Paleomagnetic study of the northern Ford Ranges, western Marie Byrd Land, West Antarctica: Motion between West and East Antarctica

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Abstract. A paleomagnetic study of Paleozoic and Mesozoic crystalline rocks in the northern Ford Ranges of Marie Byrd Land, West Antarctica, has determined a middle Cretaceous (circa 100 Ma) paleomagnetic pole and provided constraints on possible clockwise rotation of these ranges and on the rifting of east Gondwana. The $^{40}Ar/^{39}Ar$ thermochronology data from the Fosdick Mountains record a period of rapid cooling from ~700°C beginning at ~100 Ma. We relate this to extension, intrusion, and uplift associated with the beginning of rifting between Campbell Plateau and Marie Byrd Land. All rocks from the Fosdick and Chester Mountains are normally polarized. We interpret thermochronology and paleomagnetic data to infer that the region was extensively remagnetized in middle Cretaceous time. Inclinations in samples from the Chester Mountains are less steep than those from the Fosdick Mountains, which we interpret as ~25° of south tilting of the Chesters. We interpret cooling age data for the time of magnetization to infer that the tilting began after 105 Ma and ended prior to 103 Ma. We further interpret this as constraining the beginning of extension between the Campbell Plateau and western Marie Byrd Land to the interval 105 to 103 Ma. Virtual geomagnetic poles from samples of Early Carboniferous age granodiorite from the western Phillips Mountains lie on the late Paleozoic apparent polar wander path for Australia transferred to Antarctica. Directions from 29 sites in the central and eastern Phillips and Fosdick Mountains give a Middle Cretaceous paleomagnetic pole at 222.3° E, 70.5° S (A95 6.1°, KAPPA 20.0). This pole is indistinguishable from other Middle Cretaceous poles for studies further east in Marie Byrd Land. Combining middle Cretaceous poles determined for three other studies of the Antarctic Peninsula, Thurston Island, and the Ruppert-Hobbs coasts with ours gives a Pacific West Antarctic pole at 215.2° E, 73.5° S (A95 4.0°, KAPPA 528.9). This pole is discordant by 5° to 10° from synthetic mid-Cretaceous East Antarctic reference poles, but the degree of discordance is very sensitive to the choice of the specific reference pole. The lack of native East Antarctic reference poles leaves this analysis inconclusive. Accepting 10° of discordance, we favor an interpretation where Pacific West Antarctic crustal domains or microplates have rotated clockwise 40° to 90° and translated a few degrees away from East Antarctica during Late Cretaceous time.

Purpose of Study

A paleomagnetic study of igneous and metamorphic rocks from outcrops in the northern Edsel Ford Ranges of western Marie Byrd Land (MBL) was undertaken as a part of a larger geological study of this region (Figure 1). A primary goal of the overall study was to determine whether metamorphic rocks exposed in the Raymond Fosdick Mountains could be a metamorphic core complex similar to Cretaceous complexes found in New Zealand [*Gibson et al.*, 1988; *Tulloch and Kimbrough*, 1989]. Our study included geologic mapping, metamorphic petrology, U-Pb and $^{40}Ar/^{39}Ar$ thermochronology, paleomagnetism, and anisotropy of magnetic susceptibility. The paleomagnetic program had as its goals (1) determination of Carboniferous, Cretaceous, and Cenozoic poles for a Pacific West Antarctic apparent polar wander path (APWP); (2) testing whether western Marie Byrd Land was distinct from other West Antarctic microplates [*Grunow et al.*, 1991]; and (3) testing whether Marie Byrd Land is tectonically distinct from Victoria Land in East Antarctica [*Grindley and Oliver*, 1983; *DiVenere et al.*, 1994].
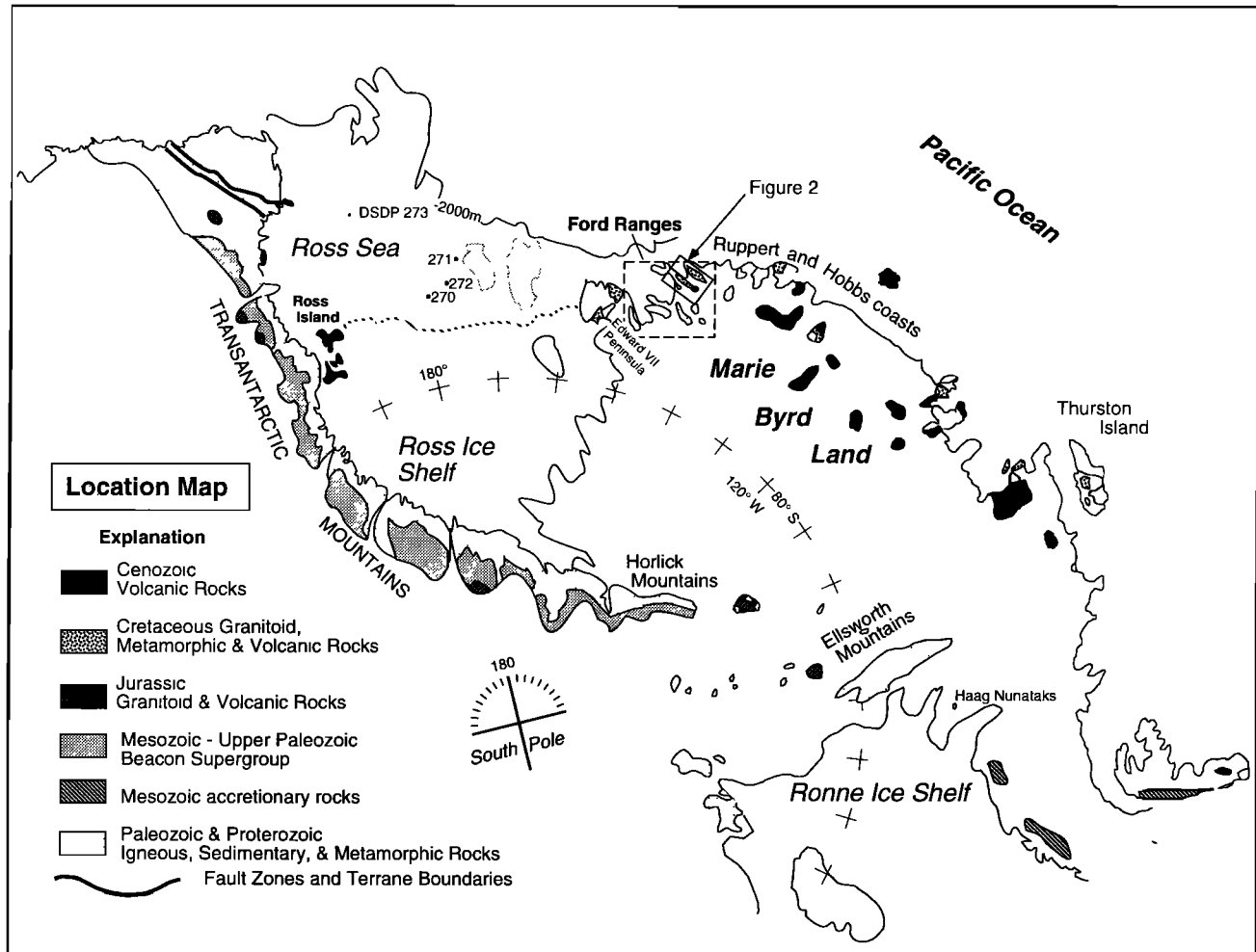
Geologic Setting

Microplates in West Antarctica

West Antarctica is proposed to comprise four separate geologic terranes or microplates [*Dalziel and Elliot*, 1982; *Dalziel and Grunow*, 1985]. These are the Antarctic Peninsula, the Ellsworth-Whitmore Mountains, Thurston Island-Eights Coast, and Marie Byrd Land. The basis for this division is the contrasting geology and tectonic histories between them, paleomagnetic data, subice deeps separating the terranes, and overlap of the Antarctic Peninsula with the Falkland Plateau in Mesozoic reconstructions. Paleomagnetic data have been interpreted to suggest that West Antarctic terranes have been fixed to one another since Middle Cretaceous time [*DiVenere et al.*, 1994]. Pre-Middle Cretaceous paleomagnetic data suggest a history of complex relative motions among the terranes and

Figure 1. Geologic setting of Marie Byrd Land in West Antarctica showing the location of the Ford Ranges, the Ruppert and Hobbs Coasts, and Thurston Island. Drill sites of Deep Sea Drilling Project Leg 28 in the Ross Sea are shown. Geology is from *Craddock et al.* [1989].

between the terranes and East Antarctica [*Grunow et al.*, 1991; *Grunow*, 1993].

Pacific West Antarctic (excluding the Ellsworth Mountains) elevation and relief are subdued in contrast to the spectacular Transantarctic Mountains and the East Antarctic Polar Plateau. Precambrian crust in West Antarctica is found in the Haag Nunataks of Ellsworth Land adjacent to Weddell Embayment [e.g., *Storey et al.*, 1988; *Tingey*, 1991]. However, Proterozoic U-Pb inheritance ages from Phanerozoic plutons in western Marie Byrd Land suggest a Precambrian component in the crust underlying this region [*Kimbrough and Richard*; 1991; *Palais et al.*, 1993]. Most Pacific West Antarctica rock outcrops consist of Phanerozoic subduction-related intrusive and volcanic rocks.

The Pacific margin of West Antarctica, including the microplates of Marie Byrd Land, Thurston Island-Eights Coast, and the Antarctic Peninsula, has been an active margin of east Gondwana for most of Paleozoic and Mesozoic time [*Borg and DePaolo*, 1991; *Elliot*, 1991; *Barker et al.*, 1991]. This margin was once continuous from Australia to South America and was subducting ine Phoenix plate during Mesozoic time [*Bradshaw*, 1989; *Barker et al.*, 1991]. In Late Cretaceous time

the continental masses of New Zealand, the Lord Howe Rise, the Chatham Rise, and Campbell Plateau (Zealandia [*Luyendyk*, 1995]), separated off from east Gondwana [e.g., *Mayes et al.*, 1990; *Lawver et al*, 1992]. Seafloor spreading between Marie Byrd Land and the Campbell Plateau began about 85 Ma [*Mayes et al.*, 1990; *Lawver et al.*, 1992] but this was preceded by about 20 million years of extension throughout Zealandia [*Bradshaw*, 1991]. The transition from subduction to extension along the margin occurred abruptly around 105 Ma in New Zealand [*Bradshaw*, 1989] and Marie Byrd Land [*Weaver et al.*, 1994]. Luyendyk [1995] explains this sudden transition by capture of a microplate piece of the subducted Phoenix plate beneath the margin by the Pacific plate. Northward motion of the Pacific plate and captured Phoenix microplate extended the margin and Zealandia.

## Extension Between East and West Antarctica

Extension between Zealandia microcontinents and Antarctica resulted in continental rifting and formation of the Southern Ocean basins. There is also evidence for extension within Antarctica, between the West Antarctic microplates and

the East Antarctic craton. Marie Byrd Land is separated from East Antarctica by the Ross Embayment, a province of horsts and grabens which underlies the Ross Sea and Ross Ice Shelf and extends eastward between the Transantarctic Mountains and Marie Byrd Land (Figure 1). The Ross Embayment is the locus of the majority of extension. Cooper et al. [1987, 1991], interpreting marine seismic reflection data, suggest two phases of extension here, a major one in Jurassic and Cretaceous time followed by a lesser one beginning in Eocene time. Marine geophysical data suggest that the second extension phase in the Ross Embayment ended in the eastern Ross Sea by mid-late Oligocene time but continues in the west within the Victoria Land Basin to present day [Cooper et al., 1991]. Middle Jurassic continental flood basalts of the Ferrar Group in the Transantarctic Mountains are believed to mark the beginning of Mesozoic extension between East and West Antarctica [Elliot, 1992; Heimann et al., 1994]. Extension in the Ross Embayment has also been related to uplift of the Transantarctic Mountains. Fission-track cooling data from these mountains can be interpreted as reflecting episodic uplift in Early and Late Cretaceous, Eocene, and Plio-Pleistocene time [Fitzgerald et al., 1986; Fitzgerald, 1992; Stump and Fitzgerald, 1992]. The major Tertiary uplift is likely related to a global plate reorganization near the beginning of Eocene time [Scotese et al., 1988].

The Ross Embayment and Marie Byrd Land are parts of the West Antarctic rift system [e.g., Behrendt et al., 1991] which has been active during Cenozoic time. Cenozoic extension was marked by bimodal volcanism [Behrendt et al., 1991]. Crustal thicknesses in the rift, including Marie Byrd Land, are half that of East Antarctica [Behrendt et al., 1991; Bentley, 1973; 1991].

Geology of the Northern Ford Ranges

Geologic ties can be made between western Marie Byrd Land and the Robertson Bay terrane in northern Victoria Land across the Ross Sea. The Lower Paleozoic Swanson Formation in western Marie Byrd Land comprising deep water quartzose sediments [Bradshaw et al., 1983], may correlate with sedimentary rocks of the Robertson Bay Group in northern Victoria Land [Wade and Couch, 1982; Adams, 1986; Muir et al., 1994]. Both regions were evidently deformed during the Cambrian Ross orogeny. The Carboniferous Ford Granodiorite (see below) in Marie Byrd Land may correlate with the Admiralty Intrusives of northern Victoria Land [Weaver et al., 1991]. Borg and DePaolo [1991] argued that Marie Byrd Land amalgamated with terranes of northern Victoria Land including the Roberston Bay and Bowers terranes, at a location exotic to Gondwana from Ordovician through Devonian time. This
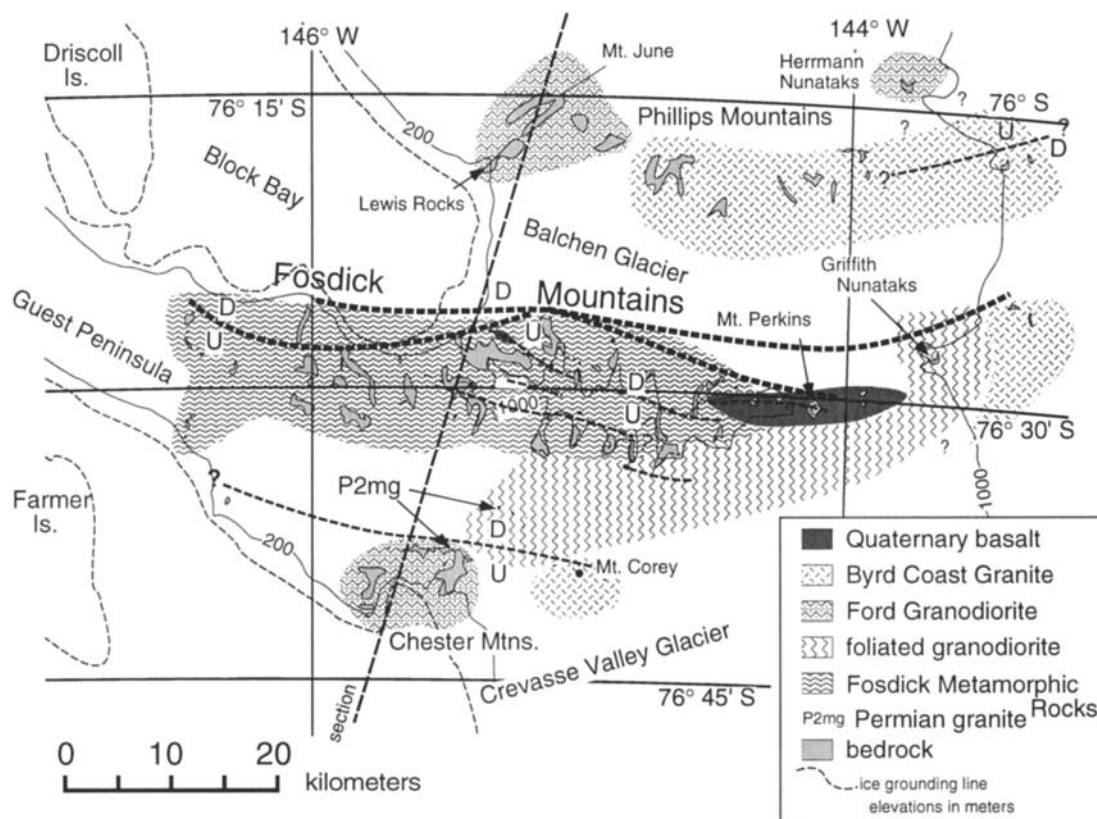
Figure 2. Geologic map of the northern Ford Ranges adapted from *Wade et al.* [1977a, 1978] and *Luyendyk et al.* [1992]. All faults are inferred. Our field mapping resulted in the following revisions to the maps of *Wade et al.* [1977a, 1978]: In the Phillips Mountains, outcrops at 145° W near Mount June are MDf not Kbc, and Herrmann Nunataks are MDf not Kbc. In the Fosdick Mountains, some outcrops mapped as Fosdick Metamorphic rocks (FMR) in the east are Cenozoic volcanics (QTv). We identified two new units: foliated granodiorite and Permian granite.
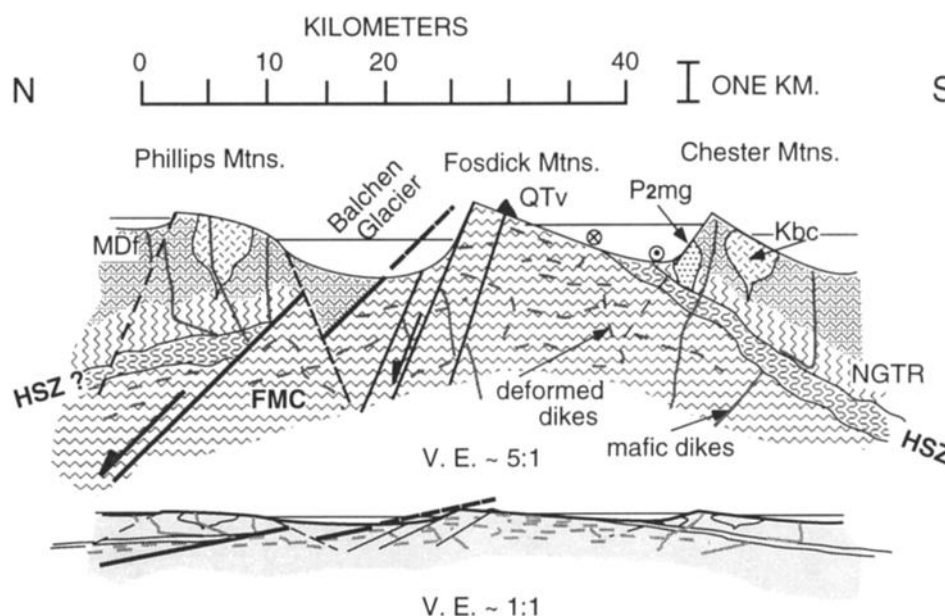
Figure 3. Hypothetical cross section through the northern Ford Ranges (see Figure 2). Abbreviations are HSZ, high shear zone; NGTR, Neptune-Griffith transitional rocks, the foliated granodiorite mapped in Figure 2.

composite terrane accreted to the East Antarctic craton by Permian time.

The Phillips, Fosdick, and Chester Mountains are located in the northern portions of the Ford Ranges of western Marie Byrd Land (Figure 1). They trend east-west and are each separated by about 15-20 km. Plutonic rocks crop out in the Phillips and Chester Mountains, while the Fosdick Mountains comprise high-grade metamorphic rocks (Figures 2 and 3). The Ford Granodiorite (MDf) is a Devonian-Carboniferous granodiorite-tonalite found in the Phillips and Chester Mountains and the Denfield Mountains immediately to the south. It is a calc-alkaline and metaluminous to peraluminous I-type granitoid [*Weaver et al.*, 1991]. Foliated hornblende-biotite tonalite or granodiorite with enclaves of gneiss (MDf?) is found at Neptune and Griffith Nunataks. *Kimbrough and Richard* [1991] reported a U-Pb zircon age of 353 Ma for MDf from the Chester Mountains. A Permian two-mica granite intrudes the MDf in the Chester Mountains and Neptune Nunataks [*Kimbrough and Richard*, 1991; *Richard et al.*, 1994]. The Byrd Coast Granite (Kbc) is a Cretaceous granite which is ubiquitous in the Ford Ranges and Edward VII Peninsula to the southwest [*Wade et al.*, 1977 a, b, c, 1978]. It has both A- and I-type characteristics [*Weaver et al.*, 1991, 1992, 1994]. Igneous textures indicate emplacement at shallow crustal depths. Ages determined by U-Pb analyses on zircons from Kbc at Mount Corey in the Chester Mountains are 105 to 103 Ma (D.L. Kimbrough, unpublished data, 1992). These Middle Cretaceous ages indentify the Kbc in the northern Ford Ranges as the A-type suite II granitoids of *Weaver et al.* [1994]. Both MDf and Kbc may be present in the Ruppert Coast to the northeast [*Spörli and Craddock*, 1981; *Bradshaw et al.*, 1991]. Although rocks similar to MDf are known in northern Victoria Land (Admiralty Intrusives), no rocks equivalent to the Kbc are known there.

The Fosdick Metamorphic Complex comprises migmatized paragneiss and orthogneiss found in the Fosdick Mountains [*Wilbanks*, 1972; *Smith*, 1992]. *Smith* [1995] has determined peak metamorphic conditions corresponding to midcrustal depths (500 to 529±70 MPa) and temperatures of 632°±78°C to 699°±67°C from geothermobarometry on paragneiss. Peak metamorphism and anatexis occurred at about 105 Ma [*Kimbrough and Richard*, 1991; *Richard* et al, 1994], contemporaneous with Kbc intrusion. In the northern Ford Ranges, mafic dikes intrude MDf, Kbc, and the Fosdick metamorphic rocks (FMR). Whereas dikes intruding the FMR are typically deformed and boudinaged, mafic dikes are undeformed within the other formations. In the central and eastern Fosdick Mountains, volcanic rocks of late Cenozoic age crop out. These are the westernmost outcrops of late Cenozoic age volcanic rocks in West Antarctica. Lavas from Mount Perkins are Pleistocene in age ($^{40}Ar/^{39}Ar$ whole rock age courtesy of W. McIntosh). We believe the Fosdick Complex has been uplifted rapidly from midcrustal depths in Late Cretaceous time [*Richard*, 1992; *Richard et al.*, 1994]. A hanging wall-footwall fault relationship is suggested between the Phillips and Fosdick Mountains (Figures 2 and 3). Although the Fosdick Mountains have cooling ages similar to New Zealand core complexes, they lack brittle structural features and low-grade metamorphic overprint typical of Cordilleran-style metamorphic culminations in the western United States [*Coney*, 1980; *Davis*, 1980] and New Zealand [*Tulloch and Kimbrough*, 1989].

The Phillips and Fosdick Mountains trend subparallel to the Transantarctic Mountains (as viewed in a polar projection), as do other mountain ranges within the Ford Ranges. Furthermore, the individual ranges trend oblique to the passive continental margin here. The north scarp of the central Fosdick Mountains is defined by spectacular cliffs up to 500 m

high. The Phillips, Fosdick, and Chester Mountains apparently form two or more fault blocks. It had been unclear to us if this faulting was associated with either or both Gondwana rifting in Cretaceous time [*Bradshaw*, 1991] or Cenozoic extension in the West Antarctic rift [*Behrendt et al.*, 1991].

Previous Paleomagnetic Studies

Three paleomagnetic studies have been completed in Pacific West Antarctica to the east of our area. In the Ruppert and Hobbs coasts of western Marie Byrd Land, *Grindley and Oliver* [1983] studied 26 sites in Cretaceous rhyolite volcanics and mafic dikes. K-Ar age dates on a subset of samples ranged from 112 to 91 Ma. They reported a pole at 241° E, 66° S, with dp = 8.7° and dm = 8.8°. *Grindley and Oliver* [1983] compared their pole to synthetic East Antarctic poles carried from Australia [*Embleton*, 1981] and New Zealand [*Grindley and Oliver*, 1979]. Both reference poles are similar and indicate a similar degree of post-middle Cretaceous motion. They concluded that Marie Byrd Land moved northeastward 200-500 km and rotated clockwise relative to East Antarctica since middle Cretaceous time. *Grunow et al.* [1991] computed six poles from sites further east near Thurston Island, including a 110 Ma pole from seven sites (210° E, 73° S, A95=7.6°). From this result and that of *Grindley and Oliver* [1983], they concluded that post-

Middle Cretaceous relative motion had occurred between Marie Byrd Land and Thurston Island.

DiVenere et al. [1994] also studied the Ruppert and Hobbs coasts region of Marie Byrd Land, including some of the localities of *Grindley and Oliver* [1983]. Using 19 middle Cretaceous site means, DiVenere et al. found a pole at 224.1° E, 75.7° S, A95 = 3.8°. They noted a difference between their pole and *Grindley and Oliver's* [1983] but close agreement with the Thurston Island pole of *Grunow et al.* [1991]. Arguing that the Grindley and Oliver pole is suspect because of undetected postmagnetization tilting. they concluded that their pole and that of Thurston Island are the most reliable. *DiVenere et al.* [1994] also constructed a synthetic APWP for East Antarctica using paleomagnetic poles from the Gondwana continents and North America. They compared the 102 Ma synthetic East Antarctic pole with their pole and concluded that significant post-Middle Cretaceous relative motion occurred between Marie Byrd Land and the East Antarctic craton.

Field Program

We conducted field studies during the 1989-1990 and 1990-1991 austral summers in the northern Ford Ranges (Project FORCE, Ford Ranges Crustal Exploration [*Luyendyk et al.*, 1992]). Drill cores or oriented hand samples were taken at 94 sites (Figure 4). Drilling was done with a solution of two parts
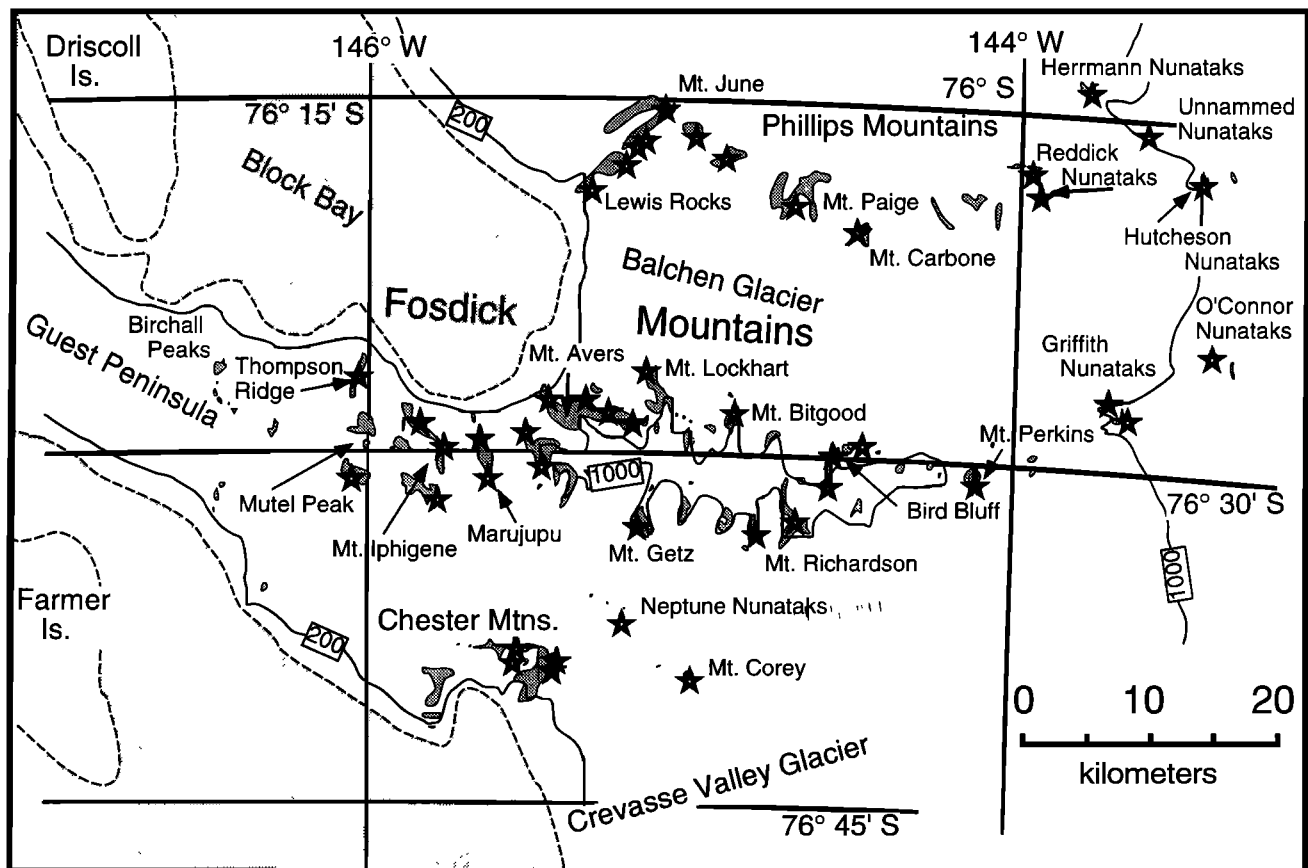
Figure 4. The northern Ford Ranges showing outcrops, paleomagnetic sampling sites (stars), and place names mentioned in the text. Not all sites yielded stable results (see Table A1).

ethylene glycol and one part water. Sun compass readings established the local magnetic variation as N088°E. Both Sun compass and magnetic orientations were taken. No significant local magnetic anomalies were detected. Retrieval of drill cores from the Kbc proved difficult owing to its coarse grain size and friable nature at some outcrops. Within the Fosdick Complex in the Fosdick Mountains, several rock types were sampled, including deformed and undeformed mafic dikes, anatectic and late-stage granites, gneiss, and leucosome and melanosome bodies. MDf, Kbc, and mafic dike samples were collected from the Phillips and Chester Mountains.

Geochronology: Age of Magnetization

Richard et al. [1994] reported the results of U-Pb and $^{40}Ar/^{39}Ar$ studies in the northern Ford Ranges (Table 1). The ages they reported were used to estimate the age of magnetization. The key assumption is that ages determined on mineral separates correspond to the times of cooling below the closure temperature for that mineral. *Richard et al.* [1994] used closure temperatures of 730°C for U-Pb monazite ages, along with 525°C for hornblende, 340°C for muscovite, 325°C for biotite, and 165°C for K-feldspar in the $^{40}Ar/^{39}Ar$ system. They interpreted these data as showing uplift and south tilting of the

Fosdick and Chester Mountains in the footwall of a normal fault in the vicinity of the Balchen Glacier (Figure 3).

MDf plateau cooling ages in the western Phillips Mountains are 356 Ma (hornblende). The hornblende age is close to the MDf crystallization age of 353 Ma found by U-Pb zircon dating in the Chester Mountains [*Kimbrough and Richard*, 1991]. Disturbed spectra from muscovite and K-feldspar in the western Phillips Mountains suggest reheating to between 150° and 250°C in parallel with middle Cretaceous high-grade metamorphism of the FMR. The $^{40}Ar/^{39}Ar$ spectra from the Chester Mountains are also disturbed. Heating above muscovite closure (approximately 340°C) occurred here in Middle Cretaceous time. At Neptune Nunataks, $^{40}Ar/^{39}Ar$ spectra show a biotite cooling age of 103 Ma (plateau age) on a foliated granodiorite sample. Spectra for hornblende on the same sample show disturbance attributed to Permian or middle Cretaceous intrusion events [*Richard et al.*, 1994]. Cooling ages for the FMR are uniformly middle Cretaceous (100 to 95 Ma). Both crystallization age and cooling age for the Kbc are middle Cretaceous. Field relations and $^{40}Ar/^{39}Ar$ results (Table 1) suggest that the mafic dikes are Early and middle Cretaceous in age.

Based on these data we propose that the FMR, mafic dikes, and Kbc magnetizations are middle Cretaceous in age and the

Table 1. Cooling Ages From the Northern Ford Ranges

Location	Rock Type	Technique	Age, Ma	Comment
Lewis Rocks, Phillips Mtns.	Ford Granodiorite	$^{40}Ar/^{39}Ar$: biotite	355 9 +/- 1 0	plateau age
Mt. June; Phillips Mtns.	Ford Granodiorite	$^{40}Ar/^{39}Ar$: hornblende	356 +/- 1.6	plateau age
Hutcheson, Phillips Mtns.	Byrd Coast granite	$^{40}Ar/^{39}Ar$: biotite	99 4 +/- 0.3	plateau age
Birchall Peaks, Fosdick Mtns.	Fosdick metamorphic rocks	$^{40}Ar/^{39}Ar$: biotite	97.9 +/- 0 2	plateau age
Mutel Peak, Fosdick Mtns.	dike in Fosdick Metamorphic Complex	$^{40}Ar/^{39}Ar$: hornblende	97.8 +/- 0.1	plateau age
Marujupu Peak, Fosdick Mtns.	Fosdick metamorphic rocks	U-Pb: monazite	106 +/- 1 0	
Mt. Avers, Fosdick Mtns	Fosdick metamorphic rocks	U-Pb. monazite	99.9	
Mt. Avers, Fosdick Mtns.	granite body in Fosdick Metamorphic Complex	$^{40}Ar/^{39}Ar$: muscovite	96 2 +/- 0.3	plateau age; 96.5 +/- 0.4 on biotite; 94.6 +/-0.2 plateau on K-feldspar
Mt. Lockhart, Fosdick Mtns.	Fosdick metamorphic rocks	$^{40}Ar/^{39}Ar$: muscovite	95.9 +/- 0 4	plateau age; 94.2 +/- 0.4 plateau on K-feldspar
Mt. Getz, Fosdick Mtns.	Fosdick metamorphic rocks	$^{40}Ar/^{39}Ar$: hornblende	100 9 +/- 0.5	98.3 +/- 0.3 plateau on biotite
Mt. Richardson, Fosdick Mtns.	Fosdick metamorphic rocks	$^{40}Ar/^{39}Ar$: hornblende	101.0 +/- 1.1	plateau age; 97.3 +/- 0.4 plateau on biotite and 95.8 +/- 0.3 plateau on K-feldspar
Bird Bluff, Fosdick Mtns.	Fosdick metamorphic rocks	U-Pb, monazite	105.7	
Griffith Nunataks, Fosdick Mtns.	NGTR;[a] biotite tonalite	$^{40}Ar/^{39}Ar$: biotite	98 0 +/- 0.1	
Chester Mtns.	monzogranite in Ford Granodiorite	$^{40}Ar/^{39}Ar$: biotite	105.2 +/- 0.3	plateau age; 219.3 on muscovite; 107 5 +/- 0.1 on K-feldspar
Chester Mtns	Ford Granodiorite	U-Pb, zircon[b]	353	
Mount Corey	Byrd Coast granite	U-Pb, zircon[b]	103	
Neptune Nunataks	NGTR[a]	$^{40}Ar/^{39}Ar$: biotite	103 1 +/- 0.5	plateau age; 271.4 on hornblende

Adapted from *Richard et al.* [1994].
[a] NGTR = Neptune-Griffith Transitional Rocks; foliated MDf?
[b] From *Kimbrough and Richard* [1991]

MDf magnetization in the western Phillips Mountains could be prior to this time. However, below we argue that the Chester Mountains were remagnetized in Cretaceous time and possibly earlier and that some MDf outcrops in the Phillips Mountains also were remagnetized at this time.

Laboratory Results

Demagnetization Experiments

Natural remanent magnetization (NRM) intensities range from 1000 milliamperes per meter (mA/m; X 10^{-6} cgs) for the lavas and mafic dikes to 0.1 mA/m for the plutonic and metamorphic rocks. Because of the low intensities and the realization that the rocks had experienced thermal magnetization overprinting, most samples used for determining paleomagnetic directions were subjected to demagnetization treatment by the continuous thermal technique in a horizontal access cryogenic magnetometer [Dunn and Fuller, 1984]. At least one sample from each site was treated by stepwise alternating field demagnetization, and a small number were subjected to stepwise thermal

demagnetization. Most dike samples and all lava samples from Mount Perkins were treated by alternating field demagnetization.

In most samples there is an indication of a sharp decrease in intensity above a (blocking) temperature (Tb) of about 320°-330°C (Figure 5). This is true for all rock types but is best displayed in samples from the Chester Mountains, Mount Bitgood, Marujupu, Mount Avers, and Lewis Rocks and Mount June. This Tb effect is not pronounced in the Kbc but is evident in dikes intruding it (Figure 5e). In samples from MDf at Lewis Rocks, low and high Tb directions are distinctly different (Figure 5b).

Some rock types from some locations show weak or no remanent intensity above this low Tb. This is pronounced at Neptune (Figure 6a) and Griffith Nunataks and some sites in the Fosdick Complex including Marujupu and Mutel Peak. At Mutel Peak the undeformed mafic dikes also exhibit this behavior (Figure 6b). Schmidt and Embleton [1981] found this same thermal behavior for basalts from southeastern Australia which they believe were remagnetized during Cretaceous time. An undemagnetized sample from Neptune Nunatak (NNH-3.1B) was given an anhysteretic remanent magnetization and then
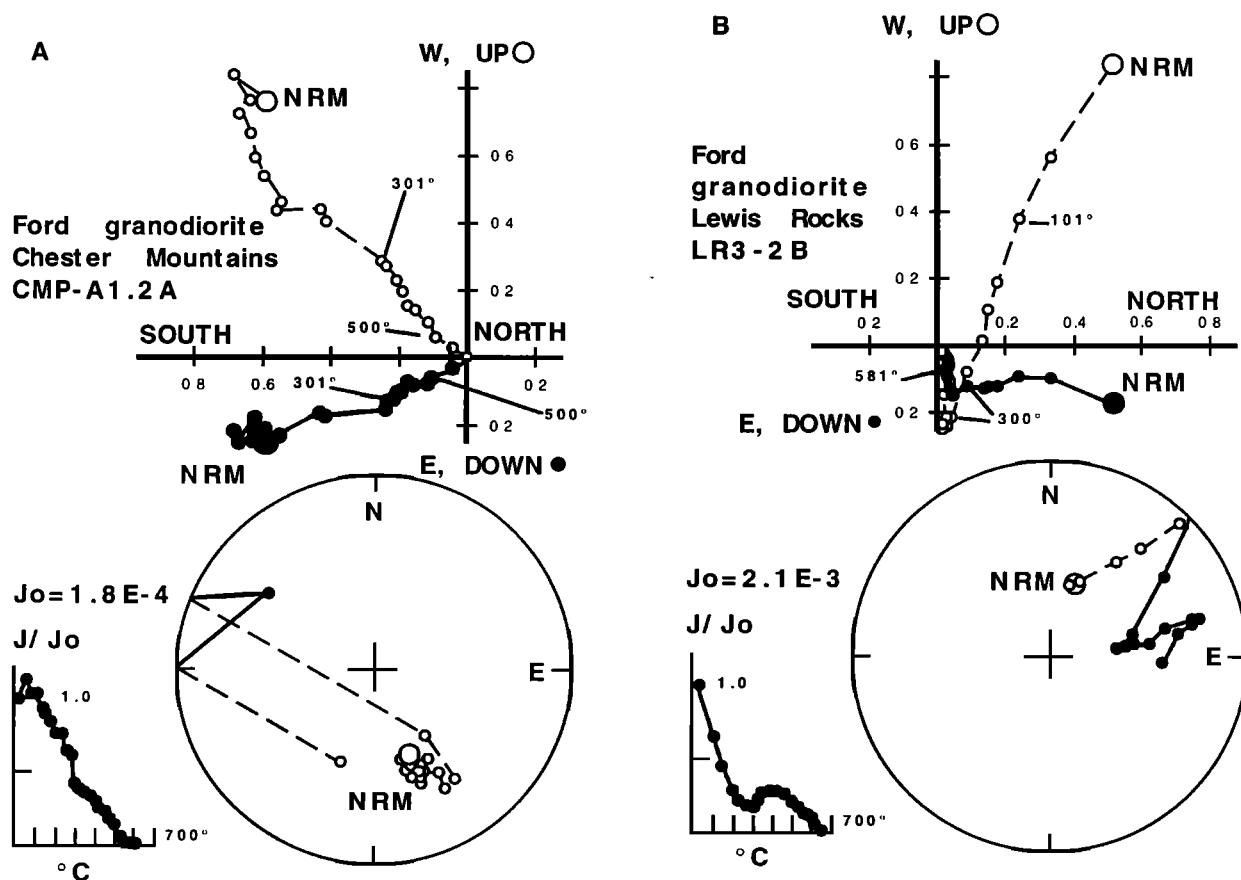
Figure 5. Demagnetization behavior of selected specimens from the MDf from (a) Chester Mountains and (b) Lewis Rocks in the Phillips Mountains; (c) Kbc from Mount Corey in the Chester Mountains; (d) FMR from Mount Bitgood in the Fosdick Mountains; and undeformed mafic dikes (e) intruding Kbc at Mount Paige in the Phillips Mountains and (f) intruding the MDf at Chester Peak in the Chester Mountains. Chester Mountains and Mount Corey directions are interpreted as tilted (dike in the Chesters, Figure 5f, shows viscous overprint posttilting); Fosdick and Phillips directions are untilted; Lewis magnetization shows pre-middle Cretaceous high blocking temperature reversed polarity direction which is possibly late Paleozoic in age.

C

W, UP ⃝

NRM

Byrd Coast granite
Mount Corey
MCH-4.1A

NRM

327"

1.0

0.5

627'

1.0

0.5

SOUTH   NORTH

N

Jo=2.0E-3

J/Jo

1.0

NRM

E

700°

°C

D

W, UP ⃝

NRM

Fosdick
metamorphic rocks
Mt. Bitgood
MBBMG-2.1A

5.0

308'

2.0

NRM   1.0 308°

4.0   1.0   582°

SOUTH   NORTH

N

Jo= 7.2 E-4

J/Jo

1.0

NRM

E

700°

°C

E

W, UP ⃝

NRM

undeformed
mafic dike
Mt. Paige
MPH 3.2B

0.8

0.6 301°

0.4

526°   **NRM**

SOUTH   0.2   NORTH

N

Jo= 0.98

J/Jo

NRM

E

1.0

600°

°C

F

NRM   **W, UP** ⃝

undeformed
mafic dike
Chester Mts.
RCMPD-2.1A

0.6

301"

0.4

0.2

SOUTH   301" 0.2   NORTH

NRM   551'

N

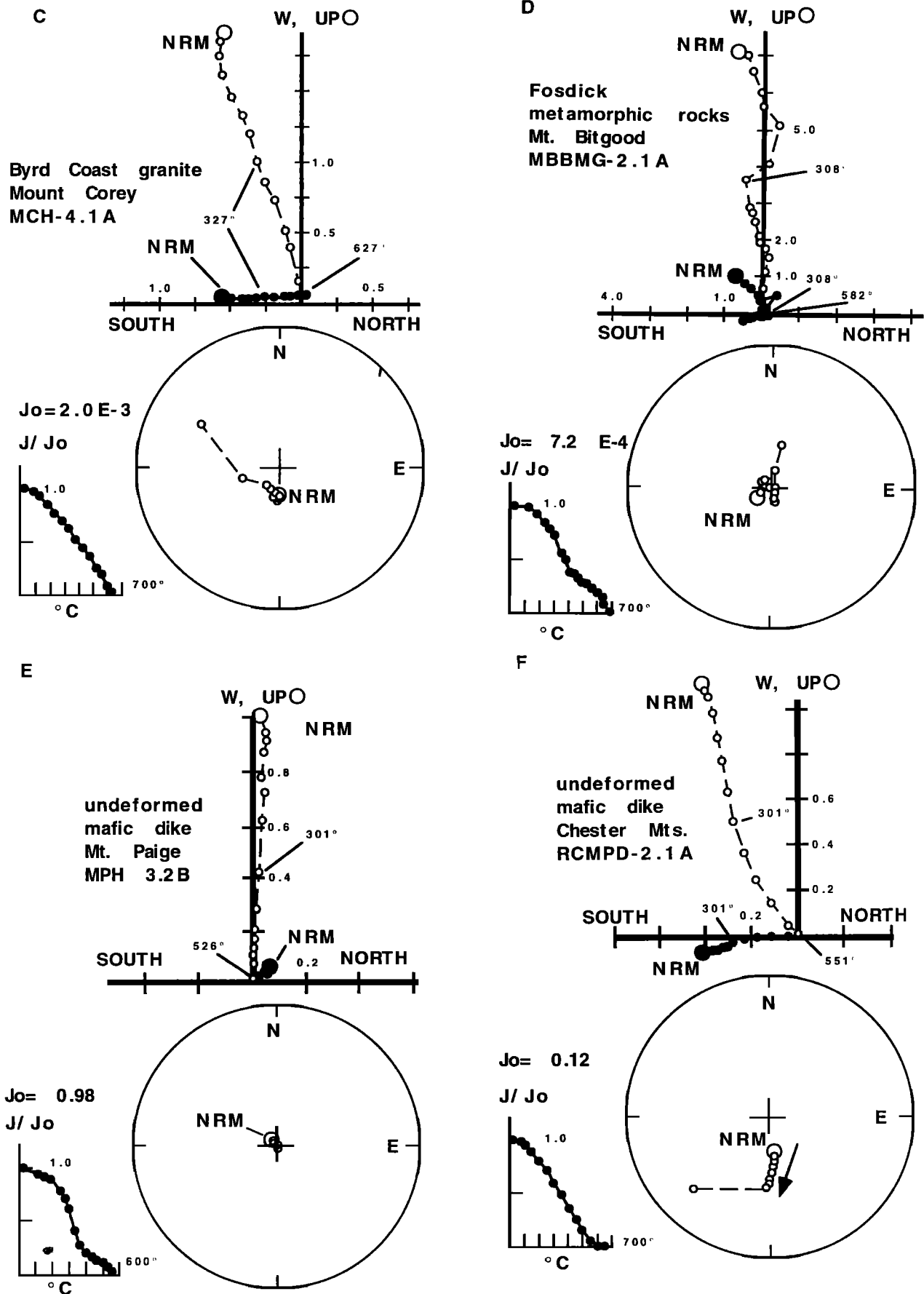Jo= 0.12

J/Jo

NRM

E

1.0

700°

°C

Figure 5. (continued)

thermally demagnetized. Partial remanence was found above 330° C and up to about 590° C pointing out that this sample has a mineralogy permitting blocking of remanence at higher temperatures Therefore, the NRM represents a partial thermal remanent magnetization, and any primary remanence may have been erased by thermoviscous effects at about 330° C over a prolonged period of time. Although the maximum Tb is near 580°C for almost all other samples, those from Lewis Rocks and some from Mount Corey are distinctive in displaying Tb near 680°C, indicating the presence of hematite here (Figures 5b and 5c).

Most well-behaved samples from the northern Ford Ranges have a stable characteristic remanence (ChRM) which is normally polarized, but at Lewis Rocks and Mount June, four sites from the MDf are reversely magnetized (Figure 5b; Table A1)[1]. Lewis Rocks samples have a normal polarity component which blocks below about 350°C.

Middle Cretaceous cooling ages and the predominant normal polarity of magnetization suggest a remagnetization of virtually all rocks in these ranges during the interval of the Cretaceous Normal Superchron. In the Phillips Mountains, middle Cretaceous remagnetization of MDf varies from complete at Herrmann Nunatak to partial at Lewis Rocks.

Site Mean Directions and VGPs

The lack of bedded units within the northern Ford Ranges precludes accurate structural control for the region and the paleomagnetic sites. A subhorizontal geomorphic surface seen in the Phillips Mountains (Mount Paige), Marujupu, and the eastern Fosdick Mountains may be the Late Cretaceous-early Tertiary erosion surface described throughout Marie Byrd Land by *LeMasurier and Rex* [1983]. This surface appears little disturbed and suggests that less than 15° or so of tilting has occurred in these ranges since Cretaceous time.

Characteristic directions were selected by a line-fitting method [*Kirschvink*, 1980]. Lines were fit to demagnetization intervals where vector end points showed a linear progression toward the origin over an appreciable loss of magnetization intensity. A stable ChRM was obtained from 55 sites; 25 sites did not yield a stable result, and the remainder were not fully processed. Site mean directions for 41 out of 45 pre-Cenozoic sites are of normal polarity and generally steep (Figure 7; Table A1). Directions from the MDf sites in the Chester Mountains have normal polarity and agree with the direction from the Kbc sites at Mount Corey immediately to the east, confirming that these MDf rocks are remagnetized.

Site mean directions from Hutcheson Nunatak and the Chester Mountains including Mount Corey are outliers from the main grouping of directions for the northern Ford Ranges; we interpret these as directions which were tilted during faulting (discussed below).
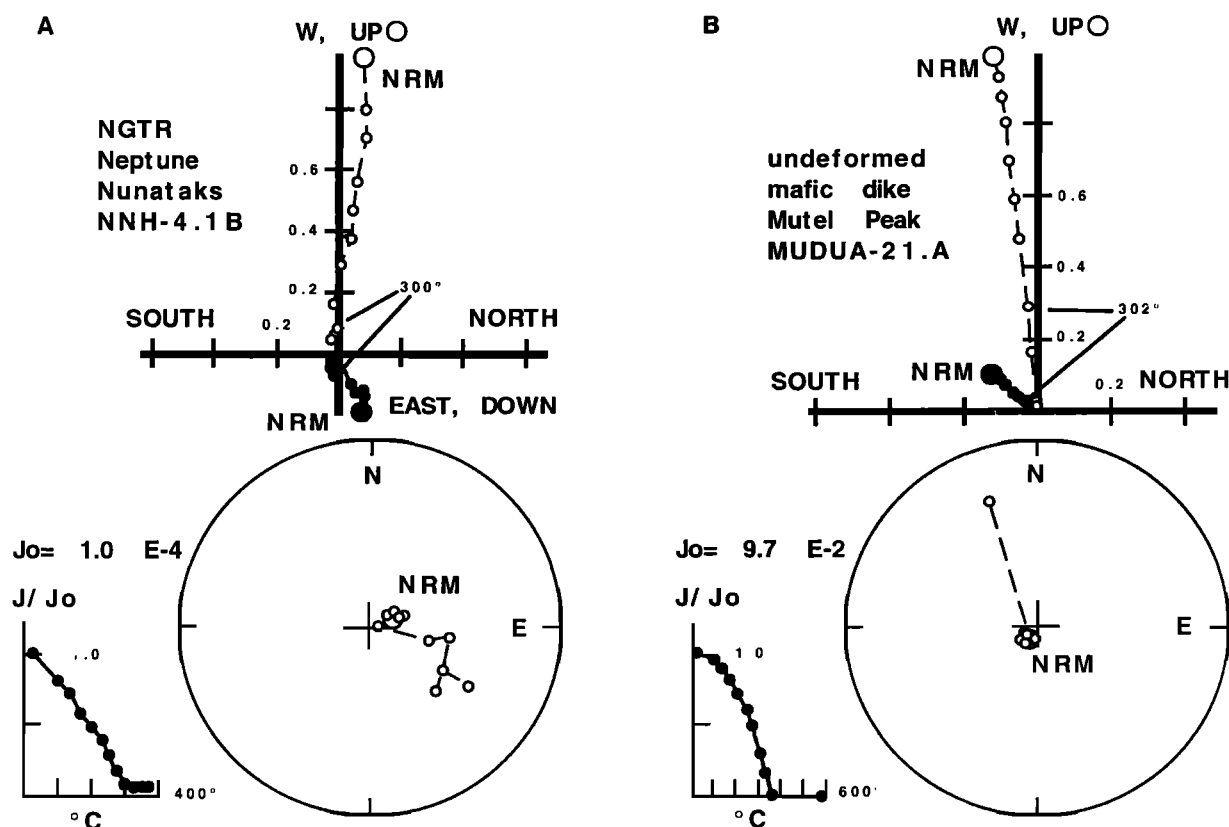
Cooling ages and reversed polarities from the MDf at Lewis Rocks in the western Phillips Mountains suggest that these magnetizations could be prior to the Cretaceous Normal Superchron (Early Carboniferous?). The two reversed Mount June MDf sites show steep inclinations consistent with the high latitude for Antarctica in either Late Carboniferous/Early Permian or post-Jurassic time. One normally magnetized site in foliated granodiorite (MDf?) at Griffith Nunataks appears to be crudely antipodal to directions from Lewis Rocks and could also have a pre-Cretaceous direction (22/89; Table A1). Two other MDf sites in the Phillips Mountains have normal polarity and steep inclination (14/90, Mount June, and 24/90, Herrmann Nunatak) consistent with middle Cretaceous remagnetization.

Paleomagnetic Poles for the Northern Ford Ranges

Paleomagnetic poles were computed from site virtual geomagnetic poles (VGPs) grouped by formation and by mountain range and also for all sites in middle Cretaceous age formations combined. Poles were evaluated against the expected values for angular dispersion of VGPs, which is higher at higher latitudes. *Butler* [1992] shows a dispersion value of 21° at polar latitudes for the last 5 m.y. in his text; he notes that paleosecular variation studies suggest that during the Cretaceous Normal Superchron dispersion was about 75% of recent values. *Mankinen and Cox* [1988] studied Plio-Pleistocene lavas from the Ross Island region in the Ross Sea and found a dispersion value of 23.5°. Accepting a range of dispersion from 23.5° to 15°, the computed range for the concentration parameter K is 12 to 29. Poles were computed by culling most-distant site VGPs until the mean pole produced $K >= 20$. This value may be too low because the dispersion of VGPs from plutonic rocks may be expected to be less (higher K) for slow cooling through a range of blocking temperatures. This culling method sometimes resulted in sites being selected for one average but not used in another where it was an outlier, for example site 30/90 (Table A1). By this method we attempted to average secular variation and omit outlier VGPs which could be due to magnetic field excursions or tilted sites.

Forty-five site mean VGPs were computed (Table A1) exclusive of sites from Mount Perkins, a Pleistocene stratovolcano which appears to be one magnetic cooling unit. The VGP for this volcano is at 343.4° E, 53.8° S, (A95 = 4.0°, K = 69, for 20 samples from 10 flows). Site mean VGPs were first grouped by formation, and separate paleomagnetic poles were computed for the MDf, the Kbc, the FMR, and the undeformed mafic dikes (Table 2). VGPs for deformed dikes within the FMR were grouped with that formation. The pole for the MDf includes two normally polarized sites (20 and 21/90; 23/90) which we interpret as Cretaceous in age due to their steep inclinations; but we cannot determine whether they are pre-118 Ma or post 84 Ma (interval of the Superchron). The MDf pole also includes two sites in foliated granodiorite at Neptune and Griffiths. The 95% confidence circles for the all

Figure 6. Demagnetization behavior for some samples from (a) Neptune Nunataks (NGTR) and (b) Mutel Peak (undeformed dike) in the Fosdick Mountains shows steep directions at low blocking temperatures and no remanence above about 350°C.

of the formation means overlap, showing that they are indistinguishable at this confidence level (Figure 8).

Poles were also computed for each mountain range (Figure 9; Table 2). Chester Mountains and Mount Corey sites were combined, Neptune Nunatak was combined with the Fosdick Mountains sites, and Hutcheson Nunatak was separated from the Phillips Mountains sites. The resulting poles are spread along an arc (Figure 9). We interpret this to show postmagnetization tilting about the east-west axis of topographic trend and inferred structural strike (Figure 2). Southward tilting of the Chester Mountains and Mount Corey of ~25 degrees indicated by the paleomagnetic directions is consistent with the same interpretation of *Richard et al.* [1994] from the gradient in cooling ages. Northward tilting of Hutcheson Nunataks by about 30 degrees is interpreted from the direction data.

A grand mean middle Cretaceous paleomagnetic pole was computed for sites in the Phillips and Fosdick Mountains excluding all MDf sites (222.3° E, 70.5° S, A95 = 6.1°, K = 20.0, n = 29). We assign an age of 100 Ma to this pole based on cooling ages (Table 1). It includes VGPs from the Kbc, FMR, and dikes which intrude these formations (Tables A1 and 2). This pole (nFR; Figure 10) is indistinguishable from the MDf pole, lending support to the idea that Cretaceous remagnetization dominates the ChRM in the northern Ford Ranges.

Virtual geomagnetic poles calculated for the presumed pre-Cretaceous sites at Lewis Rocks may be Early Carboniferous in age (Tables A1 and 2; the Griffith site 22/89 VGP appears to be distinct from the Lewis VGPs). The Lewis VGPs are close to a Late Devonian pole for the Comerong Volcanics in Australia found by *Schmidt et al.* [1986], (330.7°E, 76.9°S), when that pole is transferred to Antarctica by the Euler poles of *Royer and Sandwell* [1989] (the transferred pole is at 316.6° E, 46.2° S, A95 = 7.2). The VGPs are more distant from Australian Carboniferous poles, although the age control on these late Paleozoic poles is not strong and this time was a period of rapid apparent polar wander [*Schmidt et al.*, 1990]. These pre-Cretaceous VGPs, although based on a few samples, are significant if verified by further work. They could imply that western Marie Byrd Land has been autochthonous to East Antarctica since late Paleozoic time and that the accretion hypothesis of *Borg and DePaolo* [1991] either does not pertain to western Marie Byrd Land or this terrane was not far remote from Antarctica before accretion.

Remagnetization and Tilting

Remagnetization in Late Cretaceous Time

Remagnetization in the Ford Ranges during the Cretaceous normal polarity Superchron is suspected from the uniform
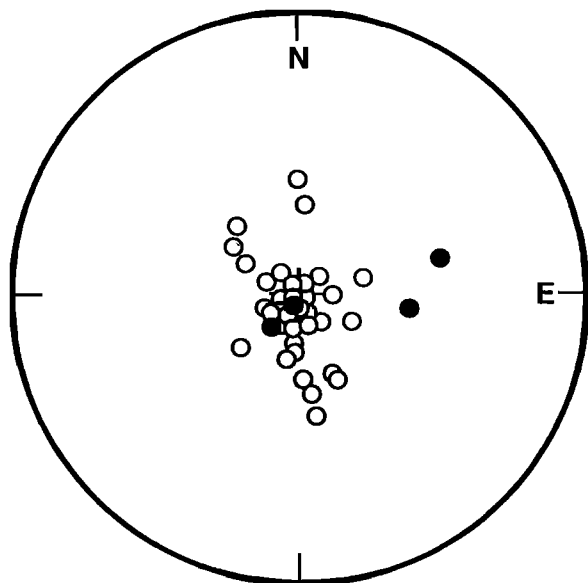
Figure 7. Site mean directions from the northern Ford Ranges. Four reversed polarity sites are from MDf at Lewis Rocks and Mount June in the Phillips Mountains (see text).

normal polarity of all sites except a few, steep ChRM directions and the predominant middle Cretaceous cooling ages in the Fosdick and Chester Mountains. The MDf in the western Phillips Mountains yields Carboniferous cooling ages (Table

1). *Richard et al.* [1994] interpret a Cretaceous heating episode here also. All sites from Lewis Rocks and two from Mount June have reversed polarity ChRM but have a normal polarity overprint at low Tb (see above). We suspect that partial thermal viscous remagnetization has occurred without resetting of the $^{40}Ar/^{39}Ar$ cooling ages. In the eastern Phillips Mountains, MDf sites are apparently fully remagnetized to the middle Cretaceous direction. The heat required for thermal remagnetization was produced during extension and rifting of New Zealand and the Campbell Plateau from Marie Byrd Land, the event which also supplied heat for anatexis in the Fosdick Complex [*Smith*, 1992].

Cretaceous remagnetization is also suspected in northern Victoria Land from several paleomagnetic studies on a variety of rocks of differing ages [*Delisle and Fromm*, 1984, 1989; *Schmierer and Burmester*, 1986; *Lanza and Zanella*, 1993]. Evidence for remagnetization includes uniform normal polarity and anomalous high-latitude pole positions. Partial thermal viscous remanence magnetization experiments (vPTRM) were done on samples by *Schmierer and Burmester* [1986], who concluded that viscous thermal remagnetization was indeed possible. *Lanza and Zanella* [1993] came to the opposite conclusion in their experiments, but we note that if a 10 million year long period for remagnetization is assumed, their experiments also could confirm the remagnetization hypothesis. Magnetic overprinting attributed to vPTRM during Cretaceous rifting has also been observed in rocks from southeast Australia [*Schmidt and Embleton*, 1981]. Our observations of remagnetization in western Marie Byrd Land considerably extend the range of this thermal effect.

Table 2. Mean VGPs and Poles in northern Ford Ranges

Formation/Ranges	Number of Sites or Formations	East Longitude	South Latitude	A 95	Kappa
Mean poles of selected formation VGPs					
MDf[a]	6	195.4	69 4	13.3	26.4
Kbc[a]	6	249.5	78.6	8.7	59.7
FMR	8	228.4	62.8	12.1	21.9
mafic dikes	12	217.2	63 3	9.3	23.0
all formations	4	219.8	69.4	11 6	63.4
without Kbc	3	215.2	65.7	11.7	111.8
Mean poles for individual ranges from selected VGPs					
Chesters and Mt. Corey	6	206.2	33.0	9.1	55.0
Fosdicks and Neptune	18	222.5	68 1	7.9	20.0
Phillips Mountains	14	219.6	72.7	8 3	24 1
Hutcheson Nunataks	2	37.9	54.5	20.3	153.6
Mid-Cretaceous Paleomagnetic Pole for the Northern Ford Ranges (From Sites in the Phillips and Fosdick Mountains Excluding All MDf Sites)					
nFR	29	222.3	70 5	6 1	20.0
Early Carboniferous? VGP for the MDf at Lewis Rocks					
MDf	3 sites	295.8	36.1	21.9	32.8
MDf	16 samples	285.6	32.5	8.4	20.2

Abbreviations are MDf, Ford granodiorite; Kbc, Byrd Coast granite; FMC, Fosdick Metamorphic Complex.
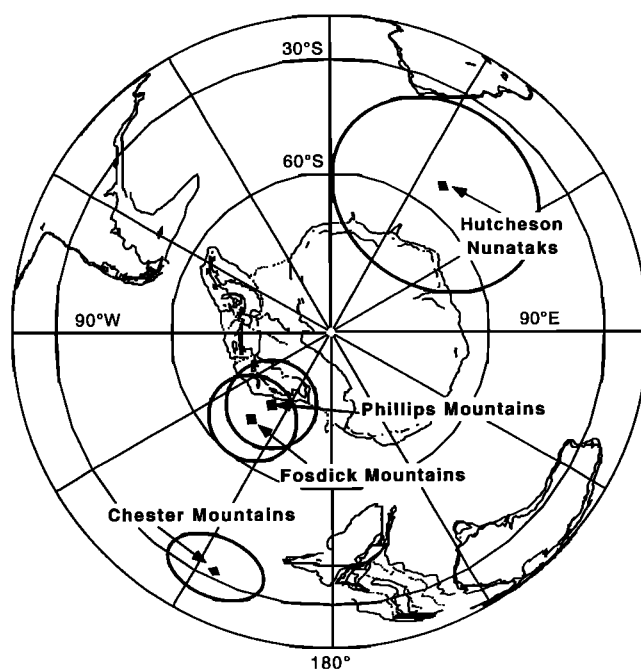[a]Non-tilted sites.
[b]VGP computed by averaging VGPs (Table A1) or sample directions. For sample average, three were omitted as outliers.
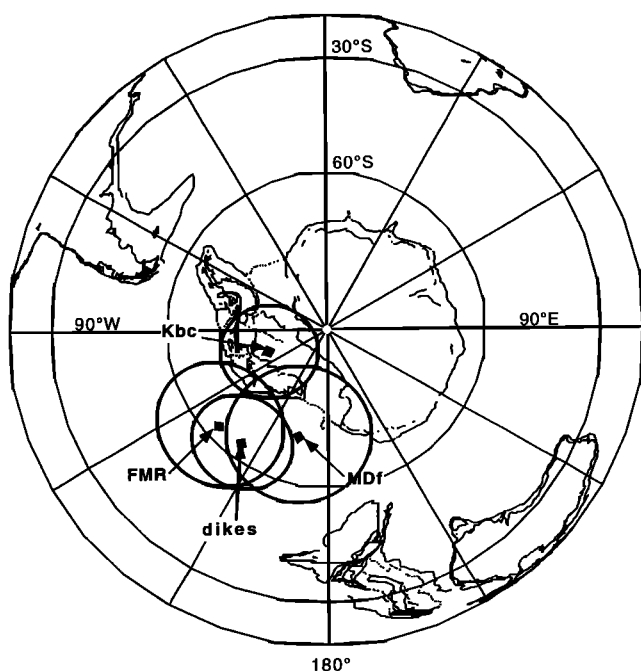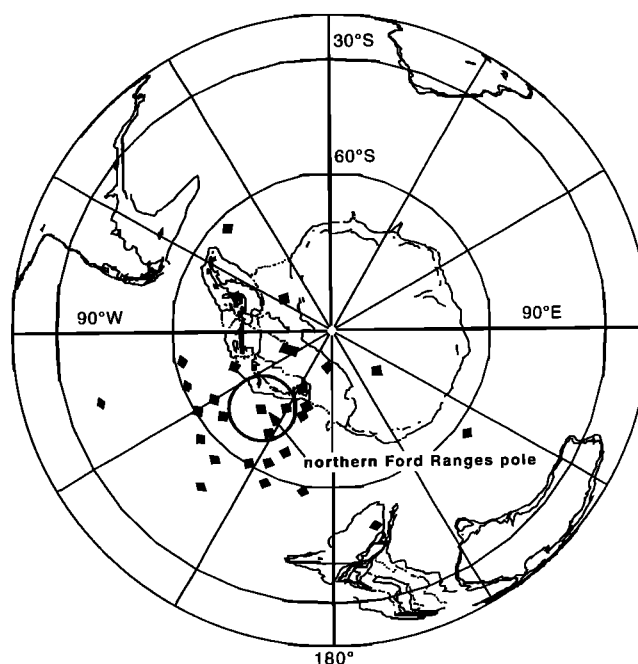
Figure 8. Paleomagnetic poles for the individual formations in the northern Ford Ranges. Abbreviations are MDf, Ford granodiorite; FMR, Fosdick metamorphic rocks; Kbc, Byrd Coast granite; and dikes, undeformed mafic dikes.

Figure 10. Site mean VGPs from the Fosdick and Phillips Mountains used to compute the paleomagnetic pole for the northern Ford Ranges (nFR).

Tilting and Structural Disturbance

Richard et al. [1994] used $^{40}Ar/^{39}Ar$ studies to interpret that southward tilting of the Fosdick Mountains, Neptune Nunataks, and the Chester Mountains accompanied rapid

Figure 9. Paleomagnetic poles for the individual ranges of the northern Ford Ranges.

cooling between 100 and 94 Ma. Demagnetization experiments suggest the Fosdick Mountains and Neptune Nunataks were remagnetized after tilting. Neptune sites show a steep remanence, a low Tb of ~325°C, and no remanence above 325°-350°C (Figure 6a). The steep inclination is interpreted here and throughout the northern Ford Ranges as an untilted middle Cretaceous direction. The $^{40}Ar/^{39}Ar$ biotite cooling age of 103 Ma (closure temperature 325°C (*Richard et al.*, 1994) from Neptune Nunatak indicates that the low Tb magnetization was acquired after this time and tilting at this site must have been complete by 103 Ma.

In the Chester Mountains, directions are tilted south (Figures 5a, 5c, and 5f) in comparison to steep directions at Neptune and other locations. A biotite $^{40}Ar/^{39}Ar$ cooling age for the Cretaceous reheating event in the Chester Mountains is 105 Ma, slightly older than the Neptune biotite age. We interpret that the Chester samples were remagnetized before the Neptune samples and before tilting ended. Directions from Kbc sites on Mount Corey are interpreted as south tilted. Tilting began here after 105-103 Ma based on U-Pb zircon age determinations. The Fosdick and Neptune magnetization was acquired after tilting ended. Assuming that the ranges tilted together, the tilting ended before 103 Ma. Therefore we can interpret that tilting of the Fosdick and Chester Mountains occurred in the time interval 105 to 103 Ma.

High Tb ChRM (between ~350° and 580°C) in the FMR must date from the time of peak metamorphism at 105 Ma [*Kimbrough and Richard*, 1991]. High Tb directions here are steep, but at some Fosdick Mountains sites they are shallower than low Tb directions. Directions from sites along the north front of the range on the Balchen Glacier dip steeply north, and directions from sites along the south side dip steeply

south. These can be interpreted as tilted directions and consistent with the general attitude of the metamorphic foliation which describes a broad, low-amplitude, east-west trending arch. These mountains also could have been tilted a large amount prior to 103 Ma, which would not be evident in the ChRM directions.

Other paleomagnetic studies in extended terranes have detected tilted fault blocks. In British Columbia, *Marquis and Irving* [1990] found inclination vectors dipping west and east on opposite flanks of a north-south trending metamorphic culmination which was uplifted and extended in Eocene time. They interpreted these as being due to tilting of the flanking blocks 38° to 41° away from the metamorphic core. In the Black Mountains of Death Valley, *Holm et al.* [1993] studied Miocene rocks disrupted by late Cenozoic extension and unroofing. They were able to identify 20° to 40° of tilting associated with gradual footwall uplift during extension.

The bulk of the Cretaceous directional data from the northern Ford Ranges and from the Ruppert-Hobbs Coasts study of *DiVenere et al.* [1994] are steep and consistent. This points out, that on the whole, large magnitude post-middle Cretaceous tilting in Marie Byrd Land is rather rare in the regions studied

In the discussion above we estimated the timing of tilting in the northern Ford Ranges to be prior to 103 Ma. This is at the beginning of the main cooling interval in the ranges of 100 to 94 Ma. We conclude further that these ages constrain the beginning of extension between the Campbell Plateau and western Marie Byrd Land to prior to 103 Ma.

Comparisons of Paleomagnetic Poles

The 100 Ma northern Ford Ranges pole found in our study is identical to the same-age pole found by *DiVenere et al.* [1994] for the Ruppert and Hobbs Coasts and to the (slightly older, 110 Ma?) Thurston Island pole found by *Grunow et al.* [1991]. The Antarctic Peninsula pole AP106 recomputed by *DiVenere et al.* [1994] is also identical to the middle Cretaceous Marie Byrd Land poles (Figure 11). The *Grindley and Oliver* [1983] pole is not near the cluster of other poles, but its confidence circle intersects both the northern Ford Ranges and Thurston Island poles (Figure 11). Following the arguments of *DiVenere et al.* [1994], we believe the Grindley and Oliver pole is superseded by their more recent work.

We computed a circa 100 Ma pole for Marie Byrd Land by combining our results and the poles of *DiVenere et al.* [1994] and *Grunow et al.* [1991]. This mean pole is at 218.7° E, 73.2° S, A95 = 5.2°, K = 563.9 (MBL-mK; Table 3) Adding the Antarctic Peninsula pole AP106M recomputed by *DiVenere et al.* [1994] yields a grand mean Pacific West Antarctic pole at 215.2° E, 73.5° S, A95 = 4.0°, K = 528.9 (pWANT100; Table 3). Both mean poles are very high precision.

DiVenere et al. [1994] computed a synthetic middle Cretaceous (circa 102 Ma) paleomagnetic pole for East Antarctica at 171.8° E, 80.3° S (A95 = 4.2°). The remagnetized poles for northern Victoria Land discussed above are not different from this synthetic East Antarctic reference pole (Figure 12). The pole for the studies of *Delisle and Fromm* [1984, 1989] was recomputed using eight of their site VGPs (204.8° E, 77.5° S, A95 = 13.2°, K = 18.5). A reasonable interpretation is that the East Antarctic reference pole of *DiVenere et al.* [1994] is accurate and that much of northern

Figure 11. Comparison of Cretaceous paleomagnetic poles from Pacific West Antarctica. Abbreviations are nFR, this study; DiV, the 100 Ma pole of *DiVenere et al.* [1994]; TI110, the 110 Ma pole of *Grunow et al.* [1991]; G&O, the middle Cretaceous pole of *Grindley and Oliver* [1983]; AP106M, 106 Ma Antarctic Peninsula pole recomputed by *DiVenere et al.* [1994].

Victoria Land was remagnetized in a middle Cretaceous thermal event associated with Gondwana rifting [*Delisle and Fromm*, 1984; *Schmierer and Burmester*, 1986]. *Fleming et al.* [1992] propose a date of 103 Ma for this alteration and remagnetization based on whole rock Rb-Sr data from the Kirkpatrick basalt.

DiVenere et al. [1994] also computed a Pacific West Antarctic pole indistinguishable from ours (212.2°E, 74.5°S, A95 = 4.6°) and found a post-middle Cretaceous angular separation of 10.2° +/- 6.2° between their pole and the synthetic East Antarctic pole. Our pWANT100 pole is compared against their synthetic East Antarctic pole in Figure 13. The poles are clearly distinct as *DiVenere et al.* [1994] found for their pole. The angular separation is 11.5° +/- 4.6°, which is indistinguishable from their result. Both calculations can be interpreted as about 1000 kilometers of post-middle Cretaceous translation between East Antarctica and Pacific West Antarctica. This calculation assumes that the separation between the poles is due to relative tectonic transport about an Euler rotation pole to the great circle path connecting the East Antarctica and Pacific West Antarctica paleomagnetic poles. An infinite number of alternative Euler relative motion poles and relative motion paths are allowed to bring the two paleomagnetic poles back together; the great circle Euler pole is only one possibility.

It is instructive to see how sensitive the separation between paleomagnetic poles is to the choice of East Antarctic reference poles (Table 4). Cretaceous East Antarctic synthetic reference poles (110 and 100 Ma) have been proposed by *Grunow* [1993]. These reference poles are single

Table 3. Paleomagnetic Poles for MBL, EANT, AP

Pole	Number of Sites, VGP or Studies	East Longitude	South Latitude	A 95	KAPPA
Mid-Cretaceous West Antarctic (WANT) Paleomagnetic Poles					
nFR[a]	29	222.3	70 5	6.1	20.0
DiV[b]	19	224.1	75.7	3.8	79.0
G&O[c]	15	247.0	65.8	8.2	20 0
TI110[d]	7	210.0	73 0	7 6	>...<
AP106M[b]	29	203.8	74 3	6 2	>...<
Grand Mean Poles					
MBL-mK[e]	3	218 7	73 2	5.2	563.9
pWANT100[f]	4	215 2	73.5	4.0	528 9
Cretaceous East Antarctic Poles					
D&F[g]	8	204 8	77.5	13.2	18 5
L&Z[h]	7	181 0	79 0	5.9	106.0
S&B[i]	16	173 5	77 0	6.8	> ..<
EANT[j]	6	171.8	80.3	4.2	>...<
E110[k]	7	198 0	76.0	4.0	>...<
E100[k]	15	179.0	80.0	8.5	21.0

KAPPA is not given for entries marked with ">...<". MBL is Marie Byrd Land, EANT is East Antarctica, and AP is Antarctic Peninsula.
[a]This paper.
[b]*DiVenere et al.* [1994].
[c]Recalculated here from *Grinley and Oliver* [1993]. Low precision sites were eliminated and site I, D converted to VGPs for averaging.
[d]*Grunow et al.* [1991].
[e]Poles nFR, DiV, TI110.
[f]Poles NFR, DiV, TI110, AP106M.
[g]Recalculated here from *Delisle and Fromm* [1984, 1989]
[h]*Lanza and Zanella* [1993].
[i]*Schmierer and Burmester* [1986].
[j]102 Ma pole of *DiVenere et al.* [1994].
[k]*Grunow* [1993], African poles rotated to Antarctica; E110 from *Gough and Opdyke* [1963], E100 from *Schult et al.* [1981].

paleomagnetic poles from studies in Africa rotated to East Antarctica via Euler poles selected from the contemporary literature by *Besse and Courtillot* [1988]. *DiVenere et al.'s* [1994] reference pole is the average of six poles from Africa, Australia, and North America rotated to East Antarctica using more up to date published Euler poles. Grunow's 100 Ma East Antarctic pole is indistinguishable from the *DiVenere et al.* [1994] East Antarctic pole, but her 110 Ma pole is quite different.

Grunow [1993] reported Antarctic Peninsula paleomagnetic poles for 155 Ma, 130 Ma, 110 Ma, and 85 Ma. The estimated age uncertainties are +/-5 m.y. Her 110 Ma Antarctic Peninsula pole is indistinguishable from the *DiVenere et al.* [1994] AP106M pole which includes her data. Grunow's Antarctic Peninsula 110 Ma and 85 Ma poles are similar to synthetic East Antarctic poles computed by her and imply little or no motion of the Antarctic Peninsula relative to East Antarctica since then. But the East Antarctica reference poles she used for comparison are different from those of *DiVenere et al.* [1994]. Comparing her AP110 pole against the *DiVenere et al.* [1994] East Antarctic reference pole, the separation is 8.6° +/- 6.5°. So they find the same Antarctic Peninsula pole but compare against different reference poles and come to opposite conclusions. Comparing our Pacific West Antarctica pole against her 110 Ma East Antarctic reference pole, the

angular separation is 5.1° +/- 4.5°; against her 100 Ma East Antarctic pole it is 10.2° +/- 7.5°.

We chose to use the *DiVenere et al.* [1994] East Antarctic pole for reference because it averages several poles and has higher precision than *Grunow's* [1993] They also estimated an error due to transferring the poles to Antarctica by plate reconstruction rotations. This allows for an increased uncertainty due to this process which may contain inaccurate plate reconstruction poles. The fact that all reference paleomagnetic poles are synthetic and not native to East Antarctica makes tectonic analyses based on a comparison of paleomagnetic poles unsatisfying. Nevertheless, we assume for the sake of argument that the 11.5° estimate of pole separation is accurate.

Relative Motions and Their Timing

A paleomagnetic discordance analysis [*Beck*, 1989; *Butler*, 1992] can be made by assuming the angular separation of the Pacific West Antarctica and East Antarctica poles is due to tectonic rotation of the study locations about a local vertical axis along with northward translation of the study locations away from East Antarctica. This analysis involves deconstructing the angular separation of the poles into components of vertical axis crustal rotation and northward
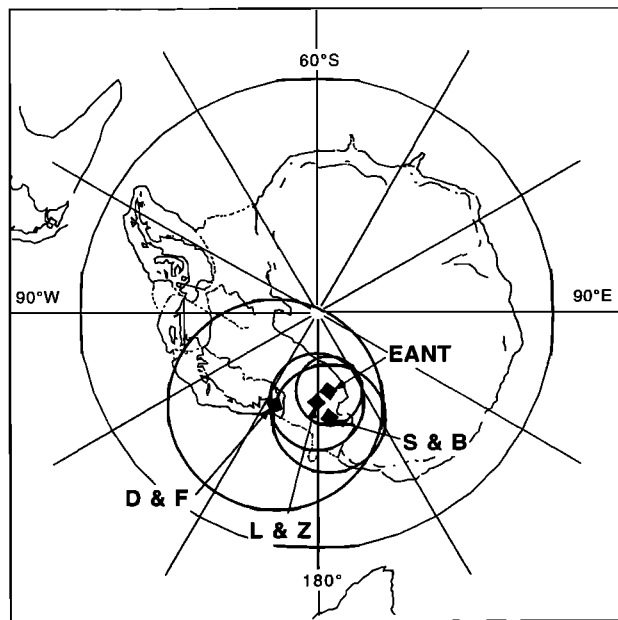
Figure 12. Comparison of remagnetized poles from northern Victoria Land with the middle Cretaceous East Antarctic reference pole of *DiVenere et al.* [1994] (EANT). Abbreviations are D&F, *Delisle and Fromm* [1984, 1989]; L&Z, *Lanza and Zanella* [1993]; S&B, *Schmierer and Burmester* [1986].

translation. The analysis computes a maximum rotation and minimum translation assuming the study location has moved directly north or south. It is also possible that a smaller vertical axis rotation has occurred and therefore a larger
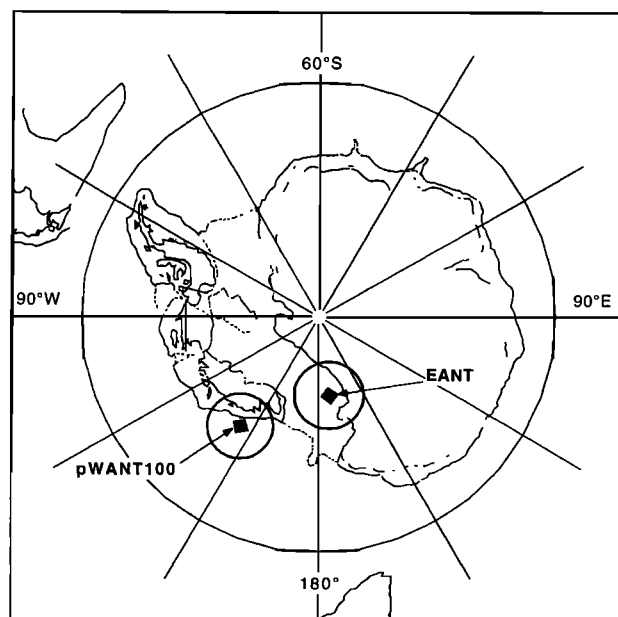
Figure 13. Comparison of the Pacific West Antarctic middle Cretaceous pole computed in this paper (pWANT100) against the synthetic East Antarctic pole computed by *DiVenere et al.* [1994] (EANT).

translation, but this would not be in a north-south direction (discussed below). Note that there is only one tectonic path (one Euler pole) by which a location could move and not undergo a component of vertical axis rotation. At high paleolatitudes where paleomagnetic poles are close to the study locations, the rotation component has a very large uncertainty and is comparatively insensitive. If the study sites lie within the circle of confidence of the observed pole, the uncertainty on the rotation estimate is undefined.

Tectonic Rotation

We treated western Marie Byrd Land, Thurston Island, and the Antarctic Peninsula as separate regions which were rotated and translated north away from East Antarctica. We could also analyze discordance of the Pacific West Antarctic mean pole, but this would imply that Pacific West Antarctica rotated as a coherent terrane, an event which would produce obvious effects in the Ross Embayment, the Weddell Sea, and elsewhere that are not seen. The observation that the Pacific West Antarctic middle Cretaceous poles are concordant to each other (agree within error at the 95% confidence level) does not rule out that Pacific West Antarctic microplates or crustal blocks have rotated individually since that time. Such is the case in southern California where fault-bounded crustal blocks have rotated within a simple shear couple [*Luyendyk*, 1991]. The different blocks have rotated similar amounts, resulting in paleomagnetic poles which are concordant, not discordant to each other, but they are discordant to North American reference poles. Alternatively, the terranes could have rotated an amount relative to each other which so far escapes detection with paleomagnetic data at the 95% confidence level. The insensitivity of discordance analysis to constraining rotation at high paleolatitudes leaves this open until other geological and geophysical data become available.

Selection of the tectonic rotation axes requires detailed knowledge of the fault pattern which may have accommodated the rotation. This is not yet possible in western Marie Byrd Land or in most of Pacific West Antarctica. We chose an axis in the northern Ford Ranges for the northern Ford Ranges pole, an axis on Thurston Island (72.2°S, 99°W) for that pole, and at the center of the Antarctic Peninsula (70°S, 65°W). The resulting rotations and translations (Table 4) can be interpreted as varying amounts of post-middle Cretaceous clockwise rotation and northward translation of these Pacific West Antarctic microplates away from East Antarctica. In the discordance analysis the inferred northward translation (extension between East and Pacific West Antarctica) for western Marie Byrd Land (the northern Ford Ranges) is one third that interpreted for the great circle analysis, 2.9° or about

Table 4a. Discordance Statistics Relative to EANT Poles: Angular Separations

Poles	Separation
pWANT100[a] versus EANT[b]	11.5° +/- 4.6°
pWANT100 versus E110[c]	5.1° +/- 4.5°
pWANT100 versus E100[c]	10.2° +/- 7.5°

[a]This paper; see Table 3.
[b]*DiVenere et al.* [1994]; see Table 3.
[c]*Grunow* [1993]; see Table 3.

Table 4b. Discordance Statistics Relative to EANT Poles: Rotations and Translations Relative to EANT Pole

	Rotation Axis	R^a	p^b
Western MBL (nFR) 222.3° E, 70.5°S[a]	76.5°S, 145°W	156 4° +/- 63.3°	-2.9° +/- 5.9°
Thurston Island TI110, 210°E, 73° S[d]	72 2°S, 99°W	33.3° +/- 26.1°	-5.3° +/- 6 8°
Antarctic Peninsula AP106M, 203 8°E, 74.3°W[e]	70°S, 65°W	20.5° +/- 13.8°	-1 0° +/- 6.0°

Translations as described by *Butler* [1992] and *Demarest* [1983]
[a]R is rotation of observed pole about axis relative to EANT pole; positive clockwise.
[b]Here *p* is translation of observed pole relative to EANT; negative northward
[c]This paper; see Table 2.
[d]*Grunow et al.* [1991]; see Table 3
[e]*DiVenere et al.* [in press]; see Table 3.

300 kilometers. But this value is not significant at the 95% confidence level (Table 4), implying that there has been no northward translation which is resolvable by the analysis. Northward translation of Thurston Island and the Antarctic Peninsula is also not significant. The 95% circle of confidence for the Marie Byrd Land pole of DiVenere et al. [1994] encompasses their study locations, so a rotation uncertainty is undefined and this pole cannot be used for a discordance analysis. However, their individual study locations are more appropriate for local tectonic rotation analyses. In this case, mean VGPs from Mount Langway, Mount Vance, and Wilkins Nunatak are clockwise rotated over 100° and significant at the 95% confidence level. Those for Mount Sinha and Peden Cliffs have significant north translation of about 9°.

The clockwise rotation values in Table 4 are all significant and can be interpreted as due to post-middle Cretaceous rotation between the individual microplates and East Antarctica. Therefore, at the 95% confidence level, the disagreement between the individual Pacific West Antarctica poles and the East Antarctica reference pole can be attributed solely to post-middle Cretaceous clockwise rotations. The fact remains that native East Antarctica reference poles are needed for a definitive tectonic analysis. However, unaltered rocks of middle Cretaceous age are sparse throughout East Antarctica, leaving this an open issue.

Structural observations in western Marie Byrd Land also suggest clockwise rotations. *Richard* [1992] and *Luyendyk et al.* [1992] noted that the middle Cretaceous extensional strain directions developed in the latest metamorphic deformation stages in the Fosdick metamorphic complex of the northern Ford Ranges are oriented north to northeast. The northeast directions are interpreted as older than the north directions. The continental margin here trends northeast to east-northeast (Figure 1). The metamorphic strain might be expected to trend northwest orthogonal to the strike of the western Marie Byrd Land continental margin here, if this margin both extended and rifted under pure shear. But these metamorphic strain directions trend 45° to 80° clockwise from a pure shear direction. Either (1) the strain markers were rotated clockwise after Late Cretaceous rifting; (2) both the extension and rifting directions were more northerly and the margin formed under dextral oblique transtension; or (3) the strain orientation during rifting was markedly different than during extension. Possibilities 1 and 2 explain clockwise rotation of the

northern Ford Ranges pole either postrifting (post-85 Ma) or during the period 105 to 85 Ma.

Fracture zone trends in the deep sea adjacent to the Marie Byrd Land margin would test possibility 2. Satellite gravity data could reveal these trends, but coverage is incomplete south of 72° S [*Sandwell and Smith*, 1992; *Lawver et al.*, 1993]. However, there is a suggested change in fracture zone trend from northwest in younger crust to more northerly in older crust both in the south and near the Campbell Plateau [*Sandwell and Smith*, 1992; *Lawver et al.*,1993], supporting interpretation 2. Further, a recent oceanographic cruise traced a north trending fracture zone toward the Marie Byrd land margin near 73° S, 150° W (Cande et al., 1995). The amount of rotation could be estimated from the difference in trend between the old fracture zones and the strain direction. Available satellite data suggest this could be 40° or 50°.

As mentioned earlier, early Paleozoic sediments of the Robertson Bay Group across the Ross Embayment in northern Victoria Land have been correlated with the Swanson Formation sediments of western Marie Byrd Land. Both terranes apparently were deformed in the Ross orogeny [e.g., *Borg and DePaolo*, 1991; *Kleinschmidt*, 1990; (G. Kleinschmidt, personal communication, 1995)]. G. Kleinschmidt has mapped structures in both terranes (G. Kleinschmidt, personal communication, 1995) and finds that trends of fold axes, thrusts, and kink bands can be interpreted to suggest that western Marie Byrd Land has rotated clockwise 30° to 40° relative to northern Victoria Land.

Therefore separate data types support an interpretation that parts of western Marie Byrd Land have rotated clockwise since circa 100 Ma. This interpretation reaffirms the original conclusion of *Grindley and Oliver* [1983]. Such an interpretation could include rotation of part or all of Marie Byrd Land as a microplate or local rotation of blocks within domains defined by conjugate fault sets. However, without further geophysical and geological data on the existence of faults which may have accommodated any rotation, the geometry of the rotated regions cannot be determined.

Translation Between Pacific West Antarctica and East Antarctica

There are few precise constraints on the amounts and timing of extension between Pacific West Antarctica and East Antarctica after middle Cretaceous time. Significant motion between East and Pacific West Antarctica could have occurred

in an interval from middle Cretaceous through early Tertiary time. Several lines of evidence suggest that motion could have occurred in at least two phases, one starting in Late Cretaceous time and another starting in Eocene time. A wide rift formed in the Ross Embayment during Mesozoic time. Middle Jurassic volcanism in the Transantarctic Mountains signaled the likely beginning of Gondwana fragmentation, and extension began in earnest in eastern Gondwana in middle Cretaceous time. This timing is constrained in part by this paleomagnetic study and that of *DiVenere et al.* [1994]. Significant uplift of the Transantarctic Mountains began in Eocene time. Extension shifted to the western Ross Sea before middle-late Oligocene time. Late Cretaceous and Cenozoic global plate tectonics reconstructions argue that East and West Antarctica were separating during Oligocene time (discussed below). But plate motions for the 20 million years that elapsed between the start of east Gondwana extension at 105 Ma and start of rifting of Zealandia from West Antarctica at 85 Ma are not constrained by marine magnetic anomalies or fracture zone trends.

Extension amounts have been estimated from crustal thickness balancing and from global plate circuits for periods after 85 Ma. *Fitzgerald et al.* [1986] suggest a maximum of 255 km of Cenozoic extension from balancing crustal thicknesses between the Transantarctic Mountains and West Antarctica. *Behrendt and Cooper* [1991] inferred 350 km of extension in the West Antarctic rift from comparing East Antarctic and West Antarctic crustal thickness. These analyses are valid if the preextension crustal composition and thickness were similar across the Ross Embayment and West Antarctic rift, a doubtful premise in our view. The direction of extension was presumed normal to the trend of the Transantarctic Mountains, so these are minimum estimates. In fact, *Wilson* [1995] has shown that Cenozoic age extension was dextral and oblique (to the southeast) to the trend of the mountains.

Kamp and Fitzgerald [1987] proposed that a maximum of 300 km of extension occurred in the Ross Embayment between 36 and 23 Ma (Oligocene), based on the plate circuit analysis of *Stock and Molnar* [1987] and geologic evidence for movement on the Alpine fault in New Zealand. They connect this with initial uplift of the Transantarctic Mountains. Cande et al. (in press) revised *Stock and Molnar's* [1987] analysis and concluded that the original premise of *Molnar et al.* [1975] is essentially correct, namely, that a plate boundary between East and West Antarctica is suggested for early Tertiary time. Cande et al. (in press) mapped magnetic anomalies and fracture zones on the Antarctic plate north of Marie Byrd Land. A three-plate analysis of the Australian, Antarctic, and Pacific plate seafloor spreading data suggests relative motion between East and West Antarctica amounting to about 300 km could have occurred between chron 31 and chron 13 time (circa 69 to 33 Ma).

Lawver and Gahagan [1994] eliminate the requirement for Tertiary extension in the Ross Embayment (less than 50 km) by adding a plate boundary between the Lord Howe Rise and western New Zealand into the plate circuit and reinterpreting

marine magnetic anomalies offshore north Victoria Land. A powerful analysis in support of this option is a very tight fit reconstruction they produced between Campbell Plateau and the Ross Sea margin and western Marie Byrd Land. This requires Ross Sea extension to precede seafloor spreading; the paleomagnetic data require it to be post 105-100 Ma.

A Late Cretaceous dextral transform fault is also proposed to connect extension in the Ross Sea to the trench at Thurston Island by *Lawver and Gahagan* [1994]. This plate boundary configuration mimics that for southern California in Late Neogene time when large clockwise rotations were produced within the San Andreas system, connecting spreading in the Gulf of California with subduction offshore northern California [*Lawver and Gahagan*, 1994; *Luyendyk*, 1991].

Conclusions

We attributed discordance between the East Antarctica and Marie Byrd Land poles to Late Cretaceous clockwise rotations within or between Pacific West Antarctic microplates and extension between West and East Antarctica in the Ross Embayment. Although rotation of the Ford Ranges and Thurston Island is significant at the 95% confidence level, northward translation for these locations is not. Therefore, at this confidence level, paleomagnetic data do not constrain the amount of post-middle Cretaceous northward translation between Pacific West Antarctica and East Antarctica. However, there are alternatives to this conclusion. Obviously, at some lower confidence level, translations would be significant. For instance, at 63% (one standard error), 5° of northward translation is significant for Thurston Island and for the Vance and Langway studies of *DiVenere et al.* [1994]. In addition, if smaller values of rotation occurred than are calculated, the calculated value of translation would be correspondingly larger and could exceed the uncertainty level. Because the rotation estimates have large uncertainties, much lower rotation values are permitted. For the northern Ford Ranges, 156° of clockwise rotation is calculated, but at the 95% level, 93° is also permitted (156°+/-63°). The corresponding translation would then be 8.5° and is significant at the 95% level.

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