Early Cretaceous paleomagnetic results from Marie Byrd Land, West Antarctica: Implications for the Weddellia collage of crustal blocks

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Abstract. A new ~117 Ma paleomagnetic pole has been defined from the study of volcanic and plutonic rocks from the eastern portion Marie Byrd Land (MBL). The new pole (185.6°E / 56.8°S, A_{95} = 8.7°) implies that the eastern portion of MBL was an integral part of Weddellia, which included the ancestral Antarctic Peninsula, Thurston Island, and Ellsworth-Whitmore Mountains blocks of West Antarctica. This pole is generally similar to a ~125 Ma pole from Thurston Island. Both poles call for major clockwise rotation and poleward motion of eastern MBL and Thurston Island between the Early Cretaceous (125-117 Ma) and the mid-Cretaceous (110-100 Ma). We propose that in the Early Cretaceous, eastern MBL and the Eastern Province of New Zealand were part of a continuous active Pacific margin of Gondwana, connecting with the Antarctic Peninsula, and distinct from western MBL, the Western Province of New Zealand, and North Victoria Land. These western terranes are thought to have accreted to Gondwana in the Devonian. Eastern MBL and the Eastern Province of New Zealand amalgamated with western MBL and the Western Province of New Zealand by the mid-Cretaceous. Major Early Cretaceous motions of the Weddellia blocks postdate the estimated initiation of seafloor spreading in the Weddell Sea and therefore may be the result of plate reorganization during the Cretaceous Quiet Zone.

Introduction

East Antarctica was the hub of cratonic Gondwana, from which South America and Africa, India, and Australia separated sequentially during Jurassic and Cretaceous times. The West Antarctic crustal provinces, largely the product of Phanerozoic tectonic and magmatic accretion on the Pacific margin of Gondwana, were profoundly affected by the changing plate tectonic regime as breakup proceeded. Marie Byrd Land (MBL) is one of the four major crustal blocks, along with Thurston Island (TI), Antarctic Peninsula (AP), and Ellsworth-Whitmore Mountains (EWM) (Figure 1), which presently make up West Antarctica [*Dalziel and Elliott*, 1982]. New Zealand, including the Campbell Plateau and Chatham Rise, was also part of West Antarctica until it rifted away in Late Cretaceous time.

The relative positions of the West Antarctic crustal blocks and their positions with respect to one another and the East Antarctic craton are fairly well known from the mid-Cretaceous to Recent from paleomagnetic studies [*Grunow*, 1993; *DiVenere et al.*, 1994] and constraints from marine geophysical data between Marie Byrd Land and New Zealand [*Mayes et al.*, 1990] , the Ross Sea [*Cooper et al.*, 1991], and

the Weddell Sea [*Barker and Lonsdale*, 1991; *Livermore and Woollett*, 1993]. For earlier times, it is apparent that the West Antarctic blocks have experienced significant tectonic translations and rotations, particularly prior to and during the Jurassic and Early Cretaceous opening of the Weddell Sea [*Watts and Bramall*, 1981; *Longshaw and Griffiths*, 1983; *Grunow et al.*, 1987a, 1987b, 1991; *Grunow*, 1993; *Dalziel and Grunow*, 1992]. However, it has been difficult to form a concise picture of the pre- mid-Cretaceous tectonic evolution due to the remoteness and scattered nature of the rock outcrops and attendant paucity of geological details and the small number of paleomagnetic studies.

Most previous plate tectonic reconstructions of West Antarctica have dealt primarily with the crustal blocks of the Weddell Sea sector (AP, TI, and EWM), collectively referred to as "Weddellia" by *Grunow et al.* [1987a], as recent work has progressed westward from the Scotia arc, and hence the largest number of paleomagnetic results are available for these. In paleogeographic reconstructions, MBL is usually left near to its present position close to the Transantarctic Mountains and North Victoria Land because of the similarity of Paleozoic rocks in western MBL and North Victoria Land. The ~100 Ma paleomagnetic results from MBL confirm a position for MBL near North Victoria Land at this time [*DiVenere et al.*, 1994], but there have been no reliable pre-100 Ma paleomagnetic results for MBL. This has created the impression that MBL, and the then-attached New Zealand microcontinent, were not attached to, and have evolved separately from, Weddellia, even
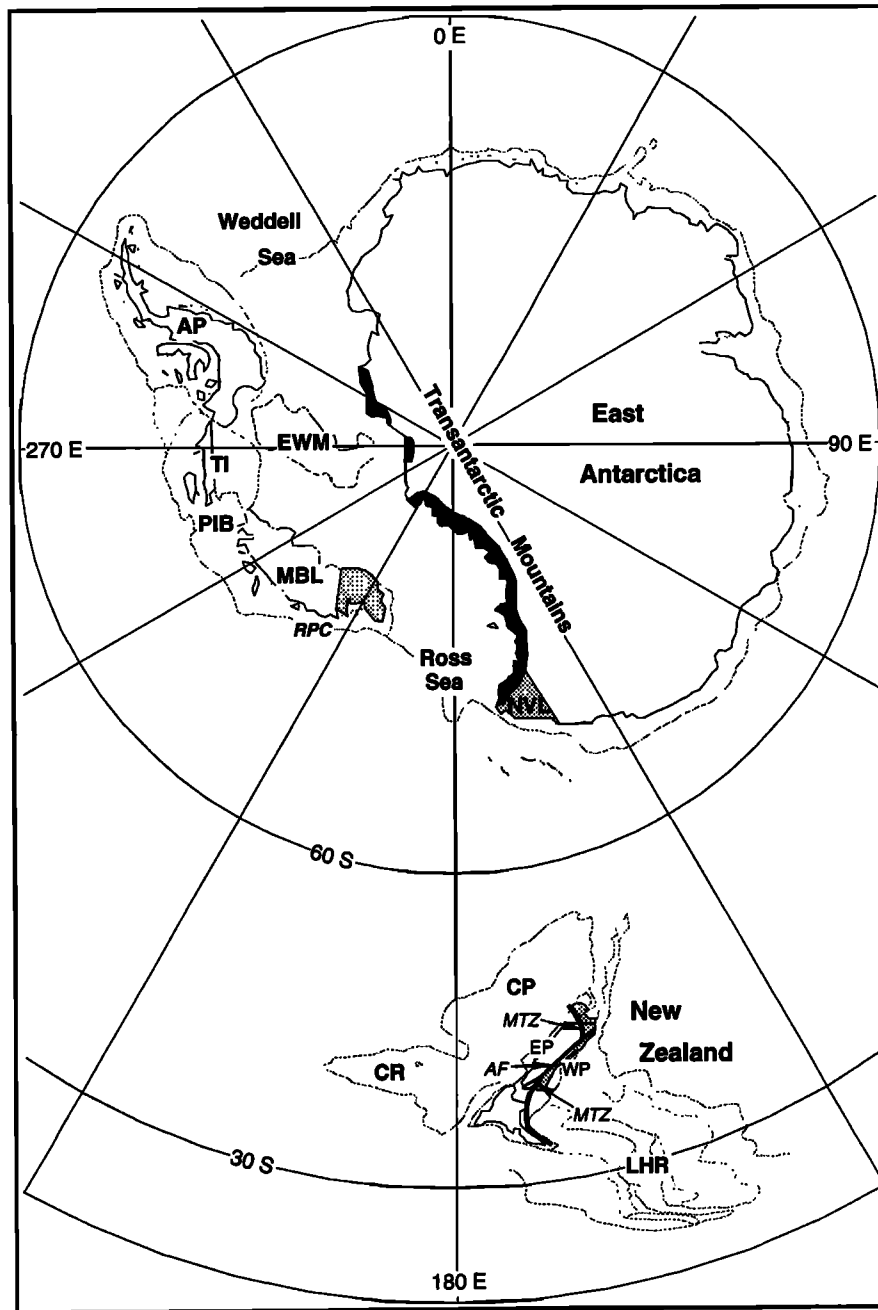
Figure 1. Map of Antarctica and New Zealand showing Marie Byrd Land (MBL), Thurston Island (TI), Antarctic Peninsula (AP), Ellsworth-Whitmore Mountains (EWM), North Victoria Land (NVL), Pine Island Bay (PIB), Ruppert/Hobbs Coast (RPC), Eastern Province of New Zealand (EP), Western Province of New Zealand (WP), Campbell Plateau (CP), Chatham Rise (CR), Lord Howe Rise (LHR), Median Tectonic Zone (MTZ; heavy solid line), the Alpine Fault (AF; medium solid line), and the Transantarctic Mountains (black shading). Gray stippled areas show the onshore extent of the presumed correlative lower Paleozoic turbidites and Devonian granodiorites.

though the Eastern Province of New Zealand appears to have been part of a continuous Gondwana convergent margin (arc, fore arc, and accretionary prism) extending from Chile through the Antarctic Peninsula to New Zealand during the mid-Paleozoic through Early Cretaceous [*Dalziel and Grunow*, 1985; *Dalziel and Forsythe*, 1985; *Bradshaw*, 1989; *Tranter*, 1991].

In this paper, new paleomagnetic data are presented from Lower Cretaceous volcanic and plutonic rocks from the

Ruppert and Hobbs Coast of MBL (Figure 2). Our interpretation of these results implies a pre- mid-Cretaceous position for at least this portion of MBL, farther removed from its current position with respect to North Victoria Land. A plate tectonic reconstruction is presented, consistent with paleomagnetic data from West Antarctica and New Zealand, that links the accretionary complexes of AP and eastern New Zealand along the Pacific margin and places the magmatic arc rocks of MBL and TI inboard of these.
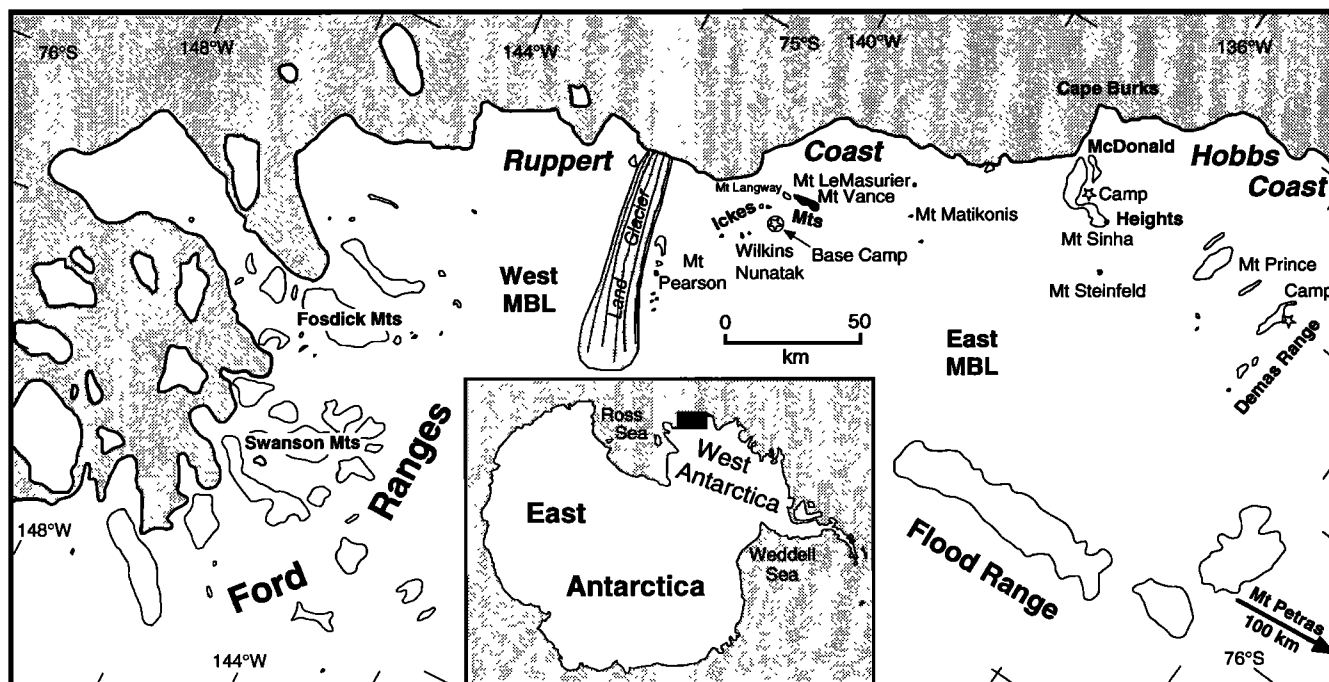
Figure 2. Locality map of the study area in Marie Byrd Land.

Geological Background

The geologic record of western MBL begins with a lower Paleozoic turbidite sequence, the Swanson Formation, which was folded and mildly metamorphosed in Late Ordovician time [*Adams*, 1986]. Similar rocks are found on Campbell Island of the southern Campbell Plateau as well as constituting the Greenland Group of western South Island, New Zealand [*Adams*, 1986]. The Robertson Bay Group of North Victoria Land, on the edge of the East Antarctic craton, is sedimentalogically similar to the Swanson Formation and Greenland Group [*Bradshaw et al.*, 1983] and has often been correlated with them, although metamorphism in the rocks of MBL and New Zealand appears to postdate the Cambro-Ordovician Ross Orogeny in North Victoria Land by about 50 Ma [*Adams*, 1986]. In the Ford Ranges of western MBL (Figure 2), the Swanson Formation was intruded by the subduction related, I-type, Devonian-Carboniferous Ford Granodiorite [*Weaver et al.*, 1991]. Similar Devonian igneous rocks are found in North Victoria Land (East Antarctica), Tasmania and Victoria (Australia), and the Western Province of South Island, New Zealand [*Grindley and Davey*, 1982; *Adams*, 1987; *Mason and Taylor*, 1987; *Laird*, 1991, *Weaver et al.*, 1991]. The Robertson Bay and Bowers Terranes of North Victoria Land, along with New Zealand and MBL, are thought to have finally accreted to the East Antarctic craton in the late Paleozoic [*Weaver et al.*, 1991; *Borg and DePaolo*, 1991; *Laird*, 1991]. However, neither the Swanson Formation nor Ford Granodiorite are found east of the Land Glacier (141°W) in MBL (Figure 2), with the possible exception of a granodiorite at Mount McCoy directly adjacent to the east side of Land Glacier. This accretion event, therefore, may not necessarily apply to all of MBL. In this paper we will refer to the two portions of MBL, separated at approximately the Land Glacier, as East and West MBL.

In easternmost MBL, diorites, quartz diorites, and granodiorites have yielded K-Ar [*Lopatin et al.*, 1974] and Rb-Sr [*Halpern*, 1972] ages ranging from 225 to 295 Ma (Permian/Triassic); work is currently in progress to test these 20-year old results. At face value, these rocks are broadly similar to a gabbro-diorite suite on Thurston Island, which has given a variety of ages ranging from about 230 to 290 Ma (^{40}Ar/^{39}Ar, K-Ar, and Rb- Sr; [*Pankhurst et al.*, 1993]). On Thurston Island, these plutons were intruded into an Upper Carboniferous granodiorite-gneiss; the parental magmas for both were emplaced in a convergent margin setting [*Pankhurst et al.*, 1993; *Leat et al.*, 1993]. This might be taken to suggest the continuity, or at least the proximity, of eastern MBL and TI since late Paleozoic times. Additionally, orthogneiss on the Bear Peninsula of eastern MBL with a ~470 K-Ar age [*Lopatin et al.*, 1974] and gneiss on Clarke Island on the TI side of Pine Island Bay (preliminary Rb-Sr age of ~445 Ma (R. J. Pankhurst, personal communication, 1993)) may suggest a relationship between these two areas as far back as early Paleozoic times.

The Swanson Formation and Ford Granodiorite of West MBL, as well as the Permian granodiorites of East MBL and TI, are intruded by Mesozoic granitoids. Lower Cretaceous subduction-related igneous rocks in MBL (the subject of this study) and New Zealand change abruptly to A-type igneous rocks between about 110 and 105 Ma [*Spörli and Craddock*, 1981; *Weaver and Pankhurst*, 1991; *Weaver et al.*, 1992; *Palais et al.*, 1993; *Weaver et al.*, 1994], apparently as a result of subduction of the Pacific-Phoenix Ridge [*Bradshaw*, 1989] and the beginning of rifting between MBL and New Zealand. Seafloor spreading between MBL and New Zealand began shortly before Chron 34 (84 Ma) [*Mayes et al.*, 1990]. In MBL, an erosional surface developed on Cretaceous and older rocks is overlain by upper Tertiary alkaline volcanic rocks [LeMasurier and Rex, 1983, 1991] that are proposed to be the result of a mantle plume [*Hole and LeMasurier*, 1994].

Sampling and Techniques

Oriented samples were collected for paleomagnetic study from all major exposed pre-Cenozoic rock units on the Ruppert and Hobbs Coast area of Marie Byrd Land. A paleomagnetic study of mid-Cretaceous (~100 Ma) rocks was reported by DiVenere et al. [1994]. In this paper we describe Lower Cretaceous paleomagnetic results from 189 oriented cores collected at 25 sites in volcanic rocks from the col between Mount Vance and Mount LeMasurier, and also from Mount Pearson, Mount Matikonis, and Wilkins Nunatak on the Ruppert Coast (17 sites), and from a granodiorite suite at Mount Sinha and Mount Steinfeld in the McDonald Heights area of the Hobbs Coast (eight sites) (Figure 2). Unpublished Rb-Sr data have given ~110 to 120 Ma ages for the volcanic units and 118 ± 2 Ma for the granodiorite suite (R. J. Pankhurst, personal communication, 1993). Unpublished zircon U-Pb data also give an age of about 117 Ma for the granodiorite at Mount Steinfeld (S. B. Mukasa, personal communication, 1993). Most of the volcanic rocks are thermally metamorphosed, and contacts are observed at Mount Vance/LeMasurier and Wilkins Nunatak with intruding ~100 Ma syenite and alkali granite from which paleomagnetic results were reported by DiVenere et al. [1994].

The cores were taken with a portable gasoline-powered drill and were oriented with a magnetic compass. All magnetic readings were checked with a sun compass at Mount Pearson, Mount Sinha and Mount Steinfeld, and three sun compass readings were also taken at Wilkins Nunatak. No sun compass checks could be made at Mount Matikonis or at Vance/LeMasurier because clouds or outcrop shadows prevented it. Magnetic variation was calculated for each site from the International Geomagnetic Reference Field [Langel, 1992], and appropriate corrections were applied to the field data. Differences between the magnetic and sun compass readings were within 2° to 3° and the magnetic compass readings were used for the core orientations. All samples were subjected to either progressive thermal demagnetization to maximum temperatures of 675°C, or progressive alternating field (AF) demagnetization to maximum fields of 100 mT. Both demagnetization methods were used for each site. Specimen directional behavior was similar under both methods, though thermal demagnetization tended to give better results for the granodiorites while AF demagnetization gave good results in the volcanic rocks. Measurements were made on an ScT two-axis cryogenic magnetometer, or a Digico spinner magnetometer for very strongly magnetized samples. Bulk magnetic susceptibility was monitored using a Bartington susceptibility bridge for all specimens after each thermal demagnetization step. Curie point determinations were made on a horizontal beam Curie balance. Sample storage, demagnetization, and cryogenic magnetometer measurements were performed in a magnetically shielded room with a nominal ambient field of ~250 nT. Additional shielding of the field demagnetizers and the cryogenic magnetometer reduces the field to less than 5 nT over the sample space.

Magnetic component directions were calculated by principal component analysis [Kirschvink, 1980] of linear segments chosen by inspection from orthogonal plots [Zijderveld, 1967]. The components thus determined were plotted on equal-area nets, and mean directions were determined by standard Fisher statistics [Fisher, 1953].

Virtual geomagnetic poles (VGPs) were calculated for each site and mean paleomagnetic poles and their associated confidence limits were calculated from these. All tests of significance between poles were made using the formal method of McFadden and Lowes [1981] at the 95% confidence level ($p = 0.05$).

Paleomagnetic Results From Ruppert Coast Volcanics

Mount Vance/LeMasurier Volcanics

Forty-four oriented cores were collected at six sites from three units in the ~117 Ma Mount Vance/LeMasurier volcanics: two sites each in a basal felsic agglomerate, a 10-m-thick feldspar porphyry, and a thick pile of amygdaloidal volcanic flows ranging from alkaline basalt to trachyte in composition (S. D. Weaver, personal communication, 1993). Heavy overcast did not allow sun compass readings to be taken. The volcanic rocks have been hydrothermally altered. The bedding dips gently to the north and strikes east-west (sites 1 to 4: strike/dip = 281° / 10°N, sites 5 and 6: strike/dip = 265° / 20°N). The rocks are strongly magnetized, with intensities of the natural remanent magnetization (NRM) ranging from 0.5 to 20 A/m, but with most samples from 1 to 3 A/m. After weak spurious magnetizations are removed, usually in the first treatment step (i.e., 10 mT or 100°C), a stable characteristic remanent magnetization (ChRM) is identified by the linear decay to the origin with further treatment (Figures 3b, 3c). Samples are not quite completely demagnetized by 100 mT (Figure 3c) and maximum unblocking temperatures and Curie temperatures for most samples are concentrated near 585°C (Figure 3d). These characteristics are consistent with magnetite as the main carrier of the magnetic remanence. No large-scale changes are seen in bulk susceptibility, and therefore magnetic mineralogy, during thermal treatment. The stable components are uniformly of normal polarity, and in situ directions are generally easterly directed with moderately steep negative inclination, and southeasterly and steep after a bedding tilt correction is applied (Figures 3e, 3f).

Four of the six samples from site 1 in the volcanic agglomerate are completely resistant to AF demagnetization to 100 mT and have maximum unblocking temperatures and Curie temperatures around 680°C (Figure 3a), consistent with remanence carried by hematite. The in situ mean direction for the four hematite bearing samples (declination (dec) = 0.3, inclination (inc) = -82.5, and a_{95} = 13.6°) is similar to the in situ mean direction of the intruding ~100 Ma syenite (dec = 349.1, inc = -75.1, and a_{95} = 2.6°) [DiVenere et al., 1994]. Site 1 was sampled in the volcanics nearest the contact with the intruding syenite; the four hematite bearing samples from this site appear to have been thermochemically remagnetized as a result of the emplacement of the syenites at about 100 Ma.

A mean ChRM direction was calculated for the Mount Vance/LeMasurier volcanics from the six magnetite-bearing site mean directions (excluding the four hematite-bearing samples from site 1). The in situ mean direction (dec = 59.9, inc = -77.9, a_{95} = 5.5°) is significantly different from the axial dipole field (dec = 0, inc = -82.6). Although the mean is not significantly different from the present-day field (dec = 75.3, inc = -75.7) at the 95% confidence level, the high stability of the magnetization, as demonstrated by thermal and alternating
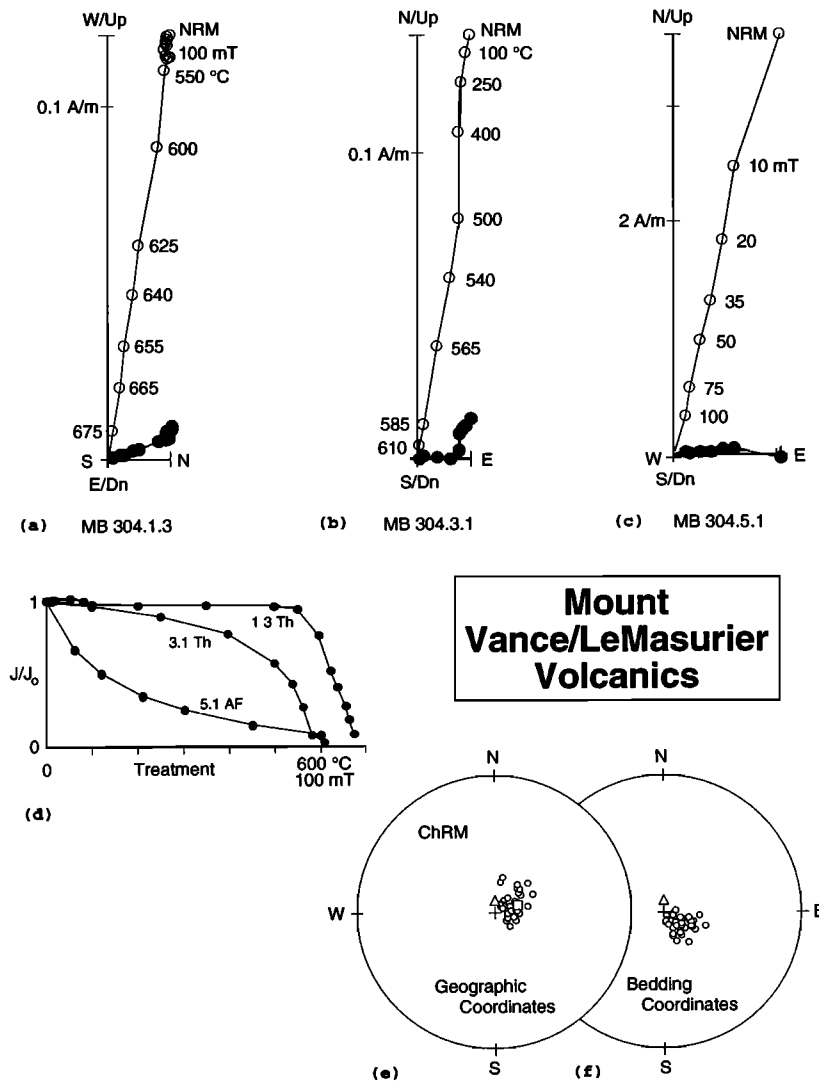
Figure 3. (a-c) Orthogonal plots of demagnetization data from Mount Vance/LeMasurier volcanics, with open symbols representing the vertical trace and solid symbols the horizontal trace of the magnetization vector; (d) remanent intensity (normalized to initial intensity) versus sample treatment; (e) equal-area projection of sample ChRM component directions before and (f) after correcting for tilt of the volcanic layering, with open symbols plotting on the upper hemisphere. Triangle represents the time-averaged dipole field direction for this location; square is the present-day field direction.

field experiments, should preclude that these rocks are carrying a recent viscous magnetization. The bedding attitudes are slightly different for sites 1 to 4 as compared to sites 5 and 6, but the difference is not great enough to serve as the basis for a fold test. The bedding tilt corrected mean direction is dec = 125.2, inc = -78.0, and a_{95} = 4.8°, with a marginal increase in the precision parameter after bedding tilt correction (Table 1). However, the ChRM mean directions (before and after tilt correction) for the ~117 Ma volcanics are significantly different from the mean direction of the intruding ~100 Ma Ickes Mountains syenite (dec = 265.2, inc = -87.1, a_{95} = 2.6°, in situ [DiVenere et al., 1994]).

The angular dispersion of the site mean virtual geomagnetic poles (VGPs) (10.5° +6° / -2.8°) is less than the expected dispersion of the field (about 20°) at the paleolatitude of Mount Vance (67°S) [McFadden et al., 1991]. Therefore, if the site means represent spot readings of the field, then our six

sites may not have adequately sampled secular variation of the field. However, it seems likely that secular variation has been at least partially averaged within-site due to hydrothermal alteration in the volcanic pile [Ade-Hall et al., 1971], as evidenced by infilling of vessicles in the basalts (assuming this alteration did, in fact, occur at the time of the extrusion of these rocks), and an extended period of elevated temperatures, as evidenced by the high Curie temperatures, implying the oxidation/exsolution of the primary titanomagnetite.

Wilkins Nunatak

Forty-five oriented cores were collected at six sites in lavas and volcaniclastic sediments on both limbs of an antiform structure at Wilkins Nunatak, located approximately 20 km SSW of Mount Vance/LeMasurier. The volcanic rocks are intruded by ~100 Ma alkali granite and syenite, which are

found throughout the Ruppert/Hobbs Coast, and are strongly metamorphosed, probably due to the mid-Cretaceous intrusion.

The intensity of NRM ranges from about 10^{-3} to 1 A/m. Progressive AF or thermal demagnetization to 10 to 15 mT or 300 to 400°C removes unstable viscous magnetizations. At higher treatment levels, all samples yield a steep negative inclination, normal polarity magnetization before tilt correction. Unblocking temperature and coercivity curves (Figures 4a, 4b, 4d) show that most samples contain

magnetizations stable to 575 to 585°C or 70 to 100 mT, consistent with magnetite as the principal carrier of remanence. Sample directions calculated from the high treatment segments of demagnetization trajectories are shown before and after tilt correction in Figures 4e and 4f.

The directions from the two limbs become dispersed after restoring the limbs to the horizontal. This appears to indicate that the magnetization was acquired after folding. However, the directions are not very well defined in many samples, and in some there is an indication (curving demagnetization

Table 1. Site Mean Directions and South Paleomagnetic Poles

Site	n/N	k	a_{95}	Direction In Situ Dec/Inc	Direction Tilt-Corrected Dec/Inc	Pole In Situ Lon/Lat	Pole Tilt-Corrected Lon/Lat	A_{95}
Mount Vance/LeMasurier Volcanics (Lon/Lat 220.60/-75.47)								
MB304.1	4/6[a]	1096	2.8	35.5/-81.2	129.8/-85.9	-	202.5/-69.2	
MB304.2	8/10	132	4.8	88.9/-78.7	135.2/-76.6	-	190.5/-52.9	
MB304.3	7/7	342	3.3	78.6/-83.0	149.2/-80.2	-	202.4/-57.7	
MB304.4	6/6	1038	2.1	75.7/-78.4	126.2/-78.4	-	186.3/-57.1	
MB304.5	7/7	119	5.6	49.2/-71.9	116.4/-72.8	-	173.7/-49.9	
MB304.6	6/7	124	6.0	48.4/-70.3	111.2/-72.4	-	169.2/-50.3	
Mean *is*	6/6	149	5.5	59.9/-77.9	-	138.1/-70.0	-	9.8
Mean *tc*	6/6	193	4.8	-	125.2/-78.0	-	185.6/-56.8	8.7
MB304.1 (ht)[b]	4/4	47	13.6	0.3/-82.5	220.1/-87.1	-	232.0/-70.6	
Wilkins Nunatak Volcanics (Lon/Lat 220.05/-75.65)[c]								
MB302.9	6/6	40	10.8	15.3/-88.7	8.8/-12.3	216.8/-78.1	-	
MB302.10	6/6	35	11.5	322.8/-87.3	6.6/-11.6	237.9/-79.4	-	
MB302.14	8/8	91	5.8	102.3/-79.1	19.8/-13.9	171.0/-62.2	-	
MB302.11	7/8	78	6.9	15.1/-81.2	279.3/-72.7	102.9/-85.0	-	
MB302.12	7/7	212	4.2	356.1/-80.8	280.0/-69.7	21.2/-86.3	-	
MB302.13	10/10	108	4.7	30.1/-87.5	282.4/-68.9	206.3/-79.6	-	
MB302.14 *tc[d]*					142.8/-72.2	-	192.5/-45.1	
Mount Matikonis Volcanics (Lon/Lat 221.18/-75.35)								
MB210.1	10/7[e]	457	2.3	11.2/-82.2	-	123.4/-87.0	-	
MB210.2	14/7[e]	157	3.2	353.4/-80.5	-	12.4/-85.6	-	
Mean	2/2	-	-	1.4/-81.5	-	52.5/-87.8	-	
Mount Pearson Volcanics (Lon/Lat 219.03/-75.90)								
MB207.1	6/7	67	8.2	263.3/-82.9	319.4/-72.4	261.2/-69.1	-	
MB207.2	8/14	77	6.4	302.7/-76.0	322.9/-62.8	311.5/-67.9	-	
MB207.4	7/10	296	3.5	250.0/-73.3	232.4/-71.1	270.9/-52.0	-	
Mean	3/3	104	12.4	271.7/-78.5	-	279.3/-64.4	-	22.4
MB207.3 (dk)[f]	3/1[g]	395	6.2	134.3/-85.4	-	201.0/-68.5	-	
Mount Steinfeld Granodiorite (Lon/Lat 224.13/-75.20)								
MB203.1	7/7	27	11.7	157.1/-66.1	-	205.9/-34.6	-	
MB203.2	6/6	87	7.2	165.7/-62.5	-	212.3/-29.4	-	
MB203.3	6/7	21	14.9	163.1/-68.4	-	211.0/-37.4	-	
MB203.4	6/7	70	8.0	148.8/-72.7	-	201.4/-44.8	-	
MB203.5	7/7	68	7.4	163.5/-69.0	-	211.4/-38.2	-	
Mean	5/5	325	4.2	160.3/-67.8	-	208.6/-36.9	-	6.3

Table 1. (continued)

Site	n/N	k	a_{95}	Direction In Situ Dec/Inc	Direction Tilt-Corrected Dec/Inc	Pole In Situ Lon/Lat	Pole Tilt-Corrected Lon/Lat	A_{95}
				Mount Sinha Granodiorite (Lon/Lat 223.85/-75.00)				
MB159.1	2/7	-	-	324.1/-83.3	-	285.4/-81.2	-	
MB159.2	5/7	103	7.6	259.9/-78.3	-	275.0/-61.0	-	
MB159.3	6/7	152	5.5	254.6/-76.5	-	274.3/-57.3	-	
Mean	3/3	141	10.4	269.6/-80.5	-	276.0/-66.5	-	20.0
Mean tc^h					178.1/-70.6	-	222.1/-40.1	17.5

n/N, number of samples accepted/number collected for site means or number of sites accepted over number of sites collected for group means; k, Fisher's precision parameter; a_{95}, radius of 95% cone of confidence about mean direction; Dec, mean declination; Inc, mean inclination; Lon, mean paleomagnetic pole east longitude; Lat, mean paleomagnetic pole north latitude (negative is south latitude); A_{95}, radius of 95% cone of confidence about mean pole; is, in situ; tc, tilt-corrected.

a   Four specimens from two of six samples.
b   Hematite-bearing sample directions (~100 Ma?).
c   Sites .9, .10, and .14 are west end volcanics; .11, .12, and .13 are east end volcaniclastics.
d   Mean corrected for post-100 Ma 12° southward tilt.

e   Specimens/samples.
f   Dike.
g   Specimens/hand sample.
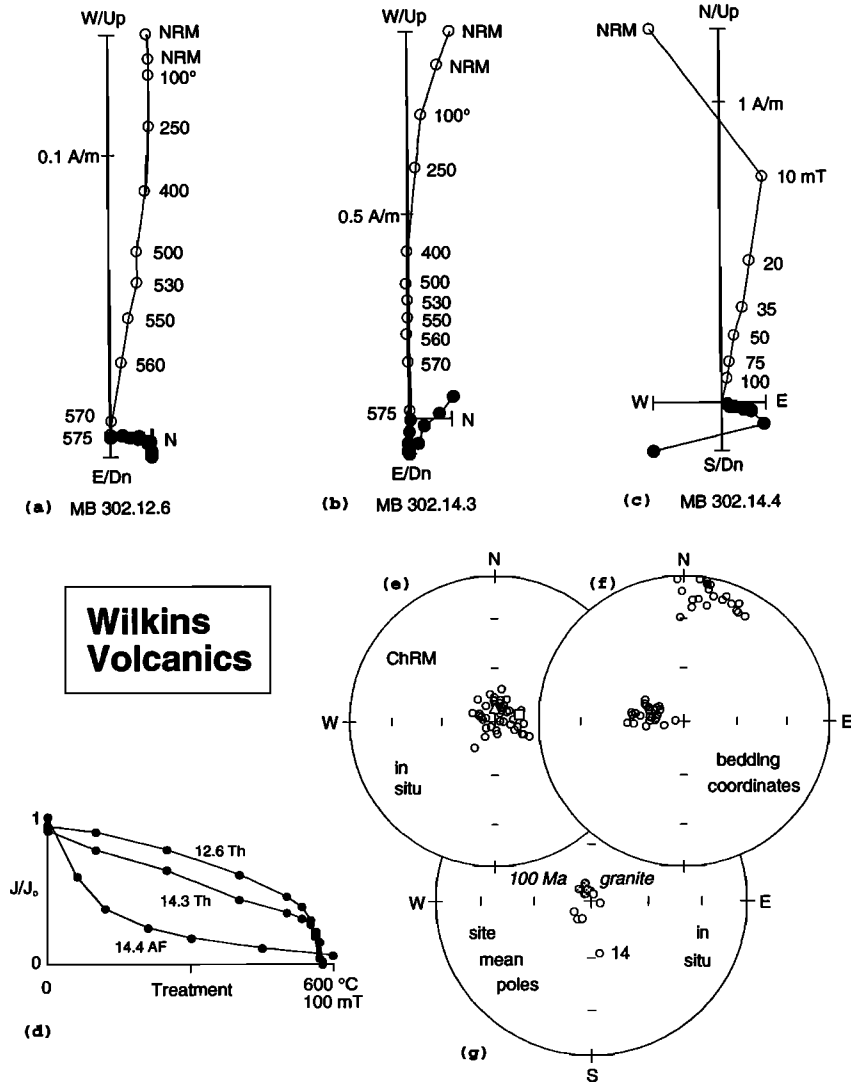h   Mean tilted about strike of foliation.

Figure 4. (a-c) Orthogonal plots of demagnetization data from Wilkins Nunatak volcanics; (d) intensity versus sample treatment; (e) equal-area projection of ChRM component directions before and (f) after tilt correction; (g) site mean poles plotted with the Wilkins 100 Ma granite poles (grayed symbols). All other symbols defined as in Figure 3.
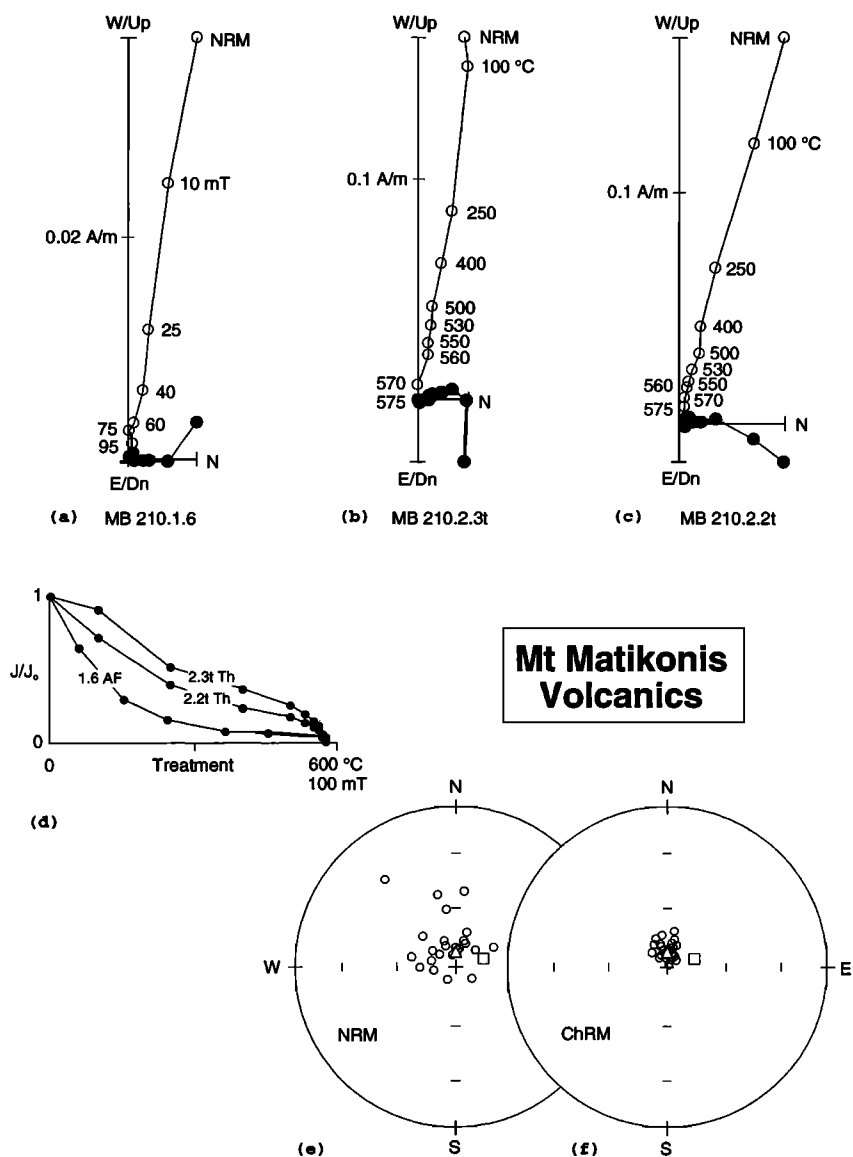
Figure 5. (a-c) Orthogonal plots of demagnetization data from Mount Matikonis volcanics; (d) intensity versus sample treatment; (e) equal-area projection of sample NRM directions and (f) ChRM component directions. All symbols defined as in Figure 3.

trajectories) of the simultaneous removal of more than one component of magnetization. Poles were calculated from each site mean direction and are compared with site mean poles from the intruding 100 Ma granite in Figure 4g. Sites 11 and 12, with weak stable behavior, fall in one group with the granite means; sites 9, 10, and 13, with intermediate NRM intensities and complicated high treatment behavior, fall in a second group somewhat farther from the granite means; and site 14, with strong, stable behavior, is distinctly different from the granite means (Figure 4g). This is taken as evidence that sites 11, 12, and 13 in volcaniclastic sedimentary rocks, and sites 9 and 10 in volcanic flows, have been largely remagnetized due to the granite intrusion, while site 14, the farthest removed from the visible contact with the granite, retains a more-or-less unaffected early (pre-100 Ma) magnetization. The mean direction for site 14 is dec = 102.3, inc = -79.1, a_{95} = 5.8° in situ (Table 1).

Mount Matikonis

Fourteen oriented cores were collected from two sites in thermally metamorphosed, bedded volcaniclastic rocks at Mount Matikonis, 40 km NE of Mount Vance/LeMasurier. The intensity of the NRM is of the order of 0.1 A/m. NRM directions are moderately scattered, but removal of low-stability components during progressive demagnetization yields well-grouped, steep upward, normal polarity directions (Figures 5e, 5f). Coercivities and maximum blocking temperatures are consistent with magnetite as the primary remanence-carrying mineral. The steep northerly direction (mean dec = 1.4, inc = -81.5) is similar to the overprint direction seen in the results from Wilkins Nunatak (Table 1). Given this similarity and the relatively high grade of metamorphism at this location, these results may also represent an overprint acquired at about 100 Ma.
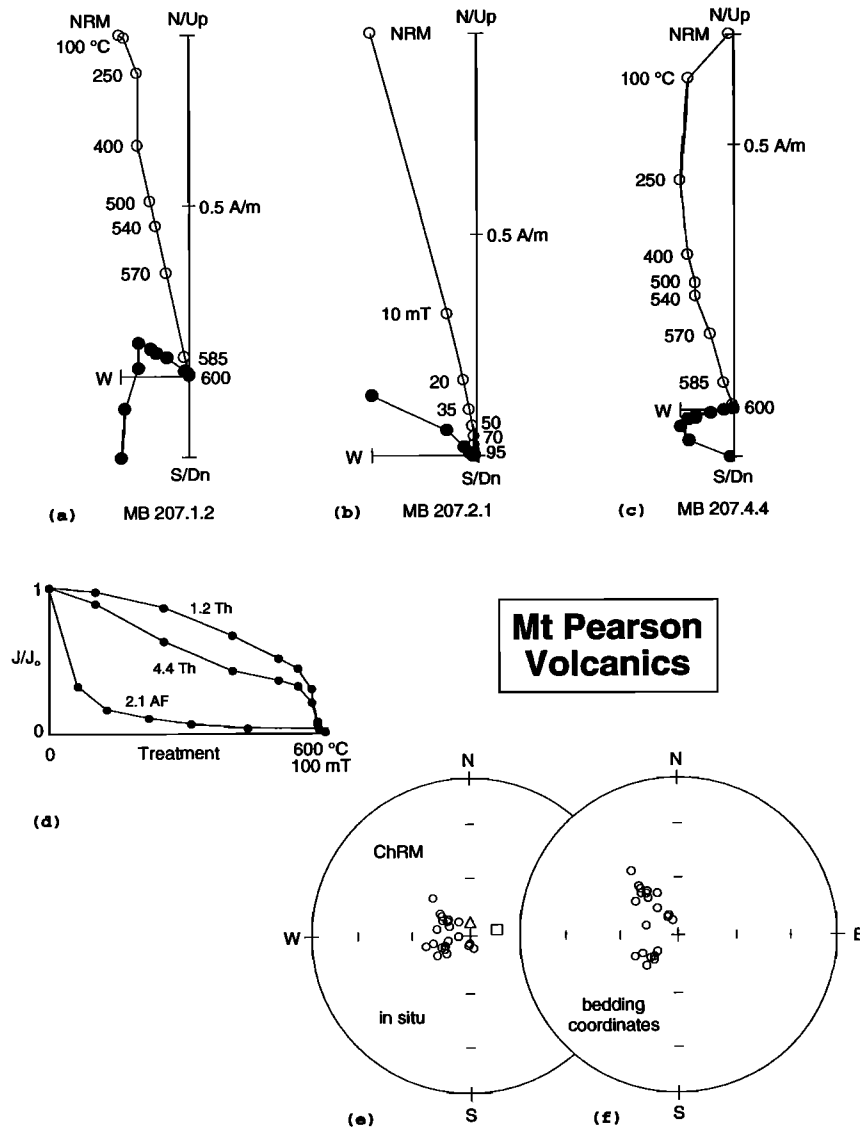
Figure 6. (a-c) Orthogonal plots of demagnetization data from Mount Pearson volcanics; (d) intensity versus sample treatment; (e) equal-area projection of sample ChRM component directions before and (f) after tilt correction. All symbols defined as in Figure 3.

Mount Pearson

At Mount Pearson, 60 km SW of Mount Vance/LeMasurier, thirty-one oriented cores were collected from three sites in a folded volcaniclastic sequence that is intensely silicified, cleaved, and jointed, with epidote needles up to 5 cm on the joint planes. The NRM intensity is typically strong, of the order of 1 A/m. Either progressive AF or thermal demagnetization yields well-defined decay trajectories with steep upward directions after the removal of viscous components (Figures 6a, 6b, 6c). Two of the sites were sampled on one limb of the fold and the third site could only be taken near the hinge of the fold because the remainder of the fold was inaccessible. The site mean directions are significantly better grouped in situ than after returning the limbs to the horizontal ($k_{in\ situ}$ / $k_{bedding}$ = 4.7), indicating that the remanence was most likely acquired after folding. The in situ mean direction (dec = 271.1, inc = -78.5, a_{95} = 12.4) (Table 1) with a relatively large error, deviates from the other

Ruppert Coast volcanics discussed above, as well as from the expected 100 Ma direction [*DiVenere et al.*, 1994]. An oriented hand sample was taken from a dike that intrudes the volcaniclastic sedimentary rocks. The mean direction from three specimens from the dike sample (Table 1) is similar to the expected 100 Ma magnetic field direction for MBL [*DiVenere et al.*, 1994]. Therefore, if the dike was actually emplaced at around 100 Ma, then the metamorphism and deformation observed in the Lower Cretaceous volcanic rocks must have occurred prior to about 100 Ma.

Paleomagnetic Results From Hobbs Coast Granodiorites

Mount Steinfeld

Thirty-four oriented cores were collected from five sites in a homogeneous granodiorite at Mount Steinfeld, approximately
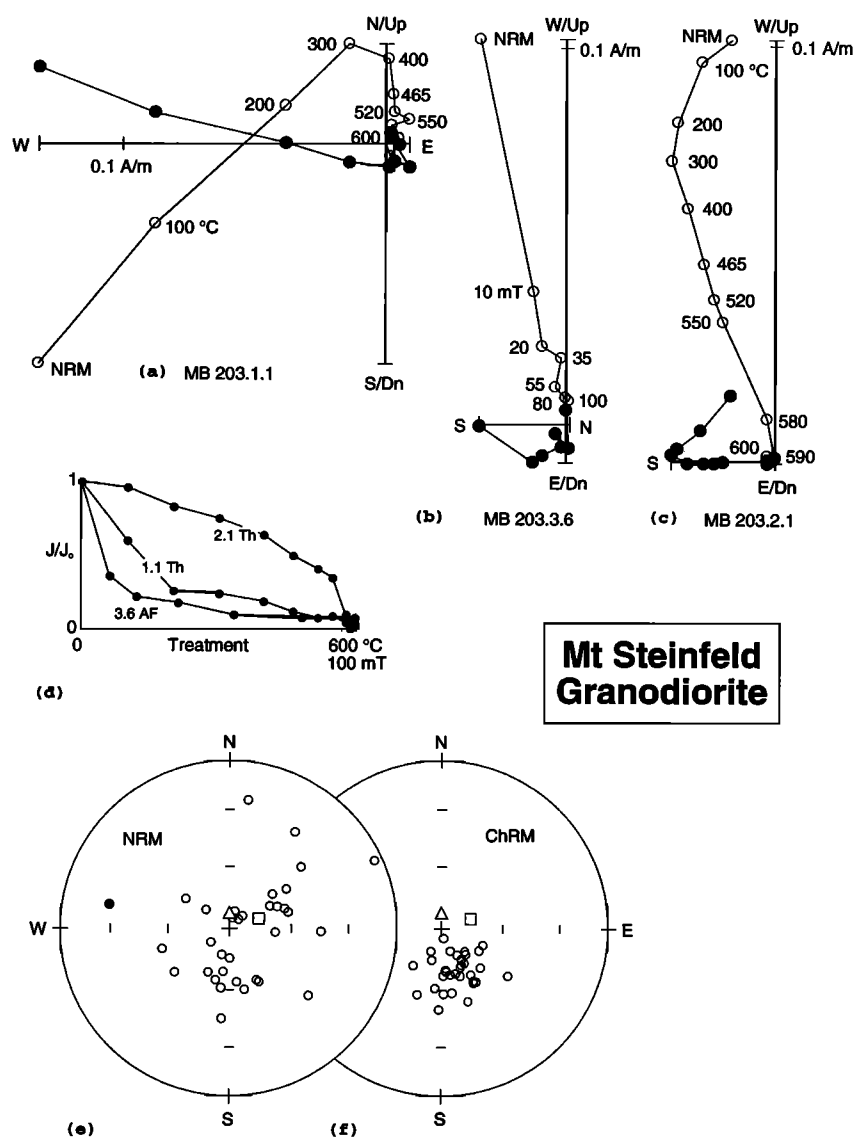
Figure 7. (a-c) Orthogonal plots of demagnetization data from Mount Steinfeld granodiorite; (d) intensity versus sample treatment; (e) equal-area projection of sample NRM directions and (f) ChRM component directions. All symbols defined as in Figure 3.

70 km ENE of Mount Matikonis. The NRM directions are fairly scattered (Figure 7e), though all but one sample have negative inclination. Remanent intensities are of the order of 0.1 A/m. A number of untreated samples were remeasured after 30 months of storage in magnetically shielded space, at which time the remanent intensity had decreased by 30% to 60%. Comparable viscous magnetizations are removed during low treatment steps of thermal and AF demagnetization yielding a moderate to steep up, south-southeasterly directed characteristic magnetization (Figures 7a, 7b, 7c). Coercivities, unblocking temperatures, and Curie point determinations (Figure 7d) are all consistent with magnetite as the primary remanence-carrying mineral. Although most samples display noisy decay trajectories, the ChRM components calculated from the high treatment portions of the demagnetization data are quite consistent (Figure 7f). The mean direction (dec = 160.3, inc = -67.8, a_{95} = 4.2) (Table 1) is similar to the tilt-corrected Mount Vance/LeMasurier volcanics result.

Mount Sinha

Twenty-one oriented cores were collected from three sites in foliated granodiorite at Mount Sinha, 18 km NNW of Mount Steinfeld. The NRM directions are scattered (Figure 8e), though all samples but one have negative inclination. Remanent intensities are of the order of 0.1 A/m. Coercivities, maximum blocking temperatures, Curie temperatures, and IRM acquisition behavior are all consistent with magnetite as the primary remanence carrying mineral. Samples from sites 2 and 3 vary in stability but generally yield moderate to steep negative inclination (normal polarity) and westerly directions of magnetization after removal of low stability components (Figures 8b, 8c, 8f). Most samples from site 1 display largely unstable demagnetization behavior (Figure 8a), though two samples yield a reasonably well-resolved steep negative inclination component of magnetization. The in situ mean direction (dec = 269.6, inc = -80.5, a_{95} = 10.4°) (Table 1) is different from the Mount
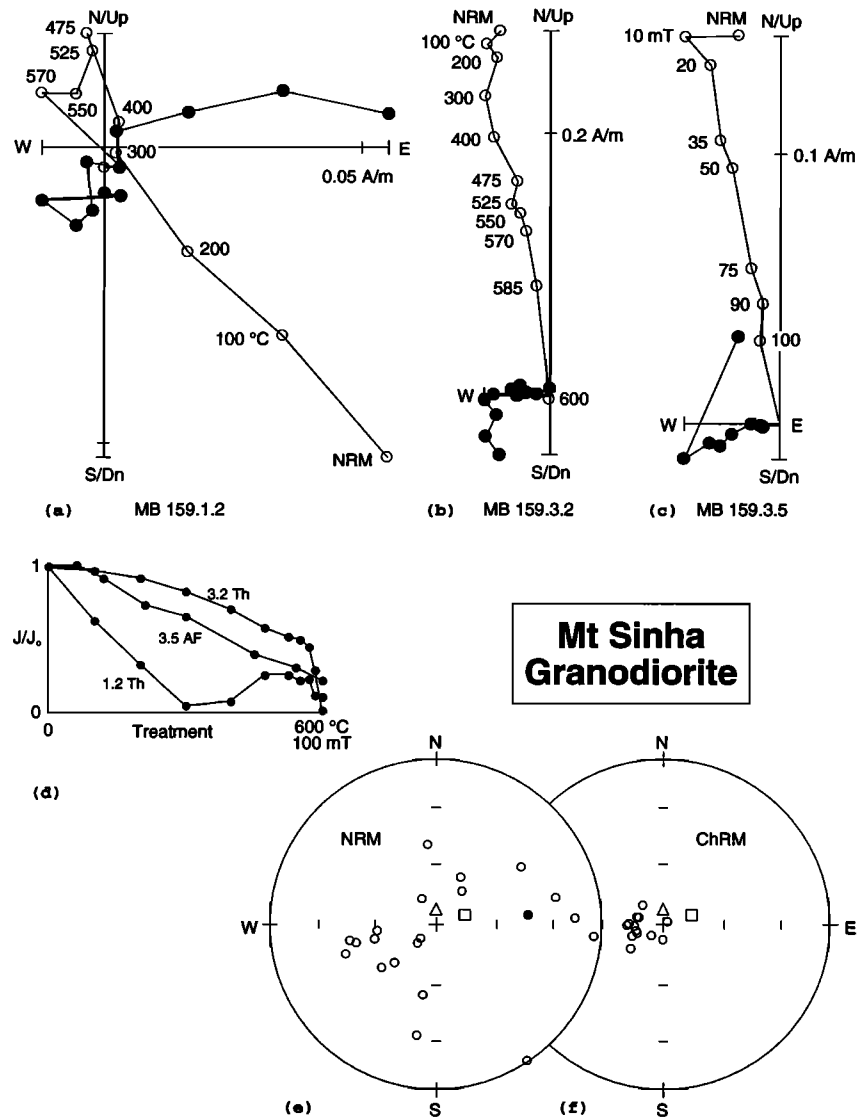
Figure 8. (a-c) Orthogonal plots of demagnetization data from Mount Sinha granodiorite; (d) intensity versus sample treatment; (e) equal-area projection of sample NRM directions and (f) ChRM component directions. All symbols defined as in Figure 3.

Steinfeld granodiorite mean direction, but similar to the mean direction of the metamorphosed volcanics at Mount Pearson.

Early Cretaceous Mean Paleomagnetic Pole

To assess the tectonic position of MBL during the Early Cretaceous, it is necessary to calculate a representative mean paleopole from the above results for comparison with paleopoles from other continental blocks. This is not completely straightforward, given the complexity of the results from the ~117 Ma units discussed above. Mean poles were calculated for each location by combining the site mean poles. The locality mean poles are widely scattered in situ (Figure 9a). However, we judge the Mount Vance/LeMasurier volcanics results to be the most reliable estimate of the Early Cretaceous pole position. They are supported by a positive contact test with the intruding ~100 Ma syenite, as described above, implying that the magnetization in the volcanics

predates the 100 Ma intrusion. The volcanic bedding was used to tilt-correct the 100 Ma syenites which provided a positive regional tilt-test for the ~100 Ma intrusions on the Ruppert/Hobbs Coast [DiVenere et al., 1994], supporting the assumption that the bedding gives a good approximation of the paleohorizontal. The tilt-corrected mean paleomagnetic pole calculated for the ~117 Ma volcanics at Mount Vance/LeMasurier from the six site mean poles is 185.6°E / 56.8°S, A_{95} = 8.7° (Figure 9b, Table 1). Though none of the remaining results may be used unequivocally to estimate the 117 Ma pole position, they give support, as described below, to the Vance/LeMasurier mean pole.

Paleopoles calculated for the results from the higher grade metavolcanics at Wilkins Nunatak, Mount Matikonis, and Mount Pearson are inconsistent, at face value, with the Mount Vance/LeMasurier pole (Figure 9, Table 1). Given the thermal metamorphism, the identified remagnetization at Wilkins Nunatak, and possible structural complications, these results
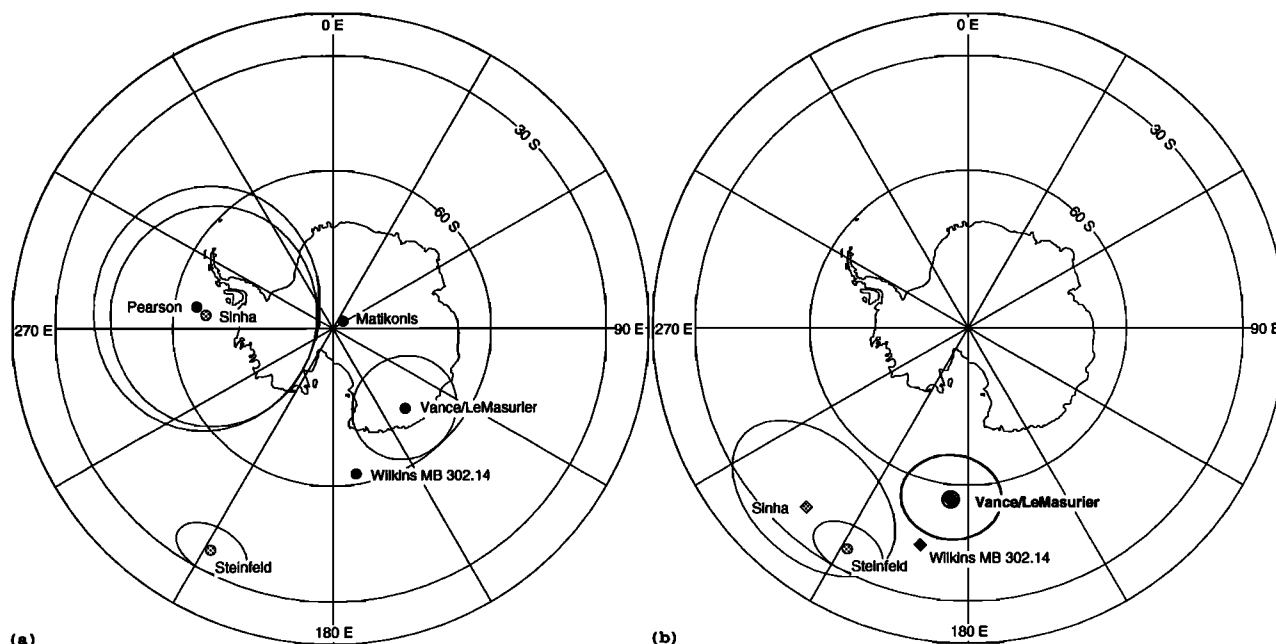
Figure 9. Locality mean paleopoles; (a) all localities in situ, and (b) selected results with tilt corrections applied as discussed in text. Circles are in situ results, diamonds are tilt-corrected results; black symbols are from volcanic units, gray symbols are from granodiorites. Error circles shown are 95%. This and Figures 10 and 11 are orthographic projections.

appear to be largely remagnetized and/or structurally disturbed, with the possible exception of one site (MB302.14) from Wilkins Nunatak, whose mean pole is offset from the Wilkins 100 Ma granite mean pole in the same sense and amount as the Mount Vance/LeMasurier mean pole is from the 100 Ma Mount Vance syenite. This supports a similar age (~117 Ma) for the site 14 remanence. If so, this would imply that the antiform at Wilkins Nunatak is a structure pre-dating cooling of the volcanic pile. Based on the mean direction in the ~100 Ma granites, we had inferred that Wilkins Nunatak was tilted, post-100 Ma, about a similar horizontal axis and by a similar amount as Mount Vance/LeMasurier 20 km to the NNW [*DiVenere et al.*, 1994]. The site 14 in situ result is shown in Figure 9b corrected for this tilt.

There is no direct paleohorizontal indicator for the plutonic rocks on the Hobbs Coast. However, the mean paleomagnetic pole from the homogeneous granodiorite at Mount Steinfeld (Figure 9, Table 1) is similar to the tilt-corrected Mount Vance/LeMasurier and Wilkins Nunatak poles (Figure 9b), also being offset to the NNW from the 100 Ma MBL mean pole. On the other hand, the mean pole from the foliated Mount Sinha granodiorite is dissimilar to the Mount Steinfeld result even though the two outcrops are separated by only 18 km and apparently represent the same igneous unit. The Mount Sinha pole may be brought into agreement with the Mount Steinfeld pole by a rotation about the strike of the foliation (strike/dip 62°/68°S). This may indicate a structural explanation for the difference between the Mount Steinfeld and Mount Sinha poles, probably related to the intrusion of the ~ 100 Ma syenites at Mount Sinha. For the lack of a better datum, the tilt correction shown for the Mount Sinha pole (Figure 9b, Table 1) is one that brings the foliation to the vertical.

The selected tilt-corrected results from Mount Vance/LeMasurier, Wilkins Nunatak site MB302.14, and Mount Sinha, and the result from Mount Steinfeld (Figure 9b)

show a good grouping and pass a regional tilt test at the 99% confidence interval (with or without Wilkins Nunatak site 14 and Mount Sinha). Assuming that the tilt-corrections for Wilkins Nunatak and Mount Sinha are approximately correct and/or that Mount Steinfeld has not been tilted, this implies that the magnetizations predate the time of tilting, which was inferred to be post-100 Ma [*DiVenere et al.*, 1994] and probably pre-84 Ma at Mount Vance/LeMasurier. The uniform normal polarity magnetizations are consistent with acquisition within the Cretaceous Normal Polarity Superchron (118 to 84 Ma). A mean pole calculated from the combined Mount Vance/LeMasurier and Mount Steinfeld site means (198.3°E / 48.3°S) is indistinguishable from a pole based on all four localities. However, given the uncertainties in the tilt-corrections for Mount Sinha and Wilkins Nunatak, and the lack of paleohorizontal control for Mount Steinfeld, we consider the mean pole for the well-supported Mount Vance/LeMasurier volcanics (185.6°E / 56.8°S, A_{95} = 8.7°, for N = 6 sites) (Table 1) to be the best estimate for the ~117 Ma south pole position for at least the Ruppert/Hobbs Coast sampling area of MBL.

Comparison of Paleomagnetic Poles

The Early and mid-Cretaceous paleomagnetic poles from MBL are compared with poles from TI and AP and the East Antarctic apparent polar wander (APW) path in order to determine relative motions (Figure 10; Table 2). The mid-Cretaceous pole for MBL (MBL 100) [*DiVenere et al.*, 1994] groups well with the 110 Ma pole from TI (TI 110) [*Grunow et al.*, 1991] and a mean pole of similar age calculated for AP (AP 106M) [*DiVenere et al.*, 1994]. These mid-Cretaceous poles are, however, significantly offset from the East Antarctic APW path determined using a global database of paleomagnetic poles transferred into East Antarctic coordinates [*DiVenere et*
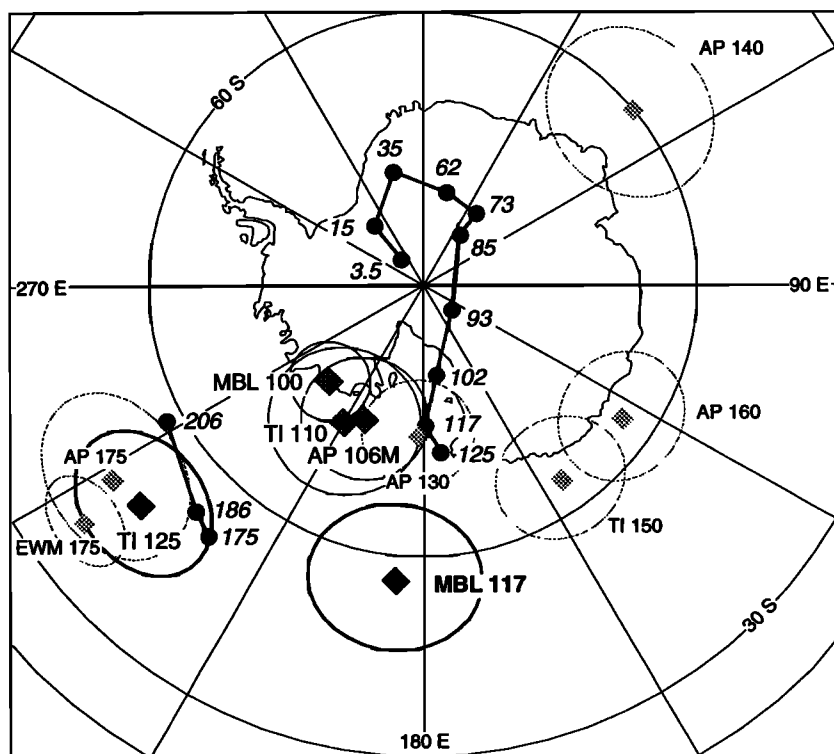
Figure 10. West Antarctic poles with A_{95} circles of confidence (diamonds) (see text and Table 2) plotted with the East Antarctic APW path of *DiVenere et al.* [1994] (circles).

al., 1994]. From the paleomagnetic comparisons and geologic evidence for Cretaceous and Cenozoic extensional tectonics in the Ross Sea region, we inferred that MBL, TI, and AP have not experienced paleomagnetically resolvable differential motion since about 100 Ma, but that there has been significant post-100 Ma motion between these Pacific-bordering West Antarctic blocks and the East Antarctic craton, and in particular, that MBL as a whole has been displaced several hundred kilometers from a position closer to Victoria Land as a result of the opening of the Ross Sea [*DiVenere et al.*, 1994].

The new ~117 Ma mean pole (MBL 117 in Figure 10), based on the results from the volcanics at Mount Vance/LeMasurier of East MBL (east of the Land Glacier), is significantly different from the ~100 Ma MBL pole (MBL 100), with an angular separation of 24 ± 9°. In contrast, the amount of APW for East Antarctica between about 117 and 102 Ma was only 6 ± 5° (Figure 10 [*DiVenere et al.*, 1994]). Therefore, East MBL must have moved independently of East Antarctica between 117 and 100 Ma.

MBL 117 is offset from the ~117 Ma East Antarctic paleomagnetic pole by 18 ± 9°. This may be resolved into components of rotation (53 ± 23° clockwise) and poleward translation (12 ± 7° southward), using the method described by *Beck* [1989], which represent the accumulated motion (rotation and poleward translation, but not longitudinal motion) of East MBL with respect to East Antarctica since about 117 Ma (actually, with respect to the 117 Ma pole for East Antarctica). Removing the post-100 Ma offset (indeterminate rotation and 11 ± 6° northward translation) yields a net poleward translation of 24 ± 9° south for East MBL between 117 and 100 Ma. Therefore, East MBL moved towards Victoria Land (which was situated near the South Pole) between

117 and 100 Ma, but since 100 Ma, MBL as a whole has moved away from Victoria Land by a smaller amount (i.e., East MBL was farther from Victoria Land at about 117 Ma than it presently is). The implied East MBL-East Antarctica relative motion between 117 and 100 Ma would be even greater if we chose to use the combined MBL ~117 Ma results (including Mount Steinfeld with or without the tilt-corrected Mount Sinha and Wilkins Nunatak site 14).

Cretaceous paleomagnetic results from the Thurston Island (TI) block show a somewhat similar pattern to those from MBL (Figure 10). The difference between the ~125 Ma pole for TI (TI 125) of *Grunow et al.* [1987a] and the ~110 Ma result (TI 110) [*Grunow et al.*, 1991] indicates 26 ± 11° of angular change for TI over this ~15 m.y. time interval, similar to the difference between MBL 117 and MBL 100. We note again that APW for East Antarctica was much smaller (~3°) over the period between 125 and 110 Ma. Therefore, as for East MBL, TI moved independently of East Antarctica during the Early Cretaceous.

The large offset between TI 125 and the ~125 Ma pole for East Antarctica [*DiVenere et al.*, 1994] has been discussed by *Grunow et al.* [1991]. The angular separation between TI 125 and the ~125 Ma pole for East Antarctica is 34 ± 9°, which resolves into 86 ± 16° clockwise rotation and 2 ± 7° southward translation, describing the accumulated latitudinal translation and rotational motion of TI with respect to East Antarctica since about 125 Ma. Removing the post-110 Ma motion of TI with respect to East Antarctica (26 ± 26° clockwise and 6 ± 7° northward) yields a net 60 ± 30° clockwise rotation and 8 ± 10° southward translation of TI between 125 and 110 Ma.

The above results from East MBL and TI show that both blocks experienced major tectonic motions with respect to East Antarctica during late Early Cretaceous times. East MBL

Table 2. Paleomagnetic Poles

Block	Age	N	A_{95}	Lon°E	Lat°N	Source
MBL	117	6	8.7	185.6	-56.8	this study
MBL	100	19	3.8	224.1	-75.7	*DiVenere et al.* [1994]
TI	150	5	7	145	-64	*Grunow et al.* [1991]
TI	125	5	7.9	232	-49	*Grunow et al.* [1987a]
TI	110	7	7.6	210	-73	*Grunow et al.* [1991]
AP	175	4[a]	9.5	238	-48	*Longshaw and Griffiths* [1983]
AP	160	10	7.1	124	-64	*Grunow* [1993]
AP	140	4	9.5	50	-60	*Grunow* [1993]
AP	130	6	5.9	182	-74	*Grunow* [1993]
AP	106M	29	6.2	203.8	-74.3	calculated in *DiVenere et al.* [1994] from site means of *Kellogg* [1980], *Kellogg and Rowley* [1989], and *Grunow* [1993]
EWM	175	8	5.3	235.2	-41.2	*Grunow et al.* [1987b]
NZ	207	24	10.6[b]	162	-24	*Grindley et al.* [1981] with updated age from *Graham et al.* [1993]
EAnt	102	6[c]	4.2	171.8	-80.3	*DiVenere et al.* [1994]
EAnt	117	4[c]	2.9	179.2	-74.9	*DiVenere et al.* [1994]
EAnt	125	6[c]	3.5	173.9	-71.9	*DiVenere et al.* [1994]
EAnt	175	17[c]	4.4	220.4	-52.7	*Kellogg* [1988]
EAnt	186	3[d]	11.0	225.3	-54.3	*Van der Voo* [1993][e,f]
EAnt	206	4[d]	7.0	242.4	-58.0	*Van der Voo* [1993][f,g]

MBL, Marie Byrd Land; TI, Thurston Island; AP, Antarctic Peninsula; EWM, Ellsworth-Whitmore Mountains; EAnt, East Antarctica; NZ, New Zealand; Lon and Lat are mean paleomagnetic pole east longitude and north latitude (negative is south latitude); N is number of sites used to calculate mean; A_{95} is the radius of the 95% cone of confidence about the mean pole.

[a] $N = 4$ group means from 24 site means.
[b] A_{95} conservatively estimated as the major axis of the confidence ellipse.
[c] Number of studies.
[d] Number of continent mean poles.
[e] Jl mean pole, 260°E / 70°N in northwest African coordinates.
[f] Gondwana mean poles rotated to East Antarctic reference frame using euler pole consistent with *Van der Voo* [1993] plate model (-12.36/-33.81/-53.29).
[g] Tru/Jl mean pole, 230°E / 70°N in northwest African coordinates.

experienced a large (~24°) southward translation towards Victoria Land between 117 and 100 Ma. The Early Cretaceous pole from TI is offset in the same sense, but the amount is not statistically significant (8° ± 10°). Unfortunately, East MBL's 117 to 100 Ma rotation can not be separated from its 100 Ma to Recent rotation because the 100 Ma pole (MBL 100) lies directly over MBL itself. Nevertheless, both East MBL and TI have experienced large (~53° and 86°, respectively) cumulative clockwise rotation with respect to East Antarctica since the Early Cretaceous, and a large (~60°) clockwise rotation characterizes the motion of TI with respect to East Antarctica from 125 to 110 Ma. In summary, the motion of East MBL with respect to East Antarctica contains a large component of latitudinal translation while that for TI is dominantly a rotation during late Early Cretaceous times; any longitudinal components of motion cannot be determined from the paleomagnetic data but must be constrained by indirect geological arguments.

There are no Cretaceous or younger rocks in the Ellsworth-Whitmore Mountains block (EWM). The ~175 Ma pole of *Grunow et al.* [1987b] (EWM 175) is similar to but significantly offset from the well-constrained 175 Ma pole for

East Antarctica (EAnt 175) [*Kellogg*, 1988]. The angular difference between EWM 175 and EAnt 175 is 15 ± 7°, which decomposes into 19 ± 9° clockwise rotation and 10° ± 6° southward translation for the total motion of EWM with respect to East Antarctica (EAnt 175) since 175 Ma. Based on geological evidence and paleomagnetic results from Cambrian sedimentary strata [*Watts and Bramall*, 1981; *Grunow et al.*, 1987b] and Middle Jurassic igneous rocks (EWM 175), *Dalziel and Grunow* [1992] concluded that EWM had been displaced from an original position within Gondwana between the Pensacola Mountains of East Antarctica and the Cape Mountains of South Africa, and had experienced a ~90° counterclockwise rotation, following Permo-Triassic folding but prior to the Middle Jurassic.

DiVenere et al. [1994] reviewed the mid-Cretaceous paleomagnetic results available from the Antarctic Peninsula (AP) and calculated a ~106 Ma mean pole from the combined northern AP results of *Grunow* [1993] and southern AP results of *Kellogg and Rowley* [1989]. This pole (AP 106M in Figure 10) is consistent with the 100 to 110 Ma results from MBL and TI, implying that AP has not experienced significant post-100 Ma relative motion with respect to MBL and TI. Like

MBL 100 and TI 110, AP 106M is offset from the East Antarctic APW path, implying a small but significant post-100 Ma motion with respect to the craton.

The Middle Jurassic pole for AP (AP 175) [*Longshaw and Griffiths*, 1983] is consistent with EWM 175 and similarly implies a moderate (20 ± 14° clockwise) rotation of AP with respect to East Antarctica since about 175 Ma, some of which is accounted for by post ~100 Ma motions [*DiVenere et al.*, 1994]. Accordingly, *Grunow et al.* [1987b] suggested that EWM and AP have moved as a single block since about 175 Ma and together rotated with respect to East Antarctica, due to the opening of the Weddell Sea.

Paleomagnetic data for the period between about 175 and 110 Ma present a less coherent picture for the motion of AP during this time. *Grunow's* [1993] Late Jurassic and Early Cretaceous AP results (AP 160 and AP 140) show very large offsets from the East Antarctic APW path, implying that AP experienced a major clockwise rotation with respect to East Antarctica between 175 Ma and 160/140 Ma, which she considered to be the result of opening of a wide Weddell Sea as a result of Gondwana breakup. This was apparently followed by a large counterclockwise rotation of AP into its present position (with respect to East Antarctica) by 130 Ma, based on the 130 Ma pole (AP 130) of *Grunow* [1993]. This counterclockwise rotation was proposed to have resulted in the subduction of as much as 1000 km of Jurassic Weddell seafloor beneath southeastern AP, giving rise to the Early Cretaceous Palmer Land deformation event in the southern AP [*Kellogg and Rowley*, 1989]. Although these rotations are lent some credence by the similarity of AP 160 with the Late Jurassic pole from TI (TI 150) [*Grunow et al.*, 1991], which also implies a major clockwise rotation of TI (with respect to East Antarctica) between about 150 and 125 Ma, the complicated sequence of large AP rotations implied at face value by the 160, 140, and 130 Ma poles belies the simple pattern represented by the bracketing 175 and 106 Ma poles. We suggest that the 160 and 140 Ma results (which do not agree well with one another) may represent localized block rotations. Alternatively, the northernmost AP, north of 64°S, could have rotated independently of the remainder of AP south of 66°S between about 160 and 106 Ma. Otherwise, a fortuitous combination of rotations is needed for all AP to account for the agreement of AP 175 with EWM 175.

There are also problems with the suggestion that AP was in its present position with respect to East Antarctica by 130 Ma [*Grunow*, 1993]. Three of the six sites that make up the 130 Ma pole of *Grunow* [1993] are from an apparently remagnetized siltstone unit. Also, the 130 Ma results are of uniform normal polarity and fall in the vicinity of the ~106 Ma mean pole for AP, suggesting the possibility of partial or complete remagnetization as a result of the widespread mid-Cretaceous intrusive event, during which time the field was of normal polarity. Therefore, we propose that the existing paleomagnetic data show that AP was in its present position with respect to MBL and TI, and near its present position with respect to East Antarctica, by about 106 Ma and not necessarily before.

More work clearly needs to be done to clarify the Late Jurassic through Early Cretaceous motions of AP. The arguments presented above suggest that the motions of AP, or at least that part south of 66°S, may be described by the relatively simple motions implied by AP 175 and AP 106M, without a major rotation during the Late Jurassic and Early

Cretaceous. This would imply a different cause for the Palmer Land deformation event in the southern AP than that proposed by *Grunow* [1993].

Tectonic Reconstruction of West Antarctica

Prior to rifting at about 100 Ma and final separation by about 85 Ma, New Zealand (including the Chatham Rise and Campbell Plateau) was adjacent to MBL [*Mayes et al.*, 1990]. Given the complementary convergent margin tectonic associations of Mesozoic calc-alkaline rocks in East MBL and the Mesozoic arc, forearc, and accretionary complex rocks of the Eastern Province of New Zealand, it is reasonable assumption that East MBL and the Eastern Province of New Zealand may have shared a common history.

The geology of West MBL (approximately west of the Land Glacier), which contains the Swanson Formation turbidites and Ford Granodiorite, is linked to the Robertson Bay and Bowers terranes of North Victoria Land and the Western Province of New Zealand. Both North Victoria Land and the Western Province of New Zealand contain likely equivalent lower Paleozoic turbidites and Devonian granodiorite. North Victoria Land, with the western provinces of New Zealand and MBL, are thought to have accreted to East Antarctica during the late Paleozoic [*Weaver et al.*, 1991; *Borg and DePaolo*, 1991]. There is, however, no clear relationship between the Eastern and Western Provinces of New Zealand across the Median Tectonic Zone [*Bradshaw*, 1989, 1993; *Kimbrough et al.*, 1993] (Figure 1).

The Permian through Lower Cretaceous arc, forearc, and accretionary complex rocks of the Eastern Province of New Zealand were formed on the convergent margin of the south Pacific rim of Gondwana, which included New Zealand, the Antarctic Peninsula and Scotia Arc, and southern South America [*Dalziel and Grunow*, 1985; *Dalziel and Forsythe*, 1985; *Bradshaw*, 1989; *Tranter* 1991]. Previous reconstructions (based on the Paleozoic geologic relations) had maintained all of MBL and New Zealand in a position adjacent to North Victoria Land similar to their mid-Cretaceous, pre-breakup position. This position leaves a large gap between the forearc sequences of New Zealand and AP, though models have been put forward to account for the gap (e.g., Figure 2 in *Dalziel and Grunow*, 1992).

Given the geologically reasonable assumption that East MBL was part of the Pacific convergent margin of Gondwana, comparison of the new 117 Ma pole with the East Antarctic APW path implies that East MBL was of the order of 1000 km more distant from North Victoria Land in the Early Cretaceous than it presently is. Based on this, we propose an Early Cretaceous reconstruction (Figure 11a) in which East MBL and the Eastern Province of New Zealand are placed adjacent to the Weddellia crustal blocks (AP, TI, and EWM). The western provinces of MBL and New Zealand are maintained in their presumed Devonian through mid-Cretaceous position adjacent to North Victoria Land. As a first order approximation, the Chatham Rise and Campbell Plateau are held rigidly to East MBL in their mid-Cretaceous, preseparation configuration. We have removed the Cenozoic deformation along the Alpine Fault from the Eastern Province of New Zealand. The present outlines of the West Antarctic crustal blocks (see Figure 1) are used in the reconstruction. The area within the West Antarctic continental outline, but between the presumed rigid West Antarctic blocks (Figures 1, 11a, and 11b), is assumed to be

a

118 Ma (M0)

b

175 Ma
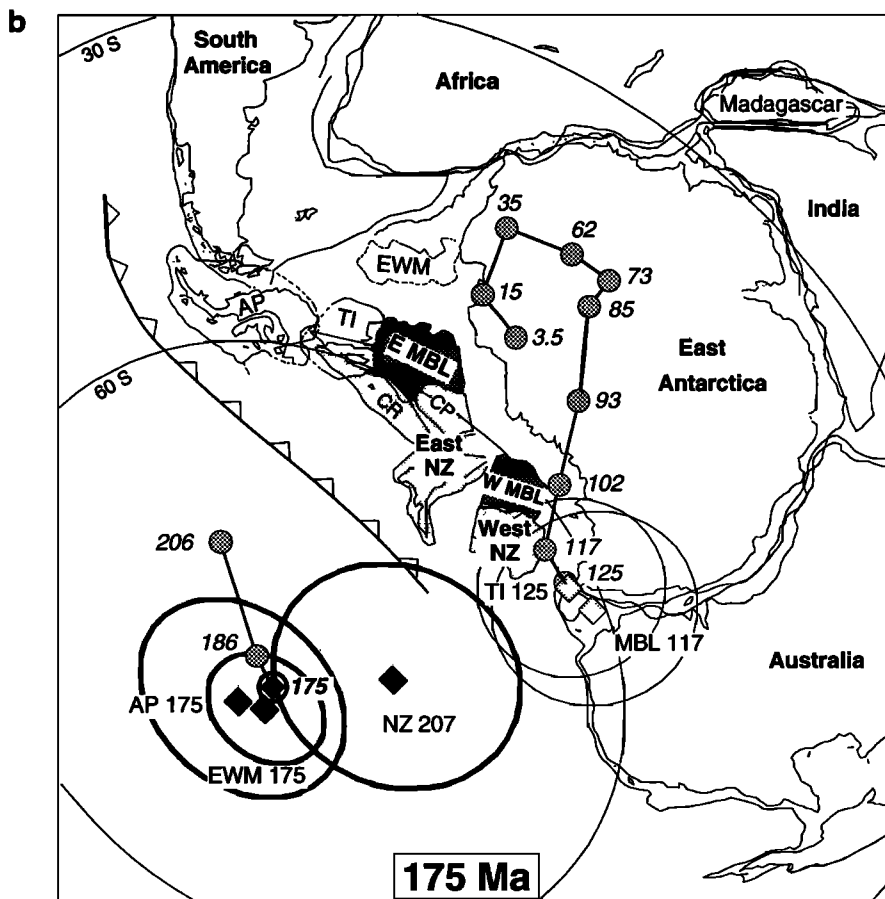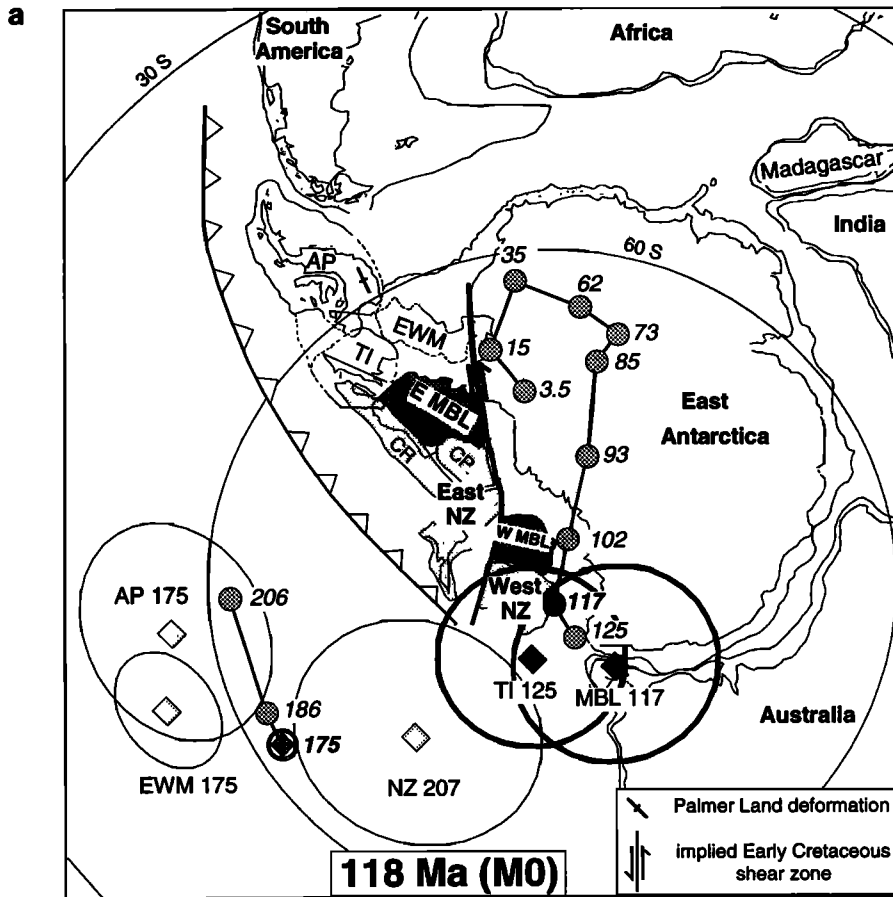
continental crust that has behaved in a nonrigid manner (in a gross sense) between the time of Gondwana breakup and the present. Our reconstruction reconciles the Early Cretaceous poles from East MBL and TI with the East Antarctic APW path while maintaining the coherence of the belt of Permian igneous rocks found in East MBL and in TI, and places the Eastern Province of New Zealand along a continuous convergent margin (Figure 11a). The reconstruction is similar to the Early Cretaceous model of *Grunow* [1993] for West Antarctica, but implies a somewhat larger amount of displacement for TI (as is in fact indicated by the TI 125 pole) and, significantly, now includes East MBL and the Eastern Province of New Zealand within Weddellia.

Relatively little adjustment of Weddellia is required in the Early Cretaceous reconstruction to produce a 175 Ma (pre-Gondwana breakup) reconstruction (Figure 11b), though AP must be moved to avoid overlap with South America. The rotation of AP shown in the reconstructions is in keeping with the clockwise rotation of the Andean magmatic arc required by the initial opening of the Rocas Verdes basin in southern South America and the Weddell Sea basin in the Late Jurassic and Early Cretaceous [*Barker et al.*, 1991]. The 175 Ma reconstruction (Figure 11b) satisfies the Middle Jurassic poles from AP and EWM, and interestingly, the Early Cretaceous poles from MBL and TI with respect to the East Antarctic APW path. The pre-breakup configuration maintains the continuity of the forearc and accretion complexes of South America, AP, and the Eastern Province of New Zealand.

Further support for these reconstructions comes from paleomagnetic data from New Zealand. If all of New Zealand is kept in its prerift, ~100 Ma position with respect to East Antarctica [*DiVenere et al.*, 1994], then the earliest Jurassic paleopole from the Murihiku Terrane of the Eastern Province of New Zealand (NZ 207, Figure 11b) (paleomagnetic results of *Grindley et al.* [1981]; revised age of *Graham et al.* [1993]) does not agree with the East Antarctic APW path, as noted by *Grindley et al.* [1981]. The New Zealand pole implies that at least the Murihiku Terrane was at a lower paleolatitude than would be the case given a mid-Cretaceous, predrift position for New Zealand [e.g., *DiVenere et al.*, 1994]. In the pre-Gondwana breakup reconstruction (Figure 11b), NZ 207 is offset from the East Antarctic APW path, but now the position of East New Zealand is consistent with the paleolatitude implied by the pole. We assumed for the reconstruction (Figures 11a and 11b) that East MBL and Eastern Province of New Zealand comprised a single block until New Zealand separated from Antarctica by about 85 Ma. The New Zealand pole may be more fully reconciled with the East Antarctic APW path if East MBL and the Eastern Province of New Zealand, together or individually, are allowed a small to moderate counterclockwise vertical axis rotation between the Jurassic and Early Cretaceous. It can be seen therefore that while MBL

117 implies that East MBL and the Eastern Province of New Zealand were part of Weddellia as late as about 117 Ma, it may be inferred from NZ 207 that this general crustal configuration had existed as early as the earliest Jurassic.

Following Gondwana breakup, the Weddellia blocks were displaced as a result of changing plate kinematics between Antarctica, South America, and Africa. A simple model would have AP moving northward with South America between the Middle Jurassic and the Early Cretaceous. Regardless of whether or not significant rotations of the Weddellia blocks occurred between 175 and 125 Ma [*Grunow et al.*, 1991; *Grunow* 1993], the new 117 Ma pole from MBL requires that East MBL, TI, and EWM were not displaced towards their mid-Cretaceous positions [*DiVenere et al.*, 1994] until after 117 Ma (Figure 11a).

Marine geophysical evidence for the age of oldest oceanic lithosphere in the Weddell Sea is equivocal, with estimated ages ranging from around 160-156 Ma (M29 to M25; [*LaBrecque and Barker*, 1981; *LaBrecque*, 1986]) to as young as about 130 Ma (M10) as indirectly inferred from the spreading history in the southwest Indian Ocean [*Martin and Hartnady*, 1986]. Ophiolitic remnants of the Rocas Verdes basin floor are dated as old as 150 Ma [*Mukasa et al.*, 1988]. Nevertheless, our model and previous paleomagnetically controlled tectonic models indicate that major rotations of the Weddellia blocks postdate these estimates for initial opening of the Weddell Sea. If the interpretations of the marine geophysical and paleomagnetic data are both correct, then the major movements of Weddellia may be linked to a plate reorganization during the Cretaceous Quiet interval which is difficult to map due to the expected absence of magnetic lineations.

Grunow [1993] related the Palmer Land deformation event in the southern AP, in which Middle and Upper Jurassic volcanic and sedimentary rocks were folded and thrusted prior to the emplacement of the Lassiter Coast intrusive suite, to the subduction of ocean crust, first created and then destroyed by the proposed large clockwise and ensuing counterclockwise rotations of AP and TI during the Late Jurassic and Early Cretaceous. The Lassiter Coast intrusions were emplaced largely between about 110 and 96 Ma [*Kellogg and Rowley*, 1989], though one unit has been dated at 128 Ma [*Pankhurst and Rowley*, 1991]. In any prebreakup reconstruction that satisfies the Middle Jurassic pole from AP while reserving space for the rest of Weddellia (which now includes MBL and the Eastern Province of New Zealand), northern AP must be placed outboard of southern South America to avoid overlap with South America. The Antarctic Peninsula must then move northeasterly with South America towards East Antarctica while rotating clockwise between breakup and the mid-Cretaceous, by which time it is expected to be nearer to its present position with respect to East Antarctica [*DiVenere et*

Figure 11. Reconstruction of the West Antarctic and New Zealand crustal blocks within Gondwana (East Antarctica fixed) for (a) ~118 Ma (anomaly M0) and (b) ~175 Ma. Diamonds are paleomagnetic poles from West Antarctic blocks and New Zealand with A_{95} circles of confidence (Table 2) shown in reconstructed positions. Connected gray circles are the East Antarctic APW path: Cretaceous through Cenozoic path is from *DiVenere et al.* [1994]; 175 Ma pole is from *Kellogg* [1988]; 186 and 206 Ma poles are Gondwana mean poles of *Van der Voo* [1993] transferred into the East Antarctic reference frame. Crustal blocks: AP, Antarctic Peninsula; TI, Thurston Island; EWM, Ellsworth Whitmore Mountains; E MBL and W MBL, East and West Marie Byrd Land; NZ, New Zealand; CR, Chatham Rise; CP, Campbell Plateau.

al., 1994]. The Palmer Land deformation may therefore have been caused by collision with EWM (which is now constrained by the new Early Cretaceous result from MBL to lie inboard of AP until after 117 Ma) or by compression of the intervening "nonrigid" crust that may have lain between AP and EWM. Alternatively, the Palmer Land deformation may have been caused by AP overriding the early formed Weddell Sea crust formed as a result of the motion of South America away from Weddellia during the Late Jurassic and Early Cretaceous. A large amount of subduction beneath the Weddell Sea side of AP is in any event not particularly appealing since it would mean two-sided subduction about a relatively narrow strip of continent.

The displacements of the Weddellia blocks eventually resulted in the suturing of East and West MBL and the Eastern and Western provinces of New Zealand. The timing of the implied suturing (between about 117 and 100 Ma) is approximately coeval with the last phase of the Rangitata II Orogeny in New Zealand [*Bradshaw*, 1989]. Though *Bradshaw* [1989] proposed that this deformation might have been caused by the approach and subduction of the Phoenix/Pacific Ridge, the motions inferred from the MBL and New Zealand paleomagnetic results suggest that the Eastern Province-Western Province amalgamation may have been at least partly responsible.

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