

GEOLOGY OF THE MARGIN OF THE VICTORIA LAND BASIN OFF CAPE ROBERTS, SOUTHWEST ROSS SEA

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This paper reviews current geological knowledge of the southwest margin of the Ross Sea. Here, strata of the Victoria Land basin are faulted along the flanks of the Transantarctic Mountains, which themselves are underlain by 180 my and older pre-rift rocks. Late Cretaceous to Paleogene rocks of basin-wide seismic sequences V3 to V5 rise to the sea floor close to the mountains and dip gently east beneath younger strata in the basin center. About 400 square km off Cape Roberts have been mapped, and a geological history inferred from ages and lithologies from correlation with the nearby CIROS 1 drill hole as well as comparison with sequences in the New Zealand region. On this basis, we believe that sediment first accumulated on the margin of the Victoria Land basin as breccia filling local half grabens at some time between 105 and 55 Ma. Coastal coal measures, shallow marine sandstone and deep-water mudstone of Late Cretaceous to early Oligocene age followed. The earliest history is represented by V5, as yet unsampled, but with its potential for revealing early rift tectonism, climate and sea level change. The overlying V4 comprises in its upper part at least over 300 m of deep water mudstone from mid-Eocene to early Oligocene age with ice-rafted debris throughout. The substantial shallowing at the base of V3 at 30 Ma may be of both tectonic and eustatic origin. V3 is a late Oligocene-early Miocene shallow water sequence of diamictite, sandstone and mudstone, providing the best record thus far of the first extensive ice sheet development in the Ross Sea sector of Antarctica.

INTRODUCTION

Cape Roberts lies on the western boundary of the West Antarctic Rift System [Tessensohn and Wörner 1991; Behrendt *et al.*, 1991]. West of the cape, the Transantarctic Mountains rise to elevations of around 2500 m 50 km inland, beyond which the land surface sinks beneath the East Antarctic ice sheet (Figure 1). Offshore, the sea floor falls away to form a broad trough whose axis lies parallel to the coast 100 km away and at depths of 900 to 1000 m.

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The bathymetric trough off the Victoria Land coast can be seen from seismic profiles (Figure 2) to follow the trend of a much older feature now filled with sediment 10 to 14 km thick, the Victoria Land basin. This basin is the westernmost of four north-south trending basins formed by extension of the Ross Sea region (Figure 1). The younger strata in these basins have been drilled on Deep Sea Drilling Project (DSDP) Leg 28 [Hayes *et al.*, 1975] in the eastern and central basins and the MSSTS-1 and CIROS-1 drill holes of the New Zealand Antarctic Programme (NZAP) in the Victoria Land basin [Barrett, 1986, 1989], and found largely to comprise glacial and glacial-marine strata of Oligocene and Miocene age, with thin patchy Pliocene and Pleistocene sequences [reviewed by Anderson and Bartek, 1992, Hambrey and Barrett, 1993]. The older strata have yet to be sampled.

The purpose of this paper is to review the geological setting of the Victoria Land basin margin and the information, both direct and circumstantial, currently available about the older strata off Cape Roberts. Single- and multi-channel seismic surveys have provided

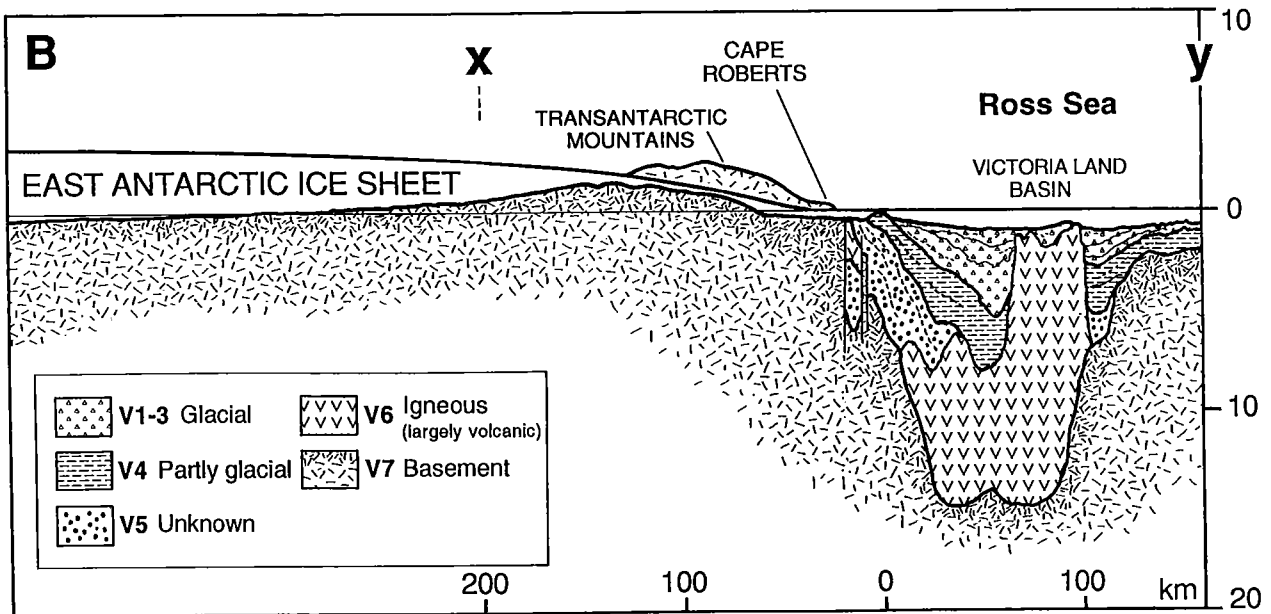
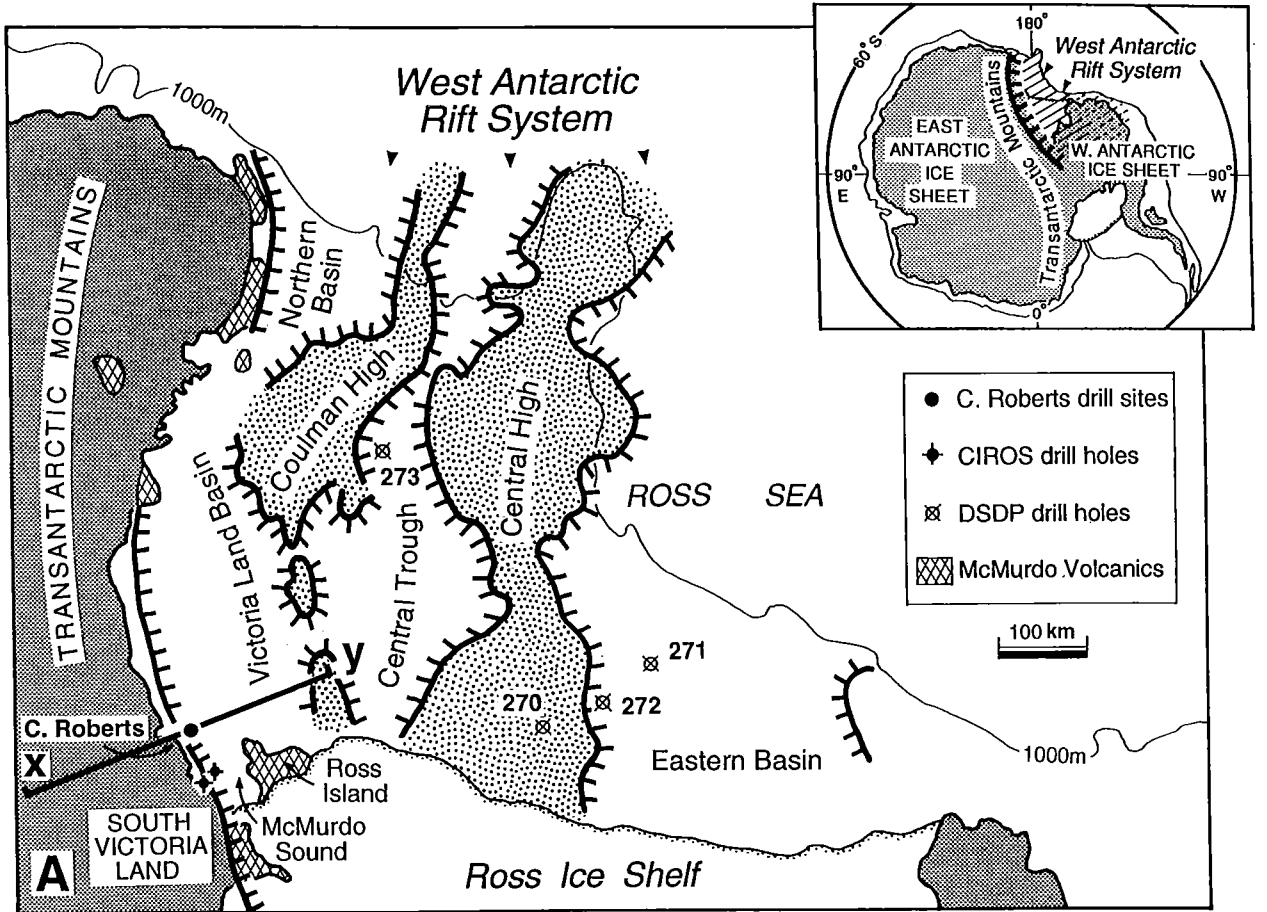


Fig. 1. (a) The Ross Sea region, showing the location of Cape Roberts in relation to the West Antarctic Rift System, the Transantarctic Mountains and sedimentary basins in the Ross Sea [after *ANTOSTRAT*, This volume]. (b) Section from the East Antarctic Ice Sheet across the Transantarctic Mountains and the Victoria Land basin [after *Cooper and Davey, 1987*]. Vertical exaggeration is 10:1. The section is expanded in Figure 2.

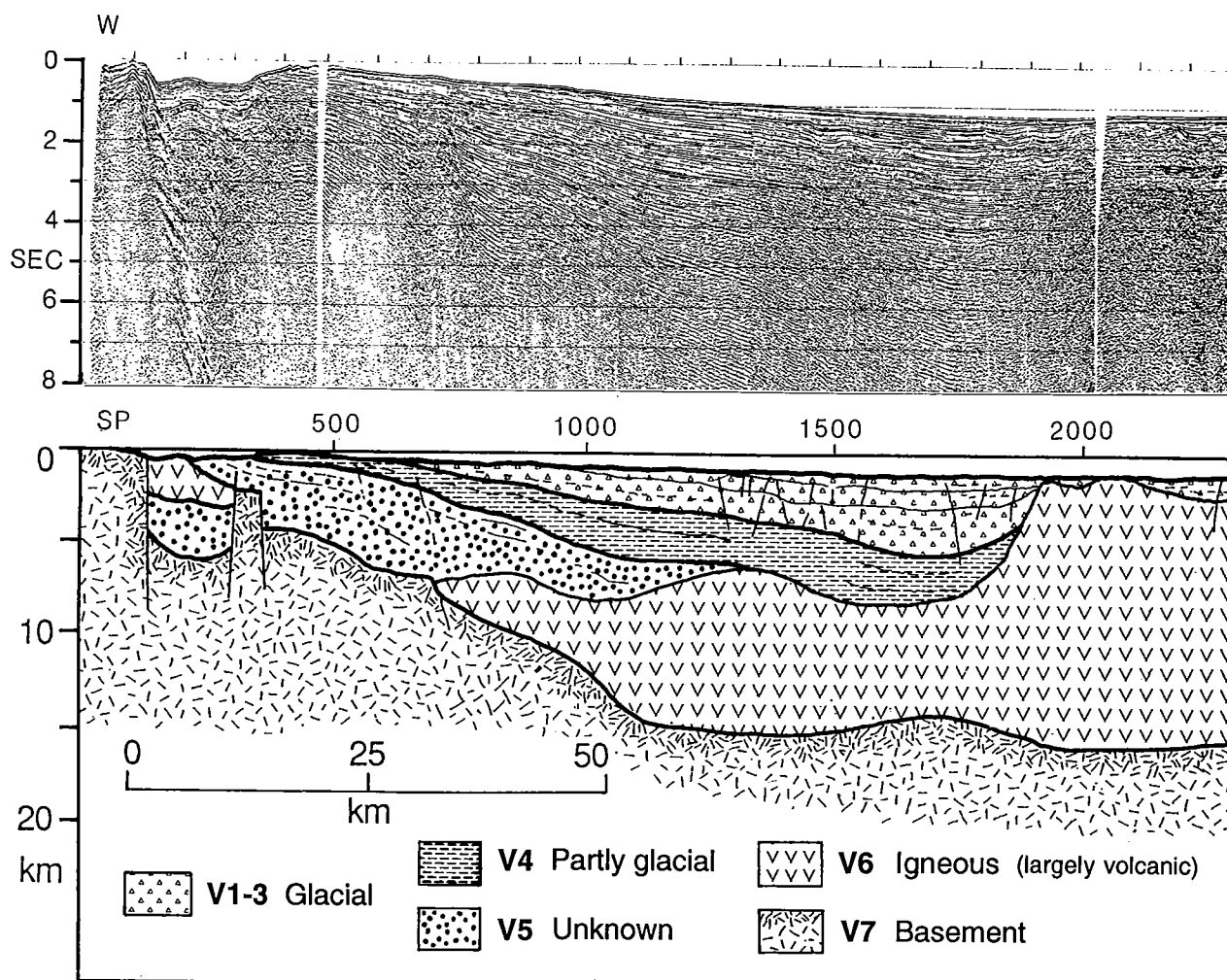


Fig. 2. Seismic profile across the Victoria Land basin with its landward end just north of Cape Roberts (USGS line 403/404 after Cooper et al. [1987]). The profile shows the oldest seismic-sedimentary sequences in the basin (V4 and V5) exposed at or near the sea floor off Cape Roberts. Vertical exaggeration is 2:1. The stratigraphy of the basin is outlined in Table 1.

TABLE 1. Seismic stratigraphy of the Victoria Land basin [after Cooper and Davey, 1987]. Modified to take into account seismic correlation of the Cape Roberts sequence with CIROS-1, and the revision of the age of the lower part of the hole [Hannah, 1994]

Unit	Thickness (km)	Velocity (km/sec)	Age	Lithology
V1	<1.2	1.7-2.3	mid Pliocene to Recent	Glacial marine sediments
V2	0.2-1.3	2.1-2.9	mid Miocene to Pliocene	Glacial marine sediments
V3	0.3-2.5	2.7-4.1	late Oligocene to early Miocene	Glacial marine sediments
V4	<1	4.0-4.9	early Oligocene and older	Marine sediments?
V5	<8	4.5-5.6	Cretaceous to early Paleogene	Marine sediments?
V6	<8		Paleogene-Recent	Basaltic volcanics
V7		5.0-7.4	Precambrian-mid Paleozoic	Basement

enough data for the mapping of several stratigraphic units over an area of several hundred square km. They show a sequence that crops out at or near the sea floor and dips east at around 2° (Figure 2). This geometry has made possible the sampling of over 1500 m of strata by drilling from the fast ice, planned for 1996 and 1997 as the Cape Roberts Project [Barrett and Davey, 1992; International Steering Committee (ISC), 1994]. The results of this review indicate that the strata are well placed to record the history of polar climate and Ross Sea tectonism in early Cenozoic and possibly Late Cretaceous times.

GEOLOGICAL SETTING

The eastern margin of the Transantarctic Mountains has long been recognized as the morphological and geological boundary between East and West Antarctica [David and Priestley, 1914; Taylor, 1922], and in the last 2 or 3 decades the margin of a major continental rift system [Tessensohn and Wörner, 1991; Behrendt *et al.*, 1991]. Recent studies have identified the boundary as a narrow zone of crustal thinning, from 35 km beneath the Transantarctic Mountains to 20 km beneath the western Ross Sea [reviewed in Bentley, 1991]. This corresponds to the change in surface elevation from flat-topped mountains and plateaus averaging 2000 to 3000 m in elevation to submarine basins reaching over 1000 m below sea level.

The Transantarctic Mountains in southern Victoria Land comprise a basement, exposed in the coastal foothills, of late Precambrian metamorphic rocks (Koettlitz Group meta-turbidites, Skelton Group meta-shelf carbonates) intruded by granitoids of the Granite Harbour Intrusives in Ordovician times [Laird, 1991]. These were subsequently covered by the slow accumulation of flat-lying largely terrestrial strata, the Beacon Supergroup [Barrett, 1991] for a thickness of more than 2 km from early Devonian to late Triassic times. Sedimentation took place in a broad back-arc [Collinson *et al.*, 1994] or intracontinental [Woolfe, 1992] basin sited largely along the present Transantarctic Mountains but extending across the present coast into the Ross Sea. The basin was sourced both from the East Antarctic craton and eastern Ross Sea. Beacon sedimentation ended around 180 Ma ago with the eruption and intrusion of tholeiitic magma - Kirkpatrick Basalts and Ferrar Dolerite [Kyle *et al.*, 1981]. The latter form extensive sills whose resistance to erosion has resulted in the plateau topography that characterizes the Transantarctic Mountains. The formation of the West Antarc-

tic Rift System and the Victoria Land basin is presumed to post-date this major igneous event.

The main morphological features of the western margin of the rift system in McMurdo Sound are shown in Figure 3 and a new compilation of the bathymetry in Figure 4. The features are from west to east:

- the *Transantarctic Mountain Front*, a north-trending 30-km wide zone of subparallel en echelon faults representing the edge of the gently tilted and raised crustal block;

- *Roberts Ridge*, an offshore bathymetric high whose crest reaches to within 150 m of sea level and is formed by old eastward-dipping strata of the Victoria Land basin (truncated to the north by the Mackay Sea Valley, presumed to be carved by Pleistocene ice during periods of glacial advance, and broadens into a shallow platform 200 m below sea level in western McMurdo Sound to the south);

- *Erebus Basin*, a broad trough almost 1000 m deep centered 100 km east of the Transantarctic Mountain Front and over the Victoria Land basin (basin largely structural in that sea floor topography follows dips of Miocene and older strata beneath - axis parallels the Transantarctic Mountain Front and can be followed 200 km north into the Drygalski Trough);

- *Ross Island*, a volcanic edifice in the middle of Erebus Basin with a volume of several tens of cubic km above the sea floor (largely a Pliocene to Pleistocene feature [Kyle, 1990] whose weight has depressed the crust around it by almost 2 km [Stern *et al.*, 1991] - similar but smaller volcanic piles, like Beaufort Island and Franklin Island, have reached the surface on the eastern flank of the basin to the north).

The change in elevation at the rift margin is primarily the result of faults that run en echelon through the foothills of the Transantarctic Mountains and are down-thrown toward the coast [summarised in Fitzgerald, 1992]. The amount and sense of movement, obtained from both field mapping and thermochronology studies, and their orientation, indicates their formation by large scale rifting in a tensional tectonic regime. Faulting parallel to the coast has also been reported offshore in both multi-channel seismic survey and single channel seismic survey seismic profiles offshore [Figure 2, Cooper and Davey, 1987]. The faults are both normal and reversed, but always at a high angle ($>60^\circ$) and show offsets ranging from tens to a few hundred meters. Figure 5 is an example that shows faulting to have persisted over a long period of time, for the faults there displace not only strata at depth, of probable Miocene age, but also relatively recent channel fill at the sea floor, and possibly the sea floor itself.

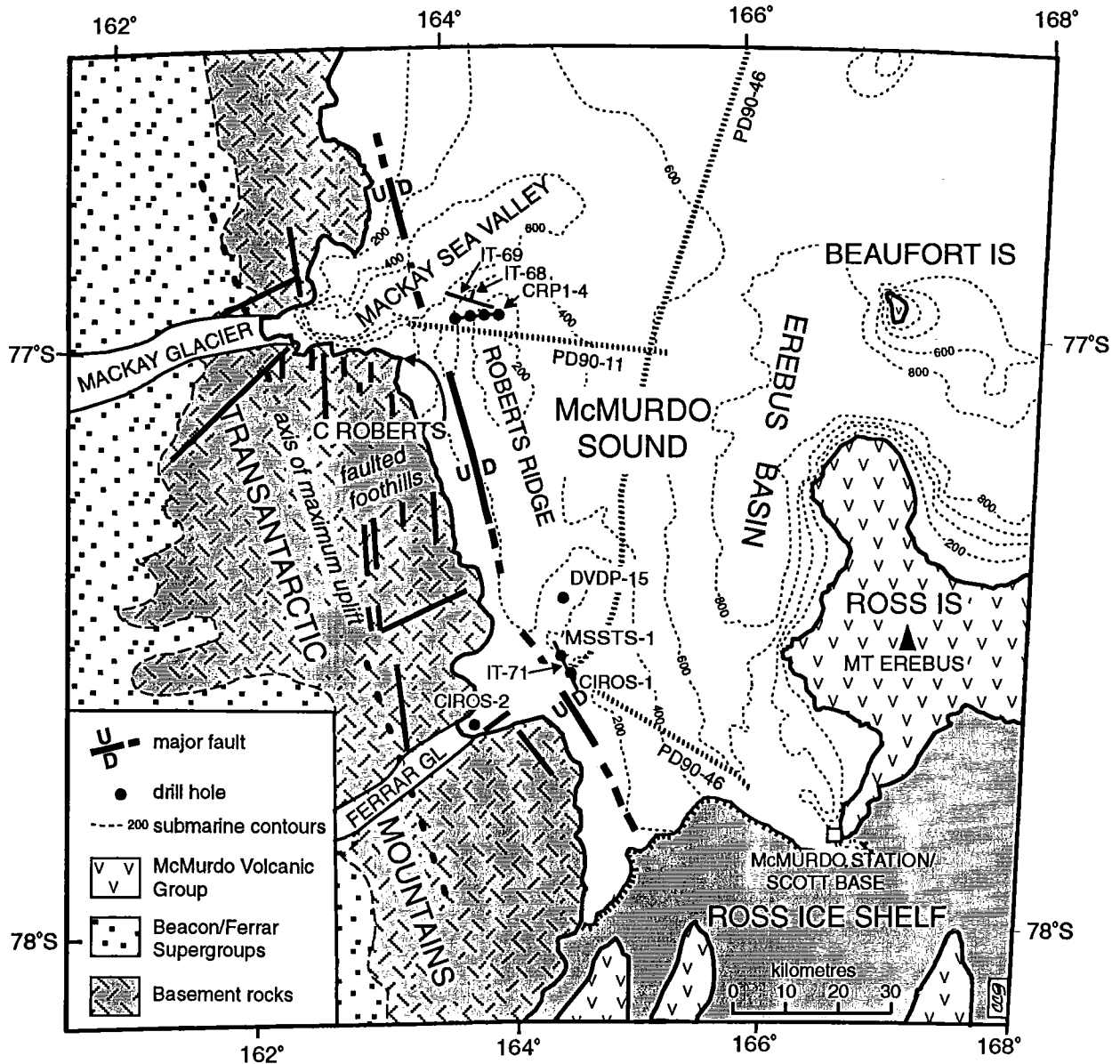


Fig. 3. Map of McMurdo Sound area showing the main geological and morphological features. Only major faults and clearly identified fault segments are shown. Sections of seismic profiles PD90-46 and PD90-11 and IT-69 and IT-71 (Figures 5, 9, 10, 11 and 13), are also marked. CRP 1-4 indicates the location for a drilling transect off Cape Roberts [ISC, 1994]. Lambert conformal conic projection.

The main bathymetric features of the rift margin off Cape Roberts are evident in the map of McMurdo Sound by Pyne *et al.* [1985], but more detail has been acquired in a survey using the USCGC POLAR STAR in 1993 [Henry and Pyne, unpublished data] with tracklines at 2 km spacing. Figure 6 shows the main features of the area from these data: the fault-bounded

trough immediately offshore recognized on United States Geological Survey (USGS) line 403 (Figure 2), Roberts Ridge, and the sharp truncation of Roberts Ridge by ice flow down Mackay Sea Valley during periods of more extensive glaciation. The survey also showed bedrock to be within a few meters of the sea floor over most of the area, presumably from scouring

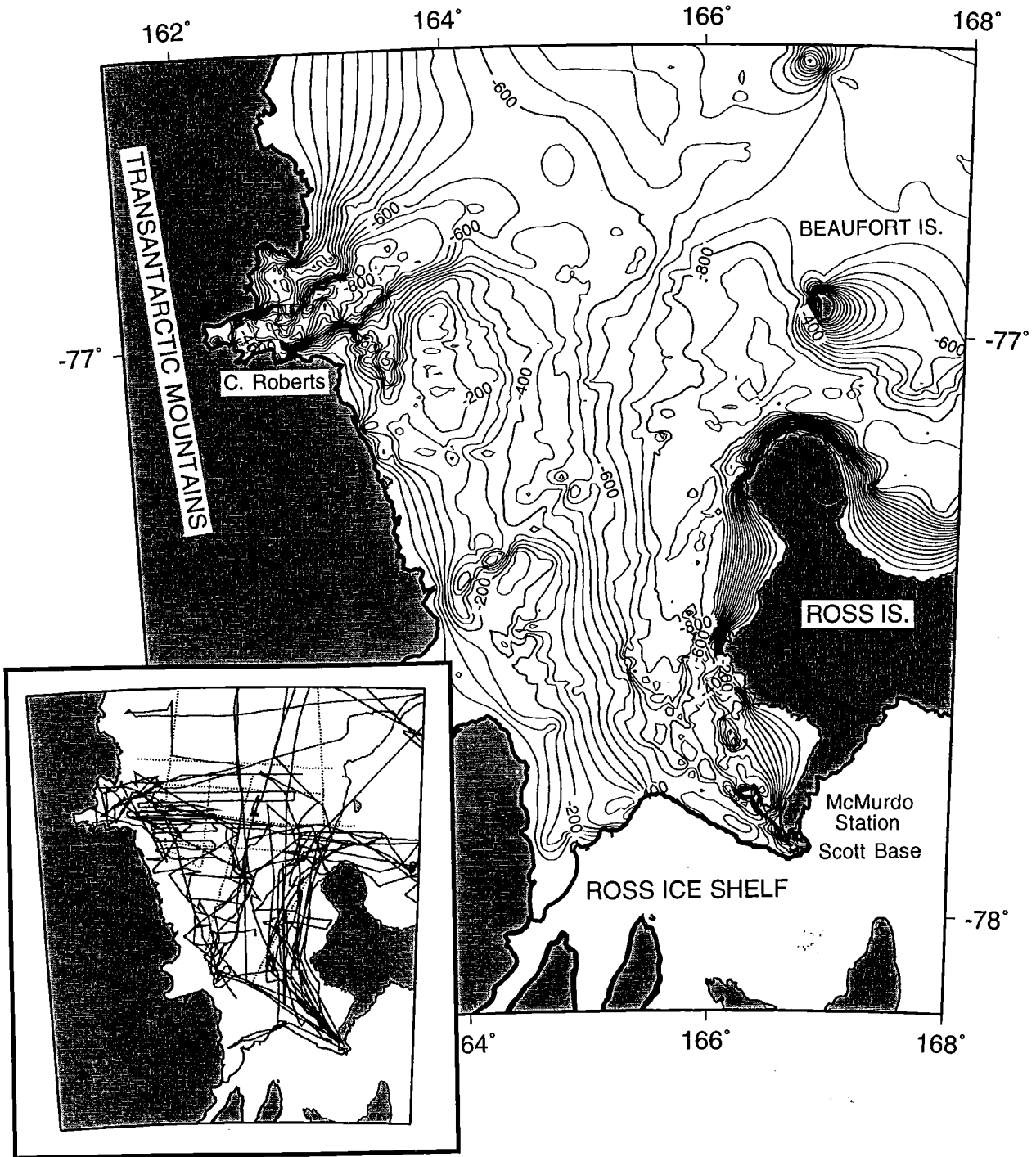


Fig. 4. Bathymetric map of McMurdo Sound. The map was constructed from surveys in the period from 1980 to 1993. The tracks are shown as an inset. Bathymetric contours at 50 m intervals. Lambert conformal conic projection.

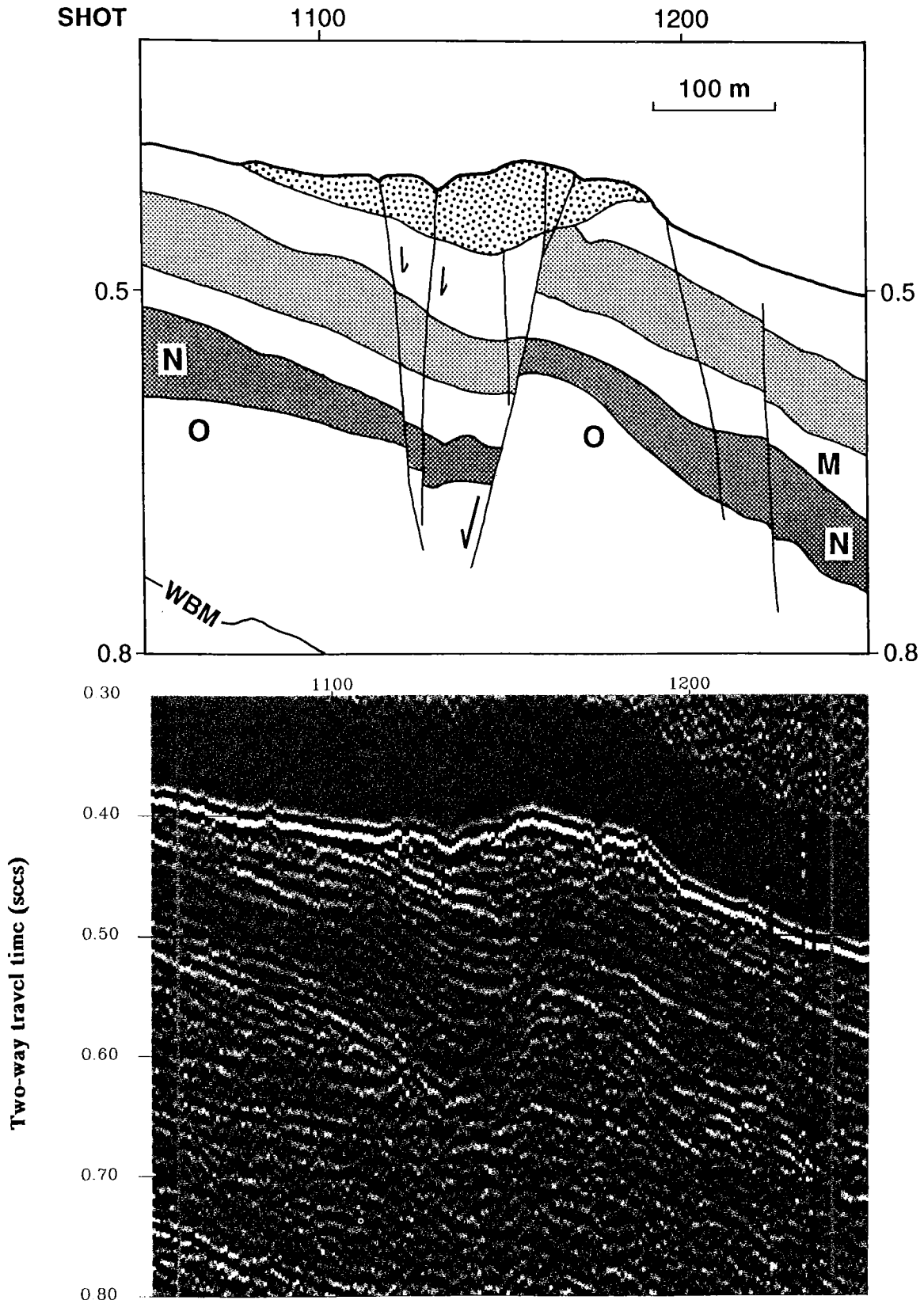


Fig. 5. A seismic profile (PD90-11) off Cape Roberts showing a cluster of faults passing through late Cenozoic strata. The faults also pass through channel fill of probable Pleistocene age and appear to reach the sea floor. Approximately to scale.

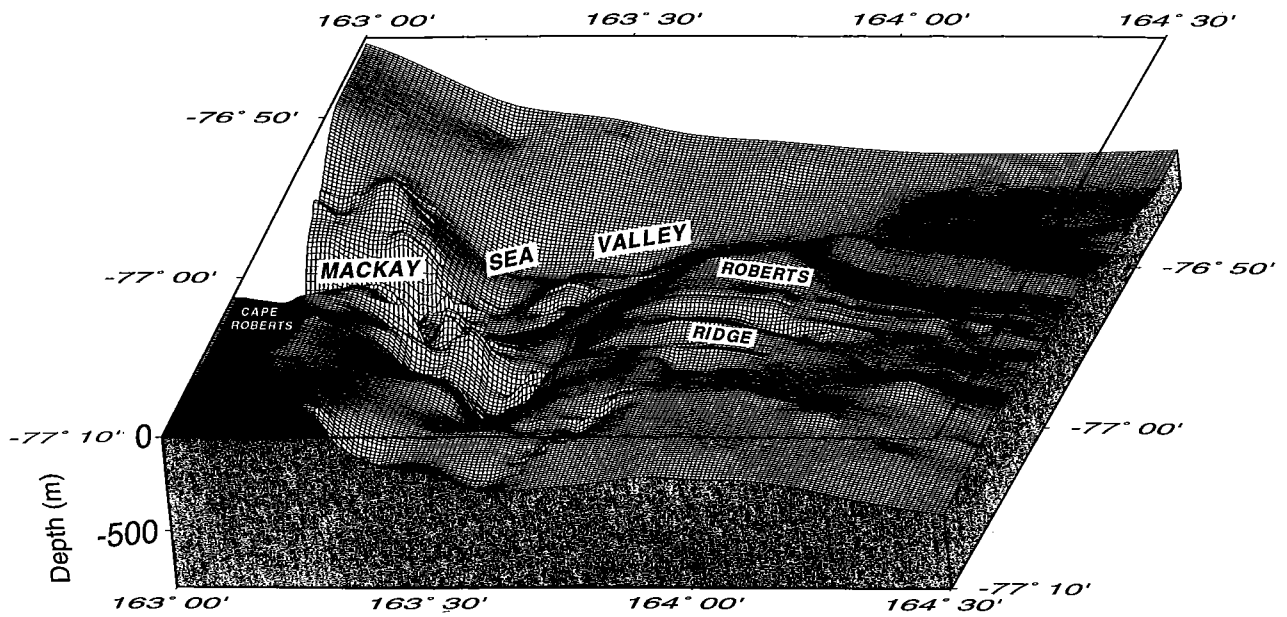


Fig. 6. Submarine topography off Cape Roberts, viewed from the southeast. Data from USCGC POLAR STAR [S.A. Henrys and A.R. Pyne, unpublished].

by Pleistocene ice. This is not so for basins in the Mackay Sea Valley, where Holocene mud reaches thicknesses approaching 100 m.

On a larger scale, the crustal geometry across the rift margin is constrained by free-air gravity measurements [e.g., Bennett and Sissons, 1984; Davey et al., 1987; Figure 7a]. They show very large gradients across the western Ross Sea coast [e.g., Smithson, 1972] and trending parallel to it and the Transantarctic Mountains. The major anomalies are the high off the coast at Cape Roberts with flanking lows over the Transantarctic Mountains and the Victoria Land basin [Davey and Cooper, 1987]. The gravity high off Cape Roberts reduces in level to the north and south. The sharp reduction in the value of gravity across the Transantarctic Mountain Front has been represented by a variety of models involving crustal thickening and density changes under the Transantarctic Mountains [e.g., Smithson, 1972; McGinnis et al., 1985; Robinson and Spletstoesser, 1986]. Modelling of the offshore gravity high [Davey and Cooper, 1987] indicates that it is associated with the asymmetric crustal thinning under the Victoria Land basin (Figure 7b). The flanking gravity lows are explained by crustal thickening and possibly a reduction in crustal density under the Transantarctic Mountains in the west, and by the younger, low density, sediments forming the Victoria Land basin

in the east. The models indicate a maximum crustal thinning to less than 20 km associated with this gravity high off Cape Roberts.

The western flank of the gravity high shows an inflection in the profile that has been interpreted by Bennett and Sissons [1984] off New Harbour and by Davey and Cooper [1987] off Cape Roberts as the western margin of the Victoria Land (sedimentary) basin and probably the fault zone forming the Transantarctic Mountain Front. In their uplift model for the Transantarctic Mountains (Figure 8a) Stern and ten Brink [1989] accept a rift graben mechanism for the origin of the Ross Sea, with the Transantarctic Mountains to Ross Sea boundary as one flank of the rift. They interpret the zone of thinning under the Victoria Land basin as a decoupling zone or free edge between the upflexed Transantarctic Mountains and the downwarped margin of the Ross Sea lithosphere. Erosion of the Transantarctic Mountains, sediment loading of the Victoria land basin and thermal effects are invoked to account for the amount of uplift and subsidence. Fitzgerald et al. [1986] thin the Ross Sea with low angle detachment faulting extending into the lithosphere, the master fault dipping west under the Transantarctic Mountains to produce the asymmetric uplift and subsidence (Figure 8b). However, Stern and ten Brink [1989] calculated that this model can achieve a maximum uplift of the hanging wall of

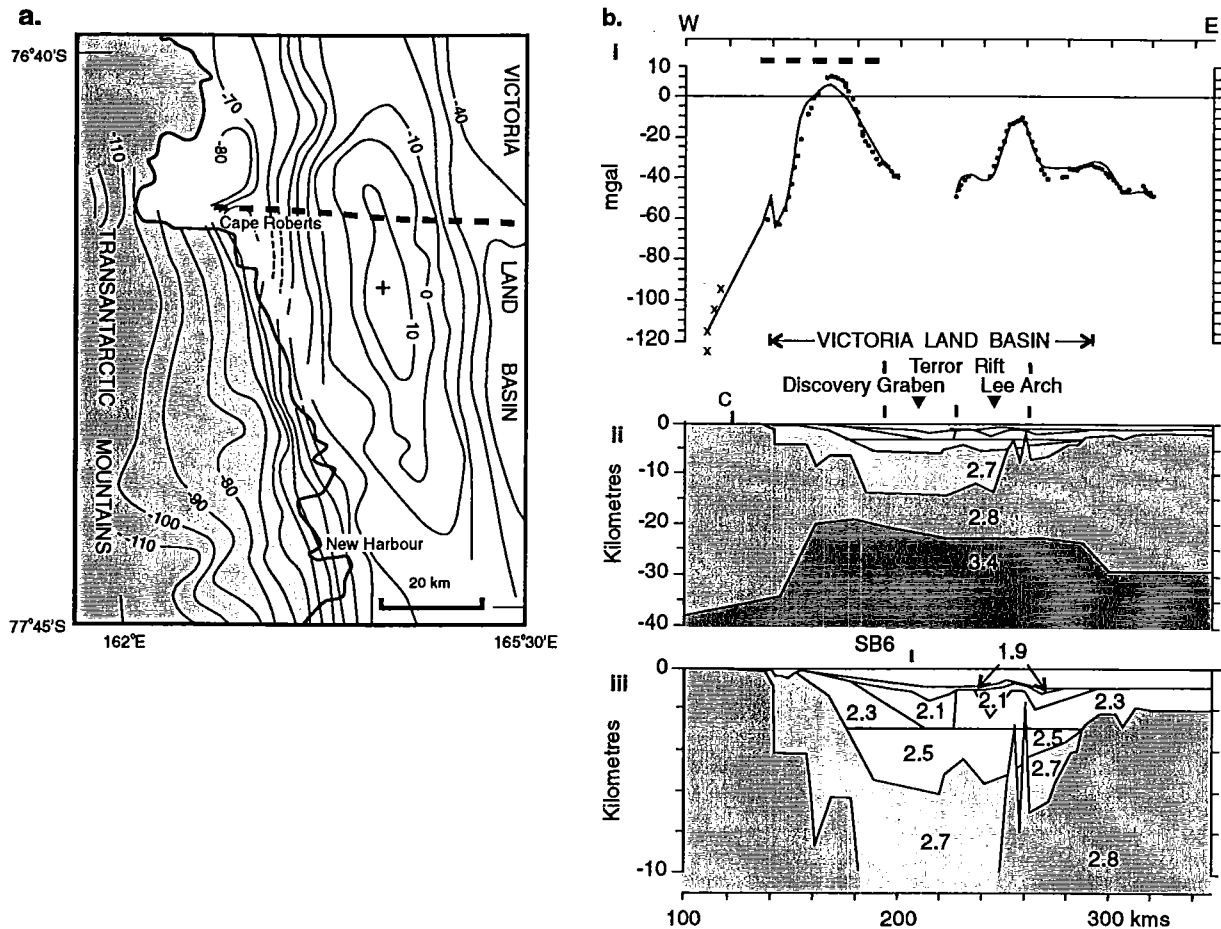


Fig. 7. (a) Free air gravity anomaly map for McMurdo Sound. Contours are at 10 mgal intervals (modified after Davey *et al.* [1987]). Heavy dashed line shows location of section in Fig. 7b. (b) Gravity model across the Transantarctic Mountain Front and the Victoria Land basin off Cape Roberts [after Davey and Cooper, 1987]. (i) Observed free-air gravity anomaly. Dots: Bouguer anomaly overland, crosses: calculated gravity anomaly, solid line: coastline. (ii) Two-dimensional model. Densities of the layers are in Mg/m^3 . Vertical exaggeration is 2.5:1. (iii) Detail of the upper part of the model in (ii). Vertical exaggeration is 10:1.

only 1000 m, in contrast to the 5000 m elevation difference observed between the summit of the Transantarctic Mountains and the Ross Sea floor.

Further evidence of the rift nature of the Victoria Land coast comes from the high heat flow [twice normal continental values, Decker and Bucher, 1982] and the extensive volcanism, which has given rise to 27 known volcanic piles with compositions largely from basanite to phonolite [Kyle, 1990]. Most are of Pliocene and Pleistocene age, but some date back to early Miocene (e.g., Mount Morning). An even older record of volcanism in McMurdo Sound comes from late Oligocene cores from the MSSTS-1 drillhole, in which volcanic grains chemically identical to the McMurdo

Volcanic Group have been described [Gamble *et al.*, 1986]. In addition, volcanic glass ascribed to the McMurdo Volcanic Group is reported to a depth of 400 m (early Oligocene - 35 Ma) in the CIROS-1 drill hole [George, 1989].

The start of denudation of the Transantarctic Mountains following initial uplift in the McMurdo Sound region has now been established from apatite fission track dating as 55 Ma [Fitzgerald, 1992]. The amount of uplift since then has been estimated at 6 km, though it is not clear to what extent rates of uplift or denudation varied through time. The timing of the beginnings of sinking and sediment deposition in the adjacent Victoria Land basin is much more speculative. It must

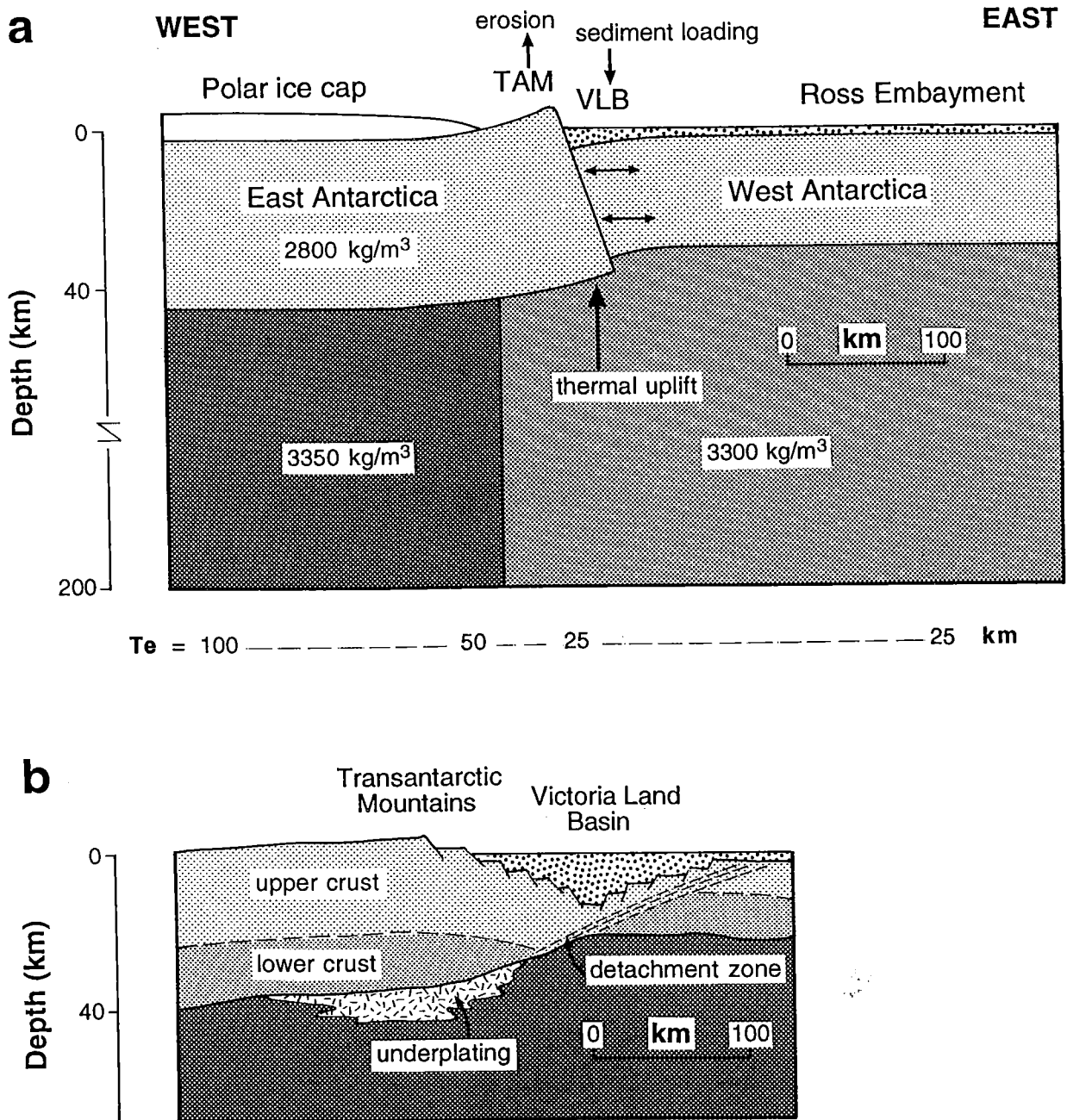


Fig. 8. Models for the Transantarctic Mountains and the Victoria Land basin. Vertical exaggeration is 2.5:1. (a) based on flexural rigidity, erosion and thermal uplift [Stern and ten Brink, 1989], and (b) based on lithospheric extension [Fitzgerald et al., 1986].

post-date the 180 m.y. Kirkpatrick Basalts and be older than the middle Eocene strata (c. 45 Ma) of V4. Most likely possibilities are 105 Ma, corresponding to the first Cretaceous rifting of the New Zealand region [Laird, 1993], and 55 Ma, about the same time as first uplift and denudation of the adjacent mountains.

REGIONAL STRATIGRAPHY

First knowledge of the stratigraphy off Cape Roberts came from a seismic survey (Table 2) by USCGC GLACIER in 1980 [D.J. Bennett, unpublished manuscript]. One of the seismic lines ran perpendicular to the

TABLE 2. Seismic Surveys off Cape Roberts

Year	Ship	Type	Length	Reference
1980	USCGC GLACIER	SCS	60 km	<i>Bennett</i> [unpublished]
1984	RV S P LEE	MCS	60 km	<i>Cooper and Davey</i> [1987]
1990	OGS EXPLORA	MCS	300 km	<i>Brancolini et al.</i> [this volume]
1990	RV POLAR DUKE	SCS	650 km	<i>Bartek et al.</i> [in press]
1993	USCGC POLAR STAR	3.5 kHz	300 km	<i>Henrys and Pyne</i> [unpublished]

coast and clearly showed a sedimentary sequence dipping gently seaward beneath the younger strata in the basin. At that time, however, the sequence could not be related to any strata of known age. An earlier seismic profiling survey had been carried out in McMurdo Sound by the USCGC Glacier in February 1974 [*Northey et al.*, 1975] but this did not extend as far north as Cape Roberts. This survey was carried out as an adjunct to the Dry Valley Drilling Project (DVDP) [*McGinnis*, 1981] for the first offshore drill hole in McMurdo Sound (DVDP15) in 1976. This hole (Figure 3) reached just 65 m below the sea floor, recovering only undated (but probably late Pliocene) basaltic sand [*Barrett and Treves*, 1981].

Lithology of strata off the Victoria Land coast was first revealed with the drilling of MSSTS-1, which reached 229 m below the sea floor in 1979 [*Barrett*, 1986]. MSSTS-1 cored through a thin Pliocene to Pleistocene glacial sequence into a late Oligocene glacial section, showing the antiquity of Antarctic glaciation in this region to be similar to the Eastern basin drilled by the M/V GLOMAR CHALLENGER in 1973 [*Hayes et al.*, 1975]. The hole intersected the widespread X and Y reflectors of *Northey et al.* [1975], indicating that the Oligocene strata cored in MSSTS-1 were extensive in the Victoria Land basin.

A regional stratigraphic framework was established for the Victoria Land basin in 1984 by the R/V S.P. LEE [*Cooper and Davey*, 1985, 1987] from 1850 km of multichannel seismic profiles, along with sonobuoy, gravity and magnetic data. They recognized a sedimentary and volcanic basin fill 10-14 km thick and six seismic units (V1-V6) above acoustic basement (V7) that could be mapped throughout most of the basin (Table 1).

One area the stratigraphy could not reach with any confidence was the western shelf of McMurdo Sound, where MSSTS-1 had been drilled in 1979. Reflection surveys had revealed a thick flat-lying sedimentary sequence, but the shallow hard sea floor created difficulties in processing out multiple reflections. However,

this was the only area that was logistically feasible for drilling from the fast ice, and a further hole was drilled in 1986. This hole, CIROS-1, was drilled 4 km south of MSSTS-1 and to a depth of 702 m. It passed through largely late Oligocene shallow marine-glacial strata (20 to 366 mbsf) and early Oligocene (now revised to include middle Eocene, *Hannah* [1994]) deep marine-glacial strata (366-702 mbsf). Although the late Oligocene strata in both MSSTS-1 and CIROS-1 were lithologically similar (diamictite, sandstone and mudstone) detailed correlation has not been possible.

A further multi-channel seismic survey was carried out in the southern part of the Victoria Land basin in 1990 by the OGS EXPLORA [*Brancolini et al.*, this volume]. Several lines intersected off Cape Roberts, one of which is shown as Figure 9, and these have confirmed and extended the regional stratigraphy and geometry developed by *Cooper and Davey* [1987]. Of particular significance are the filled channel bodies several kilometers wide and 100-200 m thick in the upper few hundred meters of strata on the western shelf of McMurdo Sound (Figure 10). Disruption of horizontal stratification by cutting and filling on this scale helps explain why detailed correlation between the CIROS-1 and MSSTS-1 drill holes was not achieved.

AGE AND CORRELATION WITH CIROS-1

About 650 km of high resolution single channel seismic data collected from the RV POLAR DUKE in McMurdo Sound in 1990 [*Anderson and Bartek*, 1992] has provided the best basis thus far for correlation between CIROS-1 on the margin of the Victoria Land basin and the basin-wide sequences of *Cooper and Davey* [1987]. Analysis of these data, which have a resolution of better than 10 m, has provided a detailed stratigraphy with 20 distinct sequences labelled from A to T and each typically a few tens of meters thick [*Bartek et al.*, in press]. The stratigraphy is best developed toward the center of McMurdo Sound, but it has been carried southwest by line PD90-46 (Plate 1) onto

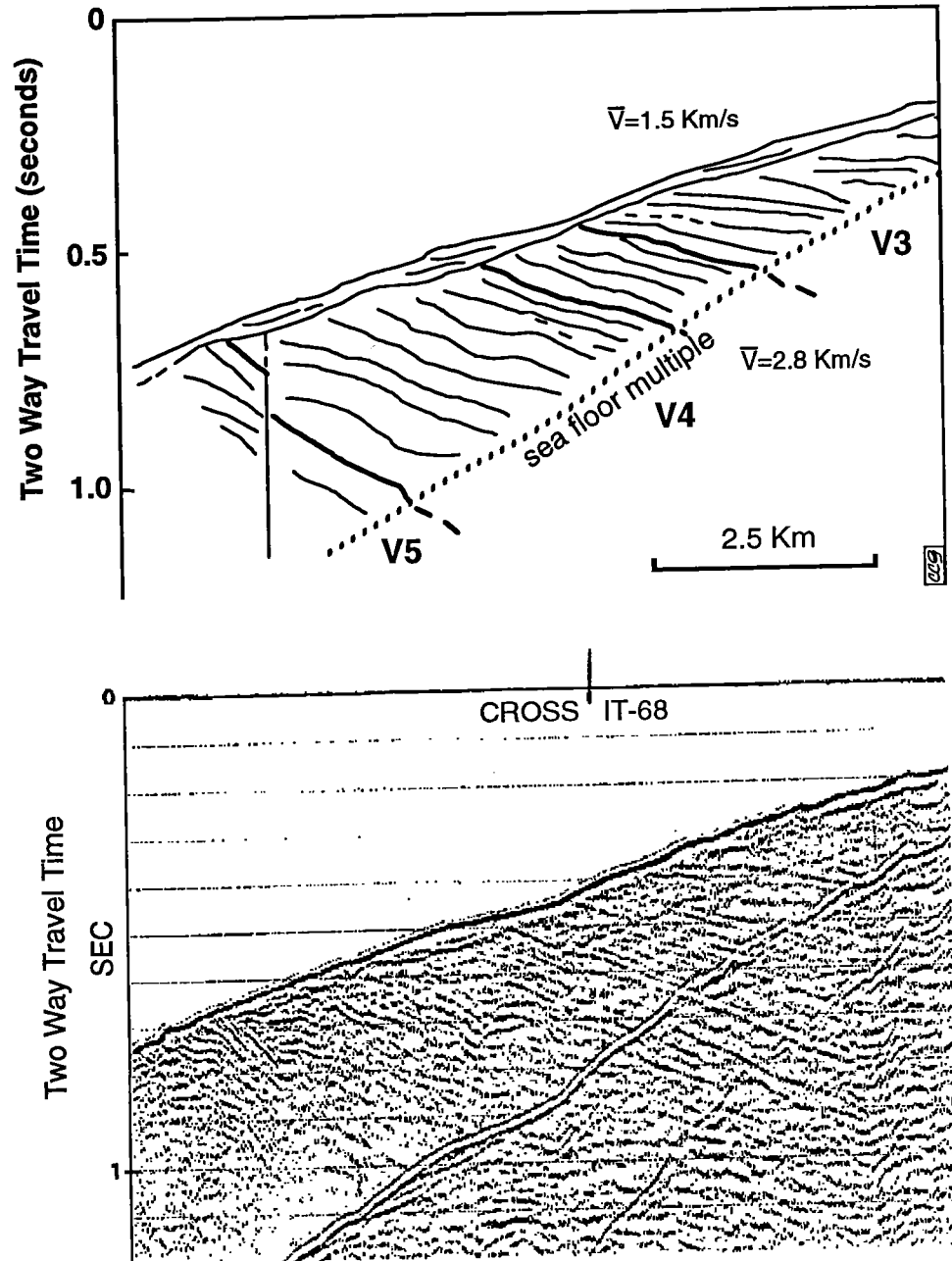


Fig. 9. Segment of interpreted seismic profile IT-69 showing the strata off Cape Roberts using the stratigraphy of Cooper and Davey [1987]. Vertical exaggeration is about 2:1.

the relatively shallow western shelf of McMurdo Sound to the CIROS-1 drill hole, and west onto Roberts Ridge by line PD90-11 (Plate 2).

Several seismic sequences (N, O, P and Q) can be traced in lines PD90-12 and PD90-46 into CIROS-1. Depths determined for sequence boundaries from PD90-

12 using two-way travel times and a velocity profile from the CIROS-1 drill hole give values that correspond roughly to significant lithologic boundaries in the core (Figure 11, Table 3). Sequences N and O are each unit with a thin diamictite at the base overlain by several tens of meters of mudstone. Sequence P is a thick

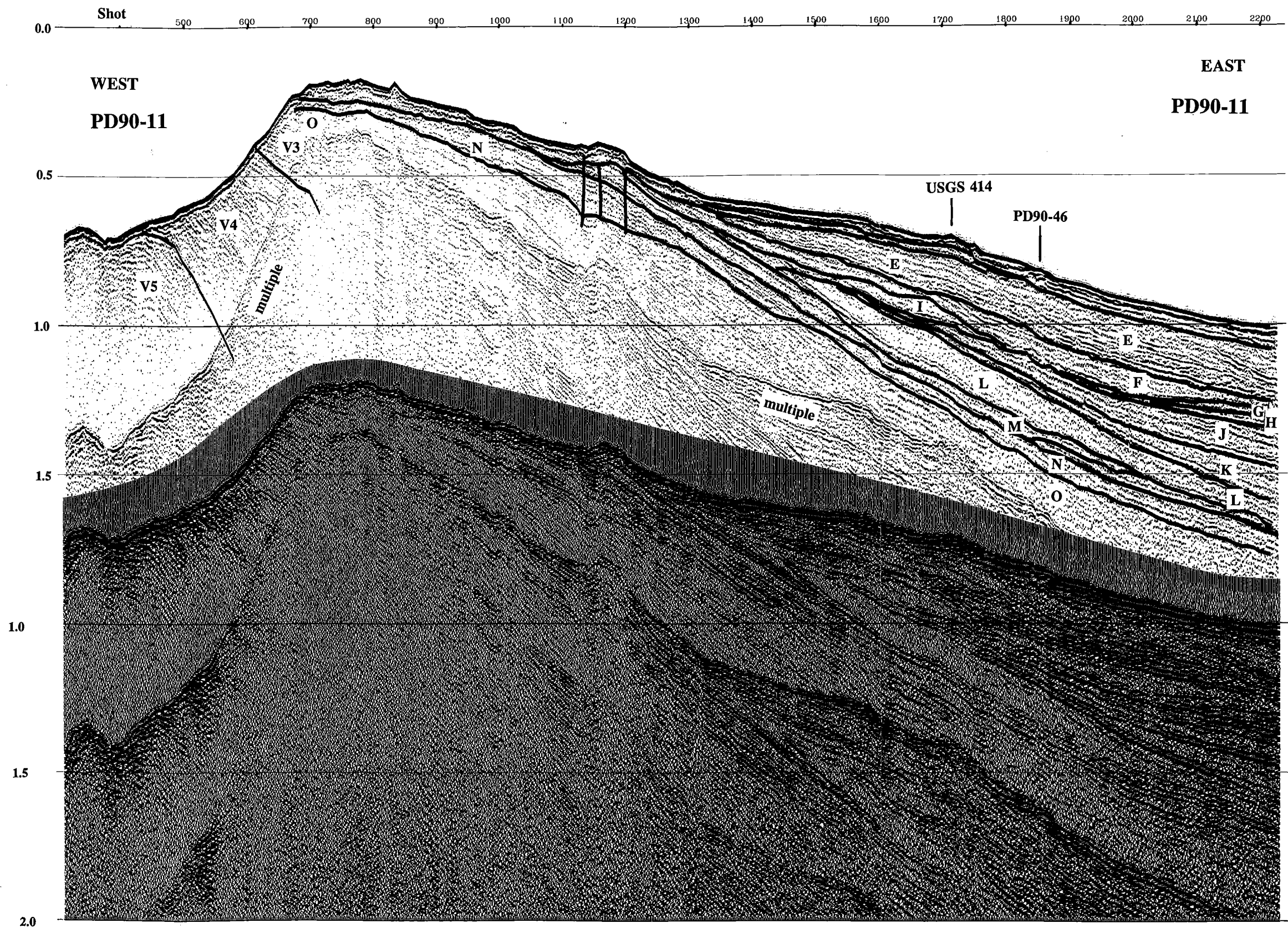


Plate 2. Interpreted single channel seismic profile (PD90-11) of Cape Roberts sequence, showing both the Victoria Land basin stratigraphy of *Cooper and Davey* [1987] and the sequences of *Bartek et al.* [in press]. Vertical exaggeration about 14:1 (water) and 10:1 (rock). See Figure 3 for location.

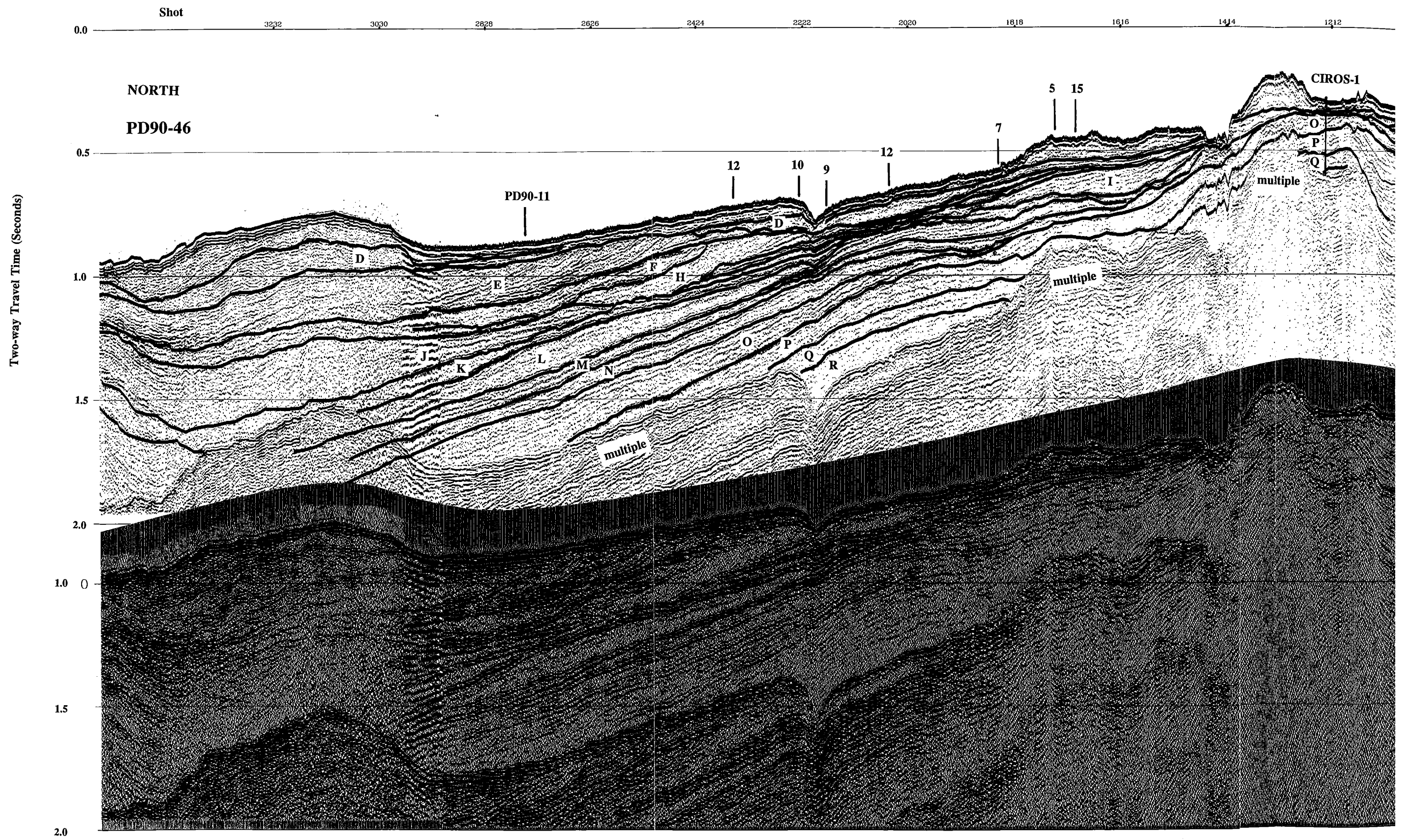


Plate 1. Interpreted single
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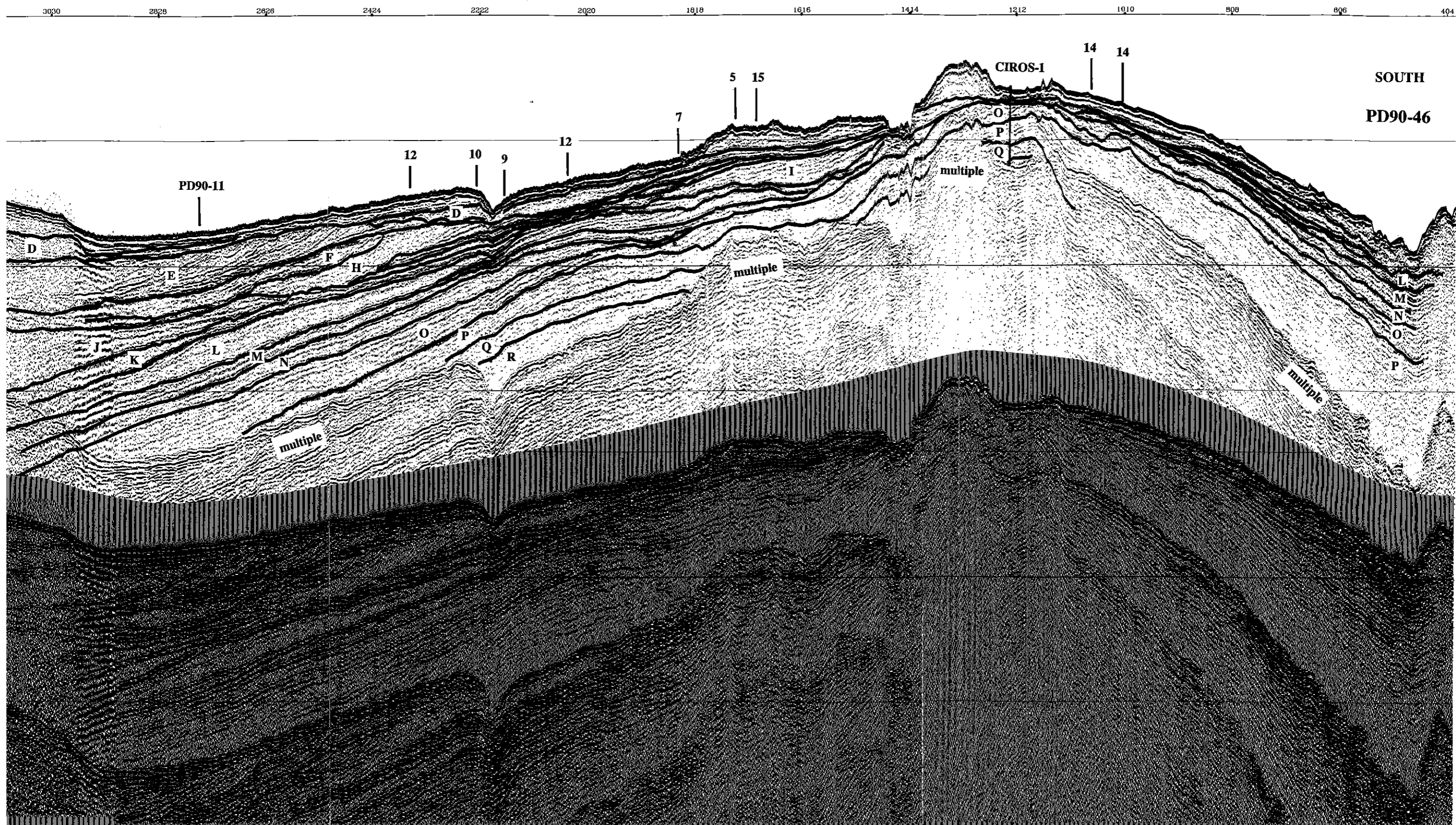


Plate 1. Interpreted single channel seismic profile (PD90-46) running north from the CIROS-1 site to the sequence off Cape Roberts [from Bartek *et al.*, in press], and southwest towards McMurdo Station. Vertical exaggeration about 30:1 (water) and 20:1 (rock). See Figure 3 for location.

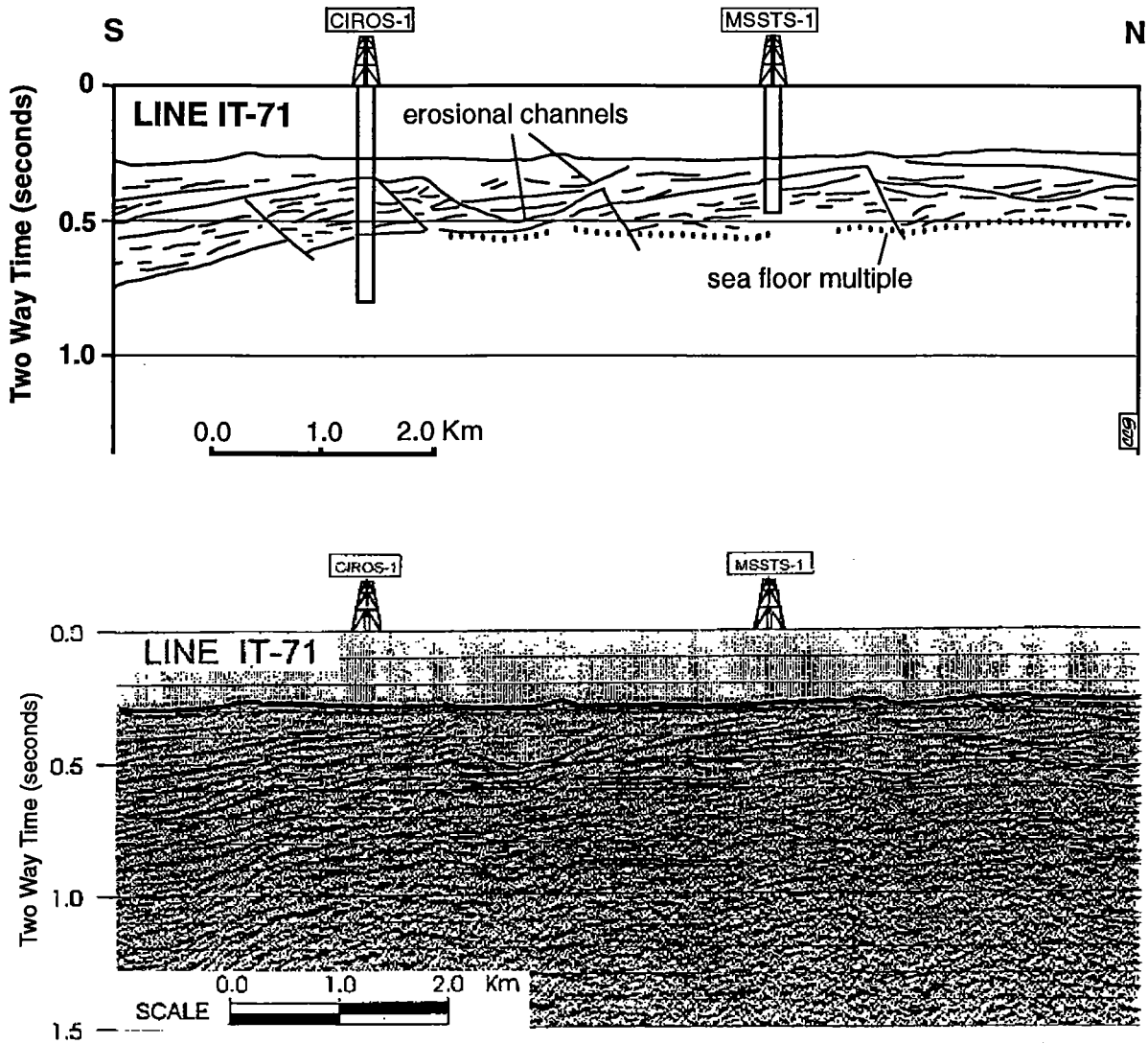


Fig. 10. Segment of interpreted seismic profile (IT-71) running across the mouth of Ferrar Valley extension and the CIROS and MSSTS drill sites. Broad shallow channels of probable glacial origin are evident in the upper few hundred meters of the sedimentary section. Vertical exaggeration is about 2:1.

composite diamictite sequence representing many periods of ice advance, but including a significant period of retreat half way through, in the form of a 15-m-thick mudstone bed. This is significant because it shows that resolution of the seismic data is still not sufficient in places such as this to resolve individual glacial cycles. Sequence Q is a coarse glaciofluvial interval that includes two separate glacial events. Its base represents the first deposition following a mid Oligocene fall in sea level at the site, thought to correspond to the fall at 30 Ma in the *Haq et al.* [1987] eustatic sea level curve.

The base of Q is correlated with the most geologically significant boundary in the drill hole at a depth of 366 mbsf. It represents a shift in facies from offshore marine muddy sandstone to fluvial sandstone and conglomerate (a shallowing estimated to be at least 300 m [Webb, 1989]), and a time break from 34 to 30.5 Ma [Harwood et al., 1989]. On the detail of this correlation, the base of Q is marked by a prominent and persistent reflector that we believe to be the well-cemented pebble conglomerate beds at around 350 m, with bulk velocities in excess of 5 km/sec, in contrast to the average for the interval at 3.5 km/sec (and 2

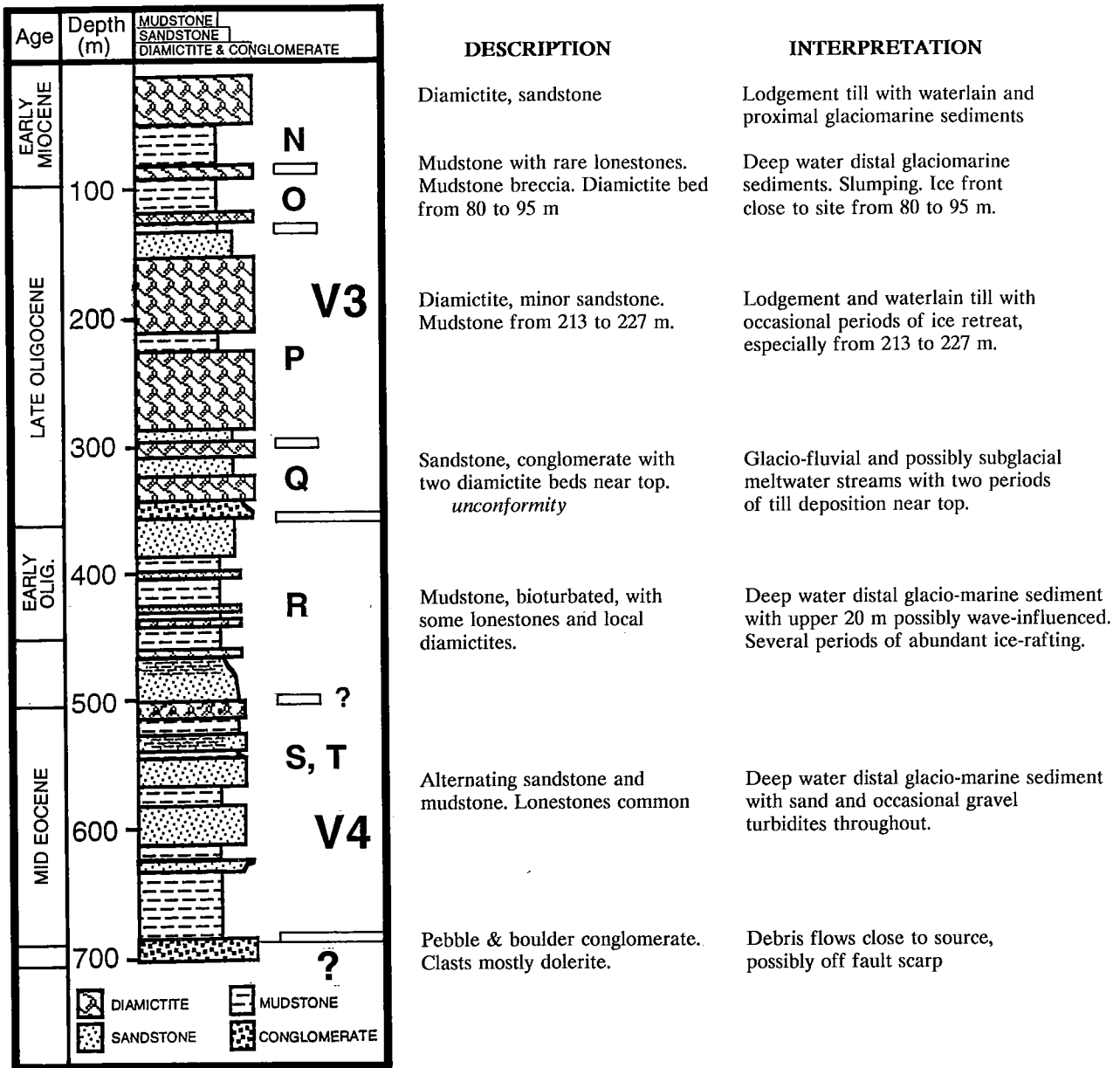


Fig. 11. Lithology of the CIROS-1 drill core [after *Hambrey et al.*, 1989]. Ages are from *Harwood et al.* [1989], apart from the revised mid-Eocene age for the interval from 696 to 500 m by *Hannah* [1994]. The Victoria Land basin stratigraphy of *Cooper and Davey* [1987] and the sequences of *Bartek et al.* [in press] are also shown.

km/sec for the underlying mudstone). The seismic reflector forming the base of Q is thus likely to be the base of the pebble conglomerate 16 m above the base of the fluvial interval rather than at the unconformity at 366 mbsf. However, the difference in depth between the strata causing the reflector and the unconformity is only

twice the resolution of the seismic record, and they may be taken for practical purposes to be coincident.

The base of Q and the 366 mbsf level in the CIROS-1 core are also considered to correspond to the base of V3 in the stratigraphy of *Cooper and Davey* [1987] by the following argument. *Henrys* [in *Barrett*

TABLE 3. Seismic sequences of *Bartek et al.* [in press] from PD90-12 with corresponding facies and ages from the CIROS-1 drill hole. Interval two way times and velocities are from their Figure 2.

Sequence	Interval		Calculated depth to base	Depth to lithological change	Age	Thick-ness	Facies from CIROS-1
	TWT	Velocity					
		2.0			?	20+ m	Diamictite
N	0.045	2.0	48 m	48 m	22-24 m.y.	47 m	Mudstone
O	0.090	2.0	90 m	95 m	24-25 m.y.	25 m	Diamictite top, then mudstone
P	0.122	3.0	122 m	120 m	25-29 m.y.	165 m	Diamictite, minor sandstone, mudstone
Q	0.233	3.5	289 m	285 m	29-30.5 m.y.	81 m	Sandstone, conglomerate, diamictite
R	0.263	?	342 m	366 m	4 m.y. unconformity 34.5-36 m.y.	134 m	Deep water mudstone, some sandstone and diamictite
S	?	?	?	500 m	c.45 m.y.	136 m	Turbidite sequence, minor diamictite
T	?	?	?	636 m	c.45 m.y.	60 m	Deep water mudstone
?	?		?	696 m	?	6 m	Dolerite boulder conglomerate
				702 m			

and Davey, 1992, Figure 3.2, and Plate 2, this paper] identified the V3/V4 and V4/V5 boundaries in PD90 tracklines 10 and 11 due east of Cape Roberts, based on comparisons with USGS line 403, which crossed PD90-11 and had the 'V' boundaries carefully located by Cooper and Davey [1987]. He then traced the base of Bartek et al.'s sequence N from PD90-46 to PD90-10 and 11, where it lies 300 m above the base of V3. This compares with a vertical distance of 252 m (calculated from velocity) or 286 m (measured from drill hole) from the base of N to the base of Q at the CIROS-1 site (Table 3), (base of N to base of Q) in Plate 1 over the entire distance from east of Cape Roberts to the CIROS-1 site and beyond, a distance of about 100 km. This link dates the base of V3 at 30.5 Ma and provides an age of 34.5 Ma (early Oligocene) for the upper part of V4.

Bartek et al. [in press] also compared the thickness of the sequences below Q (i.e., R, S and T) in PD90-46 with the thickness of strata in CIROS-1 below the unconformity, and thought it possible that the top of the boulder conglomerate (base of the deep-water mudstone) near the base of the drill hole at 696 mbsf could be the base of T. The thickness of deep-water mudstone in the lower part of CIROS-1 (330 m) is somewhat less, though not much less, than the thickness of V4 off Cape Roberts (430 m thick 15 km offshore and thinning

landward). It is possible, therefore, that the 330 m interval represents the whole of V4 at the CIROS-1 site, with a thick conglomerate section beneath. Alternatively, the conglomerate from 696 to 702 m, the bottom of the drill hole, could well be underlain by further Eocene deep-water mudstone and that prospect in balance seems more likely, as the conglomerate is interpreted as a debris flow [Hambrey et al., 1989] (Table 4).

GEOLOGICAL MAP AND CROSS-SECTION

Sufficient seismic profiles have now been collected to trace boundaries of major seismic units over the area to the east of Cape Roberts (Figure 12). The strata are found to strike consistently just west of north and to dip as a gentle monocline at 2° to the east. Only the older seismic units have been identified, i.e., V3, V4 and V5 of Cooper and Davey [1987], V1 and V2 having been largely eroded away in this area. V4 has been subdivided into 2 distinct parts, V4a and V4b. Although these units are capable of further subdivision on single channel profiles (at least 6 sequences can be recognized in V3 in some places), trackline coverage is not sufficient to resolve them across the whole area. Facies inferred for each unit are based on correlation with the CIROS-1 drill hole 70 km to the south (Figure 11, Table 3).

TABLE 4. Seismostratigraphy of the Victoria Land Basin and McMurdo Sound

Multichannel survey [Cooper and Davey, 1987]	Single channel survey [Bartek et al., in press]		CIROS-1 drill hole [Barrett, 1989]
Sequence	Sequence	Units	Age and Lithology
V1	A-D	1	Quaternary coarse glacial debris not present
V2	E-M		
V3	N-Q	2-17	late Oligocene-early Miocene diamictite, sandstone, mudstone
V4	R-T	18-21	mid Eocene-early Oligocene mudstone, turbidite sandstone, dropstones throughout
V4 or V5	?	22	??? boulder conglomerate

The sedimentary section is bounded on its western margin by two subparallel steeply dipping north-trending faults about 10 km offshore, upthrown to the west and bringing basement rocks to the sea floor. These are most likely to be granitoid bodies like the exposures around Granite Harbour. However, a sizeable positive magnetic anomaly immediately west of the sedimentary section has been recognized by Behrendt et al. [1987] and confirmed by recent German-Italian Aeromagnetic Research in Antarctica (GITARA) survey, indicating a more basic intrusive body, perhaps a gabbro.

V5, the oldest sedimentary unit, is of unknown age and lithology. It underlies the floor of Mackay Sea Valley, and lies close to the sea floor east of Cape Roberts but is truncated there by a north-trending fault. Nevertheless, V5 can be seen in seismic section, and is estimated reach a thickness there between 2 and 5 km (Figure 2). The most likely age lies between 105 and 55 Ma (see discussion on comparisons with possible New Zealand counterparts below). The prospect of Late Cretaceous strata at the margin of the Victoria Land basin is supported by the presence of Late Cretaceous foraminifera in Pleistocene moraines in lower Taylor Valley 70 km to the south [Webb and Neall, 1972]. The foraminifers could well have been reworked and carried west by Pleistocene ice from strata beneath McMurdo Sound.

V4 is presumed from CIROS-1 to be largely deep water mudstone of Eocene-early Oligocene age, and underlies the west flank of the ridge, curving eastward into the Mackay Sea Valley. However the curve is solely in response to the bathymetry, for structure contours on the base of V4 (Figure 12 - inset) indicate

the surface to be a plane dipping gently just north of east. Isopachs constructed for V4, the only unit for which both upper and lower surfaces can be mapped over a significant area, show it to thicken gently seaward from around 430 m at its westernmost extent to over 500 m, 20 km to the east. The uniformity of thickness from south to north across the Mackay Sea Valley indicates that the deposition of V4 predated the development of the Mackay drainage system, a glacially ended valley.

V3 is the youngest of the exposed strata of the Victoria Land basin in the mapped area. The sequence underlies Roberts Ridge and the area to the east with a maximum thickness of a little over 200 m attained just east of the ridge crest. It is inferred to comprise alternations of diamictite, shallow marine mudstone and sandstone of late Oligocene to early Miocene age, recording several advances of east Antarctic ice beyond the mountains and onto the basin floor.

Seismic mapping also shows a thin patch of sediment deposited over an area of 3 by 10 km on the southern margin of the Mackay Sea Valley (Figure 12). It is interpreted as channel fill on the southern margin of the valley at some time since the early Miocene when the Mackay Glacier was much more extensive.

COMPARISON WITH SEQUENCES OF SIMILAR AGE IN NEW ZEALAND

It has long been accepted that in pre-Cenozoic times Australia and Antarctica formed the major part of eastern Gondwanaland with New Zealand and West Antarctica as the Pacific continental margin [e.g.

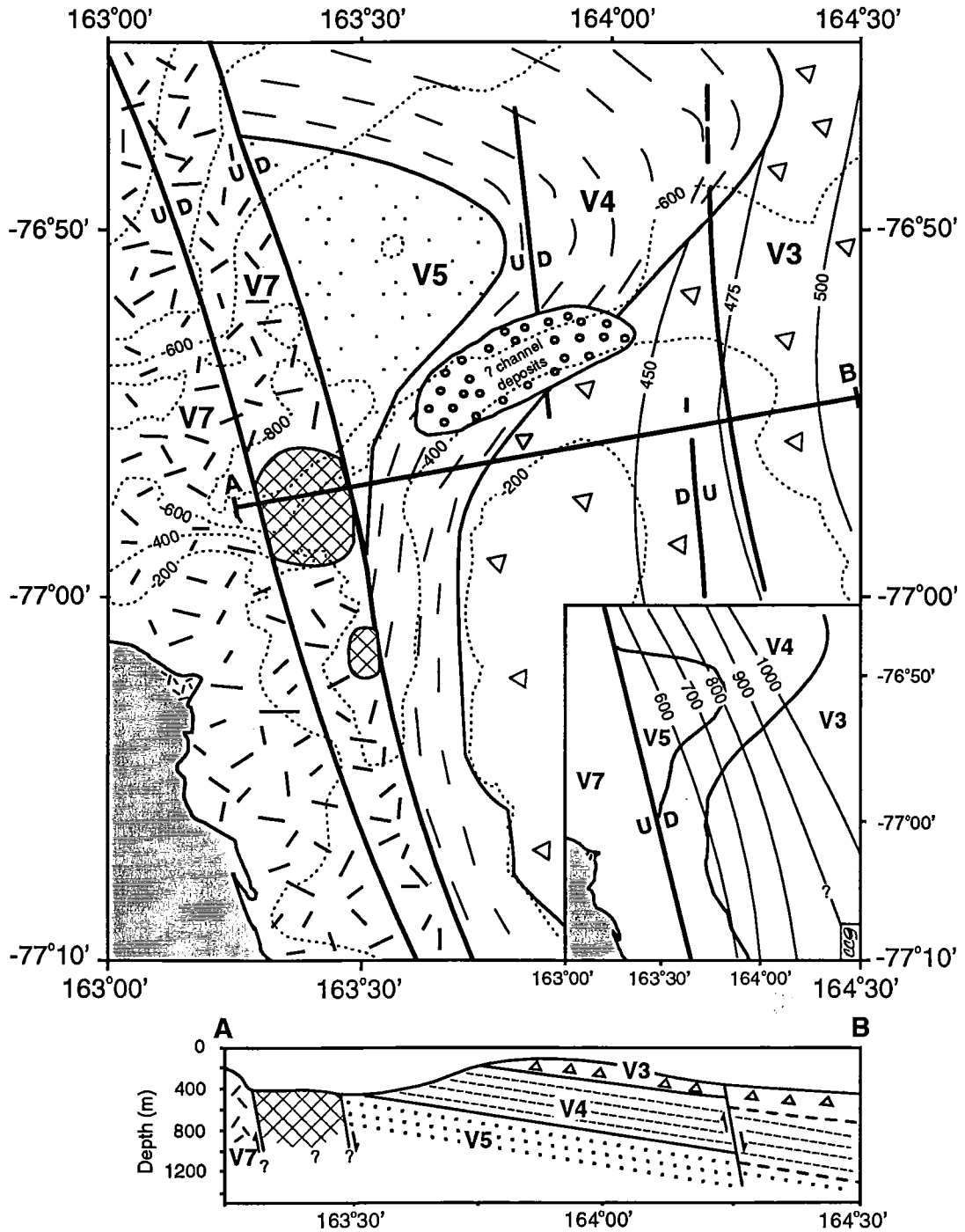


Fig. 12. Geological map and cross-section of strata exposed at or near the sea floor off Cape Roberts using the stratigraphy of *Cooper and Davey* [1987]. The map has been constructed largely from 2 north-south (USGS 401, IT-68) and 4 east-west (PD90-10, PD90-11, IT-69, USGS 403) seismic lines. The only outcrop is a small area of granitoid basement on Cape Roberts. Cross-hatched subcircular areas within the basement are inferred from magnetic surveys to be basic intrusive bodies.

Units and symbols are as in Figure 2 and Table 1. Major faults and thickness contours (in meters) for V4 are also shown. Contours in meters below sea level on the base of V4 are presented as an inset. Vertical exaggeration for the cross-section is 5:1.

Craddock, 1975; Crook and Belbin, 1978; Bradshaw *et al.* 1981], and reconstructions such as those of Lawver *et al.* [1992] indicate that the New Zealand region was once adjacent to the Ross continental shelf (Figure 13). In this section, the post-Gondwana fragmentation history of the better known New Zealand region, from mid Cretaceous to late Oligocene, is compared briefly with what is known of the Victoria Land basin margin to help provide a history for the latter.

The time period from mid-Cretaceous to late Oligocene has been most recently reviewed as the "third window" of New Zealand geology [Ballance, 1993a], in the introduction of a multi-author volume on sedimentary basins of the South Pacific (but mostly New Zealand) region. According to Ballance, the window saw the formation of all of the major marginal basins of the Southwest Pacific. We might therefore expect Ross Sea basins to have similar histories and features. The volume provides both histories for individual basins and regions as well as broader syntheses. Korsch and Wellman [1988 but written around 1980] provide a briefer but still current overview.

From around 100 to 25 Ma the New Zealand continent stretched, cooled and subsided as it separated from Australia and Antarctica [Ballance, 1993b]. This history is reflected not only in sediments on the old eastern (Pacific) margin of the continent through Cretaceous relict trench fill facies followed by the extensive deep water Whangai shale of Late Cretaceous and early Cenozoic age, but also in basins that lay largely within the continental margins, where a related but somewhat different sequence of facies is recorded.

The Great South basin off the present southeast coast of New Zealand is one of a number of basins (others include the Taranaki and Canterbury basins) that formed on and around the New Zealand continent following mid-Cretaceous rifting, and whose pattern of sedimentation might be expected to be comparable with the Victoria Land basin. Information, largely from oil company surveys and four drill holes to basement [Anderton *et al.*, 1982], has been reviewed by Carter [1988] and Beggs [1993]. Deposition began at around 100 Ma with the Hoiho Sequence [Beggs, 1993] in active grabens and half grabens during initial rifting with terrestrial conglomerates and sandy coal measures. Equivalent onshore sediments are largely conglomeratic, but include lacustrine facies, which may be more extensive offshore.

The Hoiho Sequence is covered by a regional transgressive surface that separates it from the overlying Pakaha Sequence, which ranges in age from Campanian to late Paleocene (around 85 to 60 Ma). The Pakaha

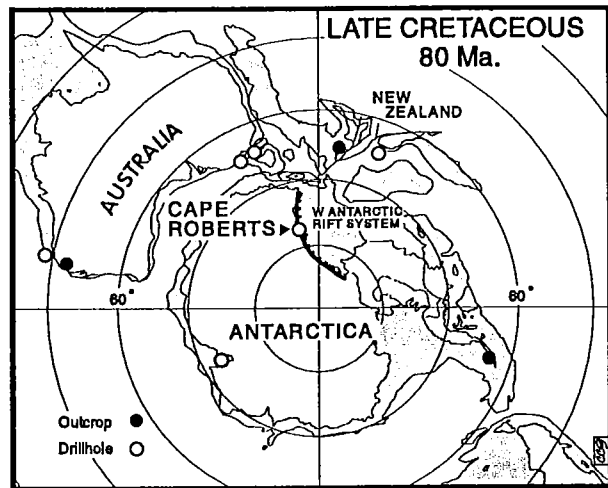


Fig. 13. Reconstruction of the Antarctic-New Zealand region 80 million years ago [after Lawver *et al.*, 1992], showing the proximity of Cape Roberts to strata of similar age in the New Zealand region.

Sequence comprises a basal shallow marine sandstone that grades upward and to the southeast into siliceous and then calcareous mudstone. To the northwest, shallow marine sandstone appears to grade laterally into terrestrial coal measures (Figure 14).

The Pakaha Sequence is unconformably overlain by the Rakiura Sequence, a dark shale over much of the basin though it grades northwestward into shoreline facies and southeastward into chalk. This pattern of lateral facies variation is much the same pattern as for the underlying sequence. Age ranges from late Paleocene to early Oligocene.

The youngest sequence in the basin, the Penrod, comprises a thin veneer (typically a few tens of meters) of late Oligocene and younger carbonate and greensand. The base of the sequence here is a widespread unconformity that effectively ends a long period of discontinuous transgressive sedimentation that began in the Cretaceous. A similar break in sedimentation occurs throughout southern New Zealand about this time and has been named the Marshall Paraconformity [Carter and Landis, 1972; Carter, 1985]. It has been linked to the then 29 Ma mid-Tertiary sea level fall [Loutit and Kennett, 1981]. Carter [1985] has argued rather persuasively for a regional sea-level rise and sediment starvation as its cause, but in many parts of New Zealand the late Oligocene is characterized by extensive thin (0-300 m) shallow marine bioclastic limestones swept by currents and possibly waves in a relatively shallow shelf setting [Nelson, 1978].

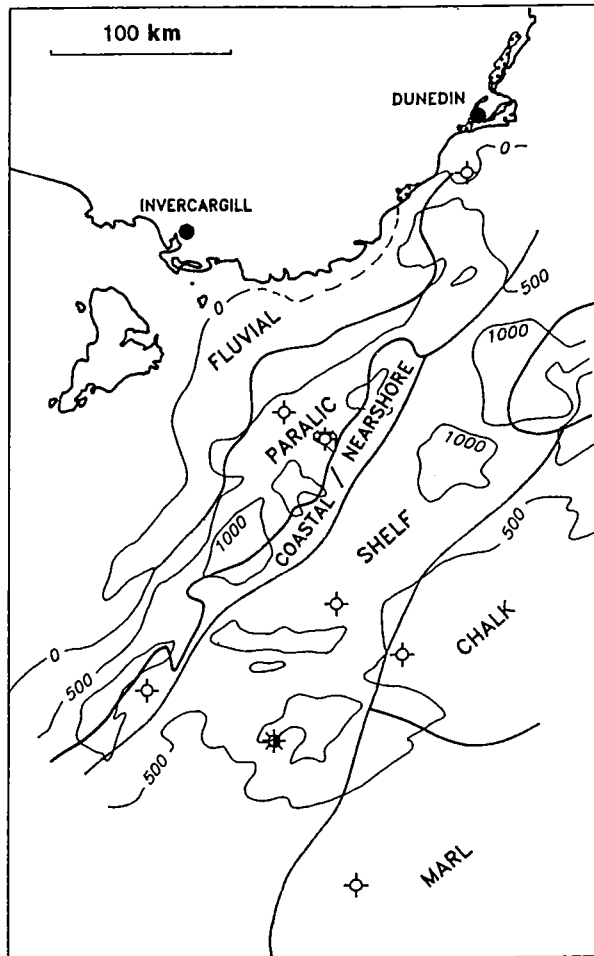


Fig. 14. Thickness and inferred facies patterns for the Pakaha Sequence (85-60 Ma), Great South basin, from Beggs [1993] based on Anderton *et al.* [1982]. The main fault system parallels the facies boundaries with greatest downthrow across the paralic to coastal boundary. Lateral facies relationships may be similar on the margin of the Victoria Land basin. Thickness contours in meters.

Korsch and Wellman's [1988] summary of events known from the New Zealand landmass is similar. Deposition began with breccias, locally as much as 1500 m thick, in a series of disconnected basement grabens across the northwest and southeast of the South Island during the first attempt at rifting of New Zealand from Australia. This is now dated at 105 ± 5 Ma (mid-Albian) [Laird, 1993]. Renewed extension from 95 to 100 Ma began a new phase of sedimentation with the deposition of Maastrichtian coal measures followed by shallow marine sequences of latest Cretaceous to Paleocene age. As glauconitic sandstone was deposited onshore, micritic limestones were deposited offshore

(Paleocene Amuri Limestone and equivalents). Basins were deepest in Eocene to early Oligocene times after which significant shallowing resulted in the extensive thin shallow marine limestones.

Late Cretaceous and early Cenozoic rifting of the New Zealand region took place with remarkably little igneous activity. Late Cretaceous flows and dykes are recorded from the eastern margin of central New Zealand but not in the major sedimentary basins or in early Cenozoic strata [Geology of NZ, 1978]. At the beginning of this period the Victoria Land basin was around 1500 km to the south (Figure 13), and part of the same landmass. As a consequence they may have shared a similar history of extension, subsidence and deposition, as outlined below and summarized in table 5. Seismic surveys have shown that the oldest sediments of the Victoria Land basin were deposited in half grabens prior to basin-wide sedimentation [Cooper and Davey, 1987], but none have been sampled or dated. Nor has it been possible yet to sample the oldest extensive seismic stratigraphic unit, V5. We have considered the possibility that the 6 m of boulder conglomerate at the base of the CIROS-1 drill hole could represent the top of V5, but think it is more likely to be the product of a debris flow like that which deposited the conglomeratic interval from 624 to 630 m [Hambrey *et al.*, 1989]. By comparison with the oldest strata in a similar situation in the New Zealand region, we believe V5, which is 2 to 5 km thick off Cape Roberts, is likely to comprise alluvial conglomerates, coal measures and lacustrine strata at least along the basin margin, though it could extend into shallow marine sediments, as is the case for the Great South basin (Figure 14).

A clearer link can be made between the relatively deep-water mid-Eocene to early Oligocene mudstones of V4 in CIROS-1 and the Rakiura Sequence of the Great South basin, and equivalents in other basins on the New Zealand platform about that time. The unconformity between early and late Oligocene strata of V4 and V3 also has a New Zealand counterpart in the Marshall Paraconformity, though their causes might differ. Furthermore, the overlying sequences in both New Zealand and the Ross Sea are similar in age (late Oligocene to early Miocene) and in their relatively thin condensed shallow marine character. Their marked difference in lithology (terrigenous with diamictite compared with bioclastic carbonate) is largely a consequence of latitude and climate.

These comparisons are on a gross scale, and with facies largely a consequence of tectonic events over a period of around 80 Ma. However, as methods of correlation improve, more drill core is recovered and

TABLE 5. Comparison of Cape Roberts strata with sequences of similar age in the New Zealand region

Age	Cape Roberts <i>This paper</i>	New Zealand platform [Korsh and Wellman, 1988]	Great South basin [Beggs, 1993]
late Oligocene-early Miocene	V3 - c. 500 m of diamictite, sandstone and mudstone	Limestone	<i>Penrod Sequence</i> 10's of m of greensand, limestone
late Paleocene-early Oligocene 60-34 Ma	V4 - c. 500 m of deep water mudstone, turbidites	Deep marine mudstone	<i>Rakiura Sequence</i> 0-1500 m of dark shale (nearshore) and chalk (offshore)
Late Cretaceous-early Paleocene 85-60 Ma	V5 - c. 2000-5000 m of strata of unknown lithology and age	Shallow marine sandstone nearshore and limestone offshore	<i>Pakaha Sequence</i> 0-1500 m of shallow marine sandstone to mudstone with chalk offshore
Late Cretaceous 105-95 Ma		Coal measures with marine incursions	<i>Hoiho Sequence</i> 0-3000 m of terrestrial conglomerate, lacustrine beds and coal measures in half grabens

more detailed work becomes possible, then eustatic and paleoclimatic influences are likely to become more apparent. Some time ago a eustatic influence was postulated for strata in the New Zealand region by *Vella* [1967] who proposed eight cycles of sea level rise and fall between the middle Eocene and early Miocene, but as *Ballance* [1993b] notes, there has yet to be a modern assessment of New Zealand Cenozoic strata in terms of sequence stratigraphy.

In the Ross Sea, the influence of eustasy combined with changing styles of glaciation has been invoked for the interpretation of seismic sequences by *Cooper et al.* [1991], *Bartek et al.* [1991] and *Brancolini et al.* [this volume], though supporting data on age and lithology are still needed. The potential for progress is indicated by results from the CIROS-1 drill hole, used here not only to provide ages and lithologies for widespread seismic sequences (V3 and V4) but also to link cycles of glacial advance and retreat with sea level fall and rise in the late Oligocene section. To extend and fill out this record, we need more drill sites and seismic data along with their integration for subsequent interpretation. The consequent improvement in documentation of Antarctic ice sheet history can then be used to gauge glacial influence on eustatic sea level changes through Cenozoic and possibly earlier times.

SUMMARY

This paper has reviewed current knowledge of strata on the western margin of the Victoria Land basin off Cape Roberts and on the edge of the West Antarctic Rift System. The strata are of interest because they are

the most accessible sequence that is likely to have recorded the history of Antarctic glaciation and sea level change for early Cenozoic and possibly older times. The strata are separated by a zone of faulting and crustal thinning seaward of the adjacent Transantarctic Mountains, which comprise pre-rift strata 180 Ma and older.

The strata include the basin-wide seismic sequences V3 to V5 of *Cooper and Davey* [1987]. Additional seismic surveys by the R/V POLAR DUKE and the OGS EXPLORA in 1990 have enabled correlation of strata off Cape Roberts with those cored in the CIROS-1 drill hole 70 km to the south [*Bartek et al.*, in press; *Brancolini et al.*, this volume]. This in turn has allowed us to map the distribution of the Cooper and Davey seismic sequences east of the main boundary fault off Cape Roberts over an area of 400 square km.

Comparison with strata and events in the New Zealand region suggests sediment began accumulating on the margin of the Victoria Land basin some time between 105 and 55 million years ago with breccia filling local half grabens. This was followed progressively some time later by coastal coal measures, shallow marine sandstone and deep-water mudstone of Late Cretaceous through to early Oligocene age.

The age and lithology of the oldest seismic sedimentary unit in the basin, V5, is presently unknown, but is a target for drilling to obtain a proximal record of early Cenozoic and possibly Cretaceous climate and sea level change [*ISC*, 1994]. The later part of the progressive marine transgression fits well with the age and lithology of V4 based on correlation with the CIROS-1 drill hole. Sequence V4 which comprises relatively deep water mudstone from middle Eocene to early Oligocene

in age is thought to correspond to the interval from 366 to 696 mbsf in CIROS-1. The strata in V4 also have ice-rafted debris throughout, indicating grounded ice at sea level at least from mid Eocene times.

The younger strata off Cape Roberts, identified as sequence V3, correspond in CIROS-1 to late Oligocene fluvial and shallow marine strata recording a number of glacial advances and changes in sea level with meter-thick beds of diamictite, sandstone and mudstone. The base of V3 is considered to be a major unconformity in the drill hole at 366 mbsf. The substantial fall in sea level and increase in the proportion of glacial facies at the base of V3, along with its regional significance of the boundary, support the correlation of this horizon with the mid-Oligocene sea level shallowing in the *Haq et al.* [1987] eustatic sea level curve. A corresponding shallowing is recorded at this time in the New Zealand region by thin but widespread bioclastic limestones.

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REFERENCES

- Anderson, J.B. and L.R. Bartek, Cenozoic glacial history of the Ross Sea revealed by the intermediate resolution seismic reflection data combined with drill site information, in *The Antarctic paleoenvironment: A Perspective on Global Change, Part One, Antarct. Res. Ser.*, vol. 56, edited by J.P. Kennett and D.A. Warnke, pp. 231-263, AGU, Washington, D.C., 1992.
- Anderton, P.W., Holloway, N.H., Engstrom, J.C., Ahmad, H.M. and B. Chong, Great South and Campbell Basins, New Zealand: Evaluation of geology and hydrocarbon potential, *N.Z. Geol. Surv., Petroleum Rep.*, 828, 223 pp, 1982.
- ANTOSTRAT (Ross Sea Regional Working Group), Geophysical and seismic stratigraphic atlas of the Ross Sea, this volume.
- Ballance, P.F., Introduction, in *South Pacific Sedimentary Basins. Sedimentary Basins of the World*, vol. 2, edited by P.F. Ballance (Series Editor: K.J. Hsü), pp. XI-XII, Elsevier Science Publishers, Amsterdam, 1993a.
- Ballance, P.F., The paleo-Pacific, post-subduction, passive margin thermal relaxation sequence (Late Cretaceous-Paleogene) of the drifting New Zealand continent, in *South Pacific Sedimentary Basins. Sedimentary Basins of the World*, vol. 2, edited by P.F. Ballance (Series Editor: K.J. Hsü), pp. 93-110, Elsevier Science Publishers, Amsterdam, 1993b.
- Barrett, P.J. (Ed.), Antarctic Cenozoic history from the MSSTS-1 drillhole, McMurdo Sound, *DSIR Bull. N.Z.*, 237, 174 pp., 1986.
- Barrett, P.J. (Ed.), Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound, *DSIR Bull. N.Z.*, 245, 251 pp., 1989.
- Barrett, P.J., The Devonian to Triassic Beacon Supergroup of the Transantarctic Mountains and correlatives in other parts of Antarctica, in *The Geology of Antarctica*, edited by R.J. Tingey, pp. 120-152, Clarendon Press, Oxford, 1991.
- Barrett, P.J. and F.J. Davey, Cape Roberts Project Workshop Report, *R. Soc. N. Z. Misc. Bull.*, 23, 38 pp., 1992.
- Barrett, P.J. and S.B. Treves, Sedimentology and petrology of core from DVDP-15, western McMurdo Sound, in *Dry Valley Drilling Project*, edited by L.D. McGinnis, pp. 281-314, *Antarctic Res. Ser.*, vol. 33, AGU Washington, D.C., 1981.
- Bartek, L.R., S.A. Henrys, J.B. Anderson, and P.J. Barrett, Seismic stratigraphy in McMurdo Sound, Antarctica: implications for glacially influenced early Cenozoic eustatic change. *Mar. Geol.*, in press.
- Bartek, L.R., Vail, P.R., Anderson, J.B., Emmet, P.A. and S. Wu, Effect of Cenozoic ice sheet fluctuations in Antarctica on the stratigraphic signature of the Neogene, *J. Geophys. Res.*, 96, 6753-6778, 1991.
- Beggs, J.M. Depositional and tectonic history of the Great South basin, in *South Pacific Sedimentary Basins. Sedimentary Basins of the World*, vol. 2, edited by P.F. Ballance (Series Editor: K.J. Hsü), pp. 365-373, Elsevier Science Publishers, Amsterdam, 1993.
- 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. *Antarct. Res. Ser.*, vol. 53, AGU, Washington, D.C., 67-112, 1991.
- Behrendt, J.C., A.K. Cooper and A. Yuan, Interpretation of marine magnetic gradiometer and multichannel seismic-reflection observations over the western Ross Sea Shelf, Antarctica, in *Geology and Geophysics of the Western Ross Sea*, edited by A.K. Cooper and F.J. Davey, pp. 155-178, Circum-Pacific Council for Energy and Natural Resources, Houston, Earth Sciences Series, vol. 5B, 1987.
- Bennett D.J., and B.A. Sissons, Gravity models across the Transantarctic Mountain Front near New Harbour, McMurdo Sound, Antarctica. *N.Z. Jour. Geol. Geophys.*, 27, 413-424, 1984.
- Bentley, C.R., Configuration and structure of the subglacial crust, in *The Geology of Antarctica*, edited by R.J. Tingey, pp. 335-364, Clarendon Press, Oxford, 1991.
- Bradshaw, J.D., Andrews, P. and C.J. Adams, Carboniferous to Cretaceous on the margin of Gondwana, in *Gondwana V*, edited by M.M. Cresswell and P.P. Vella, pp. 217-221, Balkema, Rotterdam, 1981.
- Brancolini, G., A.K. Cooper, and F. Coren, Seismic facies and glacial history in the western Ross Sea (Antarctica), this volume.

- Carter, R.M., The mid-Oligocene Marshall Paraconformity, New Zealand: coincidence with global eustatic sea-level fall or rise?, *Jour. Geology*, 93, 359-371, 1985.
- Carter, R.M., Post-break-up stratigraphy of the Kaikoura Synthem (Cretaceous-Cenozoic), continental margin, south-eastern New Zealand. *N.Z. Jour. Geol. Geophys.*, 31, 405-429, 1988.
- Carter, R.M. and C.A. Landis, Correlative Oligocene unconformities within southern Australasia, *Nature*, 237, 12-13, 1972.
- Collinson, J.W., J.L. Isbell, D.H. Elliot, M.F. Miller, and J.M.G. Miller, Permian-Triassic Transantarctic basin, in *Permian-Triassic Pangean Basins and Foldbelts along the Panthalassan margin of Gondwanaland*, edited by J.J. Veevers and C.McA. Powell, pp. 173-222, Geol. Soc. Am. Mem. 184, Boulder, 1994.
- Cooper, A.K. and F.J. Davey, Episodic rifting of Phanerozoic rocks in the Victoria Land basin, western Ross Sea, Antarctica. *Science*, 229, 1085-1087, 1985.
- Cooper, A.K. and F.J. Davey, The Antarctic continental margin: geology and geophysics of the western Ross Sea. *Circumpacific Council on Economic and Mineral Resources Earth Science Series*, vol. 5B. Houston, Circum-Pacific Council for Energy and Mineral Resources. 253 pp., 1987.
- Craddock, C., Tectonic evolution of the Pacific margin of Gondwanaland, in *Gondwana Geology*, edited by K.S.W. Campbell, pp. 609-618, Australian National University press, Canberra, 1975.
- Crook, K.A.W and Belbin, L., The southwest Pacific area during the last 90 million years. *Jour. Geol. Soc. Australia*, 25, 23-40, 1978.
- Davey, F.J. and A.K. Cooper, Gravity study of the Victoria Land Basin and Iselin Bank, in *Geology and Geophysics of the Western Ross Sea*, edited by A.K. Cooper and F.J. Davey, pp. 119-137, Circum-Pacific Council for Energy and Natural Resources, Houston, Earth Sciences Series, vol. 5B, 1987.
- Davey, F.J., K. Hinz, and A.K. Cooper, Ross Sea Gravity Anomaly Map, *Miscellaneous Series No 2, DSIR*, Wellington, NZ, 1987.
- David, T.W.E., and R.E. Priestley, *Glaciology, Physiography, and Tectonic Geology of South Victoria Land. Geology*, 1, 319 pp, British Antarctic Expedition, 1907-09. Reports of scientific investigations, 1914.
- Decker, E. and G. Bucher, Geothermal studies in the Ross Island-Dry Valley region (review paper). In *Antarctic Geoscience*, edited by C. Craddock, pp. 887-894, University of Wisconsin Press, Madison, 1982.
- 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., M. Sandiford, P.J. Barrett, A.J.W. Gleadow, Asymmetric extension associated with uplift and subsidence in the Transantarctic Mountains and the Ross Embayment. *Earth and Planetary Science Letters*, 81, 67-78, 1986.
- Gamble, J.A., P.J. Barrett, and C.J. Adams, Basaltic clasts from Unit 8, in *Antarctic Cenozoic Glacial History from the MSSTS-1 Drillhole, McMurdo Sound*, edited by P.J. Barrett, pp. 145-152, DSIR Bull. N.Z., 237, 1986.
- George, A., Sand provenance, in *Antarctic Cenozoic Glacial History from the MSSTS-1 Drillhole, McMurdo Sound*, edited by P.J. Barrett, pp. 159-168, DSIR Bull. N.Z., 245, 1989.
- Geology of New Zealand, edited by R.P. Suggate, G.R. Stevens and M.T. Te Punga, DSIR N.Z., Wellington, 1978.
- Hambrey, M.J., Barrett, P.J. and P.R. Robinson, Stratigraphy, in *Antarctic Cenozoic History from the CIROS-1 Drillhole, McMurdo Sound*, edited by P.J. Barrett, pp. 23-48, DSIR Bull. N.Z., 245, 1989.
- Hambrey, M.J. and P.J. Barrett, Cenozoic sedimentary and climatic record, Ross Sea region, Antarctica, in *The Antarctic Paleoenvironment: A Perspective on Global Change, Part Two, Antarct. Res. Ser.*, vol. 60, edited by J.P. Kennett and D.A. Warnke, pp. 91-124, AGU, Washington, D.C., 1993.
- Hannah, M.J., Eocene dinoflagellates from the CIROS-1 drill hole, McMurdo Sound, Antarctica. *Terra Antarctica*, 1 (2), 371-372, 1994.
- Harwood, D.M., P.J. Barrett, A.R. Edwards, H.J. Rieck, and P.N. Webb, Biostratigraphy and chronology, in *Antarctic Cenozoic History from the CIROS-1 Drillhole, McMurdo Sound*, edited by P.J. Barrett, pp. 231-240, DSIR Bull. N.Z., 245, 1989.
- Haq, B.U., J. Hardenbol, and P.R. Vail, The chronology of fluctuating sea level since the Triassic. *Science*, 235, 1156-1167, 1987.
- Hayes D.E. and F.J. Davey, Geophysical study of the Ross Sea, Antarctica, *Initial Rep. Deep Sea Drill. Proj.*, 28, 887-907, 1975.
- Hayes, D.E., L.A. Frakes, et al., *Initial Reports, Deep Sea Drill. Proj.*, 28, Washington, DC, US Government Printing Office, 28, 1019 p., 1975.
- ISC, Antarctic climate and tectonic history: the Cape Roberts Project, *EOS*, 75, 2-3, 1994.
- Korsch, R.J. and H.W. Wellman, The geological evolution of New Zealand and the New Zealand region. In *The Ocean Basins and Margins*, 7B, edited by A.E.M. Nairn, F.G. Stehli and S. Uyeda, pp. 411-482, Plenum Publishing Corporation, 1988.
- Kyle, P.R., D.H. Elliot, and J.F. Sutter, Jurassic Ferrar Supergroup tholeiites from the Transantarctic Mountains, Antarctica, and their relationship to the initial fragmentation of Gondwana, in *Gondwana Five*, edited by M.M. Cresswell and P.P. Vella, pp. 283-288, A.A. Balkema, Rotterdam, 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.
- Laird, M.G., The Late Proterozoic-Middle Palaeozoic rocks of Antarctica, in *The Geology of Antarctica*, edited by R.J.

- Tingey, pp. 74-119, Clarendon Press, Oxford, 1991.
- Laird, M.G., Cretaceous continental rifts: New Zealand region, in *Sedimentary Basins of the World. South Pacific Sedimentary Basins*, edited by P.F. Ballance, pp. 37-49, Elsevier, Amsterdam, 1993.
- Lawver, L.A., L.M. Gahagan, and M.F. Coffin, The development of paleoseaways around Antarctica, in *The Antarctic Paleoenvironment: A Perspective on Global Change, Part One, Antarct. Res. Ser.*, vol. 56, edited by J.P. Kennett and D.A. Warnke, pp. 7-30, AGU, Washington, D.C., 1992.
- Loutit, T.S. and J.P. Kennett, New Zealand and Australian Cenozoic sedimentary cycles and global sea level changes, *Amer. Assoc. Petrol. Geol. Bull.*, 65, 1586-1601, 1981.
- McGinnis, L.D. (Ed.), Dry Valley Drilling Project, *Antarctic Res. Ser.*, vol. 33, AGU Washington, D.C., 765 pp., 1981.
- McGinnis L. D., R.H. Bowen, J.M. Erickson, B.J. Allred, and J.L. Kreamer, East-West Antarctic boundary in McMurdo Sound, in *Geophysics of Polar Regions*, edited by G.S. Husebye, G.L. Johnson and Y. Kristoffersen, pp. 341-356, Tectonophysics, 114, 1985.
- Nelson, C.A., 1978, Temperate shelf carbonate sediments in the Cenozoic of New Zealand, *Sedimentology*, 25, 737-771, 1978.
- Northey, D.J., C. Brown, D.A. Christoffel, H.K. Wong, and P.J. Barrett, A continuous seismic profiling survey in McMurdo Sound, Antarctica. *Dry Valley Drilling Project Bulletin No. 5*, Northern Illinois University, DeKalb, 167-169, 1975.
- Pyne, A.R., B.L. Ward, A.J. Macpherson, and P.J. Barrett, *McMurdo Sound Bathymetry, 1:250,000*. N.Z. Oceanographic Institute Chart, Miscellaneous Series No. 62, 1985.
- Robinson, E.S. and J.F. Spletstoesser, Structure of the Transantarctic Mountains determined from geophysical surveys, in *Geology of the Central Transantarctic Mountains, Antarct. Res. Ser.*, vol. 36, edited by M.T. Turner and J.F. Spletstoesser, pp. 119-162, AGU, Washington, D.C., 1986.
- Smithson S., Gravity interpretation in the Transantarctic Mountains, near McMurdo Sound, Antarctica, *Geol. Soc. Am. Bull.*, 83, 3437-3442, 1972.
- Stern, T.A., F.J. Davey, and G. Delisle, Lithospheric flexure induced by the load of Ross Archipelago, southern Victoria Land, Antarctica, in *Geological Evolution of Antarctica*, edited by M.R.A. Thomson, J.A. Crame and J.W. Thomson, pp. 323-328, Cambridge University Press, Cambridge, 1991.
- Stern, T.A. and U. ten Brink, Flexural uplift of the Transantarctic Mountains. *Jour. Geophys. Res.*, 94, 10315-10330, 1989.
- Taylor, T.G., *The Physiography of the McMurdo Sound and Granite Harbour Region*, 246 pp., Harrison, London, 1922.
- Tessensohn, F. G. and Wörner, The Ross Sea rift system, in *Geological Evolution of Antarctica*, edited by M.R.A. Thomson, J.A. Crame and J.W. Thomson, pp. 273-277, Cambridge University Press, Cambridge, 1991.
- Vella, P.P., Eocene and Oligocene sedimentary cycles in New Zealand, *New Zealand Jour. Geol. Geophys.*, 10, 119-145.
- Webb, P.N. and V.E. Neall, Cretaceous foraminifera from Quaternary deposits in Taylor Valley, Antarctica, in *Antarctic Geology and Geophysics*, edited by R.J. Adie, pp. 653-657, Universitetsforlaget, Oslo, 1972.
- Webb, P.-N., Benthic foraminifera, in *Antarctic Cenozoic History from the CIROS-1 Drillhole, McMurdo Sound*, edited by P.J. Barrett, pp. 99-118, DSIR Bull. N.Z., 245, 1989.
- Woolfe, K.J., History of the Ross Sea sector of Antarctica as recorded by the Beacon Supergroup in southern Victoria Land and the Darwin Mountains. PhD thesis, Victoria University of Wellington Library, 173 pp., 1992.

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