CHAPTER 6: MAGNETIC MODELLING AND DISCUSSIONS

This chapter starts with two dimensional modelling of the negative magnetic anomaly over the amphibolite-granulite transition zone in an attempt to understand the cause of the long wavelength anomaly. The next part deals with three dimensional modelling of the geomagnetic data from the 9 m x 9 m grid. The chapter ends with a discussion of the modelling and its implications for the geology. The discussion here only pertains to the modelling as discussion of the geomagnetic and palaeomagnetic aspects where dealt with in the relevant chapters. The chapter will also incorporate a discussion of the implications of the current data set for existing hypotheses regarding their validity.

6.1 Modelling of magnetic data: Introduction

Modelling is the process by which data are used to determine important parameters (e.g. geometry, depth, horizontal position, and magnitude of magnetization) of the source body. This process is achieved by one of the following methods.

Forward modelling: From geological information and geophysical intuition one constructs a starting model. The fit between the model’s calculated anomaly and the observed anomaly is compared and if the agreement is not satisfactory, the model’s parameters are adjusted. This process is repeated until the interpreter is satisfied with the fit between the calculated and observed anomaly (Blakely, 1996).

Inverse modelling: This method involves the calculation of body parameters directly from the observed data. It optimizes the fit of the modelled anomaly to the observed anomaly automatically (Blakely, 1996). Despite the automation of this method, the solutions must be treated with caution as many models can fit the observed data equally well. This is due to the inherit ambiguity of inversion processes (Blakely, 1996). A brief discussion on linear inverse modeling can be found in Blakely (1996).
6.2 Two dimensional modelling of the detailed magnetic data over the transition zone

Previous attempts to model the magnetic anomalies in the Vredefort basement were made using the remanent magnetization direction that is found in impact melt dykes from the basement (Jackson, 1982; Henkel and Reimold, 1998). On the basis of several two-dimensional N-S profiles extracted from the aeromagnetic data-base across the anomaly, Jackson (1982) found that the anomaly could be adequately explained by a homogenous spherical body at depths of between 2 and 7 km, with an average width of 7 km. Similarly, Henkel and Reimold (1998) concluded that a homogeneously magnetised body is a feasible source, but their model involved a body that is saucer shaped, thins towards the edges and extends from the surface to a maximum depth of 4.5 km.

In this study, data points at 10 m intervals were extracted along three N-S profiles, taken from the upward continued map at 40 m altitude (Fig. 6.1). At 40 metres height one can adequately discount superficial high frequency effects that are potentially due to lightning, but still model the medium and longer wave-length anomalies. In two-dimensional modelling one assumes that the profile is taken at right-angles to the source of the anomaly and that the source is infinite in the direction perpendicular to the profile (Blakely, 1996). The three profiles in question clearly meet these criteria except for profile 1 because it is not quite perpendicular to the strike of the magnetic anomalies. Profile 1 cuts across the whole of the transition zone and this is the reason why it was chosen despite the fact that it does not quite meet the first criterion. The south and north extremities of the profiles were constrained by the aeromagnetic data. The geomagnetic data was used to extend the ground magnetic profiles during the modeling stage. All profiles were extended by 1 km in both directions. The MATLAB code given in appendix A.4 was used to calculate the magnetization for given directions of magnetization for a two-dimensional model.
The modelling was based on the assumption that the rocks in the Vredefort basement are vertical (see cross-section, Fig. 1.1, Chapter 1). Taking into account the possibility that the anomaly may be due to multiple sources within an equivalent layer, the profiles were modelled by assuming that the body was made up of 100 m wide vertical rectangular prisms that are infinitely long and with a magnetization direction of the pseudotachylites (Carporzen et al., 2005). This choice of width was based on the average size of medium wavelength anomalies recorded in this study. The author experimented with prisms width of 200, 500 and 1000 m. However, the 100 m width prisms gave the best results, in that the shape of the anomaly resembled more the observed anomaly. The author does concede that values of say 120 or 150 m will also give reasonable solutions. The magnetization of the pseudotachylites rather than the impact melt dykes was used firstly because the pseudotachylites are more abundant in the basement and secondly because they are similar in composition to the basement rocks compared with the impact melt dykes.

The algorithm that was used for the calculation of the magnetic field of the prisms was taken from Blakely (1996). In the Blakely (1996) algorithm once the magnetization direction, horizontal position, depth and width of the vertical prisms are specified the program calculates the magnetic attraction due to each prism. Vertical prisms were chosen as this best approximates the dip angle of the different rocks underlying the anomaly, (Hart et al. 2004). Fig. 6.2 is a schematic representation of the source body.
Figure 6.1. Detailed IGRF-corrected ground magnetic anomaly map over the amphibolite-granulite transition gridded to 9 m x 9 metres. Profiles 1-3 show the positions of profiles used for 2-D modeling. Note that the x-axis and y-axis are longitude and latitude respectively.
Figure 6.2. Magnetic anomaly of profile 1 (above) and schematic representation of the source body (below). The source body is divided into rectangular prisms, each 100 m in width. In this illustration, the top of each prism begins at the surface and extends to 1 km below surface. Note that in the actual modelling of the profile both ends where extended by 1 km using the aeromagnetic data.

To recover the magnetization of each prism (for each profile) that could account for the observed data, a least squares inversion was performed to fit the magnetic response of the model to the observed data. The top of each prism begins at the surface for each model. The models differ by the depth of the prisms considered, with depths to base being 1.0, 2.0, 5.0 10.0 and 15.0 km. The 5 models were considered for all three profiles. It must be noted that the models presented in this study do not represent the only possible models, but those chosen cover the range expected from geological constraints (Hart et al. 2004). Time constraint demanded that a limited number of models could be tested. Errors (see later) were estimated by taking random directions from the 95% confidence interval of
the measured palaeomagnetic direction of pseudotachylite (Carporzen et al., 2005). The corresponding NRM\textsubscript{s} and standard deviation for each direction were then calculated.

Profile 1 was modeled first and the results are presented in Fig. 6.3 and Table 6.1. The different graphs in Fig. 6.3a correspond to the depth to base for the different models. Fig. 6.3a shows that the shallower the base of the prisms, the higher the magnetizations that are needed to fill the particular volume. The modelling of profile 1 clearly shows that the highest magnetization occurs over the transition zone with the extreme northern and southern ends of the profile characterised by low magnetization values. This suggests that the transition zone is very magnetic compared with the surrounding domains. The errors for profile 1 associated with the modelling are small (0.01 to 0.20 A/m) which suggests that the impact melt direction is a reasonable approximation for the magnetic source.

Fig. 6.4 shows the recovered magnetizations for profile 2. This profile also cuts across most of the magnetic anomalies (Fig. 6.1) but is different from profile 1 in that it is trending in a NNE direction. The angle of azimuth did not seem to alter the magnetization significantly (see Table 6.1). However the minimum magnetization values obtained for all the models of profile 2 are slightly higher than the corresponding values for profile 1. This is expected since profile 2 starts very close to the transition zone where the anomaly is more intense. Again the errors associated with the modeling are small (0.002 to 0.14 A/m).

Fig. 6.5 shows the recovered magnetizations for profile 3. This profile cuts the anomalies roughly at right angles, but does not incorporate the whole of the transition zone. The range of magnetization is very similar to those of profile 2 and as expected it depends on the depth to base of the models (the shallower the body, the higher the magnetization).
Table 6.1. Two-dimensional modelling results for profiles 1-3. All models start from surface and extend to the various depths as indicated in Fig. 6.3.

<table>
<thead>
<tr>
<th>Depth to base (km)</th>
<th>Profile 1: Magnetization (A/m)</th>
<th>Profile 2: Magnetization (A/m)</th>
<th>Profile 3: Magnetization (A/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.90-13.04</td>
<td>5.48-10.32</td>
<td>5.89-10.28</td>
</tr>
<tr>
<td>2</td>
<td>1.65-7.79</td>
<td>3.33-6.65</td>
<td>3.53-6.49</td>
</tr>
<tr>
<td>5</td>
<td>0.73-4.69</td>
<td>1.87-4.49</td>
<td>1.79-4.22</td>
</tr>
<tr>
<td>10</td>
<td>0.33-3.76</td>
<td>1.33-3.84</td>
<td>1.23-3.53</td>
</tr>
<tr>
<td>15</td>
<td>0.17-3.49</td>
<td>1.16-3.64</td>
<td>1.05-3.32</td>
</tr>
</tbody>
</table>

In general, the magnetizations obtained from all the profiles are in the same range and the results are appropriate. For all the profiles, the two models of prism depths of 10.0 and 15.0 km correspond best to the range in magnetizations measured in the pseudotachylites (1.8 ± 1.4 A/m). The induced magnetization was 0.52 ± 0.69 A/m which does not appreciably affect the results of the model which is largely dominated by the remanent magnetization.

The modelling procedures indicate that the source bodies must be rock that has been melted during the impact event and remagnetised. The only rocks that are indicative of melting are pseudotachylites, but these only account for a very small percentage (about 0.4%, Reimold and Gibson, 1996) of the rocks present. So, if the pseudotachylites do not have the required volume then which rocks have? The only other rock types found in the vicinity of the anomaly are the Archaean granites and BIF. The BIF has a positive magnetic anomaly which strongly argues against a TRM. Therefore, the most likely candidate is the basement granites which must have been remagnetized in the same direction as the pseudotachylites. This is yet to be proven, as all the available data come from surface exposure and show NRM values that have high magnetization and random directions.

From the modeling, it appears one observes that the magnetization is a function of the amplitude of the magnetic anomaly; it is highest where the anomaly is most negative. For all the profiles the magnetization attains the maximum over the transition zone. This
suggests that the rocks that straddle the transition zone have a greater magnetite content compared with the surrounding rocks. It implies that if TRM is responsible for the magnetization, the rocks outside the transition zone did not reach temperatures above the Curie temperature, and therefore could not be remagnetised. The compatibility of this modelling with other existing models will be dealt with in the discussion section below.
Figure 6.3. An inversion model of the data taken at 10 m intervals and at 40 m upward continued altitude, along profile 1. The profile was modelled by assuming that the body was made up of 100 m wide vertical rectangular prisms and with a magnetization direction of the impact dykes (Chapter 5, Section 5.2). a) Recovered NRM of the model from the inversion for different depths (see key). b) NRM of a modelled body that extends to 10 km, with associated errors. c) Magnetic response of the model at 10 km, d) Difference between the raw data and the calculated magnetic response.
Figure 6.4. Magnetic inversion of profile 2 (Fig. 6.1). Diagrams a–d as for Fig. 6.3.
Figure 6.5. Magnetic inversion of profile 3 (Fig. 6.1). Diagrams a – d as for Fig. 6.3.
6.3 Three-dimensional modelling of the 9 m x 9 m grid

The unusually variable magnetic field seen in the 9 m x 9 m grid (Fig. 6.6) presented an interesting challenge. The measured NRM (see Section 6.3.1) show no particular correlation with the geomagnetic data measured at the three heights (0.55, 1.20 and 2.55 m). To calculate the magnetization that is responsible for this magnetic field, a linear inversion was performed.

6.3.1 Modelling procedure

Both palaeomagnetic and geomagnetic data indicate that the length scale at which the NRM and the earth’s magnetic field changes is roughly a metre. This implies that the source should be shallow. Moreover, a decrease in the rate of change of the magnetic field from 0.55 m to 2.55 m height (~ 30 000 nT to ~ 7 000 nT) also indicates that a shallow source is appropriate (Figs. 4.16 to 4.18, Chapter 4).

For this reason an equivalent layer will be considered that extends from the surface to 1 m below the surface. The rectangular body was divided into 1 m$^3$ (1 m x 1 m x 1 m) cube, providing a total of 169 cubes. Some cubes will fall outside the original palaeomagnetic grid, and these are used to avoid boundary effects. The dimensions of the model are based on the sampling interval which was 1 m. The centre of each cube was placed at the same spatial position where the magnetic fields and palaeomagnetic data were measured. The data for all the three heights (0.55 m, 1.20 m and 2.55 m) were used in the modeling procedures.

Two models will be considered here. The first uses the NRM directions obtained from the palaeomagnetic data and the second uses the magnetization direction found in the pseudotachylites. In both cases the magnetization recovered and the calculated anomaly will be compared with NRM values (palaeomagnetic data). The calculated anomaly was determined using the Mbox algorithm (Blakely, 1996).
Fig. 6.6b is a comparison between the computed anomaly using the NRM directions and the observed anomaly (Fig. 6.6a), while Fig. 6.6e compares the computed anomaly (pseudotachylites direction) with the observed anomaly. Using the magnetization directions (NRM) of the individual samples, the magnetic anomalies are not reproduced well (Fig. 6.6a-c), the difference between the observed and calculated anomaly being between -31462 to 28875 nT (Fig. 6.6c). This is nearly the same order of magnitude as the observed anomalies (Fig. 6.6a).

Modelling using the pseudotachylites direction (assuming a TRM source) the magnetic anomalies are well reproduced, the difference between the observed and calculated anomaly being between -7715 to 16981 nT (Fig. 6.6e). The order of magnitude of the difference between the computed anomaly and observed anomaly are on average acceptable. Between the two models the calculated anomaly using the TRM direction is a better fit compared with the model that uses the individual NRM directions of the samples.

Fig. 6.7 shows the measured NRMs (observed) and the recovered magnetization (calculated) using the NRM directions. Negative values indicate that the magnetization direction is reversed. The calculated magnetizations range from 0.4 to 284 A/m (average = 69 A/m). The value from the calculated magnetizations is larger than the range in NRM magnetizations measured from the 100 samples (34.7 A/m).

The size of the cubes were increased in order to examine the relationship between volume of the cubes and strength of magnetization. In an attempt to obtain a better fit, the modeling was repeated using 8 m$^3$ cubes resulting in 36 cubes and again into 64 m$^3$ (4 x 4 x 4 m) cube resulting in 9 cubes in all. The depths of the cubes extended from 0 to 2 and from 0 to 4 m below surface respectively. The extended models were modeled using the coherent directions of the pseudotachylites.
The magnetization obtained for the grid model consisting of 8 m$^3$ (Fig. 6.8b) sized cubes ranges from 17 to 131.5 A/m (average = 65 A/m) and for the grid model consisting of 64 m$^3$ (Fig. 6.8c) sized cubes it ranges from 0.2 to 132.6 A/m (average = 38.3 A/m). The model with the large volume corresponds to smaller magnetization. However, the reduction in magnetization is still much bigger than the magnetizations measured from melt rocks (i.e. pseudotachylites and impact melt dykes).

The interpretations and implications of all the results obtained from these modelling exercises will be dealt with in Section 6.3.2 below.

![Figure 6.6](image)

**Figure 6.6.** Magnetic modeling over the 9 m x 9 m grid at 0.55 m height. a) and d) Observed anomaly, b) Calculated model anomaly using the NRM directions, c) Difference between the observed (a) and calculated anomaly (b). e) Calculated model anomaly using the pseudotachylites direction, and f) Difference between the observed (a) and calculated anomaly (e).
Figures 6.7. Comparison between measured palaeomagnetic magnetization and magnetization determined for the model using the directions of the NRM. a) Measured NRM of the 100 palaeomagnetic samples from the 9 m x 9 m grid. b) Model using the magnetization directions of the NRM.
Figure 6.8. Magnetization recovered from modelling using the coherent direction from the pseudotachylites. a) 1 m$^3$ (1 x 1 x 1 m) sized cubes, b) 8 m$^3$ (2 x 2 x 2 m) sized cubes, and c) 64 m$^3$ (4 x 4 x 4 m) sized cubes. Note that all cubes extended from surface to the respective depth given above.
6.3.2 Interpretation of the three dimensional magnetic modelling results

The first model uses the directions from the measured NRM of the 100 samples (Fig. 6.6a and Fig. 6.7). The differences between the set of calculated anomalies and observed anomalies are quite large and magnetizations are higher than the NRM values. This indicates that a bigger body is needed to have magnetization in the same range as the measured NRM.

The model that uses the pseudotachylite directions; D=20.8°, I=57.4°, α95=1.9° and NRM of 1.8 ± 1.4 A/m (Carporzen et al., 2005) shows smaller differences between the observed and calculated data (Fig. 6.6d-f). However, calculated magnetizations are also high compared with measured NRM. Of the 100 cubes (which fall with the original palaeomagnetic grid), 70 have negative polarity, suggesting that these cubes are magnetized in the opposite direction to the impact melts (Fig. 6.7b). The remaining 30 cubes, which have positive polarity, coincide with the negative anomaly found in the IGRF magnetic anomaly map for all three altitudes. (Figs. 6.7b and 6.8.a). This suggests that the negative anomaly is due to bodies magnetized almost opposite to the current IGRF field.

For TRM typical NRM values are estimated at about 1 A/m for basalt and less than 0.001 A/m in granites (Butler, 1998). If TRM (albeit enhanced) in time proves to be the cause of the magnetization, then there should be rocks beneath the surface with a strong coherent magnetization different to the current IGRF field.

From the above it is clear that the geomagnetic data are not correlated with the palaeomagnetic data (Section 5.3) of the 100 samples from the 9 m x 9 m grid. Therefore, none of the methods discussed here can account for the geomagnetic anomaly. It appears that more work needs to be done in order to account for the geomagnetic field of the 9 m x 9 m grid.
6.4 Discussion and implications

The modelling conducted in study will be used to explain the invalidity of the existing models and then an alternative hypothesis is provided that is more compatible with the prevailing geology.

In this study, the geomagnetic data were used to explore several models (Hart et al., 1995; Jackson, 1982; Henkel and Reimold, 1998; Carporzen et al., 2005) that attempt to explain the magnetic fields over the basement core of the Vredefort impact crater. The commonality of these models is that they all link the magnetic signatures to the 2.0 Ga impact event.

The model of Carporzen et al. (2005) is based heavily on regional palaeomagnetic data across the basement floor that shows that the Archaean rocks are characterised by extremely high remanence and randomly orientated remanent vector directions. These authors link the anomaly to the impact event because of the new 2.0 Ga magnetite found along PDF’s in quartz and around the alteration halos of biotite (Cloete et al., 1999). However, randomly orientated vectors should result in a net zero magnetization and consequently a zero magnetic signature other than that of the earths field (i.e. ~28000 nT). Modelling a body of non magnetic rock surrounded by a body of magnetized rocks may result in a net negative anomaly depending on the values assigned to the surrounding rock. However, this is yet to be demonstrated.

The models of Jackson (1982), Hart et al. (1995) and Henkel and Reimold (1998) all suggest that thermal remanence is the cause of the negative magnetic anomalies in the basement and link the anomaly to a coherent magnetic vector that is found in 2.0 Ga melt rocks (pseudotachylites and impact melts) that outcrop sporadically in the basement. Jackson (1982) proposed several models to account for the magnetic anomaly. In one of his preferred model, Jackson (1982) assumed that the negative anomaly is caused by a uniformly magnetised body of intrusive melt rock that was emplaced at depths of
between 1 and 7 km beneath the surface at the time of impact. The author believes that there is no good geological reason for this, as there is no evidence of ~2 Ga intrusive rocks other than impact melts and pseudotachylite. At Vredefort, it is generally assumed that the melt sheet has been eroded away leaving only the sporadic outcrop of impact melt dykes and pseudotachylites (about 0.4% for pseudotachylites and even less for impact melt (Reimold and Gibson, 1996)) as an expression of melting and it appears that there is insufficient volume of melt rocks to cause the anomaly. Further, the ground magnetic surveys over both pseudotachylites breccias (this study) and impact melt rocks do not show an appreciable contrast between these rocks and the surrounding areas.

Henkel and Reimold (1998) went on to model the anomaly as a uniform layer of thermally remagnetised Archaean granite that extends from surface to depths of up to 4.5 km. Although thermally remagnetised basement rock can adequately explain the aeromagnetic data (i.e. at 150 m), there are several factors that argue against a uniform magnetization that is caused by TRM alone.

TRM assumes that the basement rocks under the anomaly would have attained temperatures above the Curie point (580ºC) at the time of impact and, although there is evidence for local heating in the basement (e.g. recrystallization of the quartz along the PDF’s and the local formation of micro-melts along micro-fractures and PDF’s in quartz), there is no evidence for regional heating in the vicinity of the anomaly (R. Hart, personal communication, 2005). These observations are consistent with Verwey transition measurements in the basement rocks that suggest that the basement rocks were not uniformly heated above the Curie temperature during or since the time of impact (Carporzen et al., 2006). Furthermore, if the magnetic signature associated with the transition zone was solely due to TRM, then one should expect to see a similar signature in the centre of the crater where temperatures were highest (Hart et al., 1991), which is obviously not the case (see aeromagnetic data Fig. 1.2). The author also notes that not all the rocks in the vicinity of the transition zone show the characteristic negative signature associated with the impact event. The BIF for example shows a positive anomaly that can
be modelled using the current IGRF field direction. However, one cannot discount the possibility that the BIF has been remagnetised since the time of impact.

The author concurs with Henkel and Reimold (1998) that the anomaly may be due to basement granites and granulites with the same magnetization direction as that of the melt rocks. However, the details of the ground magnetic survey obtained in this study show that the anomaly is not made up of a uniformly magnetized layer of rock, but rather consists of bands and patches of rock with different magnetization intensities. The modelling in this study is based on the “crust on edge” model (Moser et al., 2001; Tredoux et al., 1999; Slawson, 1976; Hart et al., 1990) that assumes that the rocks in the Vredefort basement are vertical (see cross-section in Fig. 1.1, Chapter 1; Fig. 4.4, Chapter 4), and shows that different vertical layers of magnetized rocks with different intensities can best account for the variations seen in the ground magnetic survey. Although the anomaly cannot be ascribed to any particular lithology (Fig. 4.4, Chapter 4), a comparison of the magnetic profiles with the geology shows that the long wavelength negative anomaly coincides with the amphibolite granulite transition. Thus, it would appear that this boundary in some way bears on the magnetic signatures of the crater.

Simulation of shock wave propagation in heterogeneous solids shows that reflection, refraction and interference lead to the localized concentration of pressure and temperature and to phase transitions at rock interfaces (Hertzs ch et al., 2005). Therefore, the author suggests that the magnetic signatures associated with the transition zone were caused by a combination of shock (pressure) and heat generated as a result of focusing and defocusing of shock waves at rheologic interfaces and the partitioning of energy at these interfaces. The rocks underlying the anomaly were remagnetised and the remanence in these rocks derives from single domain (micron-size) magnetite particles found along the shock induced PDF’s in quartz (Cloete et al., 1999) and potentially from a pressure effect on the pre-impact multidomain magnetite (Gilder et al., 2004). This is consistent with petrographic evidence, which shows that there is a marked increase in the intensity of the impact related thermal and shock metamorphism (including the formation of single domain magnetite) across the amphibolite-granulite transition (Hart et al., 1995).
Modelling of geomagnetic data over the 9 m x 9 m grid suggest that the magnetism of these rocks cannot be explained by a lightning source, plasma field or conventional TRM. Increasing the size of the model reduces the recovered NRM but not sufficiently to reproduce the observed range. More analyses are required to explore the possibility that rocks have magnetizations that are substantially enhanced.