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Tectonic Regimes and Structural Trends Off Cape Roberts, Antarctica

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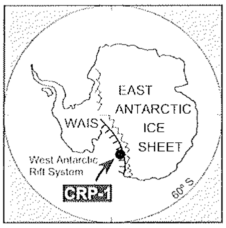


Abstract - Over 250 km of multichannel (MCS) and high resolution single channel (SCS) seismic reflection data were acquired offshore Cape Roberts, Antarctica during the United States NBP9601 Ross Sea expedition. Our interpretations of the data identify three fault arrays: two sets of rift border faults striking NW and NNE, and a third set of ENE trending faults, oblique to the north-south orientation of the asymmetric Cape Roberts Rift Basin. Two igneous bodies along the western margin of the basin, identified from both seismic and magnetic data, apparently resulted from magma ascending along pull-apart fracture systems where transfer faults cross-cut the main border fault.
The onlap sequence boundary interpreted between the gently east-dipping unit (V4a) and the more moderately dipping units (V4b and V5), is thought to correspond to a major phase of opening of the Cape Roberts Rift Basin, associated with tilting and vertical axis rotation of fault blocks along the eastern margin of the graben. The older sequences infill the Victoria Land Basin to the east but gradually thin to the west onto Roberts Ridge and in the Cape Roberts Rift Basin. We suggest that the formation of the Cape Roberts Rift Basin postdates the major rifting phases in the western Ross Sea that formed the larger and deeper Victoria Land Basin and other basins to the east.

INTRODUCTION

The western Ross Sea is distinguished by deep, sediment-filled rift basins that parallel the Transantarctic Mountains along the margin of the East Antarctic craton. These large structures are a result of extension within the West Antarctic Rift System and may be linked with the history of the Western Antarctic Ice Sheet and East Antarctic Ice Sheet through development of the mountain range (*e.g.* Behrendt & Cooper, 1991). The relationship between the rifting and glacial activity in the western Ross Sea is of importance to ongoing Antarctic research in determining the complex structural and glacial history of the western margin of the West Antarctic rift System and, in addition, providing insight on global climatic fluctuations.

Drilling in southern Victoria Land, McMurdo Sound, and the central Ross Sea, in conjunction with geophysical surveys, has contributed information on the glacial history of Antarctica. Some of the first drillsites include the Deep Sea Drilling Project (DSDP) Leg 28 in the Ross Sea (Hayes & Frakes et al., 1975); and the Dry Valley Drilling Project (DVDP) (Kyle, 1981; McKelvey, 1982; Wrenn & Webb, 1982). Later studies include the McMurdo Sound Sediment and Tectonic Studies-1 (MSSTS-1) (Barrett, 1986) and Cenozoic investigations of the Ross Sea: CIROS-1 and CIROS-2 (Barrett, 1989). Despite the drilling efforts, little is known about the time period between 160 Ma and 45 Ma (Barrett et al., 1995; Bartek et al., 1996). No rocks or sediments of this age have been sampled in the Transantarctic Mountains or in other parts of East Antarctica (Davey, 1987; Barrett et al., 1995). The oldest sediments in the CIROS-1 drillhole, were glacial and glacimarine strata of early-late Eocene in age (Hannah et al., 1997; Wilson et al., 1997).

The interpretations from seismic reflection data acquired in the western Ross Sea prior to this study (R/V S. P. Lee, 1984; OGS Explora, 1990; R/V Polar Duke, 1990), indicated that rocks of possible late Cretaceous to Palaeocene age (*e.g.* Cooper et al., 1987) crop out near or at the seafloor along Roberts Ridge, a bathymetric high approximately 15 kilometres east of Cape Roberts (Barrett & Davey, 1992; Barrett et al., 1995; Bartek et al., 1996). These results helped initiate an international drilling venture among Germany, Italy, New Zealand, the United Kingdom and the United States (International Steering Committee, 1994) (joined subsequently by Australia), which proposed a drilling programme offshore Cape Roberts, known as the Cape Roberts Project (CRP). It is anticipated that a composite stratigraphic section of over 1 500 metres will be recovered from CRP drilling, and that more information will be obtained on the palaeoclimate and glaciation history of the western Ross Sea with respect to global sea level oscillations and tectonic activity during late Cretaceous to Oligocene time (*e.g.* Barrett & Davey, 1992).

This paper provides stratigraphic and structural interpretations off Cape Roberts based on the NBP9601 geophysical data, and offers an explanation for tectonic activity that led to the formation of the Cape Roberts Rift

Basin. The implications of the findings are discussed in relation to rifting and basin subsidence in the western Ross Sea, phases of volcanism along the East Antarctic margin, and possible periods of increased uplift and denudation in the Transantarctic Mountains during the Cenozoic.

REGIONAL SETTING

GEOLOGICAL BACKGROUND

Cape Roberts is located along the southwestern margin of the western Ross Sea, at the entrance to McMurdo Sound (Fig. 1). The area is characterised onshore by the prominent north-south trending Transantarctic Mountains that reach heights of over 4 000 metres. Outcrop exposures include Precambrian to Ordovician granitic and meta-sedimentary basement rock, overlain by Devonian to Triassic sedimentary rocks of the Beacon Supergroup. Along the coast at Cape Roberts, Ordovician Granite Harbour Intrusives and distinctive Jurassic Ferrar Dolerite sills are exposed, along with foliated and non-foliated gneissic granitoids (Gunn & Warren, 1962; Fitzgerald, 1992). These basic intrusives were emplaced during a major event at approximately 177 ± 2 Ma (Heimann et al., 1994) which marks the initial stages of break-up of the Gondwana supercontinent in the Jurassic Period.

BATHYMETRY

Offshore from Cape Roberts, NBP9601 multibeam bathymetry data reveal a trough, the Cape Roberts Rift Basin, that closes to the south, and is bounded by normal fault blocks of the Transantarctic Mountain Front to the west and by a bathymetric high, Roberts Ridge, to the east (Fig. 1). The rift basin is erosionally truncated to the north in Granite Harbour by the glacial-carved Mackay Sea Valley, now filled with Pleistocene sediments (Barrett et al., 1995). Bathymetric depths range from 100 metres along the eastern and western margins of the rift basin, to depths of over 1 000 metres in the Mackay Sea Valley.

TECTONIC STUDIES

The north-south trending Roberts Ridge forms the western boundary of the adjacent Victoria Land Basin. Cooper & Davey (1985) defined the Victoria Land Basin as a rift depression, 20 km wide, that extends north of Ross Island. An estimated 14 km of strata fills the rift zone, with 5-6 km of this thought to be Palaeogene or late Cretaceous in age (*e.g.* Cooper et al., 1987). The formation of the Victoria Land Basin, as well as other major basins in the Ross Sea embayment, are thought to have been influenced by several major phases of rifting. Prior to the separation of New Zealand from Antarctica, Cretaceous extension was prevalent along the West Antarctic Rift System and in the Ross Sea embayment, while a later phase of Cenozoic tectonism was associated with volcanic activity, localised in the Victoria Land Basin (Cooper et al., 1987, 1991; Fitzgerald & Baldwin, 1996). Although the ages of these events have yet to be precisely determined, models have linked western Antarctic rifting and basin subsidence as a result of compensation downwarping to the uplift of the Transantarctic Mountains (Davey et al., 1982; Fitzgerald et al., 1986; Stern & ten Brink, 1989).

Previous geophysical interpretations in the western Ross Sea and southern Victoria Land have indicated that the major basins in the Ross Sea embayment may have been offset by transcurrent faults (*e.g.* Cooper et al., 1991). The original field mapping by Gunn & Warren (1962), and later mapping by Fitzgerald (1992) and Wilson (1995), showed evidence for a set of ENE trending faults onshore at Cape Roberts. Fitzgerald (1992) noted that the north-south striking faults along the Transantarctic Front were not parallel to the axis of maximum uplift of the Transantarctic Mountains, inferring the possibility of dextral offset along these faults to accommodate east-west extension in the Ross Sea. He also proposed that transfer faults cut the mountain range and provide conduits for major outlet glaciers. Wilson (1995) completed a fault-kinematic study from outcrops in southern Victoria Land, including Cape Roberts, which showed the presence of arrays of NNE- to NE-trending faults, oblique to the NNW-trending Transantarctic Mountains. Her fault kinematic solution suggests that dextral transcurrent motion occurred along the West Antarctic rift boundary during the Cenozoic Era. Wilson's model concluded that West Antarctic crustal block motions, associated with crustal stretching and thinning, most likely occurred during the Mesozoic Era. Salvini et al. (1997) also proposed that dextral transtension was present on most of the major NW-trending faults in northern Victoria Land and the western Ross Sea during Cenozoic time, and emphasised that east-west extension, associated with the strain regime at the time, continued to play an important role in the geodynamics of the Western Antarctic rift margin.

METHODOLOGY

In February 1996, over 250 kilometres of multichannel (MCS) and single channel (SCS) reflection seismic data were collected aboard the icebreaker research vessel, N.B. Palmer, during United States Antarctic Research Program cruise NBP9601. Hull-mounted 3.5 kHz chirp-sonar sub-bottom data, along with Seabeam 2112 multibeam bathymetry, magnetic field and gravity data, were also acquired during the study. It was possible to record MCS and SCS data along the same shiptrack lines by firing alternating sources every 5 seconds. The MCS source consisting of five, 3.44 litre generator/injector air guns and a 1 500 metre streamer was used to record 48 channels at a group spacing of 25 m. SCS data were recorded from the near trace and sourced by the firing of one 3.44 litre generator/injector air gun. All of the data were recorded digitally at 2 milliseconds sampling intervals on an OYO DAS-1 recording system. The N.B. Palmer was able to maintain a fairly constant speed over the seafloor, so that shots were equally spaced at 25 metres, and relatively open water allowed the vessel to keep to straight tracks. GPS was used for navigation.

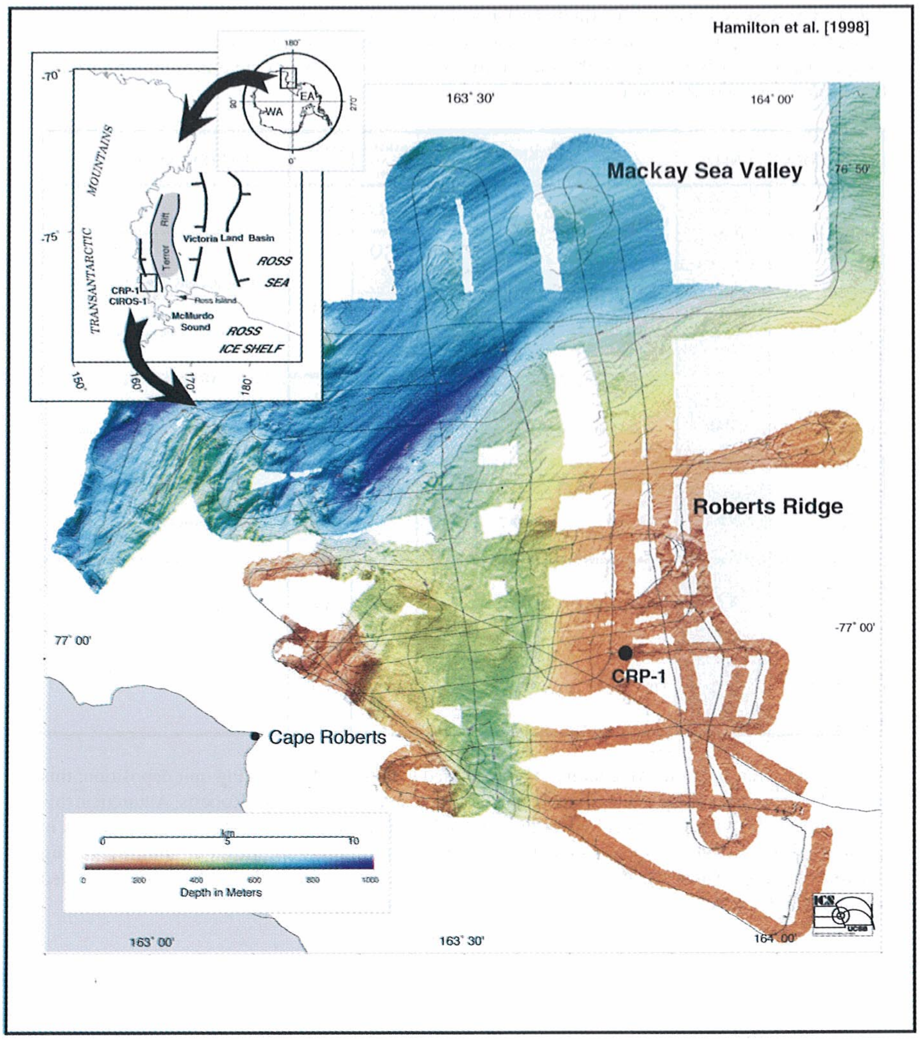


Fig. 1 - A high resolution, shaded relief bathymetric map from Seabeam 2 112 data showing the N.B. Palmer shiptrack during the NBP9601 Ross Sea expedition. Roberts Ridge, a bathymetric high on the eastern margin of the survey area, the Mackay Sea Valley, a deep glacially scoured trough to the north, and Cape Roberts Rift Basin, a V-shaped bathymetric low, are prominent features of the study area offshore Cape Roberts. The CRP-1 and CIROS-1 drilling sites are annotated.

The suppression of strong water-bottom or peg-leg multiples was one of the biggest difficulties in processing the seismic data. Velocity analyses were undertaken every one kilometre and the data were F-K filtered after a NMO correction with intermediate velocities between the primary and multiple arrivals. Median amplitude stacks were effective at removing multiple energy but degraded the data above 0.5 seconds two-way-time (TWT). In some cases, an F-K migration at 1 460 m/s was performed poststack. This process sharpened simple structures in shallow layered reflections, but could not handle moderate dips and complex structure such as is present within the Cape Roberts Rift graben. For this reason, some seismic interpretations were carried out on non-migrated seismic sections.

Several different nomenclatures have been previously developed to describe the seismic stratigraphy and geometry in the western Ross Sea and the Victoria Land Basin. Cooper et al. (1987) defined six seismic units (V1-V6) above an acoustic basement (V7). Bartek et al. (1996) used a letter nomenclature to interpret over 650 km of high resolution data acquired aboard the RV Polar Duke in 1990. Their correlation tied seismic sequences away from the CIROS-1 drillhole to the Victoria Land Basin. A comparison of the different naming systems is shown in table 1. For our study, a nomenclature similar to that developed by Barrett et al. (1995) was used as a basis for preliminary interpretations; however, the system was revised to provide a more detailed analysis of the units at Cape Roberts. The most significant difference was that Unit V4 was separated into two distinct sequences: V4a and V4b. The Unit V4b was identified by a series of high amplitude reflectors that are parallel to the underlying V5 sequence (Fig. 2). An onlap sequence boundary separates V4a and V4b.

Although drilling in other areas of the Ross Sea has provided insight on the ages and types of sediments for a given locality, unconformities, water-bottom multiples, and faults create uncertainty in the correlation of pre-late Oligocene strata from the nearest other drillhole, CIROS-1, to Cape Roberts which lies 70 km to the north. Our seismic interpretations of the NBP9601 data were compared to the

Tab. 1 - The seismic sequences interpreted offshore Cape Roberts, Antarctica, based on the NBP9601 reflection seismic data. A comparison is made to the stratigraphic nomenclatures developed by Cooper et al. (1987), Barrett et al. (1995), and Bartek et al. (1996), for study areas in Southern Victoria Land and the western Ross Sea.

TECTONICS[1]	UNIT[2]	AGE[2]	THICKNESS[2] (m)	BARRET ET AL. (1995)	BARTEK ET AL. (1996)	COOPER ET AL. (1987)	FACIES/COMMENTS[3]
Late Cenozoic Volcanism	V3	< 30 m.y. Early Miocene to Late Oligocene	0 - 250	V3	M,N,O / P,Q	V2	Glacial marine sediments
		??					Unconformity 4 m.y.[4]
Fault block tilting and rotation	V4a	~30-45 m.y. Early Oligocene to Late Eocene	0 - 800	V4	R	V3	Glacial marine sediments
							Onlap surface
Dextral transtension / Increased uplift in TAM	V4b	~45-55 m.y. Late to Mid Eocene	< 400		S,T	V4	Turbidites & deepwater mudstones
							Unconformity
Post Gondwana breakup	V5	> 55 m.y. Paleocene to Late Cretaceous	> 2500 ?	V5	......	V5	Unsampled/Unknown
Pull-aparts, crustal thinning	V6	Late Cenozoic ??	??	V6	......	V6	Volcanics[5]
Pre and syn-Gondwana breakup	V7	Pre-Jurassic?	??	V7	......	V7	Medisedimentary, volcanic & igneous basement rocks[6]

Note: TAM: Transantarctic Mountains. [1]Hypothesised tectonic activity during unit deposition; this paper. [2]Description and age of units with respect to study area offshore Cape Roberts, Antarctica; this paper. [3]Inferred from regional geology of units V3 to V7 and the drillhole CIROS-1. [4]From Bartek et al. (1996). [5]These younger volcanics are thought to be responsible for the magnetic anomalies along rift-border faults offshore Cape Roberts; this paper. [6]These rocks crop out and have been sampled onshore near Cape Roberts, along the Transantarctic Mountains Front.

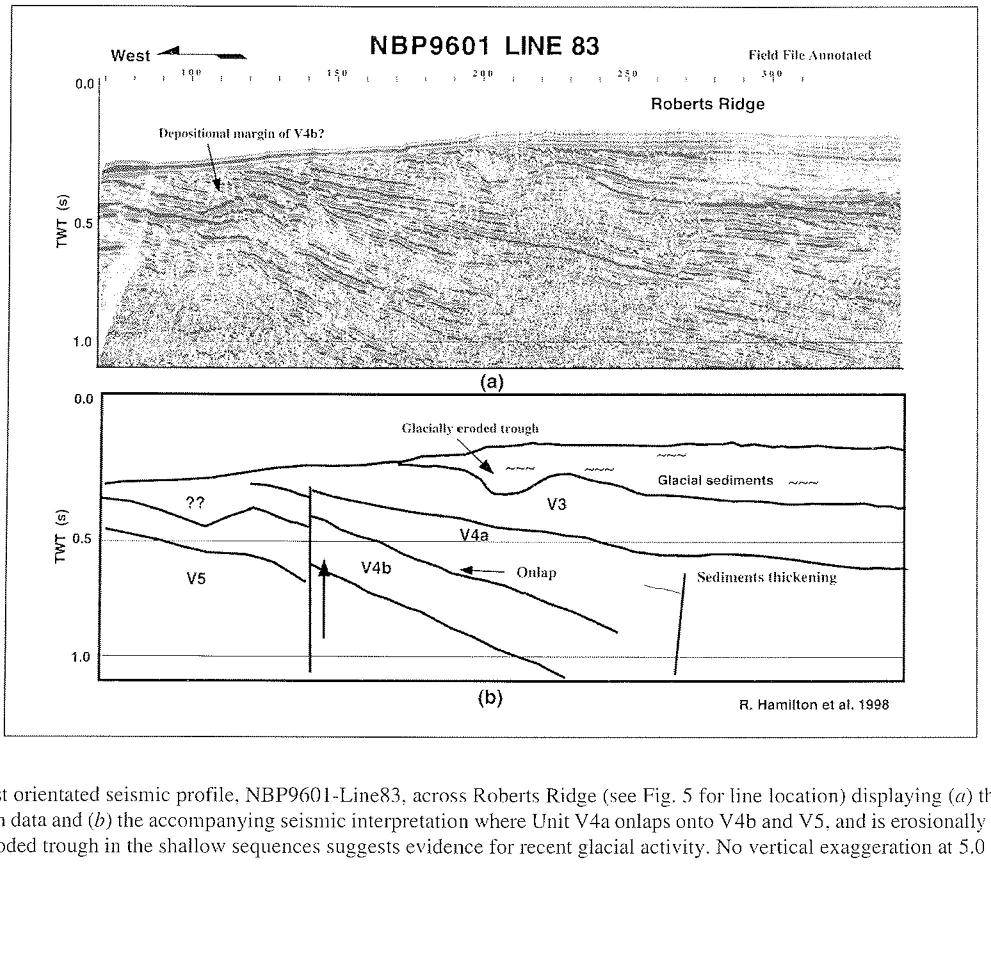


Fig. 2 - East-west orientated seismic profile, NBP9601-Line83, across Roberts Ridge (see Fig. 5 for line location) displaying (*a*) the multichannel seismic reflection data and (*b*) the accompanying seismic interpretation where Unit V4a onlaps onto V4b and V5, and is erosionally truncated at the sea floor. The eroded trough in the shallow sequences suggests evidence for recent glacial activity. No vertical exaggeration at 5.0 km/s.

interpretations previously made on older seismic profiles across Roberts Ridge including: PD90-11 (R/V Polar Duke, 1990), It-69 (OGS Explora, 1990) and USGS-403 (R/V SP Lee, 1984). In doing this, a 100 millisecond uncertainty band was identified, representing the likely location of the V3/V4 boundary (Henrys et al., this volume). The location shown in this paper corresponds to the lower limit of the band and is the same as that picked by Hamilton et al. (1997). The V3/V4 boundary shown in the Initial Report on CRP-1 (Cape Roberts Science Team, 1998) is picked higher within this uncertainty band. A more detailed analysis of the stratigraphy offshore from Cape Roberts is described in Henrys et al. (this volume).

In general, NNE- and NW-trending faults bounding the Cape Roberts rift graben were best identified on east-west seismic profiles while ENE-striking faults were more easily interpreted on north-south lines. Any NNE-rift border faults in the northern part of the study area could not be mapped because of the lack of east-west profiles there. The presence of fault-plane reflections and associated diffractions aided in the interpretion of deep faults. Multiples were very strong on the western margin of the rift basin in shallow depths, because of the high impedance contrast of the seafloor. The top of (acoustic) basement was interpreted on the basis of strong reverberating, low frequency reflections at the top of an acoustically transparent interval. Igneous intrusive bodies were inferred here from both the reflection seismic data (from the rough seafloor and associated diffractions with their outcrop) and the magnetic field data acquired during the NBP9601 expedition. The interpretations from Bozzo et al. (1997) from the GITARA IV high-resolution aeromagnetic survey acquired by the German Italian Aeromagnetic Research Programme in Antarctica in 1994/95, were also used to confirm the presence of magnetic anomalies on the western side of the Cape Roberts Rift Basin.

GEOPHYSICAL INTERPRETATIONS

STRATIGRAPHY

In general, the western seafloor slope of Roberts Ridge steepens from north to south and the easterly dipping sequences, V4b and V5, increase in dip to the south where the Cape Roberts Rift Basin is the deepest. Two east-west trending lines, NBP9601-Line83 (Fig. 2) and NPB9601-Line97 (Fig. 3) show sequences V4b and V5 to be stratigraphically conformable and dipping to the east. A more detailed interpretation of the units on Roberts Ridge (Fig. 4) shows that V4a and V3 have gentler dips and that V4a onlaps V4b, pinching out towards the west. The geometry of Unit V4a, interpreted as a west-tapering wedge, may be a result of deposition at a basin margin, and later erosion of the unit. It is estimated that V4b is less than 400 m in thickness, whereas V4a reaches up to 800 m on Roberts Ridge. Some sequences within the V3 unit appear chaotic or discontinuous, indicating that they may be glacial in origin. The units V3, V4a, V4b and V5 are the drilling objectives of the Cape Roberts Project.

TECTONICS

The V-shaped map pattern of the asymmetric (in cross-sectional view) Cape Roberts Rift Basin is defined seismically by steep NW-striking normal basement faults to the west and by NNE-trending tilted fault blocks of Roberts Ridge to the east (Fig. 5). A third set of steeply dipping, oblique ENE-striking faults was interpreted on the eastern margin of the trough and on Roberts Ridge. On Roberts Ridge, these faults show small vertical offsets in upper stratigraphic horizons, and in some cases, may have an ocean floor surface expression. These faults were difficult to correlate in the Cape Roberts rift graben because of the complex structure there; however, a down-to-the south vertical separation of acoustic basement was interpreted across inferred ENE-striking faults on a north-south seismic line through the trough (Fig. 6). Using an average velocity of 4.0 km/s for the overlying layers, a vertical separation of 800 metres for the top of Unit V5 was calculated across an ENE fault interpreted on NBP9601-Line91. The amount of vertical separation along these faults may vary along strike. Right-stepping faults were interpreted from the seismic data along the NW-striking escarpment on the west wall of the rift, and are evident on the high resolution bathymetric map (Fig. 1). The northernmost ENE-striking fault coincides with a steep bathymetric slope and is parallel to the glacially scoured Mackay Sea Valley. Buried U-shaped channel features were identified both on the southern slopes of the Mackay Sea Valley and south of the Cape Roberts rift graben, providing evidence for glacial scouring along to the north and south of the Cape Roberts Rift Basin (Fig. 2). Similar glacial channels have been interpreted on Roberts Ridge and in other areas of the western Ross Sea (Anderson & Bartek, 1992; Barrett et al., 1995).

MAGNETIC ANOMALIES

Two intrusive bodies were interpreted on the western margin of the Cape Roberts Rift Basin along NW-striking basement faults on lines NBP9601-Line86 (Fig. 7) and NBP9601-Line89. Diffractions and changes in the amplitude and shape of seismic traces on the seismic data corresponded to magnetic anomalies greater than 100 nanoTestla on the NBP9601 magnetic data. Bozzo et al. (1997) interpreted similar magnetic anomalies along the NW-trending rift-border faults with the high resolution aeromagnetic data acquired in 1994/95 (GITARA IV) by the German Italian Aeromagnetic Research Programme in Antarctica.

DISCUSSION

Previous geophysical studies in the western Ross Sea infer that Unit V4b and Unit V5 infill the Victoria Land Basin to the east; however, these sediments thin on Roberts Ridge. Our interpretations from the NBP9601 reflection seismic data indicate that Unit V4b is unconformably truncated on Roberts Ridge and that Unit V5 may still be present on the eastern side the Cape Roberts Rift Basin.

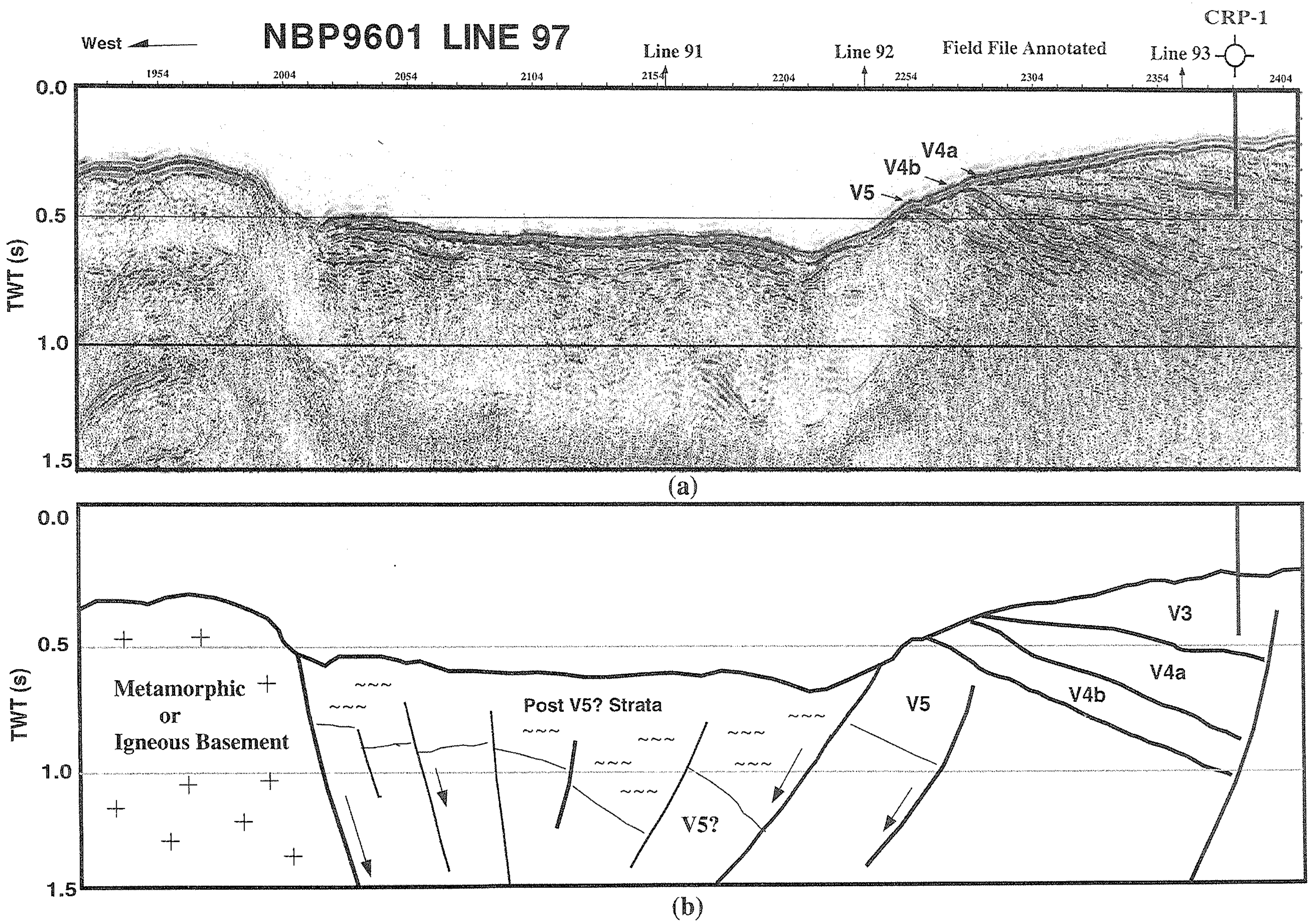


Fig. 3 - East-west multichannel seismic profile, NBP9601-Line97, displaying (*a*) uninterpreted seismic section. and (*b*) interpreted geologic units and the prominent types of normal separation faults controlling the morphology of the Cape Roberts Rift Basin. Reflectors below 1.0 second TWT on the eastern margin of the trough may represent V5 reflectors that have been offset by east-tilted normal faults. Sediments within the top 0.2-0.5 seconds TWT in the basin are interpreted to be volcanic or glacial in origin. The CRP-1 drillhole is projected onto the line. No vertical exaggeration at 5.0 km/s.

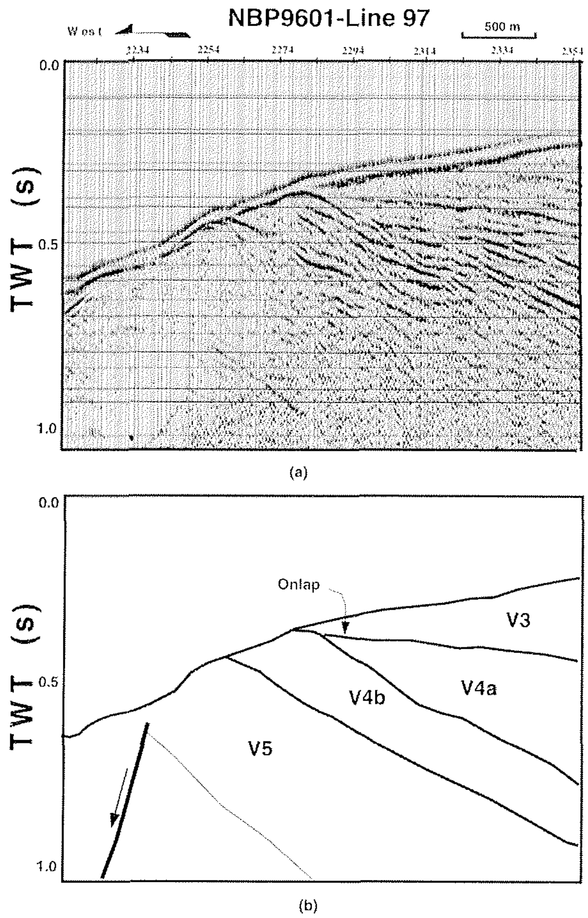


Fig. 4 - A close up of Roberts Ridge on NBP9601-Line97 showing (a) a non-interpreted seismic profile and (b) an interpreted section for the units proposed to be drilled by the Cape Roberts Project, identifying the onlap of V4a onto V4b. No vertical exaggeration at 5.0 km/s.

The apparent lack of thick, older sequences in the graben would suggest that the opening of the Cape Roberts Rift Basin occurred during later stages of Ross Sea extension. The steepest dips in the sequences interpreted along Roberts Ridge occur where the border faults converge to the south. The thicker interval of higher energy reflectors in the southern part of the Cape Roberts basin (Fig. 6) may represent a regional low, fundamentally controlled by basement block movement, that acted as a depocentre for glacial or volcanic sediments during the later evolution of the Cape Roberts Rift Basin.

The interpretations of the major fault systems at Cape Roberts, obtained from detailed seismic mapping, infer that the east and west margins of the Cape Roberts Rift Basin are bounded by normal faults which control the bathymetry; however, the structural styles across the basin differ. The western side of the basin is controlled by steeply dipping normal basement faults. The crystalline basement rocks are down-dropped a minimum of 800 m in the north and 1 300 m in the south (Fig. 6), using a velocity of 4.0 km/s from surface to top basement, averaged from velocity analyses of the NBP9601 MCS data. This does not account for any denudation of the footwall, especially in the south where the top of the basement is buried in the hanging wall and protected from glacial erosion. Faulting in the eastern part of the basin and on the western margin of Roberts Ridge is expressed in a series of east-tilted fault blocks (Fig. 8).

The ENE-striking faults mapped at Cape Roberts are interpreted as transfer faults with a normal slip component. These faults appear to offset the NW-striking faults on the west side of the basin and offset Unit V3 on Roberts Ridge. The basement blocks drop down to the south across these ENE-striking faults and are related to pull-apart fractures across the NNW-striking faults. Two igneous intrusions, inferred along the western margin of the rift basin from magnetic and seismic data, coincide with areas of high vertical bathymetric relief, and occur along vertical offsets in normal faults in the western scarp of the trough.

If the youngest offset sequences mapped along Roberts Ridge are early Miocene in age (Cooper et al., 1987; Barrett et al., 1995; Bartek et al., 1996; Cape Roberts Science Team, 1998) then reactivation along ENE-striking transfer faults may have occurred during this time. A change in the tectonic strain regime in the western Ross Sea at approximately 30 Ma (*e.g.* Salvini et al., 1997), which may be related to other volcanic and igneous events along the Transantarctic Mountains (Le Masurier & Thomson, 1990), may have reactivated these ENE-striking faults in transtensional mode (Brancolini et al., 1995; Salvini et al., 1997). In this case scenario, the ENE-striking faults offshore Cape Roberts may have been previously active (Salvini et al., 1997) during increased uplift and denudation of the Transantarctic Mountains. This may corresponding to an Eocene event (55 Ma) dated by Fitzgerald (1992) using fission track analyses in these mountains. The pull-apart fractures and magmatic activity evolved during a later transtensional tectonic regime when these faults were reactivated.

We suggest that the onlap sequence boundary between V4a and V4b could be associated with tilting, erosion and possible vertical axis clockwise rotation of fault blocks that comprise the structure of Roberts Ridge. The NW-trending faults represent the breakaway zone of the Transantarctic Mountain Front and the NNE-striking faults delimit individual tilted fault blocks of an extended terrane lying above a low angle, west-dipping detachment fault. The NNE-trending tilted fault blocks may have been rotated clockwise (~45°) from an initial NNW orientation during later dextral transtension across NW-striking faults. This structural model is consistent with a transtensional strain regime involving NW-SE-striking right-lateral faults, NNW-striking normal faults, and ENE-striking left-lateral faults. The presence of a detachment fault was inferred by applying a fault-mechanical model to the tilted fault blocks and the east side of the basin, and by comparing this model with other analogues for rotating fault blocks above detachments such as in the central Mojave Desert, California (Ross et al., 1989), and in central Idaho (Janecke et al., 1991). Fitzgerald & Baldwin (1996) also provided evidence of low angle detachments along the Antarctica margin.

The fault kinematic model of Wilson (1995) also inferred NW-SE right-lateral transtension along the Transantarctic Mountain Front. Wilson's model described

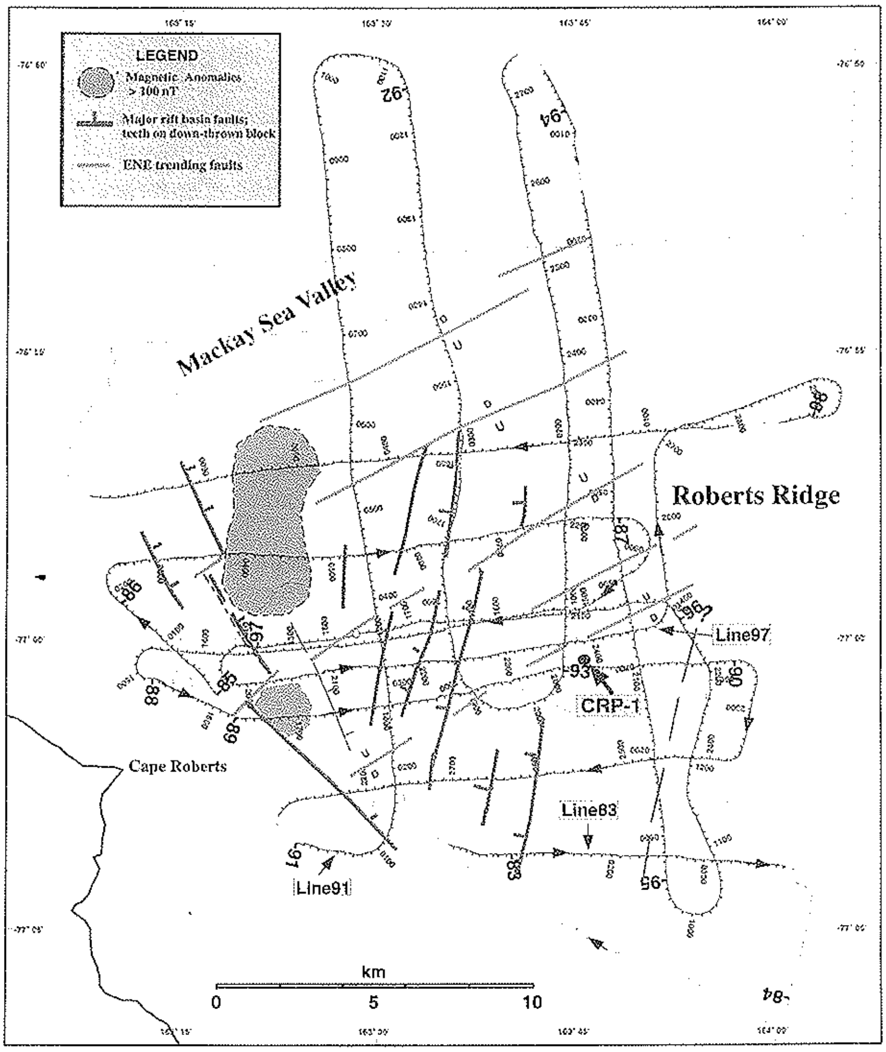


Fig. 5 - Structure map based on interpreted multichannel seismic data acquired aboard the N.B. Palmer in February, 1996. The fault trends mapped show three distinct fault systems trending NW, NNE and ENE across the V-shaped trough of the Cape Roberts Rift Basin and Roberts Ridge to the east. Magnetic anomalies occur along offsets in basement rocks along the west side of the rift basin. Arrows along the shiptrack indicate direction of travel and seismic field file numbers are annotated for each seismic line.

Transantarctic Mountain Front. Wilson's model described the rift margin as consisting of an *en echelon* array of oblique-slip faults, and would explain the right step evident in the escarpments along the western side of the Cape Roberts rift graben. We propose that, during the evolution of the Cape Roberts basin, left-oblique ENE-striking transfer faults were activated in order to accommodate dextral transtension on NW-SE-striking faults. Assuming that we are dealing with an extensional basin, these cross-faults would allow accommodation between extensional faults with different slip rates (*e.g.* Gibbs, 1984).

In comparing the mapped onshore geology with the bathymetry off Cape Roberts, we note that the southern margin of the scoured Mackay Sea Valley is co-linear with the New Glacier Fault, mapped onshore by Fitzgerald (1992). This fault appears to coincide to the southern limit of the Mackay Glacier. The projection of the New Glacier Fault into Granite Harbour correlates with a steeply dipping ENE-trending fault interpreted on seismic profiles. We suggest that both the tectonic activity and glacial erosion from Mackay Glacier are controlling the morphology of the Mackay Sea Valley.

CONCLUSIONS

The Cape Roberts Rift Basin is an asymmetric trough, bounded by igneous intrusive, granitic and meta-sedimentary basement rocks to the west, and by Roberts Ridge to the east where possibly late Cretaceous to Oligocene sediments are believed to crop out. Interpretations of seismic reflection data suggest that an onlap surface occurs between the shallow easterly-dipping Unit V4a and the moderately easterly-dipping Units V4b and V5. The V4b and V5 sequences appear to thin on Roberts Ridge in comparison with the deep, sediment-filled Victoria Land Basin to the east, suggesting that the Cape Roberts Rift Basin may have formed later than the Victoria Land Basin. The seismic interpretations from this study indicate that Cretaceous and Palaeogene sediments increase in thickness to the south and are best preserved on Roberts Ridge.

The timing for an episode of increased uplift and denudation of the Transantarctic Mountains, associated with rift-border block-faulting along the Transantarctic Mountain Front and the area offshore from Cape Roberts, may be coincident with results from fission-track analyses

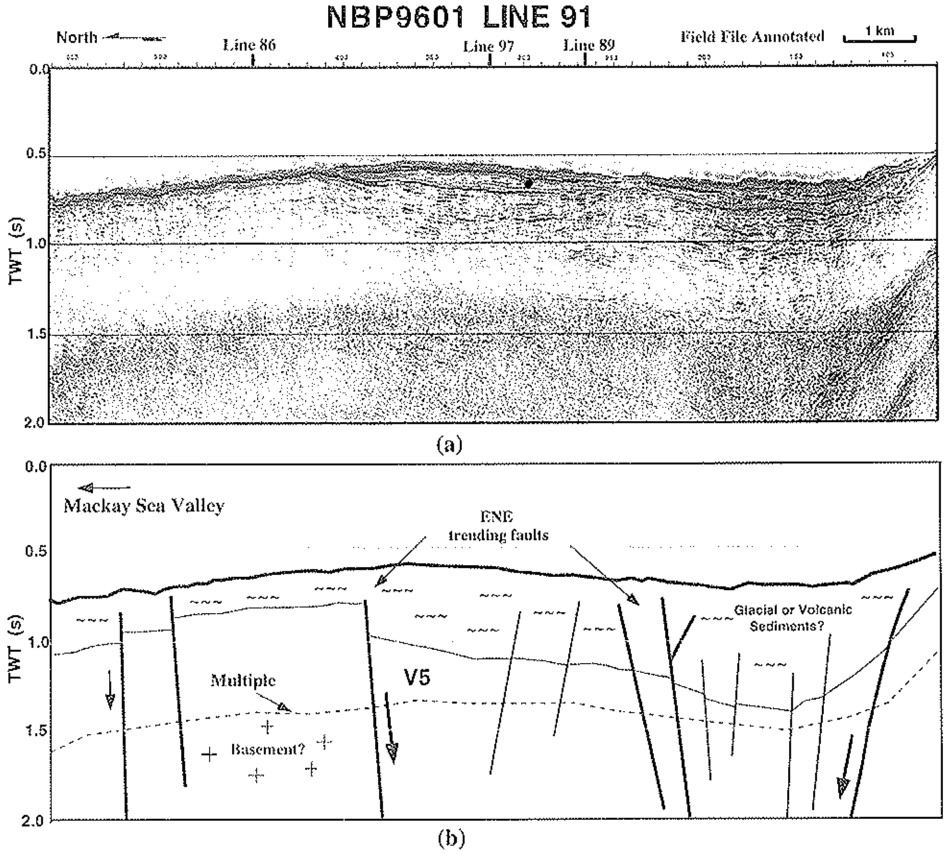


Fig. 6 - North-south seismic profile, NBP9601-Line91, showing (*a*) a non-interpreted section, and (*b*) geological and tectonic interpretations displaying vertical separation, down to the south, along ENE-trending faults. Using an averaged velocity of 4.0 km/s, the offset at field file 380 was calculated to be a minimum of 800 metres while the offset at field file 100 is approximately 1 300 metres. The increase in energy of the shallow seismic reflections towards the south, infers an accumulation of sediment in this direction while possible basement reflectors are apparently closer to the seafloor in the north. No vertical exaggeration at 5.0 km/s.

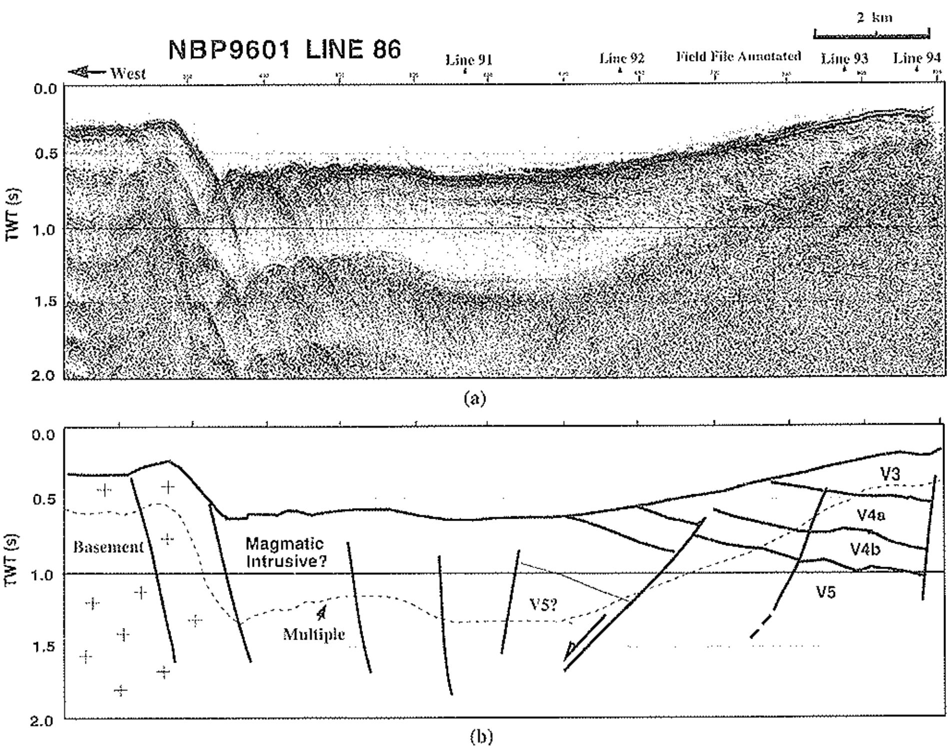
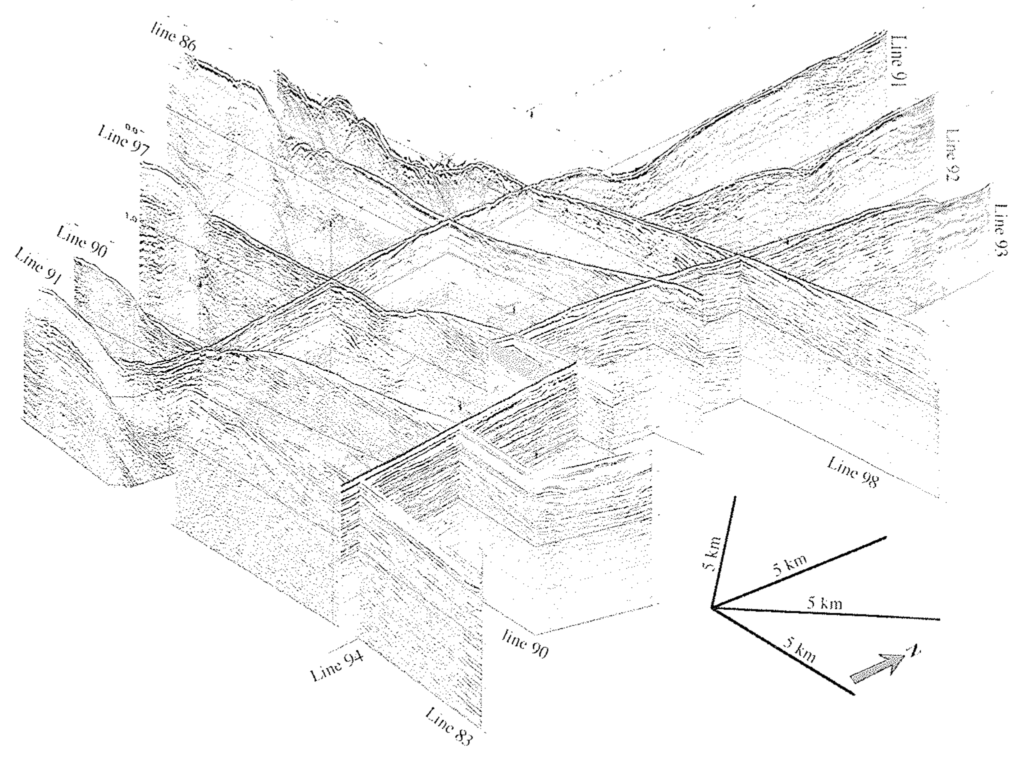


Fig. 7 - East-west seismic profile, NBP9601-Line86, displaying (*a*) a non-interpreted seismic section, and (*b*) an interpreted profile showing a series of tilted fault blocks on the eastern side of the rift graben and a large fault escarpment providing the western limit of the Cape Roberts Rift Basin. The strong diffractions on the west side of the graben are a result of steep basement faulting along which magnetic intrusions have been interpreted. No vertical exaggeration at 5.0 km/s.

a)



b)

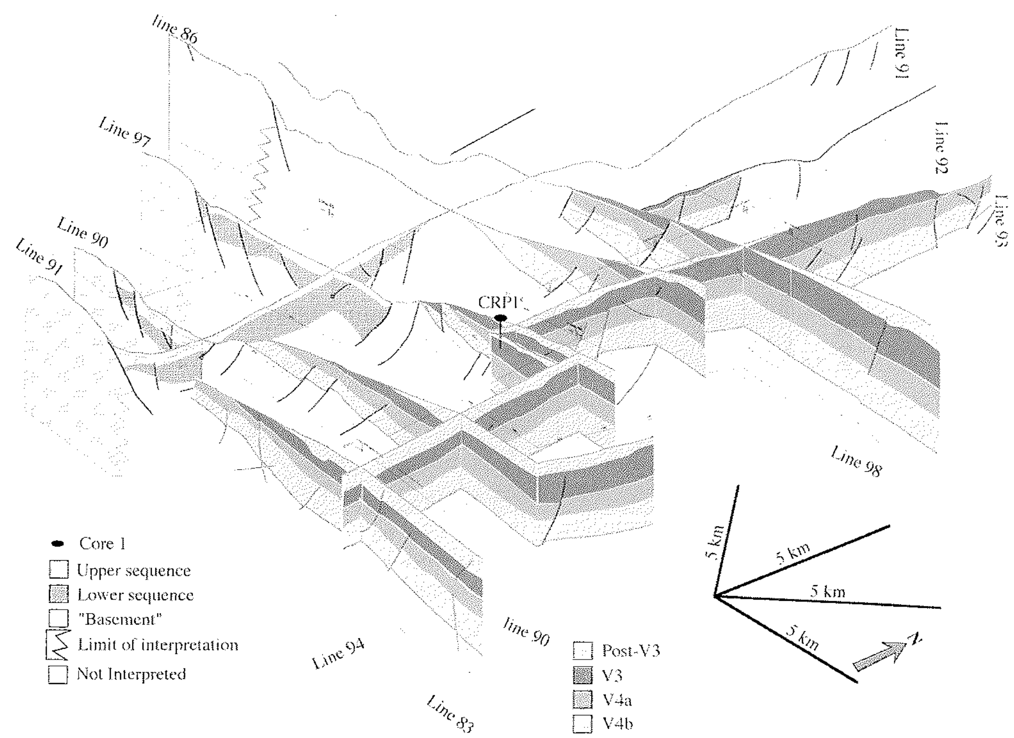


Fig. 8 - a) Fence diagram of the upper 2.0 seconds TWT of uninterpreted, non-migrated seismic reflection data for Roberts Ridge and the Cape Roberts Rift Basin. F-K filtered median amplitude stacks are shown below 1.0 second TWT for Lines 93 and 97, and below 0.5 seconds TWT for Lines 86, 89, 91, 92, and 98. A single-channel plot of Line 89 is shown above 0.4 seconds near the Cape Roberts core (CRP-1). Normal, F-K filtered stacks are shown for the other profiles and the upper sections. The view is to the northwest, and is foreshortened to correspond to a view from 30° elevation. *b)* Interpreted fence diagram at same scale as figure 8a. There is some uncertainty for the interpretation of the vertical separation across faults and for the sequence boundaries picked for the tops of Units V3 and V4b; however, the stratigraphic interpretation will be clarified with the results of the upcoming Cape Roberts drilling. The interpreted sequences within the Cape Roberts Rift Basin cannot be reliably correlated onto Roberts Ridge, and are shown as unidentified sequences. They may correspond to post-V3 (shallow) and to V5 (deep). Half-arrows show onlap or erosional truncation, and vertical lines show intersections of profiles, including several that are not shown on this figure. A high-angle, east-side-up fault is shown on Line 97, west of CRP-1, to explain possible duplication of an angular unconformity.

by Fitzgerald (1992) which indicated that a major phase of uplift and denudation of the mountains occurred at ~55 Ma. We propose that the onlap surface between V4a and V4b on Roberts Ridge post-dates this major uplift stage, and corresponds with tilting and rotation of fault blocks along the eastern margin of the graben.

Three sets of faults have been identified beneath the seafloor in the area offshore from Cape Roberts: NW- and NNE-striking rift margin faults, and ENE-striking transtensional faults. The structural style of normal faulting differs across the rift graben. Steeply dipping and NW-trending normal-separation faults on the western margin along the Transantarctic Mountain Front, display up to 800 m of east-west vertical relief of the seafloor and up to 1 300 m of vertical separation of the top of the basement. NNE-trending faults, interpreted on the eastern margin of the basin and on the western flank of Roberts Ridge, outline a series of east-tilted fault blocks. The NW-and NNE-striking fault sets can be interpreted as marking an extended terrane; the NW-striking faults are the breakaway zone and the NNE-striking faults define tilted blocks lying above a detachment fault. The NNE-trending tilted blocks may have been rotated clockwise (45°) in a dextral transtension strain regime across NW-SE-striking faults.

The ENE-striking transtensional faults, oblique to the Cape Roberts basin, were activated as transfer systems to link NW- and NNE-striking normal-separation faults associated with dextral transtension along NW-striking faults. The onset of a transtensional regime, and associated igneous events in other areas of the Ross Sea, is thought to have occurred at ~30 Ma and may be related to the emplacement of two igneous bodies, present along the western margin of the Cape Roberts trough. They resulted from magma ascending along pull-apart fractures where transfer faults cut across the main border fault. To the north of the Cape Roberts Rift Basin, an ENE-striking fault, interpreted from the NBP9601 MCS data, appears to control the morphology of the Mackay Sea Valley.

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