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Structural and tectonic evolution of the Ross Sea rift in the Cape Colbeck region, Eastern Ross Sea, Antarctica

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Abstract. The far eastern continental shelf of the Ross Sea, Antarctica, has been relatively unexplored up to now. This region and western Marie Byrd Land are at the eastern limit of the Ross Sea rift, part of the West Antarctic rift system, one of the larger regions of extended crust in the world. The Ross Sea continental shelf west of Cape Colbeck and the Edward VII Peninsula in western Marie Byrd Land was investigated using marine geophysics during cruise 9601 of the research vessel ice breaker *Nathaniel B. Palmer*. The purpose was to determine the structural framework and tectonic history of the eastern border of the Ross Sea rift and to integrate this with what is known about western Marie Byrd Land. The region mapped is characterized by a passive margin with a flat overdeepened shelf cut by the north trending Colbeck Trough, an erosional feature formed in Miocene and later time by glacial downcutting that followed the locations of existing basement structures. Seismic sequences and unconformities identified in the Ross Sea were correlated into the Colbeck shelf area. The section comprises mostly undeformed glacial marine sequences of late Oligocene and younger age that are unconformably overlying late Early to Late Cretaceous and minor early Tertiary (?) faulted sequences. This unconformity is identified as RSU6, mapped elsewhere in the eastern Ross Sea. Two units are found below RSU6, each separated by an unconformity that is here named RSU7. These sequences fill north trending half grabens in the faulted basement and are interpreted as syn rift units. Unconformity RSU7 is correlated to the West Antarctic Erosion Surface mapped onshore in western Marie Byrd Land. The lack of thick early Tertiary sediments on the shelf suggests significant vertical tectonics. This onshore and offshore region was widely faulted in late Early and Late Cretaceous time, was high above sea level and was beveled by prolonged erosion, while subsiding steadily in Late Cretaceous and Cenozoic time. Subsidence was largely due to lithosphere cooling amplified later by glacial and sediment loading in Cenozoic time. Mylonites that have late Early Cretaceous cooling ages were dredged from the southeast wall of the Colbeck Trough. This finding and normal faults that we mapped in the eastern Ross Sea we attribute to detachment-style extension in late Early Cretaceous time. This extension was directed subparallel to the trend of the present margin edge and occurred prior to the rifting of Campbell Plateau from Marie Byrd Land at ~79 Ma. Cooling events onshore western Marie Byrd Land suggest the main extension began at ~105 Ma. This is also the time of transition from subduction to extension elsewhere along the ancient Gondwana margin. Minor west tilting of the shelf during the late Cenozoic was the result of continued subsidence of the continental shelf along with possible uplift of western Marie Byrd Land associated with the Marie Byrd Land dome to the east. Early Tertiary extension in the western Ross Sea rift is not strongly reflected in the east side of the rift. A more robust correlation of the events here with the better known tectonic history on the west side of the Ross Sea rift awaits sampling and dating of the units we mapped on the Colbeck shelf.

1. East Boundary of the Ross Sea Rift in the Ross Embayment

1.1. Tectonic Setting and Significance

West and East Antarctica are separated by the Ross Embayment, a geographical feature comprising the Ross Sea and Ross Ice Shelf that is bounded on the west by the Transantarctic Mountains and on the east by the mountain ranges of western Marie Byrd Land (Figures 1a and 1b). The Embayment includes the structural province of the Ross Sea rift [*Tessensohn and Worner,* 1991]. The Ross Sea rift and western Marie Byrd Land (wMBL) are parts of the West Antarctic rift system [*LeMasurier*, 1990; *Behrendt et al.*, 1991]. The West Antarctic rift system and Transantarctic Mountains make up one of the largest extensional regimes on Earth and are comparable in size to the Basin and Range province of the western United States. The West Antarctic rift system is largely concealed under the West Antarctic ice sheet and the Ross Ice Shelf. The western border of the rift system is considered active today by many researchers because Cenozoic volcanism is now occurring here.

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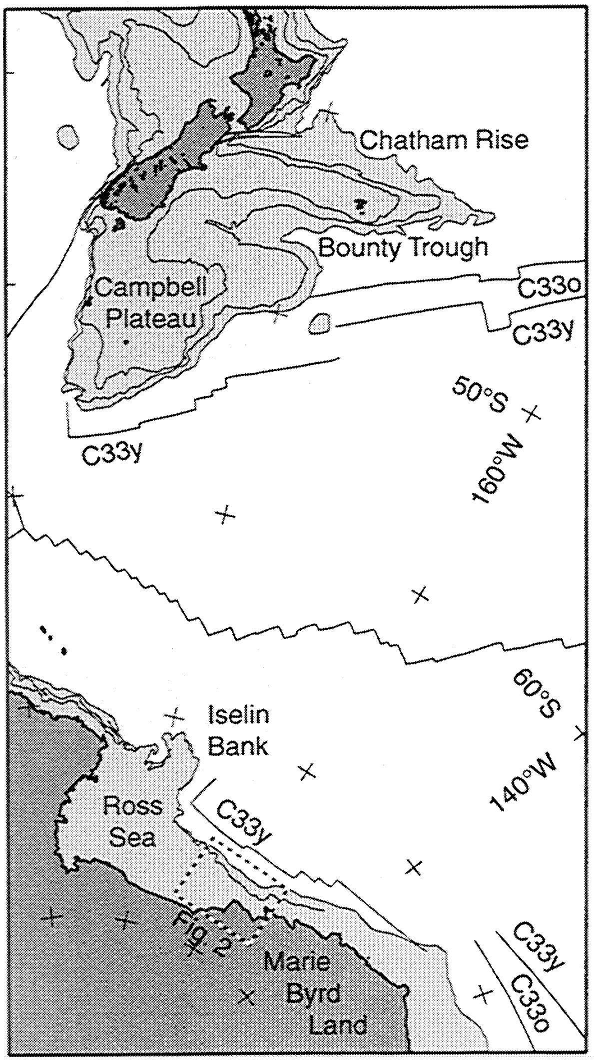


Figure 1a. South Pacific sector showing New Zealand, Chatham Rise and Bounty Trough, Campbell Plateau, and Ross Sea region of Antarctica. Modern spreading axes are shown by solid lines. Depth contours are at 1 km intervals. Magnetic isochrons 33o (79.1 Ma) and 33y (73.6 Ma) are from *Stock and Cande*, [2001]. Box outlines Figure 2.

Western Marie Byrd Land is the most prominent topographic feature of the West Antarctic rift system east of the Transantarctic Mountains. However, the tectonic history of the east side of the rift and its relation to the west side of the rift has remained obscure because geophysical data constraining this did not exist. Our goal in this study was to determine the structural setting and tectonic history of the eastern Ross Sea rift. Our specific objectives include identification of the major structures at the eastern boundary of the rift in the eastern Ross Sea offshore wMBL, determination of the timing of deformation, and integration of our findings within the overall tectonic history of the West Antarctic rift system.

Mesozoic events shaped the main structural features of the Ross Embayment [*Davey and Brancolini*, 1995]. The separation of the East Gondwana continents Australia, Antarctica, and New Zealand plus the Chatham Rise and the Campbell Plateau (Figure 1a) in Cretaceous time sets the tectonic framework for the development of the Ross Sea rift and western Marie Byrd Land. Prior to that time subduction of the Phoenix plate was occurring along the East Gondwana continental margin [*Bradshaw*, 1989]. Gondwana rifting began here in Late Jurassic (?) to Early Cretaceous time, culminating in seafloor spreading between the Chatham Rise and the Bellingshausen plate off West Antarctica before 79 Ma and between Campbell Plateau and western Marie Byrd Land before 74 Ma, [*Cande et al.*, 1995; *Stock and Cande*, 2001]. This spreading resulted in the present passive margin in the eastern Ross Sea and wMBL. Spreading in the Adare Trough in the northwestern Ross Sea (Figures 1a and 1b) during Eocene and Oligocene time [*Cande et al.*, 2000] likely influenced the development of the Victoria Land Basin and uplift of the Transantarctic Mountains [*Hamilton et al.*, 2001].

New Zealand, the Chatham Rise, and the Campbell Plateau (Greater NZ; Figure 1a) fit closely against the continental margin of the eastern Ross Sea (east of Iselin Bank; Figures 1a and 1b) in predrift reconstructions [*Lawver and Gahagan*, 1994]. Greater NZ and the eastern Ross Sea and wMBL may have had parallel tectonic and geological evolution prior to Late Cretaceous seafloor spreading. Petroleum exploration with seismic profiling and exploratory drilling on the Campbell Plateau [*Cook and Beggs*, 1990; *Beggs*, 1993] gives a relatively complete outline of Mesozoic and Cenozoic geology and events. There are parallels in the evolution of wMBL and Greater NZ up to the end of Late Cretaceous time that can guide an overall interpretation of the geology and history of the eastern Ross Sea. These include comparable basement rocks and structures. The objectives of our study were to relate mapping offshore and onshore wMBL in a common geologic framework, to interpret this in the context of Gondwana rifting, and to contrast what we found for the eastern Ross Sea rift with the west side of the rift.

1.2. Eastern Ross Sea

Basement in the Ross Sea rift is faulted into large N-S trending structures that define three basins west of 180°, the Northern Basin, Victoria Land Basin, and the Central Trough (e.g., *Cooper et al.*, [1995]; Figure 1). East of 180°, the Eastern Basin contains several kilometers of Neogene and older sediment in a broad downwarp [e.g., *Davey*, 1987; *Anderson*, 1990] (Figure 1b). Latest Oligocene and younger deformation through the central and eastern Ross Sea is limited to minor fault reactivation and gentle tilting [*Cooper et al.*, 1995; *De Santis et al.*, 1995]. Three Deep Sea Drilling Project (DSDP) Leg 28 sites were drilled in the western flank of the Eastern Basin (Figure 1b [*Hayes and Frakes*, 1975]). Cores from DSDP Site 270 sampled 365 m of late Oligocene-early Miocene subglacial and glacial marine strata beneath ~20 m of Pleistocene through Recent section. The early Miocene to late Oligocene subglacial and glacial marine sediments were deposited at ~500 m depth. These sediments overlie thin shallow water green sands of late Oligocene age, all on top of metamorphic basement rocks and sedimentary breccia with an overlying regolith. The basement rocks

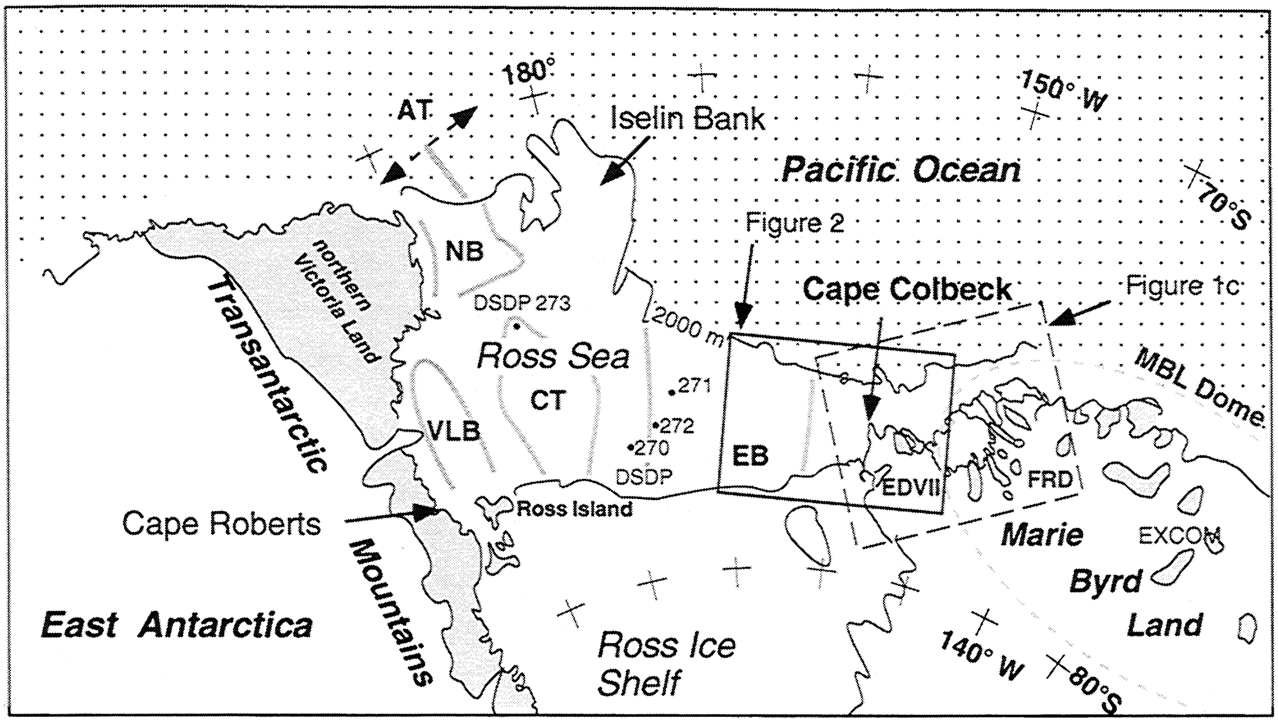


Figure 1b. Ross Sea region map showing the location of the study area (Figures 1c and 2), outcrop onshore (shaded), Deep Sea Drilling sites, the Transantarctic Mountains, Cape Roberts and Cape Colbeck. AT Adare Trough (dashed arrows indicate former spreading directions [Cande et al., 2000]); NB, Northern Basin, VLB; Victoria Land Basin; CT, Central Trough; EB, Eastern Basin; FRD, Ford Ranges; EXCOM, Executive Committee Range. The West Antarctic rift system is outlined by the light shade [LeMasurier, 1990].

contain evidence of both ductile and brittle deformation features, which, along with early Late Cretaceous fission track ages, are interpreted to indicate faulting and extension at that time [*Fitzgerald and Baldwin*, 1997]. Seismic reflection data in the Eastern Basin [e.g. Traube and Zayatz, 1993; *De Santis et al.*, 1995] have been interpreted as showing a three-stage development of the basin, starting with Late Cretaceous Gondwana rifting, then passive subsidence, followed by the start in early Miocene time or earlier of the deposition of prograding subglacial and glacial marine sequences. Aggrading Plio-Pleistocene sequences suggest regional subsidence during that time also.

1.3. King Edward VII Peninsula and the Ford Ranges of wMBL

Edward VII Peninsula is the westernmost region in MBL with bedrock topography above sea level (Figures 1c and 2). As such it arguably defines the eastern border of the Ross Sea rift. The Peninsula separates the Ross Sea from Sulzberger Bay offshore wMBL. The Ford Ranges of wMBL immediately east and north of the Peninsula are an area of significant topography in a region of thin crust [*Behrendt et al.*, 1991; *Bentley*, 1973, 1991; *LeMasurier and Landis*, 1996]. Many mountain ranges in wMBL attain maximum elevations of 1100 m, have glaciated summit plateaus, and are oriented E-W or NW-SE. Large glaciers flow to the west and seaward between the ranges, apparently through grabens (Figure 1c). These features suggest the region is an area of basin-and-range-style faulting [*Luyendyk et al.*, 1992, 1994].

Outcrops onshore wMBL provide geologic controls on the basement rock type and age and the timing of denudation, but no Tertiary strata are found here. Offshore, up to a kilometer or more of sediments are found over acoustic basement, but no age control is yet available. Consideration of the onshore and offshore data together allows a tectonic interpretation to be made that we present here.

Onshore, early Paleozoic low metamorphic grade argillites of the Swanson Formation and late Paleozoic and Mesozoic intrusive rocks of the Ford Granodiorite and Byrd Coast granite make up most of wMBL outcrop [*Adams*, 1986, 1987; *Adams et al.*, 1995; *Bradshaw et al.*, 1983; *Kimbrough and Richard*, 1991; *Luyendyk et al.*, 1992; *Luyendyk and Smith*, 1994; *Weaver et al.* 1991, 1994]. These basement rocks are correlated to similar rocks of the Buller terrane of the Western Province of New Zealand and the Campbell Plateau [*Bradshaw et al.*, 1997]. The Ford granodiorite is an I type granitiod ranging in age between 380 and 353 Ma [*Adams*, 1987]. The Byrd Coast granite comprises two suites of granites, an I type ranging in age from 124 to 108 Ma, and a younger middle Cretaceous A-type of between 102 and 95 Ma [*Weaver et al.*, 1994]. (We use "middle Cretaceous" to indicate late Early Cretaceous and early Late Cretaceous, circa 105-94 Ma). This contrast in character points to a change to an orogenic magmatic environments during middle

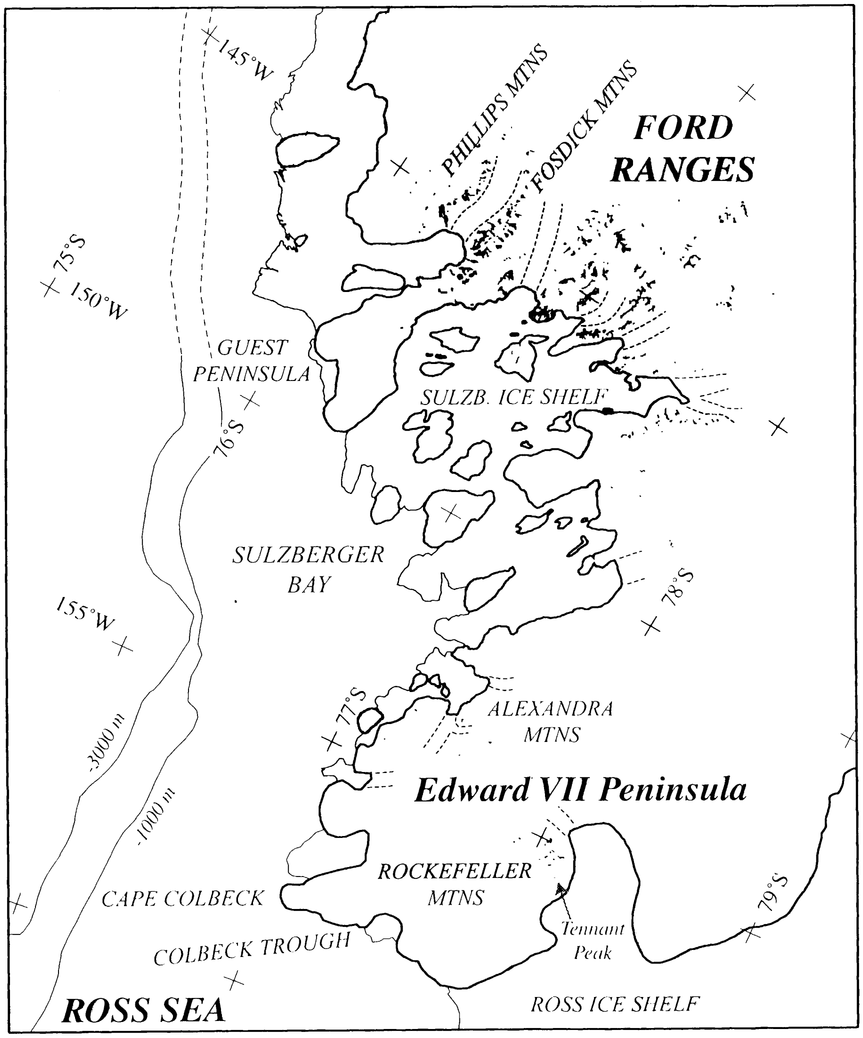


Figure 1c. Location map (see Figure 1b) showing mountain ranges and glaciers in western Marie Byrd Land. Outlines show grounding lines at the coast and for islands in the Sulzberger Ice Shelf. Bathymetric contours are shown for the edge of the continental margin, but no detail is shown for the continental shelf (see Figures 2 and 3).

Cretaceous time. The Ford granodiorite is restricted to the Ford Ranges and is not found on Edward VII Peninsula. The Swanson Formation is not found in the northern Ford Ranges. The Fosdick Metamorphic Complex comprises high-grade gneissic equivalents of the Swanson Formation found in the Fosdick Mountains in the northern Ford Ranges. High temperature (612°-700°C) peak metamorphism occurred at 105 Ma in middle Cretaceous time (Figure 1 [*Wilbanks,* 1972; *Adams and Weaver,* 1990; *Richard et al.*, 1994; *Smith,* 1992, 1995, 1997]). Gneisses forming the Alexandra Mountains on Edward VII Peninsula are of similar high grade but do not have a Swanson Formation protolith, according to sensitive high-resolution ion microprobe (SHRIMP) U-Pb zircon age distributions [*Pankhurst et al.*, 1998]. These gneisses are interpreted to originate from deep-seated contact metamorphism of host rock by intrusion of middle Cretaceous Byrd Coast granite by *Smith* [1996].

Mafic dikes of tholeiitic composition are found throughout the Ford Ranges, intruding the Paleozoic and Cretaceous plutonic rocks. In the Fosdick Metamorphic Complex they show both ductile and brittle failure. They trend both subparallel and oblique to the coastline in the Ford Ranges and to the east in the Ruppert and Hobbs Coasts [*Storey et al.*, 1999]. In those regions the average age of the dikes is 107 +/- 5 Ma with a range of 110-95 Ma [*Storey et al.*, 1999].

Young volcanic rocks in the Fosdick Mountains [*LeMasurier and Rex,* 1982; 1983; *LeMasurier and Wade,* 1990], are dated at ~1.4 Ma (^{40}Ar/^{39}Ar whole rock ages at two localities courtesy of W. McIntosh, 1992, and P. Gans, 1994). The volcanic rocks in the Fosdick Mountains define an E-W oriented lineament along the steep north face of the mountains, suggesting fault control of volcanism and ongoing or renewed uplift in Pleistocene time (Figures 1 and 2). Ultramafic nodules found in these rocks suggest that the fault system is a profound crustal structure. Normal faults trending NW-SE cut Quaternary volcanic rocks at Mt. Perkins, a small basalt volcano [*Luyendyk et al.*, 1992]

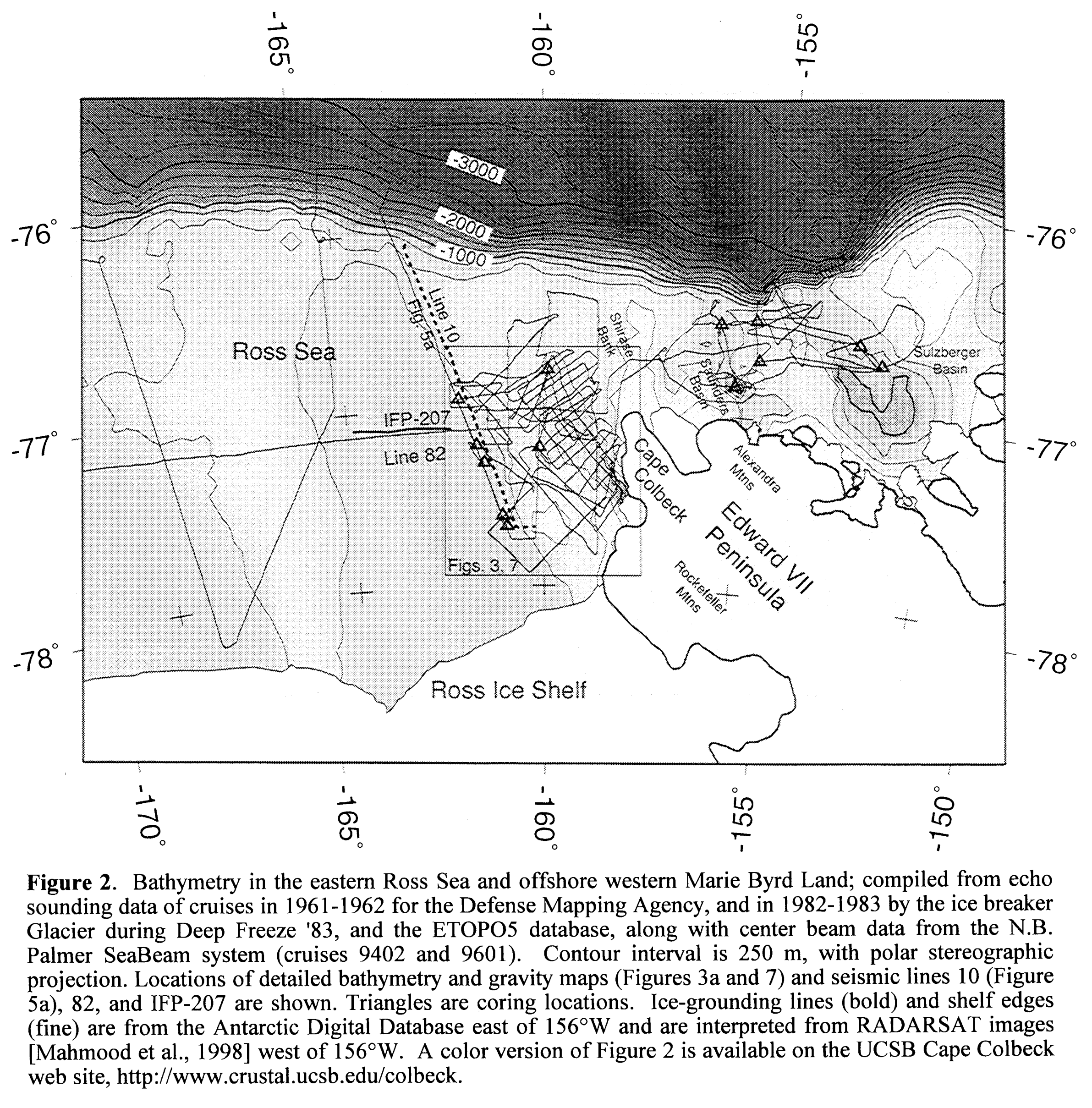


Figure 2. Bathymetry in the eastern Ross Sea and offshore western Marie Byrd Land; compiled from echo sounding data of cruises in 1961-1962 for the Defense Mapping Agency, and in 1982-1983 by the ice breaker Glacier during Deep Freeze '83, and the ETOPO5 database, along with center beam data from the N.B. Palmer SeaBeam system (cruises 9402 and 9601). Contour interval is 250 m, with polar stereographic projection. Locations of detailed bathymetry and gravity maps (Figures 3a and 7) and seismic lines 10 (Figure 5a), 82, and IFP-207 are shown. Triangles are coring locations. Ice-grounding lines (bold) and shelf edges (fine) are from the Antarctic Digital Database east of 156°W and are interpreted from RADARSAT images [Mahmood et al., 1998] west of 156°W. A color version of Figure 2 is available on the UCSB Cape Colbeck web site, http://www.crustal.ucsb.edu/colbeck.

Rocks exposed immediately onshore from the eastern Ross Sea in the Rockefeller Mountains on the Edward VII Peninsula include middle Cretaceous Byrd Coast granite and the low-grade argillites of the Swanson Formation [*Wade et al.*, 1977]. Fission track ages on Byrd Coast granite from Edward VII Peninsula [*Lisker and Olesch*, 1997] suggest cooling due to exhumation in early Tertiary time, possibly in response to tectonic uplift and minor extension. In the northern Ford Ranges, ^{40}Ar/^{39}Ar thermochronology on four minerals indicates a period of rapid cooling in the high-temperature Fosdick Metamorphic Complex from ~101 to 94 Ma [*Richard et al.*, 1994; *Smith*, 1995, 1997]; the peak metamorphic age of the Complex is 105 Ma (on monazite [*Richard et al.*, 1994]). Fission track data on apatite from these same rocks indicate further cooling in early Tertiary time [*Richard et al.*, 1994] consistent with the data from Edward VII Peninsula. These two cooling episodes can be attributed to total uplift and denudation amounting to 15-18 km in the Fosdick Mountains. The middle Cretaceous cooling period recorded in the northern Ford Ranges and in DSDP Site 270 to the west (Figure 1 [*Fitzgerald and Baldwin*, 1997]) suggests regional exhumation attributable to widespread extension during middle Cretaceous time in the eastern Ross Sea and wMBL.

1.4. West Antarctic Erosion Surface and Marie Byrd Land Dome

In central MBL, regional uplift, Oligocene and younger faulting, and alkalic volcanism are attributed to the effects of late Cenozoic mantle plume activity [*LeMasurier and Landis*, 1996; *Hole and LeMasurier*, 1994] (Figure 1b). Exposures of Cenozoic volcanic rocks here diminish in age and elevation with distance from a central topographic high (the MBL dome [*LeMasurier and Rex*, 1989; *LeMasurier and Landis*, 1996]). Basement rock exposures are few, but Oligocene volcanics are found resting unconformably on an

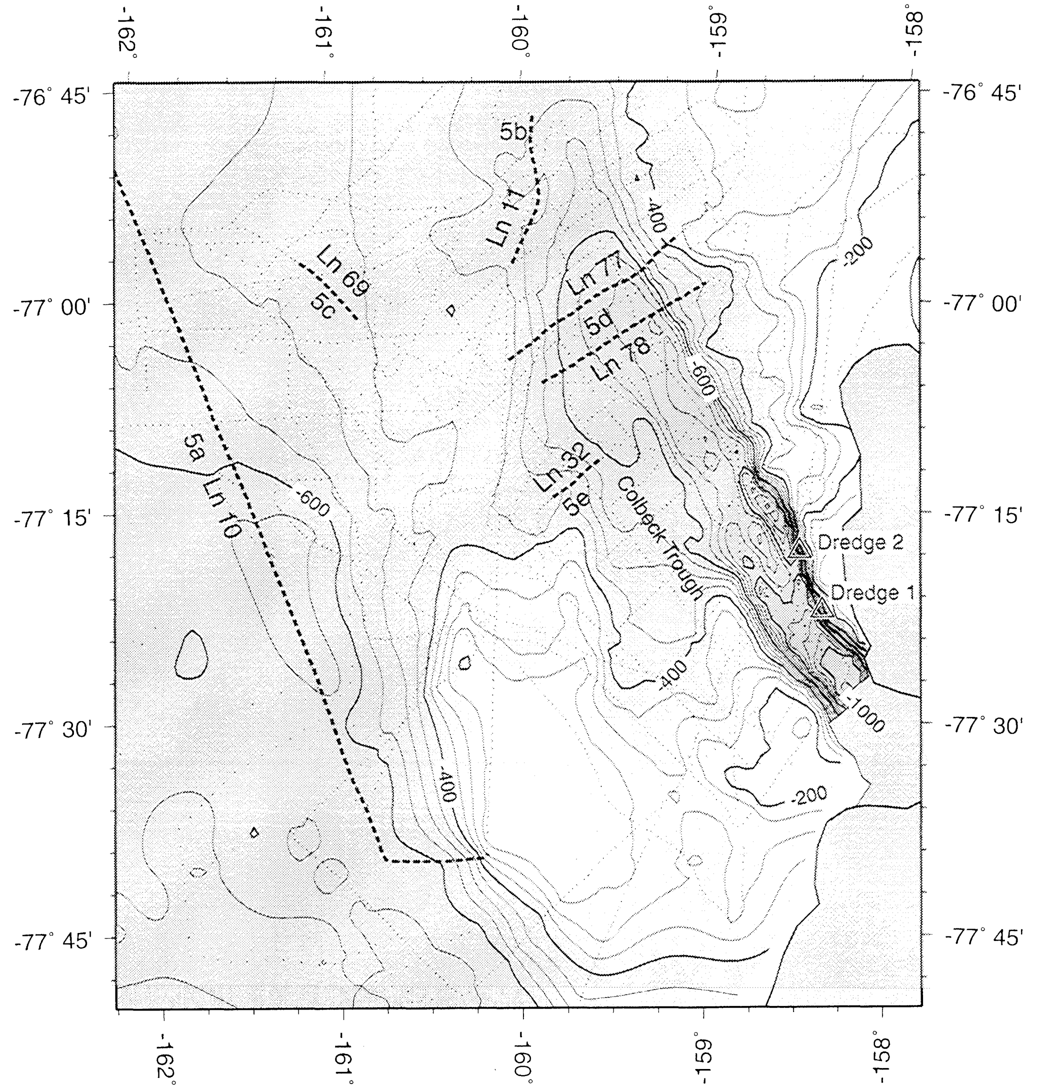


Figure 3a. SeaBeam (center beam) and wide-beam bathymetry of the Colbeck Trough region of the southeastern Ross Sea. Data are gridded at 1 km; azimuthal equidistant projection, points show location of median bathymetric depth within grid cells. Track of RVIB N.B. Palmer is shown as dotted. Bold dashed lines show locations of seismic lines in Figure 5. A color version of Figure 3a is available on the UCSB Cape Colbeck web site, http://www.crustal.ucsb.edu/colbeck.

erosional surface developed on Paleozoic and middle Cretaceous rocks (West Antarctic erosion surface (WAES) [*LeMasurier and Landis,* 1996]). In the Ford Ranges, summit plateaus found on many peaks may be remnants of the WAES. These remnants lie near elevations of 600 m or less near the wMBL coast. The WAES reaches a maximum elevation of 2700 m in the middle of the MBL dome near the Executive Committee Range (Figure 1b).

2. Marine Geophysical and Geological Survey on RVIB Nathaniel B. Palmer Cruise 9601

2.1. Systems Employed

We conducted marine geological and geophysical surveys in the eastern Ross Sea and Marie Byrd Land continental margin in January-February of 1996 during RVIB *Nathaniel B. Palmer* cruise 96-01 (NBP-9601). Data acquisition included SeaBeam 2112 swath bathymetry, chirp sonar profiling, gravity and magnetic gradiometer profiling, coring and dredging, single channel or two channels, and 44 channel seismic reflection profiling.

2.2. Survey Coverage

In the area west of the Edward VII Peninsula in the Colbeck continental shelf region, *Palmer* cruise 9601 acquired ~490 km of 44-channel seismic data and 630 km of variable -channel data (4 to 16) along with 1892 km of single-channel seismic data. Seismic sources used were a 4 or 5 gun 3.44 L Generator Injector (GI) air gun array, or a single 3.44 liter GI air gun for single-channel data. GI guns release compressed air in two precisely timed bursts to eliminate the bubble pulse. We also acquired 2591 km of chirp profiler and

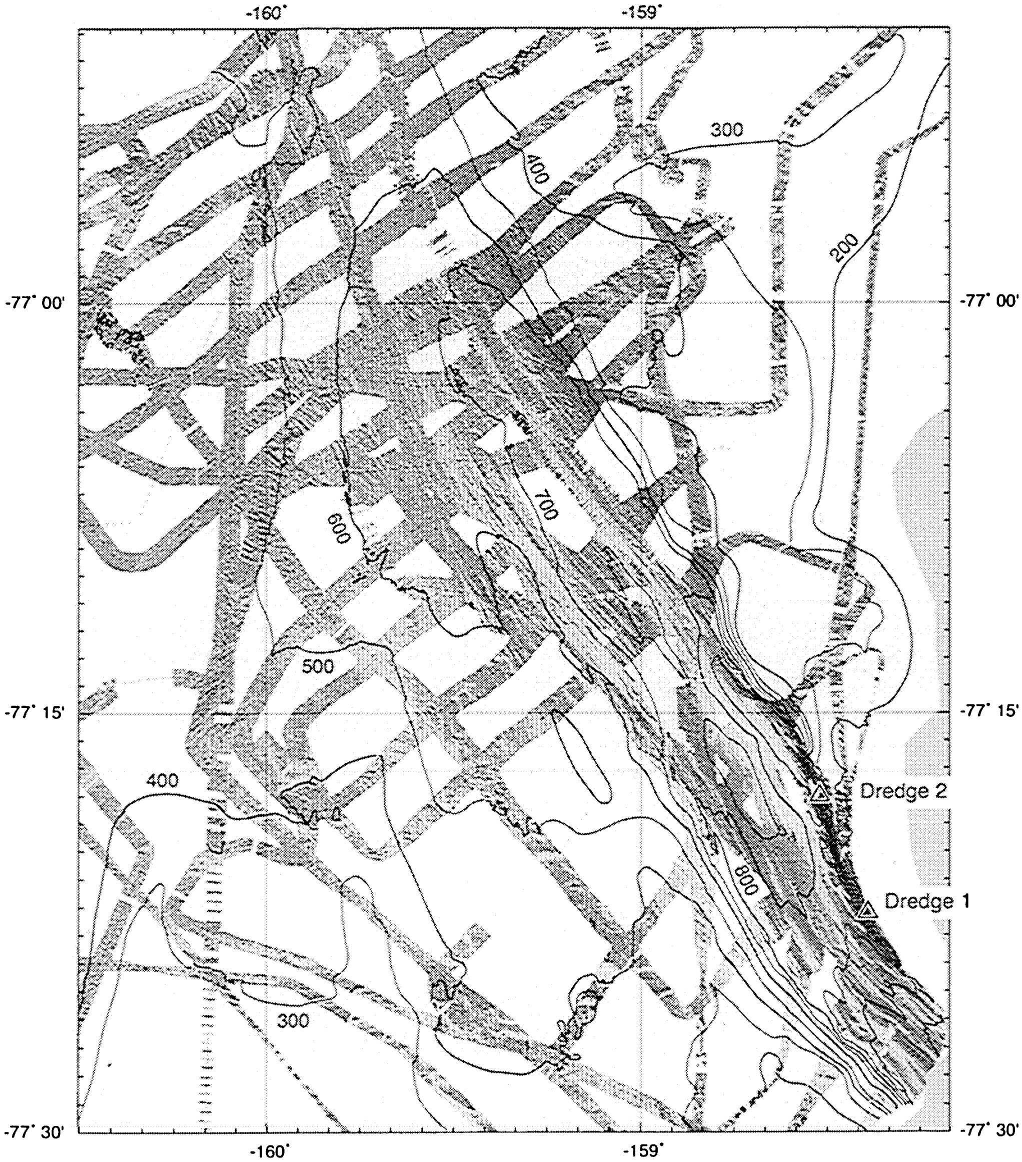


Figure 3b. Shaded-relief SeaBeam multibeam bathymetry map of the southeastern Colbeck Trough; data gridded at 50 m, Mercator projection, illumination from 050°. Contours are at 100 m interval connected by hand through data gaps. A color version of Figure 3b is available on the UCSB Cape Colbeck web site, http://www.crustal.ucsb.edu/colbeck.

multibeam data, plus continuous underway gravity and magnetic profiles on most tracks. Piston cores were taken as well as two dredge hauls in the southeast end of Colbeck Trough (Figures 2 and 3). A reconnaissance survey was also made in Sulzberger Bay off the Ford Ranges of wMBL (Figure 2), where 641 km of four and eight channel seismic data were collected, along with 797 km of single-channel seismic data, 1120 km of chirp profiler and multibeam data, as well as gravity and magnetic profiles. Six piston cores were acquired there. Seismic data were also recorded in the central Ross Sea, outbound and inbound to the Cape Colbeck and Sulzberger survey areas (partly shown in Figure 2), and offshore Cape Roberts [*Hamilton et al.,* 1998, 2001].

2.3. Seismic Reflection Data

2.3.1. Acquisition parameters. The *N.B. Palmer* towed a 48-channel streamer with hydrophone groups spaced 25 m apart; channels 3, 34, 37, and 46 did not record. The near channel was ~250 m behind the GI airguns. The maximum offset was 1425 m. Shots were spaced every 25 m so that trace spacing within common depth point reflection (CDP) gathers was 50 m. The CDP gathers and stacked traces (up to 22 fold) have 12.5 m spacing.

We collected both 44-channel and single-channel seismic reflection data by alternating shooting a single airgun and the group of five airguns and recording the alternating shots on separate systems. The single airgun data were recorded on a multielement single-channel streamer until it was damaged. After that it was recorded on the near channel, or the two near channels of the 44-channel streamer. Recording on the two channels allowed us to sort the data to 1-fold CDP "gathers" and end up with twice the spatial resolution along the profiles. Sea ice conditions often required us to deploy only part of the streamer, so that all of the data in Sulzberger Bay are eight channels or less, and much of the data in eastern Ross Sea are less than 22-fold.

2.3.2. Processing methods. The suppression of water bottom and long-period peg leg multiples was the first goal in processing the multichannel seismic data. However, it was only possible to attenuate these multiples on the higher fold (22 fold) data. The offset and source power was sufficient to remove multiples and to image strata at up to 3 s two-way travel time (TWTT) in the central Ross Sea. Strata are thinner and shallower in the eastern Ross Sea and the offset and fold are not adequate to remove a peg leg multiple from an unconformity at the base of the subglacial and glacial marine strata (RSU6; see section 3.2.2). For 22-fold profiles, interactive velocity analysis was performed every 1 km to choose velocities intermediate between primary and multiple reflections. These velocities were used for a normal move out (NMO) correction that separates primary from multiple arrivals, and the multiples were filtered out in frequency-wave number (F-K) space. The NMO correction was removed, and an analysis for stacking velocities was done every 1 km. Interval velocities are from 2100 m s^{-1} to 2600 m s^{-1} above unconformity RSU6 (section 3.2.2). Velocities beneath this unconformity are variable. The processing approach also included predictive and spiking deconvolution, band-pass frequency filtering, near-trace muting, and other standard steps. However, the relatively short (~1.5 km far offset) streamer and fast seafloor velocities resulted in incomplete attenuation of the water bottom multiple and other multiple reflections. Therefore a median amplitude stack was done after NMO to further suppress multiples. In this process each trace within a CDP gather was sorted by amplitude for each travel time (each sample), and only 50% of the traces near the median amplitude value were retained for the stacking. Many of the profiles were migrated using an F-K migration at 1460 m s^{-1}. This migration helped interpretation in relatively undeformed strata but did not handle steeper dips and complex structure. Therefore we used a velocity model and split-step migration [*Stoffa et al.* 1990] on line 10, the northern half of line 11, and on line 69.

3. Observations and Interpretations

3.1. Bathymetry on the Continental Shelf

We combined existing bathymetric data with our center beam data from the SeaBeam system to produce the map in Figure 2. The continental shelf of this portion of the Ross Sea passive margin is from 60 to 200 km wide, measured from the grounding line on Edward VII Peninsula or the Ross Ice Shelf front. Depths reach 500 m at the E-W trending shelf break. Edward VII Peninsula and Cape Colbeck and Shirase Bank separate the shelf of the eastern Ross Sea from Sulzberger Bay and the continental margin of wMBL (Figure 2). Two NNW trending troughs cut the shelf in Sulzberger Bay, that are ~15 km wide and 500 m to 1200 m deep (Saunders and Sulzberger Basins). These have U-shaped profiles and are deeper toward the continent. Shirase Bank (Figure 2) has steep linear sides trending NNW. This suggests fault control of the bank because this trend is similar to trends of basement half grabens we describe in section 3.3.

West of Edward VII Peninsula we mapped the NNW trending Colbeck Trough near 159°W (Figures 2 and 3). The southern part of this trough is ~1000 m deep with 800 m relief on the eastern side comprising steep escarpments and widespread east dipping surfaces separated by steps. The western slopes are less steep. The trough is ~100 km long and is devoid of sediment in the south. It is likely that a glacier traveled through the trough and stripped off sediment to expose more resistant basement rocks. Multibeam-images of the base of the Trough show impressive glacial scour marks and (mega) flutes (Figure 3b). The scours and flutes are many kilometers long, hundreds of meters wide, and have relief of 20-30 m and occur in sediment filled parts of the Trough as well as in places where most of the sediment has been scraped off basement. These features indicate repeated advance and retreat of grounded ice streams and outlet glaciers [Kluiving et al., 1997]. Megaflutes were also mapped in Sulzberger Basin. As we explain in section 4.2, our results show that Colbeck Trough is a glacial erosion feature that occupies NNW and NW trending half grabens and cuts across these structures on the northern continental shelf.

3.2. Seismic Stratigraphic Units in the Eastern Ross Sea and on the Cape Colbeck Continental Shelf

3.2.1. Ross Sea seismic sequences (RSS- and V) seismic stratigraphic units. We identify seismic stratigraphic sequences in our study area that have been previously mapped over extensive areas in the eastern Ross Sea. These sequences are named the Ross Sea Seismic Sequences (RSS-) and are numbered from 1 (oldest) through 8 (RSS-1 to RSS-8) and are separated by unconformities numbered 1 (youngest) through 6 (RSU-1 to RSU-6) [*Hinz and Block*, 1984; *Brancolini et al.*, 1995; *DeSantis et al.*, 1995; *Cooper et al.*, 1995]. In the western Ross Sea, *Cooper et al.* [1987] give similar seismic sequences the designation V. The relation between the RSS- and V sequences is uncertain because they cannot be correlated across the Central High that separates the Eastern Basin from the Central Trough. Correlations based on age and seismic character have been attempted and are summarized in Table 1. In our study we have defined new units RSS-2-lower and RSS-1-lower and another unconformity, RSU7 (Table 1 and Figure 4).

3.2.2. Identification and correlation of seismic stratigraphic sequences. Deep Sea Drilling Project Site 270 (Figure 1) sampled 365 m of late Oligocene-early Miocene subglacial and glacial marine strata of RSS-2 beneath ~20 m of Pleistocene through Recent section which likely comprises RSS-8 [*DeSantis et al.*, 1995; *Hayes and Frakes*, 1975] (Table 1). Other DSDP holes in the Ross Sea did not reach RSS-2 (Figure 1 [*Cooper et al.*, 1995, Plates 3and 4]). Below the glacial strata, Site 270 penetrated 26.5 m of sedimentary breccia that is believed to be locally derived and weathered in

Table 1. Proposed Correlation of V and RSS Seismic Sequences[a].

Age	V Sequence	RSS Sequence	Unconformity
Pliocene	V1	RSS-8	RSU1
		RSS-7	RSU2
Middle and late Miocene	V2	RSS-6	RSU3
		RSS-5	RSU4
		RSS-4	RSU4A
Early Miocene	V3	RSS-3	
Late Oligocene and early Miocene	V4	RSS-2-upper RSS-2-lower	Local Unconformity
Early Oligocene	V5	RSS-1-upper	RSU6
Late Cretaceous	??	RSS-1-lower	RSU7

[a]After *Cooper et al.* [1987]; *Desantis et al.* [1995]; *Barrett et al.* [2000]; *Hamilton et al.* [2001]; this paper

a subaerial environment. That unit directly overlies metamorphic basement [*Hayes and Frakes,* 1975]. In the eastern Ross Sea, seismic stratigraphy studies identify a widespread unconformity, RSU6, that separates sequence RSS-1 below it from sequence RSS-2 above it (see papers in *Cooper et al.* [1995]). RSS-1 overlies what has been interpreted as acoustic basement [*Brancolini et al.,* 1995]. Interpretations of Italian multichannel seismic data state that both RSU6 and the underlying sequence RSS-1 onlap acoustic basement and were not drilled at DSDP Site 270 [*Busetti and Cooper,* 1994]. Instead, DSDP Site 270 drilled a locally derived sedimentary breccia, characterized by "disrupted stratal reflectors," above metamorphic basement at the edge of a small half graben [*Busetti and Cooper,* 1994]. We propose to call this synextension breccia sequence RSS-1-lower, and what had been previously called RSS-1 will be called RSS-1-upper in this paper. At Site 270, RSS-1-upper is missing and the lower, graben-filling unit RSS-1-lower was sampled. Unit RSS-1- upper (previous RSS-1) was not sampled and not dated at Site 270. Fission track analysis on the metamorphic basement rock from Site 270 suggests cooling and unroofing at 90 +/- 6 Ma; the overlying breccia is assumed to be the same age by *Fitzgerald and Baldwin,* [1997].

In the Colbeck shelf study area the identity of subglacial and glacial marine sequences is constrained by correlation of seismic profile NBP9601-10 to NBP9601-82, to profile IFP-207 (Figure 2), and then to Deep Sea Drilling Project Sites 272 and 270 [*Cooper et al.,* 1995, Plates 10 and 14]. Our profile NBP9601-82 is parallel to and ~3 km south of profile IFP-207 (Figure 2), and we jump-correlate RSS-2, RSU6, and RSS-1 (RSS-1-upper) from that profile. These units and overlying post-RSS-2 units are all seen on seismic line 10 that transects the study from north to south (Figure 5a). The stratigraphy on the Colbeck shelf is summarized in Figure 4.

3.2.3. Units RSS-1-lower and RSS-1-upper and unconformity RSU7. Dipping reflections are evident within acoustic basement in the eastern Ross Sea, especially when displayed with less vertical exaggeration (e.g.,) shot point (SP) 1350 of IFP-207, plate 10 in *Cooper et al.,* 1995]. Another unit lies below the original RSS-1 and within half grabens in acoustic basement. This is consistent with the interpretation of the stratigraphy at DSDP Site 270 by *Busetti and Cooper* [1994]. In our study we define an angular unconformity RSU7 at the base of the former RSS-1. The unit below RSU7 we name RSS-1-lower and we rename RSS-1 as RSS-1-upper. (see Figure 4 and Table 1). We interpret dipping and disrupted reflections in RSS-1-lower as due to tectonic tilting (Figure 5b). In the western Ross Sea, *Cooper et al.* [1987] also interpreted half grabens within acoustic basement. They believe these formed during Cretaceous rifting and extension. We propose that the sediments in those basins are also RSS-1-lower.

On the Colbeck shelf, RSS-1-upper is a reflective flat-lying sequence that is thicker within the basins in the hanging walls of faults (Figure 5c). Its reflection character is similar to RSS-1 mapped in the Eastern Basin, and we interpret it to be the same sequence and to be of marine origin. RSS-1-upper is continuous and can be correlated throughout the southwest part of the study and also along the west flank of the northern Colbeck Trough (Figure 5d), but it may be present only in half grabens on the northwestern shelf. The base of RSS-1-upper is the angular unconformity RSU7 in the southwest shelf, and the dipping reflections beneath are within the sequence RSS-1-lower (Figure 5e). RSS-1-lower is intensely deformed, commonly tilted, and in some areas may be steeply tilted and therefore not imaged by our seismic reflection data (Figure 5c). We interpret RSS-1-lower in the Colbeck region as the same synrift breccia drilled immediately above metamorphic basement at DSDP Site 270 on the basis of reflection character and apparent age. Because RSS-1-upper is slightly offset across some normal faults on the Colbeck shelf (see section 3.3, and Figure 4), we interpret this sequence as a synextension deposit also [see *Cooper et al.,* 1995, e.g., Plate 10]. RSS-1-upper (RSS-1) pinches out eastward from the central Ross Sea, and RSS-1-lower cannot be carried west from the Colbeck region with our seismic data.

3.2.4. Units RSS-2-lower and RSS-2-upper and unconformity RSU6. Most of the flat-lying and undisturbed strata in the study area are part of the late Oligocene-early

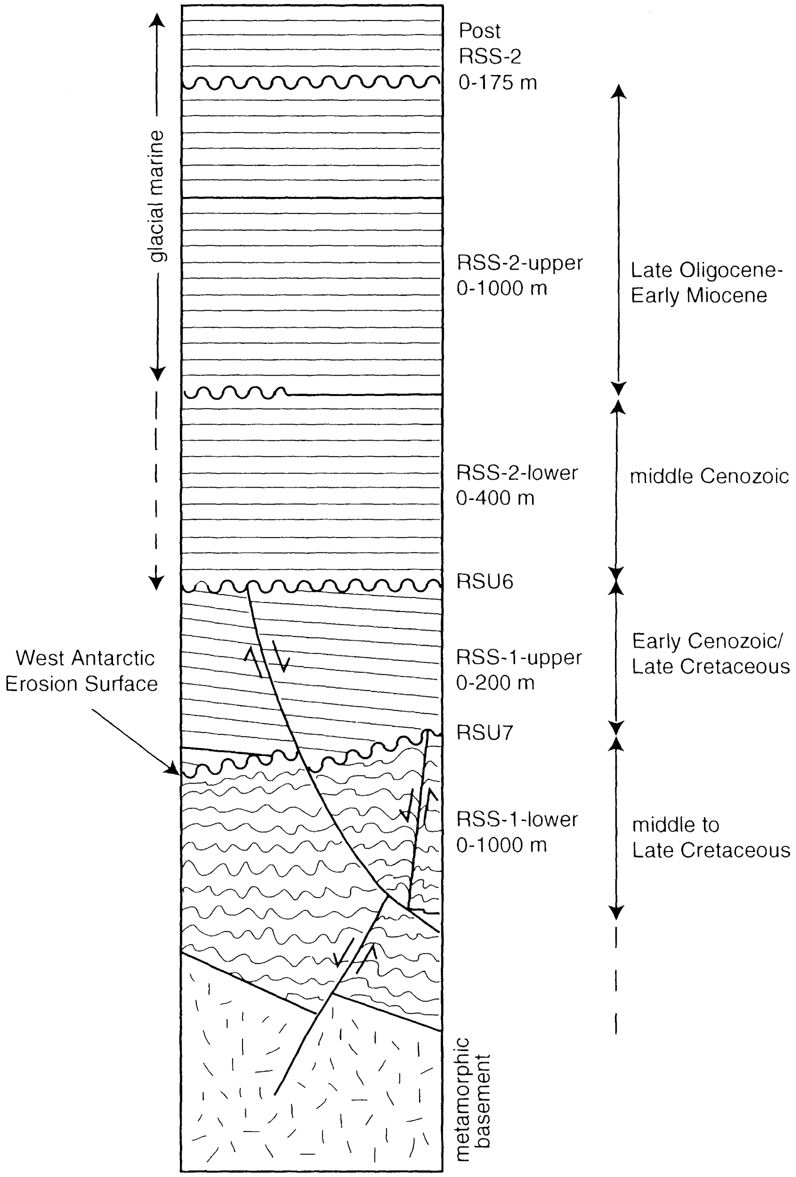


Figure 4. Schematic stratigraphy and faults in the eastern Ross Sea determined in our study. RSS-2 (upper) is jump-correlated from nearby seismic line IFP-207; RSS-1 sequences and basement are correlated to units near DSDP Site 270 (see text).

Miocene RSS-2. There is, however, another seismic sequence below RSS-2 and above unconformity RSU6 in the southern part of our study area. This unit is several hundred meters thick and downlaps to the north (Figure 5a). We define it as RSS-2-lower because its reflection characteristics are similar to RSS-2 above, showing transparent intervals between distinct stronger reflections. We rename prior RSS-2 as RSS-2-upper (Figure 4 and Table 1). The late Oligocene age of the RSS-2-upper sequence constrains RSS-2-lower to be older. In the northwestern Colbeck area, RSS-1-upper and lower are present only in local half graben basins. As a result, the two separate unconformities, RSU6 and RSU7, merge into one on the northwestern Colbeck shelf (Figure 5a).

3.2.5. Post-RSS-2 units. Thin, discontinuous seismic sequences are present over the central and southern part of the study area that we combine together as "post-RSS-2 sequences" units. On the northern shelf the post RSS-2 sequences are more continuous than in the south (Figure 5a). North of our main Colbeck survey area, RSS-2 sequences downlap, and a thick post-RSS-2 sequence is seen that might be correlated to distinct seismic stratigraphic units (RSS-3, RSS-4, etc.) with additional tie lines. Each sequence successively downlaps to the north. Along line 10 (Figure 5a; location in Figure 2) the vertical extent of these prograding clinoforms is over 1 s TWTT, or ~1 km, indicating that unconformity RSU6 had subsided to 1 km depth before deposition of the post-RSS-2 sequences.

3.2.6. Coring on the Colbeck shelf. A core taken on *Deep Freeze* 1983 [*Anderson,* 1983] near the west side of the southern Colbeck Trough dates post-RSS-2-upper

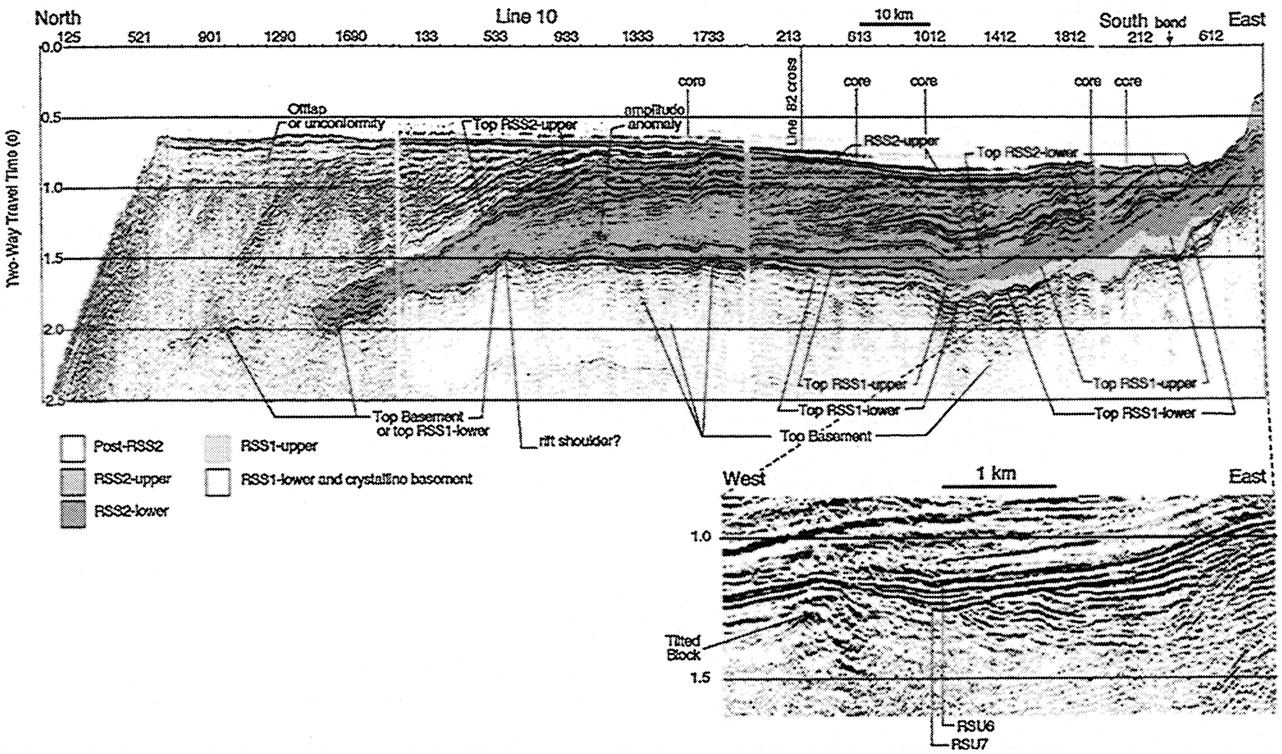


Figure 5a. Seismic profiles over Colbeck shelf; Seismic line 10 at high vertical exaggeration (about 25 times at seafloor) shows downlap of RSS-2 and younger sequences onto the combined RSU6 (top of RSS-1-upper) and RSU7 (top of RSS-1-lower) unconformities. Arrows show narrow rift basins interpreted in the basement. Dotted area is shown as the record section detail at bottom of Figure 5a, which is shown at much less vertical exaggeration (about 3.4 at seafloor). Line location in Figures 2 and 3. Split-step depth migration has been applied to this 22-fold profile and the profile redisplayed as a time section. The local peak in the top of RSS-1/basement surface south of the shelf break is interpreted to be the submerged rift shoulder formed during separation from the Campbell Plateau. A color version of Figure 5a is available on the UCSB Cape Colbeck web site, http://www.crustal.ucsb.edu/colbeck.

sediments on the southern shelf as late Miocene-early Pliocene [*Kaharoeddin and Cassidy,* 1985], or younger if sediments are reworked. L. Burckle examined core catcher samples of five cores located along the southern half of line 10 (Figures 2 and 5a) for diatom content, in an area where we interpret RSS-2-upper to be at the seafloor, within the 20 m resolution of the seismic data. His preliminary results indicate that two of these cores had Miocene/Oligocene (?) and Miocene (?) diatoms. However, Holocene radiocarbon dates have been determined for these samples, indicating that this material is reworked. The significance of the age determinations of *Kaharoeddin and Cassidy* [1985] must also be in question.

3.3. Structure and Age of Units

It is difficult to map faults in our study area because they exist mainly below the water bottom multiple, which is only removed on the few 22-fold profiles. Modeling of gravity data (section 3.6) allowed us to extend trends of some faults seen on seismic data. We interpret at least two fault sets showing normal separation, trending NNE-SSW and NNW-SSE, that cut RSS-1-upper and RSS-1-lower and bound half grabens in acoustic basement holding these sequences (Figures 5b, 5c and 7b). In RSS-1-lower, the faults are too closely spaced to map them with our widely spaced 22-fold seismic profiles. The overlying RSS-2 sequences are not faulted but show layering that is progressively tilted westward.

The structural style of RSS-1-lower is distinctly different from the younger sequences. RSS-1-lower is much more deformed than RSS-1-upper. Wherever RSS-1-lower is preserved in the study area it is tilted and disrupted, with discontinuous reflections and numerous inferred faults (Figure 5c). RSS-1-upper is relatively flat lying but is faulted by widely spaced basin-bounding faults. Angular relations between RSS-1-lower and RSS-1-upper suggest two episodes of faulting (extension) between middle Cretaceous and late Oligocene time, which is the maximum age of overlying RSS-2-upper. The RSU6 unconformity and overlying RSS-2 sequences truncate normal faults that cut the RSS-1 sequences, indicating the cessation of normal faulting by late Oligocene time (Figures 4 and 5b). Other faults are truncated by RSU7.

3.4. Dredge Sampling of Mylonitic Rocks

Over 2000 kg of rocks (103 pieces) were recovered in two dredge hauls from the base of the east wall of Colbeck Trough at its southeast end (Figures 2 and 3). Rocks

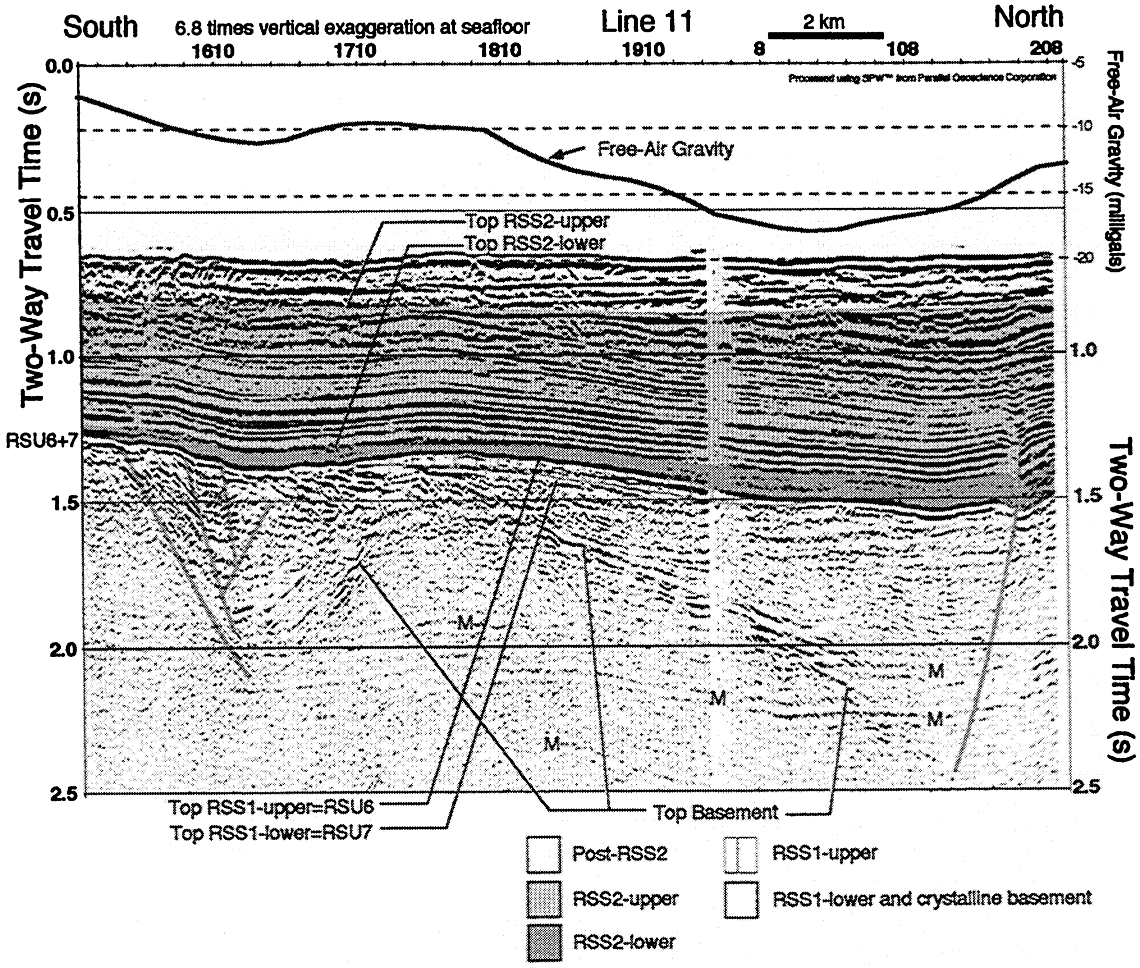


Figure 5b. Seismic profile over Colbeck shelf; The north part of seismic line 11 at vertical exaggeration of 6.8 (location in Figures 3 and 7) showing basement grabens holding RSS-1. This N-S line crosses faults that strike NW-SE (Figure 7b). Split-step depth migration has been applied to this 22-fold profile and the profile redisplayed as a time section. Multiple reflections are labeled "M". The top 0.1 s TWTT of reflections are post-RSS-2; the remaining flat-lying strata are late oligocene to early Miocene RSS-2. The interpretation of basement topography is confirmed by the Free-Air gravity data, which show local lows over the basins. A color version of Figure 5b is available on the UCSB Cape Colbeck web site, http://www.crustal.ucsb.edu/colbeck.

recovered include granitic gneiss, granite, biotite schist, metagreywacke, quartzite, and rhyolitic tuff (in order of abundance). This assemblage represents metamorphosed Swanson Formation, Byrd Coast granite and associated gneiss, and unknown volcanic rocks. The shape distribution of the pieces is 12% angular, 49% subangular, 34% subrounded, and 5% rounded).

The samples of granitic gneiss exhibit fabrics indicative of a brittle-ductile shear zone (mylonitic fault zone). Of the 103 rock samples, 83 are coarse-grained granitic gneisses with well-developed mineral lineation and proto-mylonitic to mylonitic fabric (Figure 6). The mylonites were derived from the leucocratic syenogranite phase of the Cretaceous Byrd Coast granite, confirmed by petrography, geochemistry, and SHRIMP U-Pb zircon analysis (C. Siddoway, unpublished, 2000). Consistent fabric asymmetry within individual, boulder-sized clasts of lineated s-c mylonite indicates development by plane strain simple shear in an apparently substantial shear zone. Brittle offsets show the same kinematic sense as the ductile fabrics they cut (Figure 6). This suggests that the ductile fabrics were overprinted during translation into the brittle deformation regime by progressive deformation within a single-fault system.

Samples of foliated granite cut by bands of black, flinty cataclasite and two samples of chloritic breccia indicate a brittle deformational overprint, probably developed during exhumation of the mylonites to shallow crustal levels. The material resembles that in a meter-thick cataclasite zone at Tennant Peak onshore, near the southeasterly extension of the Colbeck Trough (Figure 1c, C. Siddoway field observation, 1992), where WNW striking brittle shears have north plunging slickenlines and show down-to-north displacement. The uniformity in rock type and foliation fabric among the dredge samples, the angular or subangular shapes, the lack of facets and scratch marks, and the very high cable tension

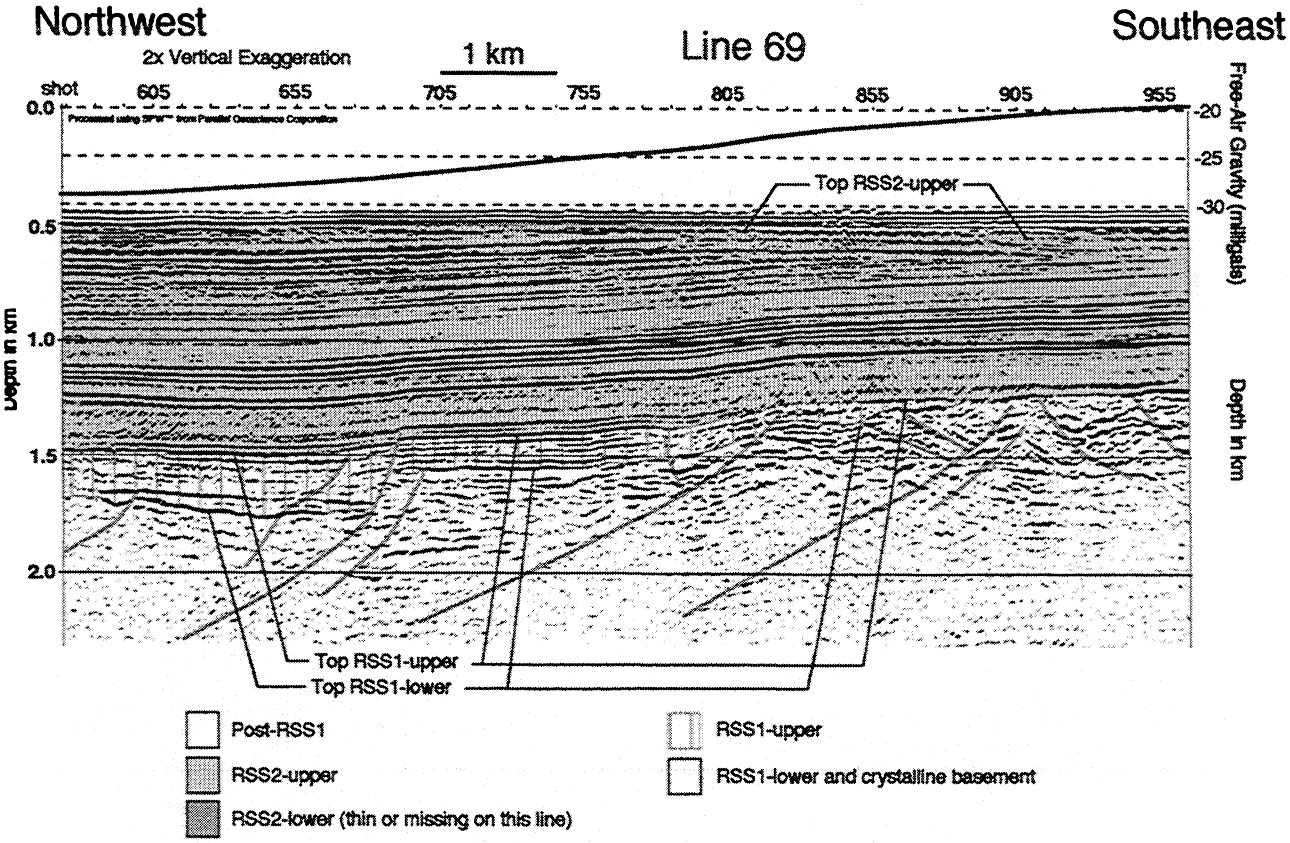


Figure 5c. Seismic profile over Colbeck shelf; A seismic depth section of the western part of line 69 at vertical exaggeration of 2, on the west side of Colbeck Trough (Figures 3 and 7). This line trends NW-SE and crosses faults that strike NNE-SSW (Figure 7b). Split-step depth migration has been applied to this 22-fold profile. A basin is predicted from gravity modeling (Figure 7d) below the RSU6 unconformity (Top of RSS-1-upper) and the flat-lying RSS-2 reflections. The trend in the Free Air gravity is consistent with basement deepening rapidly to the NW. A color version of Figure 5c is available on the UCSB Cape Colbeck web site, http://www.crustal.ucsb.edu/colbeck.

during dredging of near 27,000 pounds suggest that the samples (1) were recovered from near their bedrock source, (2) do not represent a random collection of glacial dropstones, and (3) are from a shear zone exposed by glacial erosion near the margin of Colbeck Trough. Because the glacial grounding line has only recently retreated to its present position (since 3200 years B.P. [Conway et al., 1999]), and scouring by an outlet glacier within Colbeck Trough may have occurred in Holocene time, it is likely that the dredges retrieved fresh unweathered granite bedrock from near its source.

Thermochronology studies on dredged samples of mylonite (unpublished 40Ar/39Ar data, S. Baldwin and C. Siddoway, 2000) indicate rapid thermal evolution at 98 Ma, based on K-feldspar and biotite cooling ages that are concordant with each other and the emplacement age of the Byrd Coast granite from which the mylonites are derived. With closure temperatures of 325°C for biotite and 165°C for K-feldspar, the coincidence of mineral cooling ages in dredged samples of mylonite with the emplacement age of the source granite is unlikely without tectonic exhumation as a result of extension [e.g., Richard et al., 1994].

3.5. Magnetic Field Data.

Two proton-precession magnetometers were deployed ~350 and 500 m behind the ship, although the presence of significant ice and other logistic considerations sometimes required deploying them closer to the ship and sometimes only deploying one magnetometer. Track crossover analysis of magnetic anomaly data in our dense survey in the Cape Colbeck area indicates noise of comparable amplitude to the measured variation (~200 nT), presumably due to currents in the magnetosphere associated with the southern aurora. Using simultaneous measurements from the two magnetometers as a gradiometer was of limited value, because internal consistency checks indicate that the ship's field and other sources of noise led to gradient biases commonly 10 nT km^{-1} and sometimes as high as 200 nT km^{-1}. Therefore only relatively short-wavelength anomalies (<~10 km) can safely be distinguished from time variations. The anomalies that can be confidently identified as resulting from variations with location (geologic sources) based on gradiometry have amplitudes of ~50 nT and wavelengths of 2-

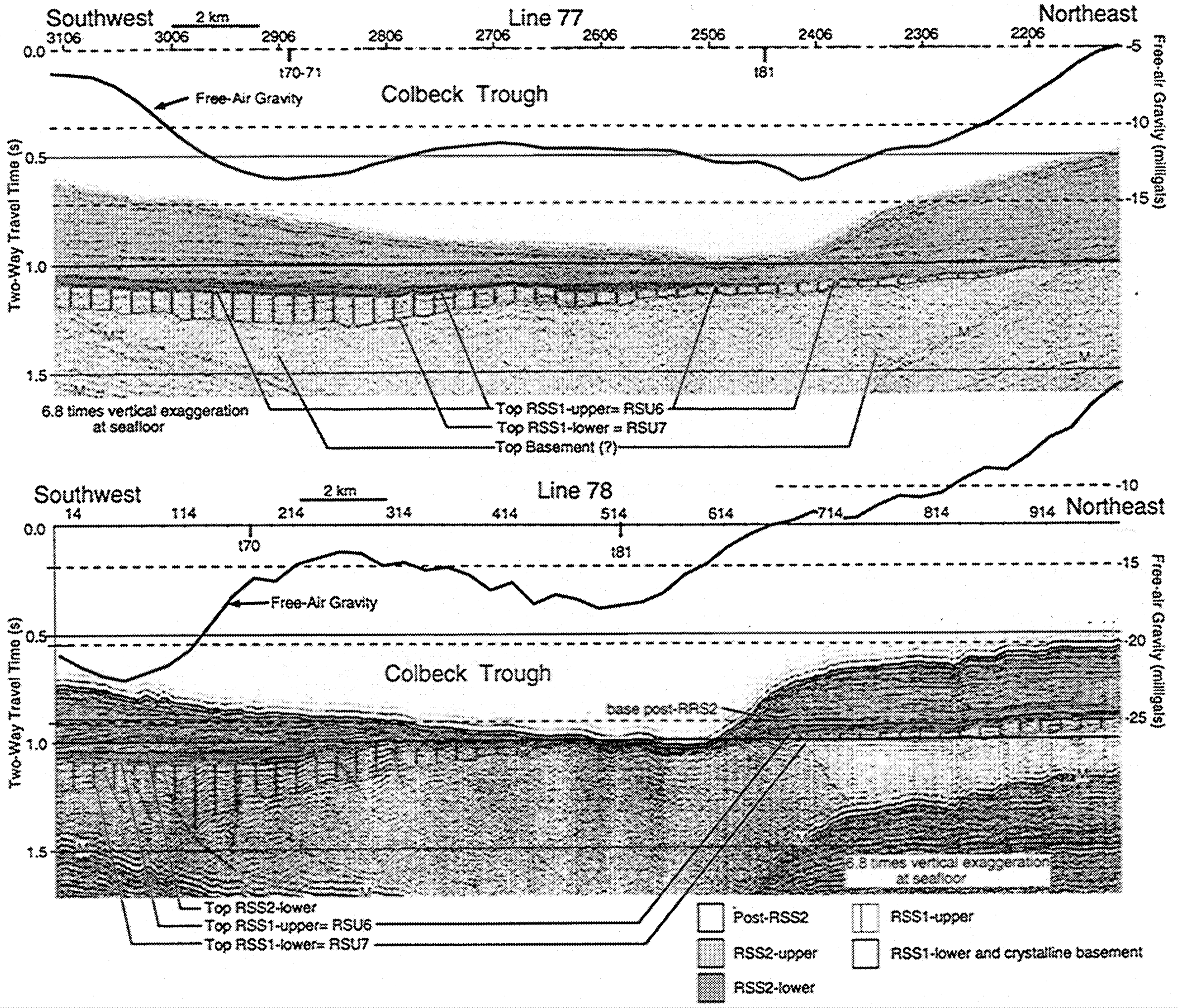


Figure 5d. Seismic profile over Colbeck shelf; Low fold (3 and 4) nonmigrated seismic lines 77 and 78 shot perpendicular to the trend of Colbeck Trough (partial; see Figures 3 and 7). RSU6 (top of RSS-1-upper) is not cut by the trough on line 77. Free-Air gravity profiles show a gravity high over the Colbeck Trough axis, suggesting a basement high here. A gravity low on the southwest of both profiles suggests a 500+ m-deep basin below RSU6. High-amplitude reflections on 22-fold line 70 (not shown) indicate that acoustic basement, probably from crystalline basement, is near 2 s TWTT at its intersection with line 78 (labeled "t70" on the figure), suggesting that the basin below RSU6 is 1 km thick. Faults are interpreted to offset RSS-1-upper on line 78; similar faults may be present on line 77 but are not interpreted. M, multiples; vertical exaggeration is 6.8 times at the seafloor on these time profiles, and is not the same as on the depth section in Figure 5c or the time profiles in Figures 5a and 5e. Line 77 is a black and white variable area with wiggle plot and Line 78 is a color variable area plot converted to shades of gray.

6 km. Two profiles with gradiometry control cross the southern Colbeck Trough, where steep escarpments expose basement over hundreds of meters of steep relief. Lack of anomalies correlating with these escarpments places an upper bound of the order of 0.5 A m^{-1} for the magnetization of the basement there. Overall, the lack of high-amplitude magnetic anomalies indicates that structures such as buried volcanic centers are not present in the Colbeck shelf area that we mapped.

3.6. Gravity Anomalies and Basement Structure

Gravity anomalies can assist the structural interpretation on the shelf, as many tracklines have gravity but not seismic data. Free-Air anomalies measured aboard the Palmer were of excellent quality, with abundant track crossovers to allow internal consistency checks. The standard deviation of 222 crossovers in the Colbeck area is 1.3 mGal, and only 3 crossover errors exceed 4 mGal. Additional data for filling gaps in the south and west were obtained from NBP9402, Eltanin 32, and RS8102 (M/V Benjamin Bowring, NZ). These have been adjusted to minimize crossover differences. Data have been projected into polar equidistant coordinates and gridded at 1 km (Figure 7).

The Free-Air anomalies (Figure 7a) show the largest amplitude over the deep Colbeck Trough (Figures 2 and 3), but elsewhere they have amplitudes of 10-20 mGal with weak

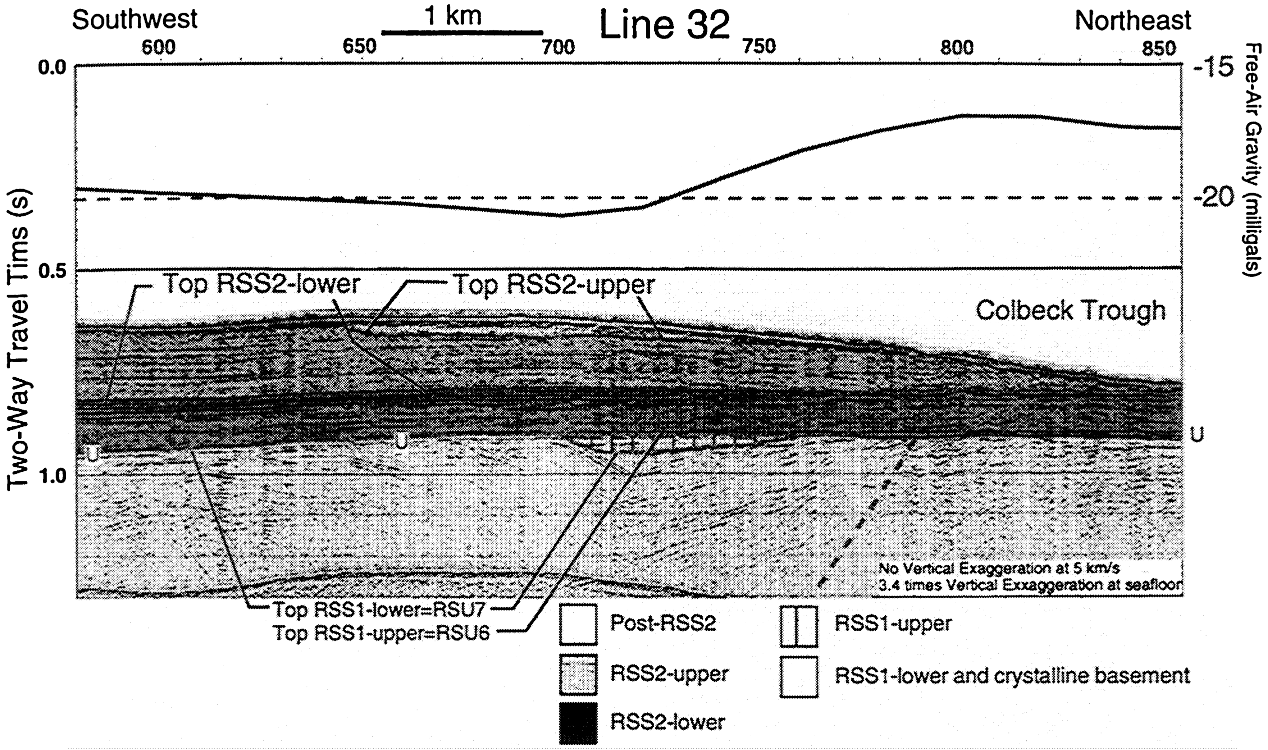


Figure 5e. Seismic profile over Colbeck shelf; Low-fold (3 and 4) seismic line 32 at vertical exaggeration of 3.4 (Figures 3 and 7) southwest of Colbeck Trough. Free-Air gravity profile shows a gravity low over a synform below RSU6+RSU7 ("U" in figure) at shot point 700 suggesting a 500 m-deep basin in basement filled with RSS-1-lower.

to no correlation with bathymetry. We incorporated a structure-contour map on the probable Oligocene unconformity (RSU6, base RSS-2-lower; Figure 7b) into a forward gravity model comprising three layers: water, younger sediments, and undifferentiated older sediments and basement (densities 1000 kg m^{-3}, 2000 kg m^{-3}, and 2650 kg m^{-3}). Forward models were calculated using the Parker [1973] Fourier technique on a 128 x 160 km grid (figures are cropped to 106 x 123 km). Tests using either finer grid intervals or two-dimensional polygon models indicate the 1-km grid interval is adequate for forward modeling even at shallow water depths.

Residuals were calculated by sampling the model grid at observation points and gridding the difference between data and model. The residual after subtracting this gravity model from the data (FAA residual, three-layer model, Figure 7c) removes nearly all of the features of the anomalies that correlate with bathymetry, while emphasizing the features that do not correlate. These features are most readily interpreted as resulting from the density contrast between older sediment (RSS-1 sequences) and crystalline basement. A short-wavelength low remaining over southeastern Colbeck Trough indicates the 2650 kg m^{-3} density used in the model is too low for the basement rock outcrops in the area.

In a few cases, steep gradients in the residual gravity anomaly occur where we have good quality seismic data, and in those cases normal faults are observed with at least 0.5 s TWTT more sediment on the lower gravity side of the fault. For example, at the north end of line 11, two half grabens clearly visible in the seismic data correspond with lows in the Free-Air gravity data (Figure 5b). Under the assumption that similar relations between gravity and basement structure will apply elsewhere, we have developed a forward model for basement topography (Figure 7d) that predicts much of the short- to intermediate-wavelength features remaining in the residual gravity anomalies. We model this surface by subdividing the basal layer of our three-layer model (undifferentiated older sediments and basement) into a layer of older sediments (RSS-1 units) with density 2200 kg m^{-3} and underlying basement with density 2850 kg m^{-3}. The basement density was chosen to match short-wavelength components of the Free-Air anomaly over the Colbeck Trough at latitudes south of 77°10'S, where basement outcrop is seen. The basement surface is constrained not to be shallower than the RSU6 and bathymetry plotted in Figure 7b; where the surfaces are the same, sediments of the RSS-1 sequences are modeled as having zero thickness. The basement shows prominent N-S and NNW-SSE trends that we interpret as reflecting basins bounded by normal faults.

The FAA residual (not shown) resulting from subtracting the effect of this additional interface has greatly reduced amplitudes at shorter wavelengths, but it has a strong regional gradient dropping 40 mGal from the north edge to the southeast corner of the plotted area. We interpret this gradient as resulting from crustal thickening toward the Edward VII Peninsula. One possible Moho configuration

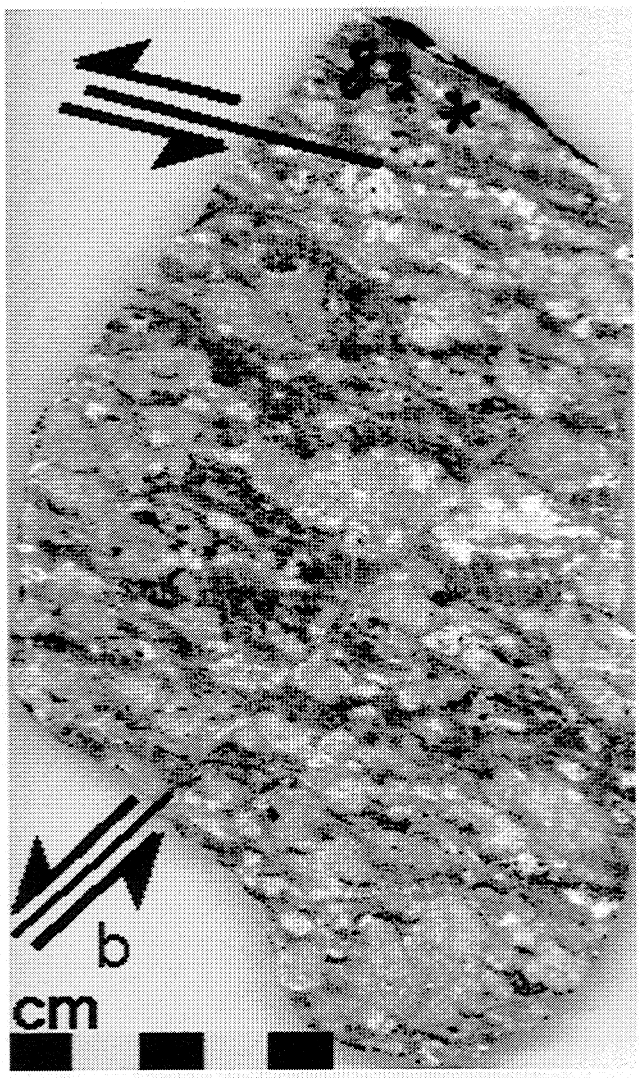


Figure 6. Dredge sample(NBP-9601-D2-83; location in Figure 3) exhibiting mylonitic fabrics (ribbon quartz, "bookshelf" feldspars, sigmoidal feldspar grains with tails) indicating top-to-left shear sense in this view, cut by a brittle fracture (indicated with "b") showing top side down to the left. The actual direction of transport in the shear zone is unknown because no oriented samples could be recovered from the dredge sites. The slab was cut parallel to the tectonic mineral lineation. Scale bar is 5 cm in length. The mylonites were derived from the leucocratic syenogranite phase of the Byrd Coast granite.

consistent with this regional gradient is shown in Figure 7e. This surface was constructed assuming a Moho depth of 19 km slightly west of the mapped area (extrapolating from Trehu et al., 1993, and Trey et al. [1999]) and assuming a density contrast across the Moho of 400 kg m^{-3}. As neither depth nor density is well constrained, the details of the Moho surface are highly nonunique, but all geologically reasonable models must have several kilometers of crustal thickening approaching the grounding line of Edward VII Peninsula. Further crustal thickening of at least 8 km is suggested by Bouguer anomalies of -50 to -80 mGal at 153°-154° W onshore western Marie Byrd Land [Luyendyk et al., 2001].

The residual anomaly remaining after subtracting the complete five-layer model is nearly flat, with a few places showing 5 mGal remaining amplitude (Figure 7f). The smoothness of the residual indicates that none of the assumptions of the forward model are inconsistent with the gravity data. Of course, the model remains nonunique, and departures from the assumption of uniform density for the older sediments and basement would lead to different details of the interpreted basement surface.

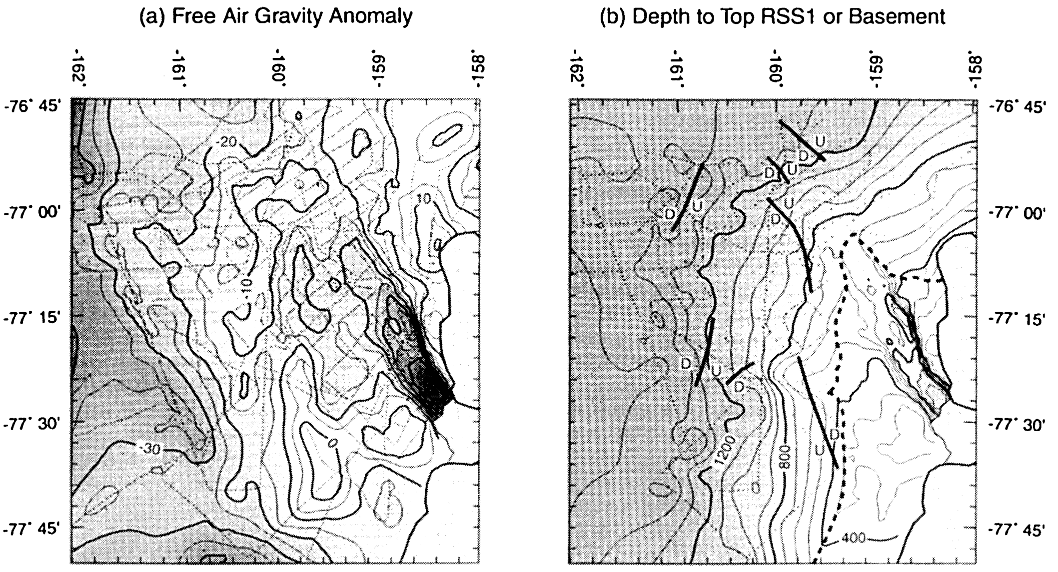
The density of most of the dredge samples is in the range of 2600-2650 kg m$^{-3,}$ lower than the basement density value we used in modeling. Refraction velocities on basement are near 4.9 km s-1 which would be more consistent with the sample densities. Basement relief will be underestimated by our analysis, where the sample densities better characterize the actual basement density. However, the density contrasts required to produce the observed anomalies with sources below the nearly flat-lying younger sediments of the RSS-2 sequences are large. The contact between sediment filling the basins and half grabens and the basement is the simplest explanation for most of the required density variation. Substantial density variation within the basement is unlikely ,particularly since no magnetic anomalies were found that might suggest volcanic rocks in the basement.

Combined interpretation of the seismic and gravity data indicates that the basement topography is controlled by half-graben and horst-and-graben structures, with relief commonly exceeding 600 m. In the north central part of the study area, basement trends are well constrained by the gravity data to be NNW-SSE, parallel to the bathymetric expression of Colbeck Trough. In the south central part of the study area, trends are only moderately constrained but appear to be N-S. The overall basement structure below RSU6 comprises "ranges" 25-40 km long spaced ~20 km and appears very similar in scale to the Basin and Range province of southern Arizona and adjacent Sonora [e.g., Nourse et al., 1994].

4. Discussion

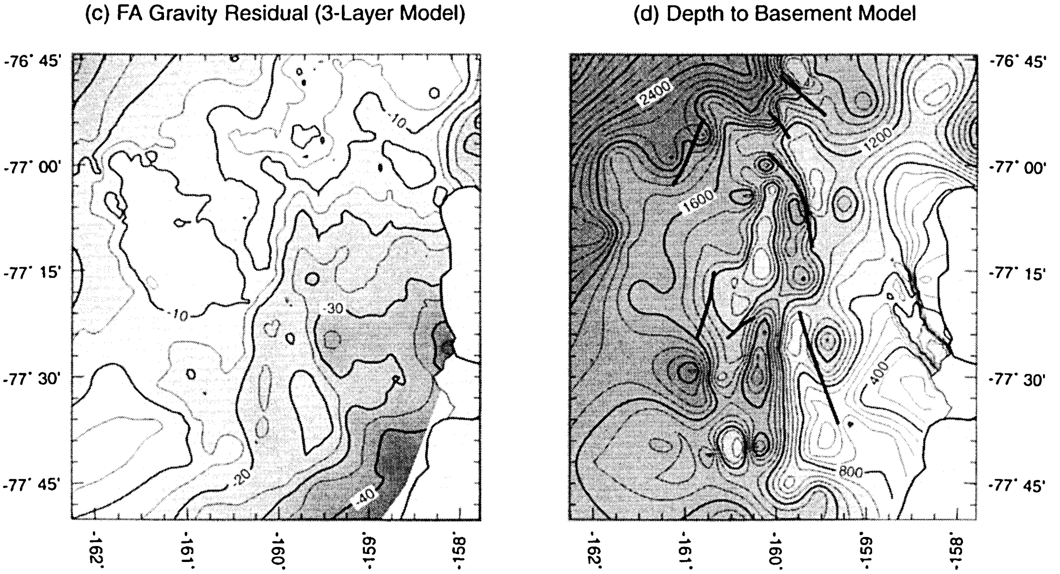
4.1. Basement Rocks on the Colbeck Shelf

The dredged rocks and geophysical data provide some constraints on the identity of basement rocks on the Colbeck shelf. The geophysical data show that the basement is dense and not magnetic; both Swanson and Byrd Coast granite were recovered in our dredges. Other constraints can be drawn from parallels with Greater NZ geology. Basement rocks of the Campbell Plateau are early Paleozoic low grade metasediments faulted into grabens and half grabens [*Cook and Beggs*, 1990; *Beggs*, 1993]. These rocks are correlated to the quartz meta-turbidites of the Greenland Group on South Island, New Zealand, to the Robertson Bay Group in northern Victoria Land, and to the Swanson Formation in wMBL [*Adams*, 1986; *Bradshaw et al.*, 1997]. The Campbell Plateau basement is intruded by middle Cretaceous granites that are correlated A-type suite of Byrd Coast granite in wMBL [*Adams et al.*, 1995; *Weaver et al.*, 1994, suite 2]. Although equivalents of the Devonian I-type Ford granodiorite are



(a) Free Air Gravity Anomaly

(b) Depth to Top RSS1 or Basement



(c) FA Gravity Residual (3-Layer Model)

(d) Depth to Basement Model

Figure 7. Gravity data and models of crustal structure in the Colbeck Trough region. A color version of Figure 7 is available on the UCSB Cape Colbeck web site, http://www.crustal.ucsb.edu/colbeck. (a) Map of Free-Air gravity anomalies (FAA) over the trough and surrounding regions. Dots show position of median observation in 1-km bins; contour interval 5 mGal, polar equidistant projection. (b) Structure contour map on probable Oligocene unconformity RSU6 between RSS-2 and underlying RSS-1 or basement based on seismic data (dots). Bathymetry is plotted southeast of dashed line where RSS-2 has been removed and RSS-1 or basement crops out. Contour interval is 100 m. Locations of faults that cut the RSS-1 sequences are shown. (c) Residual FAA calculated by subtracting a forward gravity model comprising three layers: water, younger sediments, and undifferentiated older sediments plus basement (Figure 7b), from the observed FAA (Figure 7a). Model densities are 1000 kg m^{-3} for water, 2000 kg m^{-3} for younger sediments, and 2650 kg m^{-3} for older sediments and for basement. (d) Depth-to-basement model computed iteratively to satisfy the shorter-wavelength components of the residual FAA in Figure 7c. Here layer 3 of the three-layer model (older sediments and basement) was further divided into basement with density 2850 kg m^{-3} and overlying synrifting sediments of RSS-1 with a density of 2200 kg m^{-3}. The modeled basement shows northerly to northwesterly-trending highs and lows with relief approaching 1 km. (e) Depth-to-Moho model computed iteratively to satisfy the longer wavelength components of the residual FAA in Figure 7c. Assuming a density contrast of 400 kg m^{-3} across Moho, crust thickens southeastward by several kilometers approaching the shoreline. Contour interval is 0.5 km. (f) Residual FAA calculated by subtracting the complete five-layer forward gravity model (water, young sediments, old sediments, basement, mantle) from the observed FAA in Figure 7a. Contour interval is 5 mGal.

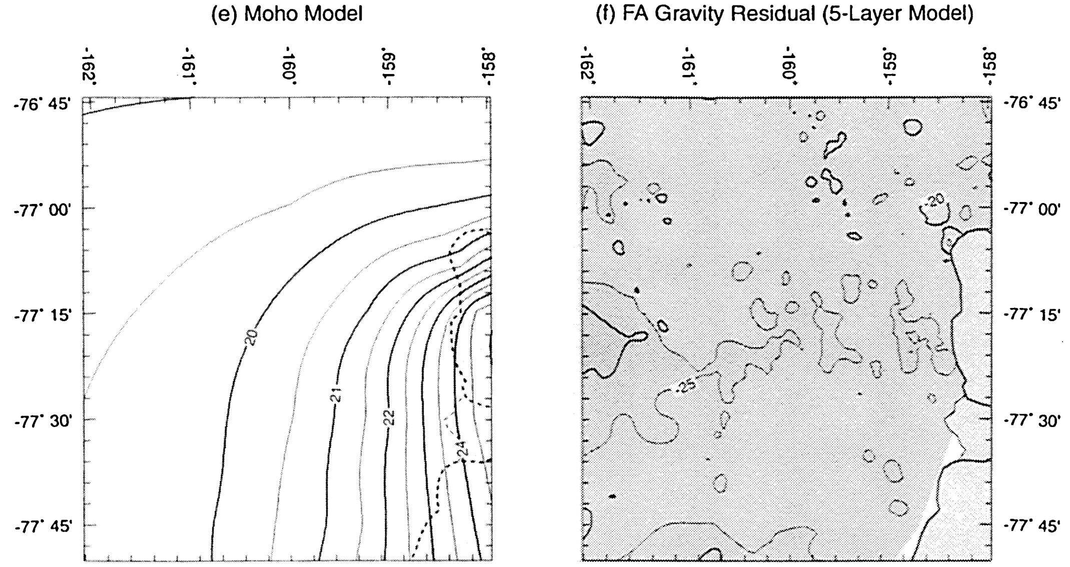


Figure 7. (continued)

found in Northern Victoria Land and western South Island, New Zealand, these rocks are not found on Edward VII Peninsula or on Campbell Plateau [*Adams*, 1987]. From our study it is reasonable to conclude that basement rocks of the Colbeck shelf are Swanson Formation or its equivalents, and Byrd Coast granite. The lack of magnetic anomalies suggests that volcanic rocks are minor on the shelf. Samples of Byrd Coast granite (and Ford granodiorite) from the Ford Ranges are very weakly magnetized (R.P. Meyer, personal communication, 2000). However, the density of the granite is not high enough to meet requirements of gravity modeling in the southern Colbeck Trough. This suggests the basement rock of the southern trough is more mafic, and possibly granodiorite or a denser rock, that we did not sample with dredging and is not exposed nearby onshore.

4.2. Origin of Colbeck Trough

The gravity model of depth-to-basement (Figure 7d) shows a pair of elongate N-S ridges and basins with a relief of 1 km. These basins generally correspond to (half) grabens or synforms where they are crossed by reflection profiles (Figures 5b-5e). The northern or outer portion of the Colbeck Trough (Figure 3) is not expressed in the modeled basement topography (Figure 7d); it is not a basement-controlled structure on the northern shelf. The outer trough does not cut through RSU6 and is therefore not related to rift structure beneath RSU6 (Figure 5d). The outer trough is post-RSU6 in age, and it cuts the post-RSS-2 units. The inner or southern trough is deep and asymmetric, with a steep east wall where basement rocks are exposed. A reentrant in the grounding line at its south end (Figures 2 and 3a) indicates that the trough continues onshore under the ice. The morphology of the southern trough, and graben structures mapped in close proximity to the southern trough, indicate that faulting of the basement has played some role in formation of Colbeck Trough.

We suggest that the trough is an expression of glacial erosion since late Miocene time of a graben system that is pre-RSU6 in age. Faulting deformed the basement, creating relief that was partly removed by erosion during the formation of the WAES (RSU7; Figures 8a and 8b). After deposition of post RSS-2 units, glaciers from onshore (Figures 1c, 2, and 3a) preferentially flowed along north and NW trending half grabens in the southeast shelf closer to shore. This glacial advance extended farther to the northwest and partially eroded the RSS-2 sequence in the Colbeck shelf graben system to produce the Colbeck Trough. Other glacial troughs were cut in the Eastern Basin later at RSS-6 and RSS-7 time (late Miocene-Pliocene [*De Santis et al.*, 1995]). Ice retreat emptied the Trough when the ice grounding line reached its present position in Holocene time [*Conway et al.*, 1999].

4.3. Tectonic History at the Eastern Boundary of the Ross Embayment

The partial exposure and minimal burial of basement and synrift sediments in the Colbeck shelf area has allowed us to map structures that may be characteristic of much of the Ross Sea. In the Colbeck shelf region we have interpreted seismic sequences separated by unconformities RSU6 and RSU7 that are characterized by very different styles of deformation. Above RSU6, glacially derived sequences RSS-2-upper and RSS-2-lower are not deformed except for gentle west tilting. They were deposited on unconformity RSU6 after onset of regional subsidence. The sequence below RSU6, RSS-1-upper, is offset on a few widely spaced, moderately dipping normal-separation faults with little tilting. The age of this phase of faulting is constrained to be older than the late Oligocene-early Miocene RSS-2 sequence. We interpret that unconformity RSU7 is synchronous with or postdates intense middle Cretaceous extensional deformation and is the offshore equivalent of the WAES (Figures 8a and 8b).

Table 2. Tectonic Events in Western Marie Byrd Land

Time	Event	Evidence
Pliocene – Quaternary	glacial erosion, limited volcanism	Colbeck Trough Fosdick Mountains volcanic rocks
Late Oligocene – Miocene	subsidence; sea level rise and glacial marine deposition, westward tilting of shelf	RSS-2 and younger units
Oligocene	sea level fall; subsidence; erosion of RSS-1 upper	RSU6 unconformity
Early Cenozoic	faulting, subsidence, and deposition	RSS-1-upper unit
Late Cretaceous	erosion of RSS-1-lower unit into WAES	WAES is a RSU7 unconformity
Middle & Late Cretaceous	extension; synrift sedimentation; basement uplift	RSS-1-lower unit, cooling of Fosdick Metamorphic Complex

We interpret RSS-1-lower as low-density synrift sedimentary breccia. We suggest that it was deposited and deformed between ~105 and 94 Ma, consistent with cooling data at DSDP site 270 [Fitzgerald and Baldwin, 1997] and in wMBL [Richard et al., 1994], and with the age of the West Antarctic Erosion Surface (WAES) [LeMasurier and Landis, 1996] . Cretaceous grabens in Greater New Zealand and on the Campbell Plateau are filled with nonmarine sediments described as alluvial fan, talus, or conglomerates, along with coal measures [Cook and Beggs, 1990; Beggs, 1993]. Late Cretaceous sediments above an unconformity are marginal marine and little deformed. Sedimentation on the Plateau after that time was marine with transgression progressing from the southeast followed by steady subsidence. The similar structural setting on the Colbeck shelf and results at DSDP site 270 suggest that the nonmarine graben fill on the Campbell Plateau most likely correlates to RSS-1-lower.

The tilted and disrupted character of RSS-1-lower and the underlying basement suggests to us basin-and-range style normal faulting and extension. Without denser seismic coverage we cannot make an accurate estimate of the amounts of extension involved. We propose that this regional-scale extension and exhumation began in the eastern Ross Sea at 105 Ma, coincident with the initiation of Gondwana rifting in the region [Bradshaw, 1989; Richard et al., 1994; Luyendyk, 1995; Luyendyk et al., 1996a] and before the Late Cretaceous denudation of part of western Marie Byrd Land (Figure 8a and Table 2). The RSS-1-lower unit was deposited in N-S and NNW-SSE trending basement grabens during this extension phase. Any basin and range topography that developed was substantially beveled by erosion before the end of extension, preserving the synrift, generally tilted RSS-1-lower strata primarily in half graben basins (Figure 8b). Slightly tilted RSS-1-upper strata are widespread across the southern shelf but were never deposited or later eroded from parts of the northwestern shelf. Continued or a later phase of faulting offset RSS-1-upper on faults trending NNE-SSW (Figure 8c), at least in the western part of the Colbeck shelf study area. This faulting is minor compared with the earlier phase.

Eustatic sea level fall in Oligocene time likely formed RSU6 (Figure 8d [Brancolini et al., 1995]). The deep unconformity mapped toward the edge of the modern shelf comprises both RSU7 and RSU6 (line 10, Figure 5a).The vertical extent of clinoforms near the shelf edge at the top of the RSS-2 sequence (Figure 5a) indicates that the unconformity surface at the base of RSS-2-lower had subsided to a depth of at least 1 km by the end of deposition of RSS-2-upper (early Miocene; Figure 8e). Late Oligocene to early Miocene glacially derived strata of RSS-2 prograded across this erosion surface during an interval of fairly rapid subsidence.

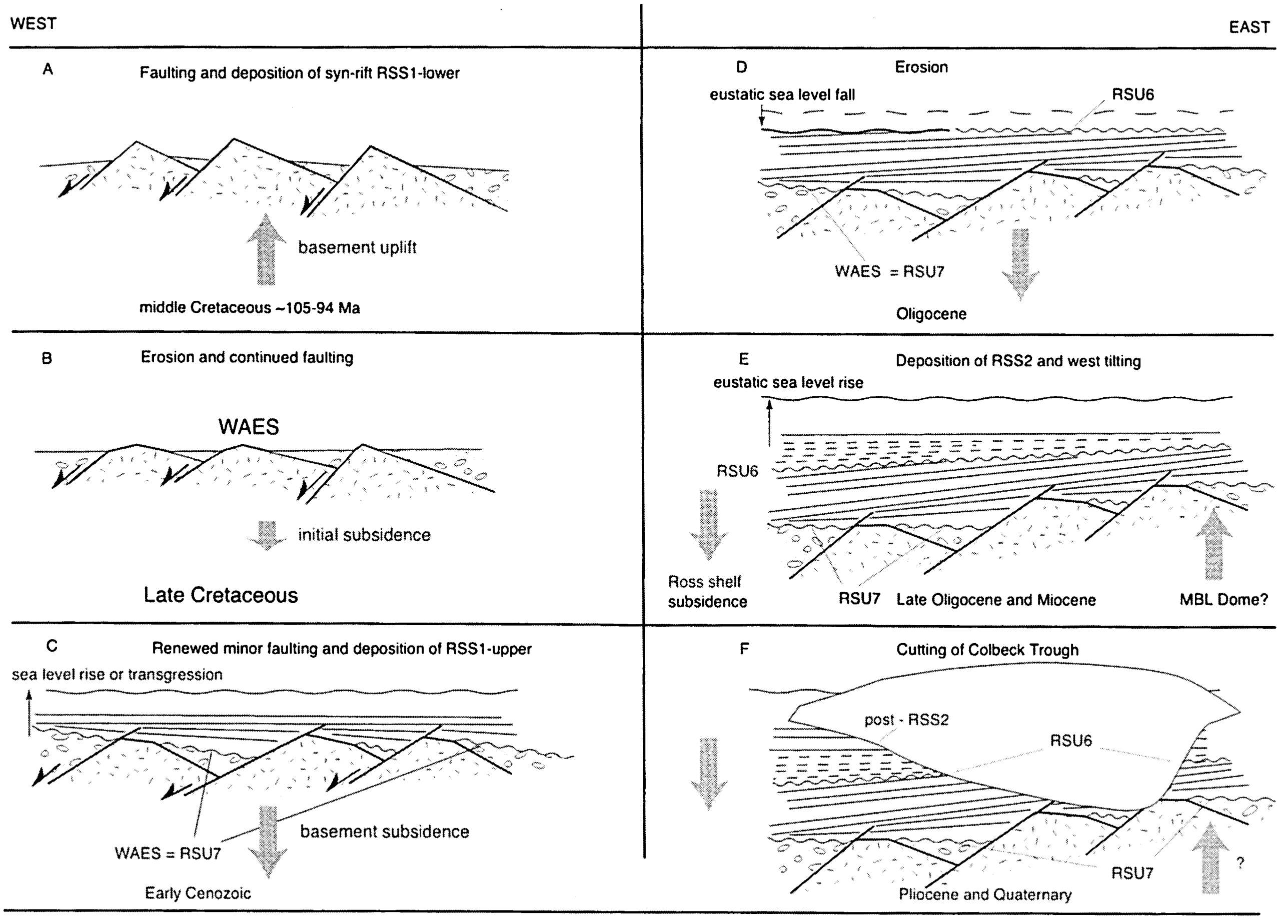
The RSS-2 sequence, RSU6, and the RSS-1 sequence below are tilted to the west; the magnitude of tilting decreases up section, recording continuous, gentle deformation during Oligocene and early Miocene time. Progressive tilting of the RSS-2 sequences is a result of subsidence in the eastern Ross Sea [De Santis et al., 1995] and may also be due to proposed mantle upwelling and basement uplift beginning at 28-30 Ma that formed the Marie Byrd Land dome to the east [LeMasurier and Landis, 1996]. This uniform west tilt produces 1 km of relief on RSU6 on the shelf in the eastern Ross Sea (Figure 7b). RSU6 reaches a depth of ~1.4 km, for a total relief on the onshore-offshore WAES of over 2 km in western MBL.

Since Miocene (?) time, outlet glaciers and ice streams have flowed along portions of favorably oriented half grabens onshore [Richard and Luyendyk, 1991]. We propose that glaciers traversed the continental shelf and carved troughs, including Colbeck Trough, into the basement or overlying sedimentary units (Figure 8f).

4.4. Timing and Magnitude of Extension in the Eastern Ross Sea

MBL middle Cretaceous paleomagnetic poles [DiVenere et al., 1994; Luyendyk et al., 1996a] permit up to a few hundred kilometers of extension between East and West Antarctica since 105 Ma. However, by constructing a tight fit of the Campbell Plateau against the eastern Ross Sea continental margin east of Iselin Bank (Figures 1a and 1b) Lawver and Gahagan [1994] constrain east-west extension in the eastern Ross Sea to <50 km after seafloor spreading began near the end of Cretaceous time (79-74 Ma) [Cande et al., 1995; Stock and Cande, 2001; Wilson, 1995; McAdoo and Laxon, 1997]. This finding would restrict any significant extension in the eastern Ross Sea to the period 105-74 Ma..

A small amount of post 74 Ma and pre-late Oligocene (pre-RSS-2-upper) extension also may have occurred in the eastern Ross Sea. Cande et al. [2000] interpret mid-Cenozoic seafloor spreading across Adare



History of the Colbeck shelf, eastern Ross Sea

Figure 8. History of tectonics and sedimentation in the eastern Ross Sea and the edge of the Ross Sea rift and western Marie Byrd Land. Thin vertical arrows depict relative rise and fall of sea level and thick areas indicate uplift and subsidence of basement. Half arrows indicate periods of active faulting. (a) Extension in the Ross Sea in Late Cretaceous time faults the basement and forms half grabens that are filled with RSS-1-lower. (b) This is followed by erosion to form the West Antarctic Erosion Surface (WAES) in Late Cretaceous time. Tectonic activity continues. (c) Continental margin subsides and/or sea level rises in Late Cretaceous or early Tertiary time, and RSS-1-upper sequence is then deposited. Renewed tectonic activity faults both RSS-1-lower and RSS-1-upper. (d) Continental margin is then exposed in a eustatic sea level drop in Oligocene time and is eroded in places into a surface represented by RSU6. (e) Subsidence and sea level rise follows and RSS-2 begins to be deposited in late Oligocene time. Margin is tilted westward while RSS-2 and younger units are deposited. (f) In Pliocene and Quaternary time grounded glaciers cross the shelf and carve the Colbeck Trough in basement grabens close to the coast and in RSS-2 and younger units farther offshore.

Trough, which is north of and aligned with the Victoria Land Basin in the western Ross Sea (Figure 1b). They calculated a 12 mm yr^{-1} full spreading rate between ~40 and ~28 Ma that represents 144 km of extension. Cande et al. [2000] suggest similar rates and amounts of extension across western Ross Sea south of the Adare Trough in the Northern and Victoria Land basins (Figure 1b). It is permissible that this mid-Cenozoic episode, which predates all or most of RSS-2-upper deposition, may be related to the faulting of RSS-1-upper. Oblique transtension has been proposed to explain Neogene deformation of the western Ross Sea [Wilson, 1995; Salvini et al., 1997; Hamilton et al., 1998, 2001]. Salvini et al. [1997] proposed that ductile deformation also occurred in the Eastern Basin. We have not seen evidence in our study for significant latest Oligocene or younger (post-RSU6) extension in the eastern Ross Sea.

Fault trends mapped offshore are consistent with those on land [Luyendyk et al., 1992]. It is notable that all significant faults trend oblique to the trend of the continental shelf edge (Figure 2). This orientation suggests, but does not require, that these faults are not related to strain that developed between the Campbell Plateau and West Antarctica at ~79-74 Ma that resulted in rifted passive margins. Grabens and half grabens in Greater New Zealand and on the Campbell Plateau trend WNW-ESE (middle Cretaceous) and ~NE-SW (Late Cretaceous [Laird, 1993]). The older grabens are oblique to the trend of the southeast rifted margin of the Plateau, while the younger grabens are parallel to it. The NNW trends of structures on the Colbeck shelf and the occurrence of mylonites in the southern Colbeck Trough suggests a relationship to NW striking, narrow mylonitic zones on land in the southern Ford Ranges. The structures on land accommodated normal to dextral oblique displacement in Cretaceous time [Siddoway, 1999]. Extensional strain in the Ford Ranges during Cretaceous-Cenozoic time has been accommodated on brittle normal faults trending NW-SE and on transcurrent faults oriented NE-SW, parallel with fault-block mountains that channel outlet glacier flow [Luyendyk et al., 1994; Siddoway, 1999; Whitehead et al., 1999]. Fault trends on land are also expressed as lineaments in satellite images [Whitehead et al., 1999].

Detachment faults have been proposed to explain tectonic denudation interpreted in DSDP Site 270 [Fitzgerald and Baldwin, 1997]. We speculate that Cretaceous extension in the eastern Ross Sea rift was thin skinned and was controlled by a detachment fault system that is partially exposed in or nearby the inner Colbeck Trough. The closely spaced faults, tilted blocks, and half grabens imaged in the eastern Ross Sea developed as upper plate structures above a shallow basement-involved detachment fault system. We interpret gently to moderately dipping faults in RSS-1-lower (Figure 5c) to sole into a master fault. Detachment faults are probably zones penetrating the basement of the eastern Ross Sea and were not imaged by our seismic data.

Though details are not well constrained, regional gravity anomalies require several kilometers of crustal thinning across the region of the Colbeck margin west of Edward VII Peninsula (Figure 7e). Under the assumption that crust was of uniform thickness prior to Late Cretaceous to early Cenozoic extension and that the crust onshore is not significantly thinned, the magnitude of extension west of Colbeck Trough is at least 20%, or much higher if onshore crust is also thinned. The dredged mylonites probably formed in a fault zone accommodating a component of that extension, perhaps in a structure separating the thinner and more extended crust of the Ross Sea from the less extended crust of Edward VII Peninsula and Marie Byrd Land. We speculate that Edward VII Peninsula is the eastern margin of the Ross Sea rift. It could be a large horst structure bounded by a series of normal faults on the basis of limited mapping we did on the shelf to its southwest. Edward VII Peninsula is possibly the footwall block across a detachment system breakaway zone exposed in the southern Colbeck Trough. The northeast border of the Peninsula may also be faulted, as is suggested by gravity anomalies here [Luyendyk et al., 2001].

4.5. Vertical Tectonics of the Eastern Ross Sea Margin and Marie Byrd Land

The eastern Ross Sea continental margin may have shared a common history with western Marie Byrd Land through much of the Cretaceous, with plutonism and extensional denudation followed by development of the low-relief West Antarctic Erosion Surface [*LeMasurier and Landis*, 1996]. The original elevation of the WAES on Marie Byrd Land is unknown but is argued by LeMasurier and Landis [1996] to have been near sea level on the basis of minimal local relief and analogy to the Waipounamu surface in New Zealand, which is overlain by Late Cretaceous marine sedimentary rocks. We disagree, and we conclude that the margin remained largely above sea level, in accordance with our finding that the shelf of the eastern Ross Sea does not contain significant sediment thickness of early Tertiary age. Our seismic data show no record of the thickness of marine sediment to be expected for a subsiding Cretaceous margin in a passive rifting environment. Findings at DSDP Site 270 require a delay of ~54 m.y. from the end of significant continental extension to the onset of marine sedimentation (from ~79 Ma, the age of the adjacent seafloor, to ~25 Ma, the age of marine sediments [Hayes et al., 1975]). We conclude that the shelf remained above sea level for much of this time period. In the Colbeck shelf area, marine unit RSS-1-upper apparently was deposited during this hiatus, but the maximum thickness is only of the order of 200 m.

We see three possible explanations for the long interval of time lacking marine sedimentation: (1) the WAES may have formed significantly above sea level and spent tens of millions of years subsiding to sea level in the eastern Ross Sea, (2) the WAES may have formed near sea level, then spent tens of millions of years submerged but starved of sediments, or (3) it could have formed near sea level followed by a long delay between extension and subsidence. Though a lack of direct evidence precludes a definitive choice among these alternatives, we prefer an interpretation of a high-elevation WAES based on the simplicity of the consequent tectonic history.

We propose the following simple scenario for the vertical tectonic history, consistent with geological evidence from western Marie Byrd Land. At 105-94 Ma (Figure 8a) the area including the Ross Sea and Marie Byrd Land was involved in an extensional orogeny involving significant magmatic input, an elevated thermal profile, and at least locally, extreme denudation by faulting or erosion [*Richard et al.*, 1994; *Smith*, 1995]. The Late Cretaceous thermal history of a portion of the middle crust exposed in the Fosdick Metamorphic complex in the Ford Ranges nearby is suggestive of regional magmatic underplating [e.g. Richard et al., 1994; Smith, 1995], as is the emplacement of voluminous mafic and intermediate intrusive rocks elsewhere in the region [*Mukasa and Dalziel*, 2000]. Further, the geochemical signature of Mesozoic intrusions in wMBL suggests mantle plume activity in Late Cretaceous *time [Weaver et al.*, 1994; *Storey et al.*, 1999]. The rheological strength of the middle crust diminished because of both the elevated thermal profile and crustal melting [*Smith*, 1997]. A major extensional province developed, with regionally distributed deformation giving way to rifting of the Campbell Plateau from Antarctica [*Luyendyk*, 1995]. Asymmetry in vertical tectonics between Campbell Plateau and Marie Byrd Land has been noted by Katz [1982] and explained by Luyendyk et al. [1992], using the continental rift detachment-fault model of Lister et al. [1991]. High surface elevation during extension is entirely possible, and substantial thermal subsidence following extension is inevitable because of conductive decay of the thermal anomaly. We interpret postextension vertical motion of both the eastern Ross Sea and western Marie Byrd Land as being dominated by thermal subsidence of an elevated region, with the more extended eastern Ross Sea subsiding more.

For all simple models of thermally driven subsidence in extended basins, and most complex ones too, the maximum subsidence rate would have occurred shortly after the maximum extension rate, with subsidence rates decreasing very gradually as a new equilibrium geotherm is established. The maximum possible thermal subsidence is illustrated by the limiting case of normal oceanic crust, which subsides 1 km in ~10 m.y., 2 km in 35-50 m.y., and 3 km in 80-120 m.y. [e.g., Parsons and Sclater, 1977]. The presence of continental crust would lead to less cooling and slower subsidence due to effects of insulation and radioactive heat production, but other factors, especially isostatic response to sediment loading, can cause faster subsidence.

At both DSDP Site 270 and the Colbeck shelf area, late Oligocene transgression was followed by continued relative sea level rise of 500-1000 m by the end of RSS-2 deposition in the early Miocene, with the Oligocene RSU-6 unconformity now at ~1 km depth. We interpret this rise as reflecting a minor acceleration of primarily thermal subsidence that began at 80-100 Ma. We estimate a Late Cretaceous elevation at the end of local extension of ~1.0-1.5 km for these areas at the margin of the Eastern Basin. This would be consistent with both areas passing through sea level at 40-25 Ma at a decreasing subsidence rate and with the total subsidence moderately augmented by loading of the shelf with glacially derived sediments. This interpretation predicts that unit RSS-1-upper is marine and is late Eocene to early Oligocene in age. The RSU6 unconformity can be most simply correlated to the global Oligocene eustatic sea level decline [*Brancolini et al.*, 1995], interpreted by Haq et al. [1987] to be a drop of ~150 m near 30 Ma. This age interpretation for RSS-1-upper and RSU6 implies that the younger normal faults we observed to cut RSS-1-upper (e.g., Figure 5c) were developed contemporaneously with spreading in the Adare Trough [*Cande et al.*, 2000]. Renewed local extension at this time may also have contributed to increased subsidence. An additional and possibly dominant factor in the increased subsidence is glacial loading at the margins of the Ross Sea, synchronous with appearance of glacially derived sediments at Site 270 [*Hayes et al.*, 1975].

Our argument is that it is easier to accept the WAES forming well above sea level than for it to form at sea level and rise as much as 3 km in MBL in response to mantle plume dynamics as proposed by LeMasurier and Landis [1996]. Formation of low-relief erosion surfaces at high elevation has seldom received serious consideration until recently. However, Gregory and Chase [1994] describe a low-relief Eocene erosion surface in Colorado that, based on paleobotanic evidence and lack of post-Eocene tectonism, formed close to its present 2.5-km elevation. They acknowledge that high-elevation, low-relief surfaces are not forming now, but they suggest several factors associated with the warmer Eocene climate that may have led to different erosion patterns less likely to incise deep canyons than at present.

We might expect that if initiation of seafloor spreading juxtaposes a new ocean margin next to a high continental plateau, dissection of the plateau would be inevitable because of erosion by streams draining the plateau at a high gradient. However, inspection of several of the world's younger rifted continental margins reveals that it is common for rift shoulders to develop that deflect drainage away from the new ocean basin. The youngest such rift shoulders are at the margins of the Red Sea, where Bohannon et al. [1989] interpret 2.5-4 km of uplift since ~20 Ma, notably postdating the earliest extensional structures which formed ~30 Ma. The generally observed topography of rift shoulders has been successfully modeled by interpreting the steep seaward facing slopes as formed by normal faulting and erosion, while the gentle landward facing slopes are formed by flexure driven by isostatic response to the tectonic and erosional unloading [*Wiessel and Karner*, 1989; *van der Beek et al.*, 1994]. At the Red Sea, at the earliest Tertiary India-Madagascar rift, and at the Late Cretaceous southeast Australia rifted margin, modern drainage is still controlled by the gentle landward slopes, flowing almost exclusively away from the rift for areas more than 200 km from the coastline. If a similar inland drainage pattern persisted for 20-40 Ma after rifting from the Campbell Plateau in West Antarctica, a gently sloping WAES could have developed very gradually, leaving only subdued remnants of the original horst and graben topography. A distant drainage outlet in the western Ross Sea or Weddell Sea would imply a low stream gradient, making a high-elevation, low-relief erosion surface more credible, whatever the details of erosion and sediment transport.

In the Colbeck survey area, marine transgression over the erosion surface was a gradual process, reflected by the absence of RSS-1-upper in the north and east, and over many basement highs, and by the northward pinching out of RSS-2-lower (Figure 5a). The absence of both RSS-1-upper and RSS-2-lower in line 10 at 30-50 km from the shelf break is at least consistent with a persistent rift shoulder that did not subside below sea level until the early Miocene. West of our area, Cooper et al. [1995, Plate 21] find that RSS-1 (upper) is thin or absent at comparable distances from the shelf break at 165°-175°W, consistent with the rift shoulder continuing across the north edge of the Eastern Basin. Onshore, where we interpret higher elevations as being supported by less extended, thicker crust, the development of the WAES could also have been gradual, at elevations close to present values. Here development of the relict erosion surface would have ended with initiation of the glacial climate, during which erosion is focused within valley bottoms but can leave higher peaks relatively intact.

Alternative explanations for the lack of lower Tertiary marine sediments require much more complicated explanations of vertical crustal motion. The option that the eastern Ross Sea was well below sea level in the late Oligocene conflicts with sedimentary and paleontologic evidence from Site 270 for a shallow, nearshore environment at that time [*Hayes et al.*, 1975]. Any option that extensive Cretaceous or lower Tertiary marine sediments have been removed by erosion requires either an early Tertiary uplift with no obvious cause or extreme sea level variations not observed elsewhere.

5. Conclusions

Our findings from the Colbeck shelf area can be blended with observations made onshore in wMBL and in Greater NZ to predict a coherent history for the region prior to Late Cretaceous seafloor spreading. Phoenix plate subduction stopped and extension of East Gondwana began at ~105 Ma [*Bradshaw*, 1989; *Luyendyk*, 1995]. The extension was pervasive over broad areas and included extension between Australia and Antarctica [*Stock and Cande*, 2001] and within the Ross Sea rift, wMBL, and the Campbell Plateau. Middle Cretaceous grabens on the Campbell Plateau and grabens we mapped on the Colbeck shelf are oblique to the trends of their respective passive margins. The basin and range structural trends onshore in wMBL also are oblique to the margin trend. The fault trends on the Colbeck shelf and onshore wMBL [*Richard*, 1992] suggest NE directed extension (in present coordinates). Dating of the end of subduction and beginning of extension in New Zealand and cooling ages for the Fosdick Metamorphic Complex and the eastern Ross Sea basement all suggest a significant middle Cretaceous extension episode that formed the faulted basement structures in the eastern Ross Sea. Drilling results from the Campbell Plateau and DSDP Site 270 indicate that the grabens in basement were filled with locally derived nonmarine sedimentary breccia. The Late Cretaceous fault trends in Greater NZ, and particularly the Campbell Plateau, are parallel to the southeast passive margin of the Plateau and the Late Cretaceous Pacific - West Antarctic spreading axis. Margin-parallel faults that could be related to Late Cretaceous seafloor spreading are lacking or minor in wMBL and on the Colbeck shelf. We conclude that the major structural deformation events in the eastern Ross Sea occurred in middle Cretaceous time prior to seafloor spreading in this sector of East Gondwana.

The middle Cretaceous extension direction was replaced in Late Cretaceous time by ~NW extension that rifted away Greater NZ from West Antarctica and created new seafloor. This extension phase was asymmetric; the Campbell Plateau underwent ~200 km of stretching [*Bradshaw*, 1991], was extensively faulted [*Laird*, 1993], and subsided below sea level while wMBL and the Colbeck shelf remained well above sea level for the remainder of Cretaceous time and possibly longer. The change in extension direction was probably well before 79 Ma as the Chatham-Bellingshausen spreading sector has significant reversely magnetized seafloor adjacent to the margin, and quite some time will be needed to develop Campbell Plateau extension and the pre-74 Ma seafloor in the Campbell Plateau-wMBL spreading sector. During this period the West Antarctic Erosion Surface was formed in MBL and on the modern shelf. The Colbeck shelf subsided through sea level in late early Tertiary time. After this time the shelf received a significant thickness of glacially derived sediments as the margin continued to subside owing to lithosphere cooling and glacial loading. The eastern Ross Sea margin (east of Iselin Bank) history contrasts with the western Ross Sea margin. Although the eastern margin was extended in middle Cretaceous time, the significant rifting in the west occurred in early Tertiary time [*Cande et al.*, 2000]. In the west this extension is associated with the formation of the Victoria Land Basin and uplift of the Transantarctic Mountains [e.g., *Hamilton et al.*, 2001]. No comparable deformation occurred in the eastern Ross Sea.

Our interpretation of the vertical history has straightforward predictions for the age and nature of the RSS-1 sequence synrift sediments either exposed or shallowly buried in the southeastern part of our survey area. We expect RSS-1-lower to be middle to Late Cretaceous and nonmarine, and RSS-1-upper to be late Eocene to early Oligocene and marine. Within the admittedly severe standards of Antarctic field work, testing these predictions will require only a moderately ambitious field program. In addition to the tectonic information provided, sediment samples in the eastern Ross Sea would also provide extremely valuable data on past climates in this sector of Antarctica.

We have already remarked on the physiographic similarity between our inferred basement topography and the modern topography of the Sonoran extensional province of southern Arizona and adjacent Mexico. We speculate that we are seeing different stages of similar vertical histories as well. The core complex phase of Sonoran extension peaked at ~25 Ma [*Nourse et al.*, 1994], and current average elevation is roughly 500 m. Erosional lowering of the surface elevation at only 20-30 m m.y.$^{-1}$ combined with thermal subsidence at half the rate of 25-Ma oceanic lithosphere, will lead to widespread marine transgression of Sonora 20-30 m.y. into the future.

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References

Adams, C. J., Geochronological studies of the Swanson Formation of Marie Byrd Land, West Antarctica, and correlation with Northern Victoria Land, East Antarctica, and South Island, New Zealand, *N. Z. J. Geol. Geophys., 29*, 345-358, 1986.

Adams, C. J., Geochronology of granite terranes in the Ford Ranges, Marie Byrd Land, West Antarctica, *N. Z. J. Geo. Geophys., 30*, 51-72, 1987.

Adams, C. J., and S.D. Weaver, Age and correlation of metamorphic basement in Edward VII Peninsula Marie Byrd Land, West Antarctica, and correlation with Northern Victoria Land and Southern New Zealand, *Zbl. Geol. Palaont. Teil I, 1/2*, 75-86, 1990.

Adams, C.J., D. Seward, and S.D. Weaver, Geochronology of Cretaceous granites and metasedimentary basement on Edward VII Peninsula, Marie Byrd Land, West

Antarctica, *Antarct. Sci., 7*, 265-277, 1995.

Anderson, J.B., Preliminary results of the *Deep Freeze* 1983 piston-coring program, *Antarct. J. U. S., 18*, 57-158, 1983.

Anderson, J. B., Geology and hydrocarbon potential of the Antarctic continental margin, in *Mineral Resources Potential of Antarctica, Antarct. Res. Ser.*, vol. 51, edited by J. F. Splettstoesser and G. A. M. Dreschhoff, pp.175-201, AGU, Washington, D. C., 1990.

Barrett, P.J., M. Massimo Sarti, and S. Wise (Eds.), Studies from the Cape Roberts Project, Ross Sea, Antarctica: Initial report on CRP-3, *Terra Antartica, 7*, 209 pp. 2000.

Beggs , J.M., Depositional and tectonic history of Great South Basin, in *South Pacific Sedimentary Basins: Sedimentary Basins of the World 2*, edited by P.F. Balance, pp. 365-373, Elsevier Sci., New York, 1993.

Behrendt, J. C., W. E. LeMasurier, A. K. Cooper, F. Tessensohn, A. Trehu, and D. Damaske, Geophysical studies of the West Antarctic Rift System, *Tectonics, 10*, 1257-1273, 1991.

Bentley, C. R., Crustal structure of Antarctica, *Tectonophysics, 20*, 229-40, 1973.

Bentley, C. R., Configuration and structure of the subglacial crust, in *The Geology of Antarctica*, edited by R. J. Tingey, pp. 335-364, Clarendon, Oxford, England,1991.

Bohannon, R. G., C. W Naeser, D. L. Schmidt, and R. A. Zimmerman, The timing of uplift, volcanism, and rifting peripheral to the Red Sea: A case for passive rifting?, *J. Geophys. Res., 94*, 1683-1701, 1989.

Bradshaw, J. D., Cretaceous geotectonic patterns in the New Zealand region, *Tectonics*, *8*, 803-820, 1989.

Bradshaw, J. D., Cretaceous dispersion of Gondwana: Continental and oceanic spreading in the south-west Pacific-Antarctic sector, in *Geological Evolution of Antarctica*, edited by M. R. A. Thompson, J. A. Crame, and J. W. Thompson, pp. 581-585, Cambridge Univ. Press, New York, 1991.

Bradshaw, J. D., P.B. Andrews, and B. D. Field, Swanson Formation and related rocks of Marie Byrd Land and a comparison with the Robertson Bay Group of Northern Victoria Land, in *Antarctica Earth Science*, edited by R. L. Oliver, et al., pp. 274-279, Aust. Acad. of Sci., Canberra, 1983.

Bradshaw, J. D., Pankhurst, R. J., Weaver, S.D., Storey, B.C., Muir, R.J. and T.R. Ireland, New Zealand superterranes recognized in Marie Byrd Land and Thurston Island, in *The Antarctic Region: Geological Evolution and Processes*, edited by C.A. Ricci, pp. 429-436, Terra Antarctica, Siena, Italy 1997.

Brancolini, G., A.K. Cooper, and F. Coren, Seismic facies and glacial history in the western Ross Sea (Antarctica), in *Geology and Seismic Stratigraphy of the Antarctic Margin, Antarc. Res. Ser.*, vol. 68, edited by A.K. Cooper, P.F. Barker, and G. Brancolini, pp. 209-234, AGU, Washington, D. C.,1995.

Busetti, M., and A.K. Cooper, Possible ages and origins of unconformity U6 in the Ross Sea, Antarctica, *Terra Antartica, 1*, 341-343, 1994.

Cande, S. C., C. A. Raymond, J. Stock, and W. F. Haxbe, Geophysics of the Pitman Fracture Zone and Pacific-Antarctic plate motion during the Cenozoic, *Science, 270*, 947-951, 1995.

Cande, S. C., J. Stock, D. Müller, and T. Ishihara, Cenozoic motion between East and West Antarctica, *Nature, 404*, 145-150, 2000.

Conway, H., B.L. Hall, G.H. Denton, A.M. Gades, and E.D. Waddington, Past and future grounding-line retreat of the West Antarctic Ice Sheet, *Science, 286*, 280-283. 1999.

Cook, R.A. and J.M. Beggs, Wildcats needed in Campbell plateau basins, *Oil Gas J., 88*, 52-54, 1990.

Cooper, A. K., F. J. Davey, and J. C. Behrendt, Seismic stratigraphy and structure of the Victoria Land Basin, western Ross Sea, Antarctica, in *The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea, Earth Science Ser.*, vol. 5B, edited by A.K. Cooper and F.J. Davey, pp. 27-65, Circum-Pacific Counc. for Energy and Miner. Resour. Houston, Tex., 1987.

Cooper, A. K., P.F. Barker, and G. Brancolini (Eds.), *Geology and Seismic Stratigraphy of the Antarctic Margin, Antarct. Res. Ser.*, vol. 68, 301 pp., AGU, Washington, D. C., 1995.

Davey, F. J., Geology and structure of the Ross Sea region, in *The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea, Earth Sci. Ser.*, vol. 5B, edited by A. K. Cooper and F. J. Davey, pp. 1-15, Circum-Pacific Counc. for Energy and Miner. Resour., Houston, Tex, 1987.

Davey, F.J., and G. Brancolini, The Late Mesozoic and Cenozoic structural setting of the Ross Sea region, in *Geology and Seismic Stratigraphy of the Antarctic Margin, Antarct. Res. Ser.*, vol. 68, edited by A.K. Cooper, P.F. Barker, and G. Brancolini, pp. 167-182, AGU, Washington, D. C., 1995.

DeSantis, L., J.B. Anderson, G. Brancolini, and I. Zayatz, Seismic record of late Oligocene through Miocene glaciation on the central and eastern continental shelf of the Ross Sea, in *Geology and Seismic Stratigraphy of the Antarctic Margin, Antarct. Res. Ser.*, vol. 68, edited by A.K. Cooper, P.F. Barker, and G. Brancolini, pp. 235-260, AGU, Washington, D. C., 1995.

DiVenere, V., D.V. Kent, and I. W. D. Dalziel, Mid-Cretaceous paleomagnetic results rrom Marie Byrd Land, West Antarctica: A test of post-100 Ma relative motion between East and West Antarctica, *J. Geophys. Res., 99*, 15,115-15,139, 1994.

Fitzgerald, P.G. and S.L. Baldwin, Detachment fault model for the evolution of the Ross Embayment, in *The Antarctic Region: Geological Evolution and Processes*, edited by C.A. Ricci, pp. 555-564, Terra Antarctica, Siena, Italy, 1997.

Gregory, K. M., and C.G. Chase, Tectonic and climatic significance of a late Eocene low-relief, high-level geomorphic surface, Colorado, *J. Geophys. Res. 99*, 20,141-20,160, 1994.

Hamilton, R., C. C. Sorlien, B. P. Luyendyk, L. R. Bartek, and S. A. Henrys, Tectonic regimes and structural trends off Cape Roberts, Antarctica, *Terra Antartica, 5*, 261-272, 1998.

Hamilton, R., B. P. Luyendyk, C. C. Sorlien, and L. R. Bartek, Cenozoic tectonics of the Cape Roberts Rift Basin, and Transantarctic Mountains Front, Southwestern Ross Sea, Antarctica, *Tectonics, 20*, 325-342, 2001.

Haq, B.U., J. Hardenbol, and P.R. Vail, Chronology of fluctuating sea levels since the Triassic, *Science, 235*, 1156-1167, 1987.

Hayes, D.E., and L.A. Frakes, General synthesis. Deep Sea Drilling Project 28, *Initial Reports of the Deep Sea Drilling Project, Leg 28*, edited by D.E. Hayes, and L.A. Frakes, pp. 919-942, U.S. Govt. Print. Off., Washington, D.C., 1975.

Hayes, D.E., L.A. Frakes and Shipboard Science Party, Sites 270, 271, 272, *Initial Rep. Deep Sea Drill. Proj.* vol. 28, edited by D.E. Hayes, and L.A. Frakes, pp. 211-234, U.S. Government Printing Office, Washington, D.C., 1975.

Hinz, K,. and M. Block, Results of geophysical investigations in the Weddell Sea and in the Ross Sea, Antarctica, in *Proceeding 11th World Petroleum. Congress, London 1983*, pp. 279-291, John Wiley, New York, 1984.

Hole, M. J., and W.E. LeMasurier, Tectonic controls on the geochemical composition of Cenozoic, mafic alkaline volcanic rocks from West Antarctica, *Contrib. to Minera. Petrol., 117*, 187-202, 1994.

Kaharoeddin, S.A., and D.S. Cassidy, Basal sediment ages of 1983 piston cores, *Antarctic J. U. S., 19*, 121, 1985.

Katz, A.R., West Antarctica and New Zealand: A geologic test of the model of continental split. in *Antarctic Geoscience*, edited by C. Craddock, pp. 31-41, Univ. of Wis. Press, Madison, , 1982.

Kimbrough, D. L., and S.M. Richard, Geochronology of basement rocks in the Fosdick Mountain region of West Antarctica and correlation with Cretaceous extensional terranes of southern New Zealand, paper presented at Sixth International Symposium on Antarctic Earth Sciences, Nat. Inst. of Polar Res., Tokyo, Japan, Sept. 9-13, 1991.

Kluiving, S.J., L.R. Bartek, B.P. Luyendyk, K.R. Zellmer, C.C. Sorlien, and F.M. Van der Wateren, (abstract,) *Eos Trans. AGU, 78* (46), Fall Meet. Suppl., F371., 1997.

Laird, M.G., Cretaceous continental rifts: New Zealand region, in *South Pacific Sedimentary Basins: Sedimentary Basins of the World 2*, edited by P.F. Balance, pp. 37-49, Elsevier Sci., New York, 1993.

Lawver, L. A., and L.M. Gahagan, Constraints on timing of extension in the Ross Sea region, *Terra Antartica, 1*, 545-552, 1994.

LeMasurier, W. E., Late Cenozoic volcanism on the Antarctic Plate: An overview, in *Volcanoes of the Antarctic Plate and Southern Oceans, Antarctic Res. Series*, vol. 48, edited by W. E. LeMasurier and J.W. Thomson, p. 1-17, AGU, Washington, D.C. , 1990,

LeMasurier, W. E., and C.A. Landis, Mantle plume activity recorded by low relief erosion surfaces in West Antarctica and New Zealand, *Geol. Soc. Am. Bull., 108*, 1450-1466, 1996.

LeMasurier, W. E., and D.C. Rex, Volcanic record of Cenozoic glacial history in Marie Byrd Land and western Ellsworth Land: Revised chronology and evaluation of tectonic factors, in *Antarctic Geoscience - Symposium on Antarctic Geology and Geophysics*, edited by C. Craddock, pp. 725-734, Univ. of Wis. Press, Madison, 1982.

LeMasurier, W. E., and D.C. Rex, Rate of uplift and the scale of ice level instabilities recorded by volcanic rocks in Marie Byrd Land, West Antarctica, in *Antarctic Earth Science,* edited by R.L. Oliver, et al., pp. 663-670, Aust. Acad. of Sci., Canberra, 1983.

LeMasurier, W. E., and D.C. Rex, Evolution of linear volcanic ranges in Marie Byrd Land, West Antarctica, *J. Geophys. Res., 94*, 7223-7236, 1989.

LeMasurier, W.E., and F.A. Wade, Chapter B. 16E, Fosdick Mountains, in *Volcanoes of the Antarctic Plate and Southern Oceans*, *Antarct. Res. Ser.*, vol. 48, edited by W. E. LeMasurier and J.W. Thomson, pp. 251-252, AGU, Washington, D. C., 1990.

Lisker, F., and M. Olesch, Cooling and denudation history of Edward VII Peninsula, Marie Byrd Land, based on apatite fission track analysis, in *The Antarctic Region: Geological Evolution and Processes*, edited by C.A. Ricci, pp. 475-480, Terra Antartica, Siena, Italy, 1997.

Lister, G.S., M.A. Etheridge, and P.A. Symonds, Detachment models for the formation of passive continental margins, *Tectonics, 10*, 1038-1064, 1991.

Luyendyk, B. P., Hypothesis for Cretaceous rifting of east Gondwana caused by subducted slab capture, *Geology, 23*, 373-376, 1995.

Luyendyk, B.P., and C.H. Smith, Geological expedition to King Edward VII Peninsula and the Ford Ranges, Marie Byrd Land, *Antarct. J. U. S., 28*, 10-13, 1994.

Luyendyk, B.P., S.M. Richard, C.H. Smith, and D.L. Kimbrough, Geological and geophysical investigations in the northern Ford Ranges, Marie Byrd Land, West Antarctica, in *Recent Progress in Antarctic Earth Science*, edited by Y. Yoshida, K. Kaminuma, and K. Shiraishi, pp. 279-288, Terra Sci., Tokyo, 1992.

Luyendyk, B.P., C.H. Smith, and F.M. van der Wateren, Glaciation, block faulting, and volcanism in western Marie Byrd Land, *Terra Antartica, 1*, 541-543, 1994.

Luyendyk, B.P., S. Cisowski, C.H. Smith, S.M. Richard, and D.L. Kimbrough, Paleomagnetic study of the northern Ford Ranges, western Marie Byrd Land, West Antarctica: Motion between West and East Antarctica, *Tectonics, 15*, 122-141, 1996a.

Luyendyk, B.P., C.C. Sorlien, and L.R. Bartek, Early Tertiary rifting in the eastern Ross Sea and offshore Western Marie Byrd Land, Antarctica, *Eos Trans. AGU, 77*(46), 312, 1996b.

Luyendyk, B.P., C.H. Smith, and G. Druivenga, Gravity measurements on King Edward VII Peninsula, Marie Byrd Land, West Antarctica, during GANOVEX VII, *Geol. Jahrb.*, in press, 2001.

Mahmood, A., J.P. Crawford, R. Michaud, and K. Jezek, RADARSAT-1 background mission - Mapping the world, *Eos Trans. AGU, 79*, 17,23, 1998.

McAdoo, D., and S. Laxon, Antarctic tectonics: Constraints from an ERS-1 satellite marine gravity field, *Science, 276*, 556-560, 1997.

Mukasa, Samuel B; Dalziel, Ian W D, Marie Byrd Land, West Antarctica; evolution of Gondwana's Pacific margin constrained by zircon U-Pb geochronology and feldspar common-Pb isotopic compositions *Geol. Soc. Am. Bull, 112*, 611-627, 2000.

Nourse, J.A., T.H. Anderson, and L.T. Silver, Tertiary metamorphic core complexes in Sonora, northwestern Mexico, *Tectonics, 13*, 1161-1182, 1994.

Pankhurst, R.J., S.D. Weaver, J.D. Bradshaw, B.C. Storey, and T.R. Ireland, Geochronology and geochemistry of pre-Jurassic superterranes in Marie Byrd Land, Antarctica, *J. Geophys. Res., 103*, 2529-2547, 1998.

Parker, R. L., The rapid calculation of potential anomalies, *Geophys. J. R. Astron. Soc., 31*, 447-455, 1973.

Parsons, B., and J. G. Sclater, An analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res, 78*, 5128-5137, 1977.

Richard, S.M., Structure and cooling history of the Fosdick Metamorphic Complex, Marie Byrd Land, West Antarctica, in *Recent Progress in Antarctic Earth Science*, edited by Y. Yoshida, K. Kaminuma, and K. Shiraishi, pp. 289-294, Terra Sci., Tokyo, 1992.

Richard, S.M., and B.P. Luyendyk, Glacial flow reorientation in the southwest Fosdick Mountains, Ford Ranges, Marie Byrd Land. *Antarct. J. U. S., 26*, 67-69, 1991.

Richard, S.M., C.H. Smith, D.L. Kimbrough, P.G. Fitzgerald, B.P. Luyendyk, and M.O. McWilliams, Cooling history of the northern Ford Ranges, Marie Byrd Land, West Antarctica, *Tectonics, 13*, 837-857, 1994.

Salvini, F., G. Brancolini, M. Busetti, F. Storti, F. Mazzarini, and F. Coren, Cenozoic geodynamics of the Ross sea region, Antarctica: Crustal extension, intraplate strike-slip faulting, and tectonic inheritance, *J. Geophys. Res., 102*, 24,669-24,696, 1997.

Siddoway, C. S., Late Cretaceous-Cenozoic structural evolution of western Marie Byrd Land (abstract), in *8th International Symposium on Antarctic Earth Sciences, 5-9 July 1999, Programme and Abstracts*, edited by D. N. B. Skinner, p. 281, Victoria Univ., Wellington, New Zealand, 1999.

Smith, C.H., Migmatites at the amphibole-granulite transition, Fosdick Metamorphic Complex, West Antarctica, in *Recent Progress in Antarctic Earth Science*, edited by Y. Yoshida, K. Kaminuma, and K. Shiraishi, pp. 295-301, Terra Sci., Tokyo, 1992.

Smith, C.H., Cordierite gneiss and high temperature metamorphism in the Fosdick Mountains, West Antarctica, with implications for breakup processes in the Pacific sector of the Mesozoic Gondwana margin, Ph.D. dissertation, 313 pp., Univ. of Calif., Santa Barbara, 1995.

Smith, C.H., Migmatites of the Alexandra Mountains, West Antarctica: Pressure and temperature conditions of formation and regional context, *Geol. Jahrb., B89*, 169-178, 1996.

Smith, C.H., Mid-crustal processes during Cretaceous rifting, Fosdick Mountains, Marie Byrd Land, in *The Antarctic Region: Geological Evolution and Processes*, edited by C.A. Ricci, , pp. 313-320, Terra Antartica, Siena, Italy, 1997.

Stock, J.M., and S. C. Cande, Tectonic history of Antarctic seafloor in the Australia-New Zealand-South Pacific sector: Implications for Antarctic continental tectonics, in *Proceedings of 8th International Symposium on Antarctic Earth Sciences, 5-9 July 1999*, edited by J. Gamble, D. Skinner, and S. Henrys, Victoria Univ., Wellington, New Zealand in press, 2001.

Stoffa, P. L., J.T. Fokkema, R. M. de Luna Freire, and W.P. Kessinger, Split-step Fourier migration, *Geophysics, 55*, 410-421, 1990.

Storey, B.C., P.T. Leat,, S.D. Weaver, R.J. Pankhurst, J.D. Bradshaw, and S. Kelley, Mantle plumes and Antarctica - New Zealand rifting: Evidence from mid-Cretaceous mafic dykes, *J. Geol. Soc. London, 156*, 659-671, 1999.

Tessensohn, F., and G. Worner, The Ross Sea rift system, Antarctica: Structure, evolution, and analogs, in *Geological Evolution of Antarctica*, edited by M. R. A. Thompson, J. A. Crame, and J. W. Thompson, pp. 273-278, Cambridge Univ. Press, New York, 1991.

Traube, V., and I. Zayatz, Main stages of development of the Eastern Basin, Ross Sea, imprinted in its structure, in *LIRA Workshop on Landscape Evolution—A multidisciplinary approach to the relation of Cenozoic climate change and tectonics in the Ross Sea area, Antarctica*, edited by F.M. Wateren, A.L.L.M. van der Verbers, and F. Tessensohn, pp. 91-94, Rijks Geol. Dienst, Haarlem, Netherlands, 1993.

Trehu, A. J.C. Behrendt, and J. Fritsch, Generalized crustal structure of the Central Basin, Ross Sea, Antarctica, *Geol. Jahrb., E47*, 291-311, 1993.

Trey, H., A.K. Cooper, G. Pellis, B. Della Vedova, G. Cochrane, G, Brancolini, and J. Makris, Transect across the West Antarctic rift sytem in the Ross Sea, Antarctica, *Tectonophysics, 301*, 61-74, 1999.

van der Beek, P., S. Cloetingh, and P. Andriessen, Mechanisms of extensional basin formation and vertical motions at rift flanks: Constraints from tectonic modelling and fission-track thermochronology, *Earth Planet. Sci. Lett., 121*, 417-433, 1994.

Wade, F. A., C.A. Cathey, and J.B. Oldham, Reconnaissance geologic map of the Alexandra Mountains quadrangle, Marie Byrd Land, Antarctica, *Ant. Geol., Map A-5*, U. S. Antarct. Res. Program, Washington D. C., 1977.

Weaver, S. D., J.D. Bradshaw, and C.J. Adams, Granitoids of the Ford Ranges, Marie Byrd Land, Antarctica, in *Geological Evolution of Antarctica*, edited by M. R. A. Thomson, et al., pp. 345-351, Cambridge Univ. Press, New York, 1991.

Weaver, S. D., B.C. Storey, R.J. Pankhurst, S.B. Mukasa, V.J. DiVenere, and J.D. Bradshaw, Antarctica-New Zealand rifting and Marie Byrd Land lithospheric magmatism linked to ridge subduction and mantle plume activity, *Geology, 22*, 811-814, 1994.

Weissel, J. K., and G. D. Karner, Flexural uplift of rift flanks due to mechanical unloading of the lithosphere during extension, *J. Geophys. Res., 94*, 13,919-13,950, 1989.

Whitehead, A.L., C.S. Siddoway, and F.W. van der Wateren, Kinematic analysis of small-scale brittle structures in the Ford Ranges, Marie Byrd Land, in *8th International Symposium on Antarctic Earth Sciences, 5-9 July 1999, Programme and Abstracts*, edited by D. N. B. Skinner, p. 316, Victoria Univ., Wellington, New Zealand, 1999.

Wilbanks, J. R., Geology of the Fosdick Mountains, Marie Byrd Land, in *Antarctic Geology and Geology and Geophysics*, edited by R. J. Adie, pp. 277-284, Universitetsforlaget, Oslo, Norway, 1972.

Wilson, T., Cenozoic transtension along the Transantarctic Mountains-West Antarctic rift boundary, southern Victoria Land, Antarctica, *Tectonics, 14*, 531-545, 1995.

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