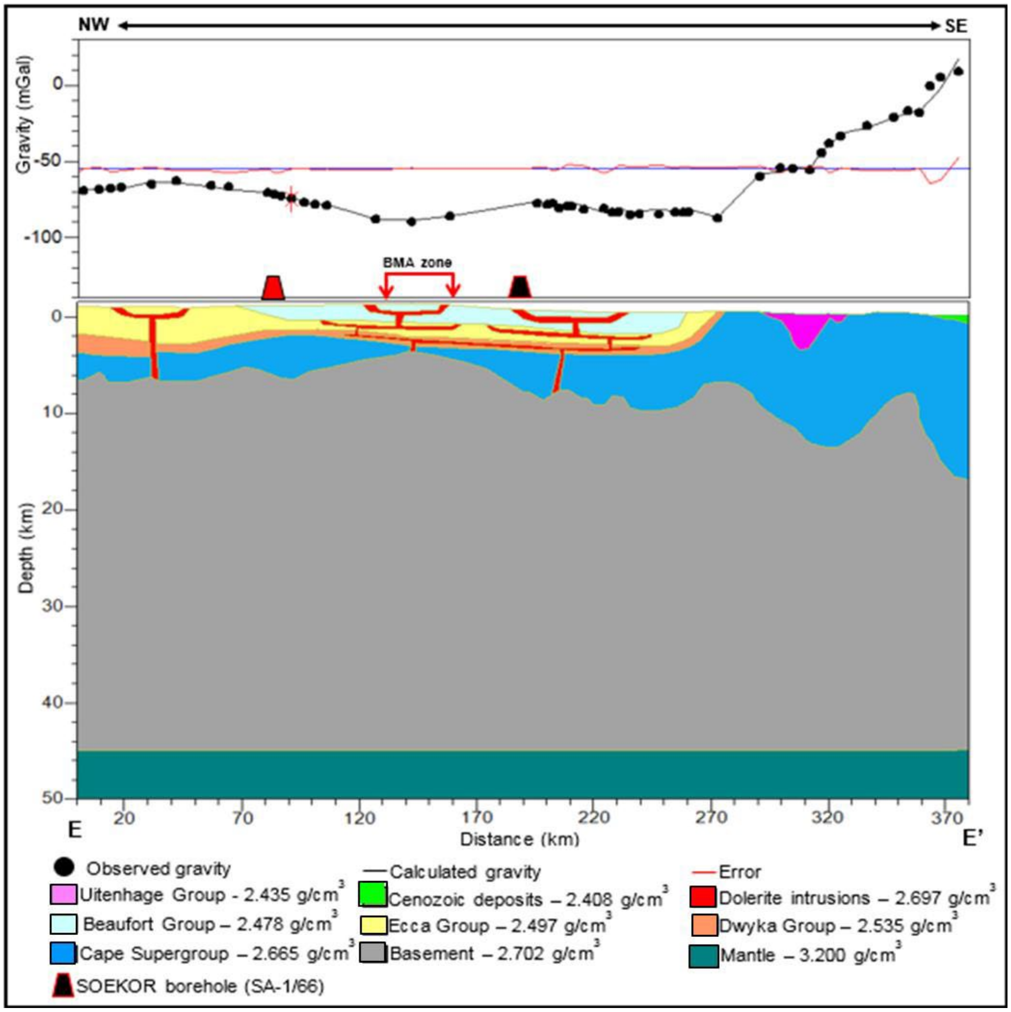


Figure 18. A geological subsurface model along profile E–E'. VE = 4.995. Initial and final RMS error are 109.2 and 1.4 Note: The Moho was allowed to vary within a depth range of 40–45 km. At borehole KC-1/70, 80 km in SE direction the base of the Dwyka Group is encountered at 1745 km. While at borehole SA-1/66, 190 km SE is at 3572 m and the top of the Whitehill Formation is encountered at 2754 m

4.3.6. Profile F–F' gravity model

Profile F–F' is about 410 km in a NW–SE striking direction (Figure 13). It extends from Williston town and runs south across the locations of SCCB and the BMA down to the coast. Along profile F-F', the maximum recorded gravity value is approximately −22 mGal while the minimum value is −100 mGal. The gravity model for profile F–F' (Figure 19) shows that both the Dwyka and Ecca Group have a uniform thickness across the profile, except in the north where the Ecca Group is seen to have acquired a significant thickness. Both of these stratigraphic sequences display intense folding towards the south. The model infer that the dolerite intrusions are not limited to the northern areas of the profile, but might occur in the south as well with no exposure on the surface.

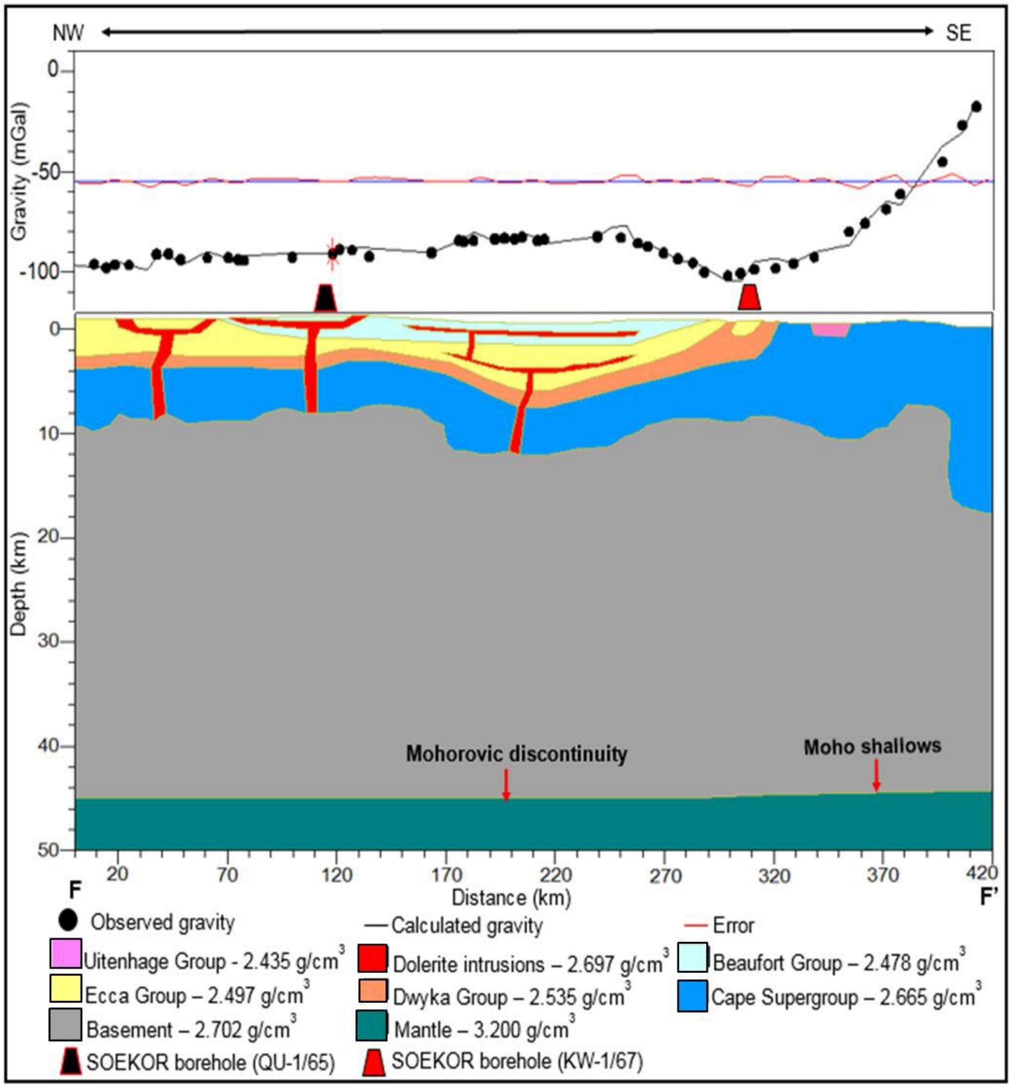


Figure 19. A geological subsurface model along profile F–F'. VE = 4.995. Initial and final RMS error are 40.3 and 1.7. Note: The Moho was allowed to vary within a depth range of 40–45 km. At borehole QU-1/65, 110 km in SE direction, the base of the Dwyka Group is at 2409 m and the top of Whitehill Formation is encountered at 1636 m. At borehole KW-1/67, 300 km in SE direction the top of Whitehill Formation is at 4360 m below the surface

4.3.7. Profile G–G' gravity model

Along Profile G–G’, the maximum gravity is –90 mGal with a minimum value of –101 mGal (Figure 20). The Dwyka and Ecca Group are encountered within the depth of 3 km below the surface with a uniform thickness throughout the basin, except in the north where the Ecca appears to be thicker. The younger Beaufort Group is thicker at the centre of the basin and thins away towards the north and south. It extends to a depth of less than 1 km below the surface**.**

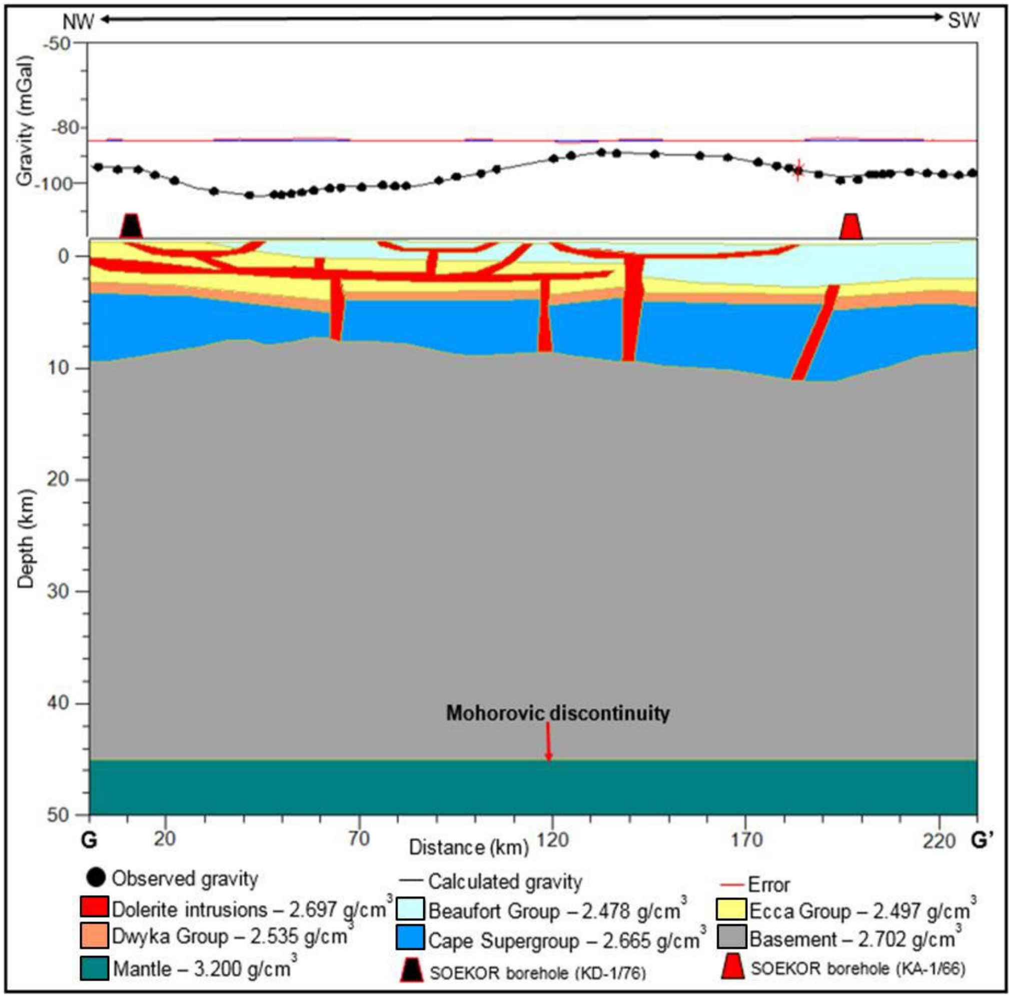


Figure 20. A geological subsurface model along profile G–G'. VE = 1.363. Initial and final RMS error are 92.6 and 1.4. Note: The Moho was allowed to vary within a depth range of 40–45 km. At borehole KD-1/76, 10 km in SE direction the base of the Dwyka Group is at 1745 m. While at borehole KA-1/66, 193 km in SE direction it is encountered at 2531 m and the top of Whitehill Formation is not well defined

5. Discussion

The area under investigation is characterised by numerous patchy high magnetic zones, including the Beattie Magnetic Anomaly (BMA). Apart from the BMA, four zones of magnetic highs occur farther north within the study area and these are marked as 2nd and 3rd anomalies on the NE portion of the map, while another two sets of similar nature are marked as 4th and 5th anomalies in the NW part (Figure 2). It is argued that some or most of magnetic signatures particularly on the northern side of the study area, where there is high concentration of signatures are due to highly magnetic Karoo dolerite intrusions. Such argument is based on ring and linear orientation/shape of magnetic signatures seen on the magnetic map, as well as the mineralogical composition of the Karoo dolerite. Based on geological field mapping, it is known that the Karoo dolerites occur and or are present as ring-like structures for sills and as linear near vertical to vertical structures for dykes. When pressurised basaltic magma rose, piercing through the layered Karoo sediments it filled cracks, faults and hollows and formed saucer-like shaped structures. Also the mineralogical composition of these rocks supports this line of reasoning as the dolerite is comprised of a significant number of magnetic minerals, such as strongly magnetic magnetite, hematite, ilmenite (weak), and pyrrhotite that are present as an accessory minerals. Magnetic depth slicing results revealed that the dolerite intrusions are pervasive in the northern part of the area and extend as far as 4308 m (Figure 6d). This gives a clue that the Karoo intrusions were emplaced near the surface, specifically on the upper crust. Hence, the magnetic signatures from dolerite dykes become weaker and eventually disappear beyond 4 km depth. [36] documented that no occurrence of sills and dykes were found to exist in the basement of the Karoo. Knowledge of the depth extent of Karoo dolerite intrusions is very crucial to Karoo shale gas exploration. However, one cannot rely on information from depth slicing alone. Well logs and seismic data is necessary to get detailed information on the widespread occurrence of these dolerite intrusions.

As observed in the magnetic depth slices 1–5 (Figure 6), the BMA signature gets stronger and broader with depth. It is suggested that the cause of such phenomena lies on the causative body of the BMA, which is believed to be the geological body hosted deep in the mid-crust, beyond 10 km depth. [3] reported that sulphide-magnetite bodies present in the Namaqua section of NMMB in the Bushmanland ore district (Broken Hill, Aggeneys, and Gamsberg ore deposits) produce magnetic signatures similar to that of BMA. Therefore, based on [3] remarks, it can be inferred that the causative body of BMA is hosted in NNMB basement below the Cape Supergroup. This also supports the observations of [5] that the source of BMA is hosted on the NNMB which is present as the crystalline basement below the Cape Supergroup. Short wavelength magnetic anomalies that occur further in the north of the study area are attributed to the dolerite intrusions and their shapes are similar to the dolerite lineaments of the Karoo. However, some magnetic anomalies that are present in the northern side of the study area (Figure 2) do not coincide with Karoo dolerite dykes and sills and yet they generate strong signatures with increasing depth, i.e. they behave in a similar manner to the BMA. This could mean that their source(s) could be due to buried dolerite intrusions at great depths or they share a similar origin as the BMA. However, [2] indicated that the low resolution regional magnetic data cannot image dolerite intrusions at depths of 1.5 km, thus suggesting the anomalies viewed can be linked to the basement rocks. The linear magnetic feature which extends from the centre to the southeastern part has been interpreted to be a DC powerline on the railway line (Figure 14). Near the surface (depth slice 1; Figure 6), the northern side of the area is characterised by weakly magnetic red patches. It is believed that some of these patches are signatures from sandstone and red mudstone outcrops of the Beaufort Group. The Beaufort Group sandstones and mudstone are composed of various minerals including weakly magnetised hematite, as well as weathered heavy metals and unconsolidated cover from dolerites.

The Bouguer gravity map of the study area (Figure 7) revealed that the southwestern Karoo basin is characterised by a variety of low and high gravity anomalous zones with gravity highs present near the coast in the south, and gravity low zones common in the north towards inland areas. The gravity highs more particularly along the coast have a long wavelength which is an indication that their source causative body is located very deep below the surface, possibly the Moho which occurs at great depths of 40–45 km inland and relatively shallow (30 km) near the coast. The negative gravity anomaly present in the northern section of the study area is likely to be resulting from lithospheric deformation resulting from thermal source plume. Moreover, it is of certainty that beyond this depth in the NE region there are no observed anomalies resulting from the Karoo dolerite intrusions. These findings are consistent with seismic reflection data and the findings made by [1] about the causative bodies of gravity anomalies that occur on the southeastern Karoo Basin of South Africa. This could suggest that some gravity anomalies in the southern main Karoo Basin, both in the west and east are due to same/similar causative bodies. The CIA occurring on the southeastern part of the study area is likely to be due to deep seated low density material that mirror the mountain ranges. It is likely that the part of mountain ranges in the vicinity of CIA are not hydrostatically compensated. Thus, the CIA could be indicative of low density material that is present in the subsurface. The linear and circular magnetic signatures that are present in the northern part of the study area (Figure 5) are likely to be due to Karoo dolerite sills and dykes. These are the common geological bodies in the Karoo that preserve this particular shape. Just like the magnetic signatures, some gravity anomalies occurring in the Bouguer anomaly map does not coincide with known geological features and they are suggested to be due to shallow subsurface bodies.

The 2½ D gravity models (Figures 14–20) are consistent with seismic refraction and magnetotelluric models within the study area, they all display that the Karoo rocks occur at depths in the south and become relatively shallow towards the north, this has been attributed to tectonic deformation. [37] described a series of subsidence and regional uplift events that are likely to have shaped the tectonic setting of the Karoo and that of the adjacent Cape Basin. Based on the gravity models, it is further inferred that the dolerite intrusions in the Karoo form a network of interconnected sills and dykes and this results in a complex structure of the basin, which could pose a serious threat or risk to the exploitation of the shale gas. The illustration of dolerite intrusions shown by the models is similar to the models constructed by [31, 34] which show a network of dolerite intrusions in the subsurface slicing through the Karoo sediments. Detailed additional studies is recommended to be undertaken in the study area to develop a 3-dimensional model using high resolution magnetic and gravity data. Such model would need to be complemented by magnetotelluric and borehole data to ascertain more accurately the geological contacts, depth and horizontal extent and the geometry of subsurface linearments. This kind of information would be essential for shale gas exploration in the southwestern Karoo Basin.

6. Conclusions

The study presents the results from a variety of methods that were utilised to probe the subsurface geology of the southwestern Karoo Basin of South Africa. Based on the results presented herein, the following can be concluded:

- Most of magnetic anomalies (linear and circular signatures), specifically on the northern part of the Cape Fold Belt owe their origin to Karoo dolerite intrusions (dykes and sills).
- The gravity high along the coast is associated with a long wavelength and that is an indication that it is possibly due to a deep seated anomalous body, probably the Moho which is relatively shallow towards the coast and deep inland as seen in the models.
- The Cape Isostatic Anomaly occurring on the south eastern part of the area is likely to be due to deep seated low density material that mirror the mountain ranges. It is likely that the part of mountain ranges in the vicinity of CIA are not hydrostatically compensated.
- The causative body of BMA is likely to be hosted or present at great depths (i.e. ≥ 10 km) deep below the surface in the Namaqua Natal Metamorphic Belt.
- The gravity models indicate that the Ecca Group which is the targeted group for shale gas exploration in the Karoo occur within the depth range of 0–4 km in the southwestern part of the basin. The gravity models indicate that the southwestern units of the main Karoo Basin extend to the depth of 4500 m in the south, near the front of the Cape Fold Belt and extend to shallows depths of 2600 m in the north. The deepest part of the basin occurring towards the south near the Cape Fold is inferred to be resulting from tectonic repition.
- The model also revealed that the Karoo dolerite intrusions (sills and dykes) are interconnected at depth and mostly concentrated at the centre of the basin, which will pose a threat to fracturing the Karoo formations for shale gas exploitation.

References

[1] Baiyegunhi C, Gwavava O. Magnetic investigation and 2½ D gravity profile modelling across the Beattie Magnetic Anomaly in the South-eastern Karoo Basin, South Africa. Acta Geophysica, 2017; 65:119–138.

[2] Scheiber-Enslin SE, Ebbing J, Webb SJ. An integrated geophysical study of the Beattie Magnetic Anomaly, South Africa, South Africa. South African Journal of Geology, 2014; 636: 228–243.

[3] Lindeque A, De Wit MJ, Ryberg T, Weber M, Chevallier L. Deep crustal profile across the Southern Karoo Basin and Beattie magnetic anomaly, South Africa: An integrated interpretation with tectonic implications. South Africa Journal of Geology, 2011; 114: 265–292.

[4] Stankiewicz J, Parsigla N, Ryberg T, Gohl K, Weckmann U, Trumbull R, Weber M. Crustal structure of the southern margin of the African continent: Results from geophysical experiments. Journal of Geophysical Resesarch, 2008; 113: 1–5.

[5] Weckmann U, Ritter O, Jung A, Branch T, de Wit M. Magnetotelluric measurements across the Beattie magnetic anomaly and the Southern Cape Conductive Belt, South Africa. Journal of Geophysical Research, 2007; 112: 1–10.
[6] Pitts B, Mahler M, de Beer J, Gough D. Interpretation of magnetic, gravity and magnetotelluric data across the Cape Fold Belt and Karoo Basin. Geophysical Journal International, 1992; 132: 535–548.
[7] Harvey J, de Wit M, Stankiewicz J, Doucoure C. Structural variations of the crust in the Southwest Cape, deduced from seismic receiver functions. South African Journal of Geology, 2001; 104: 231–242.
[8] Linol B, Chere N, Muedi T, Nemgovhela V, de Wit MJ. Deep borehole lithostratigraphy and basin structure of the southern Karoo Basin re-visited. In Linol, B. and de Wit, M.J. (2016) (Eds). Origin and Evolution of the Cape Mountains and Karoo Basin. Springer International Publishing: Switzerland, 2016; 143–157.
[9] Scheiber-Enslin SE, Ebbing J, Webb SJ. New depth maps of the main Karoo Basin, used to explore Cape Isostatic Anomaly, South Africa. South African Journal of Geology, 2015; 118: 225–248.
[10] Linol B, de Wit MJ. Origin and Evolution of the Cape Mountains and Karoo Basin. Springer International Publishing: Switzerland, 2016; 89–102.
[11] Lubke R, De Moor IJ. Field guide to the Eastern and Southern Cape Coasts.Juta and Company. Nature, 1998; 521–539.
[12] Bachtadse V, Van der Voo R, Halbich IW. Paleomagnetism of Western Cape Fold Belt, South Africa and its bearing on the Palaeozoic apparent polar wander path for Godwana. Earth and Planetery Science Letters, 1987; 84: 487–499.
[13] Booth PWK, Shone RW. The Cape Basin, South Africa: A review. Journal of African Earth Science, 2005; 43: 196–210.
[14] Bordy EM. Sedimentology of the Karoo Supergroup in the Tuli Basin (Limpopo River Area, South Africa). PhD Thesis (unpublished). Department of Geology, Rhodes University, Grahamstown, 2000; 125–148.
[15] Miller W, Armstrong R, de Wit MJ. Geology and U/P geochronology of th Gamtoos Complex and lower Paleozoic Table Mountain Group, Cape Fold Belt, Eastern Cape, South Africa. South African Journal of Geology, 2016; 119: 31–44.
[16] Johnston ST. The Cape Fold Belt and Syntaxis and the rotated Falkland Islands: dextral transpressional tectonics along the southwest margin of Gondwana. Journal of African Earth Sciences, 2000; 31: 51–63.
[17] Tankard A, Welsink PA, Aukes P, Newton R, Settler E. Tectonic evolution of the Cape and Karoo Basins of South Africa. Marine and Petroleum Geology, 2009; 26: 1379–1412.
[18] Lurie J. South African Geology for Mining, Metallurgical, Hydrological and Civil Engineering. South Africa. Lupon Publishing, 2008; 23–42.
[19] Gess R. Palaeontological heritage impact assessment for N2 upgrade between Grahamstown and Fish River. Coastal and Environmental Services, 2013; 3–18.
[20] Allen PA, Allen RA. Basin Analysis: Principles and Applications. Blackwell Publishing: Australia, 2013; 1–12.
[21] Catuneanu O, Elango HN. Tectonic control on fluvial styles: The Balfour Formation of the Karoo Basin, South Africa. Sedimentary Geology, 2001; 140: 291–313.
[22] Smith RMH, Eriksson PG, Botha WJ. A review of the stratigraphy and sedimentary environments of the Karoo-aged basins of southern Africa. South African Journal of Geology, 1993; 97:107–169.
[23] Bezuidenhout L, Doucoure M, Wagener V, de Wit MJ. Ambient noise tomography (passive seismic) to image the Cape- Karoo transition near Jansenville, Eastern Cape. In: Linol B, de Wit MJ (Eds). Origin and Evolution of the Cape Mountains and Karoo Basin. Springer International Publishing: Switzerland, 2016; 26–33.
[24] Geel C, Schulz HM, Booth P, de Wit M, Horsfield B. Shale gas characteristics of Permian black shales in South Africa: results from recent drilling in the Ecca Group (Eastern Cape). Energy Procedia, 2013; 40: 256–265.
[25] Van der Merwe WC, Stephen SF, Hodgson DM. Sequence stratigraphy of an argillaceous, deepwater basin-plain succession: Vischkuil Formation (Permian), Karoo Basin, South Africa. Marine and Petroleum Geology, 2009; 27: 310–333.
[26] Ledwaba L, Dingoko O, Cole P, Havenga M. Compilation of Survey Specifications for all the old regional airborne geophysical surveys conducted over South Africa. Report Number: 2009-0130, Council for Geoscience, South Africa, 2009; 1–8.

[27] Talwani M, Worzel JL, Landisman M. Rapid computations for two-dimensional bodies with application to the Mendocino Submarine Fracture Zone, Journal of Geophysical Research, 1959; 64: 49–59.
[28] Talwani M, Heirtzler JR. Computation of magnetic anomalies caused by two-dimensional bodies with application to the Mineral Industry shape. Computers in the Mineral Industry, School of Eath Sciences, Standford University (Public), 1964; 464–480.
[29] Won IJ, Bevis M. Computing the gravitational and magnetic anomalies due to a polygon: Algorithms and Fortran subroutines. Geophysics, 1987; 52: 232–238.
[30] Baiyegunhi C. Geological and geophysical investigation of the southeastern Karoo Basin, South Africa. MSc dissertation, Department. of Geology, University of Fort Hare, 2015; 164–187.
[31] Baiyegunhi C, Gwavava O. Variations in isochore thickness of the Ecca sediments in the Eastern Cape Province of South Africa, as deduced from gravity models. Acta Geologica Sinica (English Edition), 2016; 90(5): 1699–1712.
[32] Visser DJL. The geology of the republic of South Africa, Transkei, Bophutatswana, Venda and Ciskei and The kingdoms of Lesotho and Swaziland. Expalnation of 1: 1000 000 geological map. Pretoria: Geological Survey of South Africa, 1989; 1–2.
[33] Stankiewicz J, de Wit MJ. 3.5 billion years of reshaped Moho, southern Africa. Tectonophysics, 2013; 60: 675–689.
[34] Chevalier L, Goedhart M, Woodford AC. The influence of dolerite sill and ring complexes on the occurrence of groundwater in Karoo Fractured Aquifers: a morpho-tectonic approach. WRC Report No. 937/1/01, 2001; 1–10.
[35] Chevallier L, Woodford AC. Morpho-tectonics and mechanism of emplacement of the dolerite rings and sills of the western Karoo, South Africa. South African Journal of Geology, 1999; 102: 43–54.
[36] Neumann ER, Svensen H, Calerne CY, Planke S. Multistage evolution of dolerites in the Karoo large Igneous Province, central South Africa. Journal of Petrology, 2011; 10: 1–26.
[37] Quesnel Y, Weckmann U, Ritter O, Stankiewicz J, Lesure V, Mandea M, Langlais B, Sotin C, Galdeano A. Simple models for the Beattie Magnetic Anomaly in South Africa. Tectonophysics, 2008; 478: 111–118.

To whom correspondence should be addressed: Mr. Zusakhe Nxantsiya, Council for Geoscience, Private Bag X112, Pretoria 0001, Gauteng Province, South Africa; e-mail: znxantsiya@gmail.com