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Geophysical insights into the southern Lebombo volcanic sequences and its influence on the formation of the Zululand Basin

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Geophysical insights into the southern Lebombo volcanic sequences and its influence on the formation of the Zululand Basin

By

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718833

A dissertation submitted to the Faculty of Science, University of the Witwatersrand in
fulfilment of the requirements for a degree of Master of Science

In Geophysics

Supervised by:

Prof. S J Webb

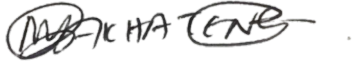
Dr S E Enslin

31 October 2025



Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.



P. T. Makhateng

31 October 2025

Abstract

The Lebombo sequence provides a glimpse into the past by studying its formation and the sequence of tectonic events that caused the mountainous monocline we see today. The Lebombo sequence is part of the failed triple junction, which had two arms that were sequences of the volcanic basalts and rhyolites and a third arm that was a dyke swarm. The cause of these structures was assumed to be due to a plume and/or lithospheric stretching. Each of these theories can be placed into the context of the Gondwana break-up. Once faulting and rifting of Gondwana began, the study area was also affected by additional crustal thinning and stretching, which led to the intrusions of the Lebombo sequence. As rifting then became drifting, the formation of the Zululand Basin occurred. The Zululand Basin formation is strongly tied to the Lebombo basement. The purpose of this study is to understand the subsurface structure and formation of the Lebombo sequence and the Zululand Basin using geophysical data.

The geology of the region consists of the Lebombo sequence outcropping to the west of the Zululand Basin and dipping eastwards to form the basement of the Zululand Basin. The Lebombo is made up of the Jozini Rhyolites and the Sabie River Basalts. The sequences are overlain by the siltstones, sandstones, and reworked volcanics of the Zululand Basin. There are extensive intrusions in the Lebombo of dykes and the Bumbeni Complex. The Bumbeni Complex forms a ridge that divides the basin into two sub-basins. Most geological maps indicate the Bumbeni Complex as a single intrusion.

In this study, the regional tectonics were interpreted from the Total Magnetic Intensity map. The regional interpretation of the area showed that the lineaments in the area do not have the same strike. The strike varies from NNE-SSW for the Jozini Formation to NW-SW for the Sabie River Basalt Formation. This change in strike could represent changes in the edge of the Kaapvaal Craton. Two 2D magnetic profiles were modelled using the open-source PyGMI software. One profile was in the northern section of the study area, where two seismic lines were used to constrain the model by determining the approximate depth of the Lebombo volcanic sequence. The observed data on

profile 2 was not fitted well due to the resolution of the modelled area in PyGMI. The second 2D magnetic profile was in the area where the Bumbeni Complex intruded to see how it would affect the lithologies around. The results showed that the Bumbeni Complex was intruded after the volcanic sequences had dipped eastwards. The aim of these profiles was to assist in understanding the transition from the outcropping Lebombo volcanic sequences to the basin fill and to investigate the formation of the Bumbeni Complex. The profile models were not as successful as expected because fitting the data was difficult due to the presence of remanence and not enough physical property measurements to constrain the models. This made it difficult to determine the orientation and thickness of the intrusive dykes in the Lebombo sequence.

A 3D inversion of the magnetic data was run, using ModelVision and UBC GIF-Tools, to determine whether the Bumbeni Ridge was a single intrusion or multiple intrusions across the basin. The results showed that the Lebombo sequence was intruded in three different places by the Bumbeni Complex to form the Bumbeni Ridge.

Future work would include paleomagnetic studies and measurements of physical properties to assist with the modelling process.

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- My family for your love and support throughout this process
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1. Introduction

South Africa relies heavily on fossil fuels for power production. With the increase in urbanisation, there is a greater energy demand (Tot et al., 2011; Yoro et al., 2016). This has led to the rise in greenhouse gas emissions (Cloete, 2010). To mitigate the effects of these greenhouse gases, South Africa has initiated the Carbon Capture and Storage project, aimed at storing carbon dioxide in underground lithologies. The storage target site is the Zululand Basin in KwaZulu Natal, South Africa. Due to the available legacy data collected by SOEKOR oil exploration in the 1960s, this area was chosen to assess the basin's hydrocarbon potential. Using legacy data, extensive research has focused on the basin to determine the feasibility of storing carbon dioxide (Cloete, 2010).

The study area is located in the northern part of KwaZulu Natal, South Africa (centred at 27°38'58" S, 32°27'51" E) (Figure 1.1). The onshore Zululand Basin has an approximate area of 7500 km² (Chabangu et al., 2014). The basin continues offshore, but for the sake of the study, the offshore area will not be considered.

The Lebombo sequence outcrop is on the western edge of the Zululand Basin. The sequence dips eastwards to form the basement of the basin. The study area has been intruded by dyke swarms and the Bumbeni Complex.

The basin formation is strongly tied to the basement structure and tectonic environment. However, not much attention has been given to the basement. The basement, which is made up of the Lebombo volcanic sequence, controlled the basin's development. This study will focus on the structure of the Lebombo volcanic sequences using geophysical and geological data. A series of models (2D and 3D) of the Lebombo will be created to determine the events leading to the basin formation. These models will be constrained using geological and potential field data provided by the Council for Geoscience; seismic and borehole data supplied by the Petroleum Agency of South Africa; and past tectonic studies done in the area by Saggerson and Bristow (1983) and Watkeys (2002).

GEOLOGICAL LEGEND						
SYSTEM	GROUP	FORMATION	LITHOLOGY	INTRUSIVE ROCKS		
QUATERNARY	ZULULAND		Alluvium			
		Berea	Red dune cordon sand			
		Muzi	Argillaceous sand			
		Uloa	Red sand			
TERTIARY						
		CREATACEOUS	St Lucia	Siltstone, sandstone		
Mzinene			Marine siltstone			
Makatini			Conglomerate, sandstone/siltstone			
JURASSIC		LEBOMBO	Moveene	Basalts		
			Jozini	Rhyolite and rhyodacite		
	Sabie River		Basalts			

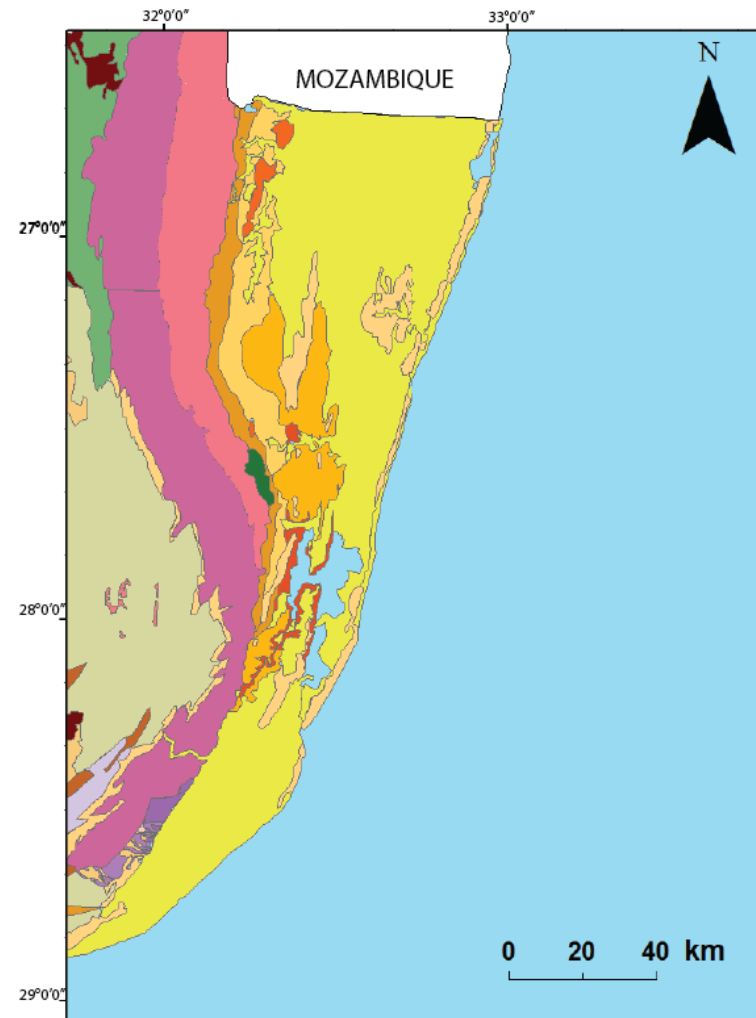


Figure 1-1: Geology map of the outcropping Lebombo volcanics and the Zululand Basin which make up the study area.

The study aims to create magnetic models of the Lebombo sequence, from where it is exposed, west of the onshore Zululand Basin, to the coastline in the east, where the Lebombo form the basement. A model of the Bumbeni Complex, forming the Bumbeni Ridge, will be tested to see if the Ridge was formed by one intrusion or multiple intrusions. These models will be used to understand the emplacement of the Lebombo sequence, the intrusions that occurred in the area and the formation of the Zululand Basin in the context of Gondwana break-up to determine the regional tectonic setting and deformational processes that could have occurred during that time.

The project aims will be achieved using potential field data to determine regional trends and highlight features in the Lebombo. Legacy 2D seismic data will aid the interpretation by showing the Lebombo sequence's cross-sectional geology and determining the variation in the basin-basement contact and change in depth.

Thesis Structure

This thesis is divided into seven chapters. The first chapter highlights the rationale of the study and specifies the aims and objectives of the study. Chapter two describes the geology of the Lebombo sequence and the Zululand Basin, the tectonic setting in which the Lebombo sequence and Zululand Basin were formed, and the geological profile models of the area. Chapter three describes the data used and the quality assurance done to ensure there were no inconsistencies in the data. Chapter four describes the methodology used in this study. Chapter five showcases the results and a detailed interpretation of the area. Chapter six summarises the key points of the study.

2. Geological and the Tectonic Environment

Regional Geology

The Lebombo sequence was emplaced during a time of extensive volcanism, the true cause of this volcanism is unknown. It has been proposed that it could have been a plume (White and McKenzie, 1995; Campbell and Griffiths, 1990; Storey, 1995), subduction (Cox, 1978, 1992), or lithospheric stretching (Gallagher and Hawkesworth, 1992). The full extent of the Lebombo sequence can be considered as part of a failed triple rift junction. The first arm is the Okavango Dyke swarm, which extends westwards towards Botswana. The second arm is the Mwenezi Monocline which extends northwards between Zimbabwe and Mozambique. The third arm is the Lebombo monocline, formed by the Lebombo sequence (Figure 2.1). The Lebombo sequence is characterised by a 700 km north-south trending structure (Watkeys, 2002; and Riley et al., 2006). The Lebombo sequence is bound to the west and east by the Kaapvaal Craton and the southerly extension of the Mozambican belt, respectively, and bound southerly by the Natal-Namaqua mobile belt (Saggerson and Bristow, 1983). The Lebombo sequence can be broken up into the northern section, central section, and southern section. The southern Lebombo sequence will be the focus of this study.

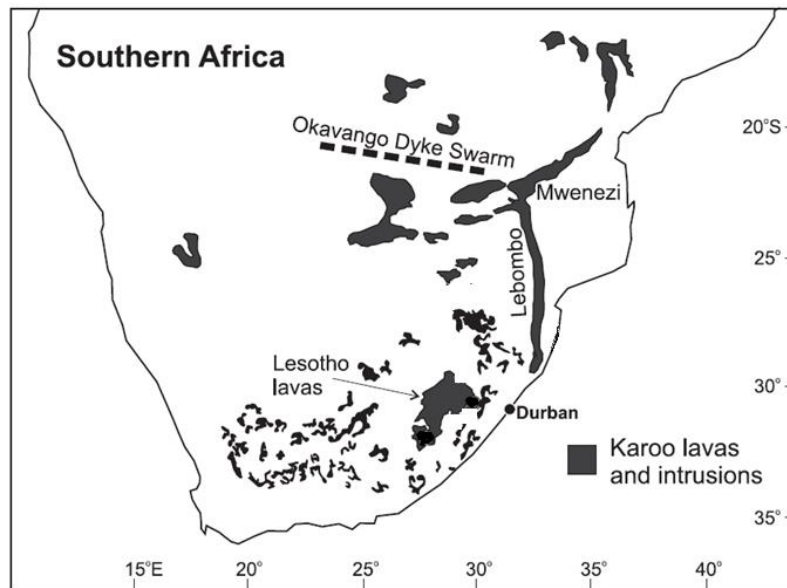


Figure 2-1: Southern Africa region showing the location of the three components of the triple rift junction (adapted from Riley et al., 2006).

Geological Background

Lebombo Volcanic Sequences and Intrusions

The Letaba River Basalt Formation (182.7 ± 0.8 Ma.) (Riley et al., 2004 and Duncan et al., 1997) forms the base of the Lebombo sequence in the study area and overlies the Karoo Supergroup (not seen on the map) (Figure 1.1), with an approximate thickness of 4 km. The Letaba Formation is overlain by the Sabie River Basalt Formation (181.2 ± 1.0 Ma) (Riley et al., 2004 and Duncan et al., 1997). The Letaba Formation is interbedded with four Olifants River Bed rhyolite units and has an approximate thickness of 4-5 km. The Sabie River Basalt Formation is overlain by the Jozini Rhyolite Formation (178.1 ± 0.6 Ma) (Duncan et al., 1997). As a result of crustal extension and monoclinial flexure, these layers went through extensive intrusion by the Rooi Rand dyke swarm (174 Ma) (Armstrong, 1978 and Hastie et al., 2014) and other dolerite intrusions (Saggerson and Bristow, 1983). The area was intruded by the Bumbeni Complex (133 ± 5 Ma) (Bristow, 1980).

Intrusive Rocks within the Lebombo sequence

The area has been intruded by different types of dykes. There are dykes that were believed to be feeder dykes to the Lebombo sequence and dykes that intruded the area after the formation of the sequence. Dykes that have affected the study area are the picrite dykes that trend north-south and crop out of the Letaba formation and were not found in the overlain formations. These dykes have a similar composition to the Letaba formation. There are basaltic dykes that have a curvilinear trend in the north and northwest direction and are the western segment dykes in the area. There is no evidence that these dykes are feeder dykes to the Sabie River Basalts. There are dolerite dykes which create topographical lineations with a north-south trend. These dykes crosscut the Karoo sediments in the Jozini Rhyolite Formation (Bristow and Cleverly, 1983). The Bumbeni Complex occurred after the Lebombo sequence. It is partially exposed near the southern termination edge of the Jozini Formation. The exposed area is the southwestern edge of the Bumbeni Ridge, which separates the Zululand Basin into two (Ncume, 2021). The Bumbeni Complex is made up of the Mpilo Trachybasalt, the Nxwala Rhyolite, and the Fenda Rhyolite (Bristow and Duncan 1983).

Zululand Basin

The Zululand Basin is the southerly extension of the Mozambique Basin. The Lebombo monocline bounds the basin's western side (Chabangu et al., 2014). The Zululand Basin is divided into two sub-basins, the Kosi Trough in the north and the St Lucia Trough in the south, separated by the Bumbeni Ridge (Chabangu et al., 2014). Borehole data indicate that the Zululand Basin is approximately 2000 m thick in the north and thins out to about 1000 m in the south (Broad et al., 2006).

The basin fill is known as the Zululand Group and comprises of red beds, reworked volcanic, siltstones, sandstones, and sandy limestones (Broad et al., 2006). The basin consists of the Makatini Formation, overlain by the Mzinene Formation, and the St Lucia Formation. The Makatini and Mzinene Formations are separated by hard ground with fauna remains, indicating a long period of non-deposition. Borehole data indicate

that these layers are approximately 722 m thick. The St Lucia Formation is separated from the Mzinene Formation by an angular unconformity and is fossiliferous compared to the rest of the formations. It has a repetition of hard ground like the Makatini and Mzinene Formations (Shone, 2006).

Tectonic environment

The formation of the Lebombo sequence and the Zululand Basin can be contextualised using the five stages of Gondwana breakup from Watkeys (2006) (Figure 5.2). Only the stages that have directly affected the study will be mentioned and numbered differently from those in Watkeys (2006). One of the main things the stages show is that the volcanism did not occur due to continental break-up but due to rifting (Watkeys, 2002). During stage 1 (185 – 175 Ma), the major event linked to the area was the movement of the Gastre Fault System, a dextral fault system. This fault system, coupled with the Karoo volcanism, resulted in weak zones within the area. During stage 2 (175 – 155 Ma), the major event involved was the separation of Africa and South America during strike-slip movement in a south-westerly direction along the Gastre Fault and the Falkland-Agulhas Fracture Zone. During Stage 3 (135 – 115 Ma), South America and Africa split from the Falkland Plateau. The Agulhas Falkland Fracture Zone, a transform fault, caused extension in the Natal area. During Stage 4 (115 – 90 Ma), basin formation occurred, marked by multiple hiatuses between the different Zululand formations.

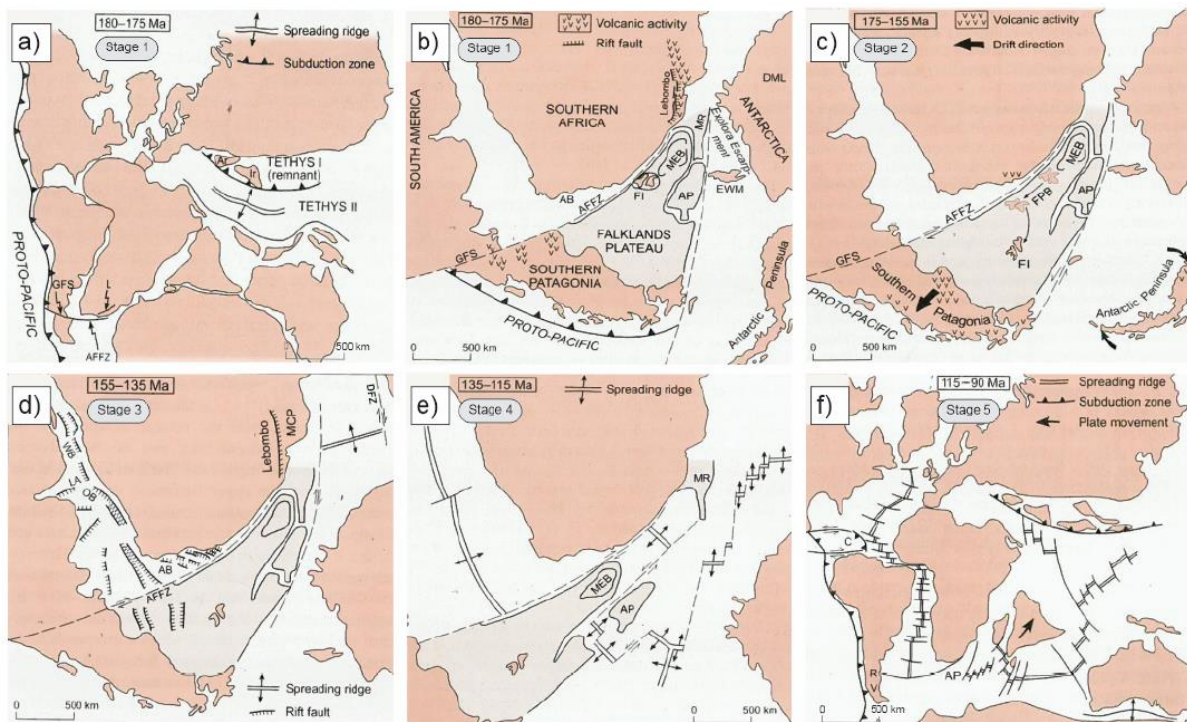


Figure 2-2: Gondwana breakup from a Southern African perspective from 180 to 90 Ma (Watkeys, 2006). AFFZ – Agulhas-Falkland Fracture Zone, AP – Antarctic Peninsula, FBP – Falkland Plateau Basin, FI – Falkland Islands, MEB – Maurice Ewing Bank, AB – Agulhas Bank, MCP – Mozambique Coastal Plain.

Geological models of the area

Studies by Watkeys (2002) and Saggerson and Bristow (1983) created similar profile models of the area near the Bumbeni Complex outcrop (Figure 5.7 (b) and (c), respectively). Watkeys (2002) focused more on describing the block faulting, dyke intrusions and the start of the dip. Bristow and Saggerson and Bristow (1983) focused on the larger region, showing the dyke intrusions and more layers of the Lebombo sequence. Saggerson and Bristow (1983) assumed that the Bumbeni Complex was intruded before the monocline occurred because it is eastward dipping like the Lebombo sequence. They also assumed the Rooi Rand dyke swarm intrusions were vertical, whereas Watkeys (2002) assumed they were tilting. Saggerson and Bristow (1983) also added additional dykes that were also tilting in a similar way to Watkeys (2002). In our model we assumed that the dykes were tilted due to the type of block faulting that occurred (Watkeys 2002).

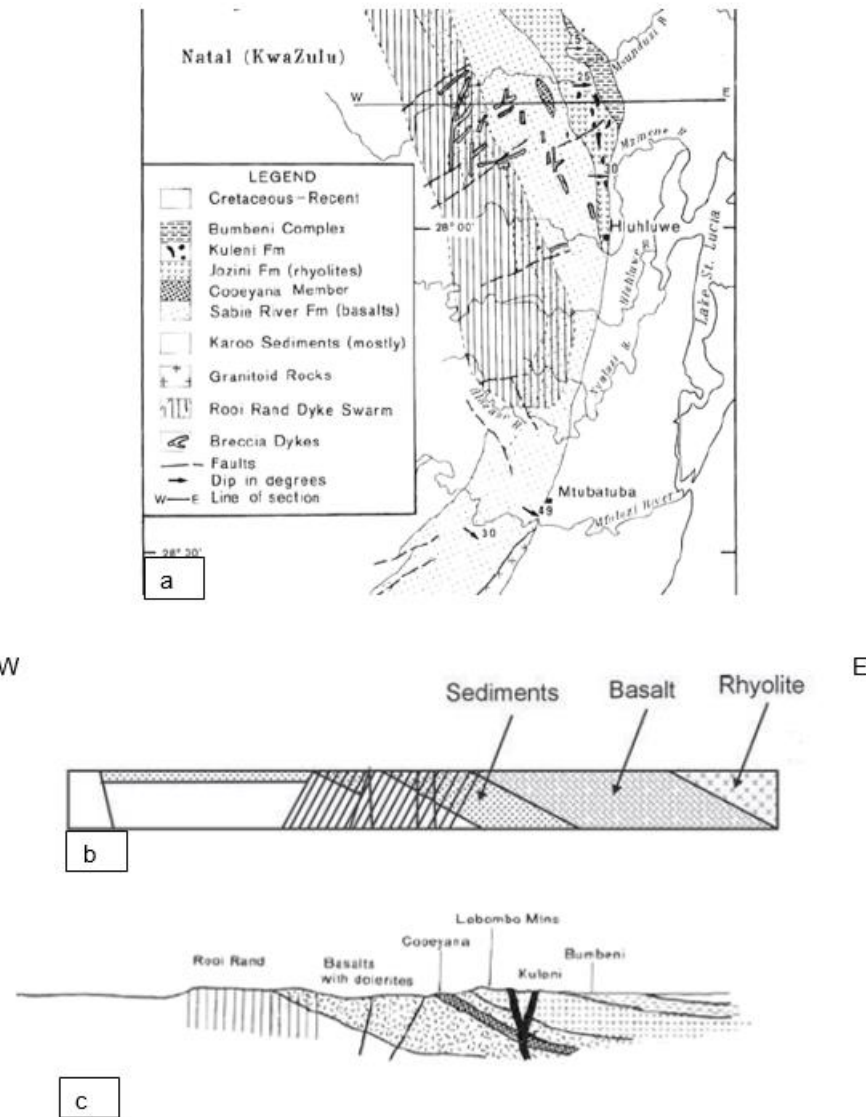


Figure 2-3: (a) Geology map from Saggerson and Bristow (1983) showing the central to lower part of the study area. Profile W-E is indicated on the map. (b) Cross section from Watkeys (2002) in an area close to the W-E marked on (a) but does not extend towards the east to cover the areas where the Bumbeni Complex has intersected. (c) The cross section indicated by W-E from Saggerson and Bristow (1983) in (a).

3. Data

Geological Data

Field mapping data in the area have a resolution of 1:250 000, and were provided by the Council for Geoscience. The data were taken from 4 separate maps and were combined to form a map of the study area (Figure 3.1). The original map's reference datum is Clarke 1880. Field mapping of intrusive lithologies, from Armstrong (1978) and Gomez (2004), within the Lebombo sequence was used to approximate the lithologies' extent within the study area.

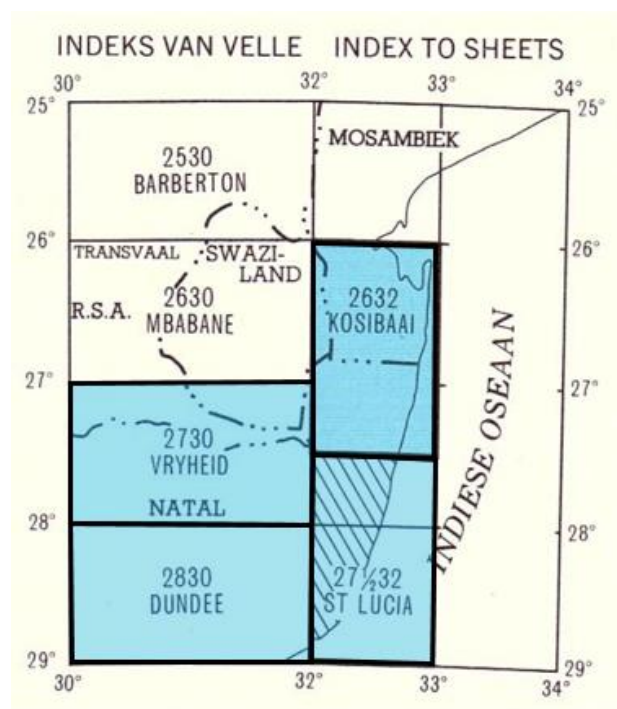


Figure 3-1: The 1:250 000 geological maps outline. The maps used in this study are highlighted in a blue polygon. These maps were digitised to their original reference frame (Clarke 1880). Each segment was used to create the geological map of the study area (adapted from Steyn and Coetsee, 1985).

Elevation Data

Elevation data were downloaded from Geosoft Seeker; these data were collected through the Shuttle Radar Topography Mission (Farr et al., 2007). Considering the study area's scale, these data have a low resolution; however, no other data available.

Potential Field Data

Magnetic Data

Magnetic data used in this study were from the Council for Geoscience (CGS) and were part of the regional aeromagnetic data collected in South Africa. Each area was divided into blocks, in some cases with varying flight directions. The data used in the study are from the Karoo 17 block (Figure 3.2) collected by Geosearch (Pty) Ltd from 1981 to 1984 (Ledwaba et al., 2009). The survey parameters are listed in Table 3.1. The reference datum was Cape coordinates with a Universal Transverse Mercator 35 South (UTM 35) projection (Stettler et al., 1999).

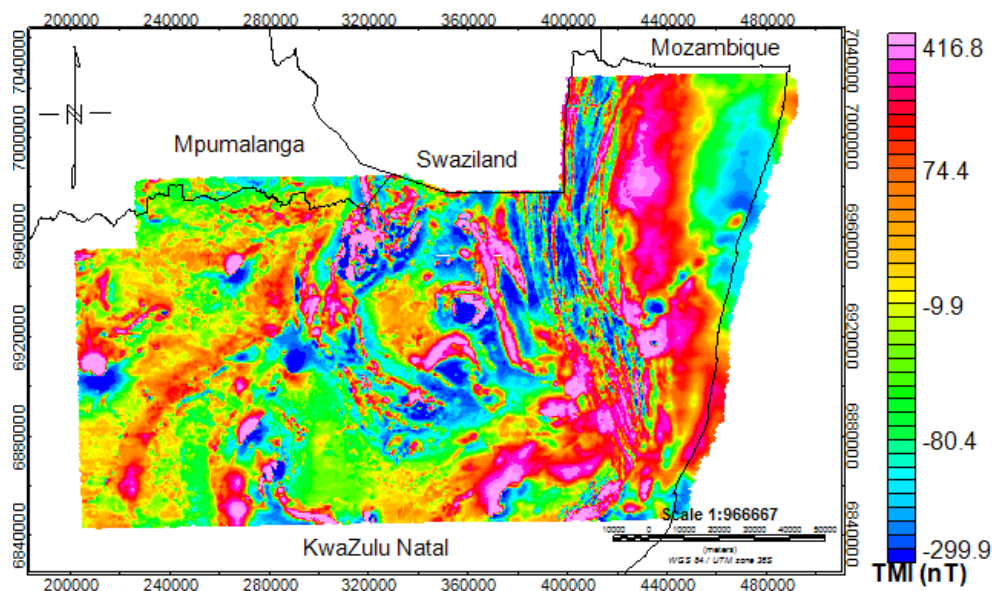


Figure 3-2: The extent of the Karoo 17 block Total Magnetic Intensity (TMI) map with a grid cell size of 250 m, in WGS 84 UTM 36S. The regional trend was removed from the data using Oasis Montaj to get the residual magnetic signal.

Table 3-1: Magnetic survey parameters for the Karoo block 17 were collected as part of the Southern Africa magnetic coverage project (Ledwaba et al., 2009).

Magnetic Survey for Karoo 17 block	
Survey flying height	100 m $\pm$ 15 m
Line spacing	1 km
Flight direction	East-West
Tie line spacing	10 km
Tie line direction	North-South
Flight speed	240 km/h

Gravity Data

The CGS has compiled gravity data for the past 80 years. The point data have variable spacing due to concentration along roads (Webb, 2009). The average spacing is 14 km. The gridded data was cropped to the Karoo 17 magnetic data block, for comparison during data interpretation (Figure 3.3). The Cape reference datum with a UTM 36S projection was used.

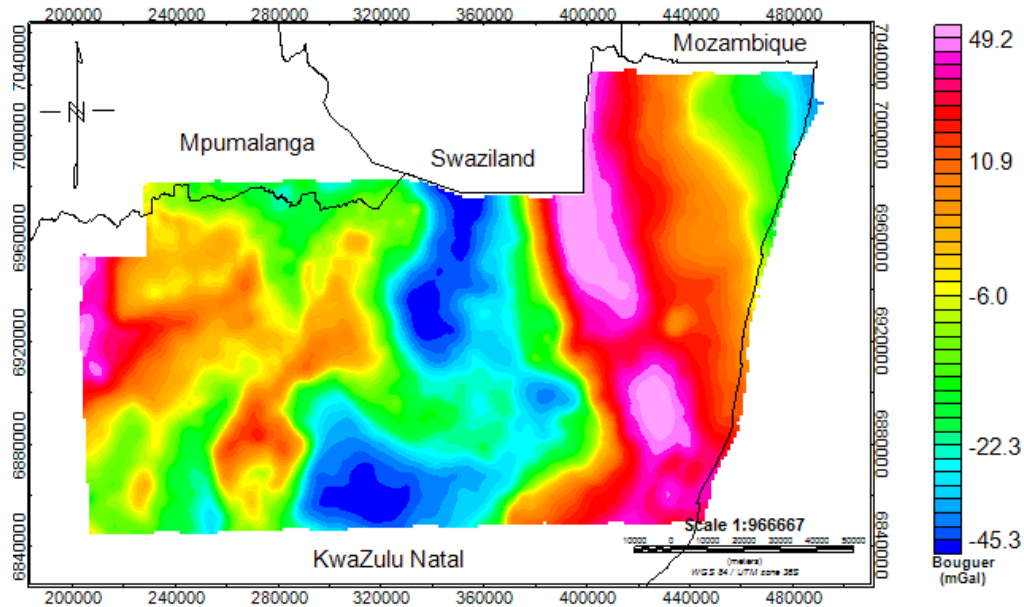


Figure 3-3: Bouguer Anomaly gravity map cropped to the Karoo 17 block of the TMI map in WGS 84 UTM 36 S

Reflection Seismic and Borehole Data

Seismic data

The onshore seismic data in the Zululand Basin were collected in the 1960s by SOEKOR, for oil exploration. The data were provided by the Petroleum Agency of South Africa for this study. The total area coverage of the seismic data is 10 419.1 km². A map indicating some of the seismic lines used in the project are shown in Figure 3.4. The seismic lines were in SEG-Y format, with coordinates in the trace headers used to plot the line on various maps using Geosoft. There were a few inconsistencies with the position and assigning trace headers due to faulty processing. The faulty seismic lines were left out because there were enough lines within the basin to achieve the project's objectives. The survey parameters, recording system, source information, and receiver information (Table 3.2) were taken directly from reports and seismic headers. The reference datum is World Geodetic System 84 (WGS 84) with a projection of UTM 36S.

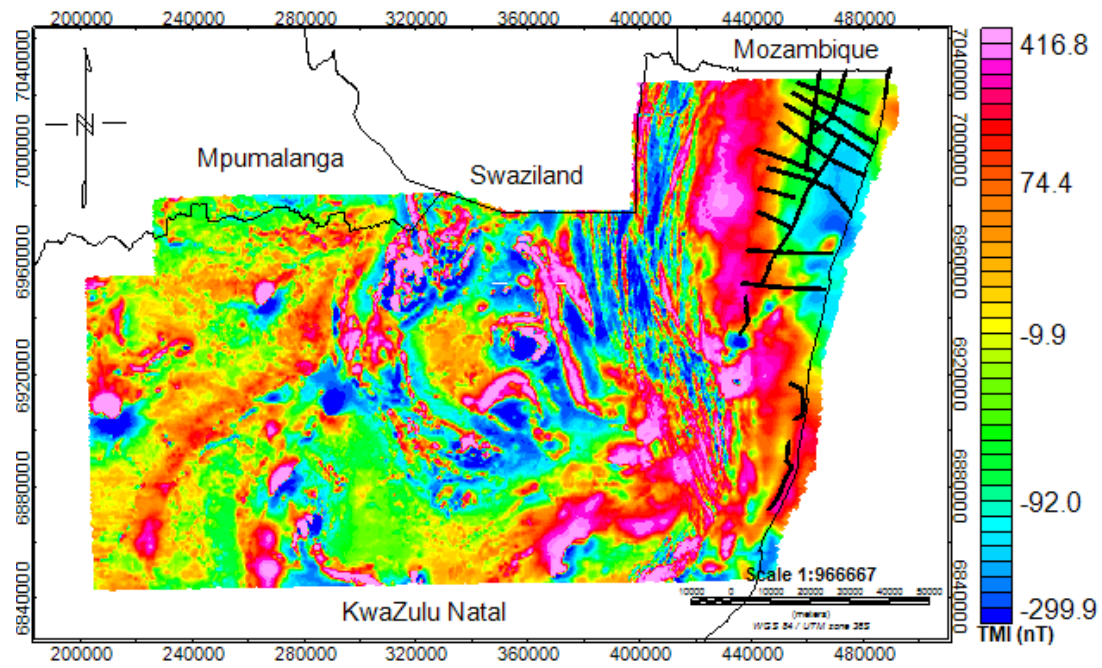


Figure 3-4: TMI map with the position of the seismic lines (indicated in black) in the study, in WGS84 UTM 36S.

Table 3-2: Reflection seismic acquisition parameters for the Zululand Basin data collected by SOEKOR in the 1960s. Unknown information was left blank. The lines displayed in the table are lines that were used in the project, g represents geophones and d represents dynamite.

	G-11-1	G-11-2
Survey parameters		
Type of survey	2D	2D
Total survey length	19.2 km	23.4 km
Offset range	30.5 m	30.5 m
Recording system		
Recording device	g	g
Number of active channels	16 g per trace	16 g per trace
Sampling interval	2 ms	2 ms
Source information		
Energy source	d	d
Receiver information		
Receiver group	5 m	5 m
Geophone type	Vertical component	Vertical component
Shot line angle to receiver line	0°	0°

Borehole data

The boreholes in Zululand Basin were drilled in the 1960s by the state oil company, SOEKOR, during oil exploration. The data were provided by the Petroleum Agency of South Africa. A total of ten boreholes are available (Figure 3.5); however, not all these boreholes intersected the basement or had complete information (Table 3.3). There were no position data available for most of the borehole, and in the case where there was position information, the reference datum and projection were unknown. Therefore, the borehole positions were digitised from the geology map. Thus, the borehole coordinates are listed in Cape datum and Geographic coordinates.

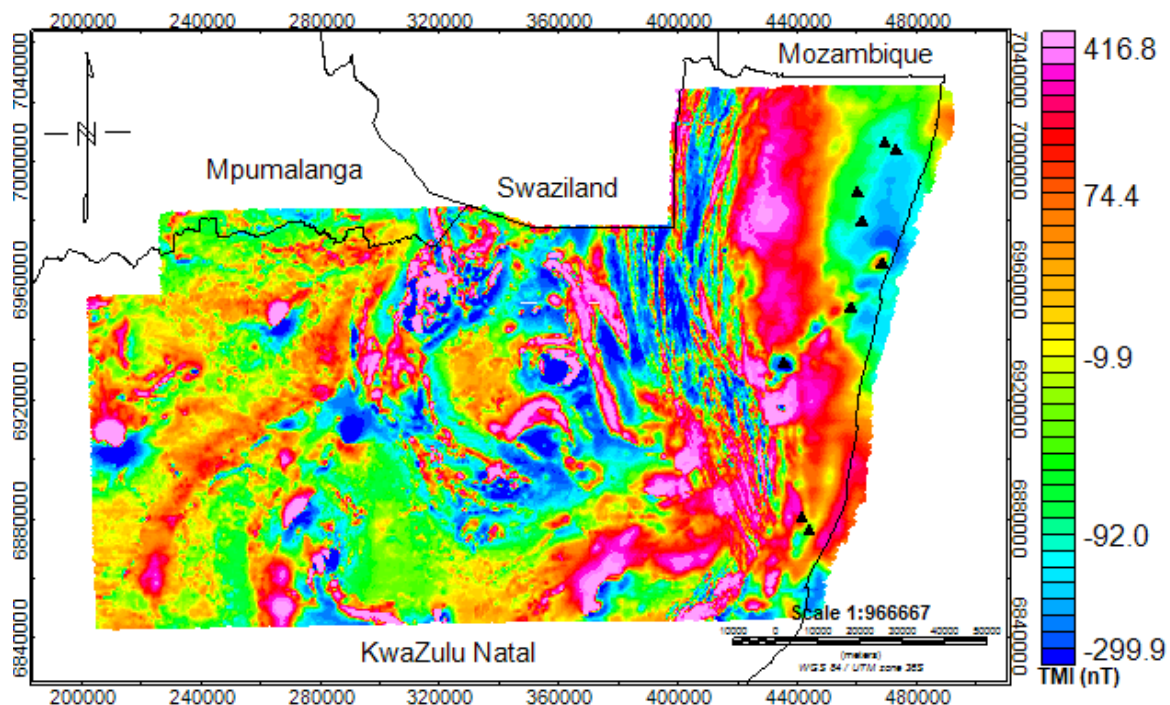


Figure 3-5: TMI map with the borehole positions (black triangles) used in the study in WGS 84 UTM 36 S

Table 3-3: Summary of the ten borehole logs drilled in the Zululand Basin by SOEKOR.

Borehole Name	Lat	Long	Elevation Ground Level (GL)	Elevation Kelly Bushing (KB)	Depth to basement (m)	Apparent dip (°)	Total depth (m)	Basement rock type	Stratigraphic unit
NZA	27°44'05"	32°20'41"			545.59	55	571.2	mylonite agglomerate to	Bumbeni Complex
ZA	27°18'19"	32°36'40"			N/A	10 (@ 1675 m)	1786.13	greywacke	Sandstone
ZB	27°26'00"	32°40'47"			1424.64	50 (@ 1470.97)	1557.53	phenocrysts	
ZC	27°5'30"	32°43'40"	43				2010.16	reddish-brown sediment with irregular talc/serpentine	Siltstone
ZD	27°43'26"	32°27'55"	17.4	20	1052		1071	lava	Bumbeni Complex
ZE	27°04'15"	32°41'09"	72.93	75.39	1867		1900	rhyolite	Jurassic volcanics

ZF	27°15'55"	32°35'49"	80.48	83.08	1914		1921	feldspar mafics	Drakensburg/Bumbeni stage of the Stomberg volcanics
ZG	27°34'11"	32°34'18"			1476		1515	Tuff (@1479) and Lava (@ 1501)	Drakensburg/Bumbeni stage of the Stomberg volcanics
ZH	28°12'26"	32°24'03"	29.9	34.1	973			Acidic lava (@973) and Basaltic lavas (@1150)	Lebombo sequences volcanic (Jurassic volcanic lavas)
ZU	28°14'35"	32°25'13"	1.5	9.7	2015		6083.5	rhyolite (@2015) and basalt (@2010)	Lebombo sequences volcanic (Jurassic volcanic lavas)

4. Methodology

Digitisation of maps and structural features

Several datasets were used in this project, and therefore, it was important to decide on a common datum and projection method. A datum represents a reference system from which a point A can be determined in a specific space B. South Africa has its reference system Hartebeesthoek94 Datum (Hart94), which uses the World Geodetic System 1984 (WGS84) as a reference ellipsoid. This was changed from the widely used Cape Datum in 1999 – a modification of the Clarke 1880 ellipsoid (Department of Rural Development and Land Reform, 2013). When the Hart94 is compared to the widely used WGS84, there is a variation in the position measurement on a standard GPS, namely, 0.3 m on the x value and 0.2 m on the y value (Department of Rural Development and Land Reform, 2013). The software used, such as Geosoft and ESRI ArcGIS, has provisions for both datum reference systems. WGS84 datum was selected for this study because it is commonly used. To measure distances accurately and efficiently, data is usually projected using the UTM projection method. The UTM method separates the Earth into 60 zones from east to west. The UTM projection transforms geographic coordinates onto a plane. Each easting and northing value within a zone represents a distance from the start point of zone one (DiBiase and Dutton -accessed 09 August 2020). The study area falls into the UTM 36S Zone. The final reference coordinate system chosen was WGS84 UTM 36S for the integrated interpretation of the data.

To ensure that the data were transformed correctly into the WGS84 UTM 36S, a base map was created using ArcMap. The base maps contained an outline of the world coastlines, cropped to the study area and downloaded from the Geosoft Seeker tool. Seeker is a tool that allows one to download spatial data stored on the Geosoft DAP servers (Geosoft Inc., 2014). The geology maps that were georeferenced and digitised in Clarke 1880 were transformed to the coordinate system used in the project and superimposed over the geology maps. The coastal boundaries of the maps were confirmed to coincide with the coastline boundaries of the geology map shapefile (Figure 4.1a). The second layer superposed onto the base map was the magnetic

data; the magnetic data appeared to pass the eastern coastline boundary (by a range between 3-6 km) (Figure 4.1b), which was assumed to be due to the aircraft turning when the data were collected. The third layer that was superposed onto the base map was the gravity grid. This grid was cropped according to the magnetic grid to focus on the study area; however, it did not extend 3-6 km past the coastal boundary but coincided with the coastal boundary because it was a ground survey (Figure 4.1c). To ensure that the seismic lines were in the correction position, borehole positions were digitised from the geology maps. Seismic lines that intersected the boreholes were compared to see whether they were plotting in the correct position. The borehole position and seismic data coincided (Figure 4.1d); using this premise, it was inferred that all other seismic lines were in the right place.

This process aimed to ensure that the transferred coordinate systems were done correctly, allowing for an accurate interpretation without introducing errors.

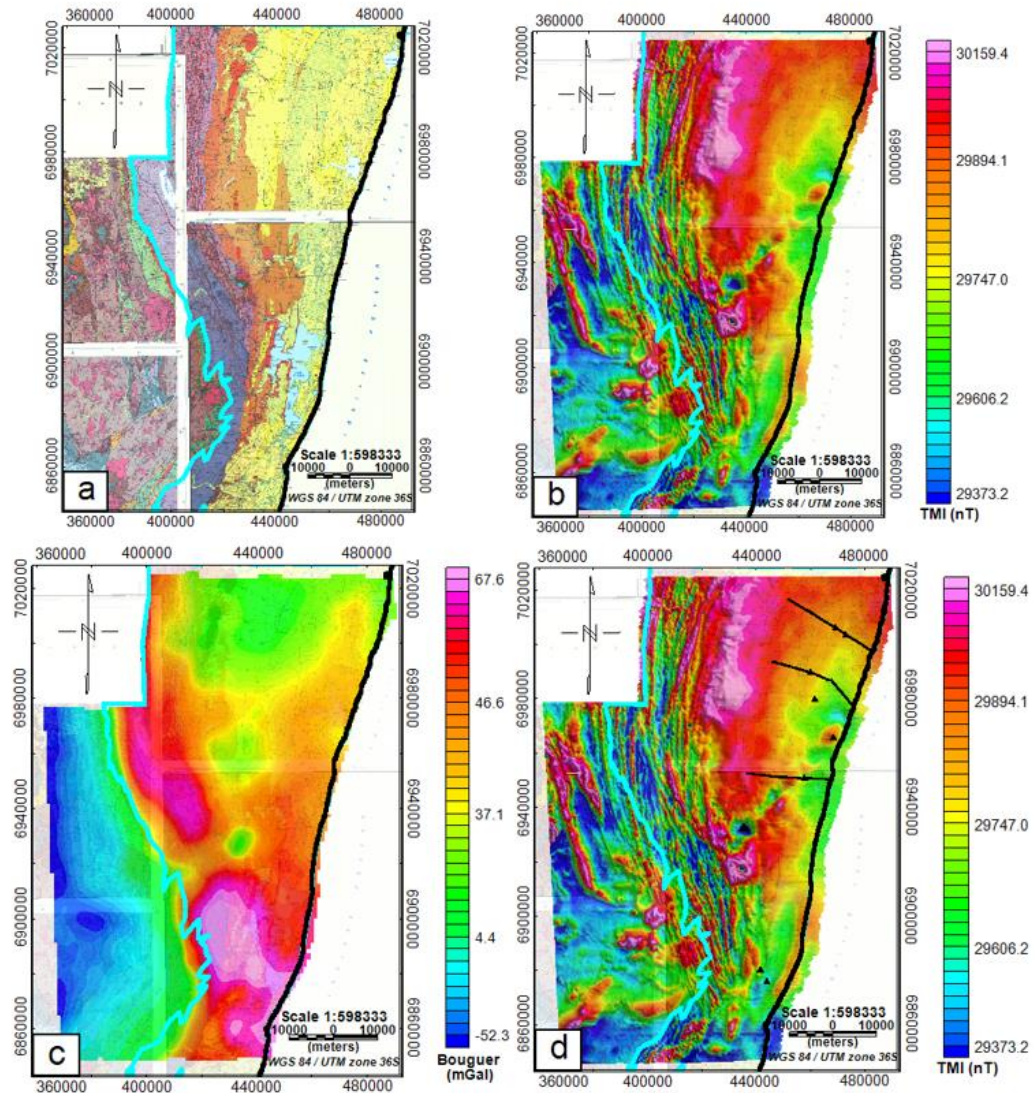


Figure 4-1: Geological and Geophysical data over the study area: (a) 1:250 000 geology map (b) Total Magnetic Intensity (TMI) map overlain the geology map (with 80% transparency). (c) Bouguer map with the geology map overlain (with 80% transparency). (d) TMI map with triangles indicating all boreholes in the study area and the black lines indicate the seismic lines that were being correlated. The coastlines are represented in black on the eastern edge of the study area, and the blue line represents the western edge of the study area.

Geological data

The (1:250 000) geological maps, provided by the CGS, were received as .tiff images and were imported into ArcGIS as raster data. These maps were digitised to their original datum (Clarke 1880). To do this, the intersection point between the latitude and longitudes values were located and marked as control points in ArcGIS, and their

values were entered. ArcGIS requires a minimum of 4 points to georeference an image (Environmental Systems Research Institute, 2016). The four edges of the map were selected to include all the data. Each geological feature was digitised by creating a shapefile that outlines the boundaries. These were put together to form a geological map of the study area. The colour bar representing each shapefile was approximated as closely as possible to the geological maps' colour bar. Additional structural points were marked along the Lebombo rhyolite layer, which indicated the extent of the dip and the direction across it. Prominent features such as the Bumbeni Ridge and regional faults from Chabangu et al. (2014) were digitised as shapefiles.

Potential Field data

Data gridding and regional trend removal

The data was received in a Geosoft database file format. When imported into Geosoft, the database had a preselected X (longitude) and Y (latitude) value, with a reference coordinate system in Cape Datum. The TMI column was marked as "final", indicating that the data were processed from the raw data by removing terrain effects and levelling. There were two options for gridding data: minimum curvature and kriging in Geosoft. Both provided similar resolution and smooth grids however, minimum curvature provided a result at a faster computing time, all data were gridded using minimum curvature. The recommended cell size for the gridding algorithm is a quarter of the line spacing. Therefore, with magnetic data having a 1 km line spacing, a grid cell size of 250 m was chosen. Once the data were gridded, a TMI grid was produced. The gridded data were cropped to a smaller region to focus on the study area's features.

Measured TMI data are a superimposed response from different geological features of varying susceptibility and depth. Deeper sources depth have a longer wavelength as opposed to those at a shallower depth. Due to the Earth's regional magnetic field, shallower depths may be masked (Dentith and Mudge, 2014). The regional field of the gridded data was removed to obtain the residual data, which was a better

representation of the geology in the study area. A trend removal was used in Geosoft, where the regional field was removed using a linear least square fitting algorithms by Cooley and Tukey (1965) and Winograd (1978). Figure 4.2 indicated the effects of removing the regional trend (shown by the arrows).

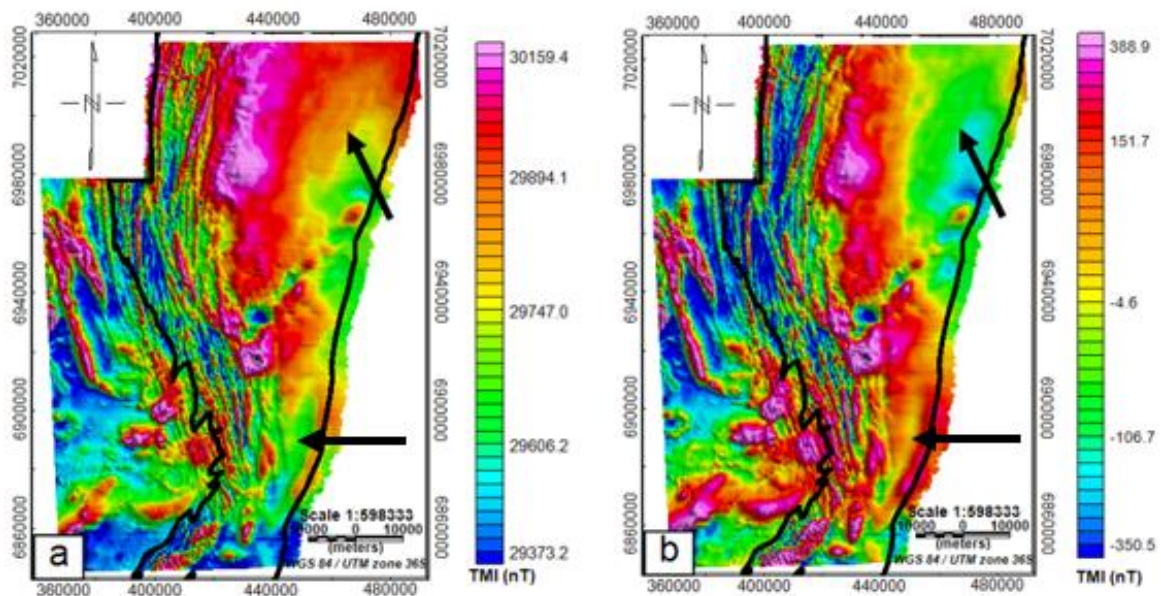


Figure 4-2: TMI map without the regional trend removed. (b) TMI with the regional trend removed (residual field). The arrows indicate the effect of the regional trend that has been removed.

Reduction to Pole

Due to the Earth's inclined magnetism in areas away from the poles, there is an offset between the centre of the body and the peak of the anomaly, that is, magnetic anomalies are not located directly above their source (Roest et al., 1993). This causes an asymmetric anomaly over geological features, making it difficult to correctly interpret the data. To correct this effect, the reduce to the magnetic pole (RTP) filter is used in Geosoft. Reduction to pole is the process of transforming the Earth's inclined magnetic field into a vertical field, similar to what would have been recorded at the

Earth's poles. This produces a symmetric anomaly over geological features. The area's inclination and declination were calculated using the International Geomagnetic Reference Field (IGRF) to reduce the data to the pole. The IGRF is a series of mathematical models to describe the Earth's magnetic field between 1900 A.D. to present (Thébault et al., 2015). The IGRF calculation in Geosoft requires the survey date, latitude and longitude channels. The survey was done over three years (between 1981 and 1983), but by looking at the database most of the lines were flown in 1981/12/31 (YYYY/MM/DD). Using the inclination and declination calculated from the IGRF, a reduce to pole filter was created, this was applied to the data. The only problem with this filter is that it assumes that there is no remanence present in the data. The effects of remanence can be seen by the marked arrows where there is no significant variation or change in gridded data after the RTP filter was applied (Figure 4.3). The algorithm used by Geosoft is:

$$L(\theta) = \frac{[\sin(I) - i \cos(I) \cdot \cos(D - \theta)]^2}{[\sin^2(I_a) + \cos^2(I_a) \cdot \cos^2(D - \theta)] \cdot [\sin^2(I) + \cos^2(I) \cdot \cos^2(D - \theta)]} \quad (4-1)$$

If $(|I_a| < |I|)$, $I_a = I$

Where I is the geomagnetic inclination in degrees, D is the geomagnetic declination in degrees, I_a is the inclination for amplitude correction (never less than I), and θ is the wavenumber.

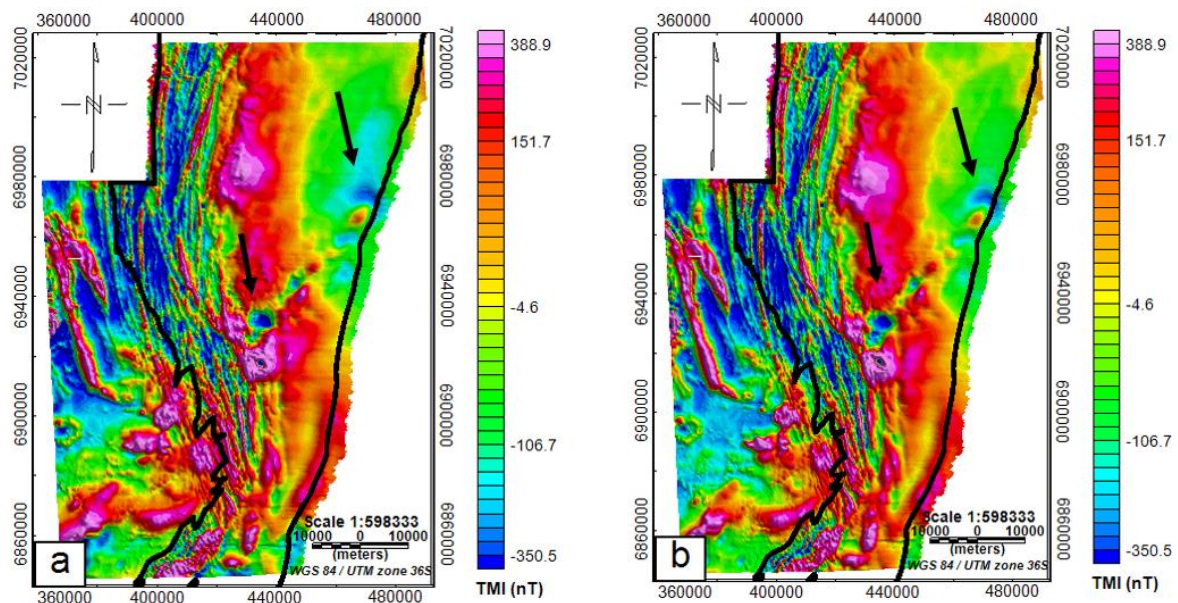


Figure 4-3: (a) Residual TMI grid. (b) Reduction to Pole (RTP) filter applied to the residual TMI grid. The arrow indicate an example of a remanent anomaly. The applied RTP filter did not change the orientation of the magnetic anomaly.

Vertical derivatives, Analytic Signal, and Tilt Derivatives

Filters are commonly used to enhance data and obtained the desired result by eliminating unwanted signals (Isles and Rankin, 2013). Three filters were used: vertical derivative, analytic signal, and tilt derivative; each filter exposed different aspects of the study area to allow for an extensive quantitative interpretation.

The first vertical derivative filter (Figure 4.4b) is an effective filter to highlight shallow features (high frequency) that have significant contrast with its surrounding (Cooper and Cowan, 2004). This filter is considered a high-pass filter and tends to increase the noise in the data. Due to the data's resolution, only the first-order vertical derivative was used rather than higher-order derivatives (Isles and Rankin, 2013).

The analytic signal (Figure 4.4c) is effective for data with remanent magnetisation (Salem, 2005). This filter is independent of the direction of magnetisation and the Earth's field (Keating and Sailhac, 2004), allowing us to study possible contacts of geological features. Thus, resulting in a ridge/signal formed over a vertical contact or a slightly displaced ridge over a dipping a contact (Dentith and Mudge, 2014). This filter was used to compliment the edge detection filters (first vertical derivative and tilt derivative) on determining the extent of the Lebombo sequence and to understand the Bumbeni Ridge.

The analytic signal equation is expressed as:

$$AS(x, y) = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + \left(\frac{\partial f}{\partial z}\right)^2} \quad (4-2)$$

Where f is the magnetic field.

The tilt derivative (Figure 4.4d) is a widely used to determine the depth to magnetic sources in an area (Li, 2006). However, it was also used to as an edge detection filter.

The tilt derivative filter is useful because it acts as an Automatic Gain Control filter (AGC). An AGC normalises the anomaly to display shallow and deep features (Beamish, 2012). Therefore, all the elements were amplified.

The tilt derivative equations is expressed as:

$$TDR(x, y) = \tan^{-1} \left[\frac{\frac{\partial f}{\partial z}}{\sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2}} \right] \quad (4-3)$$

Where f is the magnetic field.

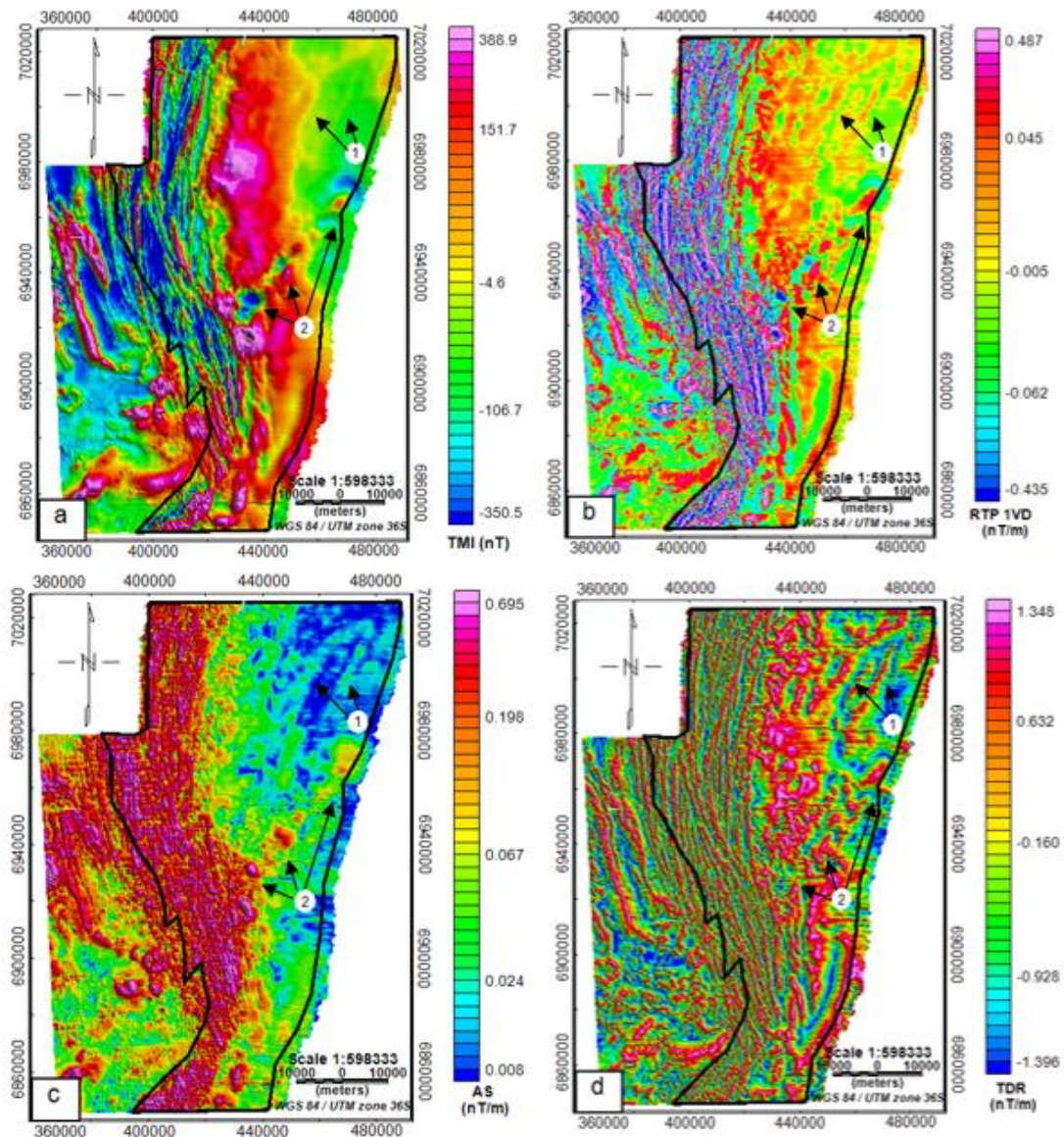


Figure 4-4: (a) Pole reduced TMI data, with the following filters applied: (b) First order vertical derivative filter, the linear features (1) are not present on the TMI data. The Bumbeni ridge (2) can be seen to vary as you move from the south-west direction to the north-east direction. (c) Analytic signal, the linear features (1) can be seen and the signal is symmetric over the Bumbeni ridge (2) compared to the pole reduced TMI data – showing that it is independent of remanence. (d) Tilt derivative (TDR), the lineaments (1) which are deeper features in the study area are well defined, although not all features are well defined, like the Bumbeni ridge (2).

Forward Modelling and Inversion

The difference between forward and inversion modelling is the amount of human interaction to reduce the difference between the observed and calculated response (Dentith and Mudge, 2014). Forward modelling involves the user iteratively adjusting the parameters such as the physical properties, shape, orientation and depth of a body to reduce the difference between the observed and calculated response (Isles and Rankin, 2013). In contrast inversion is an automated process that begins with a start-up model and systematically modifies many of the same parameters, but with minimal human intervention to achieve a similar result of reducing the difference between the observed and calculated response.

Forward modelling

Python geoscience modelling and interpretation (PyGMI) software (Cole, 2014) was used to model the profiles of the area. PyGMI is an open-source software package (Cole, 2014). The software divides the modelling area into a three-dimensional grid. PyGMI Potential Field Modelling was created to output 3D model data but, in this study, it was used for profile modelling.

The main aim was to model the first two layers of the Lebombo sequence, that is, the Jozini and Sabi River Basalts. This was to understand the contact between the basement and the overlying Zululand Basin and how it varied as one moved from west to east.

The following field parameters were used, calculated from the IGRF: declination: -17.0, inclination: -63.5, and magnetic field intensity (nT): 30 000. Two profiles were selected, one in the northern part and one in the southern part (Figure 4.5)

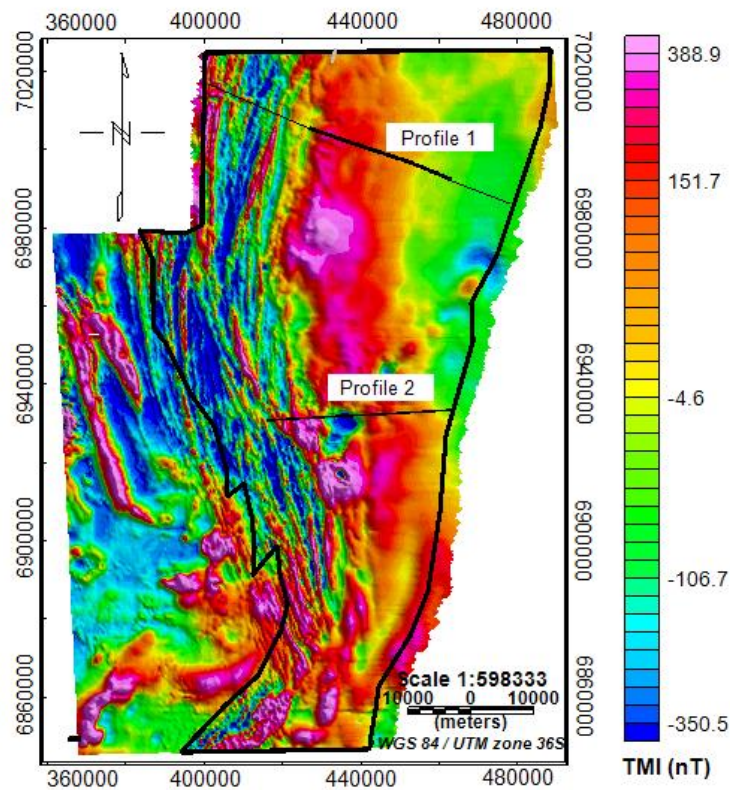


Figure 4-5: Pole reduced TMI map with two profiles that were modelled using PyGMI . Profile 1 was selected because it could be constrained using the seismic lines, G-11-1 and G-11-2, indicated in bold along the profile. Profile 2 was selected to see the interaction between the intrusion causing the anomaly and the surrounding area. Profile 2 did not have any seismic lines to constrain the model.

Profile 1 in the northern part of the basin model can be partially constrained using reflection seismic data from lines G-11-1 and G-11-2 shown in bold in Figure 4.5. These seismic lines are adjacent to one another and do not cover the entire profile, so the areas not covered by the seismic lines were extrapolated and modelled to fit the observed data. Profile 2 in the southern part of the basin could not be constrained due to no seismic lines being available in the area, but the intrusions were inferred from the inversion that will be mentioned later in this chapter.

To model the profile, magnetic residual data, digital terrain model (DTM) data, and the geology map of the study were imported into PyGMI. The DTM data was taken from

Geosoft Seeker using the Shuttle Radar Topography Mission data. The steps followed will be detailed below:

Step 1: Imported the data that will be used to model, that is, DTM and magnetic data imported as raster data, and the geology map imported as a tiff. The extent of the area was determined according to the magnetic data, which in turn defined the number of rows, columns, and layers in the model. Models larger than 100x100x100 are slower to process, depending on the hardware. In this case, the furthest the model was extended was 500x500x100 due to the laptop's processing capabilities (Figure 4.6).

Model Extent Parameters

Current Model: Profile_2_v14-test_norm_incl_decl.npz

Dataset Information

DTM Dataset: Band 1 Profile_2_dem

Magnetic Dataset: Band 1 Profile_2_res

Gravity Dataset: None

Gravity Regional Dataset: None

Other: None

Model Extent Properties

Get Study Area from following Dataset: Band 1 Profile_2_res

Upper Top Left X Coordinate: 400000.00 Columns (X): 138

Upper Top Left Y Coordinate: 6942919.33 Rows (Y): 61

Upper Top Left Z Coordinate (from DTM): 549.44 Layers (Z): 10006

Total X Extent: 69000.00

Total Y Extent: 30500.00

Total Z Extent (Depth): 1000648.44

X and Y Cell Size: 500.00

Z Cell Size: 100.00

HELP! 0% Apply changes (reset calculations) No changes

Figure 4-6: PYGMI model extent parameters used for modelling using Profile 2

Step 2: To ensure that the area was modelled as closely to the outcropping geology as possible, the distance where each layer would change on the geology map, in the layer window, was mapped into the profile window (Figure 4.7).

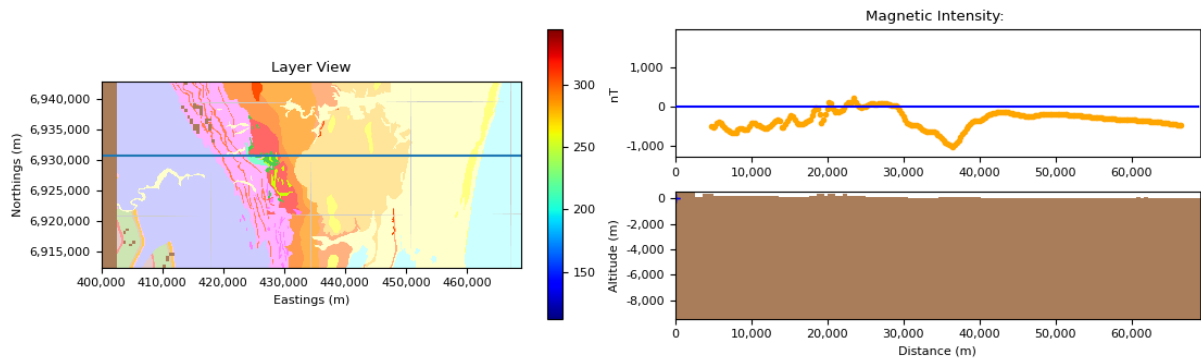


Figure 4-7: The window on the left shows the layer view, in this case the geology around Profile 2, the Easting and Northing in UTM 36S. The blue line shows the profile area being modelled. The window on the right shows the 2D profile. The orange line shows the observed data and the blue line will be the calculated data. The brown area beneath the profile signal will represent the sediments as the background with no susceptibility values. The negative altitude is the depth of the profile.

Step 3: Lithologies were created based on the geology map (sediments, Jozini Formation, Sabie River Basalt Formation, and the Jozini intrusions) and those not shown were labelled as anomaly 1 and anomaly 2.

Step 4: The area was modelled by varying the susceptibility, depth, and dip and the lithologies. The PyGMI Potential Field module was created for 3D modelling and does not assume that the profile extends infinitely perpendicular to the profile line. To mimic a 2.5D model, the lines were copied across multiple lines (Cole, 2014). Physical property data was checked on the borehole reports and requested from recent studies done at CGS on boreholes within the area, but no data was available.. Values were inferred from places near the study area and for other formations general values were used.

Table 4-1: Range of susceptibility values (SI) from other studies of physical properties (Mare, 2012). * Value used from the inversion modelling. ** Value significantly higher than expected range.

Geological unit	Susceptibility range (SI)	Reference	Susceptibility values used
Dolerite dykes	0.0013 – 0.0226	Mare et al., 2022	0.0900**
Bumbeni Complex	Not available	N/A	0.0721*
Jozini Rhyolites Formation	0.000250 – 0.0380	Hunt et al., 1995	0.00331
Jozini Rhyolite intrusions	0.000250 – 0.0380	Hunt et al., 1995	0.00452
Sabie River Basalt Formation	0.0025 – 0.0160	Hunt et al., 1995	0.0152

Inversion modelling

Two inversion software were used, each one serving a different purpose. The first was the University of British Columbia Geophysical Inversion Facility Tools (UBC-GIF Tools) software. This software provides physical property models that explain the observed data, helping to locate anomalies within an area (Williams, 2006). However, UBC-GIF tools provide less information about the spatial distribution, mainly the depth and vertical extent. This was supplemented with ModelVision, which offers better control over the inversion being performed. ModelVision uses shapes to start the inversion and inverts on parameters such as depth, vertical extent, vertices, and physical properties. Below is a description of how data was prepared and the controlled parameters for each inversion software.

UBC-GIF Tools

UBC-GIF Tools uses three main types of data to carry out an inversion. The first is the residual observed data with uncertainties assigned to the data. The residual data are a standard requirement for the inversion, and the uncertainties act as error bounds for the model. The data were prepared using Geosoft VOXI (referred to as VOXI) due to its efficiency. The VOXI option can calculate the regional IGRF, optimise data for inversion, and create error bounds. Due to the complicated magnetic signature of the Bumbeni Ridge, the study was separated into two sections (Figure 4.8). The first section is the southernmost anomaly of the Bumbeni Complex, and the second section is two of the northern anomalies of the Bumbeni Complex.

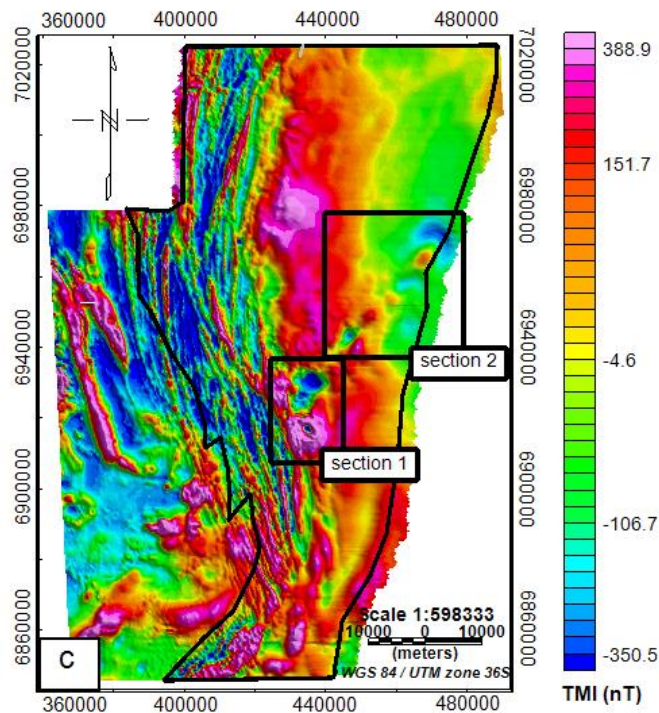


Figure 4-8: Residual TMI data with Bumbeni Ridge separated into two sections for modelling purposes.

A polygon was created for each area of focus using Geosoft. The data was imported into the VOXI project. A mesh was created arbitrarily to complete the process. The data was then optimised to have 10 data points per mesh cell. The data were gridded and compared to the original grid to ensure no valuable information was lost from the

optimisation. The regional trend was calculated and removed from the data. VOXI uses a linear trend plane (Equation 4.4). The IGRF was calculated, and lastly the error bounds were calculated with the option provided to use absolute or relative error. There was no noticeable variation in the run time and results of the UBC-GIF Tools inversion when between each error type. Therefore, an absolute error was chosen, and the error was calculated for each data point. The VOXI data was automatically saved as a Geosoft database, which was exported as a CSV file.

The data were imported into UBC-GIF Tools. Each of the following were assigned to their respective headers: the residual data, uncertainty/ error bounds, and topography data. A mesh was created with a general rule of thumb that the core mesh parameters (the mesh cells that sit directly beneath the observed data) were half of the line spacing. The depth of investigation was half of the longest length of the survey area (to allow for a deeper magnetic material to be modelled) (University of British Columbia, 2013). The padding was then varied throughout the different inversion sessions that were run. Due to the presence of remanence in the study area, a Magnetic Vector Inversion was used.

$$aX + bY + c = 0 \quad (4-4)$$

Where c is the intercept, a is the x slope, b is the y slope, X is the x origin, and Y is the y origin.

ModelVision

To accurately compare the inversion software, the data used in the UBC GIF tools inversion was used in ModelVision. With the same data used, the core parameters (datum, projection type, projection zone, and magnetic field parameters) were kept the same. A project was created in ModelVision and the core parameters were inputted. In the presence of remanence, ModelVision requires a two-step process to invert data. The first step was to invert the analytic signal data; from this step, the following were extracted: the anomaly's susceptibility, depth, position of the anomaly, and vertical

extent. The second step was to invert TMI data that was RTP. Each step will be detailed below.

Step 1: Analytic signal data was imported in the format of a Geosoft XYZ file. The parameters that were used were: X, Y, elevation, line data, and analytic signal. An elliptical pipe was chosen as the shape for the starting model because it best represented all three anomalies (Figure 4.9). The inversion was run to approximate the susceptibilities, depth extent and depth. Once a good approximation was achieved, using available borehole data as a constraint on the depth, the shape was updated into a frustum (Figure 4.10). The frustum is similar to an elliptical pipe but offers the ability to invert on points along the edge of the shape. The inversion was run again while using the process of trial and error to get a reduced RMS error while maintaining realistic values for the parameters being inverted.

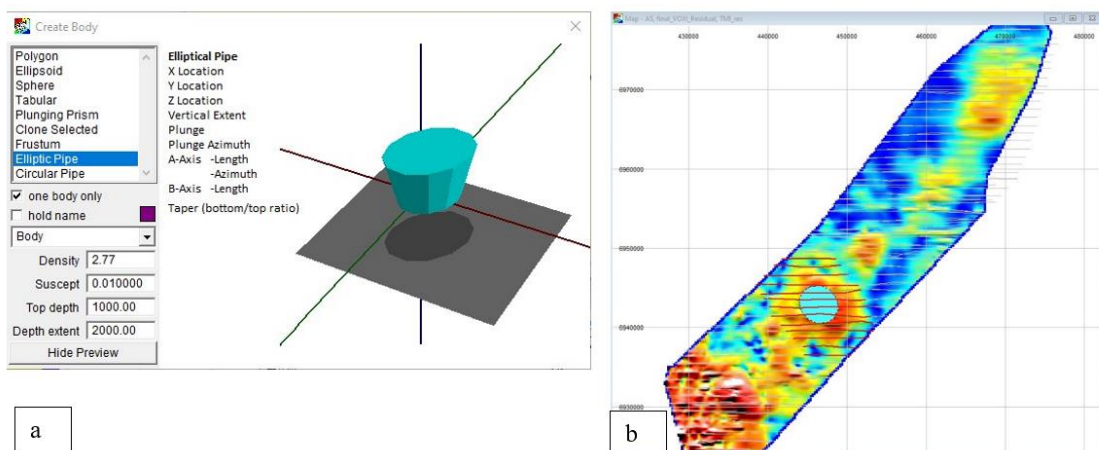


Figure 4-9: (a) ModelVision processing, elliptical pipe chosen and some of the parameters that can be converted for. (b) The elliptical pipe over the central body on an analytical signal crop of the Bumbeni Complex

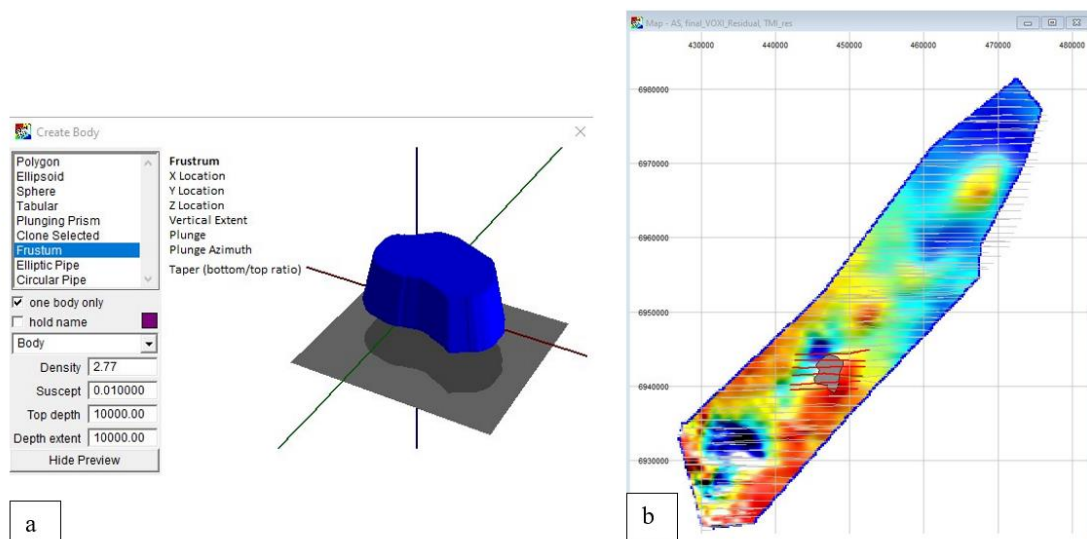


Figure 4-10: (a) ModelVision processing, frustum chosen and some of the parameters that can be converted for. (b) The frustum over the central body on an analytical signal crop of the Bumbeni Ridge.

Step 2: Once completed the pole reduced TMI was imported using the same core parameters as the analytic signal data. The results of the final inversion from the previous sub-step are kept the same. The inversion was run on the remanent parameters only until the RMS was error was reduced. These steps were repeated for the rest of the anomalies. Once completed these shapes were imported as dxf files to be viewed in any 3D model viewer in Oasis Montaj.

Seismic Interpretation

Seismic lines G-11-1 and G11-2 were interpreted to assist with the forward modelling in the area. There was no borehole intersecting these lines or borehole parameters. To approximate the intersection between the Lebombo sequence and the Zululand Basin on the seismic lines, a synthetic seismogram was created using a programme written by Westgate in 2017 from the University of the Witwatersrand. The software simulates seismic reflection data by stacking the velocity data. The depth and associated average velocity were taken from the well velocity survey of the ZU borehole, the deepest borehole in the area that was drilled into the Jozini Rhyolite and

the Sabie Rivier Basalts. A high-level interpretation of the seismic lines was done at the interface between the Zululand Basin and Jozini Rhyolite. To get the depth from the two-way travel time (TWT), I used a TWT vs Depth graph of the ZU borehole. Although the borehole does not intersect the seismic lines G-11-1 and G-11-2, an assumption was made that the boundary between the Lebombo volcanic sequence and the Zululand Basin was the same throughout the study area. This may not be the most accurate solution, but it was enough to give an approximation of the depth of the volcanic sequences.

5. Results and Interpretation

Regional

The entire study area consists of four significant magnetic signals. The outcropping Lebombo sequence has a significantly different magnetic signature than the rest of the basin. The Lebombo sequence is characterised by short wavelength anomalies and the Zululand Basin is characterised by long wavelength anomalies on the TMI map (Figure 5.1 (a)). The Lebombo sequence can be differentiated from one another, namely the Jozini Rhyolites and the Sabie River Basalts, not by their magnetic signatures but by the change in the strike, which will be further explained in the next section (direction arrows, Figure 5.1 (a)) (explained in the next section). The Jozini Rhyolite Formation can be further extended eastwards towards the Zululand Basin. This can be seen by comparing the geology shapefiles to the TMI signal (double-sided arrow, Figure 5.1 (b)). This is due to the Zululand Basin filling eastwards of the Lebombo sequence, which prevented the further mapping of the Lebombo sequence below the cover.

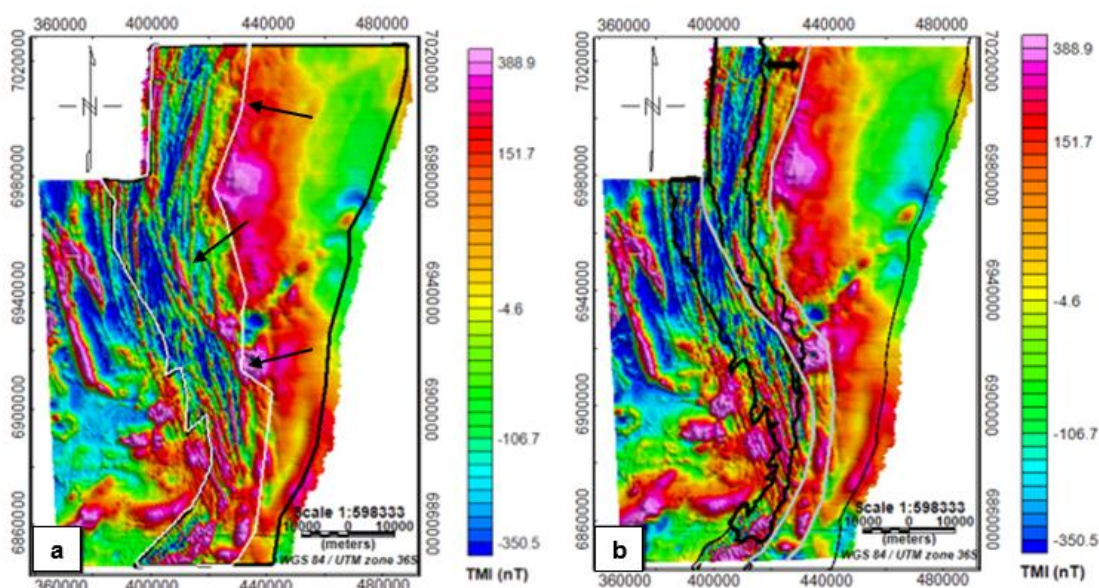


Figure 5-1: (a) Extent of the Lebombo sequence based on the interpretation of the TMI map (white boundary line). The directional arrows show the change in strike from the as one moves south from the Jozini Rhyolites to the Sabie River Basalts. (b) Originally mapped extent of the Lebombo volcanic sequence from the geology map vs the extent mapped using the TMI map, the difference is shown by the double sided arrow.

The start of the basin fill can be seen in the TMI map (Figure 5.1(a)) from the abrupt change in the wavelength of the signal, implying a significant vertical burial of the Lebombo sequence (Isles and Rankin, 2013). The Lebombo sequence dips eastwards underneath the basin fill (Du Toit, 1929). Further interpretations can be made from filters derived from the TMI map (Figure 5.2 (a)). The burial of the Lebombo sequence can be seen on the first vertical derivative (Figure 5.2(b)) and on the analytic signal (Figure 5.2 (c)), where there is a variation in the signal showing a decrease in the signal strength as you move further to the east and a change in wavelength of the signal (shown by the arrows). The tilt derivative filter, which amplifies the deeper signal, indicates that there are linear structures (shown by the arrows) that trend NE-SW (Figure 5.2 (d)). These linear structures could be evidence of the block faulting in the northern and central parts of the Lebombo sequence described by Watkeys (2002).

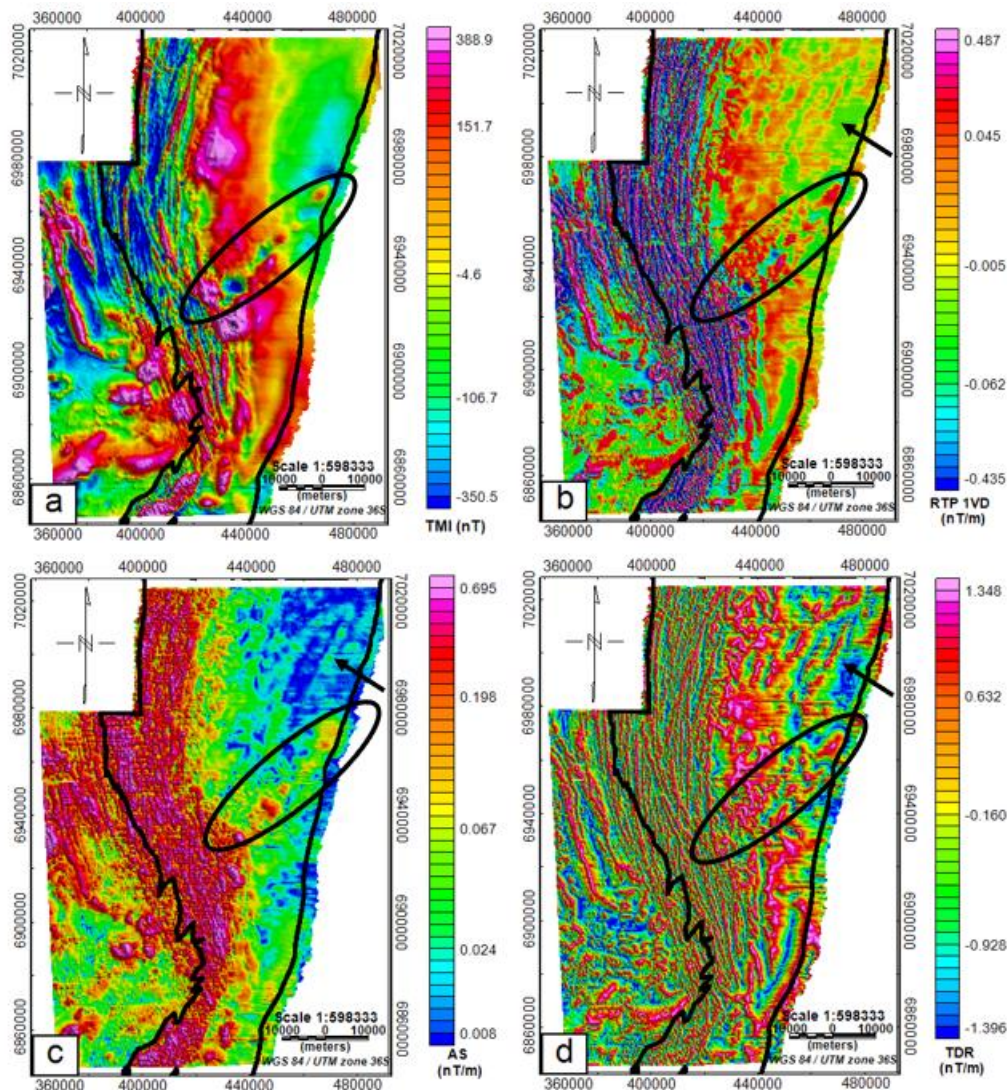


Figure 5-2: (a)TMI map - which maps (b - c) are derived from. (b) First vertical derivative. (c) Analytic signal. (d) Tilt-derivative. The arrows indicate the variation in signal from the outcropping Lembo sequence to the west and the area filled by the Zululand Basin. The ellipse shows the Bumbeni Ridge outline.

The Bumbeni Ridge can be mapped from the exposed area to the east of the outcropping area as a linear feature with a NE orientation cutting the Zululand Basin into two (indicated by the ellipse in Figure 5.2 (a-c)). The Bumbeni Ridge can be mapped into three distinct features. The first feature, marked 1, is a symmetrical magnetic low anomaly. The second and third features, marked 2 and 3, respectively, have dipolar anomalies (Figure 5.3). Anomaly 2 has a positive component on the

southern side and anomaly 3 has a positive component on the south-east side Figure 5.3 (a)). These anomalies imply that these three features were intruded/emplaced at different times. This feature also shows signs of a strong remanent magnetism from its symmetrical magnetic low. The presence of remanent magnetisation will affect the forward modelling process because there is a myriad of variations of strength and directions of the source magnetism that can fit the observed data (Dentith and Mudge, 2014; Lockhart et al., 2004). The residual Bouguer gravity map was investigated (Figure 5.3 (b)). The only feature of the Bumbeni Ridge that appears prominent on the residual Bouguer gravity map is anomaly 1.

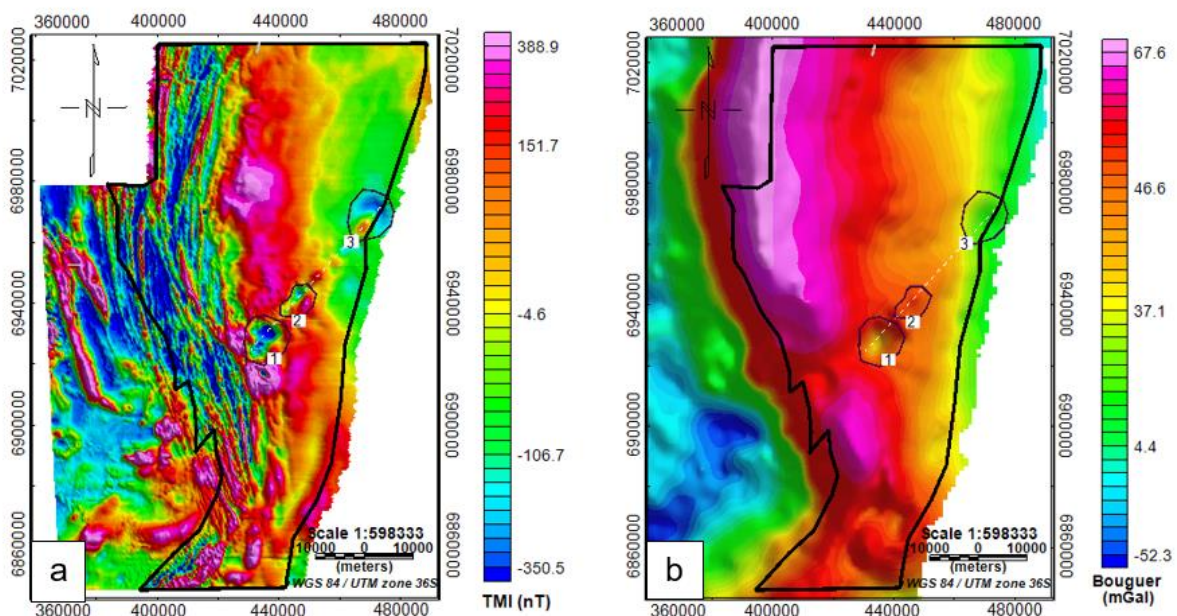


Figure 5-3: (a)TMI map with the three major Bumbeni Ridge anomalies marked by the polygons and the extent of the Bumbeni Ridge marked by the dashed white line. (b) Residual Bouguer gravity map with the three major anomalies marked, and the strike of the anomaly (white dashed line).

Lineaments

The Lebombo sequence belt can be characterised by lineaments to the west of the Zululand Basin. These lineaments were mapped using edge detection filters like the first vertical derivative (Figure 5.4 (a)) and the tilt depth derivative (Figure 5.4 (b)). The lineaments can be separated into three parts (Figure 5.4 (c)). The first is in the northern

section of the study area, which consists of predominantly NNE-SSW and NS trending lineaments covering the Jozini formation and parts of the basin (Figure 5.5 (a)). The second in the central and southern section of the basin consists of predominantly NNW-SSE trending lineaments covering the main part of the Sabie River Basalts (Figure 5.5 (b)). The third section is the bottom part of the Sabie River Basalts trending NNE-SSW (Figure 5.5 (c)). There have been multiple dyke injections in the Lebombo sequence (Saggerson and Bristow, 1983; Bristow and Cleverly, 1983; Gomez, 2001). The variation in shape (Figure 5.5 a-c) could represent the possible edge of the southeastern side of the Kaapvaal craton. This was inferred from Watkeys (2002), who stated that the northern part of the Lebombo sequence coincided with the termination of the Kaapvaal craton and the start of the Limpopo belt. The lineaments could be caused by the Rooi Rand dyke swarm extending eastwards, this swarm is sub-parallel to the Lebombo sequence and has geochemical links with Sabie River Basalt and Jozini Rhyolites (Meth, 1996). Alternatively, this could also be due to the feeder dykes or other dolerite dykes in the area. Saggerson and Bristow (1983) and Watkeys (2002) indicate that the Rooi Rand dyke swarm only intruded and terminated the west of the Lebombo sequence and did not affect the basalt and rhyolites layers.

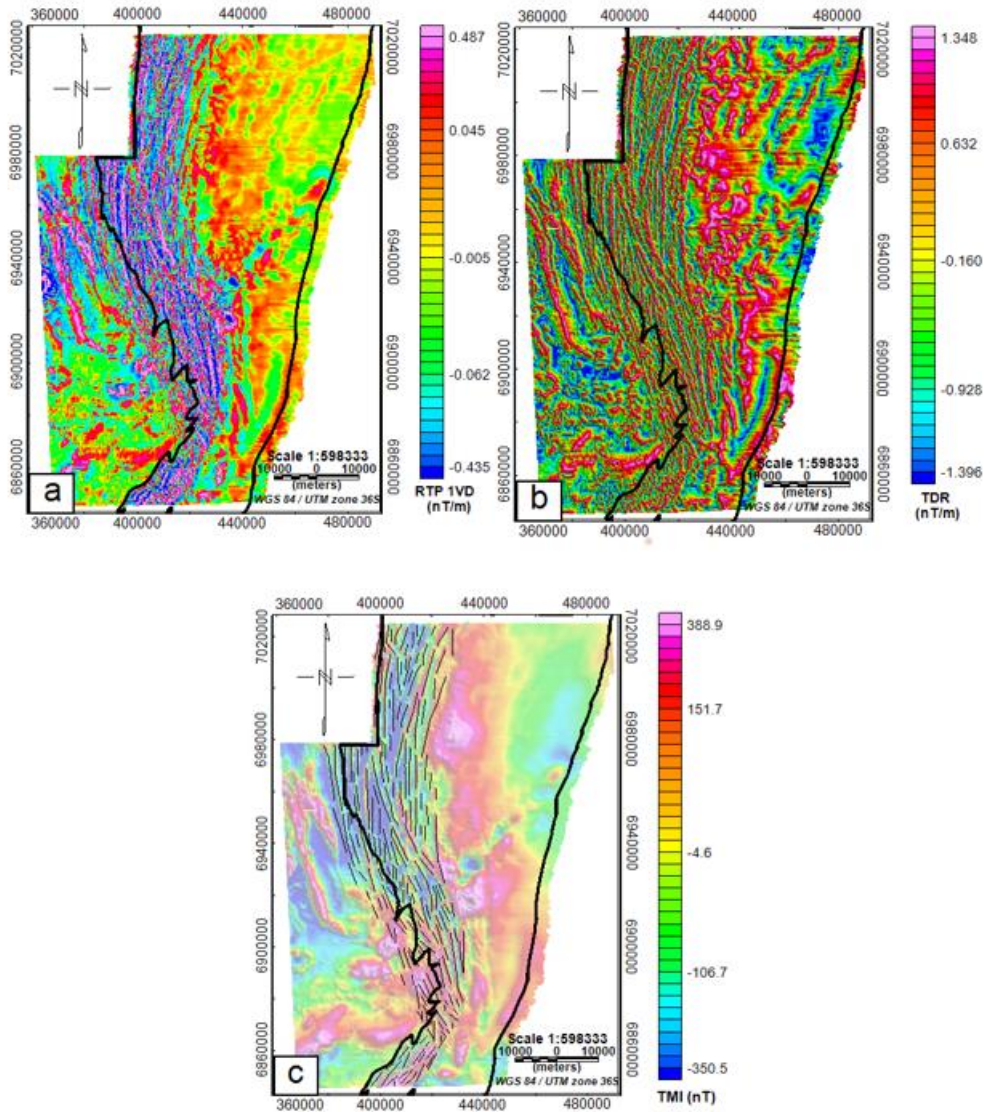


Figure 5-4: (a) First vertical derivative of the pole reduced gridded data. (b) Tilt derivative filter of the TMI gridded data, with the study area highlighted in black. (c) Pole reduced TMI with a transparency of 70% with the lineaments derived from (a) and (b) drawn in the western side of the study area. The study area is outlined in black.

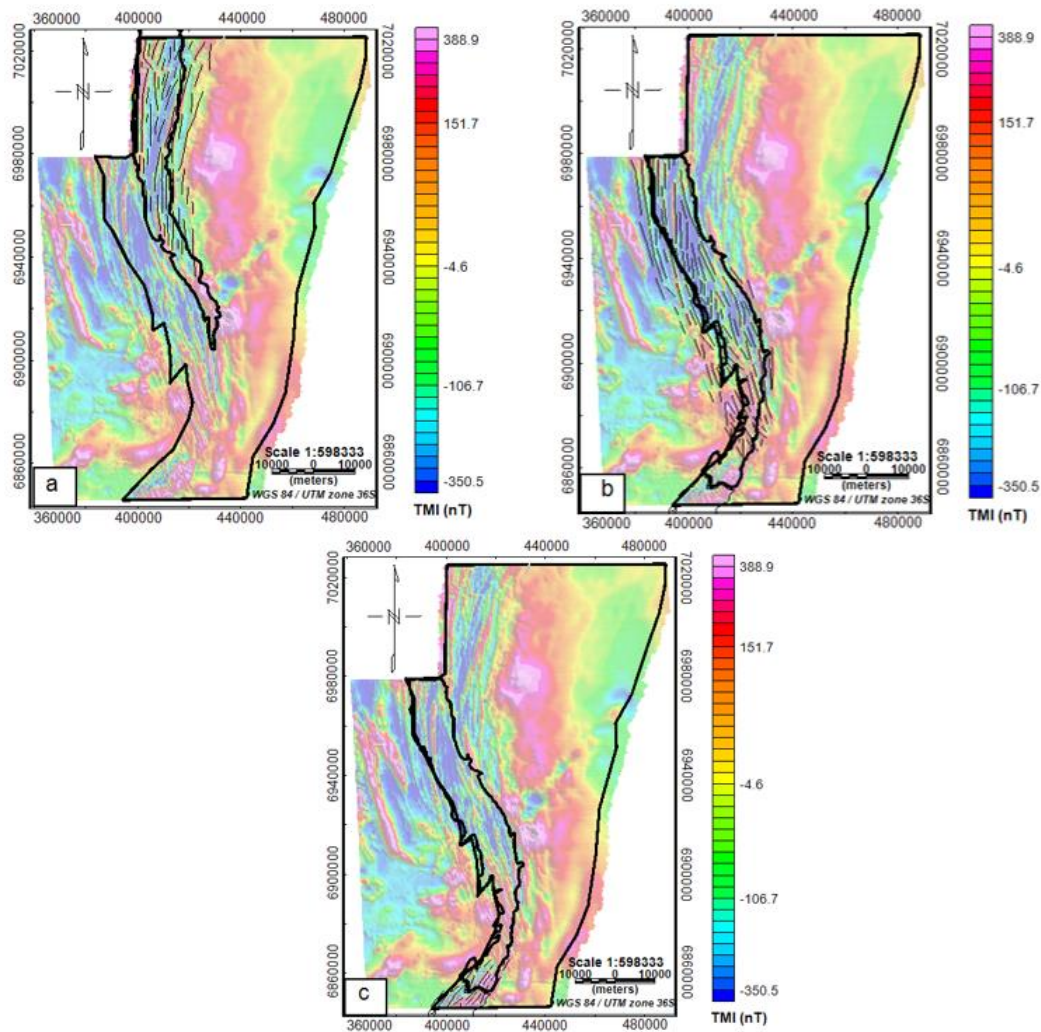


Figure 5-5: (a) The TMI map of the study area overlain by the outline of the study area and the Jozini Rhyolites and the interpreted lineaments that cover the Jozini Rhyolites. (b) and (c) The TMI map of the study area overlain by the outline of the study area and the Sabie River Basalts and the interpreted lineaments that cover the Sabie River Basalts.

Forward Modelling

The objectives were to model the intruding dykes, determine the dip of the Lebombo sequence towards the eastern side of the study area, and attempt to determine the orientation of the dykes that intruded the area and could have possibly caused the signature seen on the western side of the study area. This implies that the main zones of weakness that were intruded by the Rooi Rand Dyke swarm could have allowed for these dykes to intrude into the Sabie River Basalt Formation.

Profile 1

The aim of this model was to approximate the structure of the northern section of the Lebombo using seismic data. Due to the complex nature of the area, two seismic lines, G11-1 and G11-2 (Figure 5.6), were used to approximate the start of the Lebombo volcanic sequences. This was done by using the well velocity survey, taken from the ZU borehole, where it approximated the two-way travel time in metres. I assumed here that there weren't any variations in the lithologies to deviate from the well velocity survey. The boundary starts at 500 m marked by the blue line in Figure 5.7. The result was then extrapolated to the east, where the seismic lines aren't available. Figure 5.8 shows that the data fit poorly, with the largest offset being 250 nT, despite the constraint from the seismic data. This could be a problem remanence or an indication of the complex regional geology in the area. More physical property measurements and paleomagnetic data would be required to provide further constraints to the model.

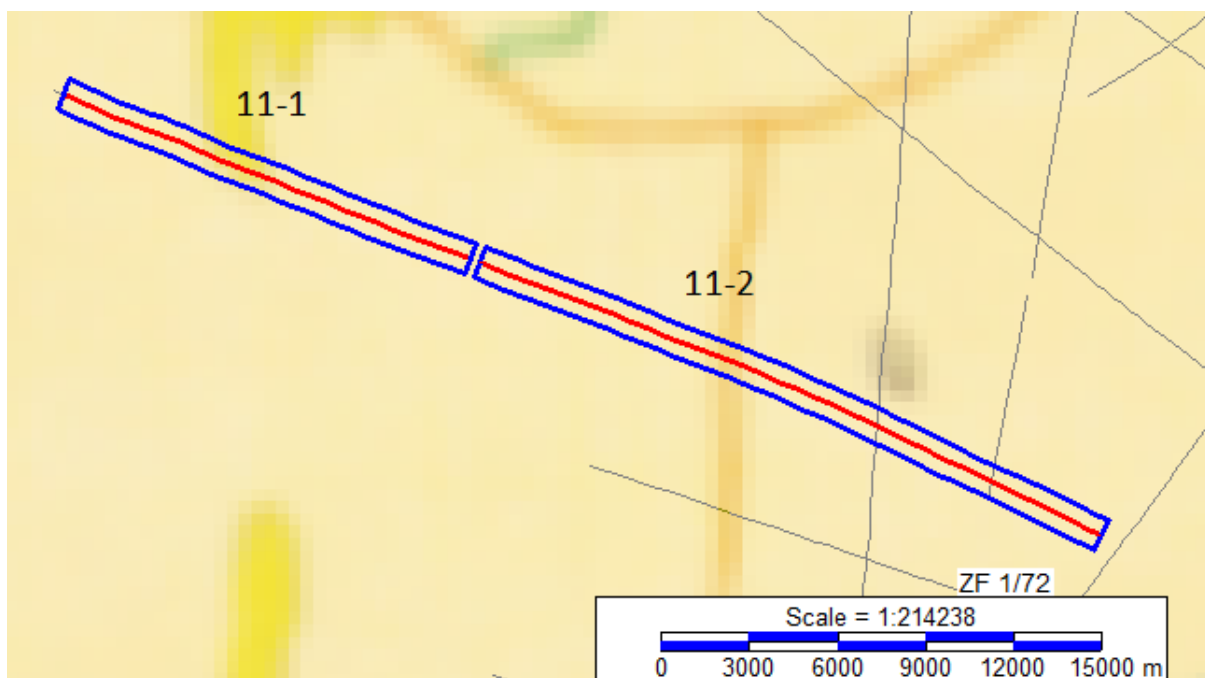


Figure 5-6: Lines G11-1 and G11 2, showing their location

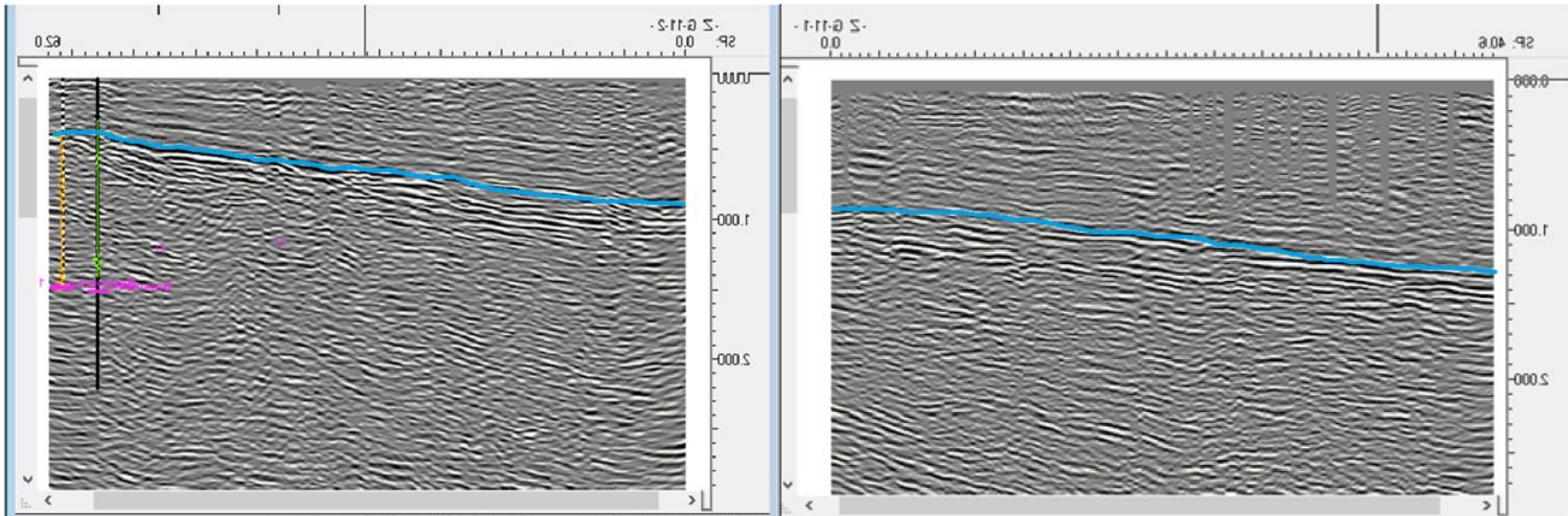


Figure 5-7: Seismic lines G11-1 and G11-2 in the area, the blue line represents the interpreted boundary layer between the Zululand Basin and the Lebombo

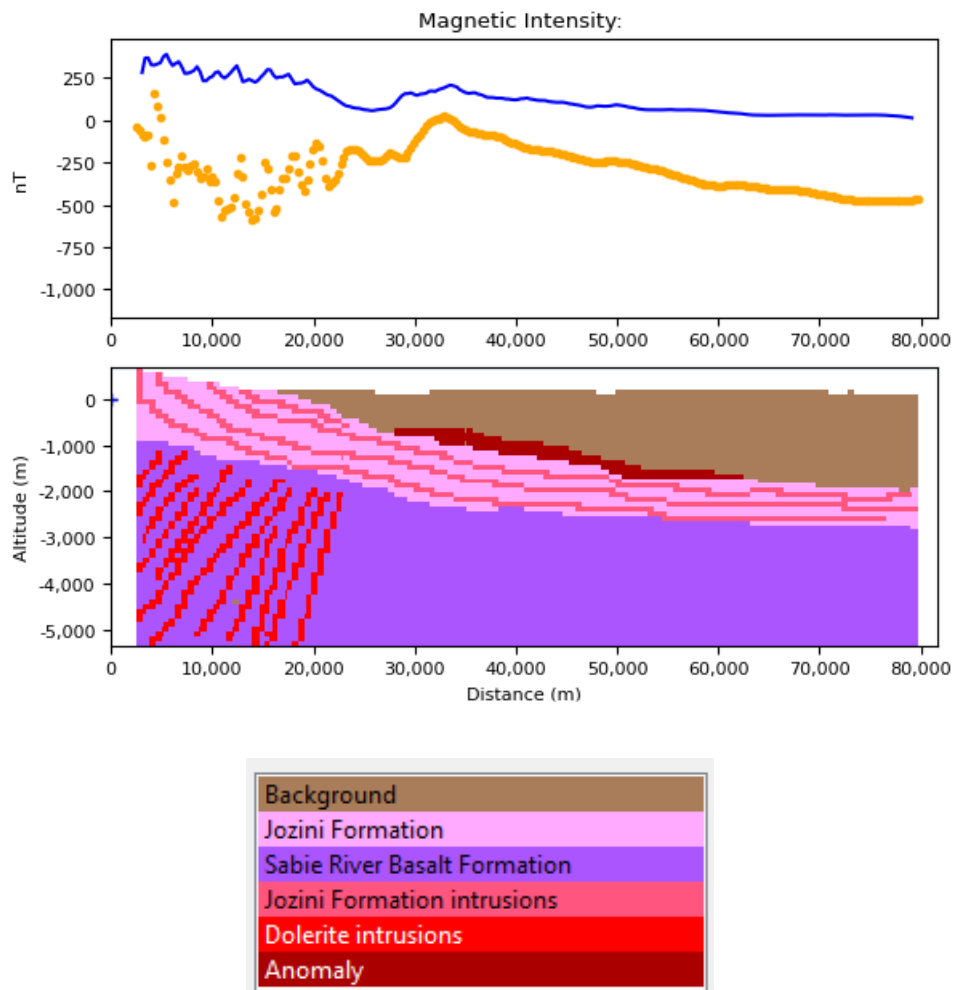


Figure 5-8: Profile 1 model in PyGMI. The lithologies are those discussed in the chapters 1 and 2. The anomaly lithology is the sill that was modelled to see if it cause the magnetic high in the TMI map. The largest offset between the observed and calculated is approximately 250 nT, this is likely due to remanence or complex geology.

Profile 2

The main aim of modelling Profile 2 was to see how the Bumbeni Ridge circular bodies intruded into the study area. The final model created can be seen in Figure 5.9. No seismic data was available for the modelled line, therefore there are no constraints on the dip, and thickness of the Lebombo sequence in that area. For this simplified model, the Lebombo sequence was assumed not to change drastically from the northern section with the layers remaining the same. The dykes were assumed to dip westwards shown by Saggerson and Bristow (1983) and were modelled freely without

specific dip parameters. Due to constraints in computing power, the size of the cell cube in PyGMI could not be finer than the 600x600x100 selected for this model. The dykes were not modelled accurately and this can be seen in the fit, this could be due to the chosen cell size.

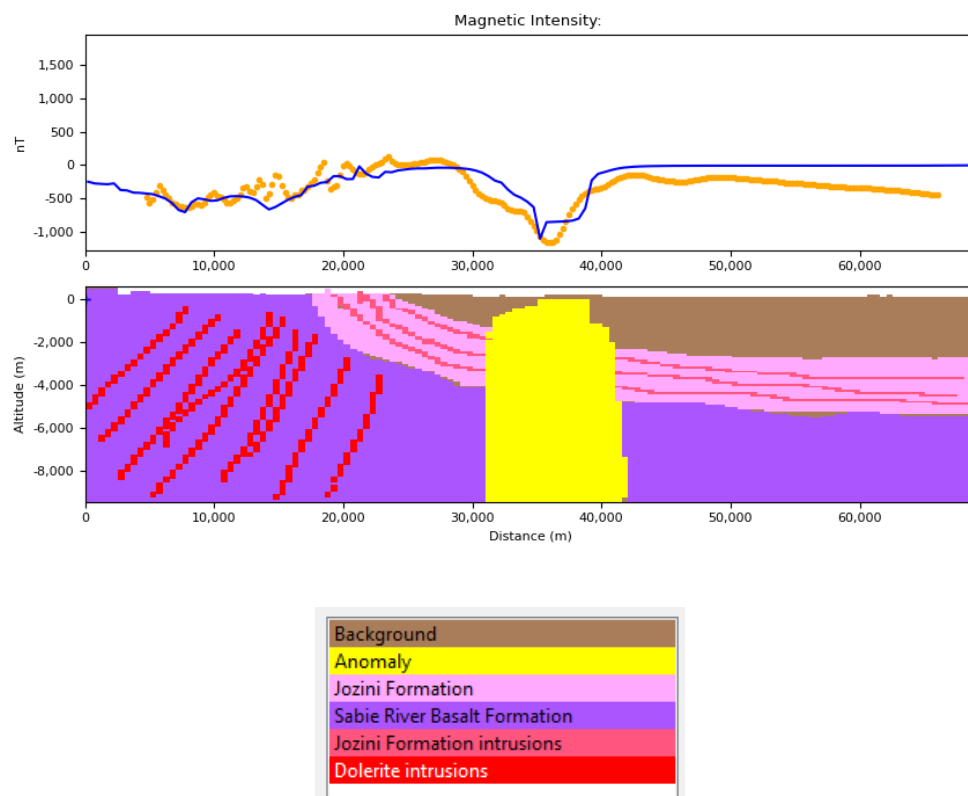


Figure 5-9: Profile 2 magnetic model. The anomaly lithology (yellow) represents the Bumbeni Complex intrusion.

Due to the presence of remanence in the area, there are a few complications in attempting to model profiles. The study area has had four magnetic reversals (Hargraves et al., 1996). This implies that the position of the magnetic poles when the rocks were magnetised are different, therefore the inclination and declination of these rocks would be different (<http://www.geol.lsu.edu/Faculty/Nunn/gl7065/index.html>). This information was not readily available during the study. Although not correct, the background susceptibility was set at positive values as if it occurred in the northern hemisphere to counteract the remanence problem experienced when modelling.

Inversion Modelling

The three anomalies of the Bumbeni ridge mentioned previously were modelled using ModelVision and UBC GIF-Tools to approximate these anomalies as single bodies to see if the inversion would converge. The area was overlaid on the TMI map to show their relative location. Figure 5.10 (a) and (c) shows the bodies that were resolved using ModelVision. Figure 5.10 (b) and (d) shows the two sections that were modelled in UBC-GIF Tools. The similar results from the two modelling packages further strengthen the idea that the Bumbeni Ridge is formed by three different bodies.

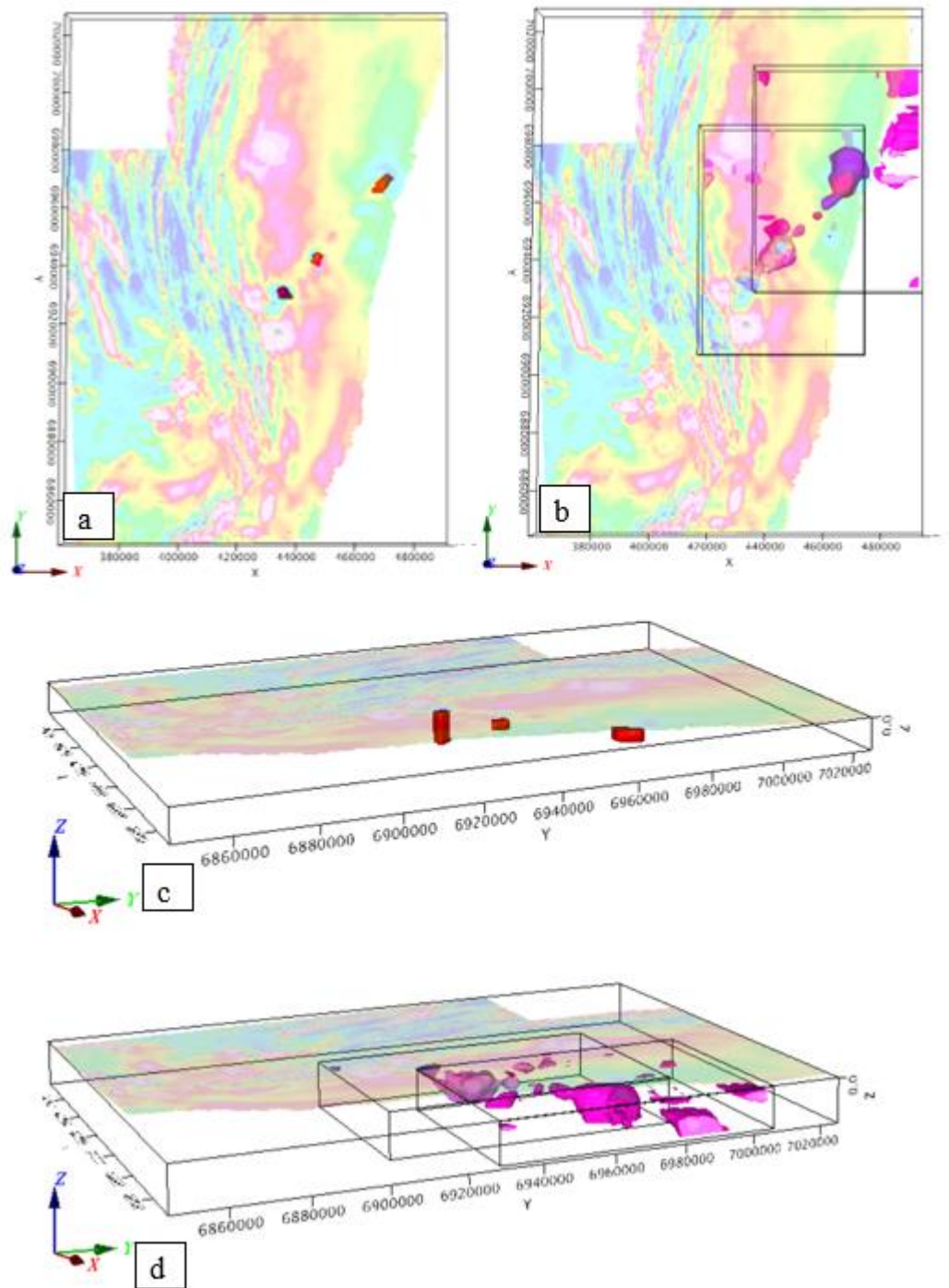


Figure 5-10: (a) Bumbeni Ridge ModelVision inversion models, with TMI overlain. Three circular features were modelled. (b) Modelled area using UBC Gif-Tools. The smaller boxes indicate the sections that the model was separated into. (c) A side profile view of (a). (d) A side profile of (b).

The approximated physical properties from ModelVision were extracted (Table 5.1). All the anomalies have a Q ratio above 1. Values are usually between 1 and 10 in many felsic and mafic rocks, indicating that the remanent magnetism is dominant (Dentith and Mudge, 2014). This is the reason the reduction to pole process did not make a difference to these features. The extent to how deep the bodies are could not be constrained from borehole data or seismic lines, therefore these values cannot be taken as a true representation of the geology.

Table 5-1: Inversion model results using ModelVision

	Susceptibility	Q ratio	Depth (km)	Depth extent (km)
Anomaly 1	0.0721	2.55	0.55	8
Anomaly 2	0.0186	8.62	1.4	2.2
Anomaly 3	0.030	1.89	1.4	2.9

6. Discussion and Conclusion

The research aimed at understanding the structure of the Lebombo sequence and its interaction with the Zululand Basin. It also tested geological models to see if they would fit the geophysical data.

The Lebombo sequence developed in an area heavily affected by Gondwana's breakup. The area experienced extensive crustal thinning due to tension from the breakup of Africa and South America through the Agulhas Falkland Fracture Zone, which had experienced movement. South America moved west relative to Africa during this time before drifting occurred between the two continents.

The formation of the Lebombo sequence was due to the period of Karoo volcanism; although this did not cause the continental breakup, it did contribute towards the weakness in the area. From the study area, we can see lineaments along the Lebombo sequence with varying strikes between the Jozini Formation and the Sabie River Basalt Formation. This could have possibly represented the edge of the Kaapvaal Craton or the possible effects of the Gondwana breakup. The Bumbeni Complex, which forms a ridge that separates the basin into the northern and southern sections, was caused by three separate intrusions, all occurring at different times, resulting in different magnetic anomalies. The effects of the remanence could also be seen on the profile models. The dyke intrusions that intruded the area were not modelled accurately and therefore cannot definitively determine the structure and strike of the dyke intrusions. Furthermore, the extent of the intrusions could not be determined if they intercept both the Sabie River Basalt Formation and the Jozini Formation because the profile models fit the observed data poorly. The presence of remanence also made it difficult to model the area well due to assumptions that had to be made during the modelling process. The lack of seismic lines and borehole data that intercepted the Lebombo sequence further added inaccuracies in the modelled data. Future work can include getting physical property data from the area using borehole ZU, a 6 km borehole that covers the Jozini Formation and the Sabie River Basalt Formation. Normalised Source Strength (NSS) can be applied to the TMI data to reduce the effects of remanence. Other extensions of the study could include

paleomagnetic work could also be done in the area to determine the necessary parameters to improve the modelling, in cases where NSS would not work efficiently. Inversion could also be performed on each of the profiles to see if a better fit can be obtained.

7. References

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