AN INTERPRETATION OF MAGNETOMETRIC DATA FROM THE LICHTENBURG AND ZEERUST DISTRICTS, WESTERN TRANSVAAL

BY

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ABSTRACT

A comparison between aeromagnetic and geological data is made in the area bounded by latitude 25°30'S and 26°15'S and longitudes 25°45'E and 26°45'E. Aeromagnetic and ground magnetic data are used to map the dykes, and magnetic, palaeomagnetic and radiometric data are used to determine the relative and actual ages of these dykes.

It was found that several suites of dykes occur within the study area and that the ages of these dykes range from probably pre-Bushveld Complex to probably post-Karoo. A significant proportion of the known dykes appear to be post-Karoo. The major dyke directions correlate with joint directions in the Chuniespoort Group and also with the present-day stress field.

Four grabens have been previously identified in the area, and it is shown that there are several other structures which have characteristics in common with these known grabens.

SAMEVATTING

'n Vergelyking is tussen lugmagnetiese en geologiese data getref in die gebied begrens deur breedtegraad 25°30'S en 26°15'S en deur lengtegraad 25°45'O en 26°45'O. Lugmagnetiese en grondmagnetiese data is gebruik om 'n kaart van gange in die gebied op te stel en magnetiese, paleomagnetiese en radiometriese data is gebruik om die relatiewe en absolute ouderdomme van hierdie gange te bepaal.

Daar is gevind dat verskeie ganggroepe in die studiegebied voorkom en dat die ouderdomme van hierdie gange wissel tussen ongeveer voor-Bosveldkompleks en moontlik na-Karoo. 'n Betekenisvolle hoeveelheid van die gange is skynbaar na-Karoo. Die hoof gangrigtings korreleer met die rigting van naatsisteme in die Chuniespoort Groep en ook met die hedendaagse spanningsveld in die studiegebied.

Vier grabens is voorheen geidentifiseer in die studiegebied. Dit is nou aangetoon dat verskeie ander strukture voorkom wat soortgelyke eienskappe as hierdie grabens besit.

CONTENTS   PAGE

CONTENTS PAGE

TABLES

CONTENTS

PAGE

FIGURES

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1. INTRODUCTION

This study concerns the outcrop pattern and possible ages of dykes in the Lichtenburg and Zeerust districts, Western Transvaal (Figure 1), as determined from magnetometric, photogeological, palaeomagnetic and geochronological data. The relationships between the country rock and the anomalous magnetic field are also discussed.

Maps of the dyke positions were produced from aeromagnetic and photogeological data. Follow-up ground work was conducted during the winter months of 1976 and, together with four later brief excursions to the field, took four and a half months to complete. Palaeomagnetic work was carried out in the Geological Survey's palaeomagnetic laboratory under the guidance of Dr D I Henthorn, and three samples of dyke material were dated radiometrically by F M Consultants. The magnetic anomalies were modelled using the IBM 370 computer at the Department of National Education.

The study area includes part of the Transvaal Highveld with a mean elevation of approximately 1 500 metres above sea level. The generally subdued relief is broken only by chert-capped hills and,in the north of the study area, by the more resistant rocks of the Pretoria Group which form the Swartruggens range. Despite the general lack of relief, the study area contains the watersheds separating the Orange,

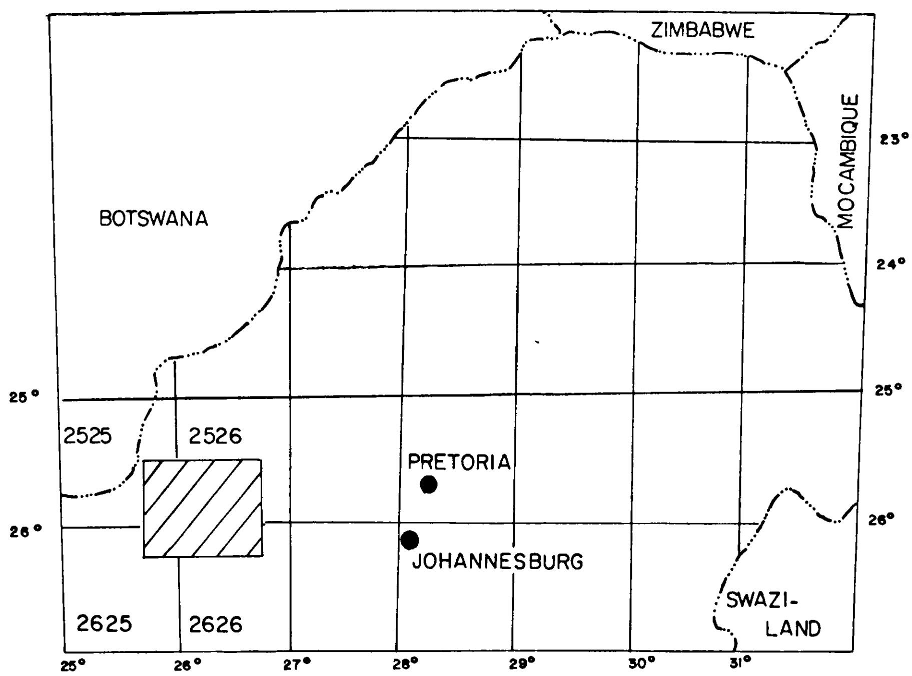

Figure 1: Study area location diagram

Limpopo and Molopo river basins. Numerous springs are present in the dolomite and the Molopo, Malmani and Groot Marico rivers all have springs at their sources (Hall and Humphrey, 1910, pp. 10 to 14).

Several farms in the Western Transvaal are irrigated using groundwater pumped from the dolomite and the Department of Water Affairs is concerned about this use of groundwater as urban water supplies drawn from springs may be affected. Part of the Department's study of the water stored in the dolomite is to identify the different groundwater compartments. These compartments are generally bounded by dykes (Enslin, 1971, p.1; Schutte, 1975?, p.1).

The dykes are very poorly exposed, but can readily be identified using magnetometric and photogeological data. Data from three aeromagnetic surveys are available and photogeological coverage of the study area is provided by jobs 493, 669, 754 and 759, and by semi-controlled photomosaics, which were compiled in 1966 and 1969 by Map Studio Productions (Pty) Ltd as base maps for two of the airborne geophysical surveys.

2. PREVIOUS WORK

Geological interest in the area began in the 1870's with the discovery of the Malmani goldfields. Later, the discovery of diamonds in placer deposits and in kimberlite dykes, and the presence of lead, zinc and fluorspar mineralisation prompted localised exploration which continues to the present day. In 1908 Hall and Humphrey produced one of the first geological maps covering part of the study area, but coverage was not completed until 1951 when the Lichtenburg sheet (Von Backström et al., 1953) was released. Recently, the study area has been completely remapped by MacCaskie (1976), Wilson (1977), Young (1977), Callow (1978), Clubley-Armstrong (1978) and Davies and Prévost (1978). Lithostratigraphic terminology was used in these later maps and for the first time many of the dykes have been mapped.

The earliest geophysical survey in the area was vertical component magnetic field measurements by the Geological Survey in the early 1950's (Mr J F Gordon-Welsh, pers. comm.). Later, the Department of Water Affairs carried out total field measurements with a proton magnetometer (Dr M P Mulder, pers. comm.). In both cases, the object was to identify dyke positions, but in neither case was the data ever compiled into a report. The Geophysical Division of the Geological Survey has been sporadically active in the study area with gravity, magnetic, electromagnetic and electrical surveys (Hauger, 1972; Darracott, 1973; Palmer, 1978; De Wit, 1978; Stettler, 1979). Hauger (1972) has produced a dyke outcrop map covering a limited area in the Western Transvaal and the Department of Water Affairs has also compiled its own maps of other small areas.

The airborne geophysical surveys of 1966, 1969 and 1971 provided regional coverage of a large part of the Western Transvaal. Both the 1966 and 1971 surveys were specifically intended to map dykes and only a magnetometer was installed in the aircraft. The 1969 survey was part of the project to obtain countrywide aeromagnetic and radiometric coverage and a spectrometer was, therefore, installed in addition to the magnetometer. From the aeromagnetic survey data Richards (1973a) produced a map of the dykes in the Lichtenburg-Zeerust area, and Enslin (1971) constructed a similar map showing the dykes outcropping in the dolomite between Rooigrond and Johannesburg. Both maps were compiled using positionally incorrect aeromagnetic data (Richards, 1973b) and were later partly recompiled in greater detail after the aeromagnetic data had been corrected (Richards and Day, 1975; Day, 1976a; Day, 1977a). The earlier (incorrect) airborne geophysical maps have unfortunately also been used extensively by the Department of Water Affairs in compiling their maps.

It is important to note that although a very great deal of ad hoc geological and geophysical work has been done by both the Department of Water Affairs and the Geological Survey, very little of this work has been adequately documented because the work was mainly directed at very local problems for which a full report was often not necessary. As a result, it is difficult to assess the reliability of much of the existing data which has often been copied and recopied so that the original source is completely unknown.

3. STRATIGRAPHY AND STRUCTURAL GEOLOGY

The geological units present in the study area are listed in Table 1 and their outcrop distribution is illustrated in Figure 2*. Farms mentioned in the text are also shown in Figure 2*.

Table 1 : Stratigraphic table

		Superficial Deposits
Ecca Group Dwyka Formation		Karoo Sequence
Daspoort Formation Strubenkop Formation Dwaalheuwel Formation Hekpoort Formation Boshoek Formation Timeball Hill Formation Rooihoogte Formation	Pretoria Group	Transvaal Sequence
Penge Formation Malmani Subgroup	Chuniespoort Group	Transvaal Sequence
Black Reef Formation		Transvaal Sequence
		Ventersdorp Supergroup
		Witwatersrand Supergroup
		Gaborone Granite
		Archaean Granite

3.1 ARCHAEAN AND GABORONE GRANITES

Archaean granite-gneiss, which is the product of granitisation 3 100 Ma ago (Van Eeden, 1972, p.12), outcrops to

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the south-east of Lichtenburg. The Gaborone Granite outcrops in the west of the study area and is 2 900 to 3 000 Ma old (Van Eeden, 1972, p.14).

3.2 WITWATERSRAND SUPERGROUP

Witwatersrand Supergroup rocks are not exposed in the study area, but sedimentary rocks of the lower portion of the Witwatersrand Supergroup have been recovered from two deep boreholes. One borehole was sited on a positive magnetic anomaly on Tweefontein 441JP near Mazista (Figure 2) and intersected these sedimentary rocks at a depth of 2 912 metres (Martini, 1976, p.2). The second borehole (Davies and Prévost, 1978, p.5) was sited on a negative magnetic anomaly on the farm Twee Buffels Geschiet 42IP (Figure 2). It intersected Witwatersrand Supergroup shales at 1 049 metres and the shales with subordinate quartzite were still being recovered when the borehole was stopped at 1 411 metres (Davies and Prévost, 1978, p.5).

3.3 VENTERSDORP SUPERGROUP

Quartzite, tuff, tuffaceous sedimentary rocks, volcanic breccia and andesitic lavas of the Ventersdorp Supergroup outcrop near Lichtenburg. Andesitic and acid lavas outcrop in the west of the study area (Davies and Prévost, 1978, p.7). The relationship between the acid and andesitic lavas is not known. The acid lavas have been classified as part of the Ventersdorp Supergroup (Hall and Humphrey, 1910, pp. 43-44; Davies and Prévost, 1978, p.7), the the Dominion Group (Van Eeden, 1972, p.15) and the Zoetlief Formation (Callow, 1978). A quartz porphyry near Lobatsi has been dated at 2600 Ma by Van Niekerk (Van Eeden, 1972, p.14), and it is assumed to be of the same age as the porphyries underlying the Transvaal Supergroup south of Lobatsi (Van Eeden, 1972, p.14). An age in excess of 2 600 Ma has been suggested for the Ventersdorp Supergroup (Van Niekerk and Burger, 1978, p.161), and the acid lavas, which are of similar age, seem likely to be part of the Ventersdorp Supergroup.

3.4 TRANSVAAL SEQUENCE

Volcanics and sedimentary rocks of the Transvaal Sequence were probably deposited from slightly before 2 300 Ma ago to about 2 100 Ma ago (Button, 1976, p.263). In the survey area these rocks are represented by the Black Reef Formation, Chuniespoort Group and the Pretoria Group.

The Black Reef Formation consists of conglomerates, quartzites and shales which rest unconformably on an irregular floor of older rocks.

Dolomite and chert with subordinate shale and limestone form the Chuniespoort Group which is subdivided into the Malmani Subgroup and the Penge Formation. The Penge Formation is mainly represented by remnants of basal banded chert which becomes more ferruginous upwards (Davies and Prévost, 1978, pp.9 and 15). Ironstone of the Penge Formation is present in the west (Young, 1977, pp.5 and 6).

In the survey area an unconformity separates the clastic sedimentary rocks of the Pretoria Group from the mainly chemical sedimentary rocks of the Chuniespoort Group. Seven formations of the Pretoria Group outcrop in the study area, the oldest being the Rooihoogte Formation which consists of a basal conglomerate, shale and quartzite. In addition a banded ironstone is developed to the west of a palaeoridge on Rhenosterfontein 304IP (Davies and Prévost, 1978, p.17). Overlying the Rooihoogte Formation are shales and quartzites of the Timeball Hill and Boshoek Formations, above which are meta-andesites of the Hekpoort Formation. The Strubenkop Formation comprises cordierite-biotite slate with interbedded ferruginous quartzite and garnetiferous ironstone. Quartzite and siltstone of the Daspoort Formation are the youngest rocks of the Transvaal Sequence in the study area.

3.5 KAROO SEQUENCE

Tillite and shale of the Karoo Sequence outcrop near Lichtenburg and together attain maximum thicknesses of about 100 metres on Graslaagte 37IP and about 70 metres on Rietdraai 51IP. These horizons thin towards the north-east (Von Backström et al., 1953, p.18). Shales recovered from boreholes on Blaauwbank 119JO and Grootfontein 115JO have also been tentatively identified as part of the Karoo Sequence (Davies and Prévost, 1978, p.18). Outliers of Karoo rocks have been preserved in palaeosinkholes, and in a graben on Rhenosterhoek 343JP (Davies and Prévost, 1978, pp. 18 and 29).

3.6 TERTIARY AND RECENT COVER

Extensive superficial cover consisting of sand, red soil, alluvium, diamondiferous gravels and calcrete is present, especially in the south-west of the study area.

3.7 IGNEOUS INTRUSIONS

Many sills have intruded the Pretoria Group and they may be divided into those which predate the Bushveld Complex and those which are contemporaneous with the Complex

(Clubley-Armstrong, 1978, pp.26 and 27). Discordant intrusions are common throughout the area and both pre-Karoo and post-Karoo dykes are recognized (Clubley-Armstrong, 1978, p.24; Young, 1977, p.12; Martini, 1974, p.5). The dykes may, however, all be composed of diabase and have been intruded during the same event (Wilson, 1977, p.48). Mid-Cretaceous kimberlite dykes outcrop near Swartruggens (Allsopp and Barrett, 1975, p.613).

3.8 STRUCTURAL GEOLOGY

Granitic basement and rocks of the Witwatersrand Supergroup form the undulating floor on which the lavas and sedimentary rocks of the Ventersdorp Supergroup were unconformably deposited. Another unconformity separates these rocks from those of the Transvaal Sequence which were deposited in a linear basin with its axis striking roughly east-north-east (Visser, 1970, p.76). This axis direction is reflected in both older and younger Proterozoic sedimentary basins and in the tectonic strike of the basement complex (Pretorius, 1974, p.3). The sediments and volcanics of the Transvaal Sequence dip gently to the north and east towards the basin centre which is occupied by the Bushveld Complex.

Two directions of regional folding are present (Pretorius, 1974, p.6). One direction, the Vaal Trend, is north-easterly.

The Lichtenburg anticline (Pretorius, 1974, p.7), also known as the Griqualand-Transvaal axis (Mayer, 1973, p.184), is a member of this trend and strikes east-north-east through the study area. The other regional folding direction, the Orange Trend, is north-westerly and includes the Koppies continental arch (Pretorius, 1974, p.7).

Faulting is commonly parallel with the fold axes and with the axes of the depositional basins. The most important faults are those parallel with the Vaal Trend (Pretorius, 1974, p.8). In the study area only the Zeerust fault is parallel with the Vaal Trend but several magnetic lineaments do have an east-north-easterly strike. The north-north-westerly fault trend is more obvious and the most prominent feature with this trend is the Groot Marico (Mr D R MacCaskie, pers. comm.) or Bokkraal (Wilson, 1977, p.58) fault zone. Several dykes striking east-south-east, north-west and east-north-east are displaced dextrally by this fault zone.

Karoo rocks overlie the older rocks unconformably. Post-Karoo tectonic activity includes the formation of "trough-structures" (Wilson, 1977, p.50) or grabens (Davies and Prévost, 1978, p.28). Wilson names these structures the Strydfontein Trough, the Doornplaats Trough, the Diepholte

Trough and the Mabaalstad Trough (Figure 2). According to Wilson (1977, pp.51 and 52), each trough is composed of a graben and a syncline which vary in relative importance along the length of the trough, but which cause very little overall displacement of the strata.

An extension of the Mabaalstad Trough (Figure 2) to the east of the study area shows the possibility of larger movements than the 10 to 15 metres estimated by Wilson (1977, p.52). Here a conglomerate bed has been displaced 500 metres westwards within the "trough" (Mr A R Clubley-Armstrong, pers. comm.). Since the sediments dip eastwards at 10° near the "trough" the apparent lateral displacement requires a downthrow of approximately 90 metres.

Drilling of the Diepholte Trough on Rhenosterhoek 343JP (Figure 2) also shows that the throw is far greater than that suggested by Wilson. One of the boreholes intersected tillite of the Dwyka Formation from 44 to 52 metres, with dolomite below 52 metres (Davies and Prévost, 1978, p.29). A sequence of clays, sand and coal overlie the tillite. The linear depression controlled by the downfaulted block is some 50 metres below the surrounding dolomite ridges and so a minimum of 100 metres downthrow is suggested by the borehole data. Similarly, borehole data from Witrand

325JP (Figure 2) indicate a downthrow of at least 90 metres into the Strydfontein Trough (Davies and Prévost, 1978, p.29). Weathered dyke material was recovered in the same borehole (Davies and Prévost, 1978, p.29). It thus appears that the "troughs" recognized by Wilson are primarily grabens as suggested by Davies and Prévost, and the use of the term "graben" is preferred for this study.

A related feature may be present on Grootfontein 115JO (Figure 2) (Davies and Prévost, 1978, p.29) where a borehole was sited over the intersection of the Trekdrif and Grootfontein dykes. No igneous material was recovered and the borehole was still in shales of Karoo type at 90 metres. Three nearby boreholes drilled by the Department of Water Affairs, however, reached dolomite within four metres (Mr J E Palmer, pers. comm.).

4. DATA AND INTERPRETATION PROCEDURES

4.1 AEROMAGNETIC AND PHOTOGEOLOGICAL DATA

4.1.1 Aeromagnetic survey details

Three aeromagnetic surveys together provide complete coverage of the area of interest (Figure 3). The flight line direction is north-south for the airborne surveys of 1966 and 1969 (3/66 and 7/69) and east-north-east to west-south-west for the 1971 survey. The flight lines are spaced approximately 2 kilometres apart for the 1966 survey, 1 600 metres apart for the 1969 survey and 1 kilometre apart for the 1971 survey, and all surveys were flown with a nominal terrain clearance of 150 metres. The total magnetic field was measured at one second intervals and so (since the specified maximum speed of the survey aircraft was 240 km/h) the maximum horizontal distance separating data samples should be 67 metres. The 1966 and 1969 data were recorded as analogue traces which were used in the compilation of aeromagnetic contour maps. The 1971 data were recorded digitally and these data were plotted as computer generated profiles, but not as contour maps.

A tracking camera in the aircraft recorded the flight path, and synchronising fiducials were marked simultaneousqualitative interpretation of the data was completed. This interpretation is discussed in section 5.

Linear magnetic features produced mainly by dykes dominate the aeromagnetic maps. These features were studied in considerable detail and a map of the dyke positions is given in Figure 4* (which can also be used as an aeromagnetic contour map overlay for Figure 2*).

Werner's 'E' line method was used to determine the dyke centres from the aeromagnetic anomalies. This technique is accurate where the anomaly is clearly defined, and is produced by a thin dyke (i.e. width $<$ depth; Parker-Gay, 1963, p.186) but becomes subject to some uncertainty where the aeromagnetic anomalies overlap or are of low amplitude.

Body centre positions are generally most accurately located where the flight line crosses the dyke at right angles, so that the east-west striking bodies are best defined by the north-south flight lines of the surveys of 1966 and 1969, and the north-south striking bodies are best defined by the east-north-east to west-south-west flight lines of the 1971 survey.

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Proportional dividers were used to transfer the positions of the dykes from the analogue aeromagnetic records to the 1:50 000 scale flight line maps. This procedure may involve errors of up to 50 metres in the dyke positions on the interpretation maps. This degree of accuracy is, however, obtained only at the points where the dykes cross the flight lines and where the anomaly is clearly recognizable.

The dykes generally showed as thin tonal features on aerial photographs which were thus used in tracing the dyke positions in the regions between the flight lines. Other photolineaments of apparently similar nature, but without associated magnetic anomalies were also mapped. Non-magnetic lineaments can be the result of fractures, faults, quartz veins or dykes.

In the absence of photogeological evidence, aeromagnetic anomalies were correlated between flight lines on the basis of anomaly shape, size, amplitude and alignment.

Semi-controlled photomosaics were extensively used as they had the advantages of a quarter-degree square format and a scale of approximately 1:50 000. A shortcoming of the mosaics was a mismatch along the boundaries of the aerial photographs used in compiling the mosaics. Repetition of detail was detected in several places and it is consequently inferred that corresponding loss of detail has also occurred. Orientation of the interpretation map was done with the aid of reference fiducial points which were common to both aeromagnetic maps and photomosaics. Topographic detail also assisted positioning.

Interpretation maps 2526CB (Groot Marico) and 2526DA (Swartruggens) in the north-east of the area (Figure 3) were not as rigorously treated as the other quarter degree square maps, and were largely compiled from interpretation of the contoured aeromagnetic maps and from the geological field sheets of MacCaskie (1976) and Clubley-Armstrong (1978). Extensive reference was made, however, to the analogue magnetic records, especially those covering map 2526CB (Groot Marico).

4.3 GROUND MAGNETIC DATA

Total field proton magnetometers were used to measure the earth's magnetic field. Most of the work was carried out with a Chemtron G2 magnetometer but a Geometrics G826 magnetometer was also used. Both magnetometers measure the earth's field to within ± 1 nT (approximately one part in 30 000). Reading repeatability was not always within this range as near-surface (short wavelength) magnetic noise of up to 30 nT amplitude was present in several places and so any slight movement of the sensor head would produce a variation between readings.

Both the Chemtron and Geometrics magnetometers were used to test the effect of different sensor-staff lengths on the attenuation of surface magnetic noise and it was found that staff length had very little effect (Day, 1976b, p.2). Initially, therefore the sensor was mounted on a two metre long staff supplied and at least two readings taken at every station, which were twenty five paces (about 20 metres) apart. Later, it was recognized that the magnetic noise was not omnipresent throughout the survey area with the result that the more convenient backpack mode was preferred. Readings, with occasional checks, were then taken every ten paces. The backpack mode proved faster to use and the closer station spacing offset the adverse effects of a very slightly higher noise level. Station spacings of as little as two metres were used where high resolution of magnetic features was required.

Magnetic storms are quite rare and only one day's work was lost through sudden magnetic field variations, which in this case seemed to be associated with an electrical storm. Because the traverses were generally short and the anomaly amplitudes were quite high, diurnal drift corrections were not usually applied to the data. Diurnal drift was monitored by returning occasionally to a local base station and was taken into account only where contouring or isometric projection were used in presenting the data (Day, 1976b; Day, 1976c).

Some of the magnetometric data collected by the Geological Survey during 1973 and 1974 were also examined. A total field proton magnetometer was used during this work, and so an almost direct comparison with the data presented here was possible. Although nothing is known about the monitoring of the diurnal drift, similar results were obtained where traverses coincided with those of the present survey. However, because of the time difference between the two sets of data, the results of the present survey are, as expected, several hundreds of nT lower than those of the earlier survey.

4.4 INTERPRETATION OF GROUND MAGNETIC ANOMALIES

Quantitative interpretation was limited to the linear magnetic anomalies produced by the dykes. Two main methods of interpretation were used to obtain depth, width, susceptibility contrast and dip estimates. These two methods were developed by Bruckshaw and Kunaratnam (1963) and by Koulomzine, Lamontagne and Nadeau (1970), and both methods assume that the causative bodies are uniformly magnetized, flat topped, semi-infinite, parallel-sided slabs.

The method of Bruckshaw and Kunaratnam (1963) involves measuring distances between characteristic points on the anomaly profile to obtain seven separate depth estimates. Ratios of three or four of the characteristic lengths are used to find the width:depth ratio and characteristic angle, from which depth factors are derived. The accurate determination of these ratios is, therefore, critical and for the anomalies examined it was found that the maximum-minimum distance was particularly crucial to the calculations. Unfortunately the anomaly minima were usually not well defined and so their positions could not always be accurately located. Similarly the background magnetic field chosen has a significant effect on the positions of the characteristic points, and this will also affect the values of the interpreted parameters.

The method of Koulomzine, Lamontagne and Nadeau (1970) involves separating the symmetrical and antisymmetrical components of the magnetic anomalies. Characteristic distances measured on the two component curves are then used to calculate two independent sets of depth and width estimates. The characteristic angle is derived from comparing the maximum amplitudes of the two components and therefore only one estimate of apparent dip can be obtained. The susceptibility contrast can be calculated by substituting the previously derived parameters into the anomaly equation. The accuracy of the susceptibility calculation depends heavily on the accuracy of the depth, width and dip calculations. These in turn depend on the accurate determination of the body centre and the regional magnetic field. If the regional and/or the body centre are in error the two components of the anomaly will produce irreconcilable results (Reford, 1978, p.35). Calculations may be made for several different body centres until consistent results are obtained. If a regional field of uniform slope is superimposed on the anomaly, its effect will appear in the antisymmetrical component (Reford, 1978, p.28). The symmetrical component is unaffected.

Werner's 'E' line method was usually suitable for locating body centres on the aeromagnetic profiles where the sensor's height above the magnetic body is generally about 150 m, but it may not be satisfactory when interpreting ground magnetic data. For the ground traverses, Lamontagne's conjugate point method (Koulomzine et al., 1970, p.820) was used as it is applicable to both thick and thin dykes provided that the bodies have horizontal tops. Logachev's construction (Koulomzine et al., 1970, p.817) was then applied to determine the regional magnetic field. Both the Koulomzine and the Bruckshaw interpretation methods are adversely affected if the body producing the anomaly has limited depth extent, since both methods have been developed for bodies of infinite depth extent.

No account was taken of possible demagnetization effects in any of the calculations. By neglecting demagnetization in thin dykes, erroneous thickness and dip-angle estimates may be expected but the body centre position and depth estimate are unaffected (Parker-Gay, 1963, p.188).

Richards (1975) produced a simple graphical method for determining the depth-to-top of thin dykes, and the method was used where applicable as a check on the interpretation results.

Curve matching was also used to check the interpretation results. A set of standard curves was available and was used where necessary. This set of curves is an expansion of Reford's set (1964) and shows the magnetic anomaly expected over inductively magnetized thin dykes with various strikes and dips at a magnetic inclination of -60°. Also, several anomalies were modelled using a computer program by Talwani and Heirtzler (1964). Modelling and curve matching sometimes proved to be the only method of obtaining satisfactory results.

Filtering and upward continuation were applied using established computer programs before interpreting some of the magnetometric data. These operations were used in an attempt to subdue noise.

The dip of the body was calculated from the characteristic angle by assuming the dyke was magnetized in the direction of the earth's magnetic field and by following the rules outlined below.

The formula derived by Reford (1978, p.14) for the anomaly produced by an inductively magnetized dyke is:

$$\Delta T = 2kTb^2 \sin d.(\theta.\sin(2I-d)+\ln R_2/R_1.\cos(2I-d))$$

where

k   is the susceptibility contrast

T   is the earth's magnetic field strength

b   is the component in the XZ plane (a vertical plane containing the traverse) of the unit vector in the total field direction d   is the dip of the magnetic body (positive downwards from the positive x-axis)

R_1 and R_2 are the distances to the edge of the dyke from a point 'x' on the traverse line

θ   is the angle between 'R_1' and 'R_2'

I   is the inclination of the earth's magnetic field (i) when projected into the XZ plane (Figure 5).

The formula can be rewritten (Reford, 1978, p.16).

$$\Delta T(x)=A.\emptyset(x)+B.\lambda(x) \text{ where } \emptyset(x)=\theta$$
$$\lambda(x)=\ell n.{}^{R_2}/R_1$$

By convention, x is positive to the north of the body.

Now $\emptyset(x)=\emptyset(-x)$ and is always positive

$$\lambda(-x)= - \lambda(x);\ \lambda(x)\geqslant 0 \text{ when } x\leqslant 0$$
$$\lambda(x)\leqslant 0 \text{ when } x\geqslant 0$$

and, for an observed anomaly

$A.\emptyset(x)=A.\emptyset(-x)$ and is positive if A is positive but negative if A is negative.

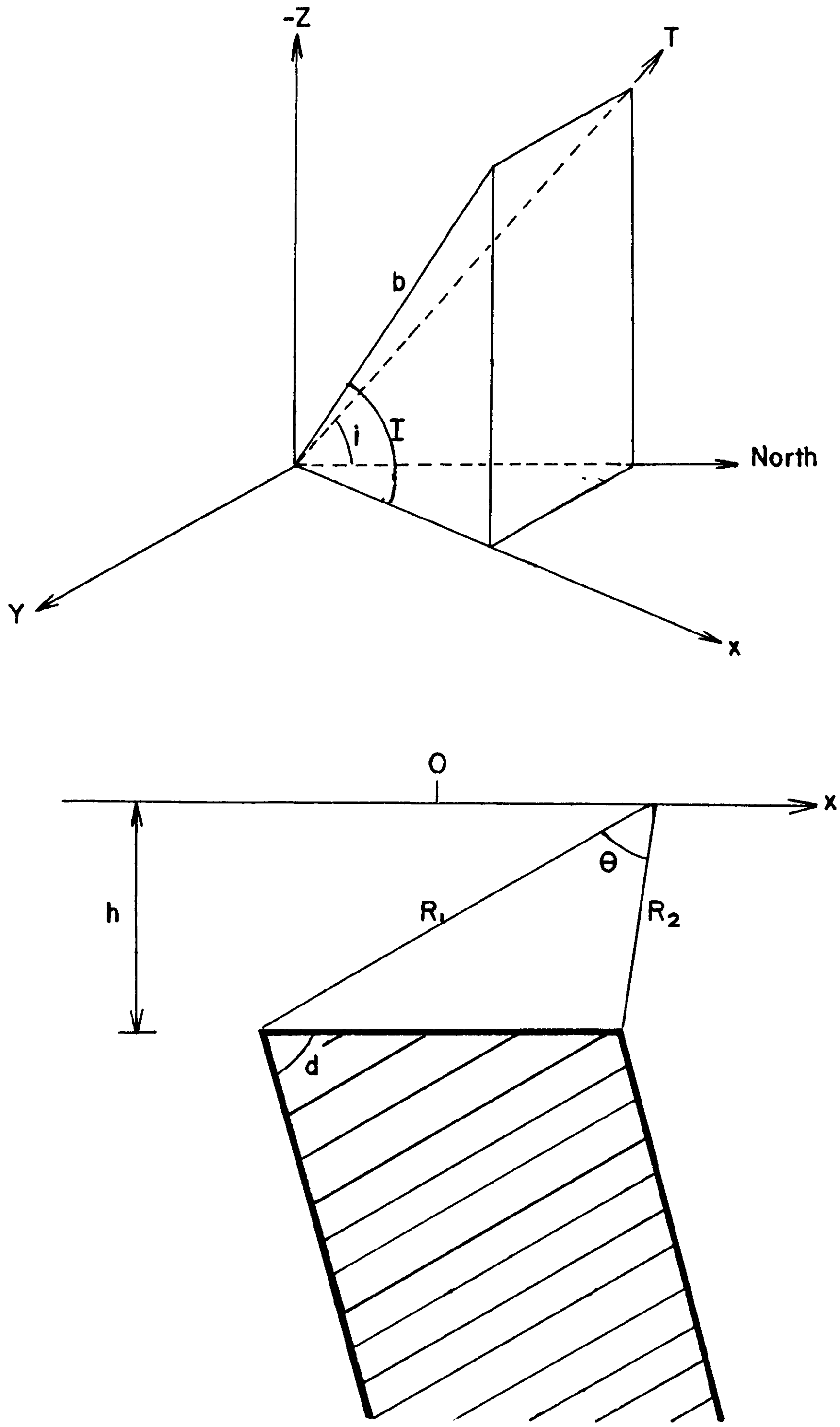


Figure 5 : Dyke geometry

$B.\lambda(x) = -B.\lambda(-x)$; $B.\lambda(x) \geqslant 0$ when $B \geqslant 0$ and $x \leqslant 0$

or when $B \leqslant 0$ and $x > 0$

$B.\lambda(x) \leqslant 0$ when $B \geqslant 0$ and $x \geqslant 0$

or when $B \leqslant 0$ and $x \leqslant 0$

It is thus possible to determine the signs of A and B by inspection of the symmetric $\emptyset(x)$ and antisymmetric $\lambda(x)$ anomaly components (Reford, 1978, p.32).

Now $A = 2kTb^2.\text{sind}.\sin(2I-d)$

and $B = 2kTb^2.\text{sind}.\cos(2I-d)$

so that the signs of 'A' and 'B' are determined solely by the characteristic angle (2I-d) whose range is $-360° \leqslant 2I-d \leqslant 180°$.

Trigonometrical functions are periodic in nature, and their inverse mappings are not unique, i.e. not functions, unless suitably restricted. (An example of this non-uniqueness is $\tan^{-1}1 = 45° \pm 180n°$ where 'n' is an integer).
In this case the inverse mapping cannot be suitably restricted and the non-uniqueness has to be taken into account when calculating the dip of the body. Neither Reford (1978) nor Koulomzine et al. (1970) refer to the non-uniqueness of the characteristic angle, but

If significant remanent magnetization is present the characteristic angle is modified to (I+J-d) (Reford, 1978, p.13) where 'J' is the inclination of the total magnetization in the XZ plane. In this case either 'd' or 'J' must be known (or assumed) to calculate the other.

4.5 PALAEOMAGNETIC STUDIES

Dyke material was collected from ten localities for measurement of susceptibility and natural remanent magnetization (NRM). Samples from five localities where outcrop was poor could not be orientated as it was impossible to decide whether the samples were in-situ or not (Day, 1977b, Appendix p.1).

Cylindrical specimens (25 mm diameter x 25 mm high) were cut from the samples and the susceptibility and NRM of each were measured.

To assess the stability of the NRM the samples were magnetically cleaned. Where the cores were not orientated, changes in the direction of magnetization during progressive demagnetization were measured relative to an arbitrary fiducial line on each core. In an attempt to obtain a better estimate of the original thermoremanent magnetization (TRM) the unorientated samples were heated to 700°C and then cooled in the earth's magnetic field. The artificially induced TRM was measured and subjected again to progressive demagnetization.

The susceptibilities of the samples were remeasured after the heating and cooling cycle and were compared with the former susceptibility results to give an indication of any possible change in magnetic mineralogy due to the heating.

4.6 GEOCHRONOLOGICAL STUDIES

Rock samples from three of the palaeomagnetic sampling localities were submitted to F M Consultants for radiometric dating by the argon-argon method.

5. GENERAL CORRELATION BETWEEN GEOLOGY AND AEROMAGNETICS

A difference in magnetic character between the two outcrops of granitic basement in the study area is evident (Figures 2 and 4). The outcrop of gneiss, migmatite and metamorphic basement near Lichtenburg is characterized by a strong north-easterly trend in the magnetic field. Easterly striking magnetic lineaments are, however, typical of the Gaborone Granite outcrop in the north-west of the study area. A small fault has been mapped near the boundary between the Gaborone Granite and the acid lavas of the Ventersdorp Supergroup (Callow, 1978). A linear negative magnetic anomaly can be traced east-north-east from this fault and may represent a (remanently magnetized) dyke intruded into the fault plane (Figures 2 and 4). This fault line may be the contact between the Gaborone Granite and the Ventersdorp Supergroup.

Andesitic lavas and pyroclastics of the Ventersdorp Supergroup outcrop both in the west of the study area and south-east of Lichtenburg and are associated with a disturbed magnetic field. Similar rocks outcropping south-west of Lichtenburg are, however, associated with a much less disturbed field. Thus, either:

(1) the volcanics south-west of Lichtenburg are less thickly developed and so produce lower amplitude anomalies,

or

(2) the volcanics are not very magnetic and the observed anomalies in the west of the study area and south-east of Lichtenburg are produced by underlying magnetic basement,

or

(3) the volcanics south-west of Lichtenburg, although also part of the Ventersdorp Supergroup, are compositionally (and hence magnetically) different from the other volcanics.

The thick non-magnetic sedimentary rocks (dolomite, chert and subordinate shales and limestones) of the Chuniespoort Group produce gentle magnetic gradients, and the linear magnetic features produced by dykes are most easily seen in this relatively undisturbed part of the magnetic field.

Ironstone, which is the source of the most prominent magnetic anomalies in the study area, is present in the Penge and Rooihoogte Formations near Zeerust and in the Strubenkop Formation. The western boundary of the Rooihoogte Formation ironstone is easily recognizable on the aeromagnetic map and the folded ironstone in the Zeerust syncline produces a broad region of magnetic disturbance.

Towards the east, beyond the Zeerust syncline, the magnetic anomalies are progressively attenuated as the ironstone becomes more deeply buried or is pinched out. In the north-east of the study area, the ironstone of the Strubenkop Formation is clearly defined by a series of magnetic anomalies. Outliers of this ironstone can be recognized by isolated anomalies over the Hekpoort Formation. The Hekpoort Formation andesites have little effect on the aeromagnetic field although the field is slightly more disturbed over the western part of the outcrop.

Several ferruginous quartzite and siltstone bands occur in the Pretoria Group. Two north-west striking rectilinear anomalies can be recognized on Kwaggashoek 448JP (Figure 4), and these anomalies correlate with an exposure of ferruginous quartzite at the base of the Nooitgedacht Member on Driefontein 414JP (Clubley-Armstrong, 1978, p.10). A negative aeromagnetic anomaly, defined by only one flight-line, occurs close to the boundary between Rietvlei 406JP and Brakfontein 404JP (Figure 4). The nearby Boshoek Formation is ferruginous in this area (Mr A R Clubley-Armstrong, pers. comm.) and the anomaly shape suggests that the magnetic body is concordant with the regional northward dip (assuming magnetization by induction). A north-easterly striking anomaly on Brakspruit 402JP (Figure 4) is defined by only two flight-lines and coincides with a finger of the Upper Shale Member of the Timeball Hill Formation projecting into the Hekpoort Formation. The shape of the magnetic anomaly indicates that it could be caused by an inductively magnetized body with a shallow dip to the north, i.e. parallel with the regional dip.

A group of anomalies on Doordrift 410JP (Figure 4) is probably caused by a magnetic body striking parallel with the flight-line direction. A similar group can be found eight kilometres to the south-east on Driefontein 414JP and Wagenboomskop 415JP. This group is parallel with a fault mapped by Clubley-Armstrong (1978) and both groups are likely to be related to ferruginous horizons in the Timeball Hill Formation.

Remnants of Lower Witwatersrand sedimentary rocks appear to be responsible for a broad positive anomaly near Mazista (Martini, 1976, p.2) and for sub-circular negative anomalies about thirty kilometres east of Lichtenburg on the farm Twee Buffels Geschiet 42IP (Davies and Prévost, 1978, p.4).

An east-west striking magnetic anomaly on Vlakplaats 407JP and Doordrift 410JP (Figures 2 and 4) coincides with the southern boundary of a sill. Most of the other concordant intrusives in the survey area do not, however, have associated aeromagnetic anomalies.

A series of rectilinear magnetic anomalies is seen to transect the anomaly patterns described above and correlates closely with the dyke system of the survey area.

6. DISTRIBUTION AND AGES OF THE DYKES, AND THEIR RELATIONSHIP TO TECTONIC FEATURES

6.1 GENERAL INTRODUCTION

The occurrence of dykes within the study area is proven beyond doubt by extensive drilling. Outcrop, however, is very poor indeed and surface observations are restricted to very occasional weathered basic igneous boulders. For this reason, early geological maps show no dykes within the study area, although it is interesting to observe that a significantly high proportion of farm tracks and roads are located precisely on known dykes.

Later researchers were able to use aerial photography and geophysical data to identify dyke positions. Although electrical and electromagnetic methods have been used successfully, the magnetic method has been the most widely and successfully used geophysical tool for dyke location. Photogeology has been useful except where the photogeological expression of the dyke has been obliterated by agricultural activity or by superficial deposits.

In the following account the nomenclature of previous workers has been retained for the dykes and faults in the study area. For convenience of description, however, seven new dyke names are introduced viz. Witklip, Paarl, Stryd, Hendriksdal, Diepkloof, Christinas and Elizabeth II. The positions of these dykes are shown in Figure 4.

6.2 DISTRIBUTION OF DYKES, FAULTS, AND JOINTS

An east-north-easterly lineament trend is clearly visible in the study area and has relatively high amplitude aeromagnetic anomalies of up to several hundred nT associated with it (Figure 4). However, not all the dykes which follow this (Vaal) trend produce high amplitude anomalies (e.g. Grasfontein dyke, Figure 4). The Groot Marico fault, Rooisloot fault and Elizabeth dyke belong to a second major lineament trend striking north-north-west. Subordinate north-westerly, north-easterly and easterly strikes are also represented. The Blaauwbank dyke follows the latter trend and has a magnetic anomaly which is similar in amplitude and form to the magnetic anomalies produced by some east-north-easterly striking dykes.

A swarm of north-westerly dykes appears to have a focal point about 8 km north of the most prominent of the sub-circular negative anomalies on the farm Twee Buffels Geschiet 42IP (Figure 4). These dykes are well seen on the aeromagnetic survey of 1971, which terminates at the Groot Marico fault (26°30'E). Although to the east of the fault the north-south lines of the 1969 survey are not favourable for north-westerly striking dykes, several dykes are recognizable on sheet 2626BA (Zwartrand) from photogeological evidence. Wilson (1977, pp.45 and 46) notes that several of the dykes display a tendency to adopt a more easterly trend when traced north westwards.

The 2200 kilometres of lineaments shown in Figure 4 were used to compile a rose diagram of the dyke directions (Figure 6). From the rose diagram, it is clear that there are two prominent strike directions centred on 075°±5° and 165°±5°. A third dyke trend at 105°±5° is not as distinct as the 075° and 165° directions.

Hammerbeck (1971, p.2) recognized three prominent joint directions, viz. 015°-020°, 075°-085° and 150°-160°, and noted that these coincide with the trends of the dykes. In the much larger area of the current study, Hammerbeck's 015°-020° direction is very poorly represented as a magnetic lineament trend, but the 075°-085° and 150°-160° directions are closely similar to the two orthogonal dyke directions (075° and 165°) noted above. Hammerbeck also identified a fourth structural direction which is identical with Wilson's (1977, p.45) Diepkloof trend. The strike of the Doornplaats "trough" (Wilson, 1977, Table 5) is also parallel with the Diepkloof trend.

Kavalieris and Martini (1976, p.308) determined that two joint directions, 092°-110° and a less well developed 177°-190°, exerted a strong control on the formation of Herbst's Cave near Zeerust and that this jointing was certainly post-Bushveld and probably post-Karoo. The average trends of the Diepholte and Doornplaats grabens lie in the range of the 092°-110° joint direction, and both the 092°-110° and 177°-190° joint directions are weakly represented as dyke trends in the study area. Again these trends (092°-110° and 177°-190°) are similar to the orthogonal trends (075° and 165°) of Figure 4. Kavalieris (1976, p.308) also observed jointing of 170° in the Apocalypse pothole near Carletonville, and suggested that it was possibly pre-Karoo.

Clearly there is a correlation between the joint directions and the dyke trends. Wilson (1977, Table 4) noted several instances of dykes wedging out or being deflected (but not displaced) by fractures, and it appears that the dykes exhibiting these characteristics post-date the fractures.

Many of the dykes follow sinuous or irregular courses and may be typified by abrupt and substantial changes in strike direction. These irregularities suggest that tensile rather than shear stresses were responsible for the fractures occupied by the dykes.

6.3 DYKE CLASSES AND THEIR CHARACTERISTICS

The forms of the magnetic anomalies may be used to subdivide the dykes, and three main classes of aeromagnetic anomaly may be distinguished:

1. negative anomalies
2. positive low-amplitude anomalies ($\leqslant$ 30nT)
3. positive high-amplitude anomalies ($>$ 30nT)

The differences between these classes were investigated on the ground and, using the interpretation methods described in section 4.4, estimates were made of the depths, widths, dips and susceptibility contrasts of the dykes (Table 2).

The negative anomalies all strike east-north-east and may be explained equally well by:

1. a near horizontal sill dipping northwards
2. a fault
3. a remanently magnetized dyke

CLASS	DYKE	AVERAGE STRIKE	LOCALITY	DATA SOURCE	TRAVERSE	DEPTH METRES	WIDTH METRES	DIP	SUSCEPTIBILITY S.I.	INTERPRETATION METHODS
2	Blaauwbank	N090°E	Kliplaagte 52 IO	Day, 1976b	RD5/1	57	33	100°	0,19	A, B, C
2	Blaauwbank	N090°E	Kliplaagte 52 IO	Day, 1976b	RD16/1	52	74	107°	0,10	C
2	Blaauwbank	N090°E	La Reys Stryd 53 IO	Day, 1976b	DR34	30	100	105°	0,11	A, B, C, D
2	Blaauwbank	N090°E	La Reys Stryd 53 IO	Richards and Darracott, 1973	DR 1 *	54	44	78°	0,13	A, B, C,
1	Greeffslaagte	N070°E	Greeffslaagte 33 IP	Day, 1976b	B 7/1	28	72	N.A.	N.A.	B, C
1	Greeffslaagte	N070°E	Lichtenburg Townlands	Richards and Darracott, 1973	DR 3	25	45	N.A.	N.A.	D
1	Greeffslaagte	N070°E	Greeffslaagte 33 IP	Day, 1976b	B 11/2	41	81	N.A.	N.A.	B
2	Lichtenburg	N070°E	Manana 26 IP	Day, 1976b	C 3/1	230	230	105°	0,13	A, B, C, D
2	Lichtenburg	N070°E	Lichtenburg Townlands			71	107	112°	0,12	B
2	Paarl	N080°E	Houthaalboomen 31 IP			7	55?	109°	0,03	B
2	Paarl	N080°E	Lichtenburg Townlands	Richards and Darracott, 1973	DR 2	20	20	117°	0,06	A, D
2	Paarl	N080°E	Greeffslaagte 33 IP	Day, 1976b	A 9/1	29	36	115°	0,06	A, B
2	Diepholte	N100°E	Rhenosterhoek 343 JP			140	140	100°	0,08	B, C, D, E
2	Strydfontein	N075°E	Kaalplaats 330 JP			125	375	80°	0,02	A, B, C, E
3	Grasfontein	N075°E	Kliplaagte 52 IP	Day, 1976b	RD 5/2	24	≤24	96°	≥0,02	A, B, C
3	Grasfontein	N075°E	Ruigtelaagte 353 JP	Stettler, 1979, Figure 35a		15	36	115°	0,04	D
3	Hendriksdal	N045°E	Uitgevonden 355 JP			8	22	110°	0,01	A, B, C
3	Verlies	N045°E	Vaalkopje 111 JO			Outcropping	30			D
3	Christinas	N030°W	Doornplaats 340 JP	Day, 1977b	F6 and F11	Outcropping	35	90°		D
3	Christinas	N030°W	Kaalbult 349 JP			Outcropping	35	~120°	0,04	D
3	Elizabeth	N010°W	Greeffslaagte 33 IP	Day, 1976b	A 6/3	24	47	108°	0,01	A, B, C
3	Witklip	N020°W	Witklip 6 IP	Day, 1976b	DR 29	10	10?	90°	0,15?	A, D
3	Witklip	N020°W	Manana 26 IP	Day, 1976b	DR 33	9	31	112°	0,05	A, B
3	Witklip	N020°W	Welverdiend 361 JP	Stettler, 1979, Figure 35b		18	36	111°	0,04	D

The data sources are quoted only when the data have been included in a report or publication. An asterisk denotes reinterpreted results which differ from the results given in the source. The key to the interpretation methods is: A - Richards, 1975; B - Bruckshaw and Kunaratnam, 1963; C - Koulomzine, Lamontagne and Nadeau, 1970; D - Curve matching; E - Upward continuation. Class 1 dykes produce negative anomalies, class 2 dykes produce positive low-amplitude anomalies (≤ 30 nT), and class 3 dykes produce positive high-amplitude anomalies (> 30 nT). NA - not applicable

Table 2 : Dyke parameters

(Richards and Darracott, 1973, pp.5 and 6; Henkel and Guzman, 1977, p.173). Two of the negative anomaly features are known to extend for several hundred kilometres (Richards, 1979, p.7), are quite rectilinear and are discordant with bedding strikes. This strongly suggests that these magnetic features are due to near vertical bodies and not due to flat-lying sills. Faults may produce the negative magnetic anomalies either by displacing sub-horizontal magnetic sediments (Richards and Darracott, 1973, p.6) or by the breakdown of magnetic minerals as a result of deep weathering along fault lines (Henkel and Guzman, 1977, p.173).

The negative magnetic anomalies are, however, not likely to be the direct result of faulting for two reasons:

(1) the negative features are continuous across several different tock types, not all of which contain significant amounts of magnetite; and
(2) weathered igneous material was recovered from boreholes sited over one of the negative magnetic anomalies (Richards and Darracott, 1973, p.5).

It is concluded that the negative magnetic anomalies are caused by remanently magnetized dykes. Further, assuming that the dykes are near vertical, the magnetization vector has a component which dips about 10° to 30° northwards in the plane of the traverse (Richards and Darracott, 1973, p.5; Day, 1980, Appendix 2, p.2.5).

The higher amplitude positive aeromagnetic anomalies are usually several tens of nT in magnitude and strike east or east-north-east. The lower-amplitude positive anomalies generally strike north-east, north or north-west although some also strike eastwards. Differences in strike direction cannot account for the observed variations in anomaly amplitude, and these variations must be due to width and/or magnetization differences between the dyke classes. This inference is broadly confirmed by the interpretation results (Table 2). The high amplitude magnetic anomalies are related to dykes which are both thicker and have a larger susceptibility contrast than the dykes producing the lower amplitude anomalies.

It was assumed during interpretation of the dykes that the positive magnetic anomalies were caused by induction only, however, "remanent magnetization must often play a significant part in the magnetic expression of normally-polarized dykes" (Hood, 1964, p.440). Palaeomagnetic data indicate that, for most samples of dyke and sill material collected, remanent magnetization dominates (Section 6.5.1). All these samples were, however, collected from surface exposures and could have been chemically altered by weathering.

The susceptibility of the Grasfontein dyke was measured using a kappameter on borehole core recovered at depths of 81 metres and 111 metres. The susceptibility of 0,05 SI units measured from the borehole core agrees well with an estimated susceptibility contrast of 0,04 SI units (Table 2). Similarly the value of 0,06 SI units measured from borehole chips compares well with an estimated susceptibility contrast of 0,05 SI units for the Witklip dyke (Table 2). In these two cases at least, it seems unlikely that a significant amount of remanent magnetization is present.

Even the most magnetic of the dykes need not contain more than three or four per cent magnetite by volume to explain the magnitude of the induced anomalies. Thus it seems likely that the effect of any remanent magnetization is subordinate to the effect of induced magnetization, and this observation adds credence to the dip estimates.

Variations in susceptibility along the same dyke may occur and may be caused by (for example) hydrothermal fluids altering the magnetic minerals. The susceptibility contrast, however, is largely determined using parameters which are themselves subject to some uncertainty, and this may account for some of the variability of the calculated values. This is especially true for thin dykes where it is impossible to separate the effects of susceptibility and width on the magnitudes of the anomalies unless one or the other is known.

6.4 RELATIVE AGES OF THE DYKES

As noted above, the magnetic anomalies may be used to divide the dykes into at least three classes which reflect differences in the geometry and/or magnetic characteristics of the intrusions. These differences suggest differences in either:

1. the stress conditions at the time of intrusion

or

2. the magnetic field direction at the time of intrusion,

or

3. the petrology of the dykes.

The differences in magnetic anomalies are, thus, a reasonable basis for making an initial classification of the dykes. Gelletich (1937) used a similar method for classifying dykes in the southern Transvaal.

In the west of the study area, offshoots, bifurcations, intersections and variations in strike direction of the dykes occur and can be used to study the relative ages of the dykes. Some age differences may be inferred from the offsets found at dyke and fault intersections. Instances of apparent sinistral displacement are visible along some of the east-north-easterly lineaments including the Doornhoek dyke and the Zeerust fault (Figure 4). The north-north-westerly Groot Marico fault dextrally displaces at least seven north-westerly and north-easterly trending dykes. Wilson (1977, p.63) suggests that the faults predate the dykes and that some of the faults were reactivated fairly recently. It is known that the reactivation of old lines of weakness during renewed tectonic activity is not uncommon in the Transvaal (Van Eeden, 1972, pp.45 to 47) and it is not inconceivable that intrusions of different ages follow similar trends or even occupy the same features.

Further information on the relative ages of the dykes was obtained by examining the dyke intersections with the aid of a magnetometer. The intersection of dykes producing positive magnetic anomalies and dykes producing negative magnetic anomalies proved particularly amenable to demonstrating their relative ages, and an example of isometrically plotted data from such an intersection is given in **Figure 7.**

Table 3 shows the suggested age relationships of some of the dykes in the study area.

6.5 ABSOLUTE AGES OF THE DYKES

Palaeomagnetic and radiometric dating methods were employed in an effort to determine the absolute ages of the dykes.

Dyke exposure within the Chuniespoort Group is very poor and only three samples of dyke material could be collected. A further seven samples were collected from dykes or sills intruding the Pretoria Group. The sample localities are marked on Figure 4, and more detailed locality maps are reproduced elsewhere (Day, 1977b, appendix 1; Day, 1980, appendix 3).

6.5.1 Discussion of Palaeomagnetic results

Of the ten sites sampled, the samples from only five sites (all collected from the Pretoria Group) could be satisfactorily orientated. The NRM vectors for these

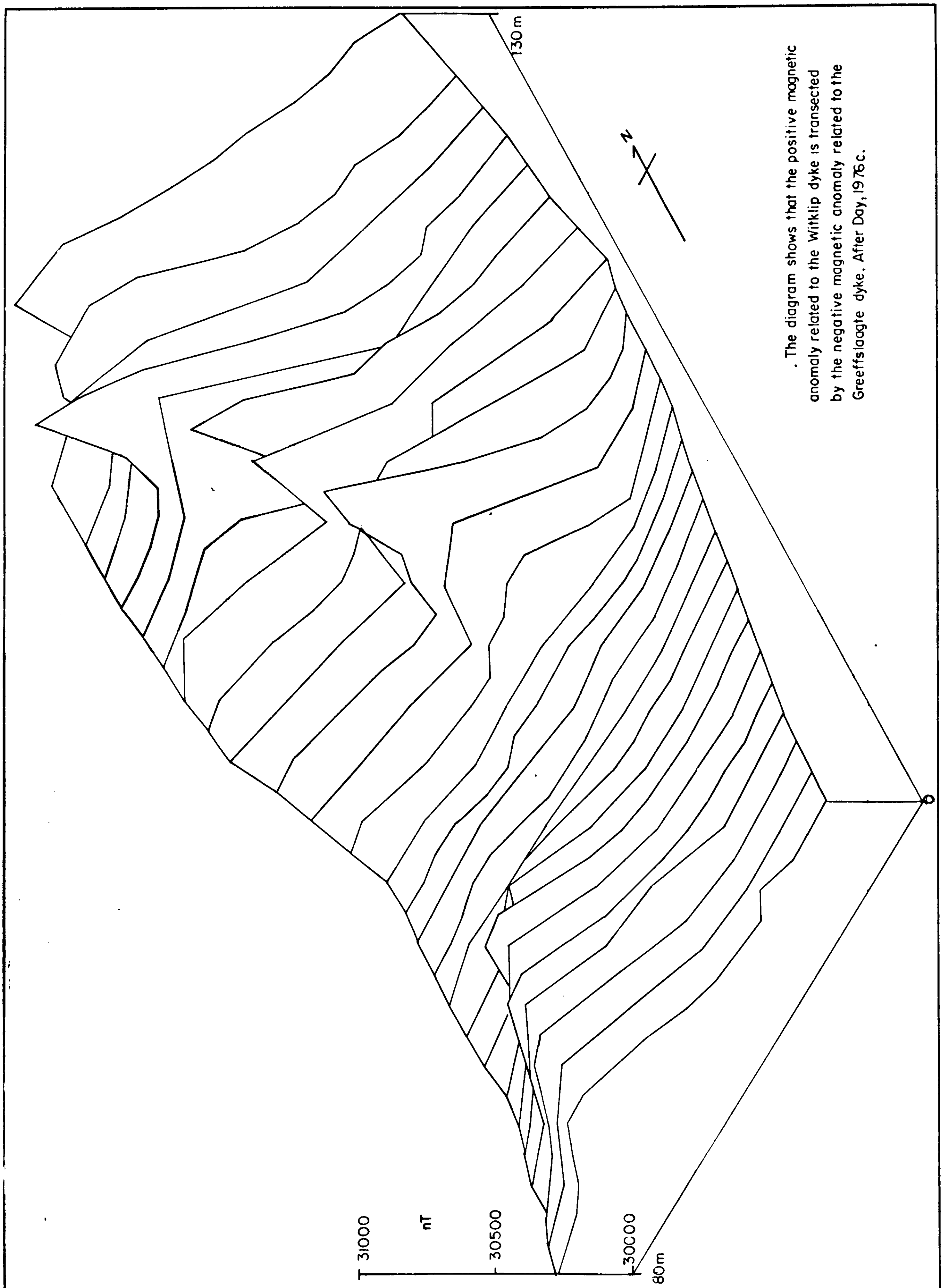


Figure 7: Isometric projection of traverse line results (Lichtenburg Townlands)

Table 3 Suggested age relationships between some dykes in the study area

Contemporary
Blaauwbank dyke contemporary with Paarl dyke.
Greeffslaagte dyke contemporary with Stryd dyke.
Displaced
Blaauwbank dyke displaced by Lichtenburg dyke.
Hendriksdal dyke displaced by Paarl dyke (Day, 1979a).
Stryd dyke displaced by Elizabeth dyke.
Greeffslaagte dyke displaced by Groot Marico Fault.
Christinas dyke displaced by Groot Marico Fault.
Doornhoek graben displaced by Groot Marico Fault (Wilson, 1977).
Witklip dyke displaced by Grasfontein dyke (Stettler, 1979).
Trekdrift dyke displaced by Verlies dyke.
Cut
Witklip dyke cut by Lichtenburg dyke (Day, 1977c).
Witklip dyke cut by Greeffslaagte dyke (Day, 1976c).
Greeffslaagte dyke cut by Paarl dyke (Day, 1977b).
Stryd dyke cut by Blaauwbank dyke (Day, 1978).
Verlies dyke cut by Blaauwbank dyke (Day, 1979a).
Hendriksdal dyke cut by Blaauwbank dyke (Day, 1979a).
Doornhoek graben cut by Christinas dyke (Wilson, 1977; Day, 1977b).

five sites (02, 03, 04, 05 and 06), however, showed considerable intra-site and inter-site variations (Tables 4 and 5). Even samples cut from the same core sometimes showed large variations. Alteration minerals were present throughout the rock samples and, since it is reasonably certain that these five sites represent in-situ exposures, it seems virtually certain that the observed variability is due to the little-understood phenomenon of chemical remanent magnetization (CRM) (Stacey and Bannerjee, 1974, p.128). The results could not be used to date the igneous bodies because of this variability of NRM direction.

Of the five unorientated samples, three (samples 2, 3 and 4) appear to have significant viscous remanent magnetization (VRM). The remaining two samples (samples 1 and 5) had large stable NRM components measured relative to arbitrary fiducial marks. The Koenigsberger ratios after alternating field demagnetization were approximately three for sample 1 and four for sample 5. These values indicate that the observed magnetic anomalies over these dykes may be dominated by their NRM and not by their induced magnetization. It is possible, however, to model the dyke anomalies by assuming induced magnetization only.

			NRM			5 mT			10 mT			20 mT			40 mT			60 mT			80 mT			100 mT		
SAMPLE No	$\chi \cdot 10^{6}$	Q'	D°	I°	$M.10^3$	D°	I°	$M.10^3$	D°	I°	$M.10^3$	D°	I°	$M.10^3$	D°	I°	$M.10^3$	D°	I°	$M.10^3$	D°	I°	$M.10^3$	D°	I°	$M.10^3$
020101	20050	50,0	150	49	23300	150	61	17837	125	69	2742	141	60	104	197	-18	≃4	242	-28	7,0	200	42	35	221	24	10,0
020102	15510	63,4	88	49	23534	-	-	-	-	-	-	55	32	81	-	-	-	195	0	6,3	-	-	-	-	-	-
020103	13210	46,7	56	36	14732	-	-	-	-	-	-	59	22	73	-	-	-	-	-	-	-	-	-	126	-44	5,1
020201	19200	134	234	5	68126	-	-	-	-	-	-	-	-	-	-	-	-	242	-9	19,5	154	13	10,2	194	70	8,3
020203	20400	102	229	4	49693	-	-	-	-	-	-	-	-	-	228	- 7	121	-	-	-	-	-	-	81	10	13,4
020301	16100	153	24	-37	58547	-	-	-	-	-	-	15	-20	7340	9	-27	712	8	-30	372	9	-28	250	-	-	-
020302	15130	167	27	-28	60835	-	-	-	-	-	-	-	-	-	15	-14	128	-	-	-	-	-	-	191	-24	6,5
020303	19130	168	25	-22	76625	-	-	-	-	-	-	-	-	-	12	-11	147	237	-52	14,2	-	-	-	151	5	14,6
020401	20620	157	156	7	77507	-	-	-	-	-	-	162	12	1880	141	3	33,5	154	25	45,8	65	-42	10,9	237	19	8,2
020402	20900	175	164	5	96685	-	-	-	-	-	-	163	10	2840	-	-	-	-	-	-	-	-	-	129	-15	12,9
020403	20130	163	159	4	86813	-	-	-	-	-	-	162	7	1145	-	-	-	-	-	-	-	-	-	358	-31	8,3
030101	490	0,01	2	-27	0,1	-	-	-	188	-37	0,24	243	8	0,02	-	-	-	-	-	-	-	-	-	-	-	-
030102	515	0,01	17	59	0,1	344	40	0,12	31	47	0,25	228	40	0,1	-	-	-	-	-	-	-	-	-	-	-	-
030103	490	0,01	104	-54	0,1	-	-	-	51	-44	0,08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
030201	578	0,04	246	-18	0,5	251	-15	0,8	247	-15	0,6	253	0	0,2	314	-42	0,1	314	-23	0,02	-	-	-	-	-	-
030202	578	0,07	255	-11	0,9	-	-	-	-	-	-	270	-9	0,26	248	71	0,05	-	-	-	-	-	-	-	-	-
030301	528	0,02	145	- 6	0,3	146	- 3	0,2	136	- 8	0,2	147	-25	0,12	76	16	0,11	-	-	-	-	-	-	-	-	-
030302	465	0,02	149	9	0,2	-	-	-	-	-	-	170	-59	0,04	-	-	-	-	-	-	-	-	-	-	-	-
030303	528	0,02	142	7	0,2	-	-	-	-	-	-	165	-60	0,08	-	-	-	-	-	-	-	-	-	-	-	-
030401	528	0,36	284	- 9	4,5	283	- 7	4,7	285	- 7	4,5	285	- 8	1,7	281	-16	1,1	279	-18	0,5	272	-14	0,2	-	-	-
030402	541	0,17	282	0	2,2	-	-	-	-	-	-	289	0	1,4	-	-	-	-	-	-	-	-	-	-	-	-
040101	201	0,08	10	-23	0,4	-	-	-	-	-	-	214	-15	0,08	205	6	0,16	-	-	-	-	-	-	-	-	-
040102	264	0,08	346	- 2	0,5	-	-	-	-	-	-	283	-22	0,08	227	-17	0,18	194	5	0,10	212	3	1,4	-	-	-
040103	214	0,11	49	3	0,6	49	1	0,4	-	-	-	63	- 1	0,1	57	83	0,1	82	-19	0,2	-	-	-	-	-	-
040201	264	0,40	214	-31	2,5	-	-	-	218	-29	2,2	213	-27	0,93	226	28	0,16	-	-	-	34	65	0,06	-	-	-
040202	264	0,33	208	-26	2,1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
040203	251	0,28	207	-34	1,7	206	-30	1,5	-	-	-	-	-	-	-	-	-	-	-	-	28	70	0,08	-	-	-
040301	276	0,12	66	-69	0,8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
040302	276	0,14	52	-57	0,9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
040303	314	0,19	70	-52	1,4	-	-	-	76	-48	1,0	81	-25	0,37	349	-17	0,10	152	-59	0,09	29	-56	0,03	-	-	-

Table 4: Remanent magnetization on progressive demagnetization, susceptibility and Koenigsberger ratio data (1)

			NRM			5 mT			10 mT			20 mT			40 mT			60 mT			80 mT			100 mT		
SAMPLE Nº	$\chi \cdot 10^6$	Q'	D°	I°	$M \cdot 10^3$	D°	I°	$M \cdot 10^3$	D°	I°	$M \cdot 10^3$	D°	I°	$M \cdot 10^3$	D°	I°	$M \cdot 10^3$	D°	I°	$M \cdot 10^3$	D°	I°	$M \cdot 10^3$	D°	I°	$M \cdot 10^3$
050101	528	0,37	155	-6	4,6	-	-	-	131	0	1,8	113	0	1.5	115	-2	1,4	127	-6	0,8	-	-	-	-	-	-
050102	515	0,48	163	-5	5,9	-	-	-	-	-	-	-	-	-	103	24	0,4	-	-	-	-	-	-	-	-	-
050103	465	0,36	169	0	4,0	-	-	-	-	-	-	-	-	-	126	7	1,2	216	29	0,41	-	-	-	-	-	-
050104	503	0,24	151	-1	2,9	143	0	3,5	122	6	1,2	77	19	0,8	72	32	0,2	74	1	0,5	306	-31	0,4	33	-12	0,5
050201	465	1,86	349	4	20,6	350	6	18,4	-	-	-	341	7	4,7	336	15	3,1	308	34	1,9	324	57	1,3	304	68	1,1
050202	490	1,15	352	6	13,5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	- -	-	356	6	0,9
050203	427	1,45	354	5	14,9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
050204	449	1,66	354	5	17,6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	336	17	1,3
050301	427	40,8	198	-1	417	-	-	-	199	-2	395	198	-2	318	200	-2	187	199	-2	188	202	-1	77	203	-1	45
050302	428	64,0	199	-4	808	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
50303	541	22,5	199	-4	293	-	-	-	-	-	-	-	-	-	-	-	-	206	-5	58	-	-	-	-	-	-
050401	490	1,50	211	-47	17,5	-	-	-	220	-52	11,2	222	-50	7,4	210	-57	4,8	-	-	-	-	-	-	-	-	-
050402	603	54,0	210	-51	778	-	-	-	-	-	-	209	-58	102	215	-57	34	-	-	-	253	-55	17,2	219	-44	12,2
060102	427	0,13	188	3	1,3	-	-	-	188	8	1,5	202	-11	1,6	177	12	0,7	161	-20	0,5	-	-	-	-	-	-
060103	427	0,09	159	-21	0,9	-	-	-	130	21	1,0	117	25	0,4	47	62	0,3	-	-	-	-	-	-	-	-	-
060104	427	0,95	203	4	9,7	-	-	-	203	2	8,7	201	-3	6,2	193	-8	3,5	190	-2	2,2	201	0	1,9	182	-16	1,5
060201	449	0,07	224	-4	0,7	-	-	-	196	30	1,4	185	52	0,5	208	44	0,7	161	38	0,5	219	-4	0,5	243	-3	0,5
060202	449	0,04	233	-40	0,4	-	-	-	210	-4	0,8	-	-	-	195	21	0,7	-	-	-	-	-	-	152	30	0,4
060203	314	0,16	233	-19	1,2	-	-	-	206	-3	0,9	-	-	-	173	0	0,6	-	-	-	-	-	-	186	-21	0,7
060301	452	0,10	97	-40	1,1	-	-	-	99	-35	1,2	-	-	-	31	-61	0,3	-	-	-	-	-	-	31	-74	0,3
060302	465	0,07	97	-36	0,8	-	-	-	102	-33	1,0	-	-	-	332	-75	0,1	-	-	-	-	-	-	-	-	-
060303	449	0,09	109	-31	1,0	-	-	-	110	-28	1,2	-	-	-	134	-37	0,2	-	-	-	80	-48	0,2	-	-	-
060304	449	0,10	112	-35	1,1	-	-	-	-	-	-	-	-	-	111	-60	0,3	-	- -	-	-	-	-	53	-43	?
060401	452	0,16	135	-42	1,7	-	-	-	-	-	-	-	-	-	138	-16	0,7	-	-	-	-	-	-	162	-14	0,2
060402	452	0,07	138	-41	0,7	-	-	-	-	-	-	-	-	-	117	-48	0,3	-	-	-	-	-	-	209	-66	0,3
060403	528	0,03	133	-49	0,4	-	-	-	-	-	-	-	-	-	157	-25	0,1	-	-	-	84	-56	0,2	-	-	-
060404	449	0,04	153	-33	0,4	-	-	-	-	-	-	170	-32	0,2	258	-8	0,1	193	-45	0,2	297	-50	0,1	-	-	-

The first two digits of the sample number give the site number, the second two digits the core or hand specimen number, and the last two digits the sample.

All the units are in the S.I. χ is the susceptibility, M is the remanent magnetization in amperes per metre, and Q' is Koenisberger's ratio.

Table 5 : Remanent magnetization on progressive demagnetization, susceptibility and Koenigsberger ratio data (2)

6.5.2 Radiometric dating results

Three samples (1, 3 and 4) were submitted to F M Consultants for radiometric dating by the argon-argon method. The results are presented in a report by F M Consultants, and are summarized in Table 6.

Table 6: Radiometric dating by the argon-argon method on three samples of dyke material

SITE	LOCALITY	ROCK TYPE	PRIMARY AGE	OTHER EVENTS
1	Mallepoos Oog 332JP	Altered quartz bearing basalt	1262 ± 8 Ma?	Completely overprinted 1262 ± 8 Ma? Hydrothermal event 1070 ± 10 Ma
3	Ottoshoop	Partially altered quartz-basalt	1740 ± 13 Ma	Hydrothermal event 1047 ± 10 Ma
4	Doornhoek 298JP	Biotite bearing sub-orphitic olivine dolerite. Only minor alteration.	2466 ± 12 Ma	Partial overprinting 1910 ± 6 Ma

F M Consultants (Report FMK/1324) suggest that, whereas the site 1 and site 3 samples may have crystallised during two different magmatic episodes, it is possible that the more altered rock from site 1 was completely overprinted by an additional event around 1262±8 Ma and that its age of crystallisation is identical with that of the sample from site 3. The overprint at 1262±8 Ma may be related to the intrusion of the Pilanesberg dykes dated at 1310±60 Ma (Van Niekerk, 1962, p.105).

Sample site 4 lies inside a tremolite facies isograde which may be related to once-overlying rocks of the Bushveld Complex (Martini, 1974, p.4). The suggested primary age of the dyke sampled at site 4 (2466±12 Ma) is greater than the accepted age of 2300-2100 Ma for the Pretoria Group which it intrudes. This "excess-age" result could be caused by either potassium leaching or, more likely, by the introduction of argon during crystallisation or subsequent metasomatism in a high fluid-pressure environment (F M Consultants report FMK/1081). The partial overprint at 1910±6 Ma recorded for this sample is probably related to the intrusion of the Bushveld Complex (1950±50 Ma) which could also be responsible for the metasomatic effects thought to account for the 2466±12 Ma dating.

6.5.3 Other evidence bearing on the absolute ages of the dykes

The aeromagnetic data indicate that the dykes extend en-echelon eastwards as far as the Pretoria-Johannesburg area, and that other dykes which have similar strikes and which produce similar magnetic anomalies occur as far north as Derdepoort and Pilanesberg. Thus:

(1) A dyke striking east-west on the farm Leeuwfontein 35JQ to the east of the Pilanesberg intrusion has been surveyed magnetically (Richards, 1973c) and has been drilled and radiodated. An age of 174±3 Ma (F M Consultants report FMK/1248) was obtained by the argon-argon method. This dyke has a similar strike and similar magnetic anomaly to the Blaauwbank, Paarl and Lichtenburg dykes.

(2) East-west striking dykes cut dykes of supposed Pilanesberg age (1310±60 Ma) between Pretoria and Johannesburg (De Meyer and Richards, 1978: Richards and Wiegmans, 1979) and are thus younger than 1310±60 Ma. One east-west striking dyke is known to intrude sedimentary rocks of the Karoo Sequence in the East Rand and, therefore must be post-Karoo Sequence (Day, 1979b, p.9).

All of these east-west dykes produce high-amplitude positive aeromagnetic anomalies (class 3 of section 6.3).

Within the study area further observations which may be pertinent to the ages of the dykes can be made:

(1) The Zeerust fault displaces an andalusite isograde in the Pretoria Group (Young, 1977, p.14) and is, therefore, associated with post-Bushveld Complex movement. The dyke which appears from magnetic evidence (Figure 4) to be intruded along the Zeerust fault may thus also be post-Bushveld Complex in age.

(2) The Diepholte graben has been shown to preserve remnants of Dwyka Formation rocks (Davies and Prévost, 1978, p.28) and so appears to be associated with at least some post-Dwyka movement.

(3) Certain similarities exist between the mapped grabens and the Greeffslaagte, Paarl, Blaauwbank and Lichtenburg dykes. These similarities are listed below.

(3.1) Characteristic broad tonal features on aerial photographs are associated with the grabens. Similar features are associated with the Greeffslaagte, Paarl and Blaauwbank dykes on the Lichtenburg Townlands Houthaalbomen 31IP and Zamenkomst 4IP (Figure 4). The Lichtenburg dyke has no photogeological expression whatsoever probably because of extensive agricultural activity. In common with other dykes in the survey area, however, the Greeffslaagte, Paarl and Blaauwbank dykes are sometimes recognizable by thin, sharply defined, light-toned lineaments or by lines of trees on aerial photographs.

(3.2) An abrupt southward decrease of 25 nT in the magnetic background field is observed across the Strydfontein graben and its westward extension. Similar southward decreases in magnetic background are observed across the Blaauwbank dyke (40 nT) on the Lichtenburg Townlands (aeromagnetic surveys), the Greeffslaagte dyke (50 nT), on the Lichtenburg Townlands (Darracott, 1973) and the Lichtenburg dyke (50 nT) in the western part of the study area (aeromagnetic surveys and Day, 1976b, Traverse DR 32).

(3.3) The known grabens have associated magnetic anomalies which can occasionally be traced beyond the mapped limits of the grabens. The Paarl, Blaauwbank and Lichtenburg dykes all have magnetic anomalies which are similar in form and amplitude to the anomalies observed over the grabens, although the Greeffslaagte dyke produces an anomaly of opposite sign (Day, 1976b).

It is concluded that the Blaauwbank and Lichtenburg dykes and possibly the Paarl and Greeffslaagte dyke are associated with (post-Karoo?) grabens. It is pertinent to note that the interpreted depth of 230 metres to the top of the Lichtenburg dyke (Table 2) is significantly greater than the 57 metres estimated by Von Backström et al. (1953, p.18) for the total thickness of Karoo rocks in this area. Although it is difficult to envisage a geologically feasible model for such a situation, it appears as if the magnetic body could be overlain by dolomite and this is similar to the situation of the Diepholte graben (Day, 1980, Appendix 4, p.4.1). Further, the presence of a graben could be used to explain the disappearance of the Witklip dyke in the vicinity of the Lichtenburg dyke (Figure 4).

(4) The Groot Marico fault and two other north-northwest striking faults (**Figure** 4) displace the (post-Dwyka) grabens (Wilson, 1977, Table 4). From aeromagnetic data, it appears that these faults have dykes intruded along their fault planes. Another fault, which is parallel with the Groot Marico fault and 25 km to the east does

not displace the 147 Ma (Allsopp and Barrett, 1975, p.613) Swartruggens kimberlite dykes (Mr A R Clubley-Armstrong, pers. comm.). Some movement along the north-north-west faulting thus appears to be post-Dwyka and earlier than 147 Ma. The associated dykes may, therefore, be post-Dwyka.

(5) At least one dyke, the Christinas dyke, from the set which appears to radiate from the farm Twee Buffels Geschiet 42IP (Figure 4) cuts through the Doornplaats graben without being displaced (Day, 1977b, p.4). It may reasonably be assumed that the Doornplaats graben, like the Diepholte graben, is post-Dwyka, and so the Christinas dyke is likely to be post-Dwyka. The other dykes which radiate from Twee Buffels Geschiet 42IP (and which include the dyke intruded along the Groot Marico fault) may thus also be post-Dwyka.

(6) Kavalieris et al. (1976, p.308) suggest that the 092°-110° and the 177°-190° joint directions in the Chuniespoort Group postdate the intrusion of the Bushveld Complex and are probably post-Karoo. The Diepholte and Doornplaats grabens have strikes which fall within the 092°-110° range and, as discussed in section 5.1, dyke trends which are closely parallel with the 092°-110° joint direction can be recognized (e.g. Diepkloof dyke). It is

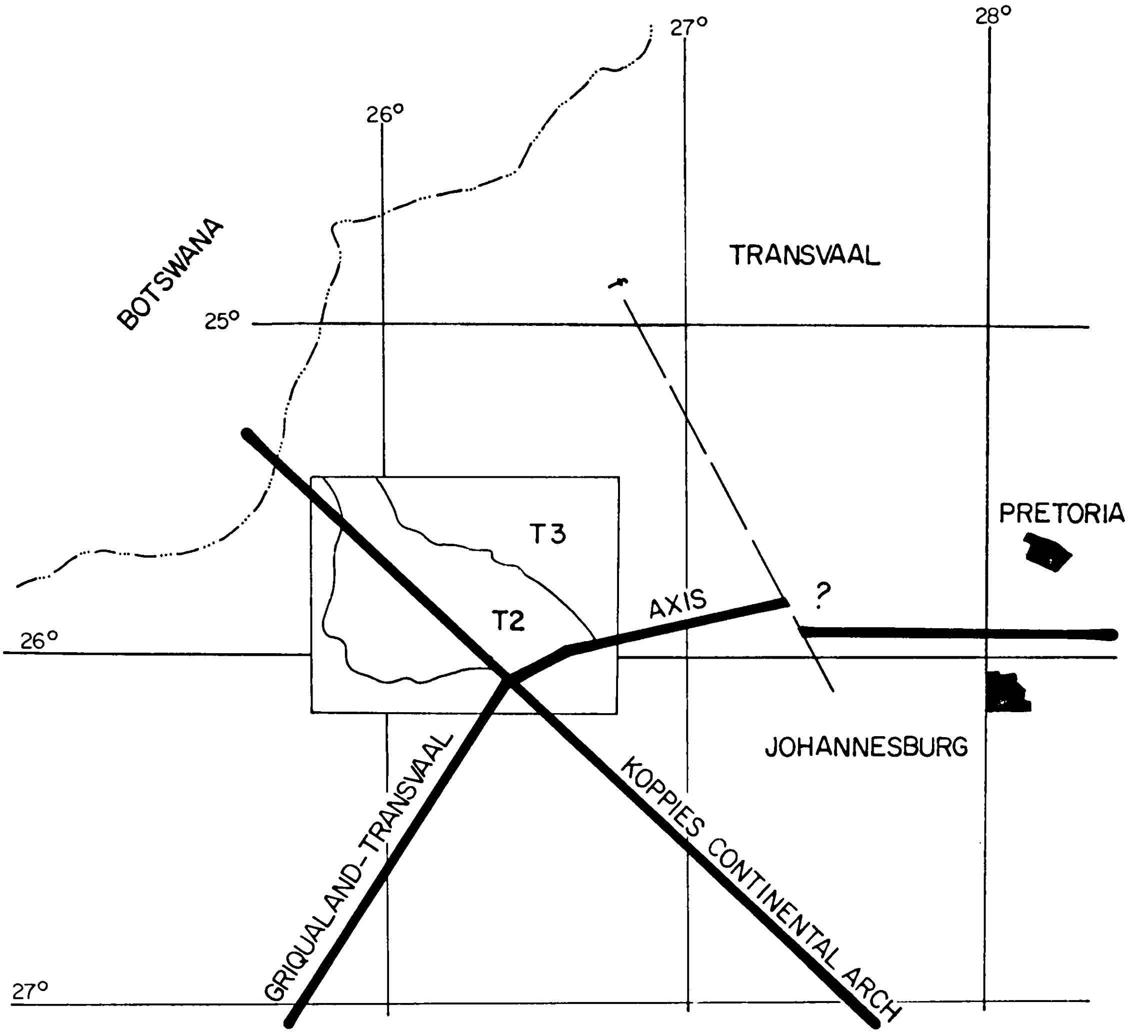
interesting to note that the 147 Ma Swartruggens kimberlite dykes have a strike direction of 103° and that the dykes radiating from Twee Buffels Geschiet 42IP have a tendency to swing round into the 092°-110° direction when traced northwards. The 177°-190° joint direction is poorly represented.

6.6 RELATIONSHIPS BETWEEN THE DYKES AND TECTONIC FEATURES

Dyke patterns are a reflection (directly or indirectly) of tectonic stresses at the time of dyke intrusion (Pollard, 1973, pp.233-234; Muller and Pollard, 1977, p.72). Many of the dykes within the study area together with other obviously related dykes to the north, west and east may be traced more or less continuously for up to 300 kilometres. These features are clearly of fundamental tectonic importance and must be related to regional structural features and stresses.

The Griqualand-Transvaal axis (Du Toit, 1933, p.9; Mayer, 1973, p.184) and the Koppies continental arch (Pretorius, 1974, p.8) both pass through the survey area and probably intersect near the farm Twee Buffels Geschiet 42IP (Figure 8). There is a general correlation between the trends of these axes and the dyke trends, although there is much disagreement in the literature about the precise

Sketch map after Pretorius (1974) and Mayer (1973).



Scale:-1 : 2 500 000

20 0 100 200 Kilometres

Figure 8: Location of continental upwarps

nature, age and positions of the axes (Van Eeden, 1972, Figure 3; Mayer, 1973 Figure 1; Du Toit, 1933, p.9; Wellington, 1929, p.42; Pretorius, 1974, Figure 4). The diagram of Figure 8 is based on Figure 1 of Mayer (1973) and Figure 4 of Pretorius (1974).

Wilson (1977, p.63) suggested that the north-north-westerly faults are the result of compensation for the emplacement of the Bushveld Complex and that they were propagated downwards into the floor sediments of the Complex but die out on entering the incompetent sediments of the Chuniespoort Group. Wilson (1977, p.66) recognized large flexures in the Chuniespoort Group and believed these to represent the plastic deformation he expected to occur in place of faulting. It is apparent from the aeromagnetic and ground magnetic data, however, that the Groot Marico fault and its associated dyke continue through the Chuniespoort Group.

Interpretation of the magnetic anomalies produced by the Blaauwbank and Lichtenburg dykes and by the dyke associated with the Diepholte graben (Table 2) often indicate dips of 70°-75° towards the south (assuming induced magnetization for these dykes). The dykes thus appear to be intruded perpendicular to the regional northward dip of the Chuniespoort Group.

The measured average directions of present day horizontal principal stresses are 001° (standard deviation 25°) and 271° (standard deviation 25°) for southern Africa (Gay, 1977, p.5). A theoretical study by Solomon et al. (1975, Figures 10 and 12) using a plate tectonic model gave principal horizontal stress directions of approximately 075° and 345°. In both cases the minimum stress is directed north-south and Anderson (1951, p.25) notes that dykes are propagated most efficiently in the direction at right angles to the least principal (horizontal) stress. It is interesting to observe that the aeromagnetic data indicate that the 075°±5° dykes are better developed than the 165°±5° dykes in frequency, length, and possibly also in width.

6.7 POSSIBLE ECONOMIC IMPLICATIONS

Wilson (1977, pp.55 to 56) by analogy with the Mississippi valley deposits in the United States of America believes that the graben features within the study area could be traps for lead, zinc and fluorspar mineralisation. Recent work, however, (Davies and Prévost 1978, p.29) is supported by the present studies and indicates that the grabens are post-Dwyka, and not penecontemporaneous with the dolomite as would be required to fit Wilson's model.

The water resources of the dolomite are of significant economic importance and the dykes are known to exert significant controls on groundwater movement. The information obtained from aeromagnetic and ground magnetic studies has shed new light on the continuity of the dykes (Day, 1976b, p.3; Day, 1978, p.4) and on the nature of the dyke intersections, and will undoubtedly assist hydro-geological studies.

Two regional upwarps, the Griqualand-Transvaal axis and the Koppies continental arch, pass through the study area, and Greeff (1968, p.104) noticed that the greatest density of kimberlite instrusions in Griqualand West is found in the vicinity of two regional anticlinal upwarps. However, the only known kimberlite dykes in the area are at Swartruggens. This may be because fractures which would have been suitable for exploitation by kimberlite were already sealed off by other intrusions (Greeff, 1968, p.110).

7. CONCLUSIONS

Aeromagnetic, ground magnetic, palaeomagnetic, photo-geological and radiometric data indicate that several suites of dykes occur within the study area. Ages of the dykes range from probably pre-Bushveld Complex to probably post-Dwyka.

The major dyke directions correlate with joint directions in the Chuniespoort Group and also with the present-day stress field, and it appears that a significant proportion of the known dykes, in particular the easterly striking dykes, may be post-Dwyka. The dykes are very poorly exposed but have considerable tectonic and hydrogeological importance, and may be of economic significance.

Minor additional information on the ages of the dykes may be gained using the techniques described in this report, but significant advances will be made only through a co-ordinated drilling program similar to that suggested by Richards (1976).

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FIGURE 2. GEOLOGICAL SKETCH MAP OF AREA.

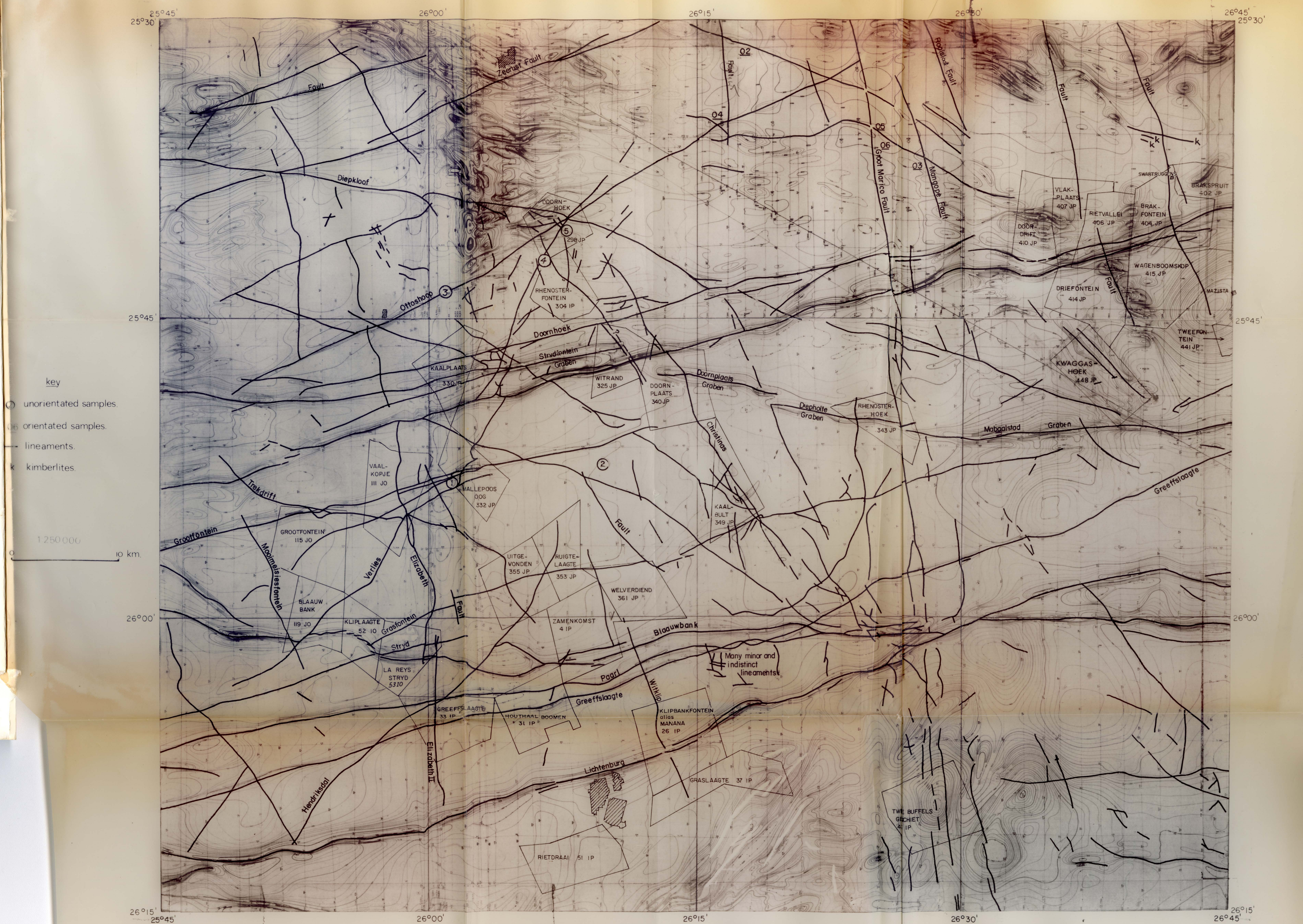

FIGURE 4. MAJOR MAGNETIC AND PHOTOLINEAMENTS, AND LOCALITIES OF SAMPLE SITES.