TECTONICS, VOL. 20, NO. 3, PAGES 325-342, JUNE 2001

Cenozoic tectonics of the Cape Roberts Rift Basin and Transantarctic Mountains Front, Southwestern Ross Sea, Antarctica

Rhea J. Hamilton,[1] Bruce P. Luyendyk, and Christopher C. Sorlien
Institute for Crustal Studies, University of California, Santa Barbara, California

Louis R. Bartek[2]
Department of Geology, University of Alabama, Tuscaloosa, Alabama

Abstract. We conducted a multichannel seismic reflection survey offshore Cape Roberts, Antarctica, and combined our findings with the results of the Cape Roberts International Drilling Project (CRP). This allows us to interpret Cenozoic tectonics in the southwest sector of the Ross Sea including the history of uplift of the Transantarctic Mountains (TAM) and subsidence of the Victoria Land Basin (VLB). Seismic stratigraphic sequences mapped offshore Cape Roberts are tilted eastward and thicken into the VLB where they comprise more than half the fill seen on seismic records. Normal faults a few kilometers offshore cut these sequences and define a north trending rift graben. Drilling results from the CRP show that these strata are latest Eocene (?), Oligocene, and younger in age; much younger than previously inferred. We interpret this pattern to be due to an episode of E-W extension and related subsidence that occurred across the major basins in the western Ross Sea during the early Cenozoic. The rift graben offshore and adjacent to Cape Roberts is bounded on the west by a major north trending fault zone. At Cape Roberts this fault system may have from 6 to 9 km of vertical separation. This fault system is part of a larger zone along the coastline in southern Victoria Land that accommodated uplift of the TAM in Oligocene time. We name it here the McMurdo Sound Fault Zone. A late Oligocene angular unconformity that is seen in seismic data and sampled by CRP drilling marks the end of east tilting of the stratigraphic sequences. We interpret this as the end of the main uplift of the TAM coinciding with a change from E-W extension to NW-SE oblique rifting at that time. Uplift of the TAM and subsidence in the VLB may be linked with seafloor spreading on the Adare Trough to the northwest of the Ross Sea between 43 and 26 Ma. This would imply a plate boundary between East and West Antarctica crossing through the western Ross Sea in Eocene and Oligocene time.

1. Introduction

A long-standing problem in Antarctic tectonic history is whether the Antarctic plate was separated into two plates during the Cenozoic [*Molnar et al.* 1975; *Stock and Molnar*, 1982, 1987]. Related to this by implication are the details of the uplift history of the Transantarctic Mountains (TAM) and subsidence of the major basins in the Ross Sea, especially the westernmost Victoria Land Basin (VLB), and how these events may be explained within a plate tectonic setting. The uplift history of the TAM was one focus of Cape Roberts International Drilling Project (CRP) recently completed at the margin of the Ross Sea adjacent to the TAM [*Barrett and Davey*, 1992; *International Steering Committee*, 1994]. We conducted a marine geophysical survey there in February 1996 using the RVIB *Nathaniel B. Palmer* (NBP9601) as part of the preparation for the CRP (Figure 1). We acquired SeaBeam 2112 swath bathymetry, chirp sonar, gravity, magnetic field, and over 250 km of single-channel (SCS; two channel and single fold) and 22-fold multichannel (MCS) seismic data.

Cape Roberts is found in the southwestern Ross Sea, Antarctica, 125 km north of the United States McMurdo Research Station on Ross Island (Figure 1). The CRP employed drilling from annual sea ice a few kilometers offshore into a suspected sequence of Cenozoic and Mesozoic strata. The CRP was aimed at recovering strata up to 100 million years in age adjacent to the range front of the TAM. The project goals are to answer questions concerning the glacial history of Antarctica, the history of the Ross Sea rift, and the uplift of the TAM. In our study we address specific issues about this sector of the southwestern Ross Sea. We emphasize results from the interpretation of our seismic reflection data that place the drilling results of the CRP in a stratigraphic and structural context. We also relate our tectonic interpretations for the southwestern Ross Sea to larger-scale plate tectonic episodes that formed and shaped the major N-S trending basins in the Ross Sea.

1.1. Tectonic Evolution of the Western Ross Sea

The important events of the Ross Sea tectonic history are believed to be of Mesozoic and Cenozoic age. The onset of the Gondwana breakup in the Jurassic left its imprint in the Ross Sea and TAM region. This was marked by a major igneous event at ~180 Ma that involved the eruption and intrusion of the Jurassic tholeiitic Kirkpatrick Basalts and the Ferrar Dolerite that are widespread in the TAM [*Kyle et al.*, 1981; *Elliot*, 1992]. *Davey and Brancolini* [1995] discussed four tectonic events that were significant in the evolution of the Ross Sea in Early Cretaceous and later time. These include (1)

---

[1] Now at IESE, Universidad de Navarra, Barcelona, Spain.

[2] Now at Department of Geological Sciences, University of North Carolina, Chapel Hill, North Carolina

Paper number 2000TC001218
0278-7407/01/2000TC001218$12.00

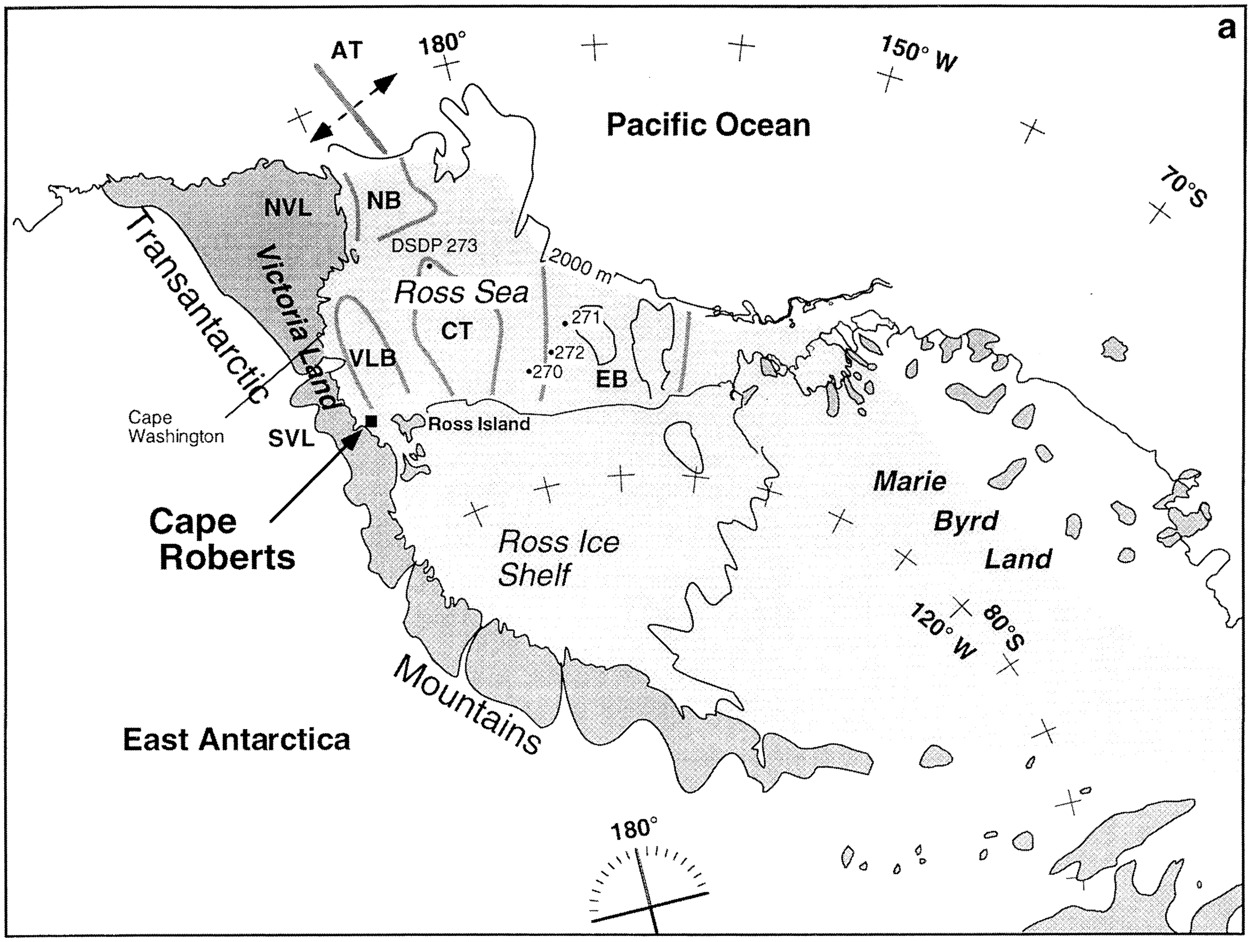

Figure 1. (a) Ross Sea region map showing the location of the study area, outcrop onshore (dark shading), Deep Sea Drilling sites, the Transantarctic Mountains, and Cape Roberts. AT, Adare Trough (dashed arrows indicate former spreading directions [*Cande et al.*, 2000]); NB, Northern Basin; VLB, Victoria Land Basin; CT, Central Trough; EB, Eastern Basin; NVL, Northern Victoria Land; SVL, Southern Victoria Land. The West Antarctic Rift System is outlined by the light shading [*LeMasurier*, 1990]. (b) Map of region including Cape Roberts and McMurdo Sound, showing the survey track of *N. B Palmer* cruise 96-01, locations of Cape Roberts Project drill holes, and the McMurdo Sound Fault Zone (dashed lines; see text). Drill holes CIROS-1 and MSSTS-1 are described by *Barrett* [1986, 1989], respectively. The Dry Valley Drilling Project (DVDP) is described by *McGinnis* [1981].

a major extension episode that began ~105 Ma that is correlated with the end of Phoenix plate subduction under Antarctica and Gondwana [*Bradshaw*, 1989; *Luyendyk*, 1995], (2) seafloor spreading between West Antarctica and New Zealand/Campbell Plateau that began ~83 Ma [*Stock and Cande*, 1999, 2001], (3) the main uplift of the TAM starting at 55 Ma [*Fitzgerald*, 1992] possibly in response to the end of spreading in the Tasman Sea and acceleration of spreading between Australia and Antarctica [*Weissel et al.*, 1977; *Cande and Mutter*, 1982], and (4) volcanism and transtensional faulting beginning in Oligocene time. Item 4 may be related to middle Cenozoic seafloor spreading in the Adare Trough northwest of the Ross Sea (Figure 1) [*Stock and Cande*, 1999, 2001; *Cande et al.*, 2000].

1.2. Stratigraphy of the Victoria Land Basin

It has been proposed that rifting and subsequent extension of the Ross Sea in the middle and Late Cretaceous time led to the initiation of the Northern Basin (NB), the Central Trough (CT), and the VLB (Figure 1) [e.g., *Davey*, 1981]. These basins were actively subsiding during Mesozoic time and during later phases of rifting in Cenozoic time. The more recent (Late Cenozoic) locus of activity in the Ross Sea has been in the Terror Rift of the VLB that is immediately east of Cape Roberts (Figure 1) [*Davey and Brancolini*, 1995].

The VLB was described by *Cooper and Davey* [1985] and *Cooper et al.* [1987, 1991] as a rift depression over 150 km wide that extends from Ross Island to Cape Washington (Figure 1). Greater than average heat flow has been measured in the VLB [*Blackman et al.* 1987] that can be explained by a shallow mantle and igneous activity in an area of extended crust. An estimated 14 km of strata fill the basin [*Cooper et al.*, 1987]. A thick section of Oligocene sediments in the Cape Roberts drill holes can be correlated to the VLB, suggesting that much of this enormous thickness of sediment is of latest Eocene and younger age[*Cape Roberts Science Team*, 2000; *Davey et al.*, 2000].

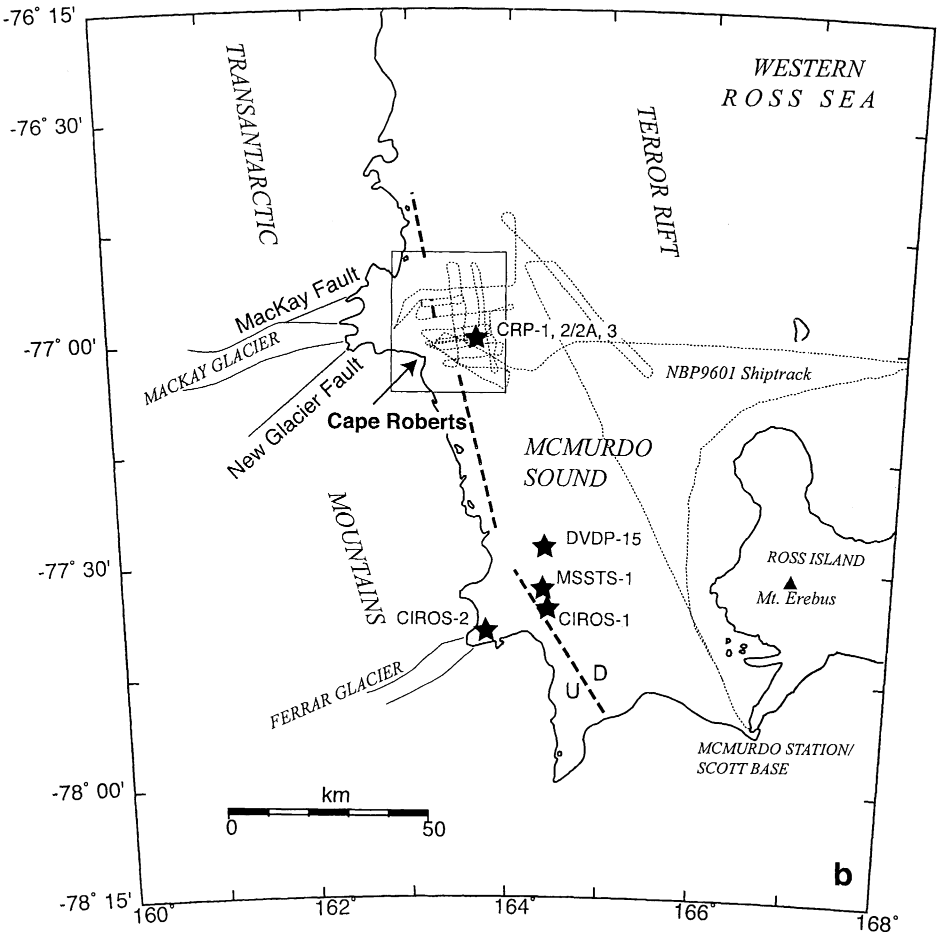

Figure 1. (continued)

Cooper et al. [1987] established a nomenclature for seismic units in the VLB and western Ross Sea based on six seismic stratigraphic units (V1-V5 sedimentary and V6 volcanic) above an acoustic basement (V7) (Figure 2). These V sequences have been correlated to seismic sequences in the Northern, Central, and Eastern Basins (Ross Sea Seismic (RSS) units and U unconformities of *Hinz and Block* [1984]) by *Brancolini et al.* [1995]. However, seismic units in the west and eastern Ross Sea do not carry across the highs bounding the basins, so that seismic lines do not tie them together. *Bartek et al.* [1996] later developed a more detailed letter nomenclature for the V sequences based on interpretations of coherent VLB seismic sequences seen on RV *Polar Duke* high-resolution seismic data. The V sequences have been correlated to Roberts Ridge offshore Cape Roberts by *Davey et al.* [2001].

Age control on V seismic sequences has been uncertain and has relied on data from a few drill sites prior to the CRP [*Davey et al.*, 2001]. Prior drill sites sampled mid-Cenozoic sections and include the Deep Sea Drilling Project (DSDP) Leg 28, Site 270 in the central Ross Sea [*Hayes and Frakes*, 1975] and the Cenozoic Investigation of the Ross Sea core at the southern end of McMurdo Sound (CIROS-1 [e.g., *Hannah*, 1994; *Wilson et al.*, 1998]) (Figure 1). The oldest sediments in CIROS-1 are glacial and glacial-marine strata that are early-late Eocene in age [*Barrett*, 1989; *Hannah*, 1997; *Hannah et al.*, 1997; *Wilson et al.*, 1998]. Unfortunately, faulting, unconformities, and shallow water bottom multiples have made the correlation of Eocene and Oligocene strata sampled at CIROS-1 to the VLB and to Cape Roberts uncertain [*Bartek et al.*, 1996; *Henrys et al.*, 1998]. Despite the previous drilling efforts, little is known about the time period between 160 and 45 Ma [*Barrett et al.*, 1995; *Bartek et al.*, 1996]. No rocks or sediments of this age have been sampled in the TAM or in other parts of East Antarctica [*Davey*, 1987; *Barrett et al.*, 1995].

The lack of stratigraphic control in the western Ross Sea has recently been addressed by the drilling efforts of the CRP. Over 1500 m of strata representing the period from 16 to ~34 million years ago have been recovered in three drill holes. More than 750 m of core were obtained from CRP-1 (oldest material Miocene) and CRP-2/2A (oldest material Oligocene) drill sites, positioned on the thick sea ice offshore Cape Roberts [*Barrett et al.*, 1998, *Fielding and Thomson*, 1999] (Figure 1) . The third site, CRP-3, drilled in November 1999, penetrated rocks interpreted as Paleozoic Beacon sandstone below Oligocene and latest Eocene (?) sedimentary rocks [*Cape Roberts Science Team*, 2000].

TECTONICS		UNIT COOPER ET AL. [1987]; this paper	AGE (from CRP-1, 2/2A -3)	BARRETT ET AL. [1995]	BARTEK ET. AL. [1996]	FACIES/COMMENTS
NW-SE rifting	Strike-slip faulting Decreased uplift in TAM; Volcanism	V3	< 21.2 Ma Miocene	V3	P/Q	Glacial marine sediments. Evidence of glacial scouring in seismics.
	90 mbsf CRP-2/2A					Unconformity
	Decreased uplift in TAM; Volcanism	V4a	23.7 - 24.1 Ma Late Oligocene		R	Glacial marine sediments. Volcanics and pumice tuff and detritus derived from granite basement
	307 mbsf CRP-2/2A; end of tilting					Angular Unconformity (above 24.1 Ma - ? below)
Progressive tilting	fault block tilting and rotation.	V4b	Late Oligocene ?	V4	S	Glacial marine sediments. Detritus from Jurassic dolerites and lavas Angular unconformity at top and onlap surface at base.
	443 mbsf CRP-2/2A					Unconformity RSU-6? (? above - 29 Ma below)
	E-W rifting Increased uplift in TAM	V5a	29 - 32? Ma Early Oligocene		T?	Glacial marine sediments. Oldest strata sampled by CRP-2/2A. No seismic evidence for angular unconformities
	330 mbsf CRP-3 ?					
	E-W rifting Increased uplift in TAM	V5b+V5c	Latest Eocene - ?	V5	?	Sandstone, conglomerate Sampled in CRP-3 ? Sampled in CIROS-1?
	Pull-aparts,	V6	Late Oligocene to Recent	V6	—	Volcanics
	Pre and syn-Gondwana breakup	V7a+V7b	≥Jurassic	V7	—	Sedimentary (Beacon), volcanic & igneous & metamorphic basement rocks

Figure 2. The stratigraphic units interpreted offshore Cape Roberts, Antarctica, based on our interpretation of Cape Roberts drilling results and the NBP9601 reflection seismic data [modified from *Hamilton et al.*, 1998]. A comparison is made to the nomenclatures developed by *Cooper et al.* [1987], *Barrett et al* [1995], and *Bartek et al.* [1996] based on interpretations in southern Victoria Land and the western Ross Sea. Ages and geologic descriptions for the V units are from *Cooper et al.* [1987] and the Cape Roberts reports (see text). V3, V4, and V5 are sedimentary units, V6 is volcanic, and V7 is acoustic basement (undifferentiated).

1.3. Transantarctic Mountains and West Antarctic Rift System

The TAM are a 4000 km long and 4 km high mountain range that was created in a nonconverging plate tectonic setting during Cenozoic time (Figure 1) [e.g., *Davey and Brancolini*, 1995]. The TAM constitute the west shoulder of a major continental rift system, the West Antarctic Rift System (WARS). The WARS also includes the Ross Embayment (Ross Sea rift [*Tessensohn and Worner*, 1991]) and western Marie Byrd Land that comprise an extended region of crust and the eastern rift shoulder, respectively (Figure 1) [e.g., *LeMasurier*, 1990; *Behrendt et al.*, 1991]. The WARS is one of the largest extensional regimes on Earth and is comparable in size to the Basin and Range province of the western United States [*LeMasurier*, 1990]. Much of the WARS lies under an ice sheet, making it difficult to determine the history and current activity in the rift. The WARS is considered active today by many researchers because extensive late Cenozoic volcanism is found here along with a rift shoulder with 4-7 km of relief at its western border along the TAM [*Behrendt et al.*, 1991; *Behrendt and Cooper*, 1991]. Evidence from apatite fission track dating [*Fitzgerald*, 1992, 1994, 1999] suggests that significant exhumation of the TAM in southern Victoria Land began at ~55 Ma. *Fitzgerald et al.* [2000] find evidence for exhumation of the western TAM in southern Victoria Land beginning in mid-Cretaceous time. *Fitzgerald* [1992] estimated the total amount of Cenozoic rock uplift in the TAM to be 6 km allowing for 4.5-5.0 km of erosion along the east side of the TAM.

1.4. Cape Roberts

Cape Roberts is located in southern Victoria Land at the foot of the TAM Front, described by *Barrett et al.* [1995] as a 30 km wide zone of faults bordering the edge of the uplifted crustal block of the TAM. The bathymetry offshore Cape Roberts consists of the V-shaped (in map view) trough that we interpret as a graben, the Cape Roberts Rift Basin (CRRB; Figure 3). This 400-500 m deep trough is bounded by the foothills of the TAM to the west and by Roberts Ridge, a 100 m deep bathymetric high ~15 km offshore [*Barrett et al.*, 1995; *Bartek et al.*, 1996]. The three drill holes of the Cape Roberts Project, CRP-1, CPR-2/2A, and CRP-3, are located on

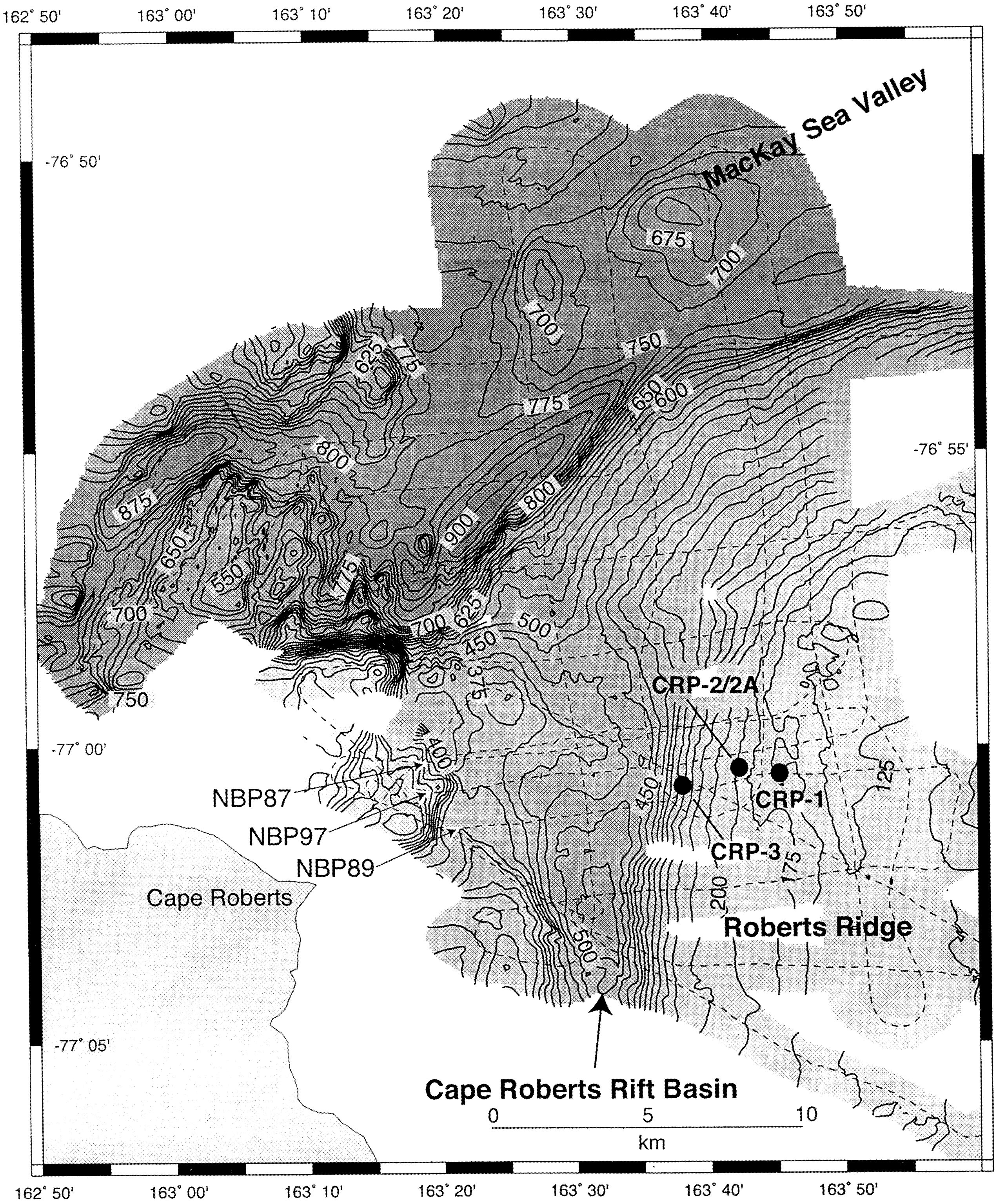

Figure 3. A high-resolution, shaded relief bathymetric map from SeaBeam 2112 data showing the *N. B. Palmer* ship track during the NBP9601 Ross Sea expedition. Roberts Ridge, a bathymetric high on the eastern margin of the survey area, the MacKay Sea Valley, a deep glacially scoured trough to the north, and the Cape Roberts Rift Basin, a V-shaped bathymetric low, are prominent features of the study area offshore Cape Roberts. The CRP-1, CRP-2/2A, and CRP-3 drilling sites are shown along with locations of seismic lines 87, 89, and 97. (The color versions of this and the seismic reflection figures are available on the web at the UCSB Cape Roberts research website, http://www.crustal.ucsb.edu/caperoberts.)

Roberts Ridge (Figures 2 and 3). The Pleistocene age MacKay Sea Valley truncates the CRRB to the north in Granite Harbour. Bathymetric depths range from 100 m along the eastern and western margins of the CRRB to depths of over 1000 m in the MacKay Sea Valley.

Along the coast at Cape Roberts, Late Precambrian foliated and nonfoliated gneissic granites form the basement rocks of TAM. These were deformed during the early Paleozoic Ross orogeny [see *Stump*, 1992]. The basement is separated from overlying Devonian to Triassic terrestrial sedimentary rocks of the Beacon Supergroup [see *Woolfe and Barrett*, 1995] by the Kukri Peneplain, a regional erosion surface found in the TAM except for northern Victoria Land [*Barrett et al.*, 1972; *Gunn and Warren*, 1962]. Basement rocks are intruded by Ordovician Granite Harbour Intrusives (granites). The Beacon Supergroup is intruded by distinctive tholeiitic Jurassic Ferrar Dolerite sills and overlain by the equivalent Kirkpatrick Basalt [*Gunn and Warren*, 1962; *Fitzgerald*, 1992; *Barrett et al.*, 1995]. The sills and basalts mark a major igneous event at ~177± 2 Ma [*Heimann et al.*, 1994], corresponding to the initial stages of Gondwana supercontinent breakup in Jurassic time. The (late) Cenozoic McMurdo alkali volcanics [*Kyle*, 1990] are found 80-150 km to the east and south of Cape Roberts at the south end of the Terror Rift. Igneous intrusions are interpreted along the west side of the CRRB that may be part of this series [*Hamilton et al.*, 1998; *Bozzo et al.*, 1997a, 1997b].

The NBP9601 geophysical data, combined with the results from the CRP holes, allow interpretations of the stratigraphic and structural relationships offshore of the TAM at Cape Roberts. We propose that a series of tectonic events, commencing with increased uplift in the TAM and E-W extension in the western Ross Sea, influenced the evolution of the CRRB and Roberts Ridge.

2. Seismic Reflection Data

Two hundred-fifty kilometers of MCS and SCS data were recorded simultaneously by firing alternating sources every 5 s. The MCS source consisted of five 3.44 L generator/injector (GI) air guns. Data were recorded on 44 live channels (out of 48), with hydrophone group spacing at 25 m and a maximum shot group range of 1420 m. Shots were equally spaced at 25 m to result in 22-fold stacks. One 3.44 L GI air gun was used as the source for the SCS data. GPS was used for navigation throughout the survey.

The suppression of strong water bottom multiples was the main goal in processing the seismic data. Velocity analyses were done every kilometer. A frequency-wave number (*F-K*) filter was applied after a partial normal move out (NMO) correction using velocities intermediate between the primary and multiple arrivals. After predictive and spiking deconvolution, both ordinary and median amplitude stacks were created. The median amplitude stacks were effective at removing multiple energy but degraded the data above 0.5 s two-way travel time (TWTT). In some cases an *F-K* migration at 1460 m/s was performed post-stack, and a split-step migration [*Stoffa et al.*, 1990] was performed (done on line 97). Both of these migrations were used to aid in interpreting the data on a line by line basis. However, the *F-K* migration could not handle reflections from the complex structures within the CRRB. Typically, the split-step migration resulted in the overmigration of reflections. Because higher frequencies are spatially aliased during *F-K* filtering, a 6-50 Hz or 6-40 Hz band-pass filter was applied to all of the final displays.

In general, there are significant problems with the data, especially reflection data from shallow water depths. This is due in part to a noisy near trace and dead third trace or to a problem in synchronizing gun firing. The fact that only near traces can be used at small travel time due to NMO stretch also made the removal of multiples in shallow water very difficult. Because stacking velocities increase for a particular interval velocity structure by 1/cosine of the dip angle [*Yilmaz*, 1987], it is difficult to choose accurate velocities for local moderate or steep dips within the CRRB.

3. Interpretations of Stratigraphy for Offshore Cape Roberts

All available MCS and SCS data (NBP9601, RV *Polar Duke* (1990), Osservatorio Geofisico Sperimentale (OGS) (1990) and U.S. Geological Survey (USGS) (1984)) were used to correlate the seismic V sequences from the VLB to the CRP drill sites on Roberts Ridge [*Davey et al.*, 2001]. This effort resolved the ambiguities in seismic stratigraphy on Roberts Ridge pointed out earlier by *Henrys et al.* [1998]. The seismic reflections were correlated to the drilling results by computing synthetic seismograms using velocity data from hole CRP-2 [*Henrys et al.*, 2001] and vertical seismic profiles in CRP-3 [*Cape Roberts Science Team*, 2000].

In our study we identified the V3-V5 and V7 sequence boundaries of *Cooper et al.* [1987] according to new interpretations of seismic data on Roberts Ridge [*Davey et al.*, 2001]. We defined a series of subsequences (V4a, V4b, V5a, V5b, V5c, V7a, and V7b) on the basis of high-amplitude reflections that show distinct characteristics and/or bound seismic sequence stratigraphic units (Figure 2).

3.1. V3/V4a Boundary

Our V3/V4a boundary was sampled by CRP-2/2A and dated at ~21 Ma [*Fielding and Thomson*, 1999]. In the northern part of the study, V3 onlaps V4a, and both units show evidence for glacial erosion.

3.2. V4a/V4b Boundary

We interpret the V4a/V4b boundary as an angular unconformity that coincides with an abrupt change in "clast and grain parameters" at 307 m below seafloor (mbsf) in the CRP-2/2A core hole [*Fielding and Thomson*, 1999; *Smellie et al*, 1999]. *Henrys et al.* [2001] present a synthetic seismogram where top V4b is interpreted at 270 mbsf in CRP-2/2A. This conflict is explained if their seismic correlation is one cycle too shallow. Drilling results date the oldest sediments above the 307 mbsf unconformity separating V4a and V4b in CRP-2/2A as 24.1 Ma [*Cape Roberts Science Team*, 2000]. The youngest dated sediments below the V4a/V4b boundary are in V5a and are ~29 Ma (Figure 2) [*Cape Roberts Science Team*, 2000]. On Roberts Ridge the V4a/V4b unconformity reflection onlaps the V4b/V5a boundary to the west (Figure 4).

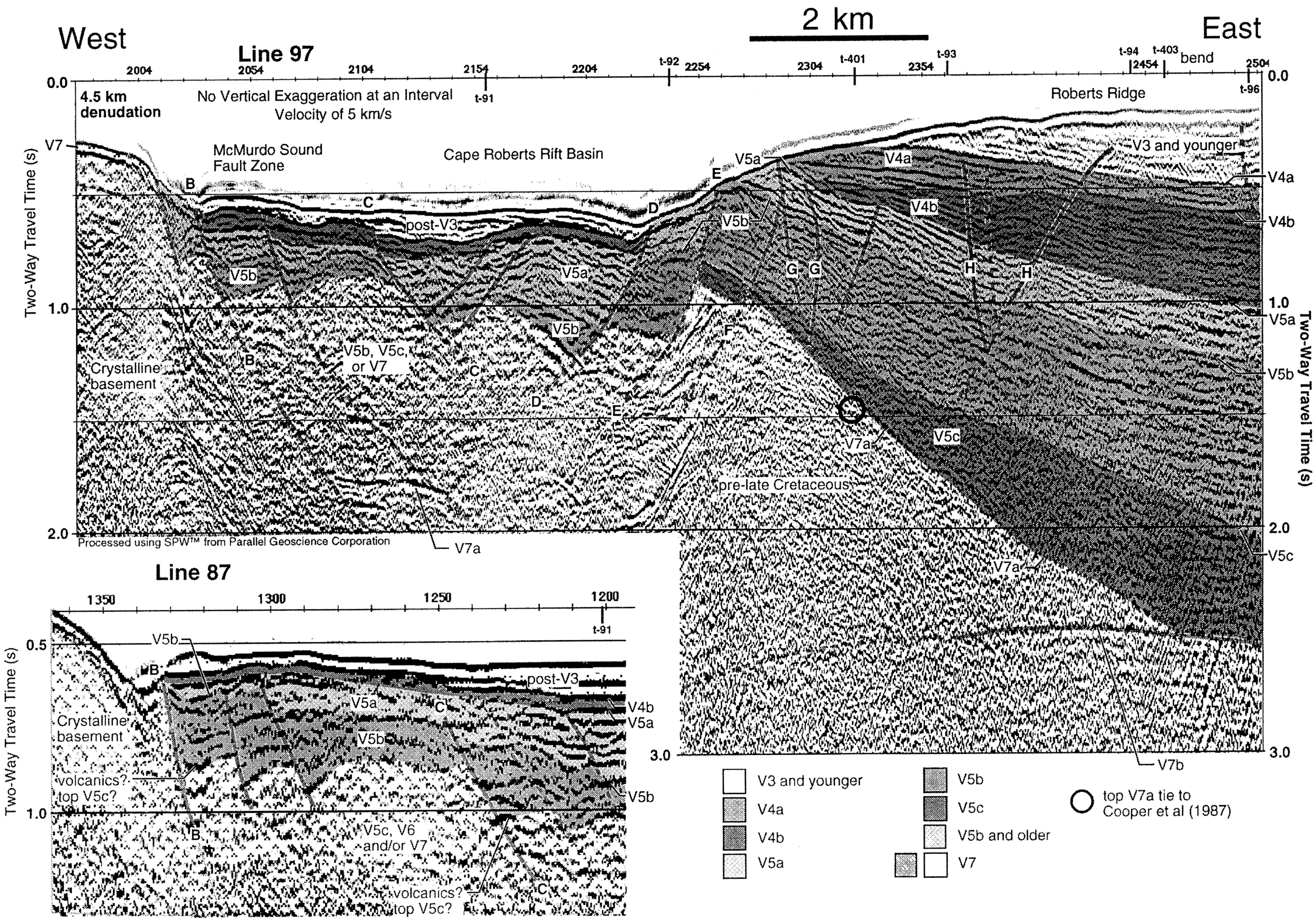

Figure 4. Nonmigrated E-W part of line 97 and part of line 87 (located on Figure 6). Line 87 is shown at 150% of the scale of line 97. An ordinary stack above 0.5 s two-way travel time (TWTT) was merged with a median amplitude stack below 0.5 s. Letters identify faults on the seismic profiles that correlate to Figures 5-7. Tie points are indicated with a "t." The circle below t-401 shows the tie to top V7 on USGS-401 of *Cooper et al* [1987]. The V7b "basement" reflection at 2.45 s TWTT can be correlated along line NBP9601-94 to a very strong reflection at 2.6 s TWTT on line IT-69 [*Davey et al.*, 2000]. Top V7a acoustic basement could lie anywhere within the light gray sequence interpreted below V5b in Cape Roberts Rift Basin. The high-amplitude reflection on line 87 between 1.0 and 0.9 s TWTT may be volcanics within V5b or an unconformity, or, between faults B and C, it might be Beacon "basement." (The color versions of this and the other figures of the seismic reflection data are available on the web at the UCSB Cape Roberts website, http://www.crustal.ucsb.edu/caperoberts.)

3.3. V4b/V5a Boundary

Unit V4b thickens toward the east into the VLB. It is separated from V5a by a sequence boundary that is an onlap surface corresponding to 443 mbsf in CRP-2/2A and to the late-early Oligocene boundary [*Fielding and Thomson*, 1999]. *Davey et al.* [2001] interpret the V4b/V5a boundary as RSU6, a regional sequence boundary defined in the Eastern Basin by *Hinz and Block* [1984]. RSU6 is older than 26 Ma, where it was first defined in the Eastern Basin near DSDP 270 [*Hayes and Frakes*, 1975]. Unit V5a crops out at the seafloor on the western side of Roberts Ridge and gradually thickens eastward, similar to V4b. The oldest strata sampled by CRP-2/2A were within the V5a unit and were dated at > 29 Ma (early Oligocene [*Cape Roberts Science Team*, 2000]). Hole CRP-2/2A reached 624 m below seafloor.

3.4. Subdivisions of V5

We subdivide V5 into subunits V5a, V5b, and V5c, separated by strong reflections. Unit V5 is several kilometers thick in the VLB, and these subdivisions allow us to discuss the timing of initial erosion in the TAM and deposition in the VLB. The velocity and two-way travel times derived by the *Cape Roberts Science Team* [2000] indicate that the reflection at the top of V5b may be an increase in velocity at a conglomerate bed near 100 mbsf in CRP-3 (their reflector "p"). It is difficult to trace the top V5c reflection to CRP-3, but it may be the top of high seismic velocity conglomerates near 770 mbsf in CRP-3 (*Cape Roberts Science Team* [2000] their reflector "w"). The V5b and V5c strata (Figure 5) thicken east toward the western VLB, where deformation of V5b is limited to gentle tilting and minor (300 m or less) separations across high-angle faults [e.g., *Cooper et al.*, 1987].

3.5. Correlation to Cape Roberts Rift Basin

The numerous unconformities, faults, and igneous intrusions offshore Cape Roberts made it difficult to correlate seismic reflections continuously across the CRRB. We interpret the reflective sequences in the upper 150 ms TWTT in the southern part of the CRRB to be a veneer of Quaternary (?) glacial sediments. A thin remnant of more reflective V4b strata is bounded above and below by unconformities in the CRRB. We correlate high-amplitude reflections seen below these sequences to be the eroded top of the V5a unit (Figure 5). The V5b unit can be traced into the basin across the west dipping faults on Roberts Ridge; however, this unit is poorly imaged. *Cooper et al.* [1987] have also interpreted V5 (undifferentiated) in the CRRB. We are unsure where top V5c is in CRRB, so we do not attempt to differentiate it there.

3.6. Acoustic Basement, V7a and V7b

Reflections from acoustic basement are seen under Roberts Ridge and in the CRRB (Figures 4 and 5). *Cooper et al.* [1987] interpreted an acoustic basement reflection (V7) as the Beacon Supergroup offshore Cape Roberts. They interpret V7 between 2.5 and 2.8 s TWTT beneath CRRB and beneath the crest of Roberts Ridge at 1.4 s TWTT. This V7 reflection, which is seen at the intersection of seismic lines USGS-401 and 403, is on strike with the location of CRP-3 (location in Figure 6). V7 picked on the USGS lines ties to a reflection just above 1.5 TWTT on NBP9601 line 97 at shot point 2320. We label this reflection as V7a. CRP-3 bottomed in sandstone interpreted as Devonian Arena Sandstone of the Beacon Supergroup [*Cape Roberts Science Team*, 2000]; this is V7a. The contact of the Beacon (V7a) with overlying Oligocene (?) conglomerate units at 823 mbsf is an erosional unconformity [*Cape Roberts Science Team*, 2000]. We identify another basement reflection, V7b, under the east flank of Roberts Ridge at 2.4-2.5 s TWTT (Figure 4). The reflection character of V7a and V7b are distinctly different. Although both are acoustic basement reflections, they are not necessarily the same geologic unit. V7b on line 97 ties to a reflection on cross line NBP9601-94 (Figure 6) that in turn ties to a reflection interpreted as acoustic basement on IT-69 by *Davey et al.* [2001]. Therefore we believe our interpretation of this reflection is robust. A reflection at 1.8 s TWTT in CRRB may be Beacon (V7a, Figure 4), but this is much shallower than the interpretation of V7 by *Cooper et al.* [1987]. This reflection could be from volcanic units (V6) instead.

4. Interpretations of Structure Offshore Cape Roberts

Our interpretations from the NBP9601 seismic reflection data suggest the presence of three distinct fault trends: north to NNW striking and NNE striking normal-separation faults bordering the CRRB, and ENE striking faults, crosscutting the graben and Roberts Ridge. A fault map on the top of V4b is shown in Figure 6. Some of the faults shown in Figures 4 and 5 are not mapped in Figure 6 because these faults do not offset V4b.

4.1. North to NNW Striking Faults

The major north and NNW striking (labeled A, B, and C) and NNE striking (D and E) normal faults dip toward the CRRB and define its V shape in map view (Figure 3). These faults were not mapped in the glacially eroded trough of the MacKay Sea Valley due to the lack of E-W seismic profiles

Figure 5. Parallel E-W seismic profiles across the escarpment separating Roberts Ridge (RR) and the Cape Roberts rift basin. Line 87 is the northernmost, and line 89 is the southernmost (Figure 6). NNE striking, west dipping normal-separation faults including "D" and "E," and NNW striking flower structures presumed to be right-lateral faults (e.g., "G") are shown. Beneath Roberts Ridge the V3/V4a boundary is locally scoured, and there is a local angular unconformity within V4a; V4a/V4b is an angular unconformity, and V4b/V5a is a subtle onlap surface on these profiles. For line 97, "TB" points to a tilted block, and "FPR" points to a non migrated, west dipping fault plane reflection. Projected location of drill holes CRP-1 and CRP-2/2A and CRP-3 are shown on line 89 (bottom). The west dipping fault F is from *Hamilton et al.*, [1998]. This fault is not mapped in Figure 6 because it does not cut the top of V4b, and its vertical separation deeper in the section is uncertain.

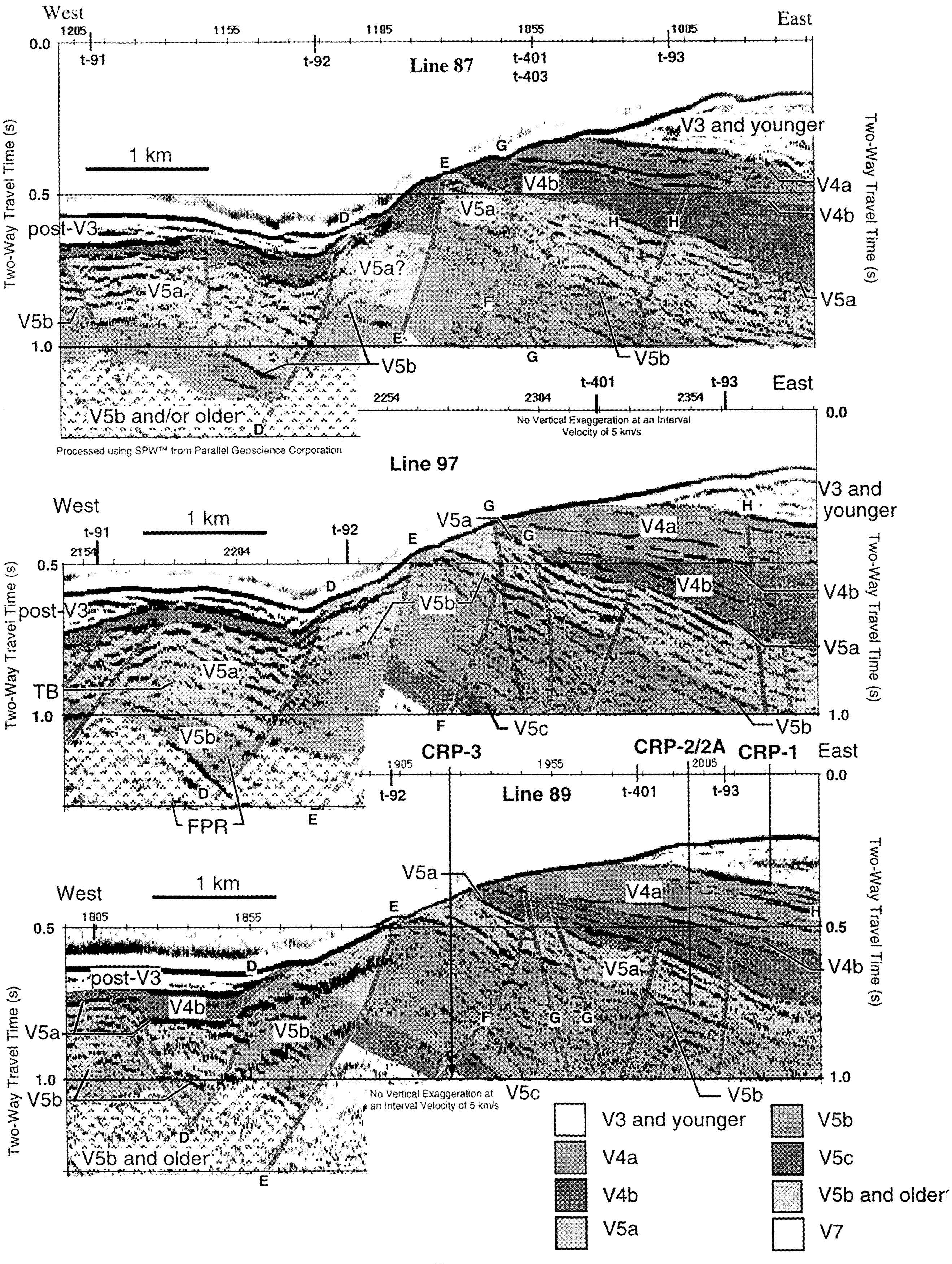
West
East
1205
1155
1105
1055
1005
0.0
t-91
t-92
Line 87
t-401
t-403
t-93
V3 and younger
1 km
G
E
V4b
V4a
0.5
V5a
V4b
post-V3
D
H
H
V5a?
V5a
V5a
V5b
F
E
1.0
G
V5b
V5b
V5b and/or older
D
Processed using SPW™ from Parallel Geoscience Corporation
t-401
t-93
East
2254
2304
2354
0.0
No Vertical Exaggeration at an Interval Velocity of 5 km/s
Line 97
V3 and younger
West
G
H
1 km
V5a
G
V4a
t-91
t-92
E
2154
2204
0.5
D
V5b
V4b
V4b
post-V3
V5a
V5a
TB
1.0
F
V5c
V5b
1.0
V5b
D
FPR
E
CRP-3
CRP-2/2A
CRP-1
East
1905
1955
2005
0.0
t-92
Line 89
t-401
t-93
V5a
West
1 km
V4a
E
1805
1855
0.5
H
0.5
D
V5a
V4b
post-V3
V4b
V5a
V5b
F
G
G
1.0
1.0
V5b
No Vertical Exaggeration at an Interval Velocity of 5 km/s
V5c
V5b
D
V5b and older
E
Two-Way Travel Time (s)
V3 and younger
V5b
V4a
V5c
V4b
V5b and older
V5a
V7

Figure 5.

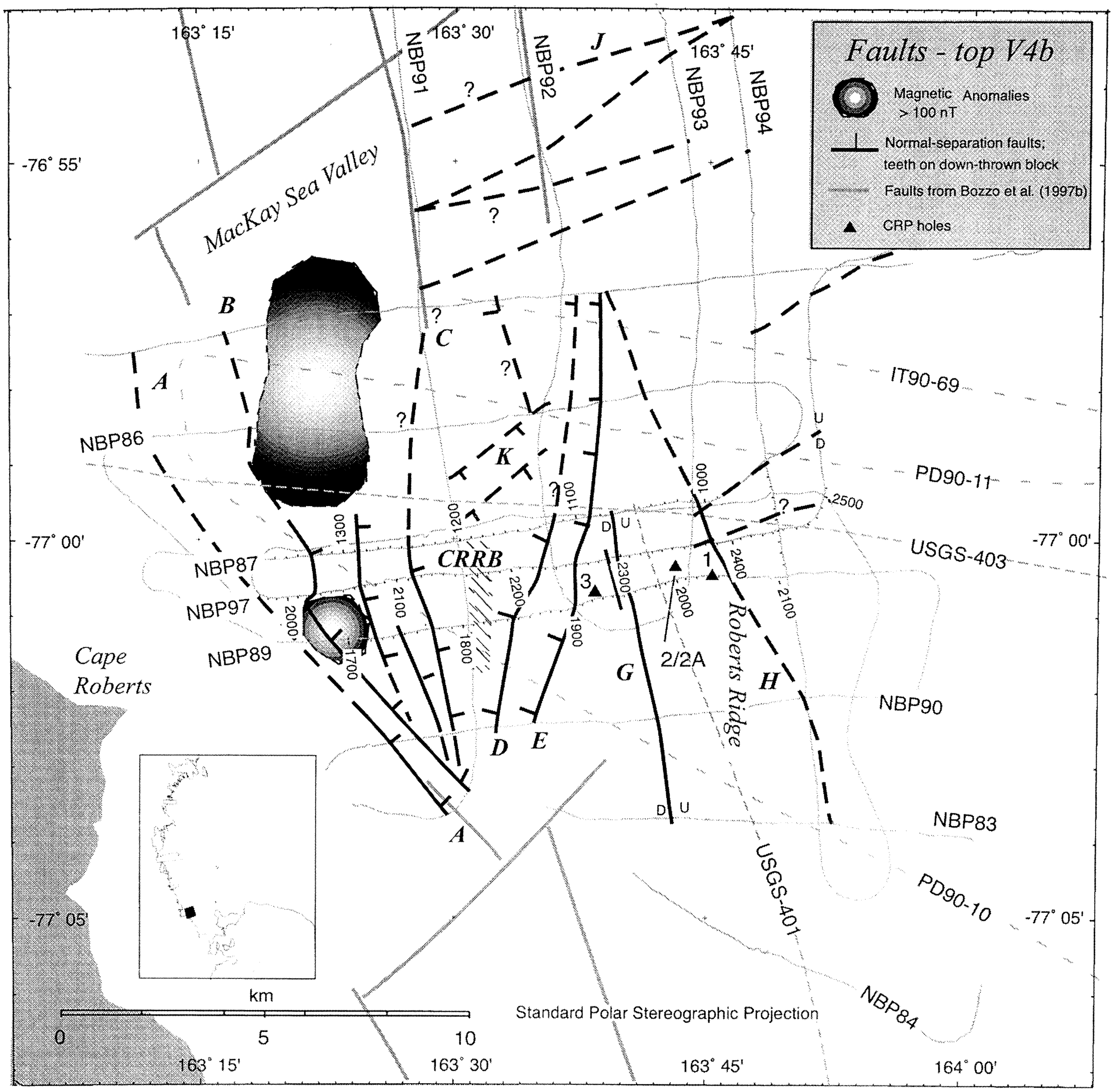

Figure 6. Fault map on top of seismic unit V4b. Shot points are shown for seismic sections displayed in Figures 4 and 5. Two fault systems striking N-NNW (A, B, and C) and NNE (D and E) outline the V shape of the Cape Roberts Rift Basin (CRRB). A set of ENE striking faults (J and K) crosses the basin and aligns with right offsets in the NNW striking faults on the west side of the CRRB, where magnetic anomalies are also present. A complex zone of faults that cannot be mapped with this line spacing is indicated by the hatched region between faults C and D. Also shown are seismic lines IT90-69, PD90-10, PD90-11, and USGS-401 and USGS-403 that are mentioned in the text. The location of Cape Roberts Drilling Project holes 1, 2/2A, and 3 are shown. Shaded lines are faults proposed by *Bozzo et al.* [1997a, 1997b] from aeromagnetic interpretations.

there. However, aeromagnetic data can be interpreted to extend the N-NNW faults across this valley [*Bozzo et al.*, 1997a, 1997b]. Closely spaced east and west dipping faults (Figures 4 and 5) break the crustal block between faults C and D in the CRRB. Our line spacing is not close enough to trace these faults along their strike. We mapped two NNW striking high-angle fault systems on Roberts Ridge (G and H, Figures 5 and 6). Fault G is mapped between CRP-2/2A and CRP-3 and is steeply east dipping. It offsets V4a on line 83 [*Hamilton et al.*, 1998, their Figure 3]. Unit V3 is not present at fault G, so it is not known if it has displaced younger units. However, V3 shows a minor separation across fault H (Figure 4).

Although both the east and west margins of the CRRB are bounded by normal faults, the structural styles vary across the graben. The west side of the basin is bound by steeply dipping, NNW striking, normal-separation faults that juxtapose acoustic basement on the west against stratified units in the CRRB (for example, fault "B", lines 87 and 97, Figure 4).

4.2. NNE Striking Faults

NNE striking faults separate Roberts Ridge from the deepest part of the CRRB (Figures 6 and 7). The vertical separation of the top of V5b across these faults is over 800 m on line 97 using an average sediment velocity of 3 km/s. Post-V4b strata are eroded from the lower flank of the west margin of Roberts Ridge. This precludes identifying the timing of later activity on these faults. A series of NNE striking, west dipping faults are interpreted between the locations of CRP-2/2A and CRP-3. These faults are interpreted to be truncated at the top of V4b and to have only 10-50 m vertical separation of reflectors within V5a [*Davey et al.*, 2001]. One of these faults is shown by *Hamilton et al.* [1998], with an uncertain interpretation of its importance (fault F, Figures 4 and 5). We retain this ambiguity; these faults do not significantly offset V5a (Oligocene) and younger units, but we cannot interpret the amount of separation of older strata across them. Fault F may have been drilled by CRP-3, where ~34 Ma conglomerate was recovered both above and below it [*Cape Roberts Science Team*, 2000]. If V5c is this conglomerate, then fault F has limited vertical separation on it (Figure 5, line 89).

4.3. ENE Striking Faults

We interpret a third set of faults striking ENE across the CRRB and Roberts Ridge. Within the CRRB, these faults have up to 0.2 s TWTT down to the south separation of V5b. Across Roberts Ridge, any separation of the top V4b and of reflections within early Miocene V4a cannot be resolved. The larger of these faults (K in Figure 6) projects southwest to align with right offsets in the NNW striking escarpment on the west wall of the CRRB. An ENE striking fault at the north end of the CRRB coincides with a steep bathymetric slope associated with the south rim of the MacKay Sea Valley (J in Figure 6). Our seismic interpretations suggest that the ENE striking faults offshore Cape Roberts align to both the ENE striking New Glacier Fault [*Gunn and Warren*, 1962] and the ENE trending MacKay Glacier Fault onshore (Figure 1).

Two intrusive bodies are interpreted on the western margin of the CRRB where right steps are present in the NNW striking faults (Figure 6). These interpretations are based on magnetic field data from the NBP9601 cruise that show anomalies here that are >100 nT. A similar pattern of right-stepping NNW to NW striking faults and ENE striking faults was interpreted by *Bozzo et al.* [1997a, 1997b] on the basis of aeromagnetic data (Figure 6).

5. Discussion: Structure and Tectonics Offshore Cape Roberts

5.1. McMurdo Sound Fault Zone

The prominent NW and NNW striking faults mapped along the western side of the CRRB parallel the Transantarctic mountain range. We believe that the NW and NNW striking faults on the west side of the CRRB played the major role in TAM uplift in this area (Figure 6, faults A, B, and C). Crystalline basement is exposed at the coast at Cape Roberts. Acoustic basement on the CRRB flank at the west end of the NBP9601 seismic profiles is assumed also to be crystalline (Figure 4). Acoustic basement in the CRRB, or top V7, which was interpreted by *Cooper et al.* [1987] to be Paleozoic sedimentary rocks of the Beacon formation, is identified by them at between 2.5 and 2.8 s TWTT on line USGS-403 (Figure 6). The range in reflection depths to V7 (our V7a) in the southern CRRB is 1.8 s TWTT (see section 3.6) to 2.8 s TWTT [*Cooper et al.*, 1987]. Average interval velocities for V5a in CRP-2/2A range from 2.4 to 3.7 km/s [*Henrys et al.*, 2001] and are similar for V5b in CRP-3 [*Cape Roberts Science Team*, 2000]. Using the interpretation of *Cooper et al.* [1987] and these velocities and allowing for travel time in the water layer, the depth of basement beneath CRRB ranges between 1.9 and 4.5 km. Assuming that V7 of *Cooper et al.* [1987] is the top of Beacon sedimentary rocks and adding 4.5 km of denudation in the TAM calculated from fission track data by *Fitzgerald* [1992] nearby at Cape Roberts gives a vertical offset for these rocks in the CRRB of between 6.4 and 9.0 km, or greater if the interval velocity of overlying unit V5 is greater.

Considering that few if any NNW striking normal faults have been mapped onshore in the TAM Front here [*Wilson*, 1995; *Turnbull et al.*, 1999], we infer that this vertical separation occurred across the NNW striking faults A, B, and C in the CRRB alone. Whether similar fault systems exist elsewhere along the entire TAM Front is not fully known. *Barrett et al.* [1995, Figure 3] show a map that indicates similar faults on trend with the NW and NNW faults we mapped both north and south of Cape Roberts, encompassing 150 km length. The fault system extends south of the Ferrar Glacier near CIROS-1 (Figure 1). We recognize this fault set as a major feature controlling the uplift of the TAM and here name it the McMurdo Sound Fault Zone. We interpret that activity on the McMurdo Fault Zone likely began no earlier than latest Eocene time (see section 5.3).

This structure could be similar to an unnamed fault zone mapped along the TAM Front near 85°30'S by *Barrett* [1965]. He estimated 3-5 km of vertical separation on this fault. *Salvini et al.* [1997, Figure 3] show a major normal fault that follows the coast from the south end of McMurdo Sound north to where it buts into the Priestly Fault in Terra Nova Bay in northern Victoria Land (~270 km north near 74°30'S). They show seismic line IT90AR-64 crossing this fault near 75°S [*Salvini et al.*, 1997, Figure 5] where it displays offset of late Cenozoic strata. They point out that north trending faults like this one in the western Ross Sea faults are older than late Cenozoic and have been reactivated in places. Without further study it is not clear if this fault and those mapped by others are the same as the McMurdo Fault Zone we show here.

Besides the McMurdo Sound Fault Zone, there is evidence for a possible detachment fault zone under Roberts Ridge in the form of a subhorizontal reflection (V7b) beneath 2.4 s TWTT on line 97 (Figure 4). This reflection can be tied to line 94 and IT-69 as we mentioned above. The thermal model for uplift of the TAM, proposed by *Stern and Ten Brink* [1989], requires the presence of a master set of NNW striking TAM-parallel normal faults, while the model of *Fitzgerald et al.* [1986] allows for a family of normal faults along the TAM front above a west dipping detachment. Our observations alone cannot distinguish between these proposals. However our seismic data support the existence of both fault systems. We interpret the reflections from the top of V7a (Beacon sandstone) to dip to the east-northeast and to intersect the top of the acoustic basement reflection V7b beneath Roberts Ridge (Figure 4). We suggest that reflection V7b represents a low-angle upper crust detachment fault that extends to the west and controls movement on the west dipping NNE striking faults along Roberts Ridge. What is not seen is the relation between this interpreted detachment and the McMurdo Sound Fault Zone, which cuts which, or if the McMurdo Sound Fault Zone includes the breakaway fault for the detachment. There may be other detachments at deeper structural levels beyond the resolution of the seismic data.

5.2. Oblique Rifting in Western Ross Sea

We propose that there is structural evidence at Cape Roberts and in the CRRB for Cenozoic oblique rifting along the western Ross Sea margin. Striated fault surfaces in southern Victoria Land and onshore Cape Roberts [*Wilson*, 1995] indicate NW-SE extension, requiring oblique rifting along the NNW striking TAM Front. Evidence for Cenozoic oblique rifting in the Ross Sea is shown by dextral offsets of prominent N-S trending basins across NW-SE striking faults [e.g., *Salvini et al.*, 1997]. Further, the NNW and NNE striking fault patterns offshore Cape Roberts resemble faults in analogue models and field examples of faulting in highly oblique rift systems [*Withjack and Jamison*, 1986; *Tron and Brun*, 1991; *Chorowicz and Sorlien*, 1992; *Clifton et al*, 2000; *Withjack et al.*, 1999]. There is a similarity between the orientation of the NNE and ENE striking faults offshore to those mapped onshore [*Wilson*, 1995]. The fact that our mapped NNE striking faults offset Oligocene strata (V4b and V5, Figure 4) supports *Wilson*'s [1995] interpretation that the striations along similarly oriented fault trends in the TAM Front are Cenozoic in age.

The ENE striking faults on Roberts Ridge (north of line 86, Figures 6 and 7) cut the early Miocene unit V4a with minor separation and therefore continued to be active later than the minor NNE striking faults located between CRP-2/2A and CRP-3 (e.g., fault F in Figure 5). However, these younger strata are eroded from above the major NNE striking faults D and E, so there are no firm constraints on the timing of activity on these faults that have larger separation. Although we know that there was only minor tilting of V4a in the footwall of these faults, we cannot rule out (minor) Miocene activity on them. *Hamilton et al.* [1998] interpret the ENE striking faults as left-oblique transfer faults linking NNW striking faults that parallel the TAM Front (A, B, and C) to faults east of Roberts Ridge that are presently unmapped. *Fitzgerald* [1992] proposed that transfer faults might set up major outlets for glaciers that cut the TAM.

Salvini et al. [1997] made the observation that Cenozoic volcanoes developed at steps in the trends of NW-SE right-lateral faults along the western Ross Sea margin. At Cape Roberts, magnetic anomalies occur on the western margin of the CRRB associated with right steps in the major NNW striking faults (Figure 6) [*Bozzo et al.*, 1997a, 1997b]. We interpret that these right steps occur at intersections of ENE-striking faults. The right steps in the NNW striking right-lateral faults are interpreted as releasing bends or pull-aparts where crustal extension has been localized [*Crowell*, 1974]. Magma has ascended where a pull-apart motion occurred during late Oligocene to early Miocene oblique rifting. The CRP-2/2A drill site encountered volcanic ash layers dated at 21.44 ± 0.005 and 24.22 ± 0.06 Ma by the ^{40}Ar/^{39}Ar method [*Fielding and Thomson*, 1999]. We suggest that the late Oligocene and early Miocene volcanic detritus sampled in CRP-2/2A reflects volcanism during oblique rifting in the western Ross Sea.

Our model for the formation of Roberts Ridge and the CRRB (Figure 8) suggests that the NNW striking faults on the western side of the basin represent a breakaway zone of the TAM Front. The NNE striking faults delimit individual east tilted fault blocks within an extended rift. NNE striking faults may have accommodated a minor clockwise vertical axis block rotation typical to dextral oblique rifts [*Luyendyk*, 1991; A. Clifton and M. Withjack, oral communication, 1999]. This structural model is consistent with a NW-SE oriented dextral transtensional shear regime involving NNW-SSE oblique right-lateral faults, NNE striking normal faults, and ENE striking left lateral faults [e.g. *Wilson*, 1995].

5.3. Age and Stratigraphic Control for Victoria Land Basin

The correlation of seismic reflections from the VLB to the drill sites CRP-1 and CRP-2/2A on Roberts Ridge by *Davey et al.* [2001] shows that the V3-V5 sequences are much younger in age than originally interpreted by *Cooper et al.* [1987]. This indicates that much of the fill of the VLB is also younger than thought. The uplift and denudation of the TAM near Cape Roberts began at 55 Ma [*Fitzgerald*, 1992], so late Eocene sedimentation rates may be as high as Oligocene rates documented at CRP-2/2A. Correlation of the V units from Cape Roberts into the VLB suggests that more than one half of its 14 km of basin fill [*Davey and Cooper*, 1987; *Cooper et al.*, 1987] may be latest Eocene and younger in age [*Davey et al.*, 2001]. The start of major Cenozoic subsidence in the VLB probably coincides with increased uplift of the TAM in the Eocene and is an isostatic response to the load of accumulating sediments in the basin supplied from the TAM [*Stern and Ten Brink*, 1989; *Ten Brink et al*, 1997].

The *Cape Roberts Science Team* [2000] found ~34 Ma breccia and conglomerate in CRP-3 in contact at 823 mbsf with sandstone presumed to be from the lower part of the Devonian Beacon Supergroup known from the TAM. They interpret USGS-403 of *Cooper et al.* [1987] to show that CRP-3 drilled the oldest strata in VLB. They hypothesize that subsidence in this part of VLB did not begin until the end of Eocene time and continued until Miocene time (17-16 Ma), when it stopped. Our interpretation of the beginning of subsidence is different. We interpret much of V5c to onlap the progressively east tilting western flanks of VLB, so that only the youngest part of V5c is present at CRP-3, with the older sediments not being present. *Fitzgerald* [1992] indicates denudation of the adjacent part of the TAM starting at 55 Ma. Material eroded from the TAM and the future site of CRP-3 needs to have been deposited somewhere, and we suggest that this was the VLB. We suggest that Eocene strata are present in V5c within the VLB. We further speculate that initial uplift of

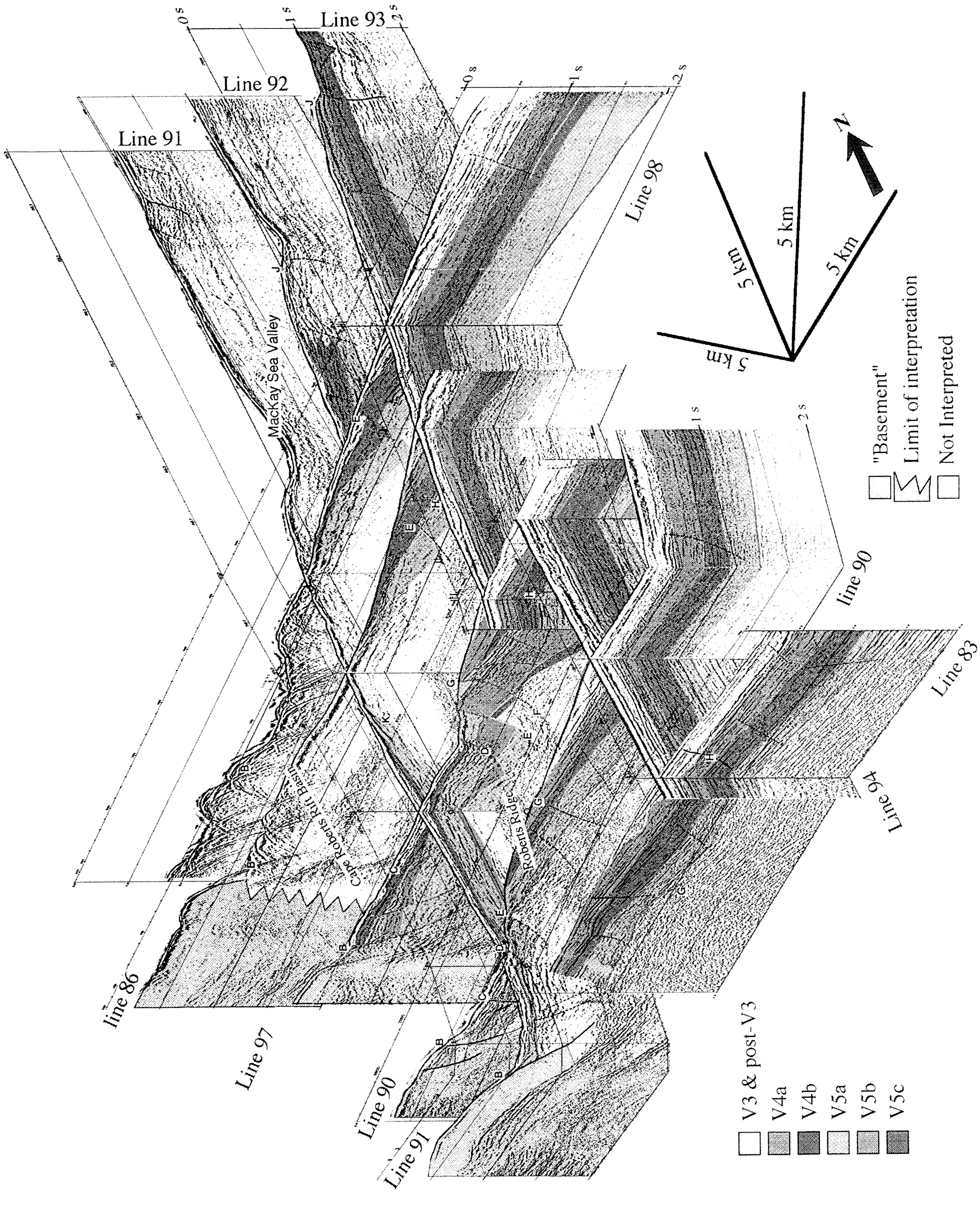
Line 93
Line 92
Line 91
Line 98
line 90
Line 83
Line 94
line 86
Line 97
Line 90
Line 91
0 s
1 s
2 s
Mackay Sea Valley
Cape Roberts Rift Basin
Roberts Ridge
5 km
5 km
5 km
5 km
N
"Basement"
Limit of interpretation
Not Interpreted
V3 & post-V3
V4a
V4b
V5a
V5b
V5c

Figure 7.

the TAM was broad and associated subsidence was displaced east of the future location of the CRP holes on Roberts Ridge (Figure 8a). Perhaps this tectonism was related to slip on a low-angle (detachment) fault sytem originating at the east side of the VLB and extending westward under the TAM. Only later, at the end of Eocene time, did the McMurdo Sound Fault Zone become important, leading to subsidence of the CRP-3 site. Otherwise, if the McMurdo Sound Fault Zone was active earlier, Eocene sediments would have accumulated offshore Cape Roberts.

5.4. Cape Roberts Rift Basin and Uplift of the Transantarctic Mountains

Our seismic interpretations suggest continuous tilting of both latest Eocene and Oligocene strata on Roberts Ridge, inferring uplift of the TAM during this period (Figures 4 and 8). During Eocene-late Oligocene phases of E-W extension in the western Ross Sea the future location of the CRRB was on the west flank of the VLB (Figure 8). Movement on the NNW striking McMurdo Sound Fault Zone could have begun as early as latest Eocene time. We propose that the NNE striking (west dipping) faults were most active in Oligocene time and ceased activity around 24 Ma.

The CRRB became a separate basin during Oligocene time (Figure 8). A thick and laterally extensive occurrence of V4a and V4b units is not seen within the CRRB. This suggests that these stratigraphic units were eroded off during uplift of the TAM or that deposition of these units did not occur in the CRRB. However, it is more likely that these units were deposited in the CRRB and removed from the basin by later glacial erosion (Figure 8).

A detachment fault extending to the west under the TAM Front, possibly related to uplift in the TAM and subsidence in the VLB, may have directly controlled movement of NNE striking faults (Figure 8). We suggest that the increase in tilting of V sequences with increased depth on Roberts Ridge and the presence of strata that thin to the west onlapping onto sequence boundaries represent continued uplift in the TAM into the late Oligocene. The overlying V3 and V4a units above the angular unconformity between V4a and V4b display much less tilting, inferring a decrease in uplift rate in the TAM at the time when they were deposited.

5.5. Rifting and Plate Tectonics

The Cenozoic tectonic history of the CRRB, Roberts Ridge, and the TAM and can be tied to plate tectonic events in the southwest Pacific. At Cape Roberts we believe the significant events are uplift of the TAM during Eocene through late Oligocene time, followed immediately by a change in extension direction from E-W to NW-SE and the formation of the CRRB. The initiation of an Eocene E-W rifting phase has been linked to uplift of the TAM starting at 55 Ma and to changes in the Australian-Antarctic spreading patterns in the northern Ross Sea between 55 and 45 Ma [*Fitzgerald*, 1992; *Davey and Brancolini*, 1995]. Seafloor spreading across the Adare Trough (Figure 1) [*Cande et al.*, 2000; *Stock and Cande*, 1999, 2001] must have affected rifting across the western Ross Sea. Magnetic lineations in the Adare Trough suggest that 180 km of E-W seafloor spreading occurred between 43 and 26 Ma [*Cande et al.*, 2000; *Stock and Cande*, 1999, 2001]. *Cande et al.* [2000] discuss a possible additional 25 km of extension between 53 and 43 Ma using an alternate anomaly interpretation. Adare Trough spreading may have been preceded in the western Ross Sea by extension in early Eocene time that marked the beginning of uplift of the TAM. It seems likely that Adare Trough spreading can account for the events offshore Cape Roberts and the extension implied for the VLB and the large thickness of Oligocene (and older) sediments in it.

An early-middle Cenozoic extension phase has been interpreted in other areas in the Ross Sea [*Marks and Stock*, 1997] that predates unconformity RSU6 [*Hinz and Block*, 1984]. This unconformity is defined as being older than 28-26 Ma in the Eastern Basin [*Busetti and Cooper*, 1994]. *Davey et al.* [2001] interpret the V4b/V5a boundary on Roberts Ridge as RSU6; it is also possible that the V4a/V4b unconformity is RSU6. Nevertheless, the end of Adare Trough spreading corresponds in time with unconformities on Roberts Ridge and, in the case of the V4a/V4b angular unconformity, the end of tilting here and possibly the end of uplift of the TAM (Figure 8). *Behrendt and Cooper* [1991] proposed that uplift of the TAM continued into Recent time, but stratigraphic relations on Roberts Ridge suggest that uplift of the TAM here ended long before present day.

As spreading in the Adare Trough and western Ross Sea decreased and ended at ~26 Ma [*Cande et al.*, 2000], a change from E-W oriented rifting to NW-SE rifting occurred [*Salvini et al.*, 1997; 1998]. The E-W rifting was oriented orthogonal to the TAM trend, but the NW-SE oriented extension was highly oblique to its trend. This change in extension direction also ended the main phase of uplift of the TAM. Oligocene time is also marked by another major plate reorganization in the southwest Pacific when the Pacific-Australia boundary moved into New Zealand to initiate the Alpine fault [e.g., *Kamp and Fitzgerald*, 1987].

6. Conclusions

The NNW striking fault system bounding the CRRB on the west that we have named the McMurdo Sound Fault Zone is a master fault zone for the uplift of the TAM. This system may

Figure 7. View to northwest of interpretation of the top 2 s TWTT of NBP9601 profiles across Roberts Ridge, Cape Roberts Rift basin, and the McMurdo Fault Zone along the front of the Transantarctic Mountains. Faults are labeled with the same letters as in Figures 4-6. The stratigraphic interpretation has been extended to CRRB and to additional profiles on Roberts Ridge from that of *Davey et al.* [2001]. (A version of this figure with color interpretation and the uninterpreted color graphics files of the reflection profiles that make up this figure are available on the web at the UCSB Cape Roberts website, http://www.crustal.ucsb.edu/caperoberts as supplemental data.) Not all faults shown are on the fault map (Figure 6) because some do not offset the mapped top V4b horizon and others cannot be mapped because the seismic profiles are not spaced closely enough.

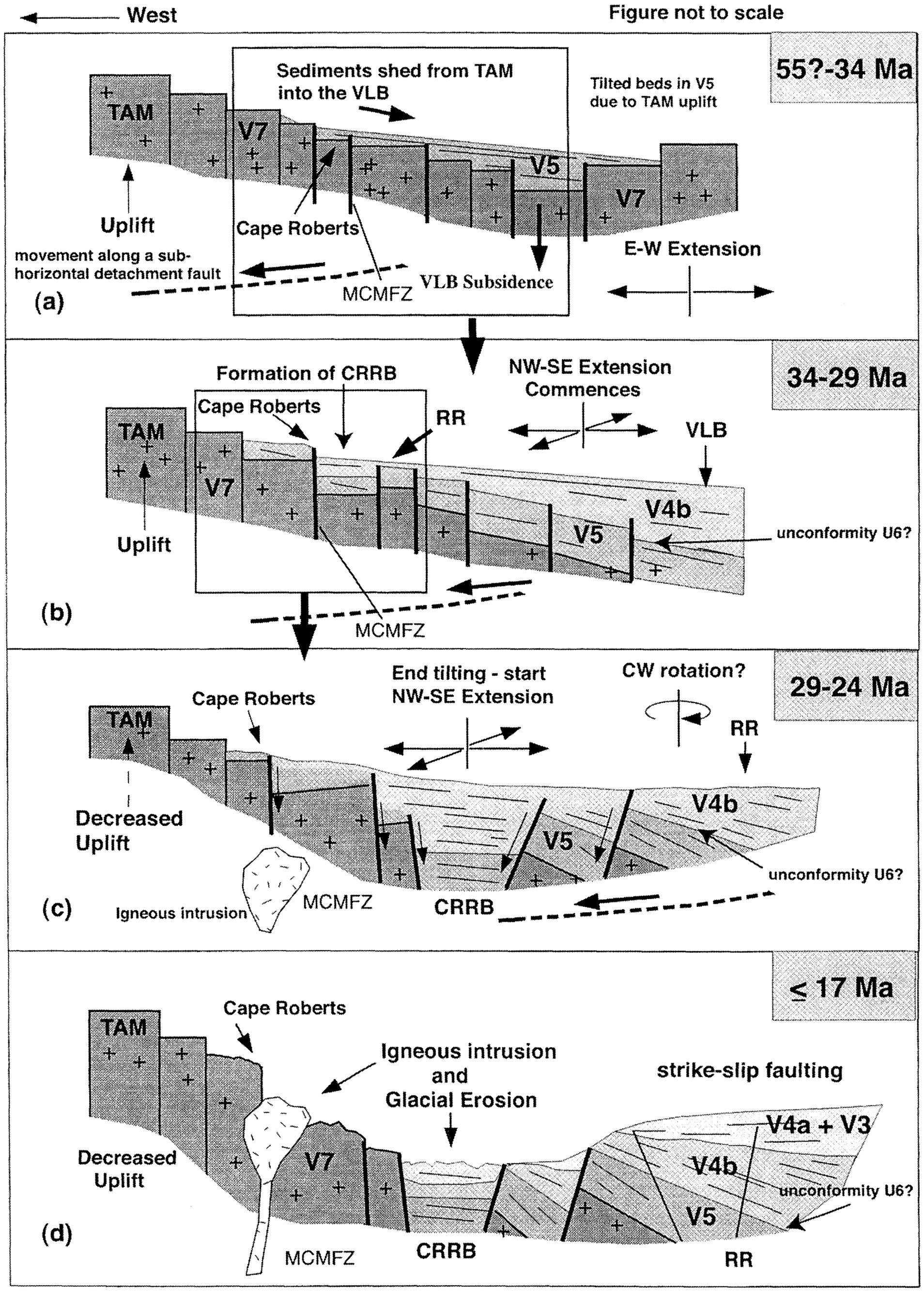

Figure 8. A model of the Cenozoic evolution of the Cape Roberts Rift Basin (CRRB) in relation to the Transantarctic Mountains (TAM), Roberts Ridge (RR), and the Victoria Land Basin (VLB). MCMFZ is McMurdo Sound Fault Zone. E-W orthogonal extension commences in the western Ross Sea, and crustal extension occurs in a low angle detachment system; increased uplift in the TAM is accompanied by subsidence of the VLB starting at 55 Ma (Figure 8a). The CRRB begins to develop at 34-29 Ma, and MCMFZ is most active (Figure 8b). End of tilting on RR, subsidence of CRRB, and uplift of TAM and start of a period of oblique extension occur (Figure 8c). An angular unconformity developed at 24 Ma. Uplift decreased in the TAM, and pull-apart structures accommodated magmatic intrusions on the western margin of the CRRB (Figure 8d). Glacial activity eroded sequences in the CRRB and on Roberts Ridge.

have from 6 to 9 km of vertical separation on faults A, B, and C in the CRRB (Figures 6 and 7). Therefore the relief in the TAM here is due to movement on faults that are now offshore. During Eocene and later time, strata were shed off the denuding TAM and filled the deeper and larger VLB to the east of Cape Roberts. The McMurdo Sound Fault Zone and NNE and ENE striking faults became active during Oligocene time and defined the CRRB and Roberts Ridge. The unconformity between V4a and V4b is interpreted by us to indicate the end of a phase of uplift of the TAM and tilting on Roberts Ridge in late Oligocene time. We also interpret a change from E-W to NW-SE rifting in the western Ross Sea across this unconformity. This unconformity coincides with the end of spreading in the Adare Trough, indicating an approximate correlation between spreading north of the Ross Sea and faulting in the VLB. The ENE striking faults that cut Roberts Ridge and the CRRB have continued motion into Miocene time. Dextral oblique movement on the NNW striking faults resulted in a releasing or pull-apart geometry across right steps in the faults that allowed volcanism along the western margin of the CRRB in Late Oligocene and Miocene time.

The fault sets offshore of Cape Roberts define a pattern consistent with transtensional dextral shear oriented NW-SE. The tilted nature of the structure of Roberts Ridge and a subhorizontal basement reflection below it suggests that the structure at Cape Roberts, including the TAM, the CRRB, and Roberts Ridge, first developed above a subhorizontal detachment system. Detachment faulting may be a common mode of deformation during Late Cretaceous and early Cenozoic time in both the western and eastern Ross Sea [*Fitzgerald and Baldwin,* 1997; B. P. Luyendyk et al., Structural and tectonic evolution of the Ross Sea rift in the Cape Colbeck region Eastern Ross Sea, Antarctica, submitted to *Tectonics*, 2000].

Acknowledgments. We acknowledge financial support from the National Science Foundation (NSF) Office of Polar Programs under grants OPP-9316712 to B. P. Luyendyk and OPP-936710 to L. Bartek and from the Institute of Crustal Studies, contribution number 0314-90TC. We thank our scientific party from the University of California, Santa Barbara, and the University of Alabama for help in the field program. Other significant contributions include Geoff Ely, who assisted greatly in the data processing; Kirsten Zellmer, who made the high-resolution multibeam bathymetry map; Scott White, who helped with the seismic displays; Fred Davey and Stuart Henrys along with other members of the Cape Roberts Science Team, who gave reviews of the Cape Roberts Project; and Giuliano Brancolini who helped in seismic interpretations. The Captain and crew of the *Nathaniel B. Palmer* are deserving of a special thank you for their assistance in the NBP9601 survey and a safe passage in the Ross Sea.

References

Barrett, P. J., Geology of the area between the Axel Heidberg and Shackleton glaciers, Queen Maud Range, Antarctica, part 2, Beacon Group, *N. Z. J. Geol. Geophys., 8*, 344-370, 1965.

Barrett, P. J. (Ed.), Antarctic Cenozoic history from MSSTS-1 drillhole, McMurdo Sound, *DSIR Bull. N. 2, 237*, 174 pp., 1986.

Barrett, P. J. (Ed.), Antarctic Cenozoic history from CIROS-1 drillhole, McMurdo Sound, *DSIR Bull. N. 2., 245*, 254 pp., 1989.

Barrett, P. J., and F.J. Davey (Eds.), Antarctic Stratigraphic Drilling Cape Roberts Project Workshop Report, 38 pp., Misc. Ser. *23*, The R. Soc. of N. Z., Wellington, 1992.

Barrett, P.J., G.W. Grindley, and P.N. Webb, The Beacon Supergroup of East Antarctica, in *Antarctic Geology and Geophysics*, edited by J. Adier, pp. 319-322, Univ. Et, Oslo, 1972.

Barrett, P. J., C. Fielding, and S. Wise, Initial Report on CRP-1, Cape Roberts Project, Antarctica, *Terra Antarctica, 5*, 187 pp., 1998.

Barrett, P. J., S.A. Henrys, L.R. Bartek, G. Brancolini, M. Busetti, F. J. Davey, M. J. Hannah, and A. R. Pyne, Geology of the margin of the Victoria Land Basin off Cape Roberts, southwest 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. 183-207, AGU, Washington, D. C., 1995.

Bartek, L. R., S. A. Henrys, J. B. Anderson, and P. J. Barrett, Seismic stratigraphy of McMurdo Sound, Antarctica: Implications for glacially influenced Early Cenozoic eustatic change?, *Mar. Geol., 130*, 79-98, 1996.

Behrendt, J.C., and A.K. Cooper, Evidence of rapid Cenozoic uplift of the shoulder escarpment of the Cenozoic West Antarctica Rift System and speculation on possible climate forcing, *Geology, 19*, 315-319, 1991.

Behrendt, J. C., W. E. LeMasurier, A.K. Cooper, F. Tessensohn, A. Trehu, and D. Damaske, The West Antarctic Rift System: A review of geophysical investigations, in *Contributions to Antarctic Research II, Antarct. Res. Ser.*, vol. 53, edited by D. H. Elliot, pp. 67-112, AGU, Washington, D. C., 1991.

Blackman, D.K., R. P. von Herzen, and L. A. Lawver, Heat flow and tectonics in the western Ross Sea, Antarctica, 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. 179-190, Circum-Pac. Counc. for Energy and Miner. Resour., Houston, Tex., 1987.

Bozzo, E., D. Damaske, G. Caneva, M. Chiappini, F. Ferraccioli, M. Gambetta, and A. Meloni, A high resolution aeromagnetic survey over proposed drill sites off shore of Cape Roberts in the southwestern Ross Sea (Antarctica), in *The Antarctic Region Geological Evolution and Processes,* edited by C. A. Ricci, pp. 1129-1134, Terra Antarctica, Siena, Italy, 1997a

Bozzo, E., F. Ferraccioli, and T. Wilson, Structural framework of a high resolution aeromagnetic survey, southwestern Ross Sea (Antarctica), in *The Antarctic Region: Geological Evolution and Processes*, edited by C. A. Ricci, pp. 50-56, Terra Antartica, Siena, Italy, 1997b

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

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, Antarct. Res. Ser.*, v. 68, edited by A.K. Cooper, P.F. Barker, and G. Brancolini, pp. 209-233, AGU, Washington, D. C. 1995.

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

Cande, S. C., and J.C. Mutter, A revised identification of the oldest sea-floor spreading anomalies between Australia and Antarctica, *Earth Planet. Sci. Lett., 58*, 151-160, 1982.

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

Cape Roberts Science Team, Studies from the Cape Roberts Project, Initial report on CRP-3, Ross Sea, Antarctica, edited by P. J. Barrett, M. Sarti, and S. Wise, *Terra Antartica, 7*, 209 pp., 2000.

Chorowicz, J., and C. Sorlien, Oblique extensional tectonics in the Malawi Rift, Africa, *Geol. Soc. Am. Bull., 104*, 1015-1023, 1992.

Clifton, A. E., R. W. Schlische, M. O. Withjack, and R.V. Ackermann, Influence of rift obliquity on fault-population systematics: Results of experimental clay models, *J. Struct. Geol., 22*, 1491-1509, 2000.

Cooper, A. K., and F. J. Davey, Episodic rifting of the Phanerozoic rocks of the Victoria Land Basin, western Ross Sea, Antarctica, *Science, 229*, 1085-1087, 1985.

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 Sci. Ser., vol. 5B, edited by A.K. Cooper and F.J. Davey, pp. 27-65, Circum-Pac. Counc. for Energy and Miner. Resourc., Houston, Tex., 1987.

Cooper, A. K., F. J. Davey, and K. Hinz, Crustal extension and the origin of sedimentary basins beneath the Ross Sea and Ross Ice Shelf; Antarctica, in *Geological Evolution of Antarctica*, edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, pp. 285-291, Cambridge Univ. Press, New York, 1991

Crowell, J.C., Origin of late Cenozoic basins in southern California, in *Tectonics and Sedimentation*, edited by W. Dickinson, *Spec. Publ. Soc. Econ. Paleontol. Mineral., 22*, 190-204, 1974.

Davey, F.J., Geophysical studies in the Ross Sea region, *J. R. Soc. N. Z., 11*, 465-479, 1981.

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., v. 5B*, edited by A.K. Cooper and F. J. Davey, pp. 1-15, Circum-Pac.

Counc. for Energy and Miner. Resourc., 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.

Davey, F.J., G. Brancolini, R. J. Hamilton, S. A. Henrys, C. C. Sorlien, and L. R Bartek, A revised correlation of seismic stratigraphy at the Cape Roberts drillsites with the seismic stratigraphy of the Victoria Land basin, *Terra Antartica*, in press, 2001

Elliot, D. H., Jurassic magmatism and tectonism associated with Gondwanaland break-up: An Antarctic perspective, in *Magmatism and the Causes of Continental Break-up,* edited by B. C. Storey, T. Alabaster, and R. J. Pankhurst, *Geol. Soc. Spec. Publ 68*, 165-184, 1992.

Fielding, C. R. A., and M. R. A. Thomson, Initial Report on CRP-2/2A, Cape Roberts Project, Antarctica, *Terra Antartica, 6*, 173 pp. 1999.

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.

Fitzgerald, P.G., The Transantarctic Mountains of Southern Victoria Land: The application of apatite fission track analysis to a rift shoulder uplift, Tectonics, 11, 634-662, 1992.

Fitzgerald, P.G., Thermochronologic constraints on post-Paleozoic tectonic evolution of the central Transantarctic Mountains, Antarctica, *Tectonics, 13*, 818-836, 1994.

Fitzgerald, P. G., Nature and evolution of the Antarctic landscape since Gondwana breakup, paper presented at 8th International Symposium on Antarctic Earth Sciences, Victoria Univ., Wellington, New Zealand, 1999.

Fitzgerald, P.G., M. Sandiford, P. J. Barrett, and A. J. W. Gleadow, Asymmetric extension associated with uplift and subsidence in the Transantarctic Mountains and the Ross Sea Embayment, *Earth Planet Sci. Lett., 81*, 67-78, 1986.

Fitzgerald, P.G., S. L. Baldwin, K.A. Farley, and P. B. O'Sullivan, Landscape evolution and exhumation of the Transantarctic Mountains in the Kukri Hills of southern Victoria Land: Constraints from Apatite Fission Track Thermochronology and (U-Th)/He dating of apatites, *Eos Trans AGU, 81,* F1102, 2000.

Gunn, B. M., and G. Warren, Geology of Victoria Land between the Mawson and Muluck glaciers, Antarctica, *Bull. N. Z Geol. Surv., 71*, 157 pp., 1962

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.

Hannah, M. J., Eocene dinoflagellates from the CIROS-1 drill hole, McMurdo Sound Antarctica, *Terra Antartica, 1*, 371, 1994.

Hannah, M. J, Climate controlled dinoflagellate distribution in late Eocene/earliest Oligocene strata from the CIROS-1 drillhole, McMurdo Sound, Antarctica, *Terra Antartica, 4*, 73-78, 1997.

Hannah, M. J., M. B. Cita, R. Coccioni, and S. Monechi, The Eocene/Oligocene boundary at 70 degrees south, McMurdo Sound, Antarctica *Terra Antartica, 4*, 79-87, 1997.

Hayes, D E., and L. A Frakes, General synthesis: Deep Sea Drilling Project 28, in *Initial reports of the Deep Sea Drilling Project, Leg 28,* edited by D. E. Hayes and L. A Frakes, pp 919-942, Nat Sci Found., Washington, D. C, 1975.

Heimann, A., T H. Fleming, D H. Elliot, and K. A. Foland, A short interval of Jurassic continental flood basalt volcanism in Antarctica as demonstrated by ^{40}Ar/^{39}Ar geochronology, *Earth Planet. Sci Lett., 121*, 19-41, 1994.

Henrys, S. A., L. R Bartek, G. Brancolini, B. Luyendyk, R. J. Hamilton, C C. Sorlien, and F J. Davey, Seismic stratigraphy of the pre-quaternary strata off Cape Roberts and their correlation with strata cored in the CIROS-1 drill hole, McMurdo sound, *Terra Antarctica, 5*, 273-279, 1998

Henrys, S. A. , C. J. Bücker, L. Bartek, S. Bannister, F. Niessan, and T. Wonik, Correlation of Seismic Reflectors With CRP-2, *Terra Antartica*, in press, 2001.

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

International Steering Committee, Antarctic climate and tectonic history: the Cape Roberts Project, *Eos Trans., AGU, 75(1)*, 2-3, 1994.

Kamp, P. J. J., and P. G. Fitzgerald, Geologic constraints on the Cenozoic Antarctica-Australia-Pacific relative plate motion circuit, *Geology, 15*, 694-697, 1987.

Kyle, P. R., Glacial history of the McMurdo Sound area as indicated by the distribution and nature of the McMurdo Volcanic Group rocks, in *Dry Valley Drilling Project, Antarct. Res. Ser.*, vol. 33, edited by L. D. McGinnis, pp. 403-412, AGU, Washington, D. C., 1981.

Kyle, P. R., Erebus volcanic province Summary, in *Volcanoes of the Antarctic Plate and Southern Ocean, Antarct. Res. Ser.*, vol. 48, edited by W. E. LeMasurier and J. W. Thomson, pp. 81-88, AGU, Washington, D. C., 1990.

Kyle, P. R., D.H. Elliot, J.F. Sutter, and P. Vella, Jurassic Ferrar Supergroup tholeiites from the Transantarctic Mountains, Antarctica, and their relationship to the initial fragmentation of Gondwana, in *Gondwana Five: Selected Papers and Abstracts of Papers Presented At The Fifth International Gondwana Symposium*, edited by M.M. Cresswell, pp. 283-287, Victoria Univ., Wellington, New Zealand, 1981.

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

Luyendyk, B P., A model for Neogene crustal rotations, transtension, and transpression in southern California, *Geol. Soc. Am Bull., 103*, 1528-1536, 1991.

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

Marks, K M., and J M. Stock, Early Tertiary gravity field reconstructions of the southwest Pacific, *Earth Planet. Sci. Lett., 152*, 267-274, 1997.

McGinnis, L.D. (Ed.), Dry Valley Drilling Project, *Antarct Res. Ser.,* vol. 33, 765 pp., AGU, Washington, D. C., 1981.

Molnar, P., T. Atwater, J Mammerickx, and S. Smith, Magnetic anomalies, bathymetry, and the tectonic evolution of the south Pacific since the Late Cretaceous, *Geophys. J R. Astron Soc., 40*, 383-420, 1975.

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

Salvini, F., F. Storti, G. Brancolini, M. Busetti, and C. De Cillia, Cenozoic strike-slip induced basin inversion in the Ross Sea, Antarctica, *Terra Antartica, 5*, 209-215, 1998.

Smellie, J L., P. Armienti, A. Bellanca, and F. M. Talarico, First indications of unroofing history of the Transantarctic Mountains from clast, grain and sand-grade sediment geochemistry of CRP-2 samples, McMurdo Sound (abstract), in *8th International Symposium on Antarctic Earth Sciences, 5-9 July 1999, Programme and Abstracts*, edited by D. N. B. Skinner, p. 285, Victoria Univ., Wellington, New Zealand, 1999.

Stern, T. A., and U. Ten Brink, Flexural uplift of the Transantarctic Mountains, *J. of Geophys. Res., 94*, 10,315-10,330, 1989.

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 (abstract), in *8th International Symposium on Antarctic Earth Sciences, 5-9 July 1999, Programme and Abstracts*, edited by D. N. B. Skinner, p. 11, Victoria Univ., Wellington, New Zealand, 1999.

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.

Stock, J., and P. Molnar, Uncertainties in the relative positions of the Australia, Antarctica, Lord Howe, and Pacific plates since the late Cretaceous, *J. Geophys. Res., 87*, 4697-4714, 1982.

Stock, J., and P. Molnar, Revised early Tertiary history of plate motion in the southwest Pacific, *Nature, 325*, 495-499, 1987.

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

Stump, E., The Ross orogen of the Transantarctic Mountains in the light of the Laurentia-Gondwana split, *GSA Today, 2,* 25-28, 1992.

Ten Brink, U. S., R. I. Hackney, S. Bannister, T. A. Stern, and Y. Makovsky, Uplift of the Transantarctic Mountains and the bedrock beneath the East Antarctic ice sheet, *J. Geophys. Res., 102*, 27, 603-27, 621, 1997.

Tessensohn, F, and G. Worner, The Ross Sea Rift System, Antarctica: Structure, evolution, and analogues, 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

Tron, V., and J P Brun, Experiments on oblique rifting in brittle-ductile systems, *Tectonophysics, 188*, 71-84, 1991

Turnbull, I. M., P. J. Forsyth, and N. Mortimer, Field tests of Transantarctic Mountains uplift models, Cape Roberts hinterland (abstract), in *8th International Symposium on Antarctic Earth Sciences, Programme and Abstracts*, edited by D. N. B Skinner, p 306, Victoria Univ, Wellington, New Zealand, 1999

Weissel, J. K., D. E. Hayes, and E. M. Herron, Plate tectonic synthesis: The displacements between Australia, New Zealand, and Antarctica since the late Cretaceous, *Mar Geol., 25*, pp. 231-277, 1977.

Wilson, G. S., A. P. Roberts, K L Verosub, F. Florindo, and L. Sagnotti, Magnetobiostratigraphic chronology of the Eocene-Oligocene transition in the CIROS-1 core, Victoria Land margin, Antarctica: Implications for Antarctic glacial history, *Geol Soc Amer. Bull., 110*, 35-47, 1998.

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

Withjack, M. O., and W. R. Jamison, Deformation produced by oblique rifting, *Tectonophysics*, 126, 99-124, 1986.

Withjack, M. O., G Eisenstadt, and R W.

Schlische, Oblique-slip normal faulting: Comparison of secondary deformation patterns in experimental models and geological examples, *Eos Trans. AGU, 80*,(17) Spring Meet. Suppl., S340, 1999.

Woolfe, K.J., and P.J. Barrett, Constraining the Devonian to Triassic tectonic evolution of the Ross Sea sector, *Terra Antartica*, *2*, 7-21, 1995.

Yilmaz, O., Seismic data processing, in *Investigations in Geophysics*, vol. 2, edited by S. M. Doherty, 526 pp., Soc. of Explor. Geophysi., Tulsa, Okla., 1987.

L. R. Bartek, Department of Geological Sciences, University of North Carolina, Chapel Hill, Campus Box 3315, Mitchell Hall, Chapell Hill, NC 27599.

R. J. Hamilton, IESE, Universidad de Navarra, Avenida Pearson, 21, 08034 Barcelona, Spain.

B. P. Luyendyk and C. C. Sorlien, Institute for Crustal Studies, Department of Geological Sciences, 1006 Webb Hall, University of California, Santa Barbara, Santa Barbara, CA 93106. (luyendyk@geol.ucsb edu)

(Received March 21, 2000;
revised December 2, 2000;
accepted January 3, 2001.)