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The Karoo Supergroup revisited and Madagascar-Africa fits

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ABSTRACT—New palæomagnetic data from the Late Permian-Early Jurassic Sakamena and the Late Carboniferous(?)-Early Permian Sakoa Group from Madagascar (Karoo Supergroup) show gross similarities with earlier published data. Palæomagnetic poles based on all studies of the Sakamena and Sakoa Groups average to 76.7°N and 290.8°E, and 51.3°N and 252.6°E, respectively, and imply palæolatitudes of 28°S and 55°S for southwest Madagascar in Late Permian-Early Triassic and Late Carboniferous(?)-Early Permian times. The majority of the data, however, are of relatively poor quality and there is no firm evidence for primary magnetic signatures. A comparison with West Gondwana palæomagnetic poles shows that the Lottes and Rowley fit produces the best palæomagnetic match between Madagascar and East Africa (Somalia). The precise Pangæa configuration is still not known, but taken at face value, the Madagascar Sakamena pole and West Gondwana reference data indicate a Pangæa B or C configuration in Late Permian-Early Triassic times. However, high quality West Gondwana poles from Late Permian-Early Triassic times are clearly absent, and there is stronger confidence in West Gondwana poles of Late Carboniferous-Early Permian age. The latter poles place parts of Gondwana at high southerly latitudes and in good agreement with the distribution of climatically sensitive lithological data.

RÉSUMÉ—De nouvelles données paléomagnétiques du Groupe de Sakamena (Permien supérieur à Jurassique inférieur) et du Groupe de Sakoa (Carbonifère supérieur(?) à Permien inférieur) de Madagascar (Supergroupe de Karoo) montrent des similitudes grossières avec les données déjà publiées. Les pôles paléomagnétiques basés sur l'ensemble des études sur les Groupes de Sakamena et de Sakoa se groupent vers 76.7°N et 290.8°E et 51.3°N et 252.6°E, respectivement, ce qui implique des paléolatitudes de 28°S and 55°S pour le sud-ouest de Madagascar au Permien supérieur / Jurassique inférieur et au Carbonifère supérieur(?)/Permien inférieur. La majorité des données, cependant, sont de qualité relativement faible et il n'y a pas de preuves solides pour des signatures magnétiques primaires.
Une comparaison avec les pôles paléomagnétiques du Gondwana occidental montre que les reconstitutions de Lottes et Rowley reproduisent le meilleur ajustement paléomagnétique entre Madagascar et l'Afrique de l'Est (Somalie). La configuration précise de la Pangée n'est pas encore connue, mais globalement parlant, le pôle Sakamena de Madagascar et la référence ouest-Gondwana indique une configuration Pangée B ou C au Permien supérieur – Trias inférieur. Cependant, les pôles de haute qualité du Gondwana ouest du Permien supérieur – trias inférieur sont nettement absents, et nous avons une confiance plus grande dans les pôles du Gondwana ouest du Carbonifère supérieur – Permien inférieur. Ces derniers pôles placent une partie de Gondwana à des latitudes sud élevées et sont en bon accord avec la distribution des données lithologiques climat-indicatrices.

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INTRODUCTION

Although the major continental blocks are generally considered to have converged to form the supercontinent Pangæa during Late Palæozoic and Early Mesozoic times, details about the Pangæa configuration and assembly timing are matters of dispute (van der Voo, 1993; Muttoni *et al.*, 1996; Torcq *et al.*, 1997). The subsequent break-up of Pangæa in Mid-Jurassic times proceeded first with two major events:

i) initiation of sea-floor spreading in the Central Atlantic; and

ii) initiation of sea-floor spreading in the Somali Basin and rifting of the South Gondwana elements (Antarctica-Australia-Madagascar-India) from Africa-South America.

Madagascar and India preserve key elements in this early break-up as they jointly rifted off East Africa at *ca* 165 Ma (Coffin and Rabinowitz, 1988).

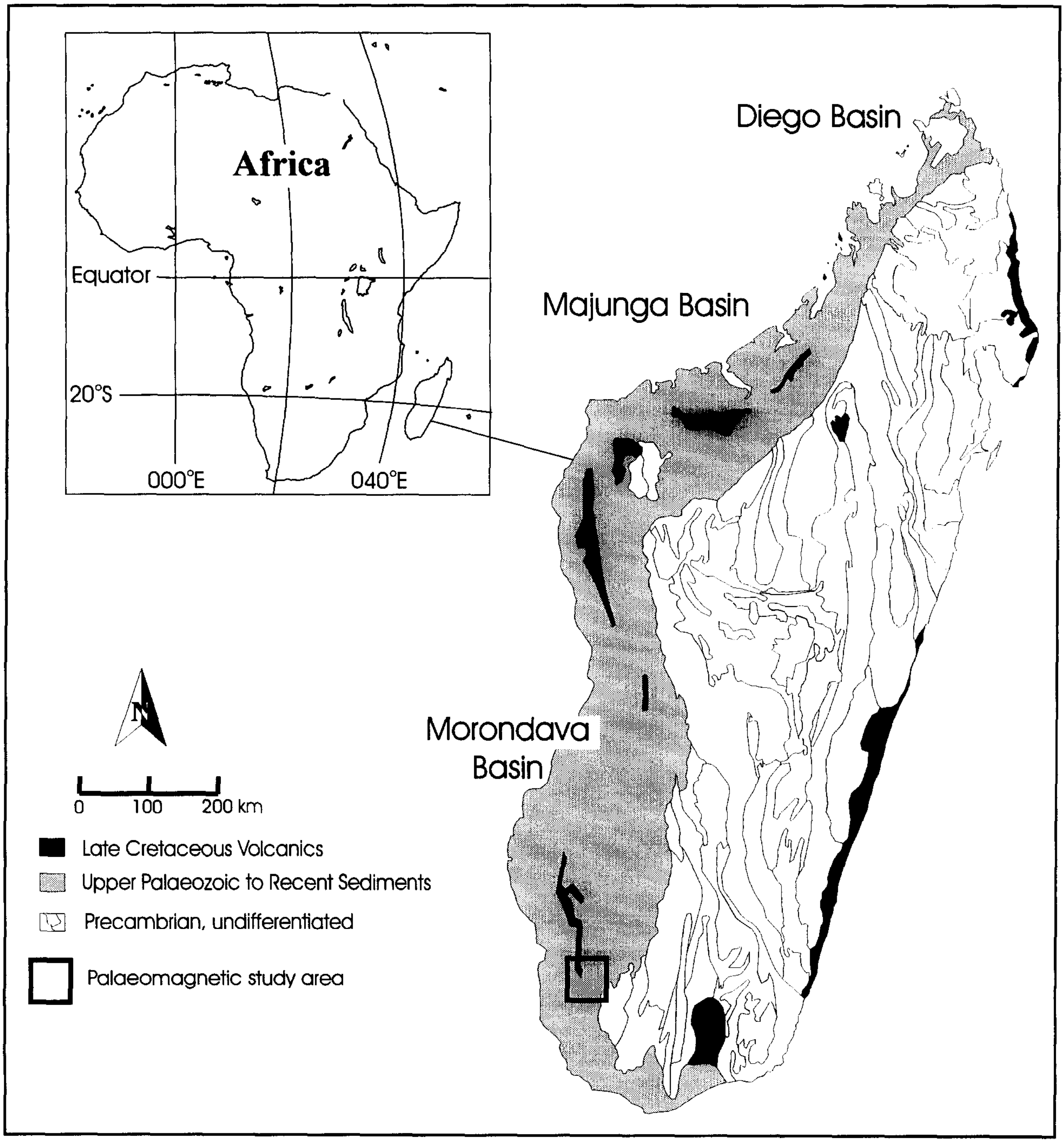


Figure 1. *Simplified geological map of Madagascar and location of the three Phanerozoic sedimentary basins. Area of palæomagnetic study in southwest Madagascar (Morondava Basin) is shown as an open box (see details in Fig. 2).*

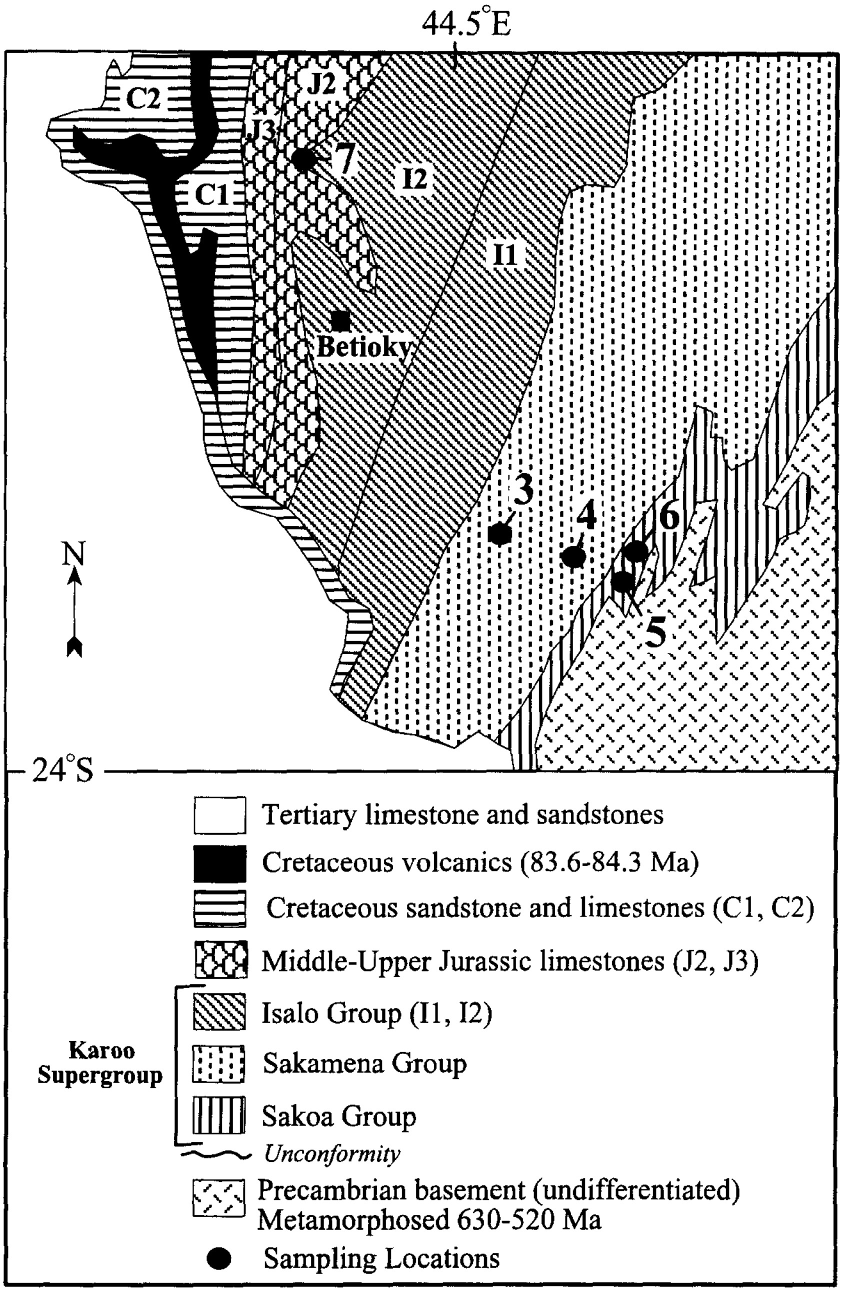


***Figure 2.** Simplified geological map of the study area (sampling box in Fig. 1). Localities 3-7 contain sub-sites (Table 1), typically located within a few hundred metres. Samples were drilled in the field and orientated with both sun and magnetic compasses; the local declination was found to be 20-22°W.*

The separation of Africa and Madagascar was preceded by a long period of continental rifting which generated basin structures filled with the Upper Carboniferous(?)-Permian, Triassic and Early-Mid-Jurassic deposits, collectively referred to as the Karoo Supergroup. Previous palæomagnetic analysis of the rifting history of the Karoo Supergroup in Madagascar included studies where no demagnetisation was carried out (Nairn 1964), or studies where a combination of blanket cleaning and subsequent averaging of the demagnetisation steps gave optimum remanence grouping (Razafindrazaka *et al.*, 1976; Embleton and McElhinny, 1975; McElhinny and Embleton, 1976; reviewed in McElhinny *et al.*, 1976). It is therefore timely to re-examine the Karoo Supergroup with modern instrumental and analytical procedures. The Madagascar data are often utilised as reference data for West Gondwana, and our main sampling intent was to test the stability of magnetisation via detailed fold and conglomerate tests within

Table 1. Site mean palæomagnetic data from the Sakamena and Sakoa Groups (Karoo Supergroup), southwest Madagascar (Isalo Group excluded due to the lack of remanence grouping at site level)

		In situ				Bedding corrected	
Rock type	Site	Dec (°)	Inc (°)	N	α_{95}	Dec (°)	Inc(°)
SAKAMENA GROUP (Late Permian)							
Coarse sandstone	3A	7.8	-32.5	6	11.2	014.2	-35.8
Coarse sandstone	3B	341.1	-49.8	4	12.6	350.8	-56.8
Fault gouge	3C	Incoherent data					
Folded sandstone bed	3D	Incoherent data					
Shale/sandstone	4A	11.3	-39	5	15.0	018.5	-42.5
Shale/sandstone	4B1	334	-44.3	5	18.3	338.4	-42.4
Shale/sandstone	4B2	334	-46.6	4	16.8	341.5	-47.6
Sandstone lens	4C	6.6	-40.3	3	17.2	357.2	-35.3
Sample mean		353.8	-37.6	27	6.9(6.7)	359.1	-43.9
Site mean		353.7	-43.8	6*	12.2(12.6)	357.5	-44.4
SAKOA GROUP (Late Carboniferous(?)-Early Permian)							
Fine grained tillite	5A	342.6	-37.6	5	12.8	015.1	-56.3
Fine grained tillite	5B	338.9	-36	5	19.2	009.2	-57.1
Fine grained tillite	5C	343.9	-43	3	17.1	023.8	-59.3
Coarse tillite	5D	319.9	-25.5	6	10.4	333.6	-56.3
Tillite boulders	5D	Irregular directional behaviour					
Fine dark sandstone	6	127.7	+58	12	4.7	205.7	+79.1
Sample mean (BP)		326.2	-44.5	31	6.7(5.9)	006.2	-66.9
mean (NP)		334.0	-34.6	19	7.3(7.3)	001.7	-58.5
Site mean BP		331.8	-40.8	5*	15.8(13.4)	007.0	-62.9

Dec(°)/Inc(°): mean declination/inclination; N: number of samples/sites*; α_{95} = 95% confidence circle; ( ): α_{95} after unfolding; BP: both polarities; NP: normal polarity.

the Karoo sequences in the Morondava basin, southwest Madagascar (Figs 1 and 2). As the results below indicate, these stability tests were mostly unsuccessful due to the poor magnetic quality of the rocks, despite careful attempts to avoid the most weathered rocks which represent a major problem.

GEOLOGICAL SETTING AND SAMPLING DETAILS

The western third of Madagascar comprises an extensive sequence of gently west dipping Phanerozoic sedimentary rocks within three basins, referred to from north to south as the Diego, Majunga and Morondava Basins (Fig. 1). The Sakoa Group, the oldest rocks in the Morondava Basin, consist of Late Carboniferous-Early Permian tillites, overlain by Early Permian coal-bearing horizons and redbeds, and Middle Permian marine limestones (Fig. 2). The Sakoa Group of the Morondava Basin is most commonly referred to as Late Carboniferous-Mid Permian in age (Besairie and Collignon, 1972), but Hankel (1994) places the basal Sakoa Group within the Early Permian (Asselian).

The Sakamena Group, which unconformably overlies the Sakoa Group, comprises Late Permian continental sandstones and conglomerates, followed by Early Triassic alternating continental sandstones and marine shales. The Middle Triassic to Early Jurassic Isalo Group in turn unconformably overlies the Sakamena Group, and consists of continental sandstones (Isalo I and II). Marine conditions started in the Middle Jurassic and are represented by interbedded limestones and shales; mixed marine and continental environments continued into the Early Cretaceous (Besairie and Collignon, 1972).

The sampling sites included units from the Lower Sakoa, Lower Sakamena and Upper Isalo (II). Originally, a sample was going to be taken from each part of the succession of the Late Palæozoic through Jurassic, but it was often found that intense weathering rendered the rocks useless for palæomagnetic studies.

Isalo Group

The Isalo II sandstones were sampled along the Onilahy River near the Tongobory bridge (Locality 7; Fig. 2). Samples were collected from a flat-lying, whitish, cross-bedded coarse sandstone unit (site 7A) and from a one metre thick grey argillaceous sandstone unit (7B, C).

Sakamena Group
The Lower Sakamena sediments were sampled at localities 3 and 4 (Fig. 2, Table 1). At locality 3 (Sakamena River), the top of the Lower Sakamena consists of sandstone units overlain by nodular shales. Sandstones are grey to slightly reddish and medium- to coarse-grained. Undulations in the lower sand unit probably relate to syn-sedimentary slump folding. The overlying unit is a gently west dipping, coarse-grained sandstone. These sandstones are cut by a 290° trending vertical brittle fault, *ca* 30 cm wide. Samples were collected from sandstone units (sites 3A, B), from a folded sand unit (3D) to derive a local fold test, and from the fault gouge in an attempt to date the brittle fault event.

Locality 4 (Rianambo River) lies stratigraphically below locality 3, and consists of alternating sandstones and dark grey shales. The lower, greyish, medium-grained sandstone layers are overlain by a folded sandstone unit (slump structure), which in turn is overlain by shale and other sandstone bands dipping gently to the west. Samples were collected from a fine-grained sandstone layer (4A), from an overlying silty shale horizon one metre above (4B), and from a sandstone lens two metres above all observed slump structures (4C).

Sakoa Group
Sakoa Group sediments were sampled at localities 5 and 6. At locality 5, where the glacial series crop out, the basal Sakoa Group consists of alternating tillite, shale and sandstone. Beds generally dip 30° to 40° to the west. Sampling included fine tillite at the upper portion of the glaciogenic deposit (5A), and fine tillite one metre (5B) and three metres (5C) above 5A. Site 5D was three metres below site 5A, where samples from Precambrian cobbles within the tillite as well as the matrix itself were collected for a conglomerate test. Locality 6 is approximately 100 m stratigraphically above the tillites, and consists of grey shale and sandstone layers. Samples were collected from a thin layer (5-20 cm) of dark grey argillaceous to silty sandstone.

PALÆOMAGNETIC EXPERIMENTS

The natural remanent magnetisation (NRM) was measured with a JR5A magnetometer in a low field magnetic environment. Stability of NRM was tested by both thermal (furnace model MMTD60) and alternating field (two-axis tumbler) demagnetisation. Characteristic remanence components (ChRc) were calculated with the least square regression analysis implemented in the SIAPD computer program of Torsvik *et al.* (1999).

Isalo Group
NRM intensities from site 7A vary from 30 to 50 mA m^{-1}, whilst samples from sites 7B and C had considerably lower intensities (0.3-0.4 mA m^{-1}). Of 39 analysed samples, 36 proved suitable for remanence component analysis. The Isalo Group yielded good individual demagnetisation examples, but the ChRc displayed an unsatisfactory grouping (Fig. 3b). As an example, Fig. 3a demonstrates a shallow, high unblocking temperature (HB) component, with northwest declination, whilst Fig. 3c shows the presence of a somewhat steeper HB component with northeast declination (after demagnetisation of an intermediate unblocking component with a northerly declination). In general, a northwest negative grouping (mostly site 7A), a northeast negative group (mostly 7B) and some aberrant directions, mostly derived from site 7C samples, are seen. Due to the overall spread of ChRc, for which there seems to be no rational explanation (flat-lying beds sampled close to one other), it was decided not to calculate site means for the Isalo Group. The bulk of the directional data would not fit the previous palæomagnetic data published from the Isalo Group (Fig. 3b; mean Isalo Group after Embleton and McElhinny, 1975).

Sakamena Group
One-hundred-and-three samples from two main localities were demagnetised, and NRM intensity varied between 0.4 and 2.5 mA m^{-1}. Seventeen samples from site 3D, collected in detail around a local fold, did not provide sensible palæomagnetic data: additionally the fault gouge (site 3C) failed to provide coherent data.

The demagnetisation data from the Sakamena Group are of poor quality (Fig. 4a-c), and HB ChRc components were typically forced through data points which showed an irregular, albeit 'systematic', decay towards the origin of the Zijderveld diagrams (Fig. 4a, b). From localities 3 and4, only 27 samples proved satisfactory, providing a fair grouping with north-northwest declinations and intermediate negative inclinations (Fig. 4d-f; Table 1). Bedding correction did not improve the directional grouping.

Sakoa Group
Seventy-four samples were demagnetised from the Sakoa Group with NRM intensities between 0.3 and 1.2 mA m^{-1}. Once again, demagnetisation quality is generally poor (Fig. 5a-c), except for a reverse

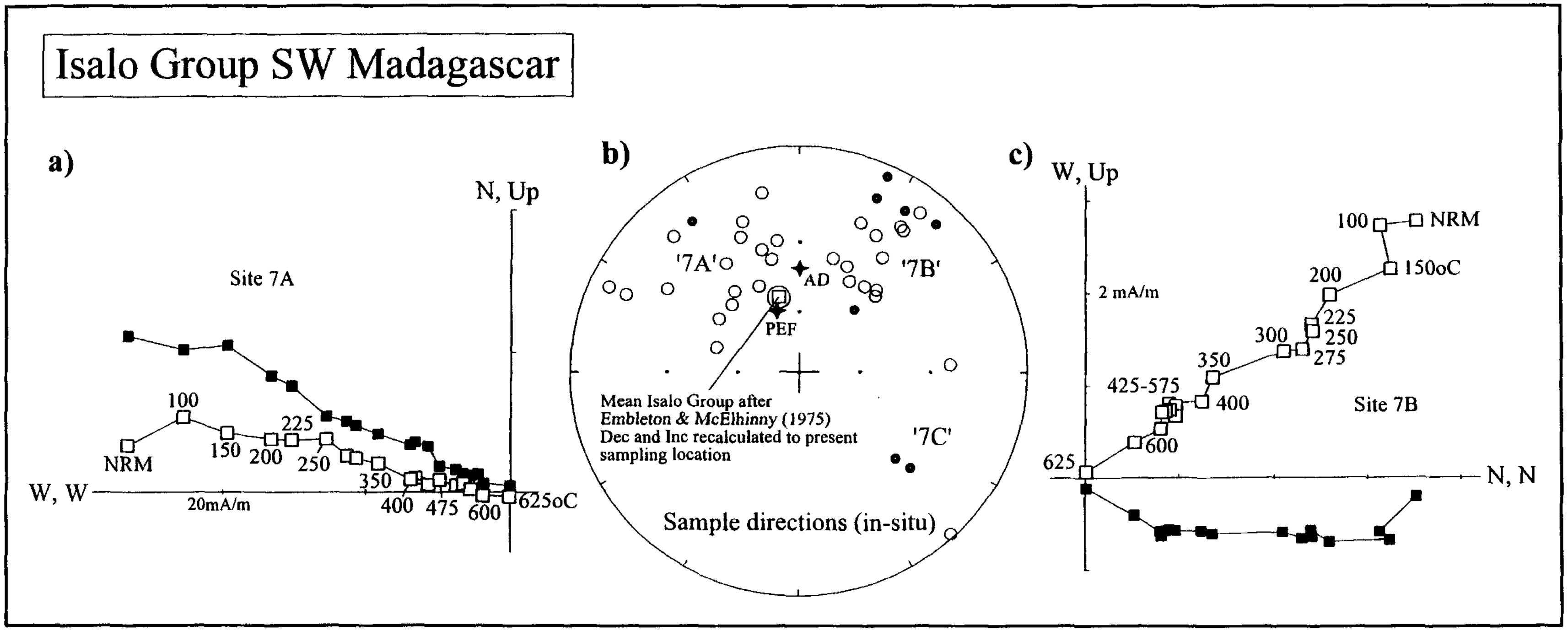


Figure 3. Typical thermal demagnetisation results (a and c) from samples of the pre-Middle Jurassic Isalo Group (Sites 7A-C) and (b) in situ *distribution (flat lying and hence no tilt correction to undertake) of characteristic remanence components (ChRc). Notice spread in ChRc; it was decided not to 'filter' and calculate a mean for the sub-sites. For comparison, the mean Isalo Group direction obtained by Embleton and McElhinny (1975) (recalculated declination and inclination to the present sampling location) is included in (b). In Zijderveld diagrams, closed (open) symbols represent points in the horizontal (vertical) plane. In stereoplot, closed (open) symbols represent positive (negative) inclinations. AD: expected Axial Dipole Field; PEF: Present Earth's Field at sampling location.*

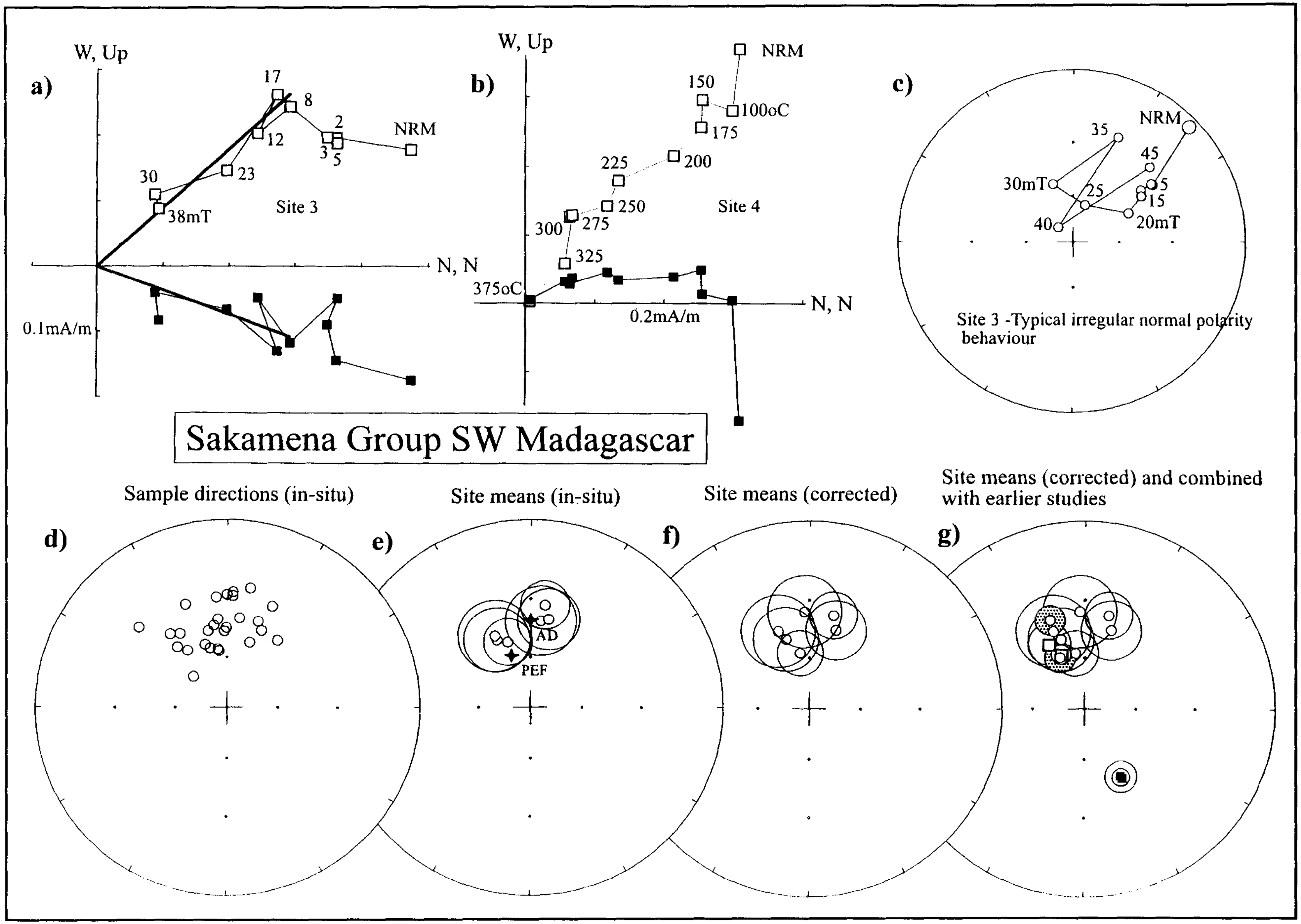


Figure 4. (a) Example of AF demagnetisation of a sample from the Sakamena Group (Late Permian). Typical fitting of a line (ChRc) through points with a somewhat irregular directional behaviour (8-38 mT), but clearly converging toward the origin of the diagram, is illustrated. (b) Example of thermal demagnetisation for a sample from the Sakamena Group with similar directional behaviour to the AF example (a). In this case, at 375°C, the remanent magnetisation intensity approached the limit of instrument sensitivity and erratic directional behaviour occurred at higher temperatures. (c) Example of very irregular but typical directional behaviour of a sample from the Sakamena Group. (d) Distribution of sample directions from the Sakamena Group (in situ). (e) Site-means (in situ) drawn with a_{95} circles. (f) Site means (bedding corrected) with 95% confidence circles. (g) Corrected site means (all of normal polarity) compared with earlier data reported by McElhinny and Embleton (1976; squared symbols: both polarities) and Razafindrazaka et al. (1976; patterned a_{95} circles: only normal polarity).

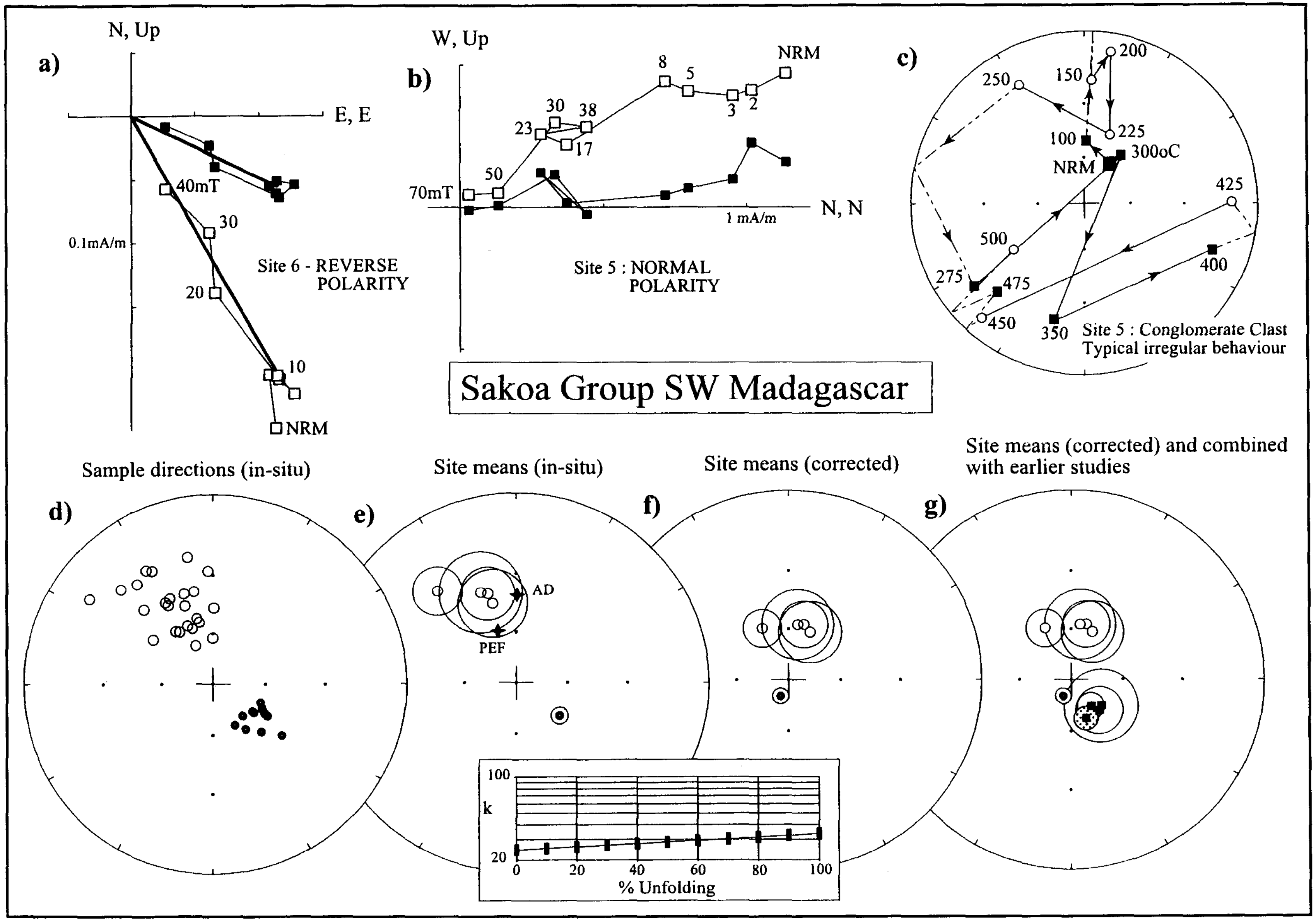
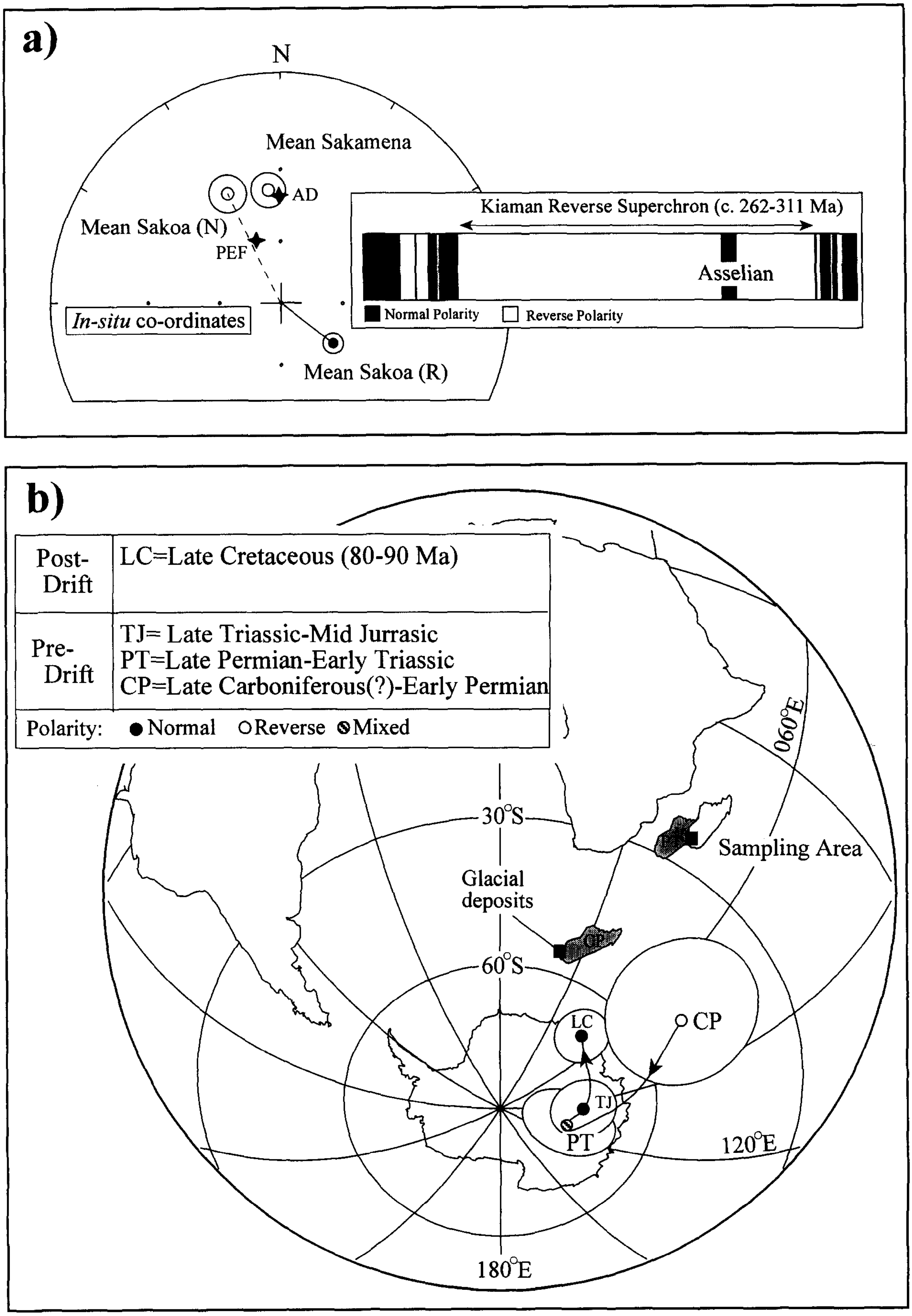


*Figure 5. (a) Example of AF demagnetisation of a reverse polarity sample from the Sakoa Group (Site 6), and, as in Fig. 4a, typical forced line-fitting through points with somewhat irregular behaviour (10-40 mT). However, reverse polarity components have a higher demagnetisation quality than normal polarity data (b) despite very low NRM intensities. (b) Example of AF demagnetisation of a normal polarity sample from the Sakoa Group. (c) Typical erratic directional demagnetisation behaviour of tillite clasts in the basal part of the Sakoa Group. (d) Distribution of dual-polarity sample directions from the Sakoa Group (*in situ*). Basal section (site 5) is of normal polarity, whilst site 6 is of reverse polarity (see stratigraphical column in Fig. 2). (e) Site-means (*in situ*) drawn with a_{95} circles. (f) Site means (bedding corrected). Inset diagram in (e, f) shows the variation in the precision parameter* k *(logarithmic scale) as a function of stepwise bedding correction (both polarities combined). Increased* k *is noted during unfolding, but is statistically insignificant (as for the Sakamena Group). (g) Bedding corrected site means (dual-polarity), compared with previous data reported by McElhinny and Embleton (1976; squared symbols: reverse polarity) and Razafindrazaka* et al. *(1976; patterned a_{95} circles: reverse polarity).*

Table 2. Summary of palæomagnetic data from the Sakamena and Sakoa Groups

Group	Age (Polarity)	Locality (°S)	Locality (°E)	Sites	Samples	Dec (°)	Inc (°)	Pole (°N)	Pole (°E)	α_{95}	Ref
Sakamena Group, Upper Part (PT1)	Early Triassic (N)	23.3	44.4	1	4	338.8	-36.7			7.2	1
Sakamena Group, Middle Part (PT2)	Early Triassic (N)	23.5	44.3	2	8	334.2	-56.7			8.4	1
Sakamena Group, Lower Part (PT3)	Late Permian (M)	22.6	45.0	4	19	333.0	-48.6			3.8	2
Sakamena Group, Lower Part (PT4)	Late Permian (N)	23.8	44.5	6	27	359.1	-43.9			6.7	3
Mean Sakamena Group (PT)	L.Permian-E.Triassic (M)	23.3	44.5	14(12)	55	346.2	-46.8	76.7	290.8	7.6	1-3
Sakoa Group, Red Series (CP1)	Early Permian (R)	23.5	44.4	2	17	158.4	65.5			6.8	1
Sakoa Group, Glacial Series (CP2)	L.Carboniferous(?)-E. Permian (R)	23.8	44.7	3	16	139.7	68.3			5.5	2
Sakoa Group, Glacial Series (CP3R)	L.Carboniferous(?)-E. Permian (R)	23.8	44.7	1	12	205.8	79.14			4.7	3
Sakoa Group, Glacial Series (CP3N)	L.Carboniferous(?)-E. Permian (N)	23.8	44.7	4	19	001.7	-58.5			7.3	
Mean Sakoa Group (CP) (only reverse polarity sites)	L.Carboniferous(?)-E.Permian (R)	23.7	44.6	6 (5)	45	149.2	70.7	51.3	252.6	9.5	1-3

Abbreviations as for Table 1; Ref: References: 1: Razafindrazaka *et al.* (1976); 2: McElhinny and Embleton (1976); 3: this study (Table 1). Statistics for individual studies are based on sample statistics for conformity with older studies (McElhinny and Embleton data are recalculated to sample means). Mean results are based on site statistics. Polarity: N: Normal; R: Reverse; M: Mixed. Note that the Sakoa Group mean is only based on the reverse polarity data.


a)
N
Mean Sakamena
AD
Mean Sakoa (N)
PEF
In-situ co-ordinates
Mean Sakoa (R)
Kiaman Reverse Superchron (c. 262-311 Ma)
Asselian
Normal Polarity
Reverse Polarity
b)
Post-Drift
LC=Late Cretaceous (80-90 Ma)
Pre-Drift
TJ= Late Triassic-Mid Jurrasic
PT=Late Permian-Early Triassic
CP=Late Carboniferous(?)-Early Permian
Polarity: Normal Reverse Mixed
060°E
30°S
Sampling Area
Glacial deposits
60°S
LC
CP
TJ
PT
120°E
180°E

polarity site in the Sakoa Group (site 6). Altogether 31 samples from the Sakoa Group proved 'satisfactory', and ChRc components group into a normal polarity (northwest declination and negative inclination) and a consistent reverse, polarity group showing positive inclinations and declinations due southeast (site 6). The basal tillites are of normal polarity. The conglomerate test was unsuccessful in as much as individual boulders showed erratic directional behaviour during demagnetisation (Fig. 5c). For the Sakoa Group some improved directional grouping was noticed during unfolding (Fig. 5e, f), but the fold test is statistically insignificant at the 95% confidence level.

INTERPRETATION OF PALÆOMAGNETIC DATA

Samples from the Mid-Jurassic Isalo Group have excellent response to both thermal and AF demagnetisation. However, sample grouping (Fig. 3b) is poor and the Isalo results are excluded in the subsequent discussion. Except for the reverse polarity Sakoa Group site (site 6), individual demagnetisation data from the Sakamena and Sakoa Groups are of poor quality, and remanence components are essentially 'forced' through rather 'noisy' data (Figs 4a and 5a). However, sample and site mean data from the Sakamena and Sakoa Group show fair groupings. Local fold tests (Sakamena) and conglomerate tests (Sakoa), which were a main sampling aim in the current study, did not provide any conclusive answers due to poor data quality (e.g. Fig. 5c).

The Upper Permian-Lower Triassic Sakamena Group reveals only normal polarity directions; a fold test is inconclusive and remanence components (*in situ* co-ordinates) plot between the expected dipole field direction (AD) and the present Earth's field (PEF) (Fig. 4e). These data compare well with those of Razafindrazaka *et al.* (1976) and McElhinny and Embleton (1976). It was noticed, however, that McElhinny and Embleton (1976) also identified two antipodal reverse polarity sites in the lower section of the Sakamena Group (Figs 4g and 6a). Razafindrazaka *et al.* (1976) make no mention of bedding corrections; it is assumed that such corrections were made. It is difficult to corroborate if the Sakamena Group magnetisations are primary; they plot close to the axial dipole and the present Earth's magnetic field direction, and the only argument for a primary signature of the Sakamena Group is the observation of dual polarity (antipodal) magnetisations which might be stratigraphically linked (McElhinny and Embleton 1976).

From the Sakoa Group a dual polarity magnetisation structure was observed, but the two polarity groups are not antipodal (i.e. do not share a common mean at the 95% confidence level), and the reverse polarity data (site 6) are much better grouped. Compared with the Sakamena Group, *in situ* magnetisations plot somewhat to the west of the axial dipole field direction (Figs 4e, 5e and 6a). The basal tillites are of normal polarity, while the overlying shale and sandstone are of reverse polarity (site 6). The latter reverse polarity accords with the results of Razafindrazaka *et al.* (1976) and McElhinny and Embleton (1976). Stepwise unfolding improves remanence grouping (only when combining both polarity groups), but like McElhinny and Embleton (1976), a statistically significant positive fold test was not achieved. The finding of a normal polarity magnetisation is worrying: First, the McElhinny and Embleton (1976) study did not find normal polarity data. Second, the normal and reverse directions are not antipodal. Third, the age of the Sakoa Group is within the reverse Kiaman Superchron (*ca* 311-262 Ma depending on the applied time scale). Following Hankel (1994), the glacial basal beds of the Sakoa Group could be of Asselian (basal Permian) age, and a short normal polarity period (Fig. 6a) has been recognised within this epoch (see Opdyke and Channell, 1996). The data presented here are from the extreme lower part of the tillite, and it is therefore possible that the Asselian normal polarity interval within the Kiaman Superchron has been recorded. However, the normal polarity data, which are of poor quality, are suspiciously similar to the younger Sakamena Group (Fig. 6a) and may very well represent a younger normal polarity overprint. It was therefore decided to exclude the Sakoa Group normal polarity directions when calculating mean directions and palæomagnetic poles (Table 2).

Figure 6. *(a)* In situ *mean directions (present study) and a_{95} confidence circles (Table 2) compared with the axial dipole field (AD) and the present Earth's magnetic field (PEF) for the sampling region. Inset diagram: Permo-Carboniferous magnetic polarity scale (Opdyke and Channel, 1996; Eide and Torsvik, 1996). (b) Palæomagnetic poles for the Sakamena and Sakoa Groups (Table 2), Isalo Group (Embleton and McElhinny 1976) and Late Cretaceous volcanics and dykes (Torsvik* et al.*, 1999) from Madagacar. All poles are plotted with confidence ovals. CP: Sakoa Group, PT: Sakamena Group, TJ: Isalo Group; LC: Late Cretaceous volcanics and dykes. Palæogeographic reconstruction of Madagascar (shaded continent) according to mean poles for the Sakamena (PT) and Sakoa (CP) Groups (Table 2). The intermediate to high palæolatitude for Madagascar calculated from the Sakoa Group data is consistent with glacial deposits in the basal Sakoa Group (lithostratigraphical equivalent of the Dwyka glacial deposits in South Africa and India). Note that all palæomagnetic poles in diagrams are plotted as south poles, but listed as north poles in all tables.*

Table 3. Some published reconstruction parameters used for Madagascar-Africa fits, and statistics on the fits

Lat. (°N)	Long. (°E)	Rotation angle (°)	CPGCD	PTGCD	Mean	Reference
-12.53	-54.96	17.46	9.7 (1)	11.0 (1)	10.4	Lottes & Rowley (1990)
-9	-47	15	12.8	11.3 (3)	12.1	Smith & Hallam (1970)
-6.685	-73.317	18.396	9.8 (2)	15.7	12.8	Yardimcilar & Reeves (1998)
16.3	148.6	-13.8	14.5	11.6	13.1	Norton & Sclater (1979)
10	150	-14.2	15.2	11.2 (2)	13.2	Coffin & Rabinowitz (1987)
1.9	105.6	-16.9	11.8	16.1	14.0	Bunce & Molnar (1977)
-3.41	-81.7	19.73	10.3 (3)	18.2	14.3	Lawver & Scotese (1987)
-7	109	-16.0	13.7	15.5	14.6	Scrutton *et al.* (1981)
-5.5	-90.6	21.12	11.4	21.7	16.6	Lawver *et al.* (1992)
0	0	0	26.3	25.3	25.8	Present position
-48	70	14	26.5	25.7	26.1	Flores (1970)

References are sorted according to the best overall fits ('Mean' column).
CPGCD = Great Circle Distance (in degrees) between the Sakoa Group pole and the reference pole (Upper Carboniferous-Early Permian).
PTGCD = Great Circle Distance between the Sakamena Group pole and the reference pole (Upper Permian-Early Triassic); Numbers in brackets are the fit ranks (1 to 3). Mean: (CPGCD + PTGCD)/2.

Because the data, except for the normal polarity directions of the Sakoa Group described above, generally correspond with those of the earlier studies (Razafindrazaka *et al.*, 1976; McElhinny and Embleton, 1976), and because of the very low number of successfully tested samples and sites in all studies to date (Table 2), it was decided to combine data from all studies to calculate mean directions and palæomagnetic poles (Fig. 6b) for the Sakamena and Sakoa Groups. In Fig. 6b the mean poles have also been included for the Late Triassic-Mid Jurassic Isalo Group (Embleton and McElhinny, 1975) and Upper Cretaceous (post-drift) volcanics and dykes (Torsvik *et al., in press*) from Madagascar. There is a somewhat disturbing lack of systematic differences between the Isalo and Sakamena Groups; this either suggests insignificant apparent polar wander, or that the Sakamena Group was reset in Middle Jurassic or younger times.

MADAGASCAR-AFRICA FITS

Several published fits exist for Madagascar-southeast Africa (most of them listed in Table 3 and Fig. 7), and these fits have been tested palæomagnetically (Fig. 8). Critical to this fitting exercise, however, are (1) good reference data from Gondwana, and in particular from West Gondwana; and (2) that the Madagascar poles are based on primary magnetisations (not yet proven). With respect to the first point, there is no intention to review the entire Gondwana database, and therefore palæomagnetic poles included in three recently published mean poles for the Late Carboniferous-Early Permian and Late Permian-Early Triassic times (Table 4) were selected, for which new mean poles were calculated (source 4 in Table 4). For comparison a high quality Late Carboniferous (Namurian-Westphalian) pole is also included from East Gondwana (Australia, Opdyke *et al.*, 1998). All poles are listed (Table 4) and plotted (Fig. 8) in South African co-ordinates, and relative rotation parameters are those of Lottes and Rowley (1990).

Given the uncertainty in the mean poles derived from the Sakamena and Sakoa Groups, overlap with the listed 'reference' poles is possible in several of the proposed Madagascar-Africa fits (Fig. 7). A common procedure to test the tightness of fits is to calculate the angular distance (GCD: great circle distance in degrees) between poles in different fits. The GCD between the Sakoa Group and the Late Carboniferous-Early Permian reference pole, and the Sakamena Group and the Late Permian-Early Triassic reference pole in some proposed Madagascar-Africa fits are listed in Table 3. A mean value was obtained by simply averaging the GCD values for the two different geological times.

The Flores (1970) fit, which differs radically from all the other fits (Fig. 7), is clearly the least satisfactory with an average GCD of 26.1° (Table 3). In general, the best fits can be invoked for the Sakoa Group, and the best match (GCD = 9.7°) is achieved by the Lottes and Rowley (1990) fit; on average this fit has also the lowest GCD (10.4°). It also produces a good fit (Fig. 8b) with the most recent Australian (East Gondwana) pole of Opdyke *et al.* (1998). The Lottes and Rowley (1990) fit is tight, and Madagascar overlaps the present day coastline of Africa (Figs 7 and 8b), but it is considered the

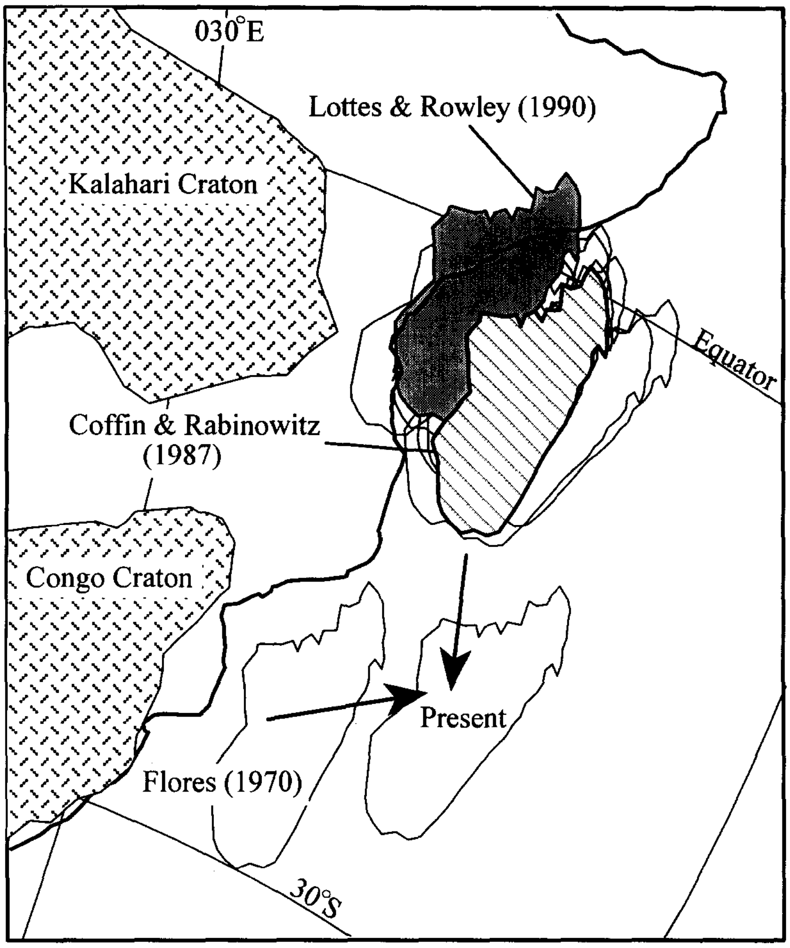


Figure 7. Some suggested fits of Madagascar with Africa (fixed) based on euler rotation data listed in Table 4. A tight (Lottes and Rowley, 1990) and a loose continental fit (Coffin and Rabinowitz, 1987) is highlighted. Note that Flores' (1970) fit deviates from all the other fits. Approximate boundaries for the Precambrian Kalahari and Congo Cratons are indicated.

best statistical fit from the palæomagnetic data. Another tight fit, based on aeromagnetic data (Yardimcilar and Reeves, 1998), also produces a good fit for the Sakoa Group (Table 3). However, given the resolution power of the palæomagnetic data, one cannot statistically distinguish this fit from less tight fits, e.g. the Coffin and Rabinowitz (1987) fit for the Late Permian-Early Triassic (Fig. 8c, Table 3), which is based on the oldest identified magnetic anomalies in the Somali Basin (Mid-Jurassic, *ca* 166 Ma). However, the Lottes and Rowley (1990) fit scores best in both time periods, and is thus recommended for future work.

PALÆOLATITUDE

If a primary magnetic signature of the Sakoa and Sakamena Group (Madagascar) is accepted, this implies palæolatitudes of 55°S and 28°S for southwest Madagascar in Late Carboniferous(?)-Early Permian (Sakoa) and Late Permian-Early Triassic (Sakamena) times, respectively. The latter palæolatitude estimate is not very different from the present latitudinal position of Madagascar (Fig. 6b), and implies a 3000 km northward drift of Madagascar during the Permian. Given the age difference between the two poles of between 30-40 Ma, this yields high northward drift velocities (8-10 cm a^{-1}) during Permian times. It is essentially this rapid Permian shift which, if correct, complicates Pangæa reconstructions. In Late Carboniferous-Early Permian times it is possible, within the resolution power of palæomagnetic data, to have an almost classic Pangæa A1 fit (Bullard *et al.*, 1965), since all the Gondwanan elements are located in the southern hemisphere (Fig. 9a). The rapid northward shift of Gondwana during the Permian, however, places parts of Gondwana in latitudes too high relative to Eurasia, and Gondwana has therefore customarily been transferred eastward to avoid continental overlap (exemplified in Fig. 9b).

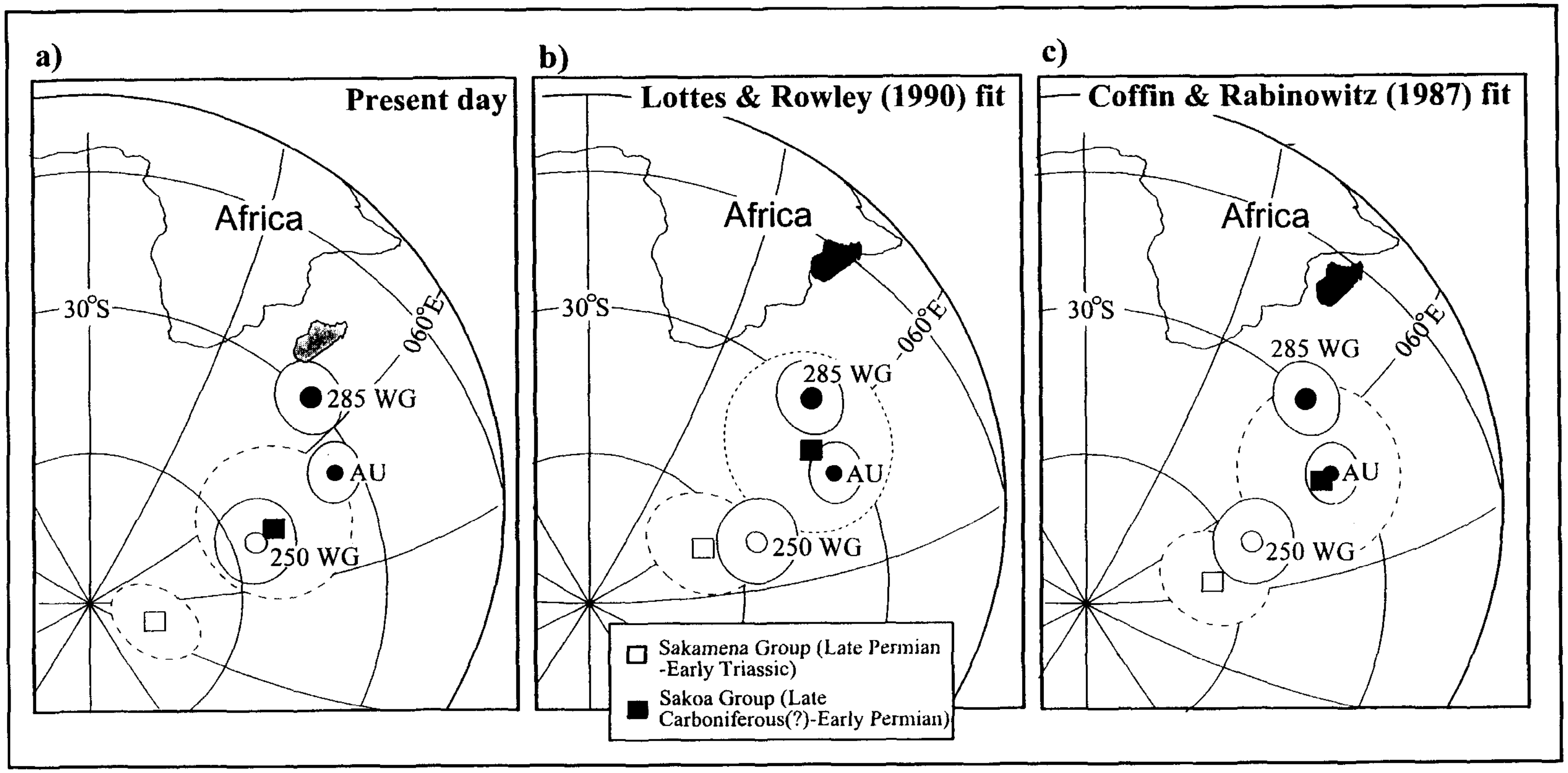


Figure 8. *(a) Comparison of mean poles from the Sakamena (open square) and Sakoa (closed square) Groups (Table 2) of Madagascar (plotted with dp/dm confidence ovals) with Late Carboniferous-Early Permian (285 WG) and Late Permian-Early Triassic Gondwana (250 WG) mean poles for West Gondwana (South America and Africa). 'Reference' poles (Table 4, source 4) are plotted in South African co-ordinates with A95 confidence circles. Note that all poles are plotted as palæomagnetic south poles, but listed as palæomagnetic north poles in Tables 2 and 4. Also included is a high quality Late Carboniferous (*ca *305-320 Ma) pole from Australia (AU) for comparison (Opdyke* et al.*, 1998; pole plotted with dp/dm confidence oval). (b) Sakamena and Sakoa Group poles compared to West Gondwana 'reference' mean poles in a tight Lottes and Rowley (1990) Madagascar-Africa fit. Diagram also portrays the relative position of Madagascar in this fit (shaded with South Africa fixed). (c) As (b), but using a less tight and magnetic anomaly based fit (Coffin and Rabinowitz, 1987).*

Table 4. Some published mean poles for South America, Africa or combined West Gondwana listed in South African co-ordinates (see Fig. 8 and text)

Data source area	A95	Lat. (°N)	Long. (°E)	Age (Range) (in Ma)	Ref
Late Permian-Early Triassic:					
South America	7.3	52.9	259.0	244 (238-256)	1
Africa	8.3	60.2	260.1	237 (235-238)	1*
West Gondwana (South America-Africa)	9.0	54.7	244.4	256 (246-266)	2
West Gondwana (South America-Africa)	8.2	55.3	253.3	250 (235-266)	4
Late Carboniferous-Early Permian:					
West Gondwana (South America-Africa)	7.0	27.4	245.7	274 (267-281)	2
West Gondwana (South America-Africa)	8.0	28.1	227.8	295 (282-308)	2
West Gondwana (South America-Africa)	5.7	32.1	227.9	272 (263-280)	3
West Gondwana (South America-Africa)	6.9	29.9	231.9	285 (263-308)	4

A95 = 95% confidence circle about poles; References: 1: Torcq *et al.* (1997) (*excluding two of their listed entries, i.e. the Morocco Issaldin and Tanzania poles); 2: van der Voo (1993, his Table 5.8); 3: Lottes and Rowley (1990); 4: this study using all the data listed in sources 1-3 (excluding existing Madagascar results). Relative fits between South America, northwest Africa and South Africa after Lottes and Rowley (1990).

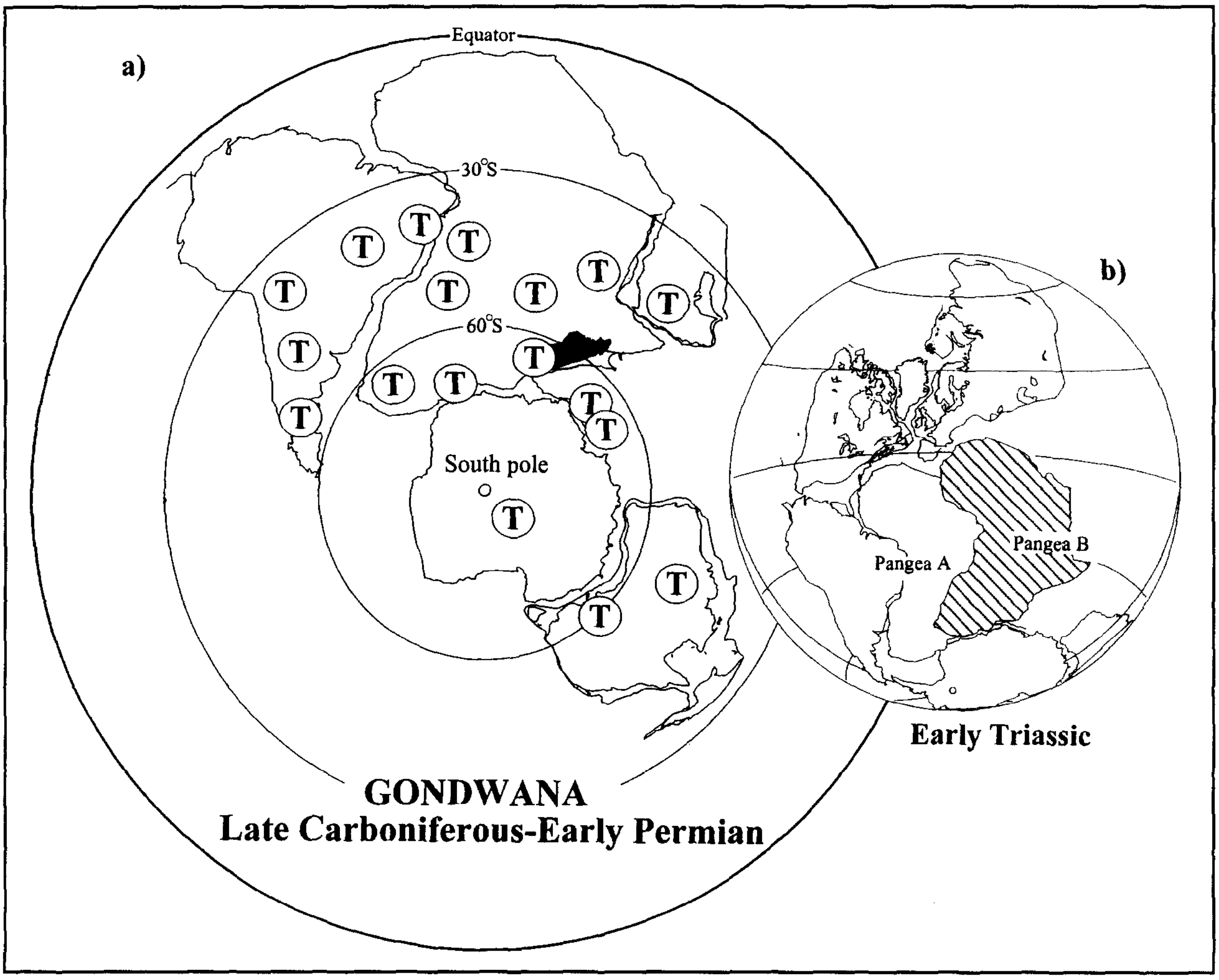


Figure 9. (a) Late Carboniferous to Early Permian reconstruction of Gondwana based on the Sakoa Group combined with West Gondwana pole shown in Fig. 8 (see also Table 4). Mean reconstruction pole latitude = 30.6°; longitude = 232.7°E (A95 = 6.8°). Continental fits are those of Lottes and Rowley (1990). Distribution of tillites is denoted T. (b) Example of an Early Triassic reconstruction (Torsvik and Eide, 1998) indicating the difference between a Pangæa A and B configuration. In the Pangæa B configuration, Gondwana is displaced eastward in order to avoid continental overlaps.

Depending on the extent of eastward Gondwana translation, Pangæa configurations have been denoted B or C (*cf.* excellent overview in van der Voo, 1993). Taken at face value, the Madagascar data suggest Pangæa B or C fits in Late Permian times. It is stressed, however, that many of the West Gondwana Late Permian-Early Triassic poles, like the Madagascar data, are of poor quality, and that the Sakamena Group magnetisation is not proven as primary. The probably more reliable Sakoa Group data reveals high southerly palæolatitudes, consistent with the presence of glacial deposits, and resulted from the Dwyka glaciation throughout Gondwana in Carboniferous-Early Permian times (Fig. 9a).

CONCLUSIONS

Demagnetisation data from rocks of the Karoo Supergroup are generally of poor quality. The best individual demagnetisation data are observed from the Middle-Jurassic Isalo Group, but poor remanence grouping precludes calculation of a group mean direction. Directional results from the Late Permian-Early Jurassic Sakamena and the Late Carboniferous(?)-Early Permian Sakoa Group show gross similarities with earlier published data. Most data, however, are of relatively poor quality and there is no firm evidence that proves a primary remanence. Local fold and conglomerate tests were inconclusive due to the poor magnetic properties of the rocks.

A comparison with West Gondwana palæomagnetic poles shows that the Lottes and Rowley (1990) fit produces the best palæomagnetic match between Madagascar and East Africa (Somalia), but other less tight fits, can be considered within the resolution of the palæomagnetic data, most notably for Upper Permian-Lower Triassic times (e.g. Coffin and Rabinowitz, 1987).

Given the lack of high quality West Gondwana poles from Late Permian-Early Triassic times, the precise Pangæa configuration is still not known, but, taken at face value, the Madagascar Sakamena pole and palæomagnetic poles utilised as reference data from West Gondwana suggest a Pangæa B or C configuration well into the Triassic. On the other hand, there is stronger confidence in West Gondwana poles of Late Carboniferous-Early Permian age. These poles place parts of Gondwana in high southerly latitudes, and is in agreement with the distribution of climatically sensitive lithological data.

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