

# Age of magnetization of Mesoproterozoic rocks from the Natal sector of the Namaqua-Natal belt, South Africa

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## Abstract

We report paleomagnetic results from Mesoproterozoic rocks from the Margate and Mzumbe terranes of the Natal belt, KwaZulu-Natal, South Africa. The Port Edward pluton, a member of the Oribi Gorge Suite, yields a pole position at 7.4°S, 327.8°E,  $A_{95} = 4.2^\circ$ . The magnetic remanence of these magnetite-bearing rocks was not acquired soon after crystallization at ~1025 Ma but only when the sampling area cooled below 500 °C at about 1005 Ma. Similar results have been reported from the western (Namaqualand) sector of the Namaqua-Natal Belt which suggests that the entire belt underwent a similar tectono-metamorphic history. The tonalitic Mzumbe Gneiss was intruded by a swarm of porphyroblastic metadolerite dykes. The magnetization of these Equeefa dykes and the gneissic wall rock is carried by titanomaghemite with Curie temperatures between 330 and 400 °C. Their magnetization was reset at about 530 Ma after burial and exhumation and they yield a pole position at 24.7°N, 17.4°E,  $A_{95} = 10.6^\circ$ . These results demonstrate the difficulty in finding rocks on the Kalahari craton that would yield pole positions to fill the data gap in the apparent polar wander path between 1.1 and 1.0 Ga, a critical time span for Rodinia reconstructions, and provide the first dated Cambrian pole position for the Kalahari craton.

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## 1. Introduction

The placement of the individual cratonic blocks within the Late Mesoproterozoic Rodinia supercontinent is only poorly constrained in part due to the lack of paleomagnetic data (e.g. Wingate et al., 2002; Hanson et al., 2004a,b). For the Kalahari craton, a key piece in the Rodinia puzzle, there are no paleomagnetic data for the critical time interval from 1.1 to 1.0 Ga. In an attempt to provide such data we carried out a paleomagnetic sampling program in the southern part of the Natal belt in KwaZulu-Natal Province of South Africa.

The Mesoproterozoic basement rocks in KwaZulu-Natal are known as the Natal Sector of the Namaqua-Natal Province, a 1500 km long metamorphic belt which rims the southern edge of the Kalahari craton. The two southern terranes of the Natal sector are characterized by the emplacement of a late-tectonic rapakivi granite-charnockite association, the Oribi Gorge suite, between 1060 and 1030 Ma (Thomas et al., 1993; Eglington et al., 2003). The southern part of the Mzumbe terrane exposes extensive outcrops of a major tonalitic orthogneiss body (Mzumbe gneiss), which was intruded by an extensive mafic suite, including a swarm of porphyroblastic metadolerite dykes (Equeefa dykes).

Here we report on a paleomagnetic study of the Port Edward pluton of the Oribi Gorge suite and the Equeefa

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dykes and their wall rock, the Mzumbe gneiss. The Equeefa dykes and the Port Edward pluton have zircon SHRIMP ages of  $1082 \pm 2$  Ma and  $1025 \pm 8$  Ma, respectively (Eglington, pers. comm.; Eglington et al., 2003), and thus could provide the desired paleomagnetic data. However, as we will demonstrate, their age of magnetization does not correspond to their age of crystallization.

## 2. Geological setting

The Natal Sector is the eastern part of the Mesoproterozoic Namaqua-Natal Province that rims the southern margin of the Kalahari craton (Fig. 1). The Natal belt is divisible from north to south into three terranes, the Tugela, Mzumbe and Margate (Thomas et al., 1994). The predominantly mafic Tugela terrane is interpreted as an oceanic crust/island arc assemblage and the granitoid Mzumbe and Margate terranes as magmatic arcs (Jacobs et al., 1993 and references therein; Arima et al., 2001). The study area is located within the Mzumbe and Margate terranes (Fig. 1). These two terranes are distinguished by distinct pre-collisional stratigraphies and are juxtaposed along a major, crustal scale shear zone; granulite facies rocks of the more southerly Margate terrane structurally overlie amphibolite facies rocks of Mzumbe terrane along the SW-dipping, NE-verging Melville shear zone (Thomas, 1989). The Mzumbe and Margate terranes are unconformably overlain by post-tectonic, unmetamorphosed and little deformed (tilted, faulted) Lower Ordovician clastic sediments of the Natal Group (Thomas et al., 1992).

The Mzumbe terrane of the Natal belt is intruded by dykes of the latest Mesoproterozoic Equeefa magmatic suite. The dykes appear to have been injected shortly after the involvement of the Kalahari craton in the Kibaran collisional event thought to reflect the incorporation of the craton in Rodinia (Jacobs et al., 1993). Subsequent to Equeefa magmatism, the Namaqua-Natal belt was subjected to the Namaquan orogenic event (Robb et al., 1999) which included the emplacement of the voluminous granitic and charnockitic magmas of the Oribi Gorge suite in the Natal belt and the Kopersberg suite in Namaqualand. Magmatism was accompanied by high-temperature, low-pressure granulite facies metamorphism. The Equeefa dykes appear to have been intruded immediately prior to, and may be related to, the Namaquan orogenesis.

The Mzumbe gneiss is the oldest magmatic component of the Mzumbe terrane and is characteristic of, and restricted to the Mzumbe terrane. Geochemical analyses indicate a high-aluminium, low-K calc-alkaline protolith, consistent with interpretation of the gneiss as the metamorphosed and deformed plutonic root of an oceanic arc (Thomas, 1989). A U–Pb zircon age of  $1207 \pm 10$  Ma is interpreted as the age of crystallization

of the intrusive protolith of the gneiss (Thomas and Eglington, 1990).

The mafic Equeefa suite intrudes the Mzumbe gneiss. The suite includes a large mafic-ultramafic body near Scottburgh and, in the southern part of the terrane, it is represented by an extensive suite of porphyroblastic amphibolitised mafic dykes. The dykes cross-cut the fabric in the Mzumbe gneiss and locally include xenoliths of foliated tonalite gneiss. Whole rock major and trace element geochemical data for the Equeefa dykes are consistent with development of these magmas in response to partial melting of a mantle source, and are similar to known continental flood basalts (Thomas et al., 1992).

Metamorphism of the Equeefa Suite is indicated by the local replacement of orthopyroxene and olivine by cummingtonite, phlogopite, chloritoid, serpentine and spinel. Corona textures, including orthopyroxene, clinopyroxene and pargasite-spinel symplectite along olivine-plagioclase grain boundaries, and pargasite along phlogopite-plagioclase grain boundaries are interpreted to have developed as a result of crystallization from a magma during synintrusive, isobaric amphibolite facies metamorphism (Thomas et al., 1992; Grantham et al., 1993). Amphibolite facies metamorphism is therefore interpreted as being broadly coeval with intrusion. The large Equeefa Suite body in the Scottburgh area has yielded a zircon SHRIMP age of  $1082 \pm 2$  Ma (Eglington, pers. comm.).

The Mzumbe and Margate terranes, including the Mzumbe Equeefa Suites, are intruded by voluminous plutons of a rapakivi granite-charnockite suite known as the Oribi Gorge Suite. The Port Edward pluton, the most southerly of the suite, consists of dark grey to green, massive, megacrystic hypersthene enderbite (e.g. Grantham et al., 1993). It intrudes high-grade gneisses of the Margate terrane. The massive character of the pluton, and the presence of igneous textures, including randomly oriented and intergrown plagioclase and hypersthene grains, argues against any significant post-emplacement metamorphism of the pluton at the sampling sites, though other plutons of the suite are transected by major ductile sinistral shear zones. The presence of magmatic hypersthene is interpreted to indicate intrusion during a high-temperature thermal event. Eglington et al. (1986, 2003) reported a U/Pb zircon age of  $1025 \pm 8$  Ma for the pluton.

## 3. Paleomagnetic analyses

The paleomagnetic samples were collected with a portable drill from seven Equeefa dykes, at five sites in the Mzumbe gneiss, and four sites in the Port Edward pluton. All samples were subjected to stepwise demagnetization and the data were analyzed by the principal component method (Kirschvink, 1980). Throughout

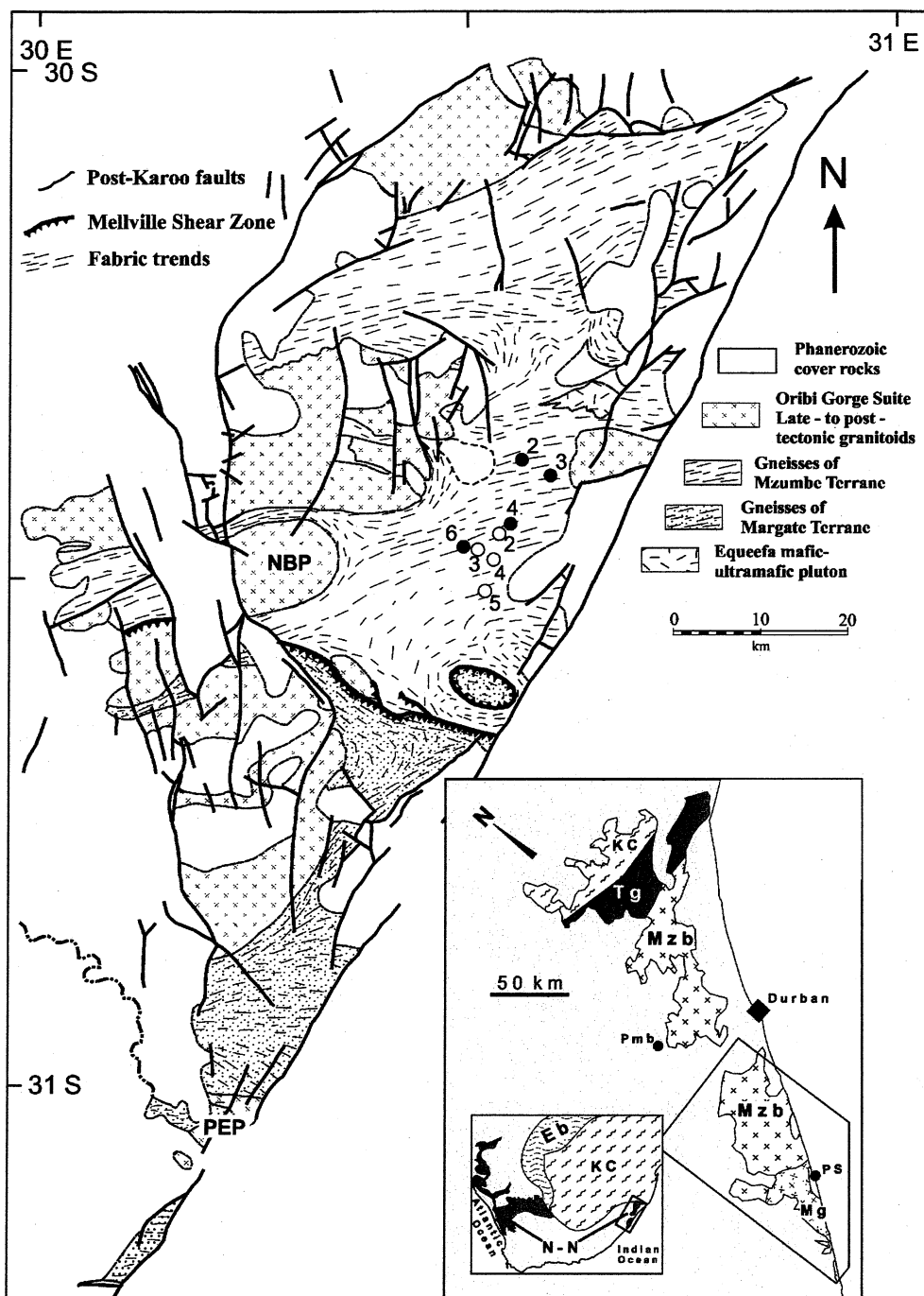


Fig. 1. Sketch geological map showing sampling localities for the Mzumbe gneiss (black circles) and Equeefa dykes (open circles). PEP, Port Edward Pluton (samples collected along a beach section); NBP, Ntumbankulu pluton. Inset maps: N-N, Namaqua-Natal Province (Mesoproterozoic); Eb, Kheiss Province (Paleoproterozoic—Eburnian); KC, Kaapvaal Craton (Archean); Tg, Tugela terrane; Mzb, Mzumbe terrane; Mg, Margate terrane; PS, Port Shepstone.

the measuring procedure, the samples remained inside a magnetically shielded room.

### 3.1. Equeefa dykes

Thermal demagnetization of the saturation magnetization identifies several unblocking temperatures be-

tween about 320 and 400 °C (Fig. 2) compatible with a high-titanium magnetite/maghemite. Thermomagnetic curves of the magnetic susceptibility show a Curie point at about 340 °C (Fig. 2). Upon further heating the susceptibility increases indicating that a new magnetic mineral is forming. The cooling curve clearly identifies this mineral as pure magnetite (Curie point 580 °C). These

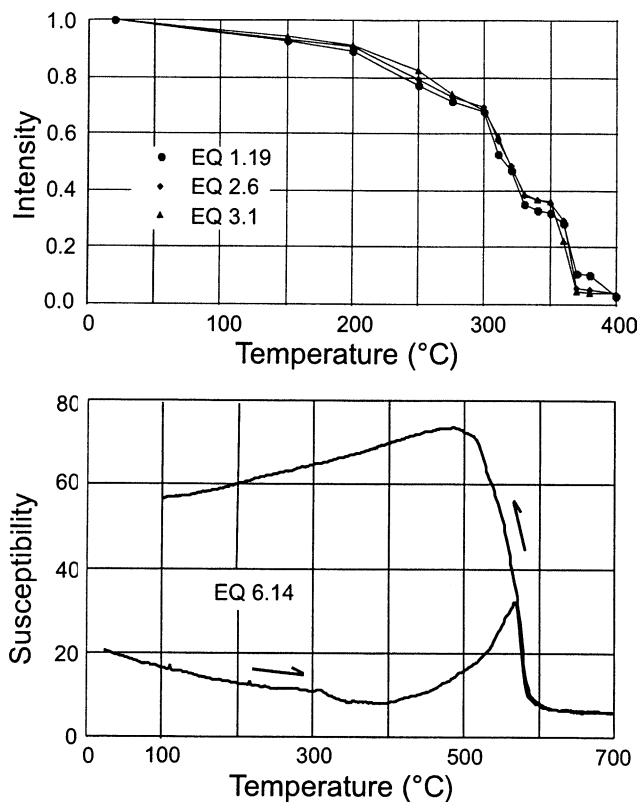


Fig. 2. Intensity of the remanent magnetization and susceptibility as a function of temperature for samples from Equeefa dykes. Thermal demagnetization indicates unblocking temperatures near 330 and 370 °C. The susceptibility curve shows a Curie point at 310 °C. Upon further heating the magnetic mineral converts to pure magnetite. This behavior is indicative of high-titanium maghemite.

data suggest that the magnetic remanence of the Equeefa samples is carried by high-titanium maghemite which ex-solves to pure magnetite and some high-titanium mineral (ilmenite?) at temperatures above about 400 °C.

As expected from the magnetic mineralogy, the samples behaved erratically above 375 °C showing large changes in intensity as well as direction. Vector component diagrams reveal well-defined characteristic directions of magnetization in the range from about 250 to 375 °C for many of the samples (Fig. 3). However, the directions for a given dyke do not form a tight cluster (Fig. 4) in contrast to what one would expect for samples from a fast-cooling rock unit. The samples from two dykes did not yield usable data and the directions from another site fall near the present geomagnetic field direction. The remaining four sites agree well with each other (Table 1). The mean of the site means has a declination of 180.6°, an inclination of -42.0°, and  $\alpha_{95} = 12.4^\circ$ .

### 3.2. Mzumbe gneiss

The Mzumbe gneiss was collected at five sites adjacent to different Equeefa dykes. Magnetically, these

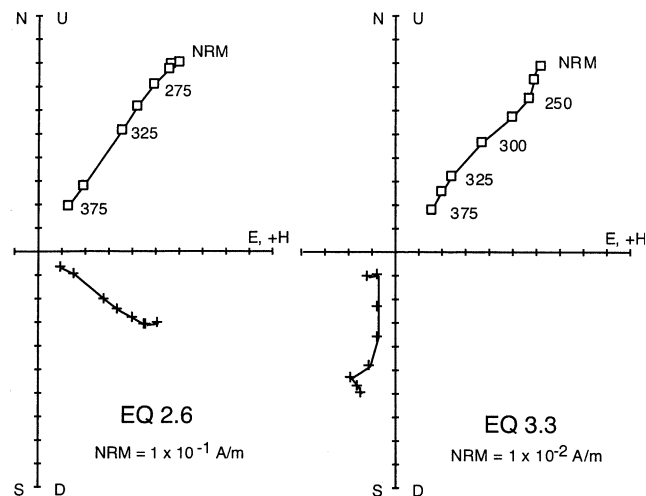


Fig. 3. Vector component diagrams for two Equeefa samples. Crosses are the projection onto the North–East–South–West plane and open squares lie in the Up–Down–Horizontal plane. Numbers indicate the demagnetization temperature in °C.

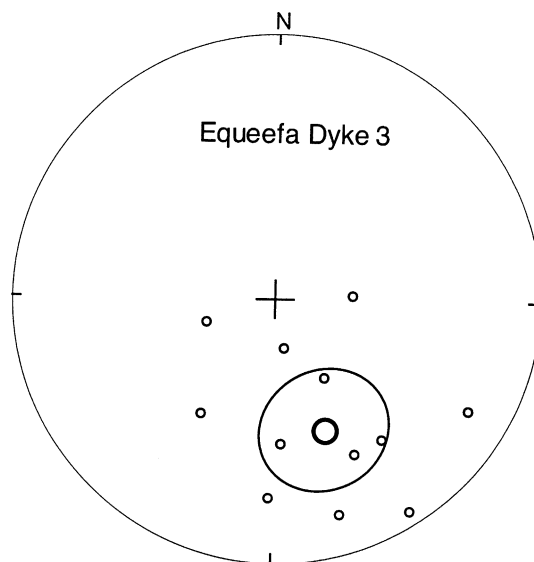


Fig. 4. Equal area net of the directions of magnetization for one Equeefa dyke. The mean is shown with its 95% circle of confidence. All points lie in the upper hemisphere.

samples behaved very much like the Equeefa samples. Thermal demagnetization of the saturation magnetization (Fig. 5) identifies a magnetic mineral with an unblocking temperature near 350 °C. In some samples, a second unblocking temperature near the Curie point of pure magnetite (580 °C) is also observed. The susceptibility versus temperature curves suggest Curie temperatures near 300 °C in sample MZ5 and near 400 °C in sample MZ3 (Fig. 5).

Progressive thermal demagnetization yielded consistent directions only below 400 °C; the behavior above this temperature was erratic (Fig. 6). Directions for individual sites cluster only moderately but the site

Table 1  
Statistical parameters of paleomagnetic data

	<i>N</i>	<i>R</i>	Dec	Inc	<i>k</i>	$\alpha_{95}$	Lat	Long
Equeefa dykes								
EQ2	12/3	9.994	138.4	−64.9	5.5	20.4		
EQ3	12/4	10.150	158.3	−45.9	5.9	19.4		
EQ4	10/4	9.199	161.5	−58.5	11.2	15.1		
EQ6	14/1	11.795	163.6	−61.7	5.9	17.9		
Mean of EQ poles	4	3.934			45.7	13.7	−16.6	191.4
Mzumbe Gneiss								
MZ2	14/1	11.440	167.3	−37.4	5.1	19.6		
MZ3	13/1	9.364	174.5	−61.0	3.3	27.1		
MZ4	13/1	10.070	−7.5	41.6	4.1	23.4		
MZ5	10/2	8.250	181.8	−35.4	5.1	23.6		
Mean of MZ poles	4	3.937			47.3	13.5	−32.5	204.3
Combined EQ and MZ poles	8	7.754			28.4	10.6	−24.7	197.4
Port Edward Pluton								
PE1	7/2	6.777	92.7	−52.4	26.9	11.8		
PE2	7/2	6.957	99.8	−43.7	139.9	5.1		
PE3	8/1	7.310	95.5	−42.3	10.1	18.3		
PE4	8/0	7.883	99.4	−44.2	59.8	7.2		
PE OHJ	6		101.0	−44.5	57.0	8.9		
Mean of PE poles	5	4.988			325.6	4.2	7.4	147.8

*N*, number of samples used/rejected; *R*, resultant vector; Dec, declination; Inc, inclination; *k*, Fisher's precision parameter;  $\alpha_{95}$ , radius of circle of 95% confidence; Lat, north latitude; Long, east longitude. PE OHJ result from Onstott et al. (1986).

means group fairly well with one site being of opposite polarity. The statistical parameters are listed in Table 1.

### 3.3. Discussion of Equeefa and Mzumbe data

The Mzumbe samples were collected within meters of the margins of Equeefa dykes and it is likely that the gneiss was remagnetized upon dyke injection. The *F*-test shows indeed that there is no difference between the two populations at the 2.5% significance level. Thus the data from the eight sites can be combined, yielding a mean declination of 166.5°, an inclination of −51.4° and  $\alpha_{95} = 9.8^\circ$ .

The time of dyke injection has been established at  $1082 \pm 2$  Ma (Eglinton, pers. comm.) which is the maximum age of magnetization. Jacobs et al. (1997) obtained  $^{40}\text{Ar}/^{39}\text{Ar}$  hornblende ages for an undeformed Equeefa dyke of  $1005 \pm 4$  Ma and  $988 \pm 3$  Ma which dates the time when the dyke cooled to below 500–600 °C. This temperature is in excess of the observed unblocking temperatures (400 °C maximum) and thus the age of magnetization is younger than 1005 Ma. Jacobs and Thomas (1996) obtained titanite fission track dates from the Mzumbe terrane. Five of the six dates agree within their error limits and yield a mean age of 530 Ma which dates the time when these rocks cooled through the ~300 °C isotherm after burial and exhumation. This temperature is very close to the magnetic

unblocking temperatures and is the best estimate for the time of magnetization of the Equeefa dykes and Mzumbe gneiss wall rock. Remagnetization of these units during regional cooling also explains why the directions for individual sites do not cluster as one would expect for a fast-cooling dyke (see Fig. 4).

### 3.4. Port Edward Pluton

The Port Edward pluton was sampled at four sites in two outcrop areas along the Indian Ocean coast. Upon thermal demagnetization, over 99% of the saturation magnetization is lost after crossing the magnetite Curie point but the samples still retain a strong magnetization of about 0.1 A/m which is carried by hematite (Fig. 7). The temperature dependence of the susceptibility confirms magnetite as the major magnetic mineral but hematite is also indicated (Fig. 7).

All samples were subjected to thermal demagnetization in 16 steps up to 650 °C. Some samples showed a distinct decrease in the intensity of magnetization upon approaching the magnetite Curie point, but most samples retained their magnetization up to at least 625 °C. Vector component diagrams typically reveal two components of magnetization (Fig. 8). A low-temperature component can be identified in the range from room temperature up to about 400 °C. The directions of the low-temperature components scatter widely and are interpreted as a viscous magnetization carried by

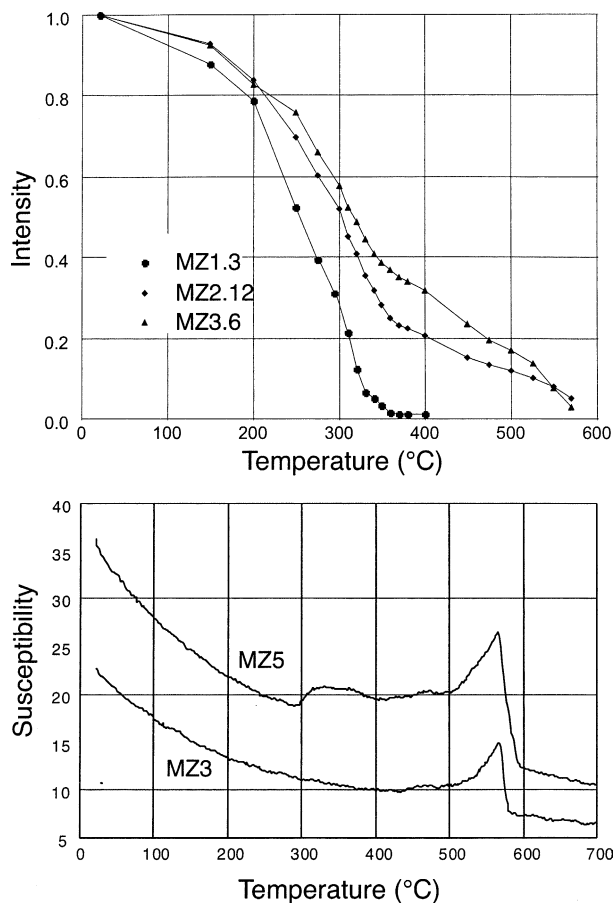


Fig. 5. Variation of the intensity of magnetization and susceptibility upon heating for samples from the Mzumbe gneiss. The low unblocking and Curie temperatures imply that high-titanium magnetite is the dominant magnetic mineral.

multi-domain magnetite. A high-temperature component is well defined in the temperature range from 450 °C or 500 °C to above 600 °C. There is no difference in directions between the samples which have a distinct magnetite-residing magnetization and those whose remanence is also carried by hematite. This implies that the hematite is the result of deuteric alterations during initial cooling of the pluton. The directions of the high-temperature components for the four sites cluster well and the statistical parameters are listed in Table 1. Included in this table are the results from six samples reported by Onstott et al. (1986). The combined site-mean direction has a declination of 98.9° east, an inclination of -44.8° and  $\alpha_{95} = 4.8^\circ$ .

### 3.5. Age of magnetization of Port Edward Pluton

The Port Edward pluton has a U–Pb zircon crystallization age of  $1025 \pm 8$  Ma (Eglington et al., 2003). Rb–Sr whole rock and biotite dates for the Port Edward pluton of  $987 \pm 19$  Ma (Eglington et al., 1986) and  $\sim 990$  Ma (Nicolaysen and Burger, 1965), respectively,

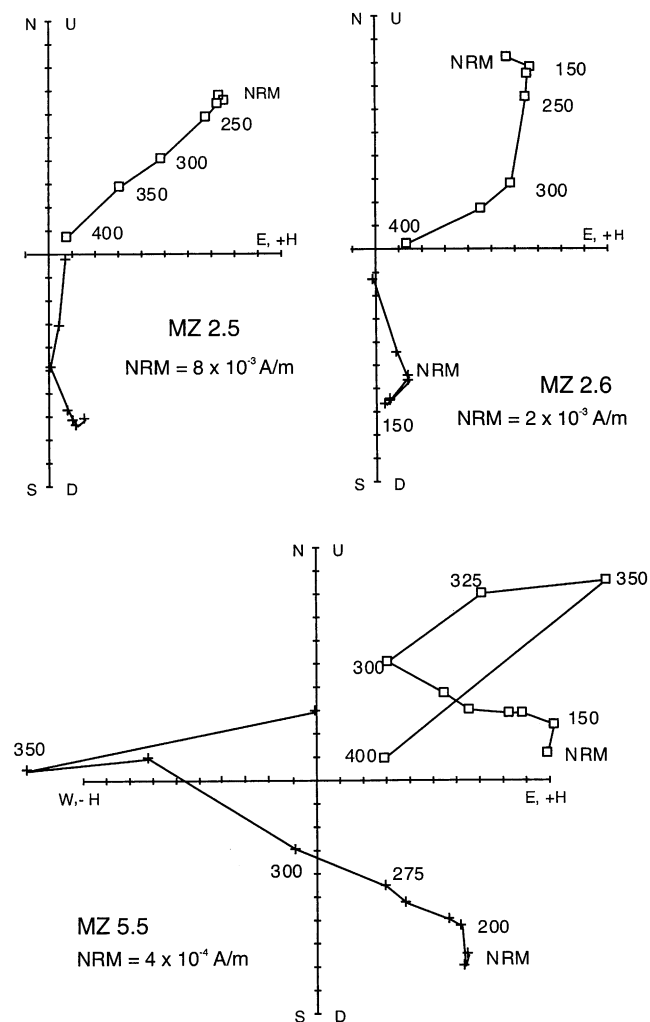


Fig. 6. Vector component diagrams for samples from the Mzumbe gneiss.

are interpreted as cooling ages, indicating post-emplacement cooling through the blocking temperature of Sr in biotite ( $\sim 300$  °C) (Thomas et al., 1993). This is consistent with the cooling histories of the Margate and Mzumbe terranes which imply that the 500 °C isotherm was crossed at about 1000 Ma. Three samples from the Mzumbe terrane yielded hornblende  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of 1002 Ma, 1004 Ma, and 1005 Ma each with a 4 Ma error (Jacobs et al., 1997). Thus an age of  $1004 \pm 5$  Ma is the best estimate for the time of magnetization of the Port Edward pluton.

### 4. Comparison with other African paleomagnetic data

The number of Precambrian pole positions from Africa is limited and many poles have only poor age control. For the time span relevant to our data, there are two clusters of pole positions (Fig. 9). The first group includes the Umkondo dolerites and lavas of

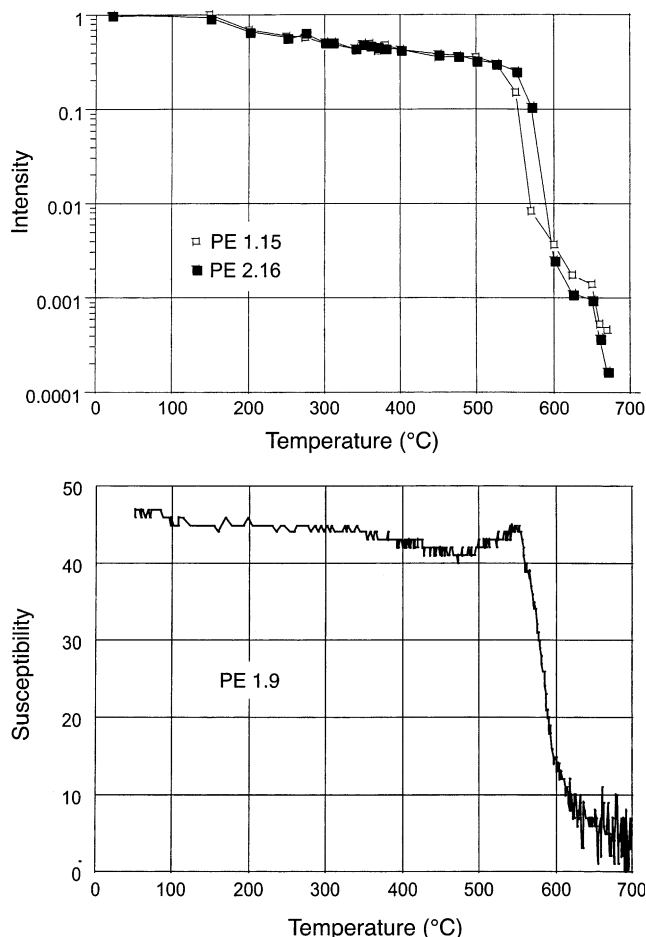


Fig. 7. Temperature dependence of the magnetic remanence and susceptibility of samples from the Port Edward pluton. Both tests indicate pure magnetite as the dominant magnetic mineral. Note that the intensity axis is logarithmic to emphasize the presence of hematite.

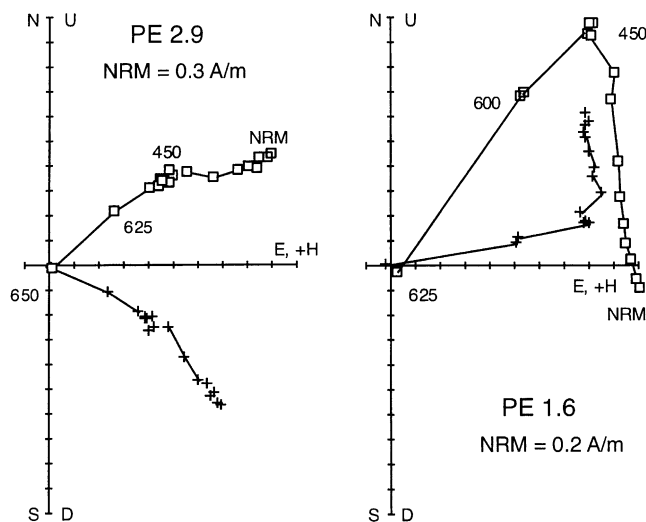


Fig. 8. Vector component diagrams for samples from the Port Edward pluton. The characteristic directions of magnetization were typically revealed after heating to 450 °C.

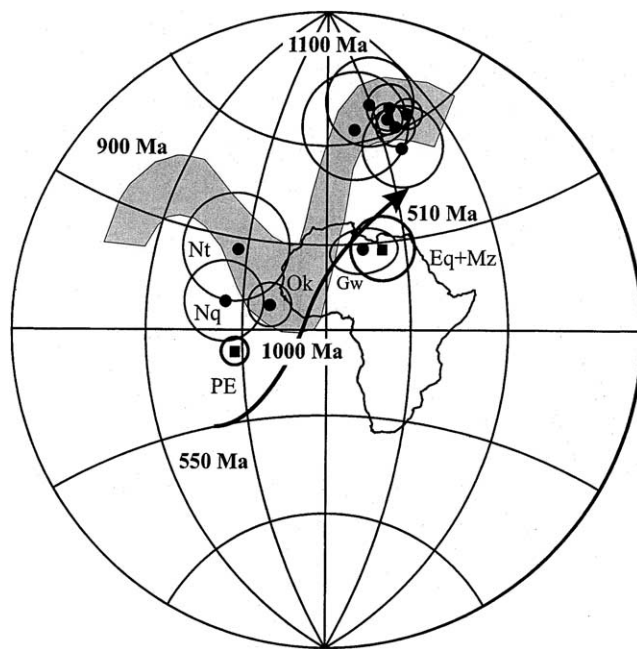


Fig. 9. Equatorial projection of pole positions from the Kalahari craton with their 95% error limits. The shaded swath is the apparent polar wander path for the time from 1000 to 900 Ma (McWilliams and Kröner, 1981) and the heavy line is the APWP for Gondwana from 550 to 510 Ma (Meert and van der Voo, 1997). Nt Ntimbankula (Maré and Thomas, 1998); Nq Namaqua (Muller et al., 1978); Ok Okiep (Onstott et al., 1986); Gw Graafwater (Bachtadse et al., 1987); PE Port Edward (this study); Eq + Mz Equeefa and Mzombe (this study). For clarity, the poles near 1100 Ma have not been labeled.

Zimbabwe (McElhinny and Opdyke, 1964; McElhinny, 1966), the post-Waterberg dolerites in South Africa and Botswana (Jones and McElhinny, 1966; Pancake, 2001), gabbros intruding the Vredefort structure (Allsopp et al., 1989), and the Timbavati Gabbro (Hargraves et al., 1994) of South Africa. Hanson et al. (2004a,b) presented additional paleomagnetic data from dolerites in South Africa and, most critically, reported their U–Pb zircon/baddeleyte dates. These new data imply that all these rocks are part of the Umkondo Large Igneous Province. Ages for the province range from  $1112.0 \pm 0.5$  to  $1106 \pm 2$  Ma with 12 of these ages falling between 1109 and 1108 Ma.

The second group of pole positions was derived from rocks in the Namaqua-Natal metamorphic belt. From the Okiep copper district of western South Africa, Muller et al. (1978) reported paleomagnetic data from 11 sites, 10 of which yield a mean pole at  $8.8^\circ\text{N}$ ,  $339.5^\circ\text{E}$ ,  $A_{95} = 7.6^\circ$ . They cite a U/Pb zircon age of  $1056 \pm 20$  Ma. From the same area, Onstott et al. (1986) report the results from five additional intrusives which they combined to yield a Namaqua mean pole at  $9.4^\circ\text{N}$ ,  $324.0^\circ\text{E}$  with an error of  $A_{95} = 13^\circ$ . Importantly, these authors performed  $^{40}\text{Ar}/^{39}\text{Ar}$  thermochronological studies and arrived at an age of 1010–1075 Ma for the

time when the rocks cooled through the magnetic blocking range (500–580 °C).

In the Natal Sector of the Namaqua-Natal belt, Maré and Thomas (1998) sampled the Ntimbankulu pluton, like the Port Edward body also a member of the Oribi Gorge suite. This pluton has not been directly dated but other members of this suite have yielded U–Pb ages between 1030 and 1060 Ma (Eglington et al., 2003). However, in view of the cooling history of this area, it is likely that the age of magnetization is about 1005 Ma.

These poles are shown in Fig. 9 together with a portion of the apparent polar wander path of McWilliams and Kröner (1981) for the time span from 1100 Ma to 900 Ma and the averaged Gondwana apparent polar wander path for the time from 550 to 510 Ma (Meert and van der Voo, 1997). Also depicted are our new pole positions for the Port Edward pluton and the combined Equeefa/Mzumbe data set. The Port Edward pole agrees reasonably well with the other poles from the Namaqua-Natal belt for which a similar magnetization age has been inferred. The Equeefa-Mzumbe pole clearly does not fall on this part of the polar wander path but falls on the smoothed Gondwana apparent polar wander path of Meert and van der Voo (1997) near 520 Ma. It closely matches the pole derived from the Graafwater Formation of the Table Mountain Group in the western Cape fold belt (Bachtadse et al., 1987). The Graafwater Formation is considered to be of Early Ordovician age based on trace fossils but its age is only firmly constrained by the age of the basement (510–520 Ma, Kisters et al., 2002) and the overlying Upper Ordovician formations (Bachtadse et al., 1987). Our paleomagnetic data suggest that the Graafwater Formation might actually be of Cambrian age.

## 5. Conclusion

The paleomagnetic analyses did not achieve the original goal of obtaining pole positions that would fill the gap in the African apparent polar wander path between 1.1 and 1.0 Ga because the age of magnetization does not correspond to the age of crystallization. Thermochronological studies in our field area, the Natal belt, as well as in the Namaqua belt demonstrate that the rock units cooled through the 500 °C isotherm only at about 1005 Ma. Thus rocks in which the magnetization is carried by magnetite or hematite, such as the Port Edward pluton, will acquire their magnetic remanence only at that time. The Equeefa dykes and the Mzumbe gneiss wall rock have magnetic blocking temperatures below 400 °C; they were remagnetized near 530 Ma after burial and exhumation.

These data point out the importance of establishing the time of magnetization. This is a particularly critical issue for the Kalahari craton because its apparent polar

wander path sweeps across western North Africa at least three times, first near 1900 Ma (e.g. Hattingh and Pauls, 1994; Evans et al., 2002; Hanson et al., 2004a,b), then around 1000 Ma, and again at about 530 Ma. It seems clear now that the entire Namaqua-Natal belt cooled below 500 °C only at about 1.0 Ga. This makes it difficult to find rocks on the Kalahari craton which could provide pole positions for the time interval between 1.1 and 1.0 Ga. The location of the Kalahari craton relative to Laurentia is well defined at about 1108 Ma (Hanson et al., 2004a,b), but their relative positions for the 100 Ma prior to and after this time are paleomagnetically unconstrained, a point also stressed by Meert and Powell (2001) and Meert and Torsvik (2003).

The Equeefa-Mzumbe pole provides an important data point for the Paleozoic Gondwana apparent polar wander path because it is the only pole from the Kalahari craton for this time and thus is a critical data point for evaluating the assembly of East Gondwana.

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