CHAPTER 1: INTRODUCTION

1.1 Background to the project

The Vredefort crater in South Africa is an erosional remnant of a once bigger impact site, with an original diameter estimated to be ~300 km (Therriault et al., 1997). The Vredefort structure has been recently declared a World Heritage Site. The basis for this award is the geological and geophysical research that has been centered on this impressive phenomenon over the last four decades. It has been established that the Vredefort structure is about two billion years old and this makes it among the oldest dated craters on earth (Kamo et al., 1996; Moser, 1997). Subsequent up-doming and overturning has unearthed a substantial section of rock through the Witwatersrand Basin and also about 1000 km^2 of well-exposed Archaean crystalline basement. This section provides a window into the deep Archaean geology of the Kaapvaal Craton, which is currently the focus of many Earth scientists worldwide mainly because some of the oldest and best-preserved rocks are exposed on the craton, but also because the craton is the source of much of the world's diamond, gold and platinum resources.

The magnetic anomalies over the two billion year old Vredefort impact structure closely follow the geological outline of the crater (Figs. 1.1 and 1.2), yet the origin of these anomalies still remains one of the outstanding questions surrounding this enigmatic and complex crater. The morphology of the crater consists of a rim of semicircular ridges of Precambrian strata (Dominion Group, Witwatersrand Supergroup, Ventersdorp Supergroup, and Transvaal Supergroup) surrounding a central flat area consisting mainly of Achaean granitic basement (Fig. 1.1). Both the rim strata and the basement rocks were turned on edge during the impact event, exposing a section of up to ~36 km through the early Precambrian and Archaean crust of the Kaapvaal Craton (Hart et al., 2004). Palaeozoic rocks of the Karoo Supergroup cover the southern side of the dome. The granitic basement is made up of two distinct geological domains: a core of 3.5 Ga mafic and felsic granulites, surrounded by an 8 km thick sequence of 3.0 Ga granite-gneiss of amphibolite grade (Moser, 1997). The transition of the amphibolite facies rocks to the granulite core is a complex geological zone that occurs over a distance of about 2 km (Flowers et al., 2003).

Aeromagnetic images over the structure (Corner et al., 1990) show strong, well-defined concentric patterns (Fig. 1.2). In the rim, the patterns reflect the different strata of the Witwatersrand Basin, the intense negative anomalies clearly being related to iron rich shales in the West Rand Group. About halfway into the basement there is a prominent negative magnetic anomaly that extends in a broad semicircular belt around most of the basement core. The anomaly has a maximum width of about 4 km in the northwest sector of the basement but tapers off towards the south along both the eastern and western limbs (Fig. 1.2). This negative anomaly is roughly centered above the region that marks the transition from amphibolite facies to granulite facies rocks (Figs. 1.1 and 1.2). The Archaean gneisses that underlie the anomaly have extremely high Q (ratio of remanent to induced magnetization), which is several orders of magnitude greater than the average value of similar rocks worldwide (Hart et al., 1995). These authors relate both the high Q values and the magnetic anomaly in the basement to the 2.0 Ga impact event. In a palaeomagnetic study across the basement Carporzen et al. (2005) found that, in addition to the high Q values, the remanent directions of these rocks where randomly orientated. This led to the suggestion that a rapidly varying plasma-generated magnetic field at the time of impact could explain the high Q and random directions of magnetization.

However, the relationship between the aeromagnetic data and the complex geology in the vicinity of the anomaly is unclear largely because of the poor resolution of the aeromagnetic data. In order to understand the relationship between the magnetic anomalies and the geology, as well as the corresponding mineralogical and shock deformation changes in this region, a high-resolution ground magnetic survey over a well-exposed section of the amphibolite-granulite facies transition zone was conducted. The study also involved magnetic modelling over the transition zone and attempted to correlate the ground magnetic data with available aeromagnetic data using upward continuation algorithms. In addition to the main survey two detailed geomagnetic surveys were conducted over small areas of variable magnetic field. The first was over a 9 m x 9 m grid within the transition zone and the second was over an outcrop of banded ironstone formation (BIF).

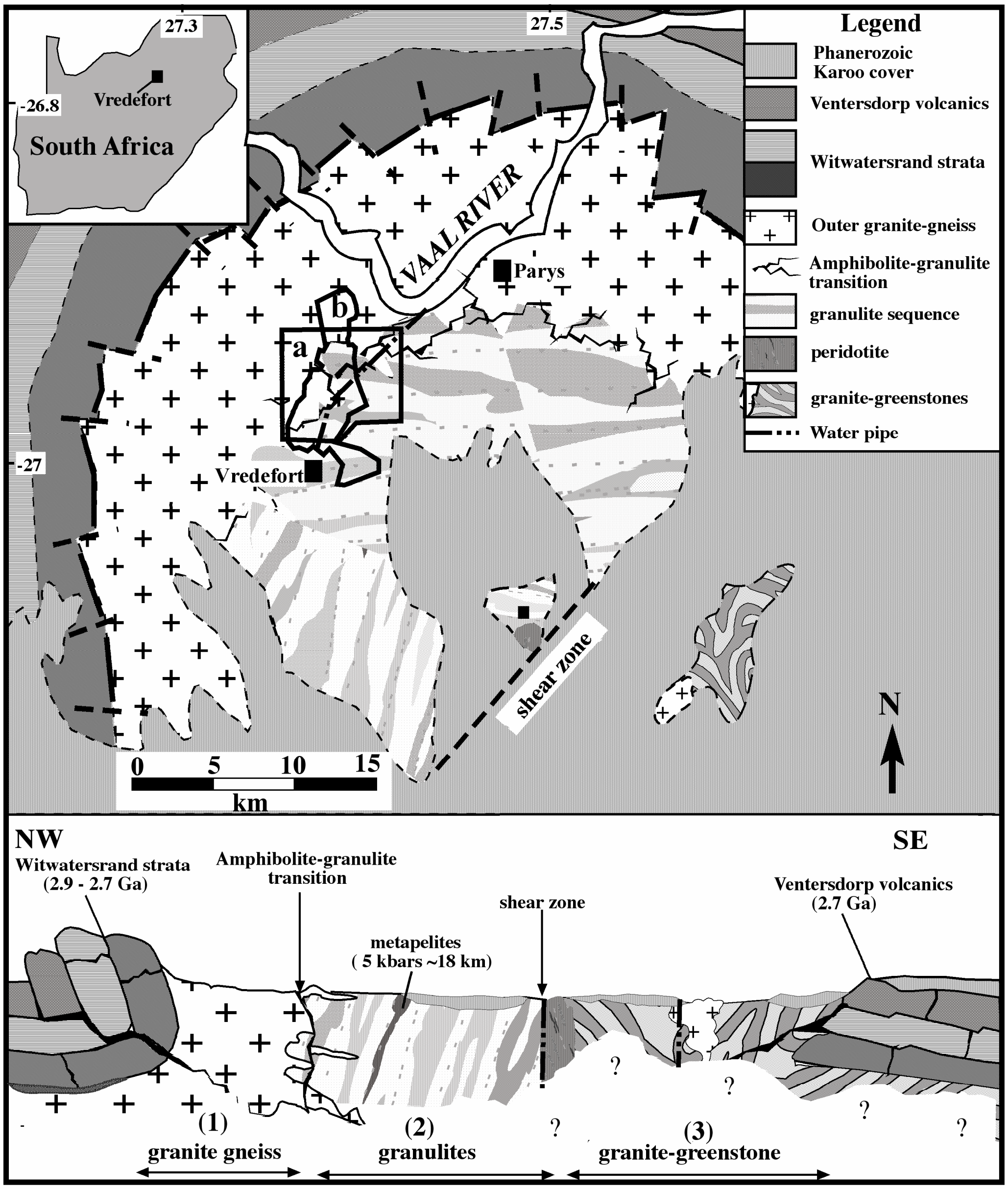

Figure 1.1. Geological map of the Vredefort structure and northwest-southeast section across it from Hart et al. (2004). Horizontal scale of cross section same as map; vertical scale exaggerated. The area marked (a) shows the area of a geological map of the amphibolite-granulite transition zone which does not include the whole of the study area (for detail see Fig. 1.3), while (b) shows the outline of the ground magnetic survey conducted in this study.

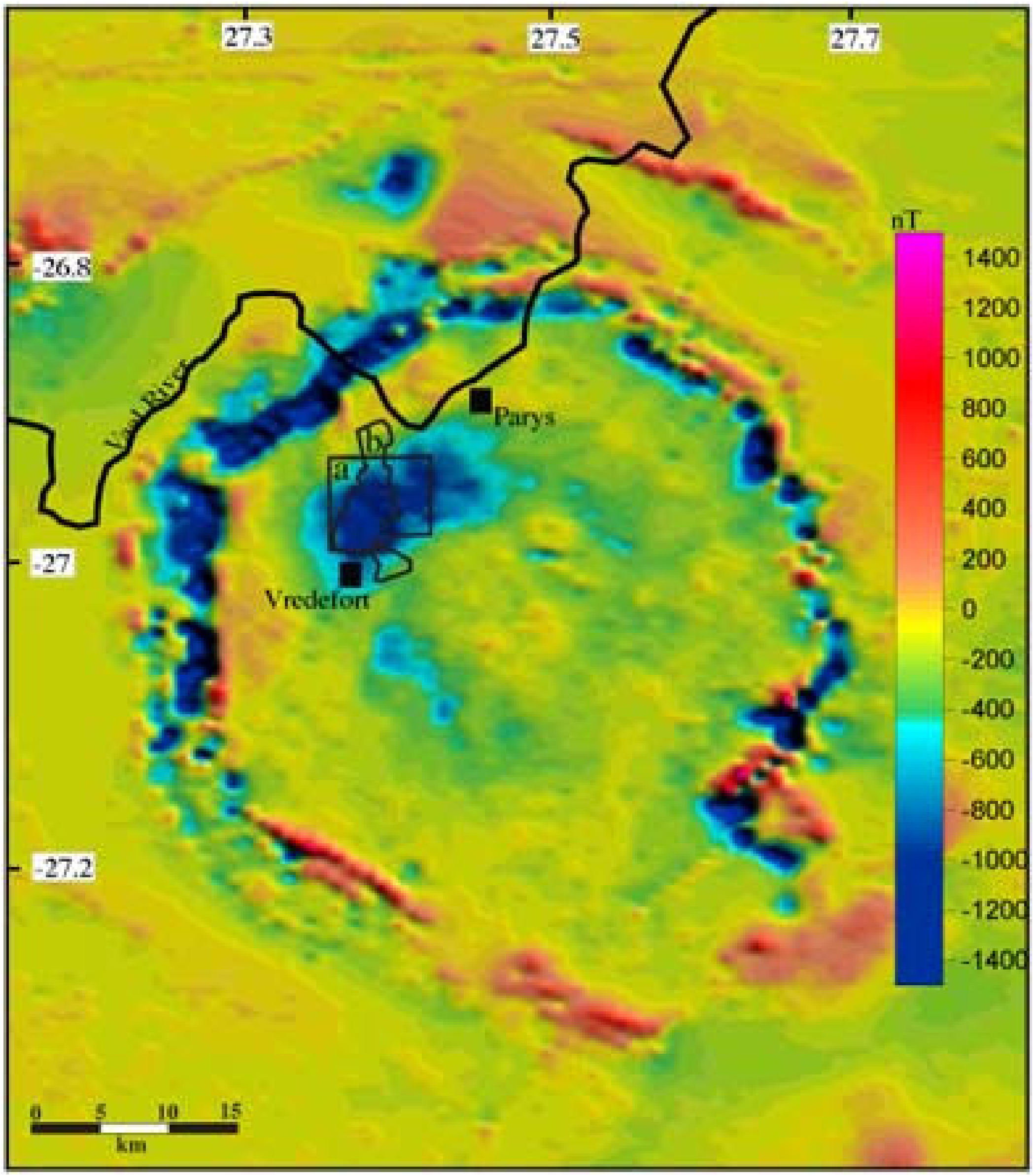

Figure 1.2. Aeromagnetic anomaly map of the Vredefort dome (Patric Cole, personal communications, 2006). The anomaly map was determined by subtracting the IGRF field (for 1977) from the observed data. Areas a) and b) similar to that of Fig. 1.1. The well defined outer negative anomaly is due to West Rand Group shales. The inner negative anomaly (the focus of this study) coincides with the transition from amphibolite to granlite facies rocks (Fig. 1.1).

1.2 Objectives of the project

The core objectives of the project were to : (1) observe variations of the magnetic field across the contacts of different geological units in the study area, (2) determine whether the various geological units have distinct magnetic signatures, (3) determine how the presence of deformation features affects the magnetic field, (4) correlate the ground magnetic data with available aeromagnetic data using an upward continuation algorithm, (5) correlate the results with findings of existing and new palaeomagnetic data of the same area, and (6) perform 2 and 3-dimensional modelling of the magnetic anomaly across the Vredefort basement.

1.3 General geological setting of the Vredefort crater

The crater consists of a core of Mesoarchaean crystalline basement surrounded by a rim of upturned strata of Neoarchaean sediments and volcanics (Dominion Group, Witwatersrand Supergroup, Ventersdorp Supergroup, and Transvaal Supergroup, Fig. 1.1). Rocks of the Karoo Supergroup cover the southern side of the crater.

The crystalline basement is made up of two terrains: (1) an inner core of 3.5 Ga mafic and felsic granulites, collectively known as the Inlandsee Leucogranofels (ILG), and (2) an outer core consisting of an 8 km thick section of 3.0 Ga granite-gneiss, metamorphosed to amphibolite grade, known as the Outer Granite Gneiss (OGG) (Stepto, 1990).

The Vredefort impact crater has been interpreted to expose a cross section through the continental crust (Slawson, 1976), possibly to depths of 36 km (Hart et al., 1990) (Fig. 1.1), and contains the only exposure of the amphibolite-granulite facies transition in the central Kaapvaal Craton. Metapelites in the granulite facies domain a few kilometres from the amphibolite-granulite facies boundary record peak metamorphic conditions of 800–900°C and 5–6 kbar, consistent with the interpretation that this boundary developed at crustal depths of 15–20 km (Schreyer, 1983; Stevens et al., 1997). The amphibolite-granulite facies isograd is recognized as a fundamental boundary within the crust and is commonly considered to designate the transition from middle to lower crustal levels (Schreyer, 1983; Stevens et al., 1997).

The transition from the OGG to the ILG terrain is a complex geological zone. This transition has been variably interpreted as an intrusive contact (Stepto, 1990) and an Archaean tectonic discontinuity subsequently reactivated by impact-related brittle deformation (Hart et al., 1990). More recently, detailed examinations of the metamorphic boundary by Flowers et al. (2003) and Lana et al. (2003) showed that it is a complicated transition zone that preserves an Archaean record of Kaapvaal Craton evolution. Lana et al. (2003) realised that the two terrains share a common tectonometamorphic history in contrast to the interpretation advanced by Hart et al. (1990).

1.3.1 Impact related shock metamorphic and deformation features

During the impact event a number of metamorphic and deformation effects occurred within the rocks of the crater. These phenomena and their different manifestations include the formation of shatter cones, melt breccias (better known as pseudotachylites), and planar deformation features (PDF) in quartz and to a lesser extent in feldspar.

Petrographic and geological observations in the basement rocks indicate that there is a complex interrelationship between the Archean geology and the 2.0 Ga impact-related shock and thermal metamorphic overprint (Reimold, 1990; Hart et al., 1991). The shock and thermal metamorphic effects do not increase progressively towards the centre of the crater as found at other impact structures (e.g. Grieve et al., 1990). In particular, the shock deformation features such as planar deformation features in quartz, reach maximum intensities in the rocks that straddle the amphibolite-granulite transition zone, and then decrease towards the centre of the crater. The thermal metamorphism, on the other hand, shows two peaks. The first also occurs in the rocks close to the transition zone and the second occurs over the centre of the crater (Hart et al., 1991).

The metamorphism in the rocks close to the transition zone manifests itself in the form of mineralogical and textural alterations and the local formation of micro-melts along micro-fractures and PDFs in quartz. The rocks in the inner core (~10 km in diameter) of the crater have been completely recrystallized reaching maximum temperatures of 900ºC (Schreyer, 1983). It is postulated that the evidence for shock deformation (e.g. PDFs) in the inner core of the crater have been obliterated by the intense thermal recrystallization (Hart et al., 1991).

Shatter cones are ubiquitous throughout the collar strata of the Neoarchaean rocks (Lilly, 1981; Albat, 1988; Hart et al., 1991) but less developed in the Mesoarchaean crystalline basement. This can be attributed to the variations in the physical and chemical properties of the different lithologies (Hart et al., 1991). The occurrence of pseudotachylitic breccias is not confined to any particular lithology. The size of the pseudotachylitic breccias ranges from centimetre-scale veins to veins hundreds of metres long. Dressler and Reimold (2004) observed that the pseudotachylitic breccias are more abundant and voluminous in the Mesoarchaean crystalline basement rocks than in the Neoarchaean strata in the rim of the crater. Reimold and Colliston (1994) and Lana et al. (2003) failed to find any notable large slip faults in the Vredefort crater and this led Gibson and Reimold (2005) to conclude that pseudotachylitic breccias are only related to shock melting. Planar deformation features in quartz minerals and other minerals in the Vredefort crater have been extensively discussed by other workers; for comprehensive explanations refer to Reimold (1990), Hart et al. (1991) and Gibson and Reimold (2005).

What is particularly relevant to this study is that in addition to the Archaean magnetite, new magnetite formed during the 2.0 Ga metamorphic event in the rocks that straddle the transition zone (Cloete et al., 1999; Carporzen et al., 2006). The new magnetite occurs in two distinct modes. In the first case it occurs as micron size magnetite particles along recrystallized PDFs in quartz; in the second it occurs in the alteration halos of biotite grains breaking down to chlorite (Cloete et al., 1999).

Although the melts along the PDF's indicate local temperatures in excess of 880ºC (Hart et al., 1991), it is difficult to estimate the regional temperatures attained during impact in the vicinity of the transition zone as all the minerals found in the granites are stable over a wide temperature range (Hart et al., 1990). Carporzen et al. (2006) identified two distinct Verwey transitions in the Vredefort crystalline basement rocks and related them to the two generations (pre- and syn-impact) of magnetite in the Vredefort rocks. The Verwey transition is a transition of magnetite from a conductor to an insulator around 120°K. This is a transition characterized by a change of the crystallographic lattice, when a magnetite crystal changes from an inverse cubic spinel to monoclinic symmetry (Moskowitz et al., 1998; Carporzen et al., 2006). During the transition, the electrical conductivity of the magnetite rises by two orders of magnitude when cooling through 120°K (Verwey, 1939). Heating the basement rocks above ~550-600°C for three minutes or above ~500°C for one hour irreversibly modifies the nature of the Verwey transition. Based on these findings, it is possible that no wholesale heating of the crater occurred above 550-600°C for three minutes or above 500°C for one hour during or since the time of impact. Interestingly, rocks in the transition zone are characterized by a single, or no, Verwey transition, indicating that they might have been heated above 600°C (Carporzen et al., 2006).

1.3.2 Detailed geology of the study area

This study is focused on a well exposed section of the amphibolite-granulite transition that was mapped by Flowers et al. (2003). The geology of this area is very complex, and boundaries between the granites and granulites are difficult to infer (Fig. 1.3). The area is divided into three distinct domains (Fig. 1.3). The *granulite facies rocks* are found in the southern part of the map while the *amphibolite facies* rocks occur in the northern part of the map (Fig. 1.3). A mixture of amphibolite facies rocks, granulite facies rocks and intrusive rocks (e.g. syenite) separates these units and this is collectively known as *the transition zone*.

The major rock types found in the granulite facies zone are mafic granulite and charnockite that outcrop in the southern part of the map and are dominated by plagioclase and clinopyroxene mineralogy (Flowers et al., 2003; Lana et al., 2003). Typically, mafic granulites occur as deformed centimeter to tens-of-meter long inclusions within the charnockitic rocks and are interpreted to be the oldest rocks in the map area (Flowers et al., 2003; Lana et al., 2003). The charnockites are mainly quartz monzonite to quartz monzodiorite in composition. The amphibolite facies rocks are mainly coarse-grained, massive to foliated granitic to granodioritic gneiss that outcrop in the northern area and the predominant minerals are quartz, feldspar, biotite and amphibole with some chlorite (Flowers et al., 2003).

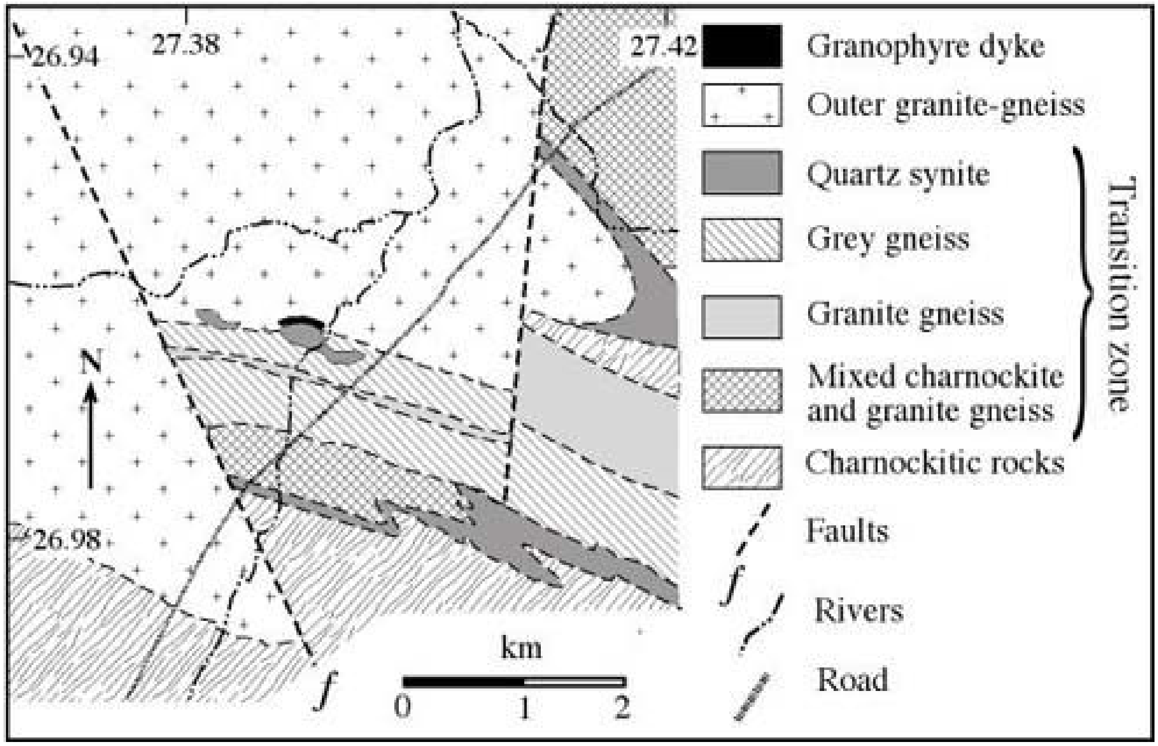

Figure 1.3. Detailed geological map of the amphibolite-granulite transition (from Flowers et al., 2003).

The transition zone between the granulite and amphibolite facies rocks contains grey gneiss, quartz syenite, dolerite dykes, and bronzite granophyre dykes (Fig. 1.3). The grey gneiss is quartz monzonite in composition and contains mafic granulite inclusions; it outcrops as a band between the charnockite and the granulites. Quartz syenites intrude the granite, grey gneiss, and charnockitic rocks. Typically, quartz syenite outcrops as elongate bodies, meters to tens of meters wide that are sub parallel to the granulite and amphibolite facies rock boundary. Dolerite dykes, locally offset by brittle faults and/or pseudotachylite veins, crosscut deformed basement. Undeformed NW-striking impact-related bronzite granophyre dykes, up to 150 m long, crosscut the Outer Granite Gneiss (OGG) and quartz syenite. Regional impact-related faults transect rocks in the basement, are characterized by pseudotachylite breccias, and juxtapose different units and structural orientations. These brittle structures are correlated with impact-related radial faults previously documented in the sedimentary rim of the Vredefort structure (Flowers et al., 2003).

1.4 Previous geomagnetic studies

A regional aeromagnetic survey over the Vredefort crater was flown by the Geological Survey of South Africa in 1977 (now Council for Geoscience) (Fig. 1.2, Corner and Wilsher, 1989). Total field data were collected along north–south flight lines at a nominal terrain clearance of 150 m, flying at 240 km/h and using a sampling interval of two seconds. The flight line spacing was 1 km and perpendicular tie-lines were flown every 10 km. In order to facilitate digital transformation, the data were flight line leveled and block leveled, thus establishing a common datum for all the surveys across South Africa. Arial photography recorded simultaneously with the magnetic data was used to position the aeromagnetic data. The interpolation of the aeromagnetic map was achieved with a grid lattice of 250 m x 250 m. The anomaly map shown in Fig. 1.2 was determined by subtracting the IGRF field (for 1977) from the observed data.

The magnetic anomaly map over the Vredefort structure is characterised by distinctive magnetic patterns (Fig. 1.2). The patterns in the rim are easy to understand as they reflect the different strata. Most prominent in the rim is a strong negative magnetic anomaly that is associated with the West Rand Group shales (Jackson, 1982). Palaeomagnetic studies conducted by Jackson (1982) and Layer et al. (1988) suggest that the Vredefort impact has a bearing on the magnetic anomaly of the shales. See Chapter 5 for discussion on previous palaeomagnetic data, which suggest that the shales were remagnetised at the time of the impact event.

About halfway into the basement there is a prominent negative magnetic anomaly that extends in a broad semicircular belt around most of the basement core. As previously noted, the anomaly has a maximum width of about 4 km in the northwest sector of the basement, but tapers off towards the south along both the eastern and western limbs (Fig. 1.2). The negative anomaly is roughly centered above the region that marks the transition from amphibolite facies to granulite facies rocks (Figs. 1.1 and 1.2). Jackson (1982) noted that the rocks which overlie the basement showed extensive remagnetization which he attributed to melt from the impact body. Corner et al. (1990) postulated that the anomaly is related to a pre-existing mid-crustal layer of magnetite rich granites.

Hart et al. (1995) gave an alternative explanation for the cause of the magnetic anomaly. They speculated that the anomaly could be caused by thermal resetting of remanent magnetism of the granitic basement rocks due to the impact event. 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.

To explain the origin of the inner negative anomaly and shed more light on the validity of the different hypotheses, magnetic modelling of two-dimensional profiles from the current magnetic survey over the study area were carried out. An attempt to explain the absence of a negative magnetic anomaly in the inner-most core of the Vredefort structure (Fig. 1.2) will also be made.