PALEOMAGNETISM OF LOWER-MIDDLE DEVONIAN AND UPPER PROTEROZOIC-CAMBRIAN(?) ROCKS FROM MEJERIA (MAURITANIA, WEST AFRICA)

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Abstract. The paleomagnetism of two sedimentary rock units from the foreland of the Mauritanides of West Africa, in the Taganet region of Mauritania (Taoudeni basin) was studied to provide constraints on the paleocontinental positions of the southern continents in the Paleozoic. Thermal demagnetization of samples from the lower to middle Devonian Gneiguira supergroup isolated a predominantly single polarity characteristic magnetization (D=135.7°, I=27.3°, alpha95=5.3° for N=10 sites/44 samples) which gives a south paleopole position at Lat=35.2°S, Long=43.6°E (dp, dm=3.0°, 5.6°). The only other direction sometimes present is one aligned near to the present dipole field axis, notably as a high temperature component of reversed polarity in 7 samples (D=177.9°, I=-26.9°) obtained from 2 sites in weathered outcrop. The Upper Proterozoic to Cambrian (?) Mejeria red sandstone unit, equivalent to the Adrar CO_{10}, although apparently unweathered has multicomponent magnetization. Most common is an intermediate temperature (300° to 550°C) direction (D=137.2°, I=14.4°, alpha95=13.2° for N=4 sites/ 17 samples) similar to the characteristic direction of the Gneiguira. A high temperature component can be isolated in 11 samples but the directions are randomly distributed.

Comparison of the Gneiguira paleopole with other middle to late Paleozoic poles from Africa and Australia suggests that either it represents a Carboniferous remagnetization or that the south paleomagnetic pole for Gondwana already was off southern Africa by the Devonian. The paleogeographic and tectonic consequences of these possibilities differ considerably for the Atlantic-bordering continents.

Introduction

Considerable controversy exists regarding the apparent polar wander (APW) path for Gondwana in the Paleozoic. A major problem is the timing of the shift in paleopole position from the vicinity of northwest Africa in the early Paleozoic (corresponding to evidence of Upper Ordovician (Ashgill) glaciation in the Saharan region) to a position off southern Africa and toward Australia in the Carboniferous and Permian (corresponding to the Late Paleozoic Gondwanan glacial deposits). Contributing to this problem are the small number of mid-Paleozoic results from Gondwana, the possibility of significant tectonic movements between southeastern Australia, where many mid-Paleozoic paleopoles have been obtained, and the rest of Gondwana (Embleton, et al., 1974), the ambiguity in polarity of pre-Devonian paleopoles (Schmidt and Morris, 1977), and the perennial uncertainty regarding age of magnetization and often of the rock units themselves (e.g., Embleton, 1972).

At present paleomagnetic results from the Msissi norite of Morocco (Hailwood, 1974), which is intrusive into Upper Devonian beds of Maider, are virtually the only data that can be considered representative of the Devonian paleopole position for Africa. Corroborative evidence for the Devonian position of Africa is sought from paleomagnetic study of lower to mid-Devonian redbeds from the Mauritanides of West Africa.

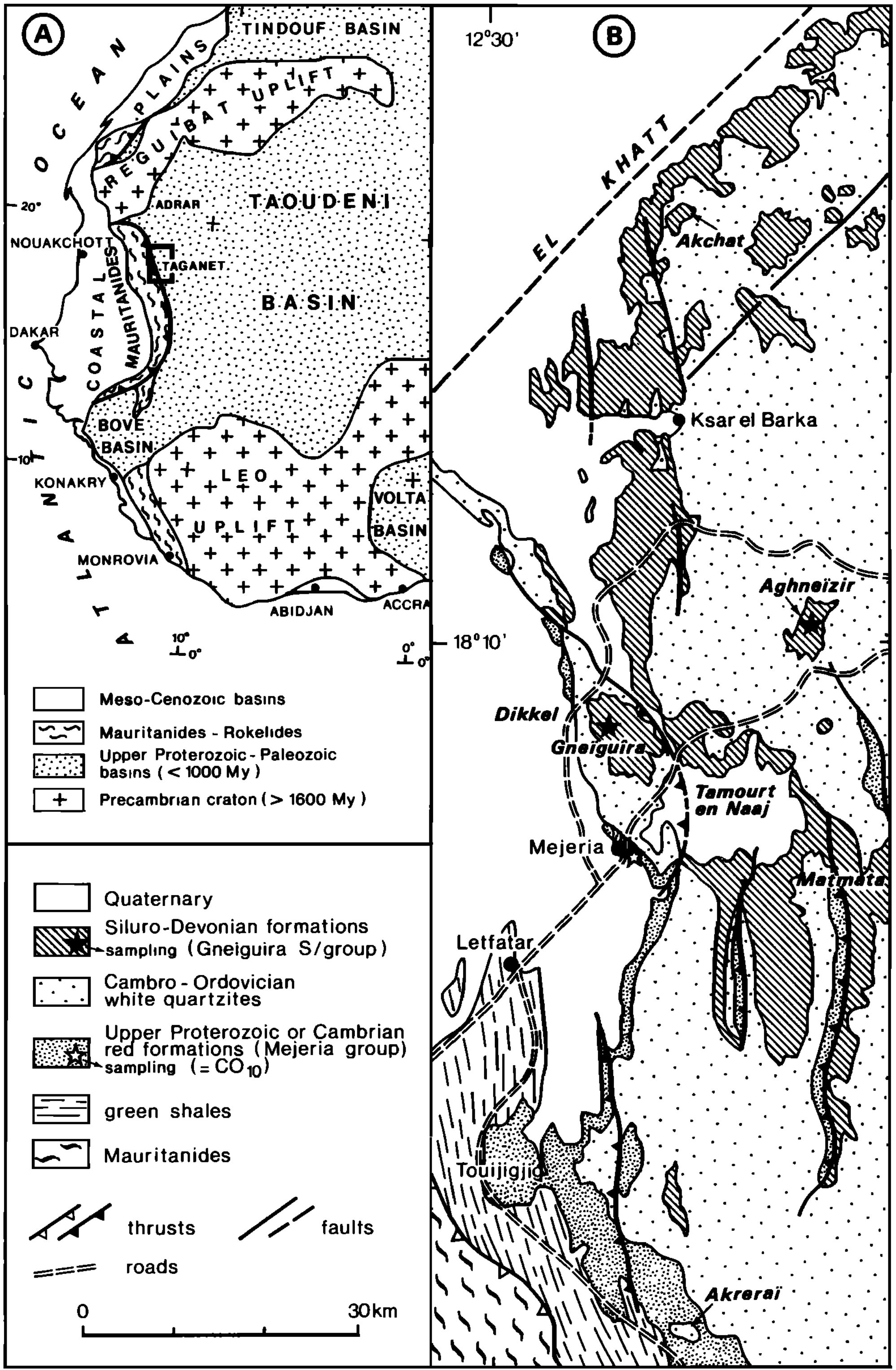

Fig. 1. (a) Sketch map of West Africa showing Mauritanide fold belt and forelands. Sampling localities for Gneiguira supergroup and Mejeria group (= CO_{10}) are in the Taganet area (enclosed in small box and shown in (b), just to the north and northeast of the town of Mejeria. (b) The map shows the outcrops of both groups and sampling localities.

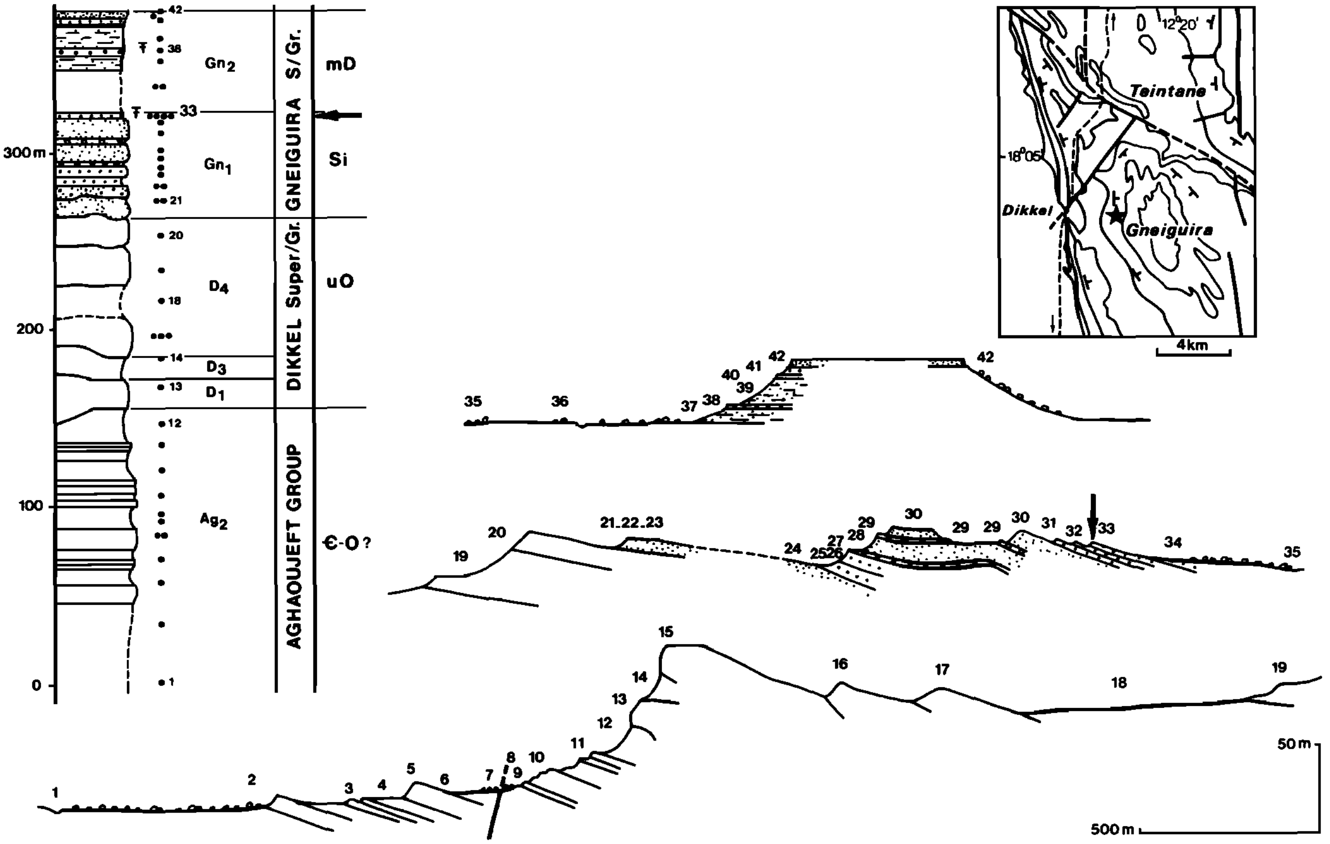

Fig. 2. Sketch map, cross-section and log of the Gneiguira syncline (East of Dikkel), showing sampling levels (sites A-G).

There was also an opportunity to sample Upper Proterozoic to Cambrian (?) redbeds from the same area and results of their paleomagnetism are included.

Geological Setting and Sampling

West Africa consists of a Precambrian granitized craton, stabilized before 1600 My, which is overlain by a several (2 to 6) kilometers thick sedimentary sequence ranging in age from about 1000 My to the Late Devonian and locally into the Carboniferous (Dillon and Sougy, 1974) (Fig. 1A). This sedimentary cover constitutes in particular the Taoudeni basin. A complex fold belt, the Mauritanide chain, is present along the western margin of the craton; basement and cover up to the Upper Devonian are folded in most of the chain (Sougy, 1962; Dia et al., 1979) and are overthrusting the Taoudeni beds up to the Upper Devonian in Adrar and Taganet (Fig. 1A).

We sampled for paleomagnetic study two sedimentary units on the foreland of the Mauritanides, just to the north and northeast of Mejeria (Lat.=17°53'N, Long.=12°20'W) in the Taganet region of Mauritania. Our primary interest was in exposures of reddish sandstones and siltstones of the Gneiguira supergroup (Fig. 1B). The age of this thin (100 to 200 m) sequence is partly Silurian (Gn1 formation) on the basis of Upper Llandovery graptolites, and partly early mid-Devonian (Gn2 formation) on the basis of Emsian-Eifelian brachiopods of marine beds interfingered with red beds.

Sampling has been done at:

1) Gneiguira syncline, on the western flank, on the structural top surface of the Gn1 formation, dipping slightly to the east (N 0°-5°E), at a point Lat.=18°02'N, Long.=12°20'W, at an altitude of 145 m (sites A to G). Facies is a medium to coarse-grained quartz sandstone, reddish in color, with shale pebbles and ripple-marks. Figure 2 gives the exact geographic and stratigraphic position of the sampling which lies between Silurian (poor in fossils here) and a Devonian fauna (level 38, Fig. 2) with Hadrophyllum, Microcyclus, Phacops, Chonetes, Schellwienella, Bryozoa, not determined specifically, but which may date mid-Devonian. The sampling has been done on a structural surface which may represent a continental interval between marine Silurian (Tarannon) and Emsian, i.e., during the Lower Devonian.

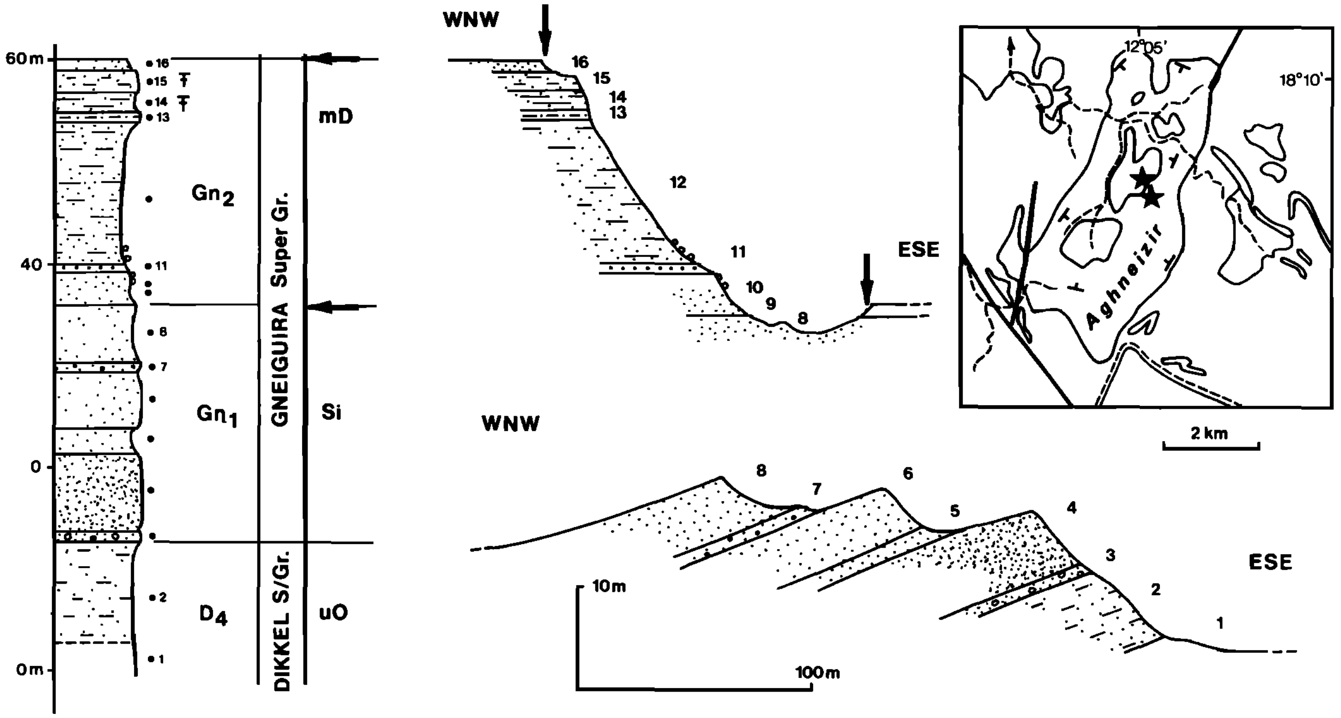

Fig. 3. Sketch map, cross-section and log of the Aghneizer syncline (30km NE of Mejeria), showing sampling levels (sites H, I near top of Gn1 and J, K, L near top of Gn2).

2) Aghneizir syncline, 30 km northeast of Mejeria (Fig. 3), on a horizontal structural surface at the top of Gn1 (same as previous sampling), on the eastern flank of the syncline, at an altitude of 280 m (sites H, I). Facies is deep purplish, coarse-grained sandstone with ferruginous tubules and staining. We had the opportunity to sample only pavement outcrop that appeared weathered.

3) Aghneizir syncline, same locality, at the top of Gn2 formation (23 m thick) at a point Lat.=18°09'N, Long.= 12°04'W (sites J, K. L). Facies is ferruginous medium to coarse-grained quartz sandstone with intercalated thin-bedded oolitic hematite. A poor Devonian fauna of Brachiopods and Crinoids has been observed in levels 14 and 15 just underneath (Fig. 3), suggesting deposition during the Middle Devonian.

A total of 52 drill-core and hand samples, oriented by magnetic compass, were collected from 12 sites. The rocks are highly indurated and appeared fresh at all but 2 of the sites (H and I) where the available outcrop is obviously weathered.

The other unit sampled is the Mejeria group, Taganet equivalent of the CO_{10} of the Plateaux d'Oujeft group in Adrar (Trompette, 1973). It consists of medium to fine-grained, reddish, feldspathic sandstones with a thickness of 125 m and which, except for cross-bedding, are essentially flat-lying. Age control is very imprecise: in Adrar a fauna of inarticulate brachiopods has been found stratigraphically higher in CO_{12} and would represent the limit Cambrian-Ordovician, so the Mejeria beds may be Cambrian or Upper Proterozoic. Twenty four oriented drill core samples were collected from six sites in exposures just east of the town of Mejeria, in the road-pass of Khang Achetf.

Natural Remanent Magnetizations

The natural remanent magnetization (NRM) of each sample was measured on a cryogenic magnetometer (Goree and Fuller, 1976) or a computerized flux-gate spinner magnetometer (Molyneux, 1971). NRM intensities for the Gneiguira samples average around 5×10^{-2} Am^{-1} except for samples taken from the weathered outcrops (sites H and I) which have NRM intensities one order of magnitude lower. Samples from the 2 weathered sites also have more scattered NRM directions compared to the good grouping of NRM directions from the other 10 sites (Fig. 4a). Different magnetic properties between fresh and weathered samples are maintained in demagnetization behavior.

NRM intensities of the Mejeria samples average about 3×10^{-3} Am^{-1} and although these rock samples all appear fresh the NRM directions show large scatter (Fig. 4b). The presence of inconsistent magnetizations is largely verified in demagnetization experiments.

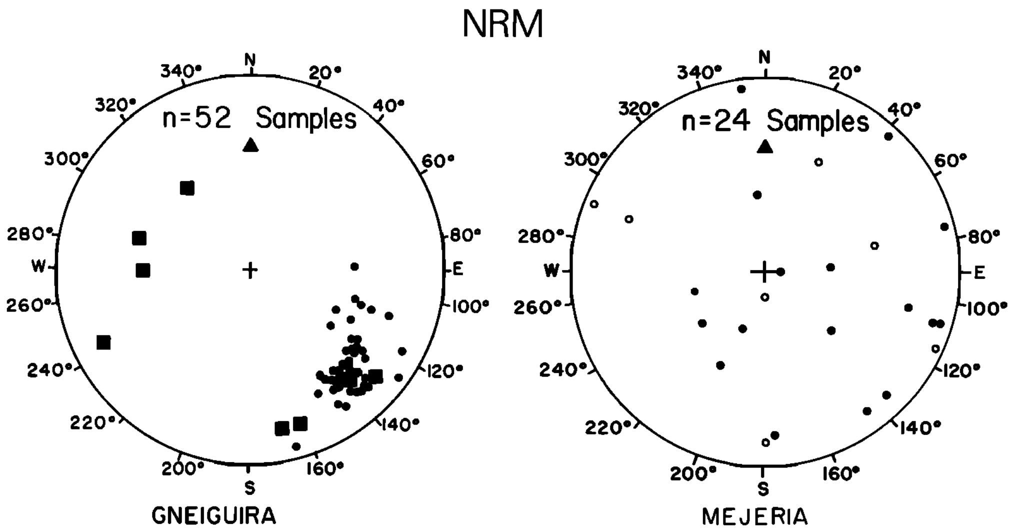

Fig. 4. Directions of natural remanent magnetization (NRM) for samples from (a, left) Gneiguira and (b, right) Mejeria (=CO$_{10}$). Solid symbols are on lower (upper) hemisphere of equal area projection. Triangle is present dipole field direction. Squares in (a) are for samples from obviously weathered outcrop; circles for unweathered samples.

Alternating field (AF) and thermal demagnetization experiments were conducted to evaluate the presence and stability of magnetization components contributing to the NRM of these rocks. The results are described below according to formation.

Gneiguira Supergroup

AF treatment to 100 mT generally has only small effect on the magnetization and the NRM are therefore judged to be of very high coercivity. All samples were consequently subjected to progressive thermal demagnetization to resolve magnetization components.

Almost all samples show a dominant, single component of magnetization with southeast declination and fairly shallow position inclination (Fig. 5a, b, c, d). The unblocking temperature spectrum is typically discrete (Fig. 6) with concentration in a narrow temperature range just below 675°C, above which the magnetization essentially disappears. Hematite is therefore the likely carrier of this magnetization which we regard as characteristic.

The characteristic magnetization can be isolated in all samples collected from the ten sites representing fresh outcrop. The characteristic directions are of single polarity (Fig. 7) and for N=10 sites, give a reasonably well-defined overall mean for the Gneiguira of Decl=135.7°, Incl=27.3°, alpha95=5.1° (Table 1). In view of the apparent difference in stratigraphic age of sites A to G (assigned to formation Gn1 and representing Lower Devonian) and sites J to L (formation Gn2, mid Devonian), separate means for these two groups of sites have also been calculated (Table 1). Despite the limited number of sites in each grouping, the mean directions for Gn1 and Gn2 can be rejected as the same at the 95% confidence level according to the test of McFadden and Lowes (1981).

In five samples, a component of magnetization in addition to the high temperature characteristic direction is revealed over an intermediate demagnetization temperature range (e.g., Fig. 5e). The unblocking temperature spectrum is more distributed in these samples and possibly reflects a contribution from magnetite to the NRM. The directions of this intermediate temperature component, determined by linear regression analysis, have a significant grouping (Table 2) whose mean (Decl=83.4°, Incl=51.9°) diverges from both the present field and the characteristic direction. Thus although this component is not well represented in this sample collection, it nevertheless requires explanation.

Only eight samples are available from the two weathered sites (H, I) and even so, several components of magnetization can be distinguished (Fig. 8). One sample from site I showed erratic behavior in demagnetization and is the only sample result from the Gneiguira that was discarded. The component most consistently present in the remaining seven samples occurs in the final stages of thermal demagnetization, typically between 600° and about 670° when the samples are fully demagnetized. This final component is significantly different from the characteristic magnetization observed in the other 10 sites and gives a mean direction of D=177.9°, I=-26.9° (Fig. 9; Table 3) which is close to a reversed polarity dipole field. In several of these samples, there is evidence for a component similar

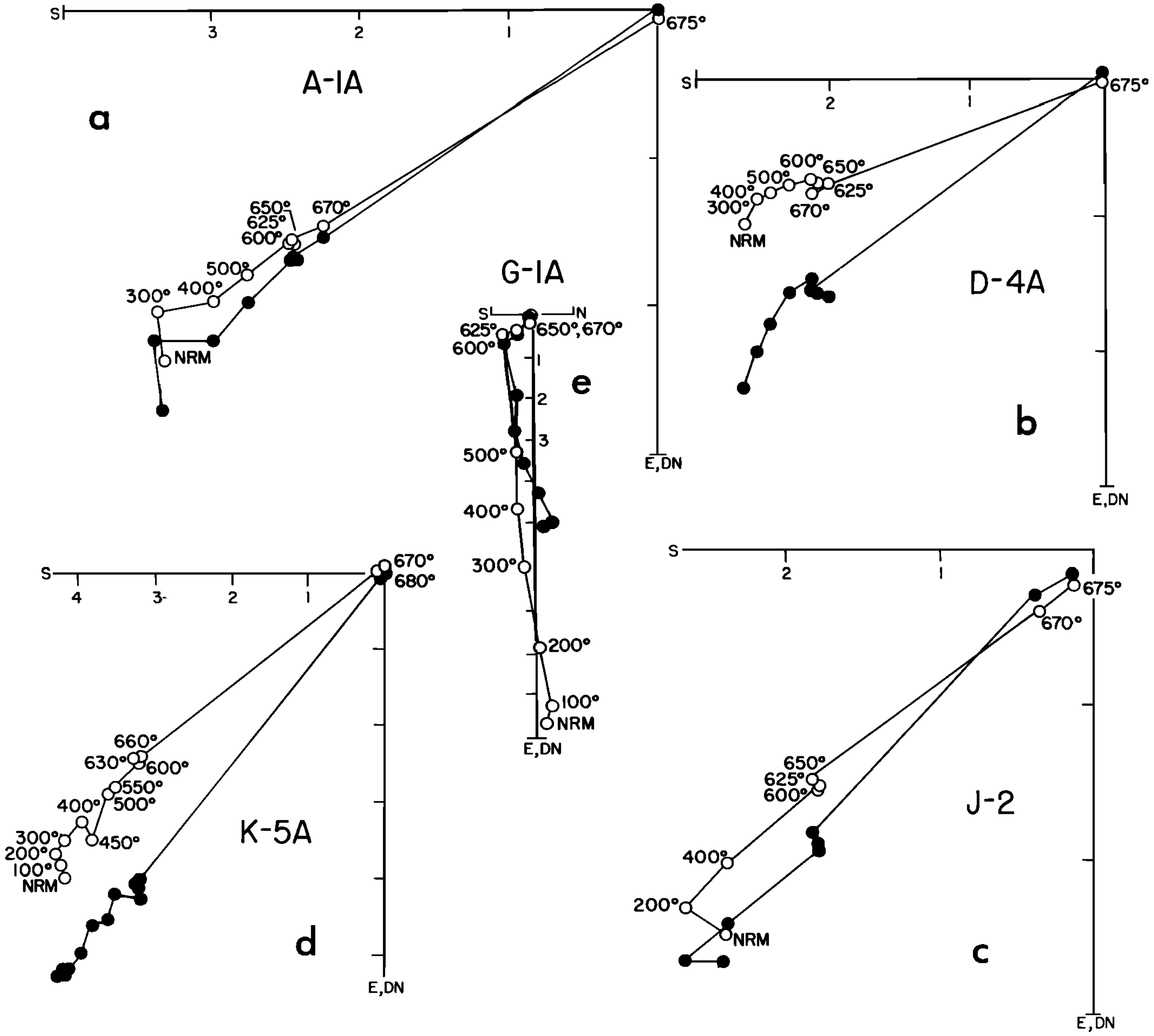

Fig. 5. Orthogonal projections of vector end-points (Zijderveld, 1967) for progressive thermal demagnetization of five Gneiguira samples from fresh outcrop. Solid (open) symbols are projections on horizontal (vertical) planes. Magnetization units on axes in 10^{-3} A/m.

in direction to the characteristic magnetization but which occurs over thermal demagnetization temperatures ranging from 100°C to only 400° or 500°C (Fig. 8a). In one sample, this intermediate blocking temperature component has a northerly declination and a shallow but negative inclination (Fig.8c) and may represent an opposite polarity. Magnetizations with unblocking temperatures to only 100°C are also present but since they are not consistent and are therefore likely to represent spurious components, they are not considered further.

Mejeria Group

Pilot demagnetization studies indicated that the NRMs are also of high coercivity but show complex vectorial behavior under thermal treatment. All remaining samples were treated at a minimum of eight temperature steps in an attempt to resolve components of magnetization. Some examples of demagnetization vector-end point diagrams are shown in Figure 10.

After initial removal by about 200° to 300°C of what appears to be recently acquired magnetization, perhaps two components of magnetization can be distinguished in many samples. Most common (in 17 of 24 samples) is a southeasterly, shallow direction revealed over an intermediate temperature range of demagnetization, from about 300° to 550°C. This component is present in all interpretable demagnetization diagrams (those characterized by linear demagnetization segments) but in each case, its trajectory is oblique to the origin. The presence of another higher temperature component is therefore implied and in eleven of these samples there is evidence for a decay to the origin of a high temperature component (Fig. 10). In the remaining samples, spurious magnetizations become dominant and no systematic demagnetization trends are apparent.

The directions of the intermediate and high blocking temperature magnetization are plotted in Figure 11. The intermediate temperature directions were determined by linear regression analysis and group around a mean of D=137.2°, I=14.4° (alpha95=13.2° for N=4 sites/17 samples). The high temperature directions were estimated using the origin as the final point and show no perceptible grouping. According to a f-ratio criterion, the distribution of the high temperature direction cannot be rejected as random at the 95% confidence level (Table 4).

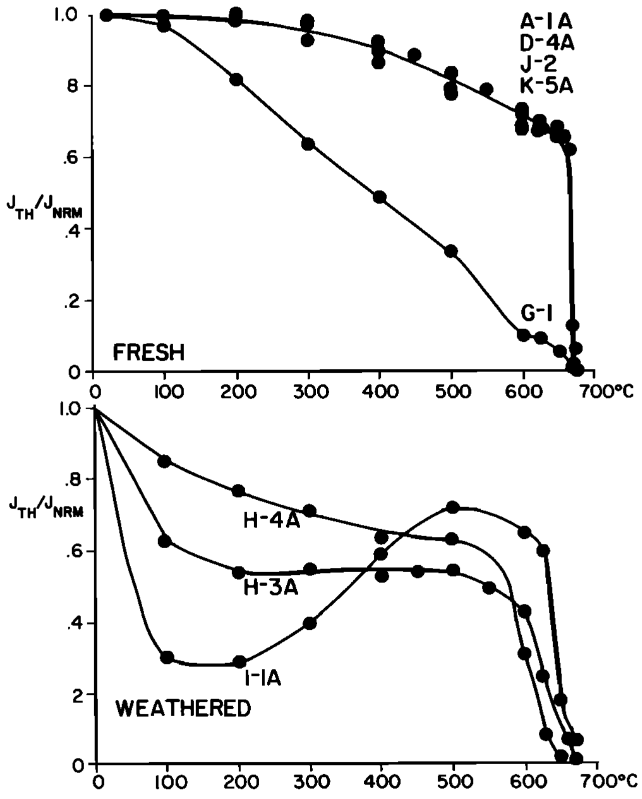

Fig. 6. Unblocking temperature curves (proportion of original NRM remaining after demagnetization temperature) for Gneiguira samples, corresponding to demagnetization vector diagrams in Figure 5 (top) and in Figure 8 (bottom).

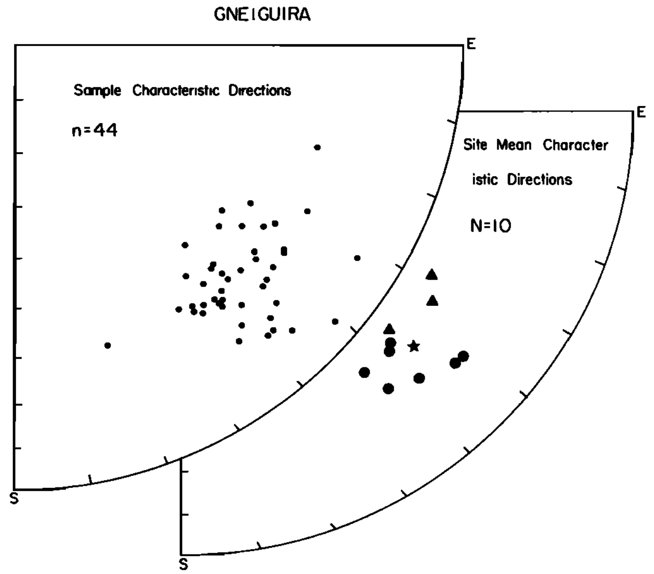

Fig. 7. Characteristic directions from Gneiguira plotted on lower quadrants of equal-area projections. Sites from Gn1 (Gn2) designated by circles (triangles). Star symbol at right is formation mean direction for N=10 sites.

Discussion of Paleomagnetic Results

Consideration of the significance of the characteristic magnetization of the Gneiguira supergroup is deferred until the next section where it is discussed in conjunction with middle to late Paleozoic paleopoles from the Gondwana continents. Although a fold or other field test is not available to help constrain the age of this magnetization, it will suffice for the ensuing discussion to state that the characteristic magnetization most likely represents acquisition in a Paleozoic field.

A small number of samples at two sites (H, I) in the Gneiguira taken from obviously weathered outcrop have multicomponent magnetizations. Directions parallel to the characteristic magnetization axis appear to be present over intermediate blocking temperatures, but the final, high temperature directions group near to the dipole field axis. The reversed polarity of this high temperature component however indicates that the magnetization was not acquired recently but sometime prior to the present interval of normal geomagnetic polarity (0-0.73 Ma). The weathering which is likely to be intimately associated with this secondary magnetization is therefore also likely to have occurred prior to the Late Pleistocene. If originally these rocks possessed the same characteristic magnetization as found in the unweathered samples, then the acquisition process responsible for the secondary magnetization has

TABLE 1. Gneiguira Characteristic Directions

Site	N/n[a]	Decl. (°)	Incl. (°)	k[b]	alpha95[c] (°)
A	6/6	144.5	29.6	721	2.5
B	5/5	138.2	31.3	196	5.5
C	5/5	137.8	31.2	278	4.6
D	5/5	138.6	21.3	87	8.2
E	5/5	143.4	23.9	37	12.7
F	3/3	131.6	17.9	59	16.2
G	3/3	133.2	17.5	44	18.8
Formation Gn1 mean (7 sites):					
		138.1	24.7	118	6.9
H	(see Table 2)				
I	(see Table 2)				
J	5/5	124.0	34.4	50	11.0
K	5/5	127.8	30.9	190	5.6
L	2/2	137.0	33.6	-	-
Gn2 formation mean (3/5 sites):					
		129.6	33.1	190	9.0
Gneiguira supergroup mean (10/12 sites):					
		135.7	27.3	89	5.1
Pole position (from supergroup mean):					
Lat= 35.5°S Long= 44.0°E (dp,dm=3.0°, 5.6°)					

[a] Number of sample directions used in calculation/ total number of samples measured.
[b] Best estimate of Fisher's precision parameter.
[c] Radius of 95% circle of confidence.

affected preferentially the high blocking temperature portion of the spectrum. In any case, these samples demonstrate that the last component removed may not necessarily be the first one acquired.

The only other consistent component identified in the Gneiguira is a more steeply inclined magnetization observed over low to intermediate demagnetization temperatures in 5 samples. This steep magnetization lies very near to a great circle joining the characteristic direction and the present dipole field (Fig. 10). Considering the small number of samples involved and this geometrical relationship, we suggest this intermediate blocking temperature component is an unresolved resultant magnetization, reflecting overlapping blocking temperatures of the characteristic and a recently acquired magnetization. In contrast to the weathered sites, the process responsible for the acquisition of a secondary (present field) magnetization in these samples preferentially must affect the lower end of the blocking temperature distribution although temperatures as high as 600°C are required for complete removal (e.g., Fig. 3e).

Interpretation of the results from the Mejeria sandstone unit is more problematical, particularly in light of the results reported by Morris and Carmichael (1978) for the correlative CO$_{10}$ unit farther to the north in the Adrar region of Mauritania. The most consistent direction we observe is of shallow inclination and southeasterly declination. A similar direction (over a similar range of thermal demagnetization temperatures, up to 550°C), was observed by Morris and Carmichael (1978), their S direction. These directions are plotted in Fig. 10 and are seen to fall close to the Gneiguira characteristic directions. This coincidence tends to support a secondary origin for this magnetization in these Upper Proterozoic or Cambrian(?) sediments.

Although the oblique demagnetization trajectory of the Mejeria secondary magnetization in this study implies the presence of at least one remaining component with blocking temperatures above 550°C, a high temperature component with a consistent direction from sample to sample was not isolated. Instead, a random distribution of high temperature directions is observed and we see little evidence for the I (initial) component (northeasterly declination, steep positive inclination) reported by Morris and Carmichael (1978) in the Adrar area. Both studies suffer from inadequate sample material for analysis (7 samples in Morris and Carmichael (1978) and 24 samples here, of which only 11 give interpretable high temperature directions) and different sampling areas are involved, conditions which limit the basis for discussion of the apparent discrepancy in observations. It is however worth pointing out that the I direction of Morris and Carmichael (1978) falls close to a great circle joining the S (intermediate blocking temperature) direction and the present field direction (Fig. 12). This suggests that their I direction may also be a resultant magnetization, similar to what we postulate for the intermediate blocking temperature component observed in 5 samples from the Gneiguira.

TABLE 2. Gneigura Intermediate Blocking Temperature Directions

Sample	Demag. Range (°C)	Decl. (°)	Incl. (°)
B-4	400-600	75.7	39.5
G-1	200-600	78.0	63.9
K-4	200-600	107.5	58.0
L-1	400-625	57.5	37.0
L-2	200-625	110.3	52.0
Mean direction (5 samples):			
D=83.4° I=51.9° k=19 alpha95=17.9°			
(R=4.79 $R_0(95\%)=3.50$)*			

*R is resultant length of sample unit vectors; $R_0(95\%)$ is test value for for random distribution at 95% confidence level.

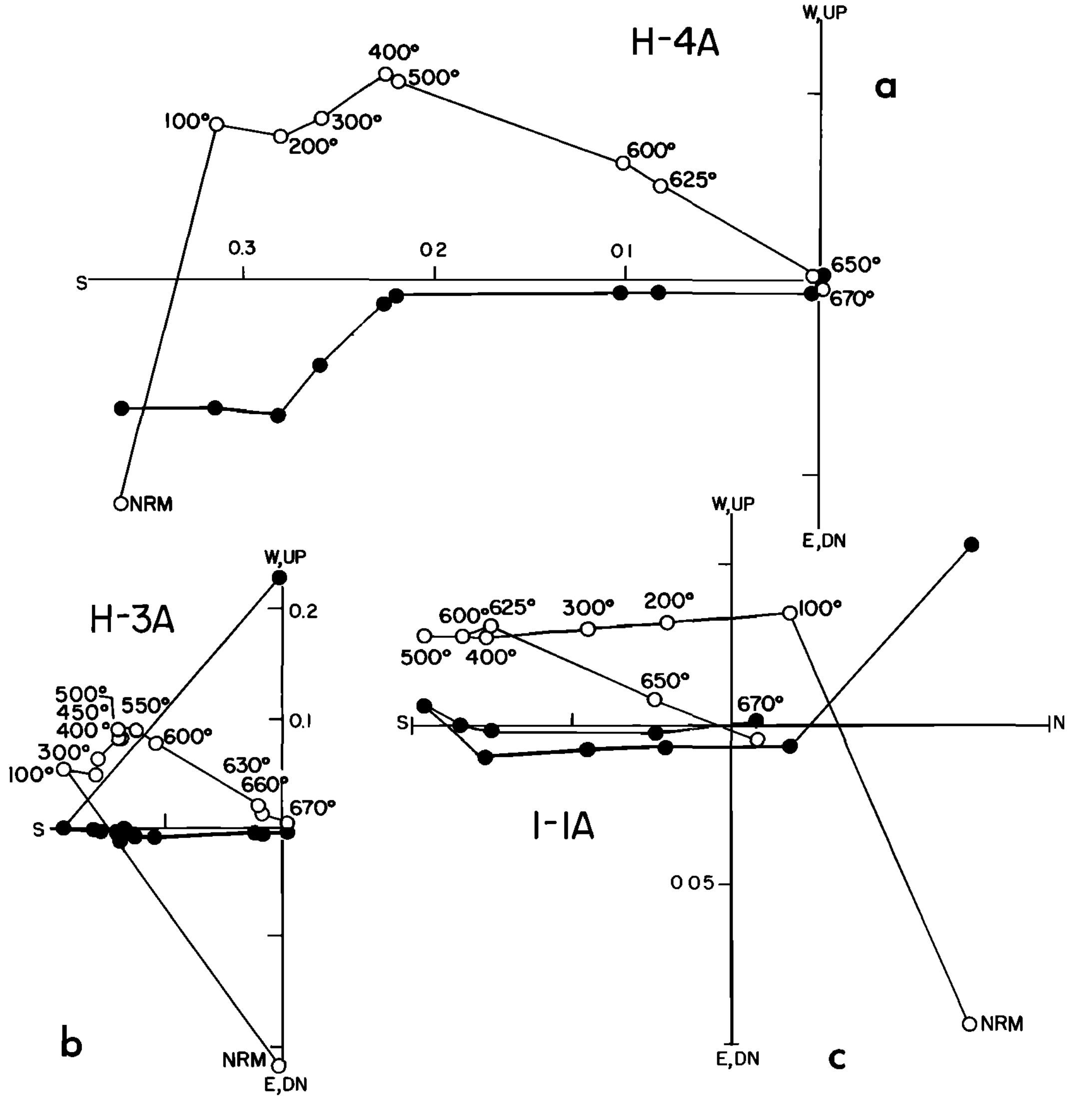

Fig. 8. Orthogonal projection of vector end-points for progressive thermal demagnetization of Gneiguira samples from obviously weathered outcrop. Solid (open) symbols are projection on horizontal (vertical) planes. Magnetization units on axes in 10^{-3} A/m.

Middle to Late Paleozoic APW for Gondwana

The characteristic magnetization of the Gneiguira remains for discussion. Other magnetizations isolated in the Gneiguira and Mejeria units appear to be either similar in direction, uninterpretable, of relatively recent origin, or as unresolved resultants containing more recent magnetization and do not need to be considered explicitly further.

The characteristic direction for the Gneiguira formations, Gn1 and Gn2, correspond to paleopole positions at 38.4°S, 43.8°E and 28.6°S, 44.5°E, respectively (Table 1). Although the mean directions of the two formations are statistically different, their close proximity and tight circles of confidence suggest that secular variation may not be effectively averaged in the relatively few sites available from each formation. Consequently, the mean paleopole for the two formations combined (33.5°S, 44.0°E for N=10 sites) is considered more representative of the time averaged field recorded in the lower to middle Devonian Gneiguira. The strata are virtually horizontal at the sampling localities so neither are tilt corrections required nor is a fold test possible.

There are few mid-Paleozoic paleomagnetic results from Africa available for comparison but it is apparent that the Gneiguira pole disagrees

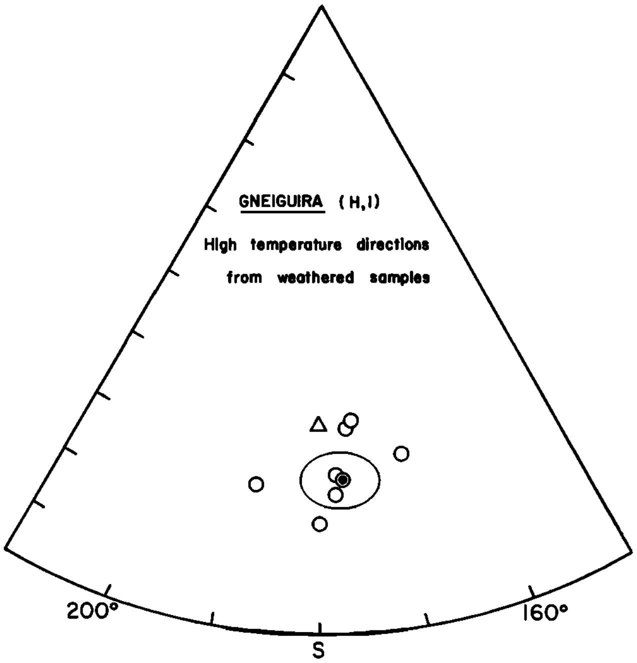

Fig. 9. High temperature directions in Gneiguira isolated in 7 samples from obviously weathered outcrop plotted on upper segment of equal-area projection. Triangle is present dipole field axis of reversed polarity, encircled symbol and oval show, respectively, the mean and its 95 percent confidence limit.

with the only other Devonian pole available from this continent, obtained from the Msissi Norite which is regarded as Late Devonian (Hailwood, 1974). The Msissi indicates a south pole position in central Africa whereas the Gneiguira paleopole lies off southern Africa, more in the general vicinity of the pole position obtained from the Dwyka varves (McElhinny and Opdyke, 1968) (Fig. 13). The Dwyka paleomagnetic results are supported by a positive fold test but there is some uncertainty as to the age of the deposits. The Dwyka lies at the base of the Karoo System and in southernmost Africa is conventionally considered to be Late Carboniferous or Permian. McElhinny and Opdyke (1968) however favored an Early Carboniferous age for the Dwyka (at least in the sampling areas in Rhodesia, Zambia and Tanzania) citing plant fossil evidence indicating an Upper Devonian or Lower Carboniferous assignment, the lack of agreement of the Dwyka paleopole with well-established Permo-Carboniferous Gondwana poles (shown also in Fig. 13), and the presence of normal polarities which are more compatible with acquisition of magnetization prior to the Kiaman reversed polarity interval which extends from the Late Carboniferous (Namurian or Westphalian) to the latest Permian (Irving and Parry, 1963; Irving and Pullaiah, 1976).

It is in any case feasible to consider the Gneiguira as remagnetized sometime in the Carboniferous and by default to regard the Msissi directions as providing a good indication of the (Late) Devonian paleomagnetic field for Africa. The general proximity of the intermediate blocking temperature directions in the Mejeria, the S direction in the correlative CO_{10} unit in Adrar, and the Gneiguira characteristic direction are admittedly an indication of remagnetization. However, even though no direct evidence to constrain magnetization age, such as a fold test, is available for the Gneiguira, the small but significant difference in mean directions between the lower Devonian Gn1 and the middle Devonian Gn2 formations can be used to argue against a common time or mode of remagnetization. Moreover, the presence of a large secondary component of remanence of recent origin in the NRM, the increase in within-site scatter in directions after AF demagnetization to only 30 to 45 mT, and the lack of field evidence for original magnetizations suggest that the interpretation of the Msissi directions as a valid indicator of the late Devonian paleofield for Africa is also not unequivocal. Thus an alternative possibility can be considered; that the Gneiguira characteristic magnetization records a paleopole position in the vicinity of southern Africa by the early to mid-Devonian, as has been suggested previously, for example, by McElhinny and Briden (1971). Unfortunately, the available paleomagnetic data for the mid-Paleozoic of the other Gondwana continents do not allow an easy resolution to the discrepancy in the African Devonian data and in fact are equally difficult to interpret.

The interpretation of the Paleozoic paleomagnetic field of Gondwana is greatly complicated by uncertainty in the tectonic history of southeastern Australia where much of the data has been obtained; the wide variety of Paleozoic APW paths proposed for Gondwana (e. g., McElhinny and Embleton, 1974; Morris and Schmidt, 1977; Morel and Irving, 1978; Goleby, 1981) is in large part a function of the manner and extent to which the southeastern Australian paleopoles are included. Confusing the issue further is that Tertiary or Recent remagnetization directions in Australia give paleopoles on a Gondwana reconstruction that tend to fall near middle to late Paleozoic poles.

Without entering into an extended discussion of

TABLE 3. Gneiguira Secondary Directions At Weathered Sites

Site	N/n	Decl. (°)	Incl. (°)	k	alpha95 (°)
H	5/5	177.4	-29.3	135	6.6
I	2/3	178.8	-21.1	-	-
Mean direction (7/8 samples):					
		177.9°	-26.9°	131	5.3°

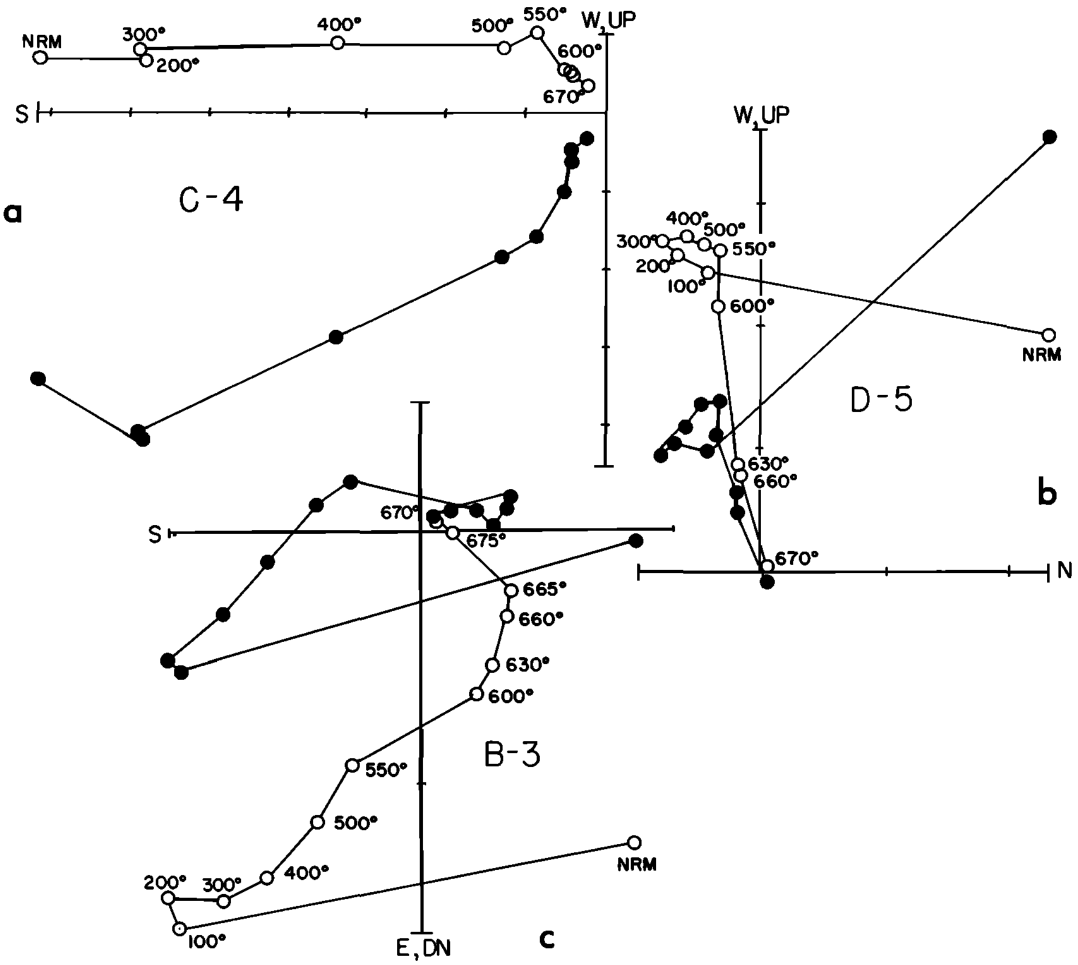

Fig. 10. Orthogonal projection of vector end points for thermal demagnetization of three samples from Mejeria group (=CO_{10}). Solid (open) symbols are projections on horizontal (vertical) planes. Magnetization units are in 10^{-3} A/m.

the various proposed APW paths, the uncertainty in the Devonian pole position for Gondwana can be illustrated by considering a select group of critical Australian poles from predominantly Devonian-age rocks. This group generally conforms to the most reliable category (A) in the compilation by McElhinny and Embleton (1974), except that the Lochiel Fm. pole is deleted because it is now considered unreliable (Embleton and Sheperd, 1977). The mid-Devonian Housetop Granite pole (category C) is however included here because there are now supporting data from the mid-Devonian to early Carboniferous Mulga Downs Group of western New South Wales (Embleton, 1977). These poles are plotted in Figure 13 in African coordinates on the Smith and Hallam (1970) reconstruction for Gondwana. Also included are the better established mean pole positions from Upper Carboniferous (Cu), Lower Permian (Pl) and Permo-Triassic (P-Tr) rocks from South America and Africa for comparison with the Australian poles.

Critical to an assessment of the Gondwana Paleozoic APW path is the age of the Mereenie sandstone and the significance of its magnetization (Embleton,1972). Stratigraphic constraints indicate that the Mereenie is younger than Late Ordovician and fish fossils indicate that it is at least in part Devonian. The NRMs of the 33 original samples were suspiciously well-grouped near to the present field direction and the reported pole position was based on only 11 tilt-corrected sample directions after being "successfully" cleaned by thermal demagnetization (14 sample directions stayed near to the present field even after 650°C). Nevertheless, the Mereenie result is important because it provides virtually the only mid-Paleozoic Australian paleopole from the stable interior of the continent to compare with the more numerous paleopoles obtained from the more tectonically complex southeastern area of Australia. However, the uncertainties associated with the Mereenie make the apparent agreement of its paleomagnetic pole

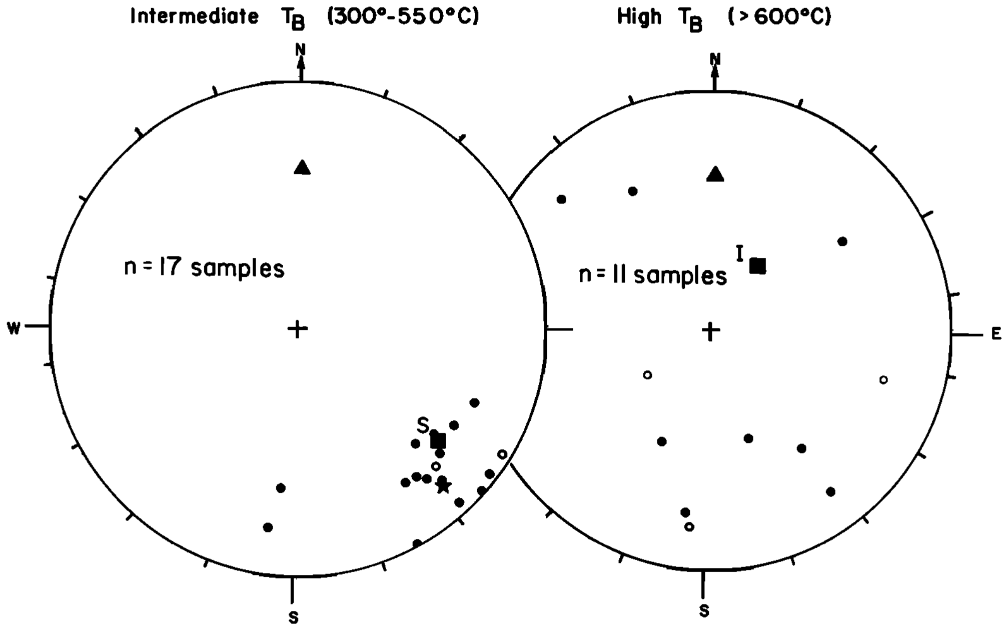

Fig. 11. Directions of intermediate (left) and high (right) unblocking temperature directions isolated in samples from Mejeria group. Filled (open) symbols on lower (upper) hemisphere of equal area projections. Triangle is present dipole-field direction. Star (left) is mean direction for intermediate blocking temperature component in 17 samples. Squares show the mean S (intermediate temperature) direction and I (high temperature) direction obtained by Morris and Carmichael (1978) from CO_{10}, a unit correlative to the Mejeria group in the Adrar region.

with the Msissi pole (Figure 13) open to several interpretations.

One possibility is that the Mereenie and Msissi provide mutually supportive data for a later Devonian pole position in central Africa, hypothesis DA, broadly consistent with the APW paths proposed by Morris and Schmidt (1977) and Morel and Irving (1978). Not well explained by this model however is a set of apparently coeval poles, loosely grouped but distinct in location from the Msissi and Mereenie poles, from the mid-Devonian Housetop Granite, mid-Devonian to early Carboniferous Mulga Downs Group, and the Gneiguira supergroup. This set would imply that the paleomagnetic pole was already off southern Africa, near to the documented late Paleozoic position, by the early to mid-Devonian (hypothesis DB). Morris and Schmidt (1977) include a rapid polar shift in the late Devonian, from essentially position DA to DB of Figure 13, in an attempt to include this latter set of poles; Morel and Irving (1978) postulate that the polar shift occurred in the Early Carboniferous and would probably regard the Devonian poles included in position DB as remagnetized either in the Tertiary or the Carboniferous. Goleby (1981) summarizes without providing details new paleomagnetic investigations of Paleozoic rocks from (southeastern) Australia. These data foster the proposal that the Mereenie sandstone and its magnetization should be regarded as early to middle Silurian which would necessitate rejection of the Msissi pole as a late Devonian direction if Goleby's Australian APW path is to be applicable to all of Gondwana. This is generally consistent with hypothesis DB since the APW path

TABLE 4. Mejeria Red-Sandstone Directions

a. Intermediate Temperature Component(300-550°C)

Site	N/n	Decl. (°)	Incl. (°)	k	alpha95 (°)
COA	5/5	144.4	22.4	10	24.9
COB	3/4	133.8	10.7	7	49.5
COC	5/5	146.8	12.3	11	24.2
COD	4/5	123.9	11.6	18	29.6
COE	0/3	-	-	-	-
COF	0/2	-	-	-	-
Mean (4/6 sites, 17/24 samples):		137.1°	14.4°	49	13.2°

Pole position:
Lat= 40.5°S Long= 49.9°E (dp,dm= 6.9°,13.5°)

b. High Temperature Component (600°C)

Mean direction (11/24 samples):	147.7°	50.8°	1.3	76.9°
(R=3.42	R_0(95%)=5.28)*			

*See Table 2 notes.

of Goleby appears to be drawn through the Housetop and Mulga Downs poles.

Common to the APW paths of Goleby (1981), Morel and Irving (1978) and Morris and Schmidt (1977) is that some form of a loop is shown to include the Silurian and Early Devonian paleopoles from southeastern Australia which McElhinny and Embleton (1974) previously considered to reflect motion of a separate plate over this time interval. The general agreement of the Gneiguira pole with the possibly primary paleomagnetic pole from the Housetop granite of Tasmania could therefore be fortuitous although Embleton (1978) and Embleton and Giddings (1977) argued on the basis of concordant Australian early Paleozoic paleopoles that Tasmanian rock formations provide paleomagnetic data which relate to the main platform of Australia.

The Devonian pole position for Gondwana is clearly difficult to resolve with the available data. These data appear to give contradictory information and some results must be arbitrarily considered to be either anomalous or secondary (e.g., hypotheses A and B). Alternatively, the apparent inconsistencies can be regarded as a reflection of a rather complex apparent polar wander pattern with very rapid polar shifts that seem improbable or at least difficult to test at present. Nevertheless, it might be of interest to consider some of the paleogeographic and tectonic consequences of perhaps the two simplest possible interpretations (DA and DB) discussed above.

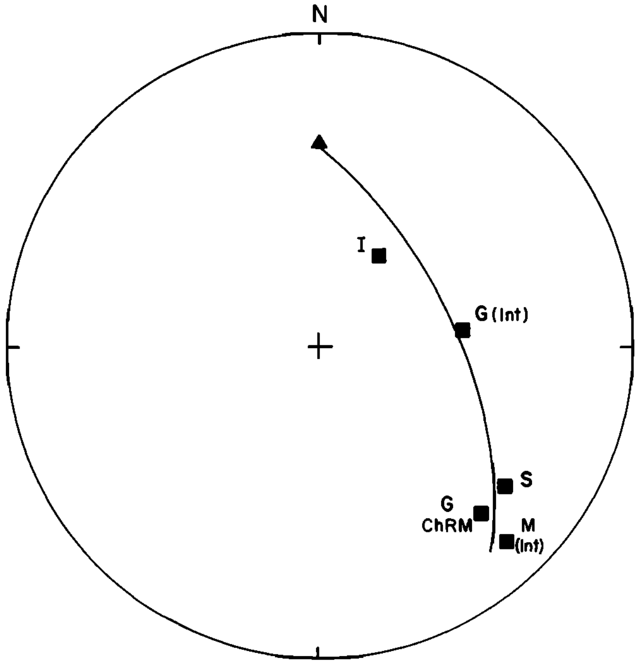

Fig. 12. Directions of present dipole field, (triangle), the mean characteristic (G ChRM) and the intermediate blocking temperature (G Int) directions for the Gneiguira, the intermediate blocking temperature direction (M Int) from the Mejeria, and the intermediate (S) and high (I) blocking temperature directions reported by Morris and Carmichael (1978) for CO_{10}, a unit correlative to the Mejeria from the Adrar, all plotted on lower hemisphere of equal-area projection. Curve is trace of great circle drawn from present dipole field to mean of G ChRM, M Int, and S.

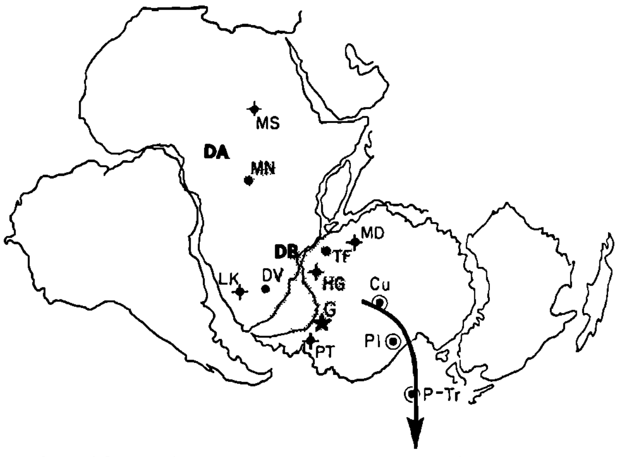

Fig. 13. Middle to late Paleozoic paleomagnetic poles for Gondwana plotted on a reconstruction by Smith and Hallam (1970). Mean Late Carboniferous pole (Cu) from Valencio et al. (1975); mean early Permian (Pl) and Late Permian-Early Triassic (P-Tr) poles from Daly and Pozzi (1976). Individual poles shown are from Africa: Msissi norite (MN), Gneiguira (G) and Dwyka varves (DV); from Australia: Mereenie sandstone (MS), Housetop granite (HG), and Mulga Downs Group (MD) Lower Kutting (LK), Paterson toscanite (PT) ;from South America: Taiguati Fm. (TF). DA and DB are two alternative positions considered for the mid-Devonian paleopole position for Gondwana based on different interpretations of these data.

Paleocontinental Consequences

Alternative paleocontinental reconstructions of the Atlantic bordering continents for the middle to late Devonian are shown in Figure 14. The reassembly and paleolatitudinal position for this time interval of the northern continents or Laurussia (Laurentia, Baltica and Armorica) are after Van der Voo (1982) and can be regarded as well known in comparison to the position of the southern continents.

Two positions are shown for the northern margin of Gondwana which illustrate the alternative Devonian pole positions discussed above, DA and DB. The position labelled DA is based on the Msissi pole whereas DB corresponds to the mean pole position of the Housetop Granite, Mulga Downs, and the Gneiguira poles (23°S, 45°E, in African coordinates). It should be emphasized that these alternative Devonian pole positions for Gondwana are not the only possibilities, for example, the early to middle(?) Devonian pole

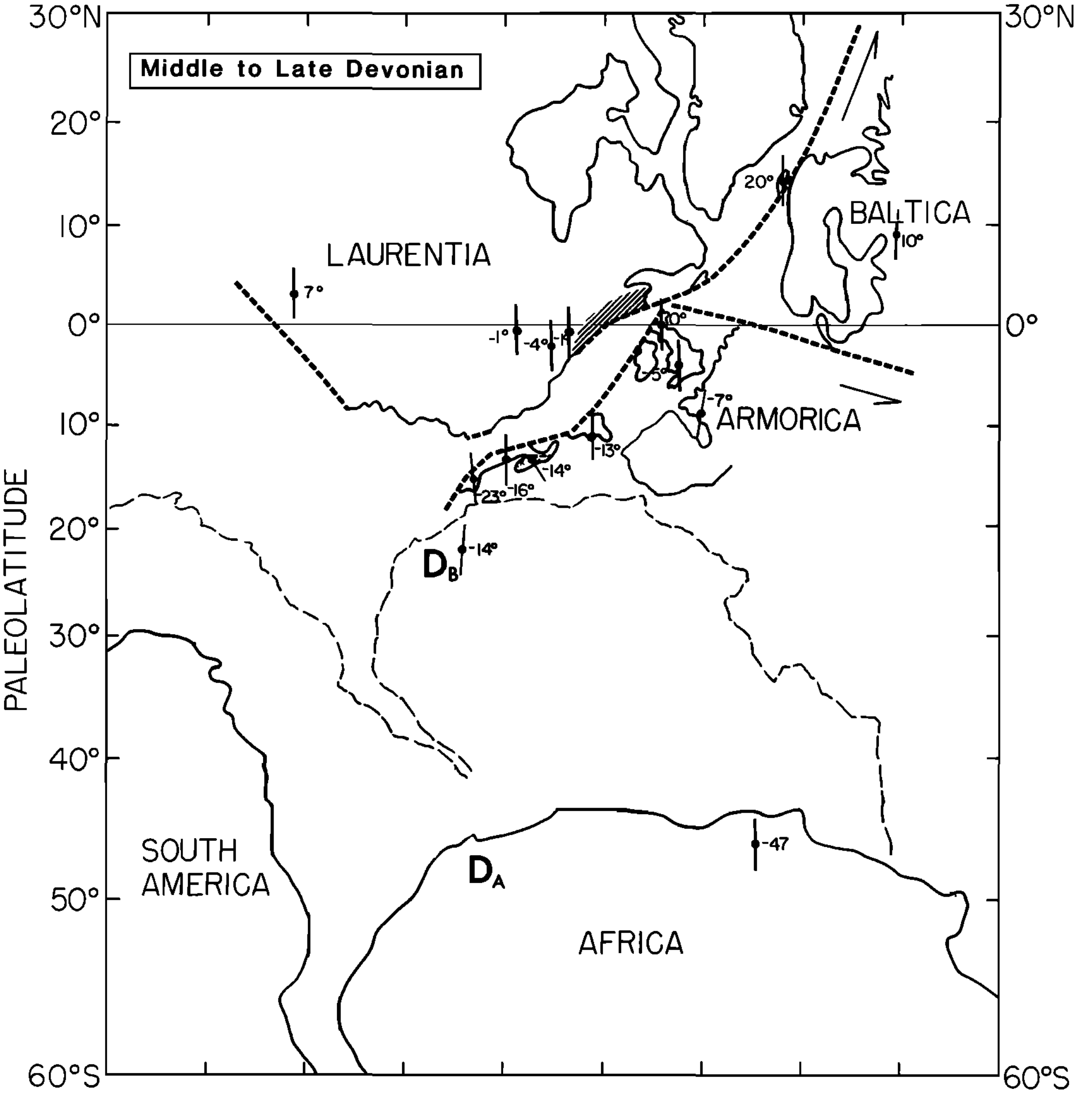

Fig. 14. Paleocontinental reconstruction of Atlantic-bordering continents in the middle to late Devonian on Mercator projection. Reassembly and paleolatitudinal position of northern continents (Laurentia, Baltica and Armorica) after Van der Voo (1982); meridional axis and paleolatitude shown for reported paleomagnetic results compiled in Van der Voo and Scotese (1981). Facing margins of reassembled southern continents shown in two alternate positions, DA and DB, according to different interpretations of the available Devonian paleomagnetic data (see Figure 13 and text). Msissi location and paleomagnetic parameters used to determine postion DA. Star shows sampling locality of Gneiguira with meridional axis and paleolatitude from characteristic direction; the Gneiguira paleopole was averaged with the Housetop and Mulga Downs poles to determine position DB so the paleolatitude determined from the Gneiguira does not exactly correspond to its inferred position on model DB.

positions of Goleby(1981) on the southeastern Australia track are well removed from both DA and DB if applied to Gondwana. Rather, positions DA and DB appear to represent the most likely alternatives for the available African results which are not inconsistent with alternatives for the Australian data.

Position DA has been adopted for the (Late) Devonian of Gondwana in several recent reconstructions (e.g., Irving, 1977; Van der Voo and Scotese, 1981; Kent, 1982) and implies the existence of a wide ocean separating the facing margins of Laurussia and Gondwana (Figure 14). The existence of a broad ocean at this time suggests the model of the southern margin of Laurussia as of Andean type, with northward subduction, responsible for the Acadian orogenic belt without collision (Van der Voo, 1982); progressive closure of this ocean by the end of the Carboniferous eventually resulted in the Alleghanian-Hercynian collisional belts (LeFort and Van der Voo, 1981).

Position DA for the Devonian of Gondwana is also an important basis for the concept of Armorica (Hercynian Europe) as a separate plate for some period in the Paleozoic. Latest Precambrian and Cambrian paleopoles for Armorica and Gondwana are similar, suggesting that these land areas were juxtaposed as they are today and moved in unison (Hagstrum, et al., 1980). The subsequent history of relative movement is unclear because Ordovician and Silurian paleomagnetic data from Gondwana are considered inadequate for a definitive comparison to coeval paleopoles from Armorica (Van der Voo, 1982). However, the wide divergence found between late Devonian poles from Armorica and Gondwana (i.e., the Msissi pole or position DA) has led to the conclusion that the two must have separated by this time (Jones et al., 1979).

Adoption of position DB for the mid to late Devonian of Gondwana dramatically alters the paleocontinental setting outlined above. The northern margin of Gondwana (Africa-South America) would be in much lower paleolatitudes already by the end of the Devonian and any ocean separating the facing Atlantic margins would be very much reduced (Figure 12). A paleomagnetic basis for a separate Armorica plate would also be weakened since its APW path would be compatible with that of Gondwana in the Devonian. Thus Armorica may have remained as a promontory of Africa for much of the Paleozoic.

The Acadian orogenic belt has been suggested to be the result of a collision of Armorica with the already assembled landmass of Laurentia and Baltica (Kent, 1980). In an alternative paleomagnetic model for the assembly of Laurussia (Van der Voo, 1979), Armorica and Laurentia collide earlier to produce the Ordovician Taconic orogeny. For either model, the continued juxtaposition of Armorica and Africa implied by hypothesis DB for the Devonian position of Gondwana means that any ocean separating Laurentia-Baltica and the combined landmass of Armorica-Gondwana would be effectively closed after the major collision, either in the Ordovician (Van der Voo, 1979) or more probably, in view of extensive Silurian and Lower Devonian marine deposits in eastern North America and recently reported paleomagnetic data from Armorica (Perroud et al., 1983), in the Devonian (Kent, 1980). The collision, which culminated in the Hercynian-Alleghanian movements, might indeed have been a very long-lasting process, longer than originally envisaged by LeFort and Van der Voo (1981) but perhaps still compatible with the indentation model they suggested in analogy with the prolonged effects of the impact of India with Asia which is thought to account for the Himalaya mountain chain (Molnar and Tapponnier, 1978; Tapponnier et al., 1982).

Even if the Gneiguira is regarded as remagnetized (and the paleopoles from the Housetop and Mulga Downs are also considered remagnetized or invalid for all of Gondwana), there seems to be a consensus that the paleomagnetic pole for Gondwana was in the vicinity of southern Africa no later than the early (pre-Kiaman) Carboniferous. This is indicated in particular by Carboniferous paleopole positions (Figure 13) from the Dwyka of Africa (McElhinny and Opdyke, 1968), the Lower Kutting volcanics and the Patterson toscanite of Australia (Irving, 1966), and the Taiguati Formation of South America (Creer, 1970), which all include normal polarity directions. Since the northern continents were in approximately the same paleolatitudinal position in the early Carboniferous as in the mid to late Devonian, any ocean separating them from the facing margin of Gondwana must have been already effectively closed in the very early stages of, if not prior to, the Alleghanian/Hercynian orogeny. Associating the closure of this ocean with the Acadian/late Caledonian orogeny in the Devonian (hypothesis DB) seems logical but of course needs to be verified.

Considering the ramifications of the Devonian paleopole position for Gondwana, additional paleomagnetic data are desperately needed. The high internal consistency and stability of the Gneiguira characteristic magnetization, combined with the location of the rock unit on a stable shield area of Africa, suggest that the paleopole obtained provides a good constraint for the APW of western Gondwana for some period in the middle to late Paleozoic. However, the absence of independent evidence to constrain the age of this magnetization seriously compromises its usefulness in an objective assessment of Devonian paleomagnetic data; the problem is compounded by a similar lack of constraint for almost all other mid-Paleozoic paleomagnetic poles available from Gondwana. An important objective of future work will be to find well-dated rock units that are amenable to a fold or other field test to determine magnetization age.

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