CHAPTER 5: PALAEOMAGNETISM

5.1 Magnetism in Rocks

In order to understand the nature of the problem being investigated, it is necessary to provide information regarding rock magnetism. This summary is largely derived from Blakely (1996), Dunlop and Ozdemir (1992) and Butler (1998).

Magnetization is defined by

$$M = \frac{1}{V}\sum_{i} m_i \qquad 5.1$$

Where the m_i are individual dipole moments and V is the volume of the body.

5.1.1 Types of Magnetization

In rocks, magnetization can also be expressed as the vector sum of all induced and all remanent magnetization components:

$$M = \chi H_0 + M_r \qquad 5.2$$

where χ is magnetic susceptibility, H_0 is induced magnetization, and M_r is remanent magnetization. *Induced magnetization* is the net magnetization acquired by a rock containing ferromagnetic minerals when it is exposed to an external magnetic field. *Remanent magnetization* is permanent magnetisation acquired by a rock when magnetic minerals settle under an external field.

Diamagnetism, Paramagnetism and Superparamagnetism: Most materials are diamagnetic, meaning that their induced magnetic axes are at an angle of 180 degrees to the magnetising force. Some are paramagnetic, in which case the induced magnetic axis is in the same direction as the external field. Superparamagnetism (SPM) occurs when the remanence and coercivity (the strength of the external field required to make the remanent magnetization go to zero) particle decreases within the mineral (Butler, 1998).

Ferromagnetism: Ferromagnetism occurs when all of the magnetic moments in the mineral are aligned parallel to one another (Butler, 1998).

Antiferromagnetism: When equal numbers of atomic moments are aligned in opposite directions such that the atomic moments cancel one another, no net magnetization is produced resulting in antiferromagnetism (Butler, 1998).

Ferrimagnetism: This occurs when one of the following happens: atomic moments are aligned in opposite directions but are not of equal number, or the same number of atomic moments are aligned in opposite directions but have different amplitudes resulting in a small net magnetization (Butler, 1998).

5.1.2 Natural Remanent Magnetism

Remanent magnetism can be acquired in several different ways. These are discussed below. This summary is also derived from Blakely (1996), Dunlop and Ozdemir (1992) and Butler (1998).

Thermoremanent magnetism (TRM)

When a rock cools below the Curie, or blocking, temperature under the influence of an external magnetic field, it acquires thermoremanent magnetization (TRM).

The orientation of the induced field is the same as that of the external field and its intensity depends on the intensity of the external field. Most igneous and high-grade metamorphic rocks acquire TRM (Butler,1998).

Chemical remanent magnetism (CRM)

Chemical remanent magnetization occurs when chemical changes form ferromagnetic minerals below their blocking temperatures in an external magnetic field resulting in the rock acquiring a magnetization. Chemical changes include low-temperature oxidation, exsolution, diagenesis and dehydration, and CRM is most often found in sedimentary rocks.

The way in which this type of remanent magnetization is acquired is similar to the process of TRM in that it involves the growth of new minerals through a critical volume. The main difference is that it depends on a blocking volume rather than a blocking temperature. The blocking volume is the volume at which the relaxation time increases dramatically. Less than this volume, grains grow from the superparamagnetic to the stable single domain state.

Detrital remanent magnetism (DRM)

Detrital remanent magnetization occurs mostly in sedimentary rocks and is acquired during deposition and consolidation of sediments (Butler, 1998). Ferromagnetic minerals in the detritus are partly realigned in the direction of the prevailing magnetic–field (Dunlop and Ozdemir, 1997). There are two kinds of DRM: depositional detrital remanent magnetism, when alignment of original NRM vectors occurs during deposition, and post-depositional detrital remanent magnetism, when alignment occurs after deposition but just before lithification.

Viscous remanent magnetism (VRM)

When a rock is exposed to a weak external field for long enough, it can acquire a magnetization known as viscous remanent magnetization. This secondary magnetization is acquired long after the rock has been formed, and involves the gradual realignment of magnetic moments of grains with relatively short relaxation times. VRM components in rocks are therefore parallel to the present geomagnetic field. It has been observed that grains with relaxazation times less than 10^9 yr are potentially subject to VRM (Butler 1998).

Isothermal remanent magnetism (IRM)

Isothermal remanent magnetization is acquired when a rock is subjected to a large steady field (1-1000 mT) for a short time period (less than a minute) at constant temperature. Lightning strikes are an important source of this form of magnetization. Because outcrops on ridges are prone to lightning strikes, their remanence should be considered with caution as it might have been totally reset. For a magnetic mineral in an external field below approximately 50 nT, IRM involves irreversible domain wall translation. Above 50 nT, IRM is caused by irreversible domain rotation of multi domain (MD) grains or moment rotation of single domain (SD) grains (Butler, 1998).

5.2 Previous palaeomagnetic studies in the Vredefort structure

Previous palaeomagnetic studies in the Vredefort basement have been conducted by Hargraves (1970), Jackson (1982), Layer et al. (1988), Hart et al. (1995), Salminen et al. (2002) and Carporzen et al. (2005).

Hargraves (1970) conducted a palaeomagnetic study of the mafic intrusives (granophyre dykes) in order to determine their age relative to the Vredefort impact event. Based on the palaeomagnetic pole position obtained, he concluded that these rocks were formed (intruded) shortly after the impact event.

Jackson (1982) studied the magnetization of the Archaean basement complex and collar rocks in order to model the magnetic anomalies associated with these rocks. Only 6 of the 18 samples collected (5 samples were from basement rocks and only 1 sample from shale) yielded coherent remanent directions, with a palaeomagnetic pole position that is associated with the 2.0 Ga impact event. He proposed that the magnetization of these rocks were reset as a result of the Vredefort impact event.

Layer et al. (1988) conducted a palaeomagnetic study of shales from the central and western parts of the Witawatersrand basin. From 17 localities, they calculated a coherent remanent magnetization direction and obtained a palaeomagnetic pole defined by the following position: 17˚ N, 46˚ E, k = 22 and α_{95} = 8˚. When they compared this pole with other poles across Southern Africa, they found that it corresponds to the age range from 1950 to 2050 Ma. This suggests that the Vredefort impact event had a bearing on the magnetic signature associated with the West Rand Group shales.

Hart et al. (1995) conducted a palaeomagnetic study of the basement rocks in order to understand a negative magnetic anomaly associated with these rocks. The samples yielded a coherent remanent direction, and this led them to postulate that the basement rocks were reset at the time of the impact event.

Salminen et al. (2002) conducted palaeomagnetic studies of the different lithologies from the Vredefort and Johannesburg domes. The main objective of this study was to use the palaeomagnetic results to aid in the calibration of the apparent polar wander path of the Kaapvaal craton. They found that the NRM directions of the rocks that post-date the impact event were randomly oriented. They interpreted this as a normal phenomenon expected of rocks that have undergone numerous tectonic events. NRM directions of the shales were associated with a coherent direction consistent with the observation made by Jackson (1982) and Hart et al. (1995). Their results were also similar to the observation made by Hart et al (1995) in another respect in that the basement rocks were characterized by high Q values.

Recent studies show that palaeomagnetic measurements on rocks from the floor of the Vredefort crater fall into two distinct groups (Carporzen et al., 2005). Rocks such as impact melts and pseudotachylite that crystallized soon after the impact event were found to have coherent magnetization directions. Pseudotachylites yielded the following parameters: declination, D=25.0º, inclination, I=57.2º, α_{95}=3.9º and NRMs of 6.2 ± 5.7 A/m. Parameter α_{95} is the radius that the mean direction lies within 95% confidence and this is equal to twice the standard deviations of the data (Butler, 1998). The possibility that the true mean is more than α_{95} of the calculated mean is 5 %. Corresponding values for the impact melts are: D=20.8º, I=57.4º, α_{95}=1.9º and NRMs of 1.8 ± 1.4 A/m (Carporzen et al., 2005). All the Archean granite-gneisses on the other hand were found to be randomly oriented and with much higher NRM intensities.

The possibility that lightning may be the cause of the high NRM's and random directions of magnetization in the granite-gneisses has been discussed by Carporzen et al. (2005). Coherent directions were found in 74 % of the impact melt dykes (43 samples from 12 sites) that crystallized after the crater formed. These impact dykes are representative of the area surveyed by Carporzen et al. (2005) for analysis of basement rocks and the results suggest that about 26% of the rocks in the basement have been affected by lightning. Subtracting 26% of the granite-gneiss and granulite samples with the highest intensities yields a range in NRM's from 0.01 to 22.0 A/m (average: 5.7 A/m) and this sub-population still has randomly oriented magnetic directions. What this means is that the samples from basements rocks (granite-gneiss) have high NRM's in general and are randomly oriented even if the samples suspected to have been struck by lightning are removed.

In addition to the above there is another rock type which has magnetization values different to the ones mentioned above. The banded ironstone formation (BIF) yielded the following parameters: declination, D=105.9º, inclination, I=25.9º, α_{95}=20.1º and NRMs of 920 ± 5.7 A/m (Carporzen et al, 2005). This suggests that the BIF either was remagnetised long after the impact event or was not affected by the impact event. It is possible that the BIF was not affected by the impact event since only part of the basement rocks experienced tempetarures above the Curie temperature which could result in resetting of the magnetization (Carporzen et al., 2006).

5.3 Palaeomagnetic results of the samples over the 9 m x 9 m grid

New palaeomagnetic experiments were undertaken in order to help explain the unusually high magnetic anomalies observed by D Jacobs (personal communication, 2005) and in this study. Palaeomagnetic measurements were made on 100 samples taken from the 9 m x 9 m grid over the granulites. The geomagnetic measurements over the same area were presented in Chapter 4. The AGICO JR-5 spinner magnetometer was used to measure the magnetic remanence of the samples and the bulk susceptibility measurements were made using an AGICO KLY-2 kappabridge (see Chapter 2). The samples were collected by L Carporzen who also prepared them for laboratory measurements. However, the author did all the laboratory analyses under the guidance of L Carporzen.

The NRM values and bulk susceptibility are given in Appendix B (Table B1 and B2), and Fig. 5.1 shows stereonet plots of the NRM directions. The NRM directions from the 9 m x 9 m grid are completely random just like the rest of the basement (Fig. 5.1).

The natural remanent magnetization intensities of the samples range from 0.16 to 450 A/m and average of 34.7 A/m. The NRM intensities from the 9 m x 9 m grid are much higher than those reported by Carporzen et al. (2005). As stated above Carporzen et al. (2005) noted that the effect of lightning might have been underestimated in interpreting the values they reported. It must also be made clear here that all the data were taken from exposed outcrops (which are not protected from lightning strikes). Whether or not the high magnetization values observed in the palaeomagnetic data can explain the unusually high magnetic anomalies is the subject of Chapter 6 where 3-D modeling will be performed. However, the random directions associated with these samples makes it difficult to explain the coherent pattern in the geomagnetic data (see Chapter 6).

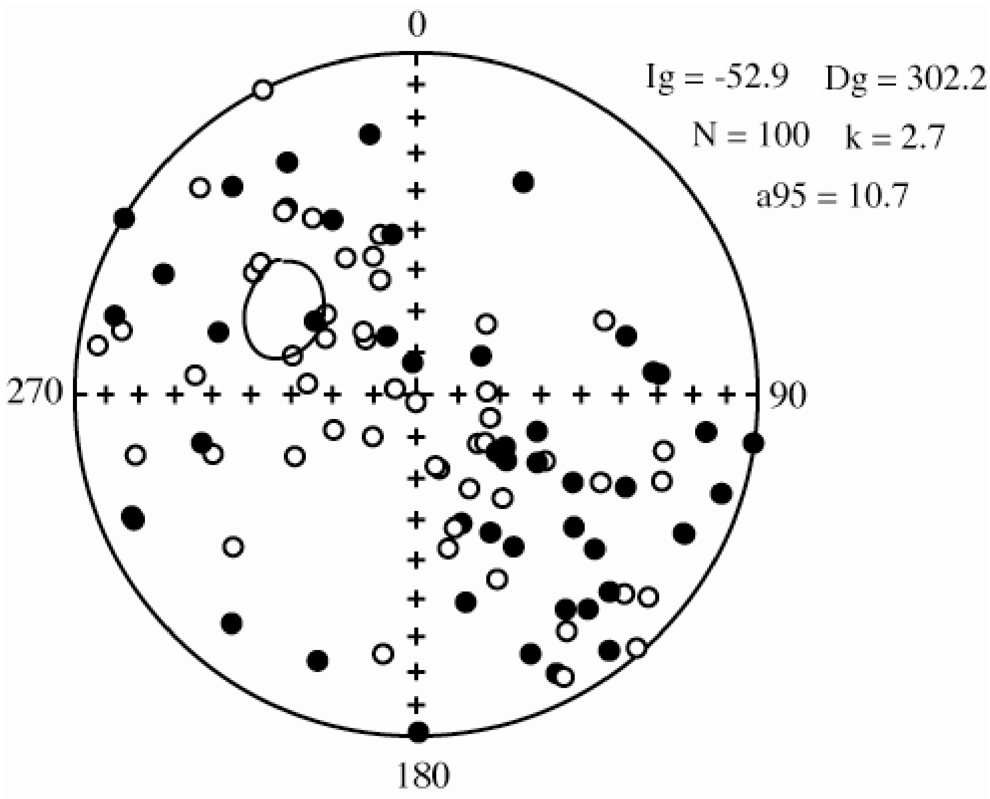

Figure 5.1. NRM directions for the 100 samples collected over the 9 x 9 m grid discussed in Chapter 4. Filled and open circles are lower and upper hemisphere projections of the magnetization component directions respectively. Abbreviations are: Ig and Dg the inclination and declination of the mean direction respectively; k the precision parameter, N the number of samples; a_{95} the confidence limit.

5.3.1 Anisotropy of magnetic susceptibility

In addition to the magnetic susceptibility, the principal directions $k_1 > k_2 > k_3$ of the magnetic ellipsoid of anisotropy were measured. k_1, k_2 and k_3 are commonly known as maximum, intermediate and minimum susceptibility directions.

The following set of equations presented by Jelinek (1981) describes the characteristics of the magnetic anisotropy in terms of ratios between the principal directions:

- Magnetic lineation (which characterizes the intensity of the linear-parallel orientation of ferromagnetic minerals in a rock)

$$L = \frac{k_1}{k_2}$$

- Magnetic foliation (which characterizes the intensity of the planar-parallel orientation of ferromagnetic minerals in a rock)

$$F = \frac{k_2}{k_3}$$

- Percentage of anisotropy (also known as degree of magnetic anisotropy)

$$P' = \left[\exp(2(a_1^2 + a_2^2 + a_3^2))\right]^{1/2}, \text{ where } a_1 = \ln\frac{k_1}{k_b} \text{ and } k_b = \frac{k_1 + k_2 + k_3}{3}$$

- The shape of the magnetic ellipsoid of anisotropy

$$T = 2\frac{\ln k_2 - \ln k_3}{\ln k_1 - \ln k_3} - 1$$

The above sets of empirical relations are pivotal in describing the shape and orientation of the magnetic minerals, known as magnetic fabric. The values of T, which range from -1 to +1, determine the geometry of the magnetic ellipsoid of anisotropy. It is oblate when T is positive. In this case, the magnetic ellipsoid of anisotropy is flattened ($k_1 \sim k_2$ but $k_2 > k_3$) and the magnetic foliation is perpendicular to the minimum susceptibility direction, k_3. It is spherical when T = 0. In this case all the principal directions are equal ($k_1 > k_2$ and $k_2 \sim k_3$). It is prolate when T is negative. In this case the magnetic ellipsoid of anisotropy is enlarged ($k_1 \sim k_2 << k_3$) and the direction of the magnetic lineation is equal to the maximum susceptibility direction k_1, (Hrouda, 1982).

Fig. 5.2a is a stereonet plot showing the directions of principal susceptibilities, Fig. 5.2b is a Flinn diagram (plot of the ratios k_1/k_2 vs k_2/k_3) showing the magnetic lineation and

Fig. 5.2c is a plot of T against P'. Fig. 5.3a shows a strong lineation in a NE-SW direction for the minimum axes and both the maximum and intermediate axes show a NW-SE trend. The Flinn-diagram (Fig. 5.2b) shows that most of the anisotropy ellipsoids have an oblate shape. This is confirmed in the T vs P' figure where T is positive for most samples (95%), indicating that the shape of the anisotropy ellipsoids are oblate. One sample from the T vs P' graph lies on the T = 0 axis implying that the shape of the anisotropy ellipsoid is spherical in this case. The percentage of anisotropy (P') ranges from 0.05 to 0.4 (average = 0.2 ± 0.02). These patterns do not correlate with the directions of the NRM vectors (Fig. 5.1).

It is clear that the highly erratic NRM directions could indicate that lightning might have been responsible. However, the patterns observed in the principal directions of anisotropy could not have been caused by lightning. The metamorphic foliations (~ 45º due West) are parallel to the maximum and intermediate susceptibility directions (Carporzen, 2005 and this study). Such an observation has important implications for the Carporzen et al. (2005) plasma hypothesis. In an attempt to explain the negative magnetic anomaly associated with the basement rocks, Carporzen et al. (2005) conducted a regional palaeomagnetic study across the basement floor. They found that Archaean rocks were characterised by extremely high remanence and randomly orientated remanent vector directions. They explained these phenomena by suggesting that extremely intense randomly oriented magnetic fields (which were due to the impact event) were responsible for causing the randomization of the vectors and producing the high remanence associated with the Archaean rocks. This is the basis of the much talked about plasma hypothesis. Among other things, Carporzen et al. (2005) argued that the principal directions of magnetic anisotropy must have been random due to the plasma generated fields. However this observation is at variance to the data presented here.

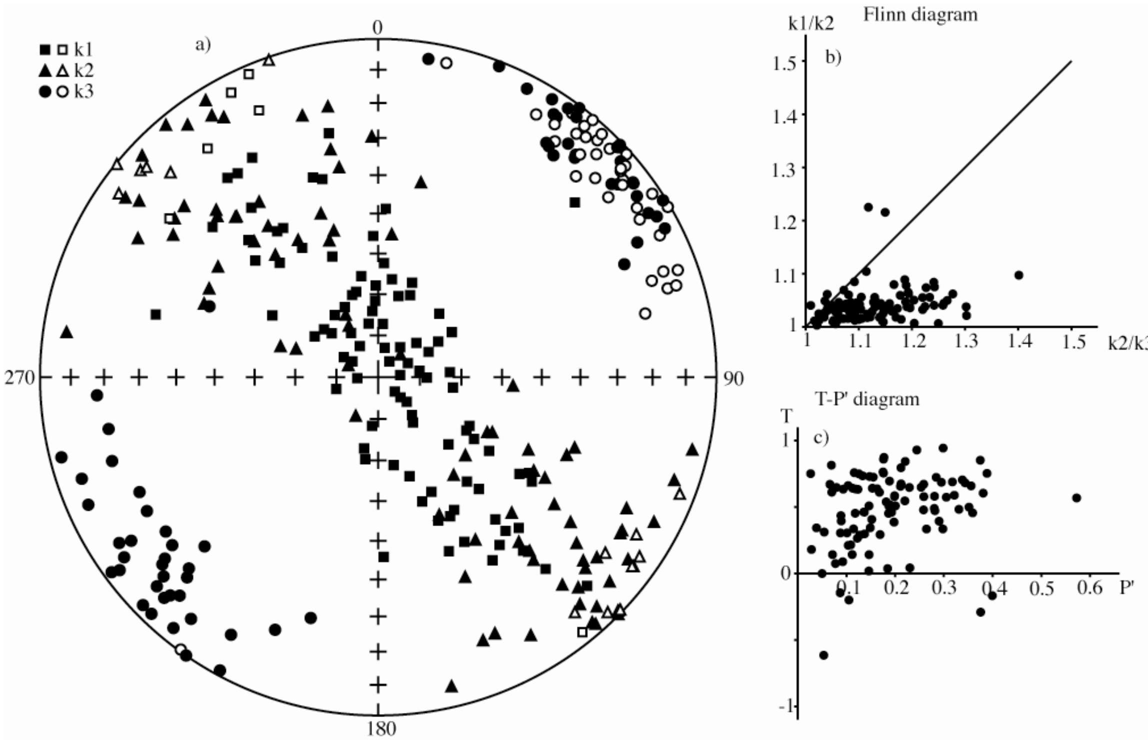

Figure 5.2. Results of the anisotropy of magnetic susceptibility of the 100 samples. (a) Directions of principal anisotropy of magnetic susceptibility axis (k_1, k_2 and k_3). (b) The relation between the magnetic lineation and magnetic foliation. (c) The relation between the magnetic anisotropy degree (P') and the shape of the magnetic ellipsoid of anisotropy (T). In (a) filled and open circles are lower and upper hemisphere projections of the magnetization component directions respectively.

5.4 Interpretation of palaeomagnetic data (current study)

Two patterns have emerged from the palaeomagnetic analysis. The first is characterized by random directions associated with the NRMs of the samples (Fig. 5.1). The second is the lineation that is associated with anisotropy of magnetic susceptibility (Fig. 5.2), in that the trend in the anisotropy data coincides with metamorphic foliation observed in the granulite rocks (Lana et al., 2003).

Clearly the scattered pattern displayed by the NRM data (Fig. 5.1) is typical of lightning strikes but could also be generated by the plasma hypothesis. However, the anisotropy in magnetic susceptibility is less likely to be affected by lightning but it would be affected by the plasma field. The observed patterns displayed by the anisotropy of magnetic susceptibility data (Fig. 5.2) could survive lightning but not plasma, and this is a strong negation of the plasma hypothesis.

Principal directions of the anisotropy of magnetic susceptibility (AMS) can be used to determine current directions from sediment, flow-directions from magma and finite strain directions from rocks that experienced considerable tectonics (Borradaile and Henry, 1997). This also makes it possible to directly infer the metamorphic fabric of granitic rocks from the AMS measurements (Borradaile and Henry, 1997). In this study the principal directions of the AMS were found to coincide with the observed metamorphic fabric which suggests that at least some of the rocks were not heated too high to attain melting at the time of the impact event. This is also in agreement with Carporzen et al. (2006) Verwey transition measurements in the basement rocks that suggest that the basement rocks were not wholly heated above the Curie temperature during or since the time of impact.