ANNALI DI GEOFISICA, VOL. XXXVI, N. 2, May 1993

Crustal extension, the exhumation of mid-crustal rocks, and the formation of basin-and-range structure in the northern Edsel Ford Ranges, western Marie Byrd Land, West Antarctica

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Abstract
The western Marie Byrd Land region of West Antarctica has experienced two episodes of crustal extension since Late Triassic (?) time. The first is associated with the rifting away of New Zealand and the Campbell Plateau from Gondwana and the origination of a continental margin here. Plate separation was well underway between about 90 to 80 Ma but this was preceeded by extension and rifting which possibly was active as early as Jurassic time. Following this episode, Cenozoic extension in the West Antarctic rift system occurred throughout the Ross Embayment and a large portion of West Antarctica including Marie Byrd Land. The plate tectonic setting for the latter episode is unclear. During Gondwana rifting and prior to sea floor spreading, extension oblique to the present margin exhumed mid-crustal rocks which are now exposed in the Fosdick Moubtains in the northern Ford Ranges. These mountains may be the footwall of a metamorphic core complex. In Cenozoic time renewed extension in the Ford Ranges created basin-and-range topography and resulted in basaltic volcanism in the Fosdick Mountains.

1. Introduction

We have conducted field studies in the northern Ford Ranges of Marie Byrd Land (MBL) during the austral summers of 1989/90 and 1990/91 (Project FORCE: *Fo*rd *R*anges *C*rustal *E*xploration; Kimbrough *et al.*, 1990; Luyendyk *et al.*, in press; fig. 1 and 2). One of our objectives was to study the structure and origin of the mountain ranges here. Our research program included geologic mapping of rocks, structures, and strain indicators, and sampling for studies in geochronology (U-Pb on zircons and monazites, $^{40}Ar/^{39}Ar$ thermochronology), metamorphic history, paleomagnetism and anisotropy of magnetic susceptibility (AMS). The field work included investigations in the Chester, Fosdick and Phillips Mountains in the northern Ford Ranges. These mountains comprise three E-W belts at the northern limit of the ranges (the boundaries are approximately 76°S to 76°45′S and 148° W to 143° W; fig. 2 and 3).

2. Exploration in the Ford Ranges

The Ford Ranges were first sighted by Admiral Richard E. Byrd and his crew in a flight from Little America on the eastern Ross Ice Shelf in December, 1992 (Byrd, 1933). The first trail party reached the region in 1934 from Little America II. A second trail party explored the area from Little America III in 1940. In 1960 a U.S. Geological Survey party travelled to the Clark Mountains in the southern Ford Ranges from Byrd Surface Camp at 80° S, 120° W. During the summer seasons of 1966 through 1969, the U.S. Antarctic Research Program established a heli-

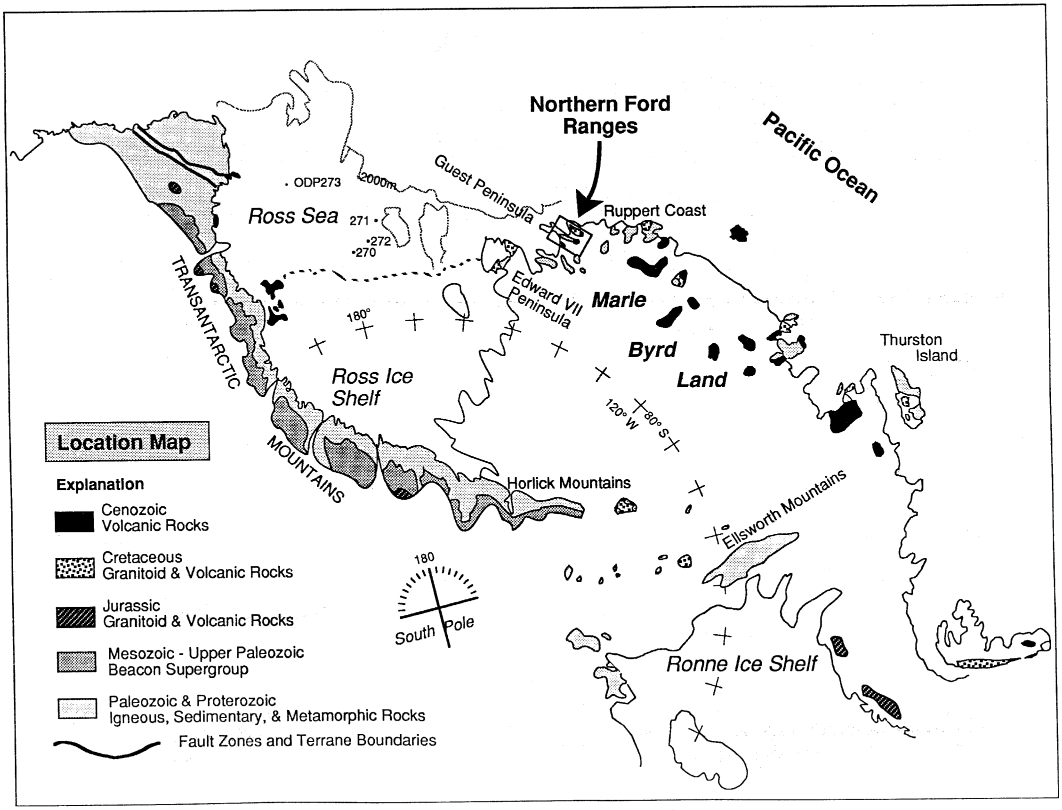

Fig. 1. Location map showing the study area, Marie Byrd Land, The Ford Ranges, the Ross Sea and ice shelf, and the Transantarctic Mountains. Outlined areas are rock outcrop.

copter camp near 77° S, 144° W. On this expedition the first major topographic surveying, geologic mapping, and gravity and aeromagnetic measurements were conducted. In 1978- 79 a New Zealand trail party visited most of the mountains in the central portions of the Ford Ranges. No other explorations occurred until the visits to the northern mountains in 1989-91 by us. Besides the FORCE party, a U.S.-New Zealand-U.K. multi- national team (SPRITE) stopped at several outcrops in the Ford Ranges using Twin Otter aircraft in 1990-91.

3. Tectonic framework

In Gondwana reconstruction Marie Byrd Land lies inboard of New Zealand and the Campbell Plateau (fig. 4). During Paleozoic time this margin of Gondwana was the site of subduction (Dalziel *et al.*, 1987; Elliott, 1991; Storey, 1991). The subduction zone shortened in time with its western edge migrating eastward. Rifting away of New Zealand and the Campbell Plateau from Marie Byrd Land was apparently transtensional and dextral. Evidence for this is found in strain indicators in the northern Ford Ranges and is presented below.

Gondwana rifting was accompanied by uplift and erosion in MBL. Le Masurier and Rex (1983) noted that much of Marie Byrd Land contains uplifted sub-horizontal erosion surfaces to which they assign a Late Cretaceous-Early Tertiary age. West Antarctic rifting occurred during Cenozoic time and produced faulting and bi-modal volcanism in Marie Byrd Land which began in Oligocene time (Le Masurier, 1990). Glaciation in West Antarctica may have begun in earnest in

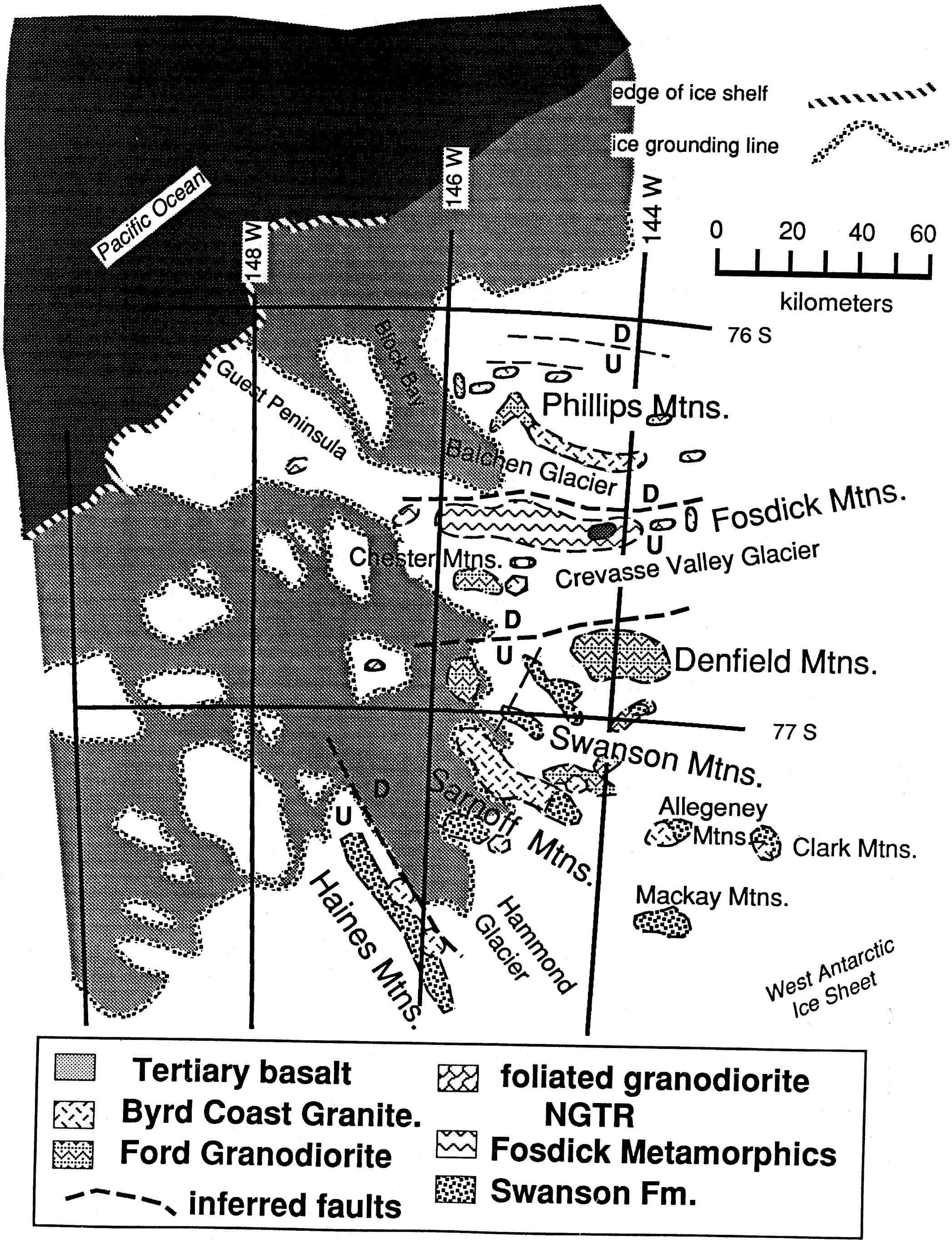

Fig. 2. Generalized geologic map of the Edsel Ford Ranges, Marie Byrd Land, compiled from mapping by Wade *et al.* (1977a,b; 1978), Weaver *et al.* (1991) and results of the FORCE project (Luyendyk *et al.*, in press).

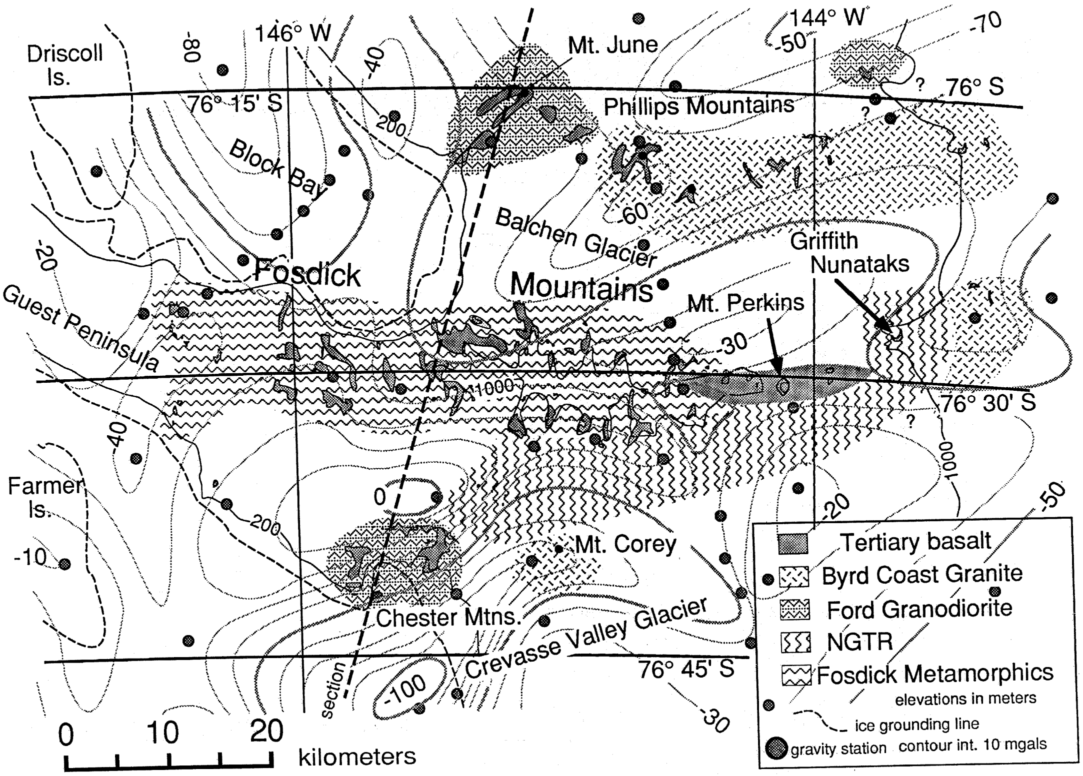

Fig. 3. Revised geologic map of the northern Ford Ranges. Base map from Wade *et al.* (1977a, 1978). NGTR = Neptune-Griffith transitional rocks; see the text. Bouguer gravity (terrain-corrected) is from Beitzel (1972). Anomalies were calculated by replacing ice thickness (density 900 kg/m^3) measured with surface radar soundings with rock (density 2670 kg/m^3).

Oligocene time (Bartek *et al.*, 1991). Many of the exposed peaks in the Ford Ranges exhibit glacial striae suggesting that the ice sheet here may have been many hundreds of meters thicker in the past (Wade, 1937; Richard and Luyendyk, in press).

The rifting history for western Marie Byrd Land may parallel that proposed for the Ross Sea and Embayment. Cooper *et al.* (1991) recognize a Cretaceous episode, and an Eocene and younger episode there corresponding with uplift of the Transantarctic Mountains and subsidence of the Terror Rift.

4. Geology of the northern Ford Ranges

The Phillips and Chester mountains comprise Devonian granodiorite (Ford Granodiorite; MDf; 353 Ma in the Chester Mountains; Luyendyk *et al.*, in press) and Cretaceous granite (Byrd Coast Granite; Kbc; 105 Ma at Mount Corey and in the eastern Phillips Mountains). These mountains are 10 km to the north and south respectively of the Fosdick Mountains. Inheritance ages of 1200-1300 Ma from U-Pb discordia on MDf imply Precambrian contributions to source magmas (Luyendyk *et al.*, in press). The Balchen Glacier flows westwards in a valley between the Phillips and Fosdick Mountains. Ice thickness measurements by radar (Beitzel, 1972) indicate that this glacier is on the order of one kilometer thick while the remainder of the Ford Ranges is covered by about 500 meters of ice. The north face of the central Fosdick Mountains is marked by vertical cliffs over 500 meters high. The Fosdick Mountains include spectacular exposures of

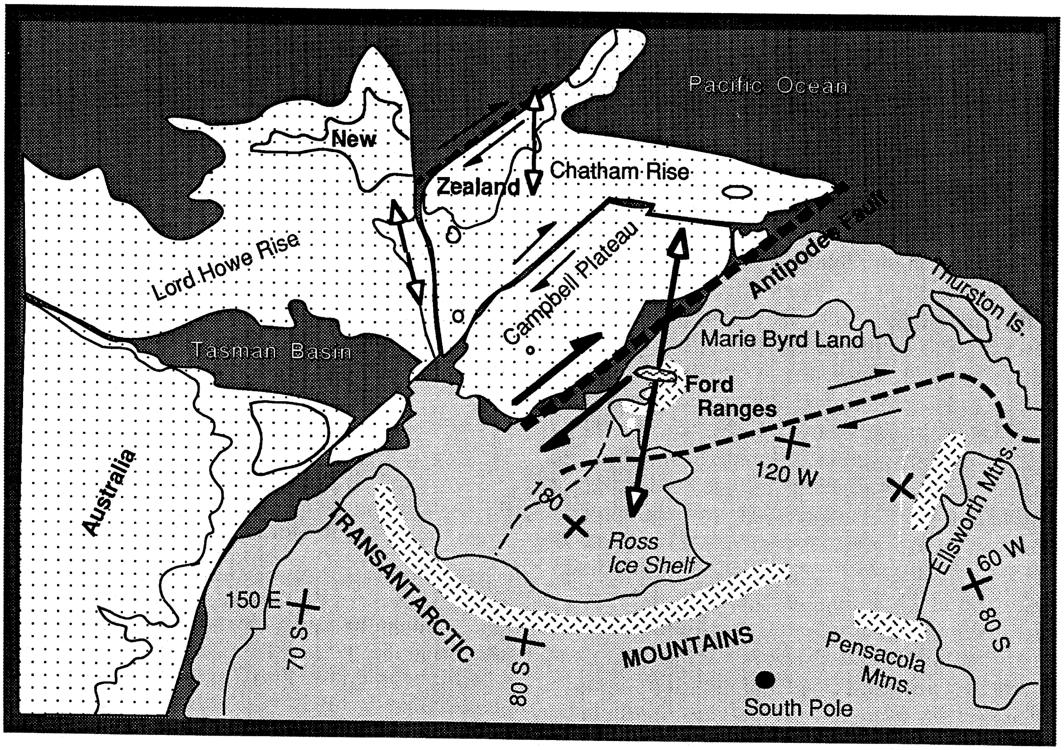

Fig. 4. Continental reconstruction of southeast Australia, new Zealand, and adjoining Antarctica prior to Gondwana rifting in the late Cretaceous time. After Grindley and Davey (1982). Strain indicators in the Fosdick Mountains (large open arrows; see fig. 6 and Richard, in press) suggest transtensional (dextral) rifting consistent with their interpretation of the dextral Antipodes fault at the margin of Marie Byrd Land. Smaller open arrows on New Zealand are Gondwana rifting strain indicators in the Paparoa metamorphic complex (lower left; Tulloch and Kimbrough, 1989) and in the Mount Somers rhyolite (Oliver, 1977; Andrews *et al.*, 1987).

migmatite overlain in the east by Pliocene volcanic rocks (K-Ar age; Le Masurier and Wade, 1990). The Early Paleozoic Swanson Formation (Wade and Couch, 1982; Bradshaw *et al.*, 1983), a shallow marine turbidite and tuff sequence, crops out in ranges about 30 km to the south of the Fosdick Mountains. The basement for the Swanson Formation is not exposed. Both the Byrd Coast Granite and the Ford Grandiorite are found in intrusive contact with the Swanson Formation to the south (Wade, 1937; see maps of Wade *et al.*, 1977b; 1978).

Bouguer gravity, corrected for ice thickness and topographic effects, was measured throughout the Ford ranges by Beitzel (1972). In The northern Ford Ranges a gravity high cuts across the trend of the mountains (fig. 3). A deep gravity low is located over the western Crevasse Valley glacier south of the Chester Mountains (fig. 3). The gravity anomalies have relief on the order of 100 milligals suggesting substantial density contrasts below the rock surface.

The erosion surface of Le Masurier and Rex (1983) may be present in the northern Ford Ranges. The best candidates are the flat tops of Mount Paige in the Phillips Mountains and Marujupu in the Fosdick Mountains. The eastern summit of the Fosdick range also is flat-topped.

The Fosdick Metamorphic Complex (FMC) consists of metapelite gneiss intruded by granodiorite and tonalite (see Wilbanks, 1972; Smith, in press). The sedimentary protolith is possibly the Swanson Formation. The orthogneiss protolith is possibly the Ford Grandiorite. Two prograde metamorphic episodes affected the FMC; the last episode had peak conditions of 5.6 kbar and (720÷780)°C (mid-to-upper crustal depths; Smith, in press.) Ages on synmetamorphic orthogneiss sills suggest the latest episode is early Late Cretaceous in age (D.L. Kimbrough, work in progress, 1992). At Neptune Nunataks a Permian-age granite body cross-cuts an apparently older foliation indicating that one metamorphic episode was prior to this time. The metamorphic grade decreases southward from granulite and upper amphibolite facies in the cliffs of the north-central Fosdick Mountains to amphibolite grade in the south-central mountains, to greenschist grade at Neptune Nunataks (fig. 3). $^{40}Ar/^{39}Ar$ studies on hornblende, muscovite, biotite, and K-feldspar show almost complete cooling of the FMC took place between 100 and 94 Ma (Richard, in press), which is prior to the inception of sea floor spreading offshore. The FMC contains deformed and boudinaged mafic dikes. During a retrograde phase, north-northeast-south-soutwest extension resulted in extension veins and minor ductile normal faults, and the intrusion of undeformed mafic dikes into the FMC, MDf, and Kbc.

Paleomagnetic data suggest a widespread remagnetization event during the Late Cretaceous normal polarity superchron (Cisowski and Luyendyk, 1991). All results are normal polarity from all Paleozoic and Mesozoic rock types; the remanence directions from MDf are almost or exactly identical to directions from adjacent outcrops of Kbc (fig. 5). A Late Cretaceous paleomagnetic direction from the Ruppert Coast volcanics just to the north of the Ford Ranges shows $I = -84°$, $D=223°$, alpha 95 = 4.5° (Grindley and Oliver, 1983), which agrees with directions for many sites except for the Chester Mountains and Mount Corey (fig. 5). In the Chester Mountains and at Mount Corey a few kilometers to the east, directions are up to the south. This result can be interpreted as post-magnetization southward titlting of about 20 to 30 degrees. Using the same reasoning, the Phillips Mountains are untilted (that is, site directions are not different from the Ruppert Coast direction) except for about 30 degrees or northward tilting at Hutcheson Nunataks at the extreme east end of the range. Local areas of the Fosdick Mountains are either untilted, or tilted southward somewhat less than the Chester directions. The Ruppert Coast pole, and the pole from the «untilted» sites in the northern Ford Ranges, are different from East Antarctic and other West Antarctic Cretaceous poles (Grunow *et al.*, 1991), suggesting clockwise rotation and/or destral motion of MBL relative to East and West Antarctica since Cretaceous time (Grindley and Oliver, 1983).

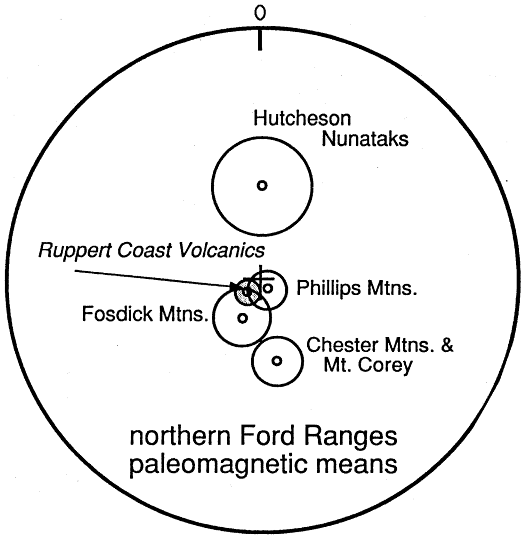

Fig. 5. Average of site mean directions for paleomagnetic sites in the Fosdick Mountains (FMC; 4 sites), Phillips Mountains (MDf; 6 sites), the Chester Mountains (MDf) and Mount Corey (Kbc, 5 sites), and Hutcheson Nunataks (Kbc; 2 sites) compared with the Ruppert Coast direction of Grindley and Oliver (1983; mid-Cretaceous; 26 sites).

AMS data from the migmatites show a preferred north-northeast-south-southwest lineation, consistent with structural observations (fig. 6). Boudinaged deformed dikes in the FMC preserve an older lineation with no consistent orientation. The higher levels of the complex exposed at the south edge of the Fosdick Mountains and at Neptune Nunataks show a strain direction which is more north-south. A dextral high-strain zone was found between these southern outcrops and the rest of the Fosdick range (Luyendyk *et al.*, in press). Possibly this zone is a tectonic boundary between two regimes.

The geomorphic expression of the ranges, the facies relations within the Fosdick Metamorphic

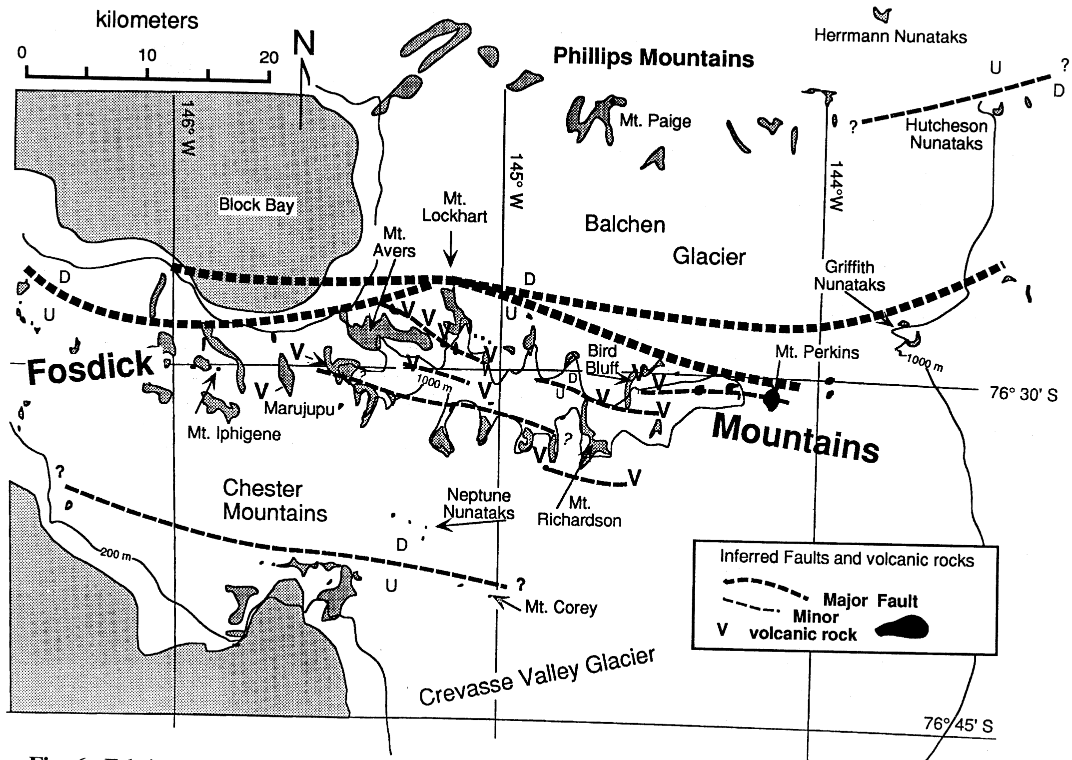

Fig. 6. Fabric of the anisotropy of low-field magnetic susceptibility in the Fosdick Metamorphic Complex and Neptune-Griffith Transition Rocks (NGTR). Each symbol is a site average of several specimens.

Complex, the map distribution of $^{40}Ar/^{39}Ar$ cooling ages in the complex (Richard, in press), and the tilted paleomagnetic directions, all suggest that the Fosdick (and Chester?) Mountains are part of a south-tilted structural block. The outcrop pattern of volcanic rocks and lineations visible on aerial photographs and a SPOT satellite image suggest a network of east-west–trending faults within the three ranges (fig. 7).

5. Crustal extension

Our initial working hypothesis was that the Chester, Fosdick, and Phillips Mountains represent a metamorphic core complex with the FMC exposed in the core of a broad E-W anticlinorium. Field investigations have not revealed evidence in support of this proposal. We did not discover an exposed detachment fault, or a mylonite zone, chloritic breccias, or syntectonic sediments. It must be said however, that most of the area is covered by snow, ice, and glaciers so that lack of such evidence is not compelling. Furthermore, the Fosdick complex is an exposure of mid-crustal rocks which show little evidence of brittle deformation. The upper zone of brittle deformation and mylonites may have been removed by erosion. It is clear however, that virtually all the cooling (exhumation?) of the FMC occurred during Gondwana rifting.

Exhumation of the FMC in an extension environment is supported by the rapid cooling of the FMC, inferred large-throw normal faults between the Fosdick and Phillips Mountains (fig. 8), structural and AMS strain indicators, and the occurrence of undeformed mafic dikes in Kbc, MDf and the FMC. A core complex or asymmetric rift model (*e.g.*, Coney, 1980; McCarthy *et al.*, 1991) suggests that the FMC is lower plate exposed in a window through an upper plate (fig. 8). It is not clear whether the Phillips and

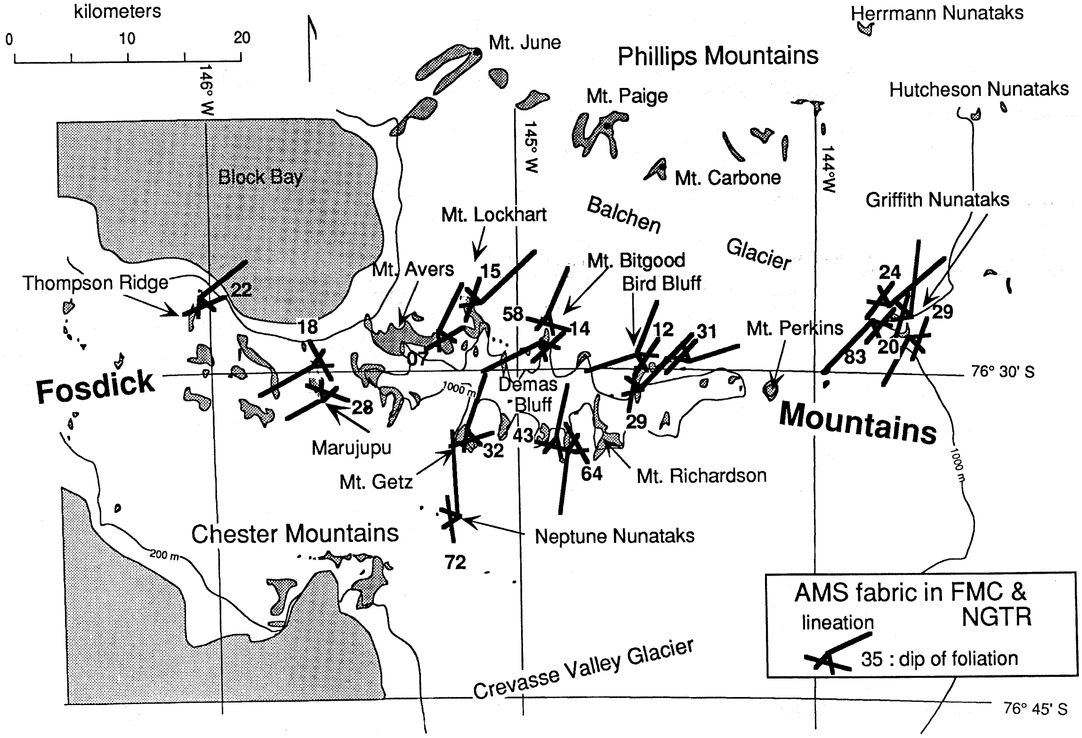

Fig. 7. Map of volcanic rock outcrops and inferred Cenozoic faults in the northern Ford Ranges. Faults are inferred from topographic lineation, offset of the early Tertiary erosion surface (see text), alignment of volcanic outcrops, and paleomagnetic directions interpreted to have been tilted. Not shown are minor NW-SE–striking post-volcanic normal faults (down-to-the-north) near and on Mount Perkins, and N-S faults at Mt. Iphigene (dip slip), Neptune Nunataks, Mt. Corey and Bird Bluff. The major frontal fault of the Fosdick Mountains may be a reactivated Cretaceous normal fault (see fig. 3).

Chester-Corey Mountains are upper or lower plate in such a model. Paleomagnetic directions in the Chester-Corey Mountains are interpreted to be tilted south (fig. 5). If these mountains were on the upper plate of a core complex centered on the Fosdick Mountains the tilt would be expected to be northwards the axis of the culmination. Using paleomagnetic results Marquis and Irving (1990) suggested this style of upper-plate brittle deformation in a symmetric core complex in the Southern Omineca belt in British Columbia. Asymmetric rifting of a layered lithosphere including isostatic rebound by viscous flow (Wdowinski and Axen, 1992) is a workable solution. In this model the Phillips Mountains are within the upper-plate allochthon and the Fosdick and Chester-Corey Mountains are lower plate or footwall; a detachment fault underlies the Phillips and fronts or extrapolates above the north edge of the Fosdick Mountains. Calculations by Wdowinski and Axen (1992) indicate that roughly 50 km of extension could account for 15 km of exhumation of the footwall in a central dome and substantial tilts of footwall rocks away from the dome such as we have inferred for the Chester and Corey Mountaines. Not explained by their model are the very large gravity anomalies mapped over the ranges.

An alternate model for exhumation of the FMC is domino-style normal faulting (*e.g.*, Miller, 1991) that is down on the north side with southward tilting of blocks. Once again, such

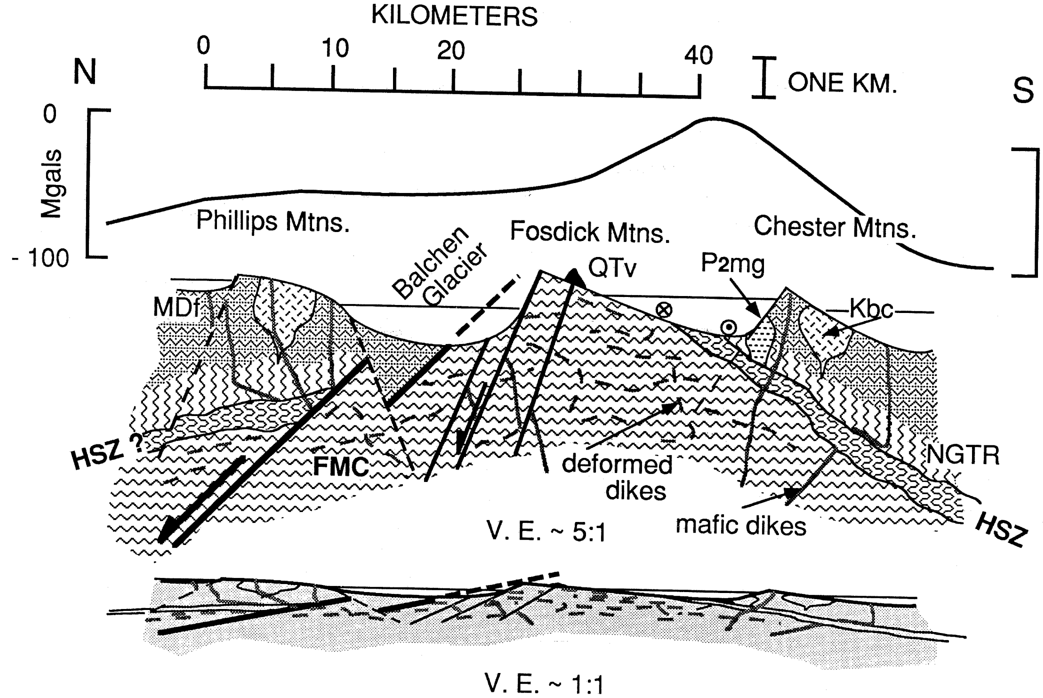

Fig. 8. A proposed cross-section through the Phillips, Fosdick, and Chester Mountains; see fig. 3 for the location. The bouguer gravity contoured by Beitzel (1972) is also shown. QTv = Cenozoic volcanics; Kbc = Byrd Coast granite; P2mg = Permian biotite-muscovite granite found at Neptune Nunataks; MDf = Ford granodiorite; NGTR = Neptune-Griffith transitional rocks; FMC = Fosdick Metamorphic Complex; HSZ = high-strain zone mapped on the south side of Mt. Richardson (sense of motion shown as cross=away and dot=toward reader).

faults are not obvious. This tilting is consistent with our structural and paleomagnetic interpretation for the Chester and Corey Mountains but not for the Phillips Mountains. But tilting in the northern Ford Ranges also may be due to Cenozoic block faulting. Exhumation of the FMC could have occurred on a low-angle normal fault now dipping north under the Phillips Mountains, or a high-angle fault on the north side of the Fosdick Mountains, or both (fig. 8). Crustal-scale, high-angle normal faults could give rise to gravity lows on the faulted sides of half- grabens. Local gravity lows over the Crevasse Valley Glacier south of the Chester Mountains (~ –100 Mgals; fig. 3), over the Balchen Glacier between the Fosdick and Phillips Mountains (~ –50 Mgals; fig. 3), and north of the Phillips Mountains (~ –100 Mgals; Beitzel, 1972), can be interpreted to suggest large throw, crustal-scale, north-dipping and steep normal faults (down to the north) on the south side of the Crevasse Valley and Balchen glaciers and the north side of the Phillips Mountains. These anomalies could be caused by thick accumulations of low-density sedimentary rock beneath the ice surface. The paleomagnetic data suggest that the Phillips Mountains block is not tilted, requiring a south-dipping fault on the south side of this range to explain the low-gravity anomaly over the Balchen Glacier. This interpretation defines the Balchen Glacier valley as an aymmetric graben, with over 15 kilometers of throw on its south side in the Fosdick Mountains and only a few kilometers in the north side.

Regardless of the mechanism by which the FMC was exhumed, the timing is complex. A first analysis suggests Gondwana rifting as a key event. The Kbc was intruded to shallow levels then (Weaver *et al.*, 1991) and cooling ages for the FMC are also in this time frame, arguing that a large amount of exhumation occurred as a result of this rifting. Along with this evidence, Gondwana reconstructions (*e.g.*, Grindley and Davey, 1982) point to a regional pattern of Cretaceous plutonism (and volcanism) extension (Bradshaw, 1991), and exhumation of metamorphic basement (for example, the Paparoa Core Complex in West Nelson, New Zealand; Tulloch and Kimbrough, 1989). Other lines of evidence suggest that Late Cenozoic rifting was important. The individual mountain belts of the Ford Ranges, including the Chester, Fosdick, and Phillips mountains, trend subparallel to the Transantarctic Mountains and also oblique to the trend of the MBL continental margin (best seen in polar grid coordinates). The Transantarctic mountains were possibly uplifted mostly in the last few million years in concert with vigorous extension throughout West Antarctica (Beherendt and Cooper, 1991). Mountains in the Ford Ranges form a basin-and-range topography with the basins filled by enormous glaciers. Additionally, Tertiary and Quaternary bi-modal alkalic volcanism in Marie Byrd Land suggests an origin from rifting (Le Masurier, 1990). Volcanic centers in the Fosdick Mountains trend sub-parallel to the range strike inferring Late Cenozoic faulting as a control of both range uplift and volcanism (fig. 7). The thickness of ice in the Balchen Glacier suggests that this Cenozoic uplift was on the order of 1.5 kilometers or less. Fission track studies on apatite suggest that no more than this amount of uplift (cooling) could have occurred during Cenozoic time (P. Fitzgerald and S.Richard, work in progress).

Glacial striae are found at several locations near the tops of the Fosdick and Phillips Mountains. These indicate a south-to-north flow, at a high angle to the present westward and southwestward glacial movement. Also, clasts of the Swanson Formation, which crops out only south of the Chester Mountains, are found in some moraines. Evidently, glacier flow has changed from northerly to westerly (Richard and Luyendyk, in press). Very possibly, block faulting formed topography which reoriented glacier flow. Because the West Antarctic ice sheet is Oligocene or possibly even Quaternary in age, basin-and-range faulting may be of this age also.

A two-stage extension process for exhumation and mountain building is clearly possible and is consistent with rifting models for the Ross Seas region (Cooper *et al.*, 1991). Cooling ages suggest that the FMC was near the surface by 94 Ma, and this rock uplift would be the result of Gondwana rifting. The rapid cooling (uplift) suggests tectonic unroofing via large displacement faults. Topografy formed during initial rifting was soon reduced to a Late Cretaceous/Early Tertiary erosion surface, prevalent throughout Marie Byrd Land and New Zealand (Le Masurier and Rex, 1983). This surface is believed to be present in both the Phillips and Fosdick Mountains. Brittle deformation features of a metamorphic core complex could have been removed during this episode of erosion. Cenozoic block faulting and possibly glacial erosion would provide the final exhumation and form the present topography. Two generations of faults may exist with the older generation dipping at a lower angle than the younger (fig. 7 and 8).

Our presumably Late Cretaceous paleomagnetic directions agree with the Late Cretaceous pole of Grindley and Oliver (1983) for the adjacent Ruppert Coast region and both of these directions are discordant from East Antarctica. Therefore, the same conclusions can be drawn for the northern Ford Ranges as for the Ruppert Coast: that these regions (western MBL) have been part of West Antarctica, have experienced (200÷500) km displacement relative to East Antarctica, and may have rotated a small amount clockwise relative to other West Antarctic regions, since mid-Cretaceous time (Grindley and Oliver, 1983; Grunow *et al.*, 1991).

6. Gondwana rifting

A key observation is that the individual ranges in the Ford Ranges trend east-west or northwest-southeast, oblique to the continental margin, suggesting that their formation is due to north-south and/or northeast-southwest (local) extension in the Cenozoic West Antarctic rift system. However, the Cretaceous-age strain indicators in the FMC are also close to the same directions, inferring that the extensional strain direction in the Ford Ranges has not changed greatly since early

Late Cretaceous time, and also that the Gondwana continental margin of western MBL resulted from transtension rather than pure shear (extension was not oriented northwest-southeast, perpendicular to the trend of the margin; fig. 4). The western MBL margin may therefore be more accurately described as an inactive transform margin rather than a rifted passive margin.

As was pointed out by Katz (1982), MBL underwent uplift during and after Gondwana rifting whereas the once adjacent Campbell Plateau of New Zealand subsided. A model for the development of passive continental margins by detachment faulting (asymmetric rifting) by Lister *et al.* (1991) unifies Katz'observation with the geology of the northern Ford Ranges (fig. 9). By applying their model, MBL is interpreted as the uplifted hanging wall of an asymmetric rift, while the Campbell Plateau is the subsided attenuated crust of the footwall overlain by tilted blocks of an upper plate. The FMC is the footwall exposed near the continental margin. The Kbc is the anorogenic granite of the model, while basaltic underplating is expressed as deformed and undeformed mafic dikes in the northern Ford Ranges and Ruppert Coast.

7. Remaining questions

We are left several major questions about this ragion:

– What are the basement rocks of western Marie Byrd Land? A related question is what is the significance of the Precambrian inheritance ages for the Ford Granadiorite?

– What was the source terrane for the Swanson Formation?

– By what process did the Swanson Formation, the probable protolith for the FMC metapelites, reach depths of near 20 kilometers, and when?

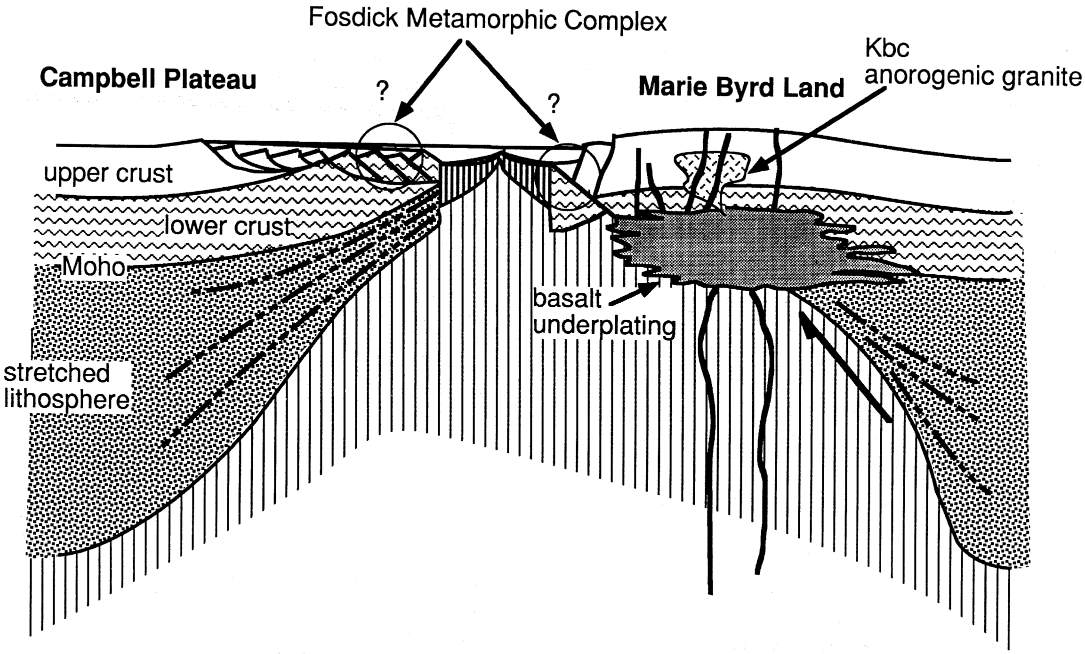

Fig. 9. Gross architecture of upper-plate and lower-plate passive margins resulting from continental extension by detachment faulting (from Lister *et al.*, 1991). This figure depicts our vision of the structural geometry at the time of Gondwana rifting between Marie Byrd Land and New Zealand. We correlate the upper-plate margin with Marie Byrd Land and the lower-plate margin with the Campbell Plateau of New Zealand. The Fosdick Metamorphic Complex is exposed in the footwall stranded on the hanging wall plate.

– Where are the large faults which accommodated extension during Mesozoic time?

– Are transtensional structures present in the continental margin?

– What is the age of the post-rifting erosion surface in the northern Ford Ranges?

– What is the structural cause and tectonic significance of the bouguer gravity features?

– When did continental glaciation begin in the Ford Ranges and did Cenozoic block faulting change the flow direction of glaciers here?

– What relative portion of the exhumation of the FMC is Late Cenozoic in age?

– What portion of exhumation of the Fosdick Mountains can be attributed to glacial erosion?

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