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COMMUNICATION

A new palæomagnetic pole for the Dwyka System and correlative sediments in sub-Saharan Africa

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ABSTRACT—Palæomagnetic data from sediments deposited during the Permo-Carboniferous Dwyka glaciation of Gondwana has been obtained from South Africa, Zimbabwe and Tanzania. Biostratigraphic and geochronological constrains indicated that the sediments are Early Carboniferous to Early Permian in age. Seventy-two sites were collected from diamictites, siltstone and rythmites. Twenty-two of these sites yielded positive results, rythmites being the most successful lithological type sampled. The dominant direction isolated was down and to the east-southeast. However, three sites from the northwest Cape Province yielded directions up and to the northwest, the normal polarity in Early Permian coordinates. Normal polarities within the Kiaman at this time are known from elsewhere (Dunkard Subchron). Virtual geomagnetic poles were calculated from each site and a palæomagnetic pole was calculated after correcting each site for bedding tilt. The sites group more closely after they have been corrected for tilt and have passed a fold test. The palæomagnetic South Pole falls at 67°E and 25°S, α95 of 12°.

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INTRODUCTION

The Dwyka system in the southern part of Africa consists of sediments deposited under glacial conditions in marine and non-marine environments (Visser, 1997). These sediments are often dominated by diamictites above a basal unconformity and are present over a large area from Tanzania to the Republic of South Africa (Visser, 1997; Wopfner, 1999). Other rock types are also present in these sequences. Some, such as mudstones and rythmites, have been interpreted in some areas, such as Tanzania and Zimbabwe, as glacial varves (Bond, 1952). Similar rocks in South Africa have also been interpreted as turbidite deposits (von Brunn and Statten, 1987). These sediments are the debris left behind by the great Permo-Carboniferous glaciation, which covered a large part of Gondwana.

Previous palæomagnetic studies have been reported on Dwyka-age sediments from Zimbawe by Nairn (1960) and a palæomagnetic pole position for these was reported on rythmites collected from Tanzania, Zimbabwe and Zambia (McElhinny and Opdyke, 1968). The results of this latter study yielded a palæopole position in southern Africa, which has been used for many years as part of the polar wander path for Gondwana (Rapalini, 1998; Smith, 1999). McElhinny and Opdyke (1968) suggested that these results were Lower Carboniferous in age since normal directions of magnetisation were observed. Visser (1990), however, suggested an Early Permian age for these sediments, based mostly on spores and pollen. Recent palynology has shown, however, that the onset of glaciation dates back to Early Carboniferous in South Africa (Streel and Theron, 1999). The

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importance of the Dwyka Pole, in construction of the polar wander curve for Gondwana, would indicate that a restudy of these sediments using modern techniques was called for. This restudy was undertaken beginning in 1998 while the first author was on sabbatical leave at the University of Cape Town, South Africa.

GEOLOGY

South Africa

The sediments of the Dwyka Group crop out along the southern margin of the Karoo Basin in the Cape Fold Belt (Vissar, 1990; Turner, 1999). The outcrop belt swings to the north, flanking the western margin of the Karoo Basin and following the bend of the Cape Fold Belt as it swings from east-west to a north-south trend. Along the northern margin of the Karoo Basin, the Dwyka crops out along the southern margin of the ancient Cargonian upland where Dwyka deposits rest uncomformably on basement. The outcrop belt in this region is discontinuous and of variable thickness. The group crops out along the eastern and northeastern margins of the Karoo Basin in Kwa Zulu-Natal where the Dwyka sediments are deposited uncomformably on pre-existing topography. The group is up to 800 m thick along the southern margin of the basin and thins towards the north and northeast (SACS, 1980; Visser, 1990; Cole, 1992).

The age of the Dwyka sediments is difficult to establish because they are mostly unfossiliferous. However, overlying and underlying beds do contain plant remains. The time of precise onset of Dwyka sedimentation is not known since the Dwyka sediments usually rest uncomformably on a glaciated surface developed on sediments of the Witteberg Group south of latitude 32°50'S. The lowermost glacial sediments were estimated to be ~307 Ma ago (Visser, 1997), leaving a hiatus of ~30 Ma between it and the underlying Witteberg Group. However, the duration of the hiatas at the base of the Dwyka has long been a matter of debate. Streel and Theron (1999) have recently re-evaluated the miospores, fish, fauna and mega flora of the Waaipoort Formation (upper Witteberg Group) immediately underlying the first glacial deposits and found that the formation is no older than the Middle Tournaisian. The sediments of the uppermost Witteberg Group (Waaipoort Formation) exhibit glacial features, such as soft sediment deformation ascribed to glacial action and the presence of drop stones. Streel and Theron (1999) concluded that glaciation begins during deposition of the uppermost Witteberg sediments. Thus, the timing of the beginning of glaciation is not tightly constrained but is likely to be Late Tournaisian or Visean (Early Carboniferous). Global cyclic deposition, like those recorded in the cyclotherms of the North American Carboniferous, begin in the Namurian and terminate at the end of the Stephanian. This cyclic deposition is thought to be caused by the waxing and waning of the Southern Hemisphere ice sheets (Wanless and Shepard, 1936; Heckel, 1986; Veevers and Powell, 1987) and, therefore, may give an estimate of the Gondwana glaciation.

The termination of a glaciation in South Africa is constrained by the overlying formations, which are thought to be of Early Permian age. Pollen reported from the northern outcrop belt of the Dwyka indicates a Stephanian to Early Artinskian age for those sediments (Vissar, 1990). Vissar believes that the glaciation persists to the top of the Artinskian since coal beds along the northern and northeastern margin of the Karroo Basin yield Kungurian and Artinskian palynological ages. Juvenile zircons from two tuff horizons in southern Namibia give Pb/U dates of 302 ± 3.0 Ma and 299.2 ± 3.2 Ma (Bangert *et al.*, 1999) for the top of the deglacial sequences. This would be latest Carboniferous in recent time scales (Jones, 1995; Gradstein and Ogg, 1996; Menning *et al.*, 2000). In the southern part of the Karoo Basin, U/Pb radiometric analysis on zircons from interbedded tuffs from the lowermost beds of the post-glacial Prince Albert Formation (Ecca Group), which immediately overlies the Dwyka Group, gives dates of 288 ± 3.0 and 289 ± 3.8 Ma (Bangert *et al.*, 1999). This places the last deglaciation close to the Permo-Carboniferous boundary. U/Pb dating on zircons from tuffs about midway up from the base of the Dwyka have yielded an age of 297 ± 1.8 Ma (Bangert *et al.*, 1999). Thus, the Dwyka Group in southernmost Africa spans about 50 Ma and is mostly confined to the Carboniferous. The upper 400 m of the Dwyka Group, however, represents < 10 Ma, or about 20%, of the entire glacial period. The age of the palæomagnetic data probably range between about 340 and 290 Ma and can be no younger then 288 Ma (Asselian) or older than 343 Ma (Late Tournaisian). However, a majority of the sites are likely to be Late Carboniferous in age.

Zimbabwe

The principal occurrence of Karoo sediments in Zimbabwe occurs in the Zambesi Basin of northwest Zimbabwe, which trends northeast to southwest and the axis along which the Zambesi River flows. Glacial sediments of Dwyka age crop out at the base of the sequence and were first recognised by Bond (1952). Similar age sediments crop out north of the Zambesi River in Zambia. The outcrops and stratigraphy of these sediments has recently been reviewed by Lepper (1992).

The principal lithologics present in Dwyka-age sediments are diamictites and varvites resting unconformably on rocks of Precambrian age. The varvites exhibit graded bedding on a scale from 0.5 mm to 1.0 cm in thickness and are grey to cream in colour with occasional hematitic staining. These sediments become lithified toward the Zambesi River. However, on the eastern margin of the basin, the varves are often poorly lithified and probably were not deeply buried (Lockett, 1979). Lepper (1992) described the petrology of these sediments in some detail. The dating of the sediments relies on spores and plant remains and the sediments are believed to be Late Carboniferous and Early Permian in age (Falcon, 1975).

Tanzania

In Tanzania, Dwyka-age sediments are present at the base of the Karoo sediments in several of the sedimentary basins. Sampling took place in the Ruhuhu Basin where glacially derived sediments were first described by Wopfner and Kreuser (1986). They are described in detail by Wopfner and Diekmann (1996) and are named the Idusi Formation (Wopfner, 1999). The Idusi Formation rests unconformably on Ubendian migmatites. This unconformity is well exposed in the type section of the Idusi Formation in the Idusi Gorge. The formation is up to 240 m in thickness. Glacigene diamictites are present in the base of the section, overlain by black and grey mudstones, sandstones and green laminated mudstones that have been interpreted as glacigene lacustrine varves. The formation is capped by sandstones of the coal-bearing Mchuchuma Formation. Microfloral assemblages from the upper part of the formation have been placed in the earliest Permian (Asselian: Foster and Waterhouse, 1988). A Gangamopteris plant assemblage of Early Permian age is also present in the upper part of the formation (Wopfner and Diekmann, 1996).

SAMPLING

Where possible, fine-grained sediments were sampled with a portable drill taking cores 2.54 cm in diameter and were orientated with a magnetic compass. All sites were located by a global positioning system. In the past, rythmites have yielded the best palæomagnetic results. However, this lithology is not common in most out crops and other types of sediments were also sampled. Samples were often taken from clast-poor diamictites in the hope that casts, which were included in sampled cores, might be non-magnetic or unstable so that the magnetisation of the matrix might dominate magnetically. Table 1 lists all sites, which gave significant results; in South Africa, 45 sites were sampled in the Cape Province, Kwa-Zulu Natal and the North West Cape Province. All of the sampling sites were in road cuts and riverbeds (Fig. 1).

Nineteen sites were sampled from the Idusi Formation in the Ruhuhu Basin, Tanzania, consisting of diamictites, black and grey shales, siltstones and green rythmites. Sandstones and conglomerates are also present, but these were not sampled. All sites were taken along riverbank exposures of the Nyamangami, Mchuchuma, Lilangu, Kipololo and Nyamajilu Rivers. The first of the collecting areas was east of Ruanda Mission. However, the largest collections were made west of the village of Nkomangombe.

Samples were collected from 18 sites in Zimbabwe from exposures in the Zambezi Block. In all cases, the sampled exposures were in stream- or riverbeds. The collecting areas were in the Chofa River near Chofa School in the watershed of the Kahanda River in the Jompani resettlement area near Sanyati. Samples were also collected in the Sengwa River Valley near the Rio Tinto Coal Mine. In the collection from Zimbabwe, samples were taken from varves, siltstones and diamictites.

PALÆOMAGNETIC RESULTS

All samples were treated by stepwise thermal demagnetisation in a commercially available oven and cooled in a very low magnetic field space within a magnetically shielded room. Each sample was demagnetised in up to 14 steps to temperatures as high as 680°C. The measurements were made in a commercial cryogenic magnetometer. The resultant vector was determined by line fitting techniques described by Kirschvink (1980). These directions were combined using the statistics of Fisher (1953). The results of thermal demagnetisation will be discussed by regions.

South Africa

Forty-five sites were sampled in a variety of lithologies, but only ten sites yielded internally coherent results. Representative demagnetograms are shown in Fig. 2. Stable isotope and fluid inclusion work on these deposits indicates significant low temperature (180–200°C) fluid-induced diagenetic overprint, probably related to the tectonics of the Cape Fold Belt to the south (Egle *et al.*, 1998). This may have adversely affected the magnetisation of these sediments. The sample illustrated in Fig. 2a gives what is regarded as completely incoherent demagnetisation data; and, unfortunately, many sites show this type of behaviour, particularly those taken in diamictites

Table 1. Dwyka site mean statistics

Site	Site Coord. Lat°S	Long°E	Dip/DDA	n/N	D_b	I_b	Pol	κ	α_{95}	VGP Lat°	Long°	Lithology
South Africa												
6	33.2	20.5	22/109	5/5	87.7	68.5	R	23.4	16.1	63.2	-24.2	Diamictite
9	33.2	20.5	30/176	5/5	183.8	68.3	R	35.9	12.9	13.0	-71.5	Diamictite
15	31.3	19.1	10/340	4/5	322.6	-70.7	N	232.8	6.0	56.1	-54.6	Diamictite
16	31.3	19.1	10/340	3/5	312.5	-66.0	N	79.3	13.9	69.6	-50.5	Diamictite
17	31.3	19.1	10/340	4/5	317.4	-66.6	N	232.7	6.0	67.3	-53.6	Diamictite
19	32.3	19.6	0/	4/8	112.9	57.8	R	35.4	15.7	82.9	-36.1	Siltstone
20	32.3	19.6	5/201	3/6	103.7	68.2	R	23.3	26.1	65.8	-32.8	Rythmite
49	29.7	30.5	0/	5/11	70.1	72.6	R	22.3	16.6	61.3	-15.2	Diamictite
50	29.8	30.4	0/	5/6	114.9	54.0	R	44.7	11.6	97.2	-35.6	Rythmite
54	28.2	30.8	0/	3/5	110.8	61.3	R	24.0	25.7	86.5	-33.4	Mudstone
Tanzania												
62	10.5	34.9	13/81	5/5	228.7	69.3	R	17.9	18.6	2.4	-32.5	Grey Siltst.
64	10.3	34.7	13/166	5/5	115.3	63.8	R	59.4	10.0	79.1	-25.0	Grey Siltst.
65	10.3	34.7	13/166	5/5	104.3	69.9	R	39.3	12.4	71.4	-16.7	Grey Siltst.
81	10.3	34.6	7/123	6/6	133.5	69.6	R	103.8	6.6	65.8	-33.2	Grey Siltst.
Zimbabwe												
99	18.0	29.5	14/223	7/7	111.3	68.0	R	336.9	3.3	70.7	-27.2	Varve
100	18.0	29.5	0/	5/5	64.0	78.3	R	183.7	5.7	49.8	-7.2	Varve
103	18.0	29.5	0/12	5/5	48.6	58.5	R	414.6	3.8	66.9	17.0	Varve
104	18.0	29.5	5/220	5/5	52.7	58.2	R	537.3	3.3	69.3	14.8	Varve
105	18.0	29.5	0/	5/5	48.0	35.7	R	115.8	7.1	83.1	29.6	Varve
106	18.0	29.5	0/	5/5	60.1	49.8	R	1123.0	2.3	79.9	14.5	Varve
107	18.0	29.5	12/170	5/5	109.0	65.4	R	319.8	4.3	74.7	-25.9	Varve
108	18.0	29.5	15/164	8/8	66.2	76.6	R	1523.5	1.4	52.8	-6.5	Varve

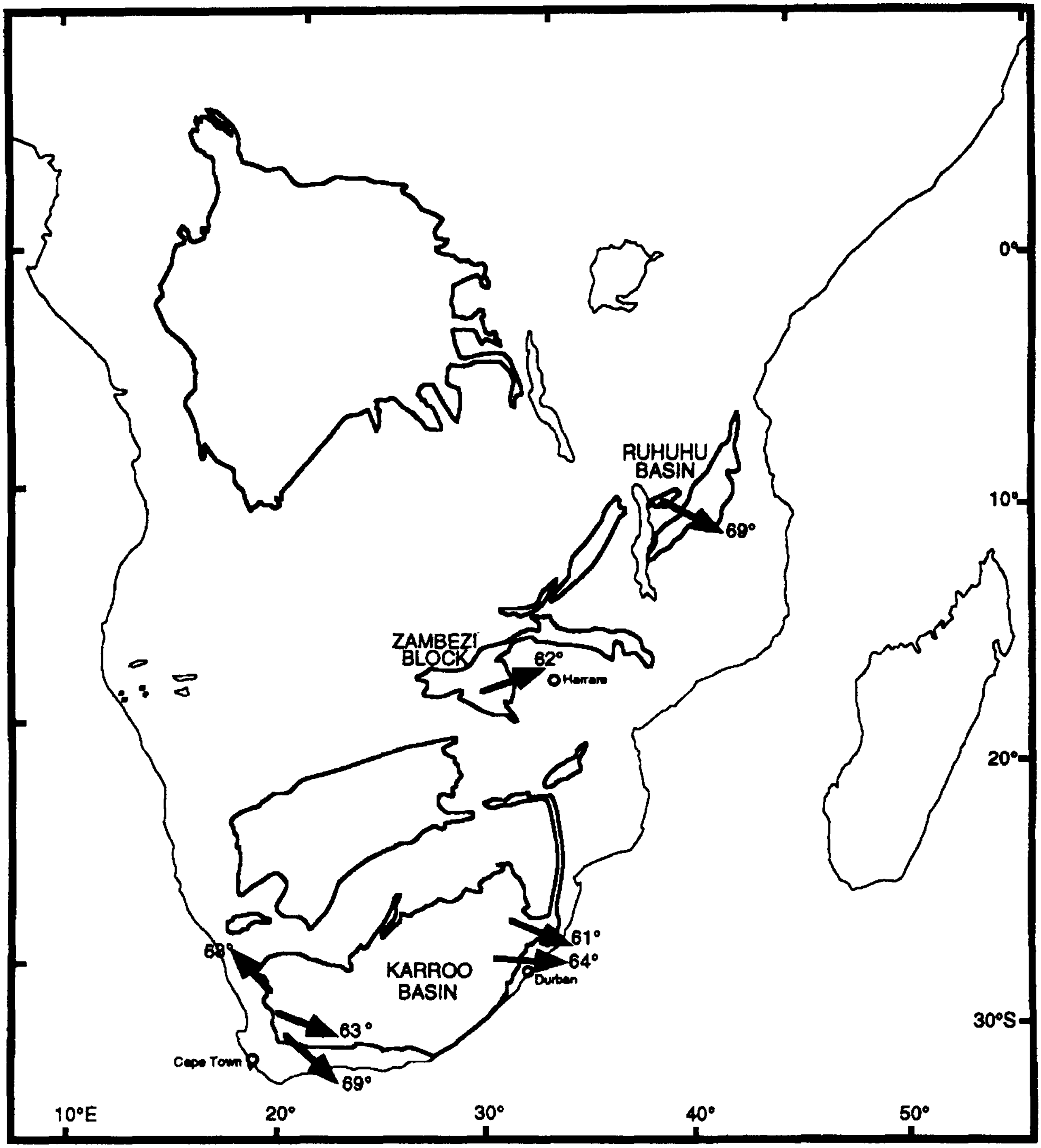

Figure 1. Depositional basins with Karoo sediments south of the Sahara. Sampling areas indicated by the base of the arrow, which indicates the declination of the Dwyka results. The inclination is given by the numerals at the end of the arrows.

flanking the Cape Fold Belt. However, some individual sites yield directions down and to the east or southeast (Fig. 2b); sites 6 and 9, which were collected in a road cut at the Waushope Memorial on R-1 near Matjiesfontain in folded beds, gave good results. These samples were taken in the lower part of the Dwyka Group in this section and are, therefore, likely to be Early-Mid Carboniferous in age. Other sites nearby did not yield usable data. Sites 13 through 21, taken from the northwest part of the Karoo Basin in the vicinity of Elansvlei and Nieuwoudville, yielded good results from clast-poor diamictites. Three of these sites gave normal directions of magnetisation, up and to the northwest (Fig. 2c). Sites from the region around Prieska failed to yield coherent results and were strongly overprinted.

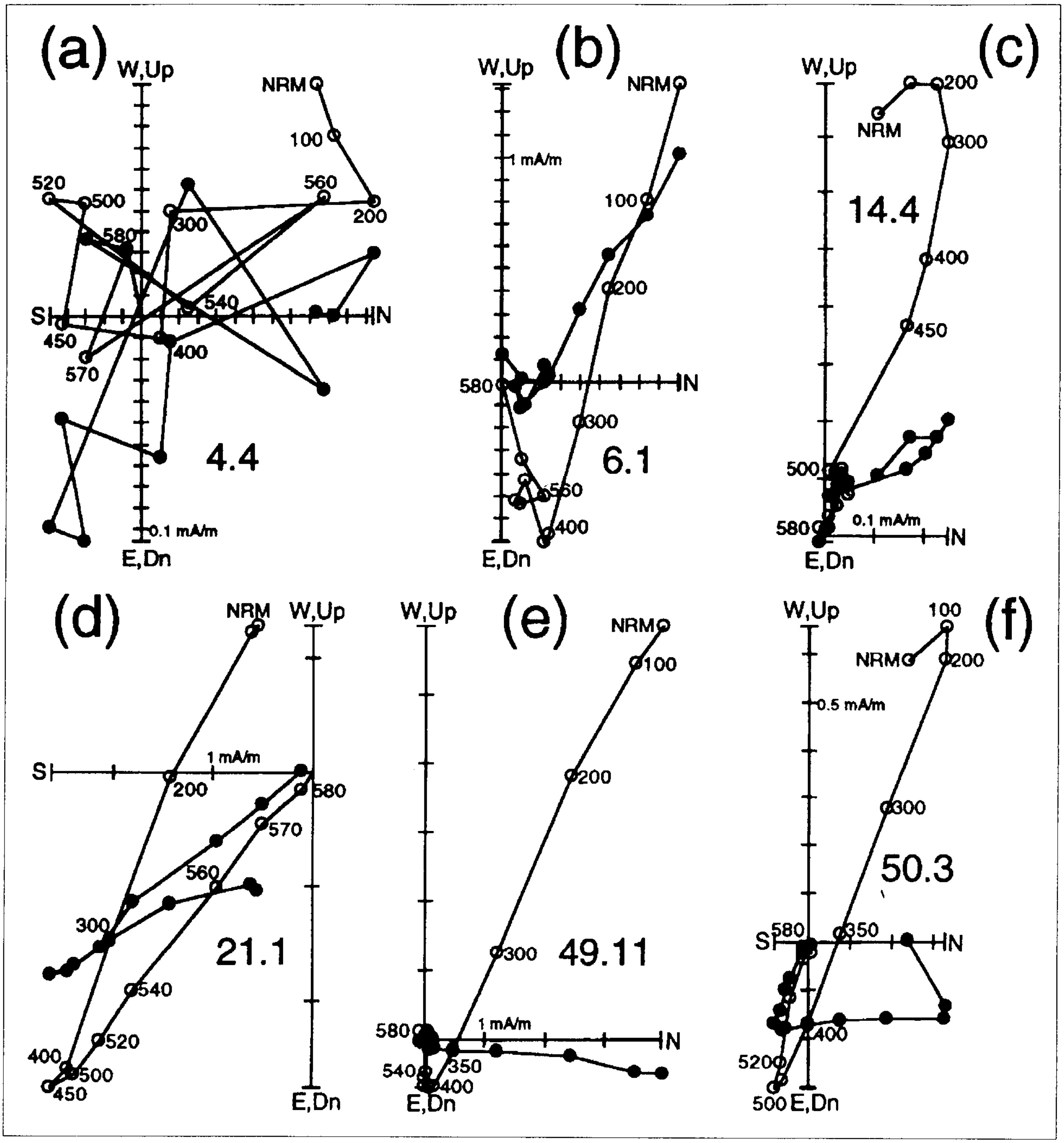

Figure 2. Demagnetograms for selected South African sites. The magnetisation vectors after the heat treatment specified are plotted on two of the three possible orthogonal planes. ● are plotted on the horizontal plane and ○ are plotted on a vertical plane.

Sites taken from Kwa-Zulu Natal gave mixed results with good data being obtained from clast-poor diamictite from the Ummlas Quarry and varvites from near Pietermaritzburg (Fig. 2d). However, a varvite site near Ishlandwana gave scattered results. The palæomagnetic results from South Africa seem to depend upon the region sampled and the state of weathering of the samples. The Kwa-Zulu Natal and the North West Cape yielded the highest proportion of successful sites.

Zimbabwe

Eighteen sites were collected from three areas in Zimbabwe. Sites 95 through 98 from the Chofa River gave components in the direction of the present Earth's field. Sites from the Sengwa River Valley near the Rio Tinto Coal Mine gave poor results, with very weak magnetic intensity and a small present-day overprint.

The sites taken from the region around the Jompani Resettlement area in the watershed of the Kahanda River were the most successful. Ten sites were sampled in glacial rythmites described by Lockett (1979). The Dwyka-aged sediments here are quite thin with a diamictite overlying what is interpreted to be lacustrine varves. This region is unlikely to have been deeply buried by later sedimentation and the sediments are poorly lithified. As a result, a majority of the sites were hand sampled and the varvites were soft enough to be cut with a knife. Bedding tilts were shallow with no overall regional dip.

Thermal demagnetisation of these varvites, in most cases, detects only a very small overprint (Fig. 3b). The principal component is directed down and to the east with dips of up to 70°. The direction of magnetisation persists to temperatures up to 680°C, an indication that the magnetic carrier is hematite. These sediments are usually light grey or blue-grey, indicating that the hematite is probably detrital as no red colouration is observed. These sediments gave the best results in this study.

Tanzania

The 19 sites collected from Tanzania gave variable results, and only four of these sites gave good results. The best data set was derived from nodules in a green varved lacustrine sequence (Fig. 3f). Unfortunately, most of the rythmite sequences observed had very weathered outcrops so that they were impossible to sample. The other successful sites were taken from dark shales and siltstones. The direction observed slopes steeply down to the east-southeast. A second direction is observed in some of the diamictite sites, directed toward the south with shallow inclinations (Fig. 3c; Table 1).

BOREHOLES FROM SOUTH AFRICA AND ZIMBABWE

Two cores containing rythmites were obtained from borings in South Africa originally curated by J. Vissar, who graciously allowed the cores to be sampled for palæomagnetic research. The cores are from the northern Dwyka facies and are from the Welkom Goldfields and the Postmasburg-Kurnman area. These cores are unorientated but yielded good inclination-only data. A further two cores were obtained from Zimbabwe, drilled by Union Carbide 15 km east of Wankie and near Lupane, and again good results were obtained. The inclination obtained from these cores ranged from 55° to 70° in good agreement with outcrop data.

DISCUSSION

Altogether 23 sites yielded data that could be regarded as acceptable. The best results were obtained from the semi-consolidated Zimbabwe varvite localities, which all have $\alpha95$s below 10°. Other sites are not so well grouped; only those with $\alpha95$s up to 26° or less were accepted for further analysis and the statistics (Table 1). The results will be described by regions, starting with South Africa.

The successful sites from the Republic of South Africa were taken from exposures in folded structures of the Cape Fold Belt, as well as from flat-lying or slightly tilted outcrops elsewhere in South Africa. Only two of the sites collected from the fold belt yielded usable results; however, this was sufficient to provide a positive tilt test. The concentration parameter 'K' is at a maximum after unfolding the beds 100%, indicating a prefolding acquisition of the remanence for the characteristic component of magnetisation. The samples usually display a low temperature component of magnetisation directed in the direction of the present magnetic field, to the north. It is interesting that the samples taken from the Cape Fold Belt do not seem to have a synfolding magnetisation. This also seems to be true for the results from the Collingham Formation, which was sampled but did not yield any direction of magnetisation, except that of the present Earth's field. This situation is very different from the results obtained from other fold belts, where synfolding magnetisation is common.

It is notable that both polarities of magnetisation are present in the data set. Normal directions of magnetisation are seen in sites near Nieuwoudville in Dwyka rocks from the uppermost sections of the Dwyka Group. These are most likely to be Late Carboniferous-Early Permian in age. Therefore, the direction of magnetisation in these sites is almost 180° from those of the other sites from South Africa; and since these sediments are Late Carboniferous-Early Permian in age, they should be within the Kiaman-reversed superchron. In other parts of the world, normal directions of magnetisation are also observed in the Kiaman. The first evidence for normal directions of magnetisation in the Late Carboniferous or Early Permian were presented by Helsley (1965) from the Dunkard series of West Virginia. These observations of normal polarity near the base of the Permian have been supported by other studies, in particular that of Symonds (1990) in a study on sediments from Prince Edward Island, Canada. It is entirely possible that the results from near Nieuwoudville represent this same subchron. The directions of magnetisation for the ten sites that yielded acceptable results are given in Table 1. The north palæopole for these ten sites falls at 32°N latitude and 250°E longitude.

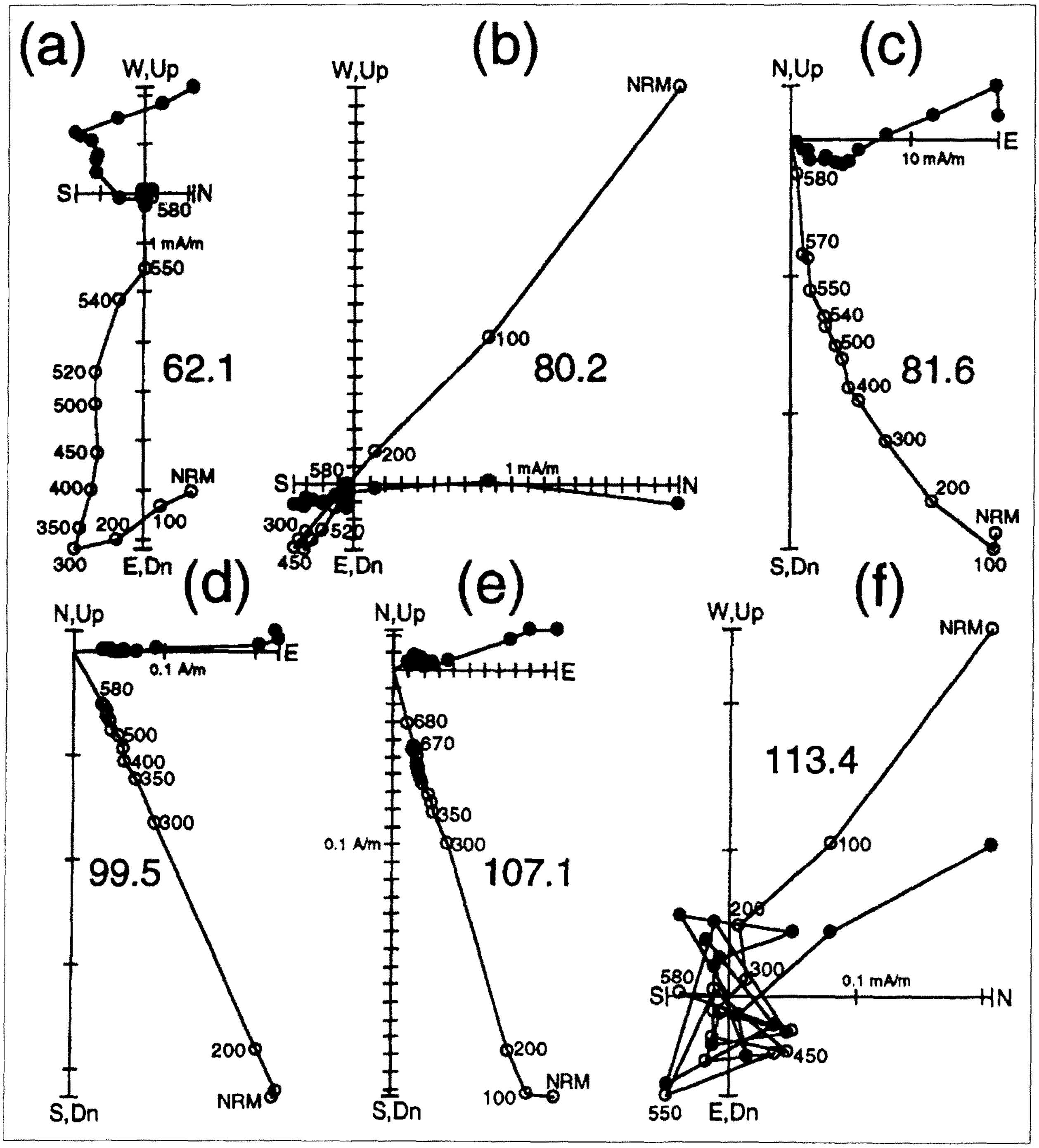

Figure 3. Demagnetograms for selected Tanzanian (a, b, c) and Zimbabwean (d, e, f) samples. ● are plotted on the horizontal plane and ○ are plotted on a vertical plane.

The Zimbabwe results were from eight sites, all varved sediments, which yielded excellent results (Table 1). Only reversed polarity of magnetisation was observed. The successful results were obtained from a rather restricted area in the Jompani Resettlement area near Senyati. Therefore, a question exists as to how much time is represented in the collection. The direction of magnetisation is more towards the east than the results from South Africa. However, the dispersion is not really tight ($\alpha95$, 13°), therefore, sufficient time seems to be represented in the collection to average out secular variation. The north palæopole position for the Zimbabwe results falls at 4°S latitude and 250°E longitude.

The results from Tanzania represent results from only four sites (Table 1). These sites yield directions that slope steeply down to the southeast, all with reversed polarity. The sites are separated geographically and probably temporarily. The number of sites is too small to calculate a palæopole position.

A palæopole position was calculated using 22 acceptable sites from the three regions (Fig. 4). The sites are widely distributed geographically so that it is not possible to calculate a mean pole position from the site directions. A mean palæopole position was calculated from the site virtual geomagnetic poles. This palæopole falls at 20°N latitude, 248°E longitude. This pole position passes the fold test of McFadden (1990) at the 95% level; the critical value is 5.460 and the *in situ* (scos1) value is 7.000. After correcting for bedding tilt, this value becomes 1.503, indicating that the tilt test is positive at the 95% confidence level.

This palæopole is very different from the one calculated by McElhinny and Opdyke (1968). There are many more sites in the present study, but the major difference may lie in the improved technology that is now available, in particular, the more sensitive magnetometers. It has been suggested by others that the results originally obtained from the Galula area in Tanzania have been rotated by fault motion along the margin of the Rukwa Rift, where they are exposed. The sites from Zambia and Zimbabwe all had inclinations over 80°. The single site in the 1968 study from Zimbabwe yielded a normal direction of magnetisation with the direction rising steeply up (81°) towards the northeast (62.5°). Two of the sites in this study yield results within 3° of this result but with a reversed direction (sites 100 and 108). It seems reasonable to suggest that, like South Africa, the results from Zimbabwe have two polarities. A recent study of Dwyka sediments from Madagascar also reports two polarities (Rakotosolofo *et al.*, 1999).

The Dwyka Pole may be compared with recent mean pole positions for Africa calculated by McElhinny and McFadden (1999). Figure 5 shows McElhinny and McFadden's meanpoles for 320, 300 and 280 Ma. The pole for the Dwyka-age sediments falls between the 320 Ma mean poles and the 300 Ma pole, but is not significantly different from either.

The Dwyka results from Africa are now in close agreement with other Late Carboniferous and Early Permian poles from Africa and show that the Antarctic portion of Gondwana was on the South Pole at the time of the maximum glaciation of Gondwana. It is now vital that more Early Carboniferous results be obtained for Gondwana, so that the motion of the South Pole across Gondwana can be better delineated.

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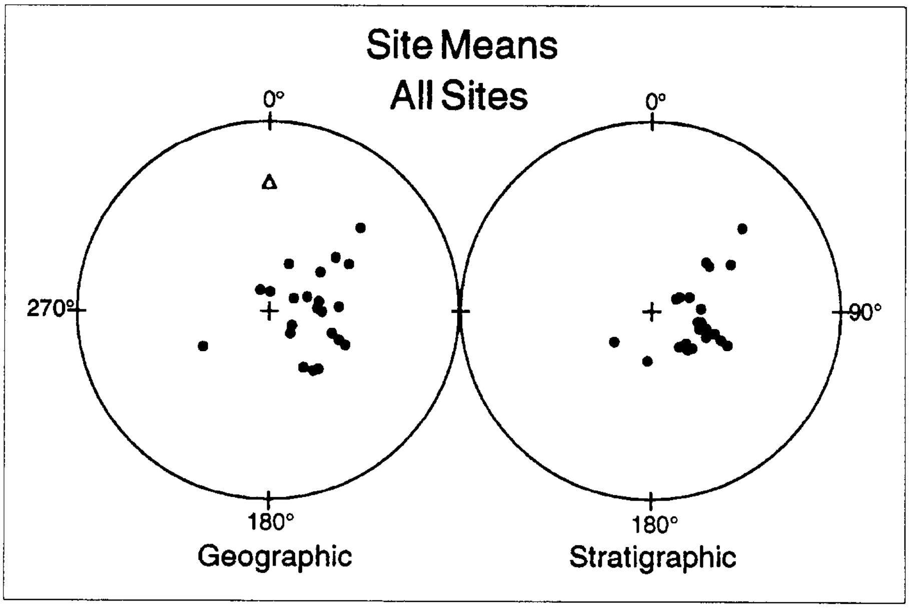

Figure 4. *Site mean directions of magnetisation are plotted on a stereographic (Wulf) net. Filled circles plotted on the lower hemisphere before (geographic) and after (stratigraphic) correcting for bedding tilt. Normal site mean directions of magnetisation have been rotated 180 degrees. D represents the present dipole field for southern Africa.*

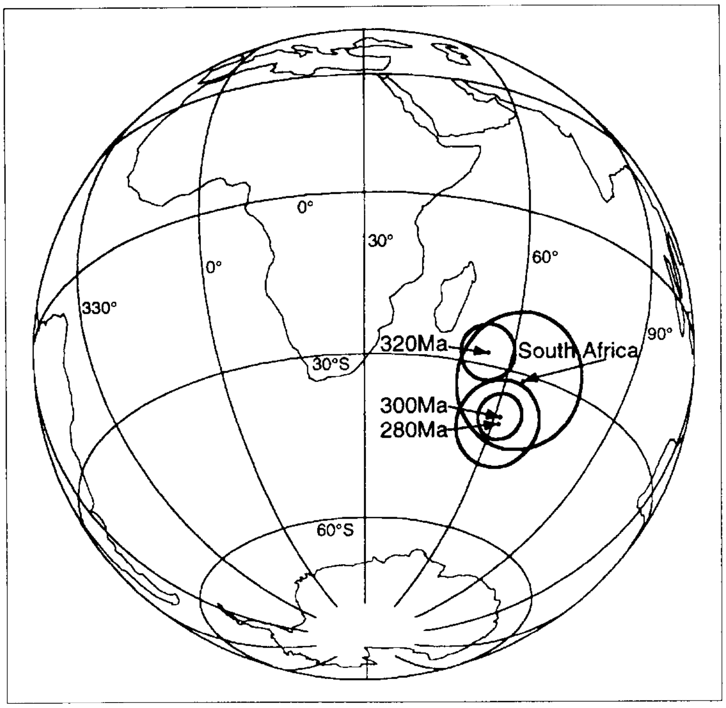

Figure 5. *Pole position of Dwyka sediments rotated to northwest African coordinates and compared to mean African poles from 320, 300, 280 Ma of McElhinny and McFadden (1999).*

the University of Zimbabwe and by the Zimbabwe Geological Survey. In South Africa, the authors would like to thank Profs V. von Brunn and J. Visser, who went in the field and provided samples from drilled cores. N.D.O. would also like to thank M. Opdyke, who served as his loyal field assistant for most of the South African field work. Without the support of those mentioned here, and many others, this study could not have been successful.

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