ELLSWORTH-WHITMORE MOUNTAINS CRUSTAL BLOCK, WESTERN ANTARCTICA: NEW PALEOMAGNETIC RESULTS AND THEIR TECTONIC SIGNIFICANCE

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Abstract. Preliminary paleomagnetic study of granitic and sedimentary rocks from the Ellsworth-Whitmore Mountains crustal block (EWM), West Antarctica, leads to the following conclusions: (1) The EWM has a paleopole for the Middle Jurassic located at 235°E, 41°S, (α_{95} = 5.3, N = 8 sites) assuming that no widespread regional tilting has occurred since the magnetization measured was acquired. A Middle Jurassic paleolatitude of 47°S is indicated for the sites and precludes an original location for the EWM block south of the Antarctic Peninsula crustal block (AP). (2) This pole is not significantly different from the previously published Middle Jurassic paleopole obtained from rocks of the northern Antarctic Peninsula. The combined AP-EWM paleopole, compared to the Middle Jurassic mean paleopole obtained from igneous rocks of the Ferrar Supergroup in East Antarctica, suggests about 15° tectonic clockwise rotation of the AP and EWM. Since the AP and EWM poles coincide, these two crustal blocks may have moved as one unit since the Middle Jurassic. (3) The new data are compatible with two different Gondwanaland reconstructions. The first considers the AP and EWM as separate entities. The second is based on the movement of the AP and EWM as one block. For the Middle Jurassic, both reconstructions would locate the EWM west of Coats Land and south of the Falkland Plateau, with the adjacent AP located south of southernmost South America. (4) Enigmas concerning the structural trend and isolation of the thick Ellsworth Mountains Paleozoic succession persist.

West Antarctica and the Pacific Margin of Gondwanaland

West Antarctica and New Zealand are the most difficult parts of Gondwanaland to reconstruct. This is partly due to the extensive tectonism that occurred along the margin of the Pacific Ocean during and since fragmentation of the supercontinent. It is also partly a result of the extensive ice cover in Antarctica. Yet, as has been pointed out elsewhere, the tectonic evolution of this region has important implications for understanding of global plate interaction, paleoclimate, and paleobiogeography. It was with this in mind that the joint U.K.-U.S. West Antarctic Tectonics Project was initiated [Dalziel and Pankhurst, this volume]. Paleomagnetic studies are clearly an essential part of such a project, especially in the light of evidence that some geologic terranes bordering the Pacific Ocean have been displaced large distances [Coney et al., 1980; Van der Voo et al., 1980; Stone et al., 1982]. Existing paleomagnetic data suggest that the four major crustal blocks of West Antarctica (Figure 1) have been in close proximity to the East Antarctic craton at least since the Late Jurassic to Early Cretaceous (for review see Dalziel and Grunow [1985]). The data base is not extensive, however, and there are indications from "overlap" in Gondwanaland reconstructions, from geologic correlation, and from some of the paleomagnetic results, that limited relative motion of these blocks and of East Antarctica has occurred (for review see Dalziel and Elliot [1982]). Radiometric ages of approximately 175 Ma reported from granites in nunataks south of the Ellsworth Mountains [Craddock, 1983] gave cause for optimism that paleomagnetic poles might be obtained for a critical time period prior to Gondwanaland breakup. At this time (Middle Jurassic [Kent and Gradstein, 1985]), Antarctica was in a middle latitude position, and hence subsequent rotations should be resolved more readily than with poles for the Cretaceous and Tertiary when Antarctica was at a very high latitude [Norton and Sclater, 1979; Delisle, 1983].

During the 1983-1984 and 1984-1985 field seasons, therefore, two of us (A.M.G. and I.W.D.D.) made extensive collections for paleomagnetic studies in the Ellsworth-Whitmore Mountains crustal block (EWM), the adjoining Thiel Mountains (part of the Transantarctic Mountains) (Figure 2), and the Thurston Island-Eights Coast crustal block (Figure 1). The collection sites were chosen on the basis of the field observations described by Storey and Dalziel [this volume]. The samples were studied in the paleomagnetic laboratory at Lamont-Doherty Geological Observatory by A.M.G. and D.V.K. Radiometric age control for the study is provided by the work of Millar and Pankhurst [this volume]. Although few of the exposed rocks are ideal for paleomagnetic study, primarily due

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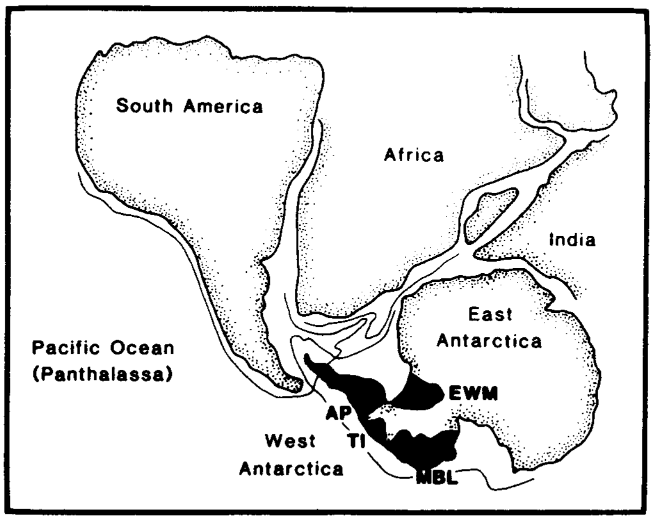

Fig. 1. Gondwanaland reconstruction of Norton and Sclater [1979]. West Antarctic microcontinents [from Dalziel and Elliot, 1982]: AP, Antarctic Peninsula crustal block; EWM, Ellsworth-Whitmore Mountains crustal block; MBL, Marie Byrd Land crustal block; and TI, Thurston Island-Eights Coast crustal block.

to the absence of paleohorizontal markers, some of the results already obtained from our first season's collecting in the EWM do provide new insights into the tectonic evolution of West Antarctica and hence of the Pacific margin of Gondwanaland. It is therefore appropriate to present here a summary of these results and our joint interpretation of them.

Ellsworth-Whitmore Mountains Crustal Block

The geology of the Ellsworth-Whitmore Mountains crustal Block is summarized in the paper by Storey and Dalziel [this volume]. The thick Paleozoic sedimentary sequence of the Ellsworth Mountains is comparable to the Gondwana craton cover exposed along the Transantarctic Mountains and the southern coast of Africa. Especially notable is the occurrence of upper Paleozoic glacial deposits, the Whiteout Conglomerate, and *Glossopteris*-bearing Permian strata, the Polarstar Formation [Craddock, 1969]. Together with the isolation of the mountains and their anomalous north-south structural grain, this stratigraphic comparison led Schopf [1969] to propose that the crustal block containing the Ellsworth Mountains has been displaced from an original location along the eastern margin of the Weddell Sea between the Transantarctic Mountains and the Cape Mountains of southern Africa.

The geology of the Ellsworth Mountains themselves has been recently (1979-1980) studied by a large group of scientists and is to be described in a forthcoming memoir [Craddock et al., 1986]. A paleomagnetic project was part of this effort. Preliminary results have been described by Watts and Bramall [1981]. They interpreted the data as being compatible with a 90° counterclockwise rotation of the Ellsworth Mountains relative to the East Antarctic craton since deposition of the Cambrian strata they studied. The detailed results of their extensive collecting have yet to be published. We therefore confined our work in the Ellsworth Mountains to collecting from the Permian Polarstar Formation that was not visited by Watts and Bramall.

With the exception of the Stewart Hills we collected material from all other isolated nunataks or groups of nunataks in the EWM (Figure 2). The highly deformed metasedimentary strata of the Stewart Hills were judged to be unsuitable for paleomagnetic study. This part of the collection comprises Ellsworth Mountains, Permian sedimentary rocks; Haag Nunataks, Precambrian gneiss and minor intrusions; Hart Hills, undated gabbro (hand specimens only); Martin Hills, undated metasedimentary rocks; Moreland Nunatak, undated sedimentary strata; Mount Johns, undated sedimentary strata; Mount Moore, deformed metasedimentary rocks (hand specimens only); Mount Woollard, undated gneiss, amphibolite, and pegmatites; Nash Hills, Middle Ju-

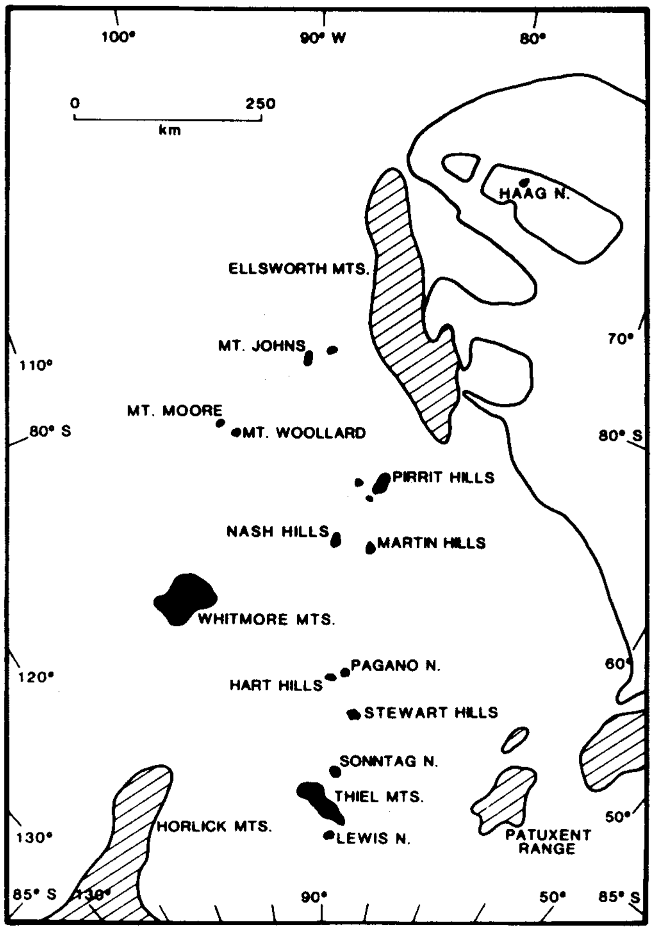

Fig. 2. Map showing sample localities in the Ellsworth-Whitmore Mountains crustal block.

rassic granite, aplite, and undated metasedimentary rocks; Pagano Nunatak, Middle Jurassic granite and aplites; Pirrit Hills, Middle Jurassic granitic rocks, aplites, and undated metasedimentary rocks; Whitmore Mountains, Early to Middle Jurassic granitic plutons, aplites, and undated metasedimentary rocks.

It should be noted that we include here the Precambrian rocks of Haag Nunataks within the EWM, although the nature of the basement in the latter region is indeterminate [Garrett et al., this volume]; see also Dalziel et al. [this volume].

Sampling and analytical procedures. A total of 480 oriented drill core samples and 24 oriented hand samples were collected from 101 sites at 12 locations in the EWM. Usually, six cores were taken at each site. At least one sun compass reading was made at each locality; the sun compass readings agreed to within 3° of magnetic readings.

Measurements of the natural remanant magnetization (NRM) of the samples were made using a cryogenic magnetometer. Pilot samples from most sites were progressively demagnetized using alternating field (AF) and/or thermal demagnetization. AF demagnetization was normally done in steps of 10 mT up to a peak of 90 mT, while in thermal demagnetization, steps of 100°C up to a temperature of 500°C were used. Beyond 500°C, smaller steps were taken up to a maximum temperature of 670°C.

Vector end-point diagrams were used to plot the information obtained from demagnetizing the pilot samples. After analysis of these diagrams, effort was concentrated on the remaining cores from the most promising and/or critical localities. All samples from the selected localities were measured with a minimum of 10 thermal or seven AF demagnetization steps and plotted on vector end-point diagrams. The component directions were calculated using linear regression analysis [Kirschvink, 1980].

Paleomagnetic results. The turbidites of the Permian Polarstar Formation of the northern Sentinel Range of the Ellsworth Mountains, although potentially critical tectonically, proved to be unsuitable for paleomagnetic study. Neither thermal nor AF demagnetization could define a consistent direction between seven sites around a fold. The samples were fairly weak, with NRM intensities between 10^{-3} and 10^{-4} A m^{-1}, and only AF demagnetization defined any type of linear trajectory. The median demagnetization field was 40 mT. Adding the bedding correction to the results did not improve the grouping of directions. The Pirrit Hills and Whitmore Mountains granites and aplites, and the Mount Woollard metamorphic rocks, proved to be magnetically unstable in that convincingly linear demagnetization trajectories were not found. The aplites from all localities were found without exception to be very weak or magnetically unstable. Studies of the Haag Nunataks, Hart Hills, Martin Hills, Moreland Nunatak, Mount Johns, and Mount Moore samples have not been completed.

Granite, aplite, and calcareous siltstone were sampled from 12 sites in the Nash Hills. The granite pluton has yielded an Rb-Sr whole-rock isochron indicating an age of 175 ± 8 Ma [Millar and Pankhurst, this volume]. The sedimentary rocks are hornfelsed and appear to be roof pendants in the granite body. Granite samples from two sites in the Nash Hills were demagnetized using AF. A single component of magnetization with a downward dipping direction to the northwest was found (Figures 3a and 4). In addition, hornfelsed calcareous red siltstone from two sites was seen to be partially magnetically overprinted by the intrusion of the granite. This overprint magnetization has a directly antiparallel direction (upward dipping to the southeast) to that of the Nash Hills granite (Figure 3b). AF demagnetization defined this secondary direction more clearly than thermal demagnetization (Figures 3c and 4). The fine-grained granite at the contact with the sedimentary country rocks at Nash Hills tended to give upward dipping directions to the southeast, but with poorly defined linear demagnetization trajectories. It seems that the chilling at the margin of the granite and the baking of the adjacent sedimentary rocks occurred during a normal polarity interval, while the main coarse-grained body of the granite intrusive recorded a later reversed polarity interval.

The magnetically overprinted metasedimentary rocks in the Nash Hills also contained a more thermally stable component of magnetization (560° to 670°) (Figures 3c and 4). These red siltstones (strike 340°, dip 45°NE) yield mean directions of D = 14.8°, I = 29.2°, α_{95} = 7.9°, and n = 12 samples resulting in a the paleomagnetic pole at 285°E, 8°S, dp, dm = 4.8°, 8.7°. After tilt corrections the directions are D = 21.2°, I = 0.8°, α_{95} = 8.4°, n = 12 samples and the paleomagnetic pole is located at 292°E, 7°N, dp, dm = 4.2°, 8.4°.

At Pagano Nunatak, four sites in coarse granite and four sites in aplitic dikes were collected. The granite yielded an Rb-Sr whole-rock isochron with an age of 175 ± 8 Ma (Middle Jurassic), virtually identical to the Nash Hills granite [Millar and Pankhurst, this volume]. The four granite sites were thermally demagnetized to reveal a single very high blocking temperature component (at 580°C) with an upward dipping direction to the southeast (Figures 3d and 4). Pagano Nunatak directions are very similar to those of the hornfelsed sedimentary rocks from the Nash Hills.

The sample mean characteristic directions for the Nash Hills and Pagano Nunatak are shown in Figure 5. Samples were combined to give a site mean, and site means combined to give a unit mean. The site mean characteristic directions of the Nash Hills samples (N = 4 sites) give a unit mean of D = 137.6°, I = -64°, K = 182.5, and α_{95} = 6.8° after inverting the directions of the two granite sites (Figure 4). This corresponds to a paleomagnetic (south) pole position at 233.1°E, 39.5°S (dp, dm = 8.7°, 10.9°), and a paleolatitude for the locality of 45.7°S. The site mean directions for the Pagano Nunatak samples (N = 4 sites) have a unit mean of D = 141.6°, I = -65.5°, K = 254.6, and α_{95} = 5.8° (Figure 4). The paleomagnetic (south) pole position for Pagano Nunatak is at 237.7°E, 42.6°S (dp, dm = 7.6°, 9.4°), and the paleolatitude of Pagano Nunatak is 47.6°S.

The results for the combined Nash Hills and Pagano Nunatak site directions converted to vir-

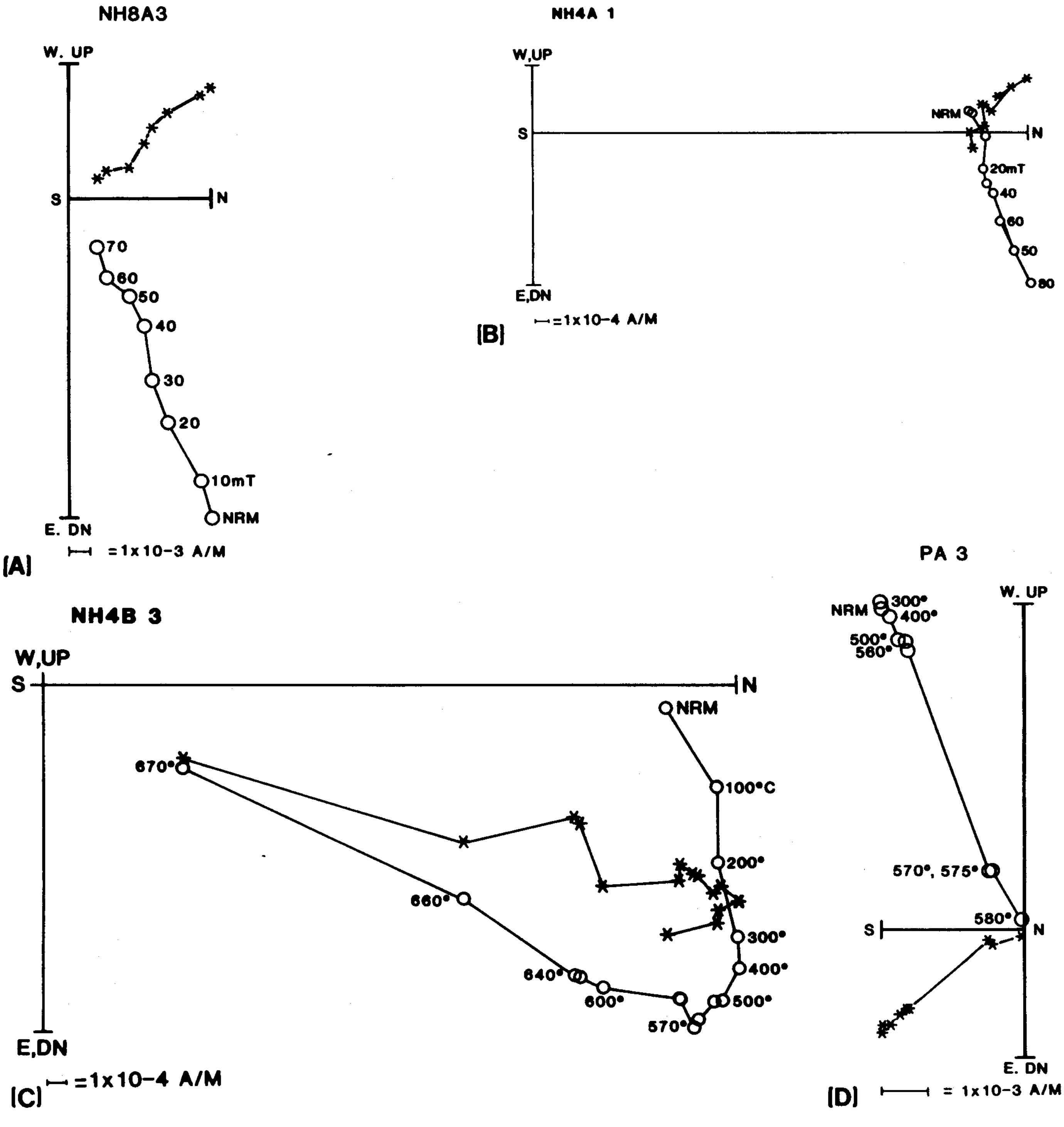

Fig. 3. Orthogonal projection of vector end points [Zijderveld, 1967] showing demagnetization behavior of samples from the Nash Hills and Pagano Nunatak. Open circles (stars) are projections on vertical (horizontal) planes at indicated levels of AF or thermal cleaning. Demagnetization fields in millitesla; temperatures in degrees Celsius. Magnetization units on axes are labeled. (a) Nash Hills granite. (b) Nash Hills baked metasediment using AF demagnetization. (c) Nash Hills baked metasediment thermally demagnetized. (d) Pagano Nunatak granite.

1. Nash Hills (81° 53'S, 89° 23'W)

Site	N/n	Lithology	Polarity	Treatment	Decl.	Incl.	K	α95	Lat.	Long.
NH1A	3/12	Granite and Metasedimentary Rock	N	AF	-	-	Unstable	-	-	-
NH1B	2/8	Granite and Metasedimentary Rock	Mixed	AF	-	-	Unstable	-	-	-
NH1C	6/6	Aplite	N	AF, TH	-	-	Unstable	-	-	-
NH1D	1/7	Granite	N	AF	-	-	Unstable	-	-	-
NH3A	6/7	Granite	R	AF	307.6	67	194.3	4.8	-44.4	224.8
NH3B	2/6	Aplite	N	AF	-	-	Unstable	-	-	-
NH3C	3/8	Aplite	N	AF	-	-	Unstable	-	-	-
NH3D	1/6	Dike	R	AF	-	-	Unstable	-	-	-
NH4A	3/6 6/6	Metasedimentary Rock Overprint (Thermal component)	N	AF, TH TH	143.6 3.9; 11.2(T)	-62.9 28.8; 9.8(T)	651.4 28.6; 94(T)	4.8 12.7; 6.9(T)	-37.6 -7.3; 3(T)	238.2 274.5; 281.8(T)
NH4B	3/6 6/6	Metasedimentary Rock Overprint (Thermal component)	N	AF, TH TH	143.6 25.3; 31(T)	-68.4 28.7;-8.2(T)	599.7 219.7;219.5(T)	5 4.5; 4.5(T)	-44.9 -7.9; 11.1(T)	239.3 295.2; 302.2(T)
NH8A	5/6	Granite	R	AF	315.8	57.1	171.2	5.9	-31.7	230.2
NH8B	1/6	Aplite	R	AF	-	-	Unstable	-	-	-

Unit mean 4/12 sites (17/25 samples, omitting unstable sites) for the Middle Jurassic:

D = 137.6° I = -64° K = 182.5 α_{95} = 6.8°

Pole position: 39.5° S lat., 233.1° E long., dp, dm = 8.7°, 10.9°

2. Pagano Nunatak (83° 42' S, 87° 40' W)

Site	N/n	Lithology	Polarity	Treatment	Decl.	Incl.	K	α95	Lat.	Long.
PA	4/5	Granite	N	TH	132.9	-67.9	76.6	10.6	-46.5	230.3
PB	5/5	Granite	N	TH	137.2	-62.8	65.6	9.5	-39.4	233.2
PC	2/6	Aplite	-	AF, TH	-	-	Unstable	-	-	-
PD	2/6	Aplite	-	AF, TH	-	-	Unstable	-	-	-
PE	2/6	Aplite	-	AF, TH	-	-	Unstable	-	-	-
PF	6/6	Granite	N	TH	155.4	-62.7	60.7	8.7	-38.4	249.9
PG	2/6	Aplite	-	AF, TH	-	-	Unstable	-	-	-
PH	5/6	Granite	N	TH	139.1	-67.5	85.3	8.3	-45.4	235.8

Unit mean 4/8 sites (20/22 samples, omitting unstable sites):

D = 141.6° I = -65.5° K = 254.6 α_{95} = 5.8°

Pole position: 42.6° S lat., 237.7° E long., dp, dm = 7.6°, 9.4°

COMBINED NASH HILLS-PAGANO NUNATAK POLE POSITION: 41.2° S lat., 235.2°E long., A_{95} = 5.3°, N = 8 sites

Notes: N/n = number of samples used in mean calculation/total number of samples; Treatment = demagnetization technique used; AF, alternating field and TH, thermal; K = estimate of precision parameter; α_{95} = radius of circle of 95% confidence; dp and dm are the semi-axes of the oval of 95% confidence; A_{95} = radius of circle of 95% confidence for mean poleposition; T = tilt corrected

Fig. 4. Site mean characteristic directions of the Nash Hills and Pagano Nunatak.

tual geomagnetic poles define a mean pole at 235.2°E, 41.2°S (α_{95} = 5.3°) (Figure 4). No tilt correction has been applied given the lack of any paleohorizontal marker. This will be discussed below.

Comparison with other results. Numerous paleomagnetic studies have been undertaken on igneous rocks of the Ferrar Supergroup in the Transantarctic Mountains. The Ferrar Supergroup comprises the Ferrar diabase sills and dikes, the Kirkpatrick basaltic lava flows, and the Dufek layered mafic igneous complex. Many of the results are of questionable validity, however, due to insufficient sampling, inadequate cleaning procedures,

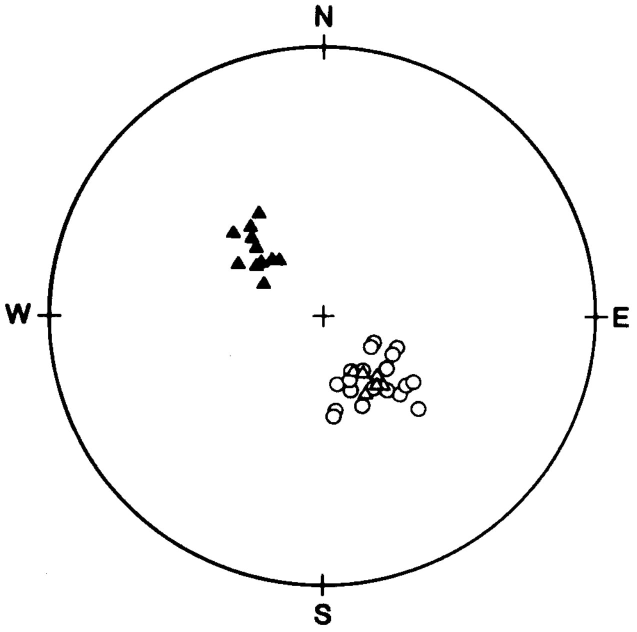

Fig. 5. Distribution of characteristic cleaned-sample directions from the Nash Hills and Pagano Nunatak. Solid (open) symbols are on lower (upper) hemisphere of equal-area projection. Circles (triangles) are samples from Pagano Nunatak granite (Nash Hills granite and baked metasediment). Ten samples rejected from 47 samples.

and incompletely published data. Nevertheless, the published poles from 15 localities along the entire length of the Transantarctic Mountains define a mean pole at 220.3°E, 54.8°S, α_{95} = 3.9° (Table 1). McIntosh et al. [1982] earlier calculated essentially the same mean pole (220°E, 55°S) from 11 localities. Individually, however, the locality poles range between 207.6°E and 231°E longitude and between 44°S and 68.6°S latitude. It is not clear whether this reflects secular variation, contaminated magnetizations, or unrecognized tectonic disturbances. Ages for the Ferrar igneous rocks based on K/Ar and Ar/Ar analyses range primarily between 160 Ma and 180 Ma [Elliot et al., 1985]. Kyle et al. [1981] believe that the main Ferrar activity was around 179 ± 7 Ma but that there may have been a younger magmatic event at 165 ± 2 Ma based on Ar/Ar analysis. Different ages of intrusion may also contribute to the scatter in the published Ferrar paleomagnetic results.

The only Early to Middle Jurassic pole from West Antarctica published prior to this study is one by Longshaw and Griffiths [1983]. They sampled acid to basic dikes and a granodiorite pluton dated by the Rb-Sr method at approximately 175 Ma and lava flows dated at approximately 175 Ma (R. J. Pankhurst, personal communication, 1985) in Graham Land, the northern part of the Antarctic Peninsula. They determined a mean paleopole at 238°E, 48°S, α_{95} = 9.5°, and N = 4 localities.

TABLE 1. Middle Jurassic South Pole Positions for East Antarctica

	n/N	Cleaning Technique	Polarity	Pole Longitude °E	Pole Latitude °S	Reference
Allan Hills	19/2	AF	N	226.8	47	Funaki [1983]
Beardmore Glacier	13/9	AF	N	221	59	Briden and Oliver [1963]
Brimstone Peak	29/12	AF	N	218	56	Cherry and Noltimier [1982]
Dufek Massif	98/-	AF	N&R	223	60	Beck et al. [1979]
Ferrar Glacier	57/5	NRM	N	218	58	Trunbull [1959]
Gorgon Peak	26/13	AF	N	230	56	Cherry and Noltimier [1982]
Mesa Ragne	60/15	AF	N	210	64	McIntosh et al. [1982]
Mount Falla	84/14	AF	N	222.6	53.8	Ostrander [1971]
Mount Fleming dike	15/1	AF	N	220.5	68.6	Funaki [1983]
Queen Alexandra Range (sills)	42/7	AF	N	220.2	54.2	Ostrander [1971]
Storm Peak	72/12	AF	N	231.5	44.1	Ostrander [1971]
Theron Mountains	8/8	NRM	N&R	224	54	Blundell and Stevenson [1959]
Wright Valley	26/1	AF	N	208	45.3	Funaki [1983]
Wright and Victoria valleys	83/46	AF	N	220	45	Bull et al. [1962]
Vestfjella dikes	109/24	AF/TH	N&R	207.6	54	Lovlie [1979]
Mean (A_{95} = 3.9; 15 studies)				220.3	54.8	

Notes: n, number of samples; N, number of sites; AF, alternating field demagnetization; TH, thermal demagnetization; A_{95}, radius of circle of 95% confidence for mean paleopole.

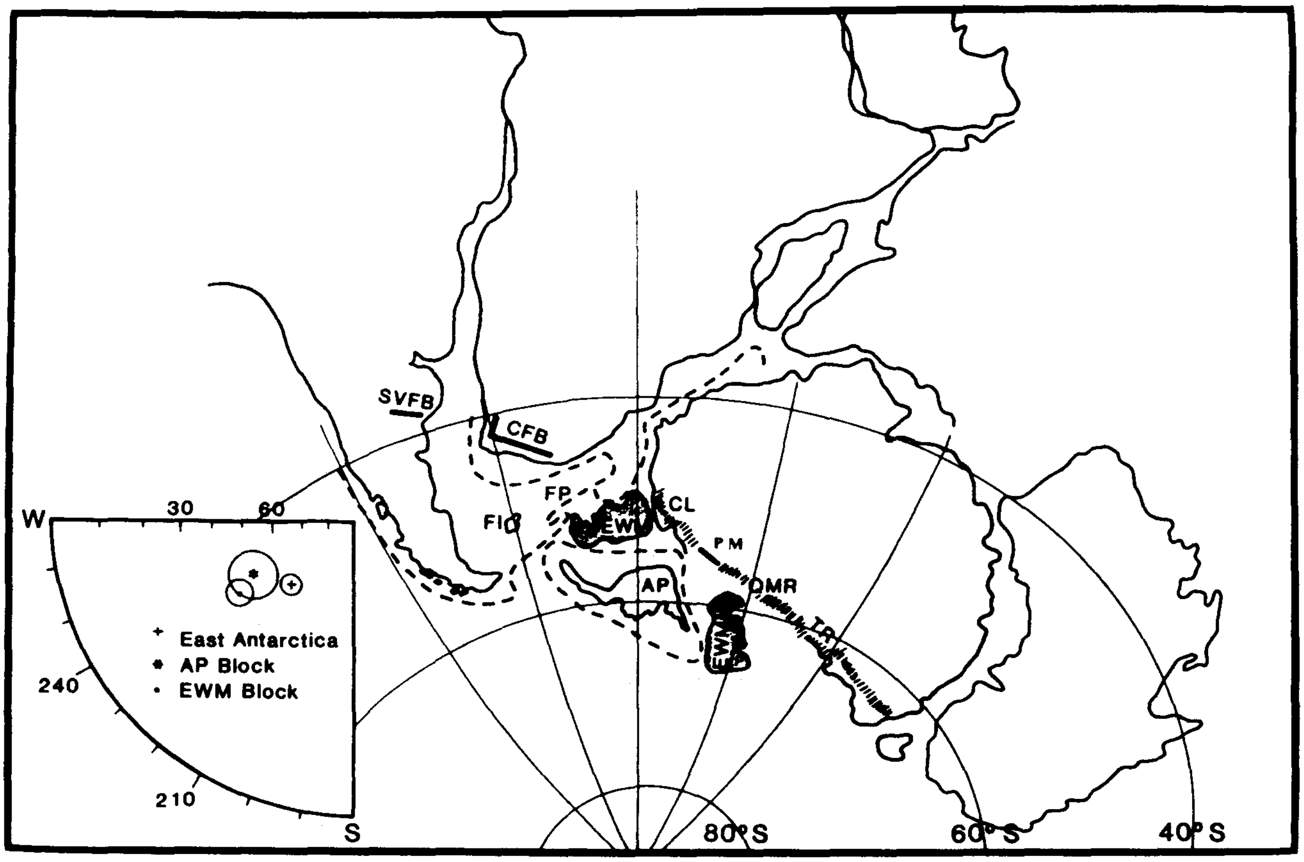

Fig. 6. A separate Ellsworth-Whitmore Mountains crustal block (EWM) located north of the Antarctic Peninsula crustal block (AP) using Norton and Sclater's [1979] reconstruction for the other Gondwanaland continents in the Early to Middle Jurassic. Thick solid lines indicate structural trends; hatched areas indicate outcrops of flat-lying Gondwana sequence cover rocks in Transantarctic Mountains. Note that the position of the EWM south of the AP [Longshaw and Griffiths, 1983] places the sample localities (P) 18° farther south than the data indicate. The equal-angle stereographic projection shows the EWM pole (small solid circle), the AP pole (star) and the East Antarctic (Ferrar) pole (plus) for the Middle Jurassic with their associated circles of 95% confidence. A 17° ± 9° counterclockwise rotation would restore the EWM pole to the Ferrar pole; a 15° counterclockwise rotation would restore the AP pole to the Ferrar pole [Longshaw and Griffiths, 1983]. PM is Pensacola Mountains; CFB, Cape Fold Belt; CL, Coats Land; FI, Falkland Islands; FP, Falkland Plateau; P, Pagano Nunatak; QMR, Queen Maud Range; SVFB, Sierra de la Ventana Fold Belt; TR, Transantarctic Range; large solid circles, Haag Nunataks; dashed lines, edges of continental shelf or inferred margin of continental block.

Longshaw and Griffiths did not apply a tilt correction to their results, as they did not have any paleohorizontal markers. Their interpretation of the findings is that an approximate 15° counterclockwise rotation about a pole at 0°E, 65°S would restore the Antarctic Peninsula to its Middle Jurassic position with respect to East Antarctica. This rotation would align their northern Antarctic Peninsula pole and the East Antarctic (Ferrar Supergroup) poles for that period of time. Longshaw and Griffiths separate the EWM from the Antarctic Peninsula crustal block (AP) and suggest a Jurassic position for the EWM that is consistent with the interpretation of Watts and Bramall [1981]. However, they move the southern part of the EWM to the west so that the Haag Nunataks are near the East Antarctic craton and the Ellsworth Mountains parallel to the Queen Maud Mountains of the Transantarctic Range (see Figure 6).

Tectonic Interpretation

Before discussing in detail the tectonic interpretation of our results, the validity of the findings must be considered because of the lack of a paleohorizontal marker. Pagano Nunatak and the

TABLE 2. Mean Middle Jurassic Paleomagnetic South Pole Positions for East and West Antarctica

	Age	Pole Longitude °E	Pole Latitude °E	A95	Reference
Antarctic Peninsula (intrusives)	175	238	48	9.5	Longshaw and Griffiths [1983]
EWM Block (intrusives and overprinted metasedimentary rocks)	175	232.2	41.2	5.3	this study
Mean AP-EWM		237	45.8	6.4	this study
East Antarctica (intrusives and extrusives)	160-180	220.3	54.8	3.9	this study

Nash Hills are located approximately 200 km apart in a north-south direction and yield the same paleomagnetic pole. Radio ice-echo sounding and aeromagnetic data indicate that the main topographic and magnetic fabric of the bedrock in this region is approximately east-west [Dalziel et al., this volume]. This fabric appears to be controlled by horsts and grabens. A depression known as the Thiel Trough extends across the EWM separating Pagano Nunatak from the Nash Hills. It is therefore unlikely that Pagano Nunatak and the Nash Hills are located on the same fault block. Yet they do yield the same paleomagnetic pole. A tilt correction of 11°S about an axis of 84°E would restore the EWM pole to the mean Ferrar pole, and an 8°S tilt correction about an axis of 91°E would restore the Antarctic Peninsula pole of Longshaw and Griffiths [1983] to the Ferrar pole. Fault blocks would therefore need to have tilted approximately the same amount and direction over a large region (the Antarctic Peninsula localities are 1500 km from the Nash Hills) to explain the coincidence of Antarctic Peninsula, Pagano Nunatak, and Nash Hills poles. This possibility certainly exists, but seems unlikely. Moreover, no regional tilting is apparent in the structural fabric of the Ellsworth domain [Storey and Dalziel, this volume]. The north to northwest trending hinge lines of upright folds in the Paleozoic succession are for the most part subhorizontal.

Proceeding, therefore, under the assumption that no tilt correction is warranted and that sufficient time is represented to average secular variation, since both normal and reversed intervals are present in the rocks (i.e., the Nash Hills and Pagano Nunatak directions are representative of the Middle Jurassic field), it now remains to determine a reasonable tectonic reconstruction consistent with the paleomagnetic, geologic, and space constraints.

We first note that the Middle Jurassic poles from the AP and the EWM are not statistically different, i.e., angular separation is under 7°, less than the α_{95} of 9.5° for the AP pole. We can therefore combine the individual locality mean poles from the AP and the EWM and calculate an overall West Antarctic Middle Jurassic pole at 237°E, 45.8°S, α_{95} = 6.4°, and N = 6 localities. Since both the AP and EWM poles differ from the Ferrar pole, it is not surprising that the combined West Antarctic pole also differs significantly from that of the Ferrar (Table 2). There is no discrepancy between the predicted and observed paleolatitude for the AP (54°S), but there is a 12° discrepancy for the EWM predicted (59°S) versus observed (47°S) paleolatitude. A 15° ± 10° counterclockwise rotation would eliminate the separation of the AP-EWM pole from the Ferrar pole. Within the paleomagnetic constraints, the AP and EWM may therefore have moved as a single or closely related unit since the Middle Jurassic with respect to East Antarctica.

The stratigraphic succession of the Ellsworth Mountains is broadly similar to that of the Gondwana craton cover in the Cape Mountains of southern Africa, the Falkland Islands and the Transantarctic Mountains [Schopf, 1969], and so it seems reasonable to conclude that the EWM should remain near the craton of Gondwanaland. Also, the timing of the Ellsworth Mountains deformation must be syn-Permian or post-Permian, which is the time of the Cape (Gondwanide) Orogeny of du Toit [1937].

Space constraints related to paleolatitudes depend on the choice of Gondwanaland reconstruction. We select the Norton and Sclater [1979] reconstruction because of their extensive use of seafloor data and the good agreement of East Antarctic and Australian Early Jurassic paleopoles with this fit [Irving and Irving, 1982]. The Middle Jurassic East Antarctic south pole used in calculating the mean Gondwanaland pole in the Norton and Sclater reconstruction differs insignificantly (5° of longitude at 55° latitude) from that determined for the Ferrar Supergroup by us from the published data. The paleomagnetically permissible locations for the EWM are (1) west of South America, (2) east of Australia, and (3) between South America, Africa, and East Antarctica.

We dismiss the first two possiblities as unrealistic. An EWM position west of South America would place the Paleozoic Gondwana craton cover succession of the Ellsworth Mountains outboard of a pre-Late Jurassic Pacific margin subduction complex [Dalziel and Forsythe, 1985]. Placing the EWM east of Australia requires a very large displacement and seems incompatible with the seafloor spreading history of the southeastern Pacif-

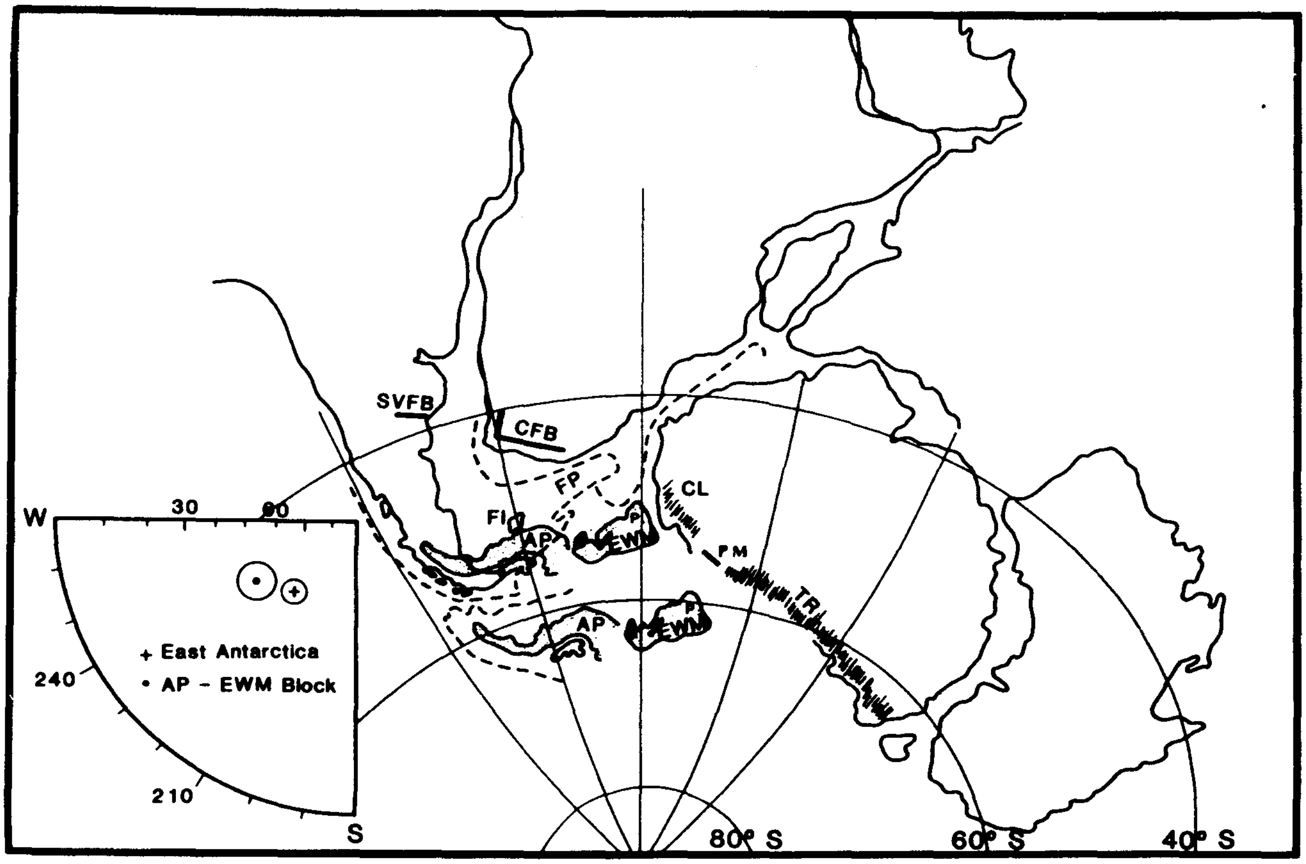

Fig. 7. A combined AP-EWM using Norton and Sclater's [1979] reconstruction of the other continents. The new paleomagnetic data predict the northern position shown for the AP-EWM. This creates an unacceptable overlap in this Gondwanaland reconstruction. Space constraints thus force an AP-EWM to the more southerly position shown on the diagram. This is 9° farther south than expected on the basis of the AP and EWM paleomagnetic results. Modifications in the Gondwanaland reconstruction and removal of the effects of extension in the EWM could eliminate the overlap. The AP-EWM (small solid circle) and East Antarctic (Ferrar) (plus) poles are plotted, with their respective circles of 95% confidence, on the equal angle stereographic projection. A 15° ± 10° counterclockwise rotation would restore the AP-EWM pole to the East Antarctic pole. Thick solid lines indicate structural trends, hatching indicates areas of flat-lying Gondwana-sequence cover rocks. See figure 6 caption for explanation of abbreviations.

ic Ocean and Tasman Sea. The third possibility results in two different tectonic reconstructions for the EWM and AP, which will be discussed below.

Within the constraints of the available paleomagnetic data, it is possible for the AP and EWM block to have moved as separate units. In support of this hypothesis is the occurrence of a major structural break along the Evans Ice Stream between the EWM block and the base of the AP [Doake et al., 1983; Garrett et al., this volume]. The reconstructed position of the AP could be as Longshaw and Griffiths [1983] proposed near the tip of South America (Figure 6). Their placement of the EWM near the Queen Maud Mountains is mainly based on space considerations and predicts an EMW paleolatitude near 65°S. However, our data show it to be near 47°S. An 18° difference in paleolatitude is beyond the errors of the analysis, and we can therefore exclude the Longshaw and Griffiths position for the EMW. Instead, we suggest that if the AP and EWM moved separately, then the AP can be positioned as suggested by Longshaw and Griffiths, but the EWM can be fitted north of the AP, into the space south of Africa, west of Coats Land, which would place the EWM at the required paleolatitude of about 47°S (Figure 6).

The alternative reconstruction, as previously mentioned, would be to keep the AP and EWM as one unit, since their poles are not significantly different. There may have been little movement of the AP relative to the EWM across the Evans Ice Stream since the Middle Jurassic. By strictly observing the rotation and paleolatitude constraints, we find that the AP overlaps southernmost South America on the Norton and Sclater [1979] reconstruction (Figure 7). The EWM is located east of the Antarctic Peninsula, south of Africa, and west of Coats Land. We can avoid gross overlap by using the outside limits of error of our paleomagnetic data and the mean Gondwanaland reference pole of Norton and Sclater [1979]; the EWM would then be near 56°S instead of our mean value of 47°S (Figure 7).

The large amount of overlap between the AP and South America shown in Figure 6 could be caused by several factors: the cumulative errors of our pole determination and the reference poles, minor motion along the East Gondwanaland-West Gondwanaland boundary, extension in South America [Gust et al., 1985] and in the AP-EWM [Garrett et al., this volume], and finally, very minor motion between the AP and EWM, i.e., not paleomagnetically discernible.

Discussion

We conclude that there are two possible reconstructions. If one takes the Norton and Sclater [1979] reconstruction and AP-EWM poles at face value, then there is no room for a combined AP-EWM because the AP would overlap with South America at 55°S in the Middle Jurassic. A separate EWM could fit in the space south of the Falkland Plateau and west of Coats Land (Figure 6). Alternatively, if the Norton and Sclater [1979] reconstruction and/or paleolatitudinal placement is modified slightly, then a combined AP-EWM, especially with the effects of extension removed, might be permissible (Figure 7). We emphasize that the position of the EWM is very similar in both of these models; we just cannot distinguish between these two reconstructions until the uncertainties in reference poles, seafloor geophysical data, and amounts of extension and tilting are better resolved.

Neither of these models disagrees with the results of Watts and Bramall [1981] if normal polarity is assumed for their Late Cambrian data. They noted that about a 30° counterclockwise rotation would then align their Ellsworth Mountains Late Cambrian pole with the early Paleozoic Gondwanaland polar wander path. If that is the case, then little rotation of the EWM from the Late Cambrian to the Middle Jurassic would be indicated. If their assumption of reversed polarity is correct, then over 100° of counterclockwise rotation would be needed between the Late Cambrian and the Middle Jurassic. It is interesting to note that our mean Nash Hills pole from the tilt-corrected thermal component of the red siltstones (292°E, 7.2°N) is virtually indistinguishable from the pole determined by Watts and Bramall [1981] in the Ellsworth Mountains (296°E, 4°N), 300 km north of the Nash Hills. If these rocks are of similar age to the Watts and Bramall samples (Late Cambrian), it would suggest that there has not been significant rotation between the Ellsworth Mountains and the Nash Hills.

The enigmas remain, then, of why the Ellsworth Mountains structural trend is at a high angle to the Cape Fold Belt-Transantarctic Mountains trends (Figures 6 and 7) and of why the thick Paleozoic succession of the Ellsworth Mountains dies out Pacificward (northward in present coordinates). The structural trends may not need to be aligned. Basement control seems likely, for example, in the case of the rocks on the Falkland Islands that change abruptly from east-west to northeast-southwest along the line of Falkland Sound [Greenway, 1972]. At present, however, there does not seem to be an obvious explanation for the "disappearance" of the thick (>10 km [Craddock, 1969]) Ellsworth Mountains succession along strike toward the Pacific.

Acknowledgments. We are grateful to our colleagues in the U.K.-U.S. West Antarctic Tectonics Project for their advice and criticism. Logistic support was provided jointly by the British Antarctic Survey (Natural Environment Research Council) and the Division of Polar Programs, National Science Foundation, Washington, D. C. (grant 82-13798 to I.W.D.D.). The efforts of the Air Unit of BAS and the Antarctic Development Squadron (VXE6) of the U.S. Navy were invaluable.

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