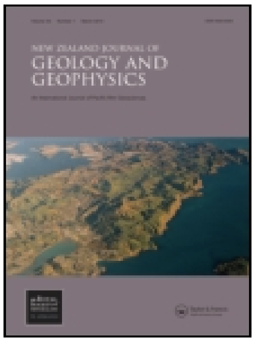

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Sedimentary basins of the Ross Sea, Antarctica

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Abstract Seismic refraction and variable angle reflection measurements made using sonobuoys at 48 sites in the Ross Sea have been interpreted to define seismic velocity-depth structure of the deep sedimentary basins underlying the Ross Sea. Three major basins exist in the region and the data show distinctly different seismic velocity-depth functions for each. In the east the continental shelf is underlain by a basin containing up to 4 km of sediments which show a simple linear increase in velocity with depth. This basin is considered to have formed partially in response to loading by glacial sediments since the Oligocene. A major trough of sediments, also up to 4 km deep, underlies the western part of central Ross Sea. The velocity-depth functions consist of several (usually 3) segments with linear velocity increase with depth, with the gradient of the segments increasing with depth. The trough is aligned approximately north–south and is considered to have been formed by a failed crustal rift in the Late Cretaceous or early Tertiary. The third sediment basin is a trough running along the eastern side of the Transantarctic Mountains from McMurdo Sound to Coulman Island. About 3 km of sediments occur in this trough and show a distinct layered velocity structure. The trough has formed in association with the uplift of the Transantarctic Mountains, possibly as a result of compressive lithospheric motion.

Keywords Ross Sea; Antarctica; seismic surveys; refraction; reflection; sedimentary basins; Cenozoic; tectonics

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INTRODUCTION

The Ross Sea and the adjacent Ross Ice Shelf lie along the boundary between the ancient continental craton of East Antarctica and the tectonically younger West Antarctica (Fig. 1). This boundary zone forms a morphologically depressed region extending across Antarctica from the Ross Sea to the Weddell Sea. It coincides with a zone of thinner continental crust which has been suggested as arising from crustal rifting (e.g., Herron & Tucholke 1975, Molnar et al. 1975). The western margin of the boundary zone (adjacent to East Antarctica) is formed by the linear mountain chain of the Transantarctic Mountains, along which uplift has been occuring probably since the Jurassic and at an increasing rate in the Cenozoic.

Previous geophysical work in the Ross Sea (Houtz & Meijer 1970, Houtz & Davey 1973, Hayes & Davey 1975, Northey et al. 1975, Wong & Christoffel 1981) and on the Ross Ice Shelf (Crary 1963, Robertson et al. 1982) have shown the existence of thick sedimentary sequences in the region and have inferred a large areal extent for them. The sequences are known from drilling results to contain sediments of Neogene age, but early Tertiary sediments are only found as erratics. However, Houtz & Davey (1973) and Davey (1981) consider that the deeper sediments in the Ross Sea basins would probably be at least early Tertiary in age and possibly as old as Late Cretaceous. Wong & Christoffel (1981) also suggest an early Tertiary age for the oldest sediments underlying McMurdo Sound.

In this paper we present interpretations of 25 new sets of seismic refraction and variable angle reflection sonobuoy measurements made in the Ross Sea during the 1980–81 season (Fig. 1). These and previous geophysical measurements, including 23 sonobuoy measurements reported by Houtz & Davey (1973) are used to define the gross structure of the sedimentary basins underlying the Ross Sea.

THE SEISMIC MEASUREMENTS

The seismic records were obtained onboard MV *Benjamin Bowring* using SSQ41A military sonobuoys and a 120 in^3 airgun firing at a 9-s repetition rate. The seismic data were displayed as variable density records on an EPC graphics recorder and also recorded on an FM magnetic tape recorder for replay purposes.

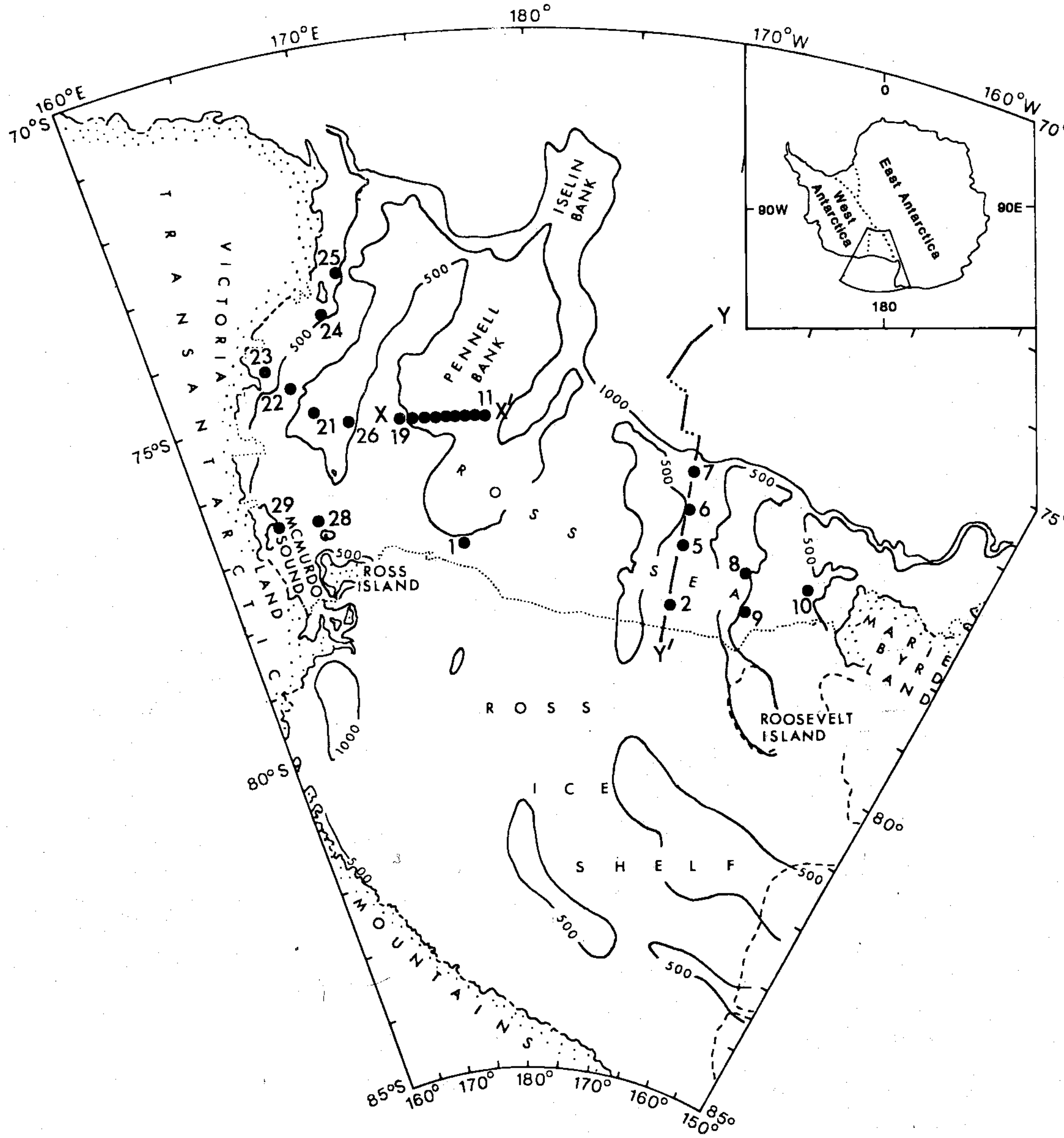

Fig. 1 The Ross Sea region of Antarctica. Dotted line on the main map is the northern limit of the Ross Ice Shelf. Dotted lines on the inset map outline the Ross and Ronne Ice Shelves. The sonobuoy seismic measurements recorded in 1981 are located by the solid circles. Y–Y′ and X–X′ locate the profiles shown in Fig. 8 and 9 respectively.

Few of the new sets of measurements recorded refractors giving straightline segments on the time-distance records. Most refractors recorded showed pronounced curvature, suggesting that subbottom seismic velocities are continuously variable functions of depth (Fig. 2). This was also noted in earlier work in this region by Houtz & Davey (1973). They interpreted their data in terms of a single linear velocity-depth function. However, given the good quality of most of these new seismic data, where the data indicated a continuously varying velocity-depth relationship, the time-distance data were inverted into a velocity-depth profile using the Herglotz-Bateman technique (Bullen 1979). The travel-time data were reparametised into terms of range and ray parameter and inverted using the method described

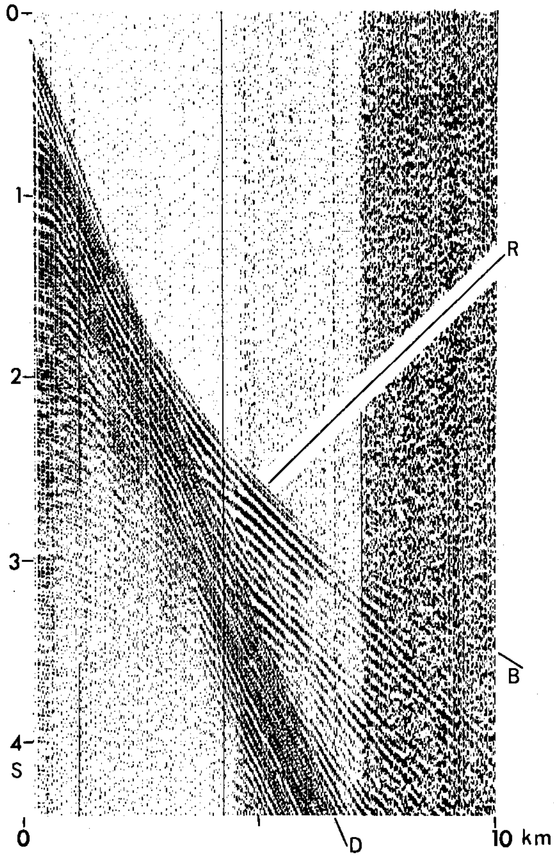

Fig. 2 A variable density record of sonobuoy seismic measurements showing curvature in the refracted arrival data, marked R, and the deeper, assumed basement refractor, marked B. D is the direct water wave arrival.

by Houtz et al. (1981), the data being digitised at approximately every 200 m of range. For comparative purposes several data sets were interpreted using the Tau-Zeta linear inversion method of Dorman & Jacobson (1981). Eight sets of sonobuoy data from *Eltanin* cruise 52 (Houtz & Davey 1973) were also inverted using these techniques. On some sonobuoy data sets a high-velocity deep refractor is observed on the time-distance data, usually occurring slightly later than the highest velocity on the curved portion of the first refractor arrival plot. The high velocity and the separate nature of the arrivals suggest they probably came from basement rocks. The highest sediment velocity measured is assumed for sediments between the sediments detected and basement rocks. Other seismic data sets showing refraction travel-time data composed of straightline segments were interpreted using standard intercept time methods. Variable angle reflection solutions to give interval velocities were obtained where possible.

The results of the interpretations are shown in Fig. 3–5 and are given in Tables 1 and 2. They show 3 distinct groupings which correspond to different regions: eastern Ross Sea, central Ross Sea, and western Ross Sea. Most of the results for the eastern region (Fig. 3) show single linear velocity functions with depth. The gradients of the velocity-depth functions are low, being about 0.9/s, perhaps indicating a steady continuous deposition of fairly homogenous sediments. Gregory (1977, fig. 37) has shown velocity-depth curves for shales and sandstones. A simple linear velocity increase with depth would be similar to his curve for shales if the near-surface part of the section had been eroded away. Houtz & Davey (1973) note the high seafloor sediment velocity in the eastern region and suggest that several hundred metres of sediments may have been eroded from this region. The drilling results from Deep Sea Drilling Project (DSDP) sites 270 to 272 (Hayes et al. 1975a) showed that the marine glacial sediments sampled are primarily mudstone. The simple velocity-depth profile obtained in the eastern region may be indicative of a mudstone-shale lithology.

The second group of velocity-depth profiles (Fig. 4) are for central Ross Sea. They are characterised by several, commonly 3, linear segments to the velocity-depth curve with a decrease in the gradients of the segments with depth. Some of the measurements were over the southern part of Pennell Bank and on these there is a reversal in the gradient trend near the seafloor. The velocity-depth gradients and the depth below seafloor of gradient changes are similar from 1 set of measurements to another and may thus be related to geological events common to the whole central region. The interpretation of the gradient or the gradient changes in terms of geological conditions is difficult. However the velocity-depth profiles show a similarity with those for sandstones (Gregory 1977, fig. 5). The changes in gradient in the upper part of the profiles are asociated by Gregory with the effect of cementation or consolidation of the sands. This would suggest either a different source or a closer source for the sediments of the central Ross Sea region compared with those of the eastern region. Alternatively, the changes in gradient may, for example, mark a change in deposition rate or a hiatus in deposition.

In the western part of Ross Sea, along the Transantarctic Mountain front, the sonobuoy results show distinctly segmented travel-time curves, indicating more discrete velocity layering in the sedimentary section. The velocity sections (Fig. 5) show that there are distinct layers with velocities of about 2.0

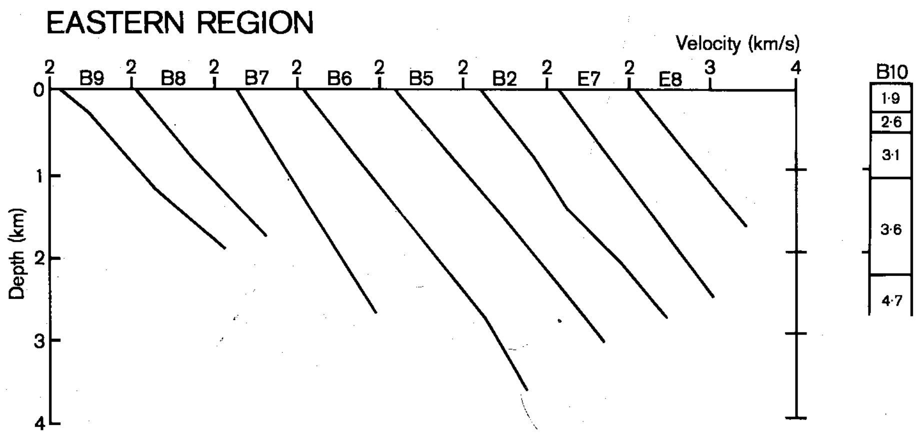

Fig. 3 The velocity-depth profiles for the seismic sonobuoy stations in the eastern region. Note the horizontal scale is offset by 1 km/s for each sucessive sonobuoy station. Depths, in kilometres, are below seafloor. Results from seismic measurements which showed straightline segments on the refraction travel-time plots are presented as depth columns with constant velocity layers, velocities are in km/s. The *Bowring* data have the prefix B, *Eltanin* cruise 52 data the prefix E.

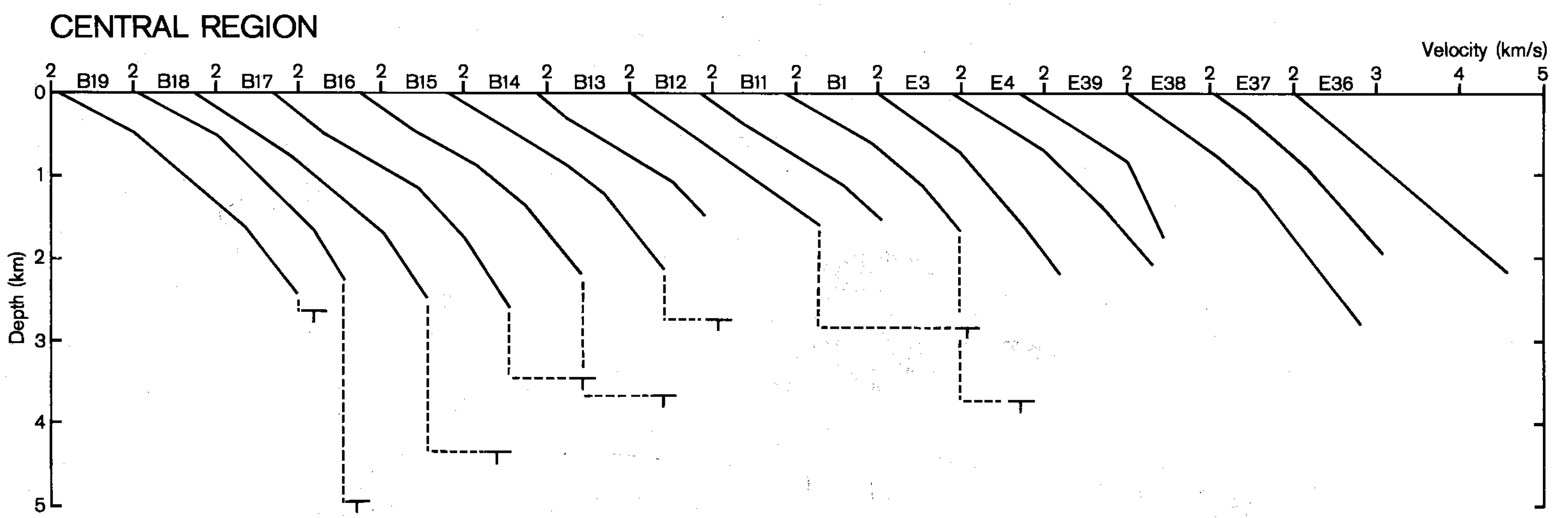

Fig. 4 The velocity-depth profiles for the seismic sonobuoy stations in the central region. Assumed velocities are shown dashed. Other details as for Fig. 3.

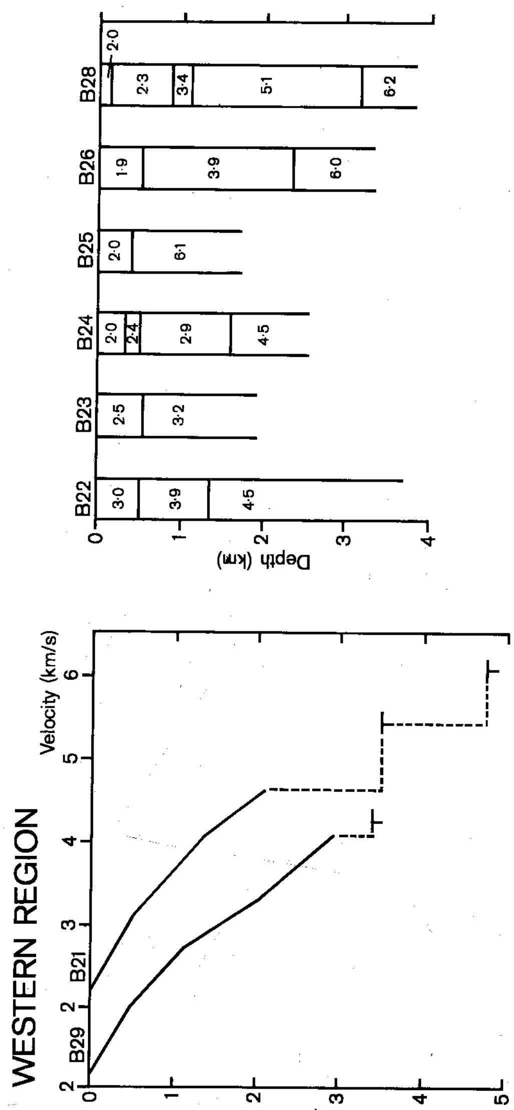

Fig. 5 The velocity-depth profiles for the seismic sonobuoy stations in the western region. Other details as for Fig. 3.

km/s, 3.0 km/s, 4.0 km/s, and basement (>5 km/s). Similar velocities were obtained in McMurdo Sound by Wong & Christoffel (1981). However, B21 and B29 showed similar continuous velocity-depth profiles to the central group.

The distribution of sediment thickness in the Ross Sea from the sonobuoy results given above and from data in Houtz & Davey (1973) and Wong & Christoffel (1981) are shown in Fig. 6 together with data on the Ross Ice Shelf and on land summarised by Davey (1981). The depth from sealevel to the maximum seismic velocity measured together with that velocity are given at each observation point. Velocities over 5 km/s in the case of a layered velocity structure, or velocities of the deep refractor below the rocks giving the fastest arrivals on the curved time-distance plots, are assumed to be basement. The results delineate 3 major sedimentary basins where sediments are in excess of 3 km thick. These are the Eastern Basin (Houtz & Davey 1973), the Central Trough (Houtz & Davey 1973, Hayes & Davey 1975) and the Victoria Land Basin. The sediment thickness isopachs for the Ross Sea shelf are shown in Fig. 7.

THE SEDIMENTARY BASINS

The Eastern Basin

The Eastern Basin underlies most of the Ross Sea to the east of 180° and extends from the continental slope southwards under the Ross Ice Shelf (Davey 1981). The sedimentary layers dip gently towards the centre of the basin and towards the shelf edge where the dip steepens sharply. Low-angle folds striking approximately north–south lie along both east and west margins of the basin (Houtz & Davey 1973). At the shelf edge the section appears to be building outwards as a prograding sedimentary wedge. Around the margin of the basin, where the sedimentary layers dip significantly, there is a marked angular unconformity overlain by a thin cover of sediments built up in low north–south-trending banks. This unconformity can be traced across the centre of the basin where it is not so marked (Houtz & Davey 1973). The sonobuoy refraction results presented here show that the depth and shape of the basin inferred by Houtz & Davey (1973) is largely correct, although no basement velocities were definitely detected on the sonobuoy data in the deeper part of the basin. Metamorphic basement, older than mid Cretaceous, must lie at a greater depth.

The age and development of the basin cannot be resolved in detail without further data, but some general comments can be made. DSDP data (Hayes et al. 1975a) along the western margin of this basin

Table 1 Sonobuoy solutions for Ross Sea—curved ray paths.

Sonobuoy	Location		Water Depth	v_0	v_1	h_1	v_2	h_2	v_3	h_3	v_4	h_4	Basement			
	Latitude	Longitude	km	km/s	km/s	km	km/s	km	km/s	km	km/s	km	v_B km/s	h_B km	$v_{B'}$ km/s	$h_{B'}$ km
B1	77°20'S	175°36'E	0.520	1.85	2.90	0.60	3.50	1.1	3.96	1.65			4.70	3.85		
B2	78°13'S	169°59'W	0.555	2.15	4.45	2.80										
B5	77°21'S	170°02'W	0.555	2.22	4.67	3.07										
B6	76°46'S	169°57'W	0.520	2.05	4.25	2.78	4.75	3.64								
B7	76°12'S	169°46'W	0.565	2.20	3.95	2.73										
B8	77°29'S	165°10'W	0.445	2.05	2.32	0.38	3.00	1.06	3.65	1.80						
B9	77°59'S	165°01'W	0.464	2.10	2.50	0.30	3.28	1.22	4.12	1.92						
B11	75°29'S	177°25'E	0.435	1.85	2.35	0.40	3.45	1.20	4.05	1.55						
B12	75°29'S	176°54'E	0.404	2.00	4.28	1.63							6.05	2.86		
B13	75°28'S	176°23'E	0.385	1.90	2.20	0.30	3.45	1.07	3.90	1.50						
B14	75°28'S	175°49'E	0.343	1.75	3.67	1.20	4.38	2.15					5.05	3.76		
B15	75°28'S	175°10'E	0.320	1.70	2.40	0.48	3.08	0.82	3.70	1.34	4.40	2.20	5.40	3.70		
B16	75°28'S	174°34'E	0.298	1.70	2.22	0.45	3.45	1.18	4.03	1.82	4.55	2.60	5.40	3.50		
B17	75°28'S	173°51'E	0.328	1.77	3.05	0.87	4.02	1.70	4.55	2.46			5.40	4.35		
B18	75°28'S	173°15'E	0.513	2.08	3.25	0.70	4.20	1.68	4.50	2.20			4.70	5.00		
B19	75°28'S	172°31'E	0.537	2.05	2.97	0.50	4.33	1.62	4.95	2.45			5.15	2.65		
B21	75°12 S	167°12'E	0.470	2.12	3.10	0.52	4.00	1.32	4.60	2.07			5.40	3.50	6.05	4.75
B29	76°34'S	163°51'E	0.500	2.15	3.05	0.52	3.70	1.15	4.32	2.10	5.05	2.92	5.20	3.38		
E3	76°59'S	174°48'E	0.372	2.00	2.97	0.62	3.80	1.66								
E4	77°06'S	174°49'E	0.406	1.80	3.00	0.72	3.67	1.38	4.30	2.05						
E7	76°21'S	166°25'W	0.398	2.07	3.40	1.69										
E8	76°26'S	166°50'W	0.398	2.10	4.00	2.50										
E36	74°30'S	176°33'E	0.265	2.00	4.58	2.17										
E37	74°30'S	176°05'E	0.398	2.02	2.47	0.32	3.12	0.92	4.05	1.93						
E38	74°30'S	175°37'E	0.441	2.05	3.55	1.17	4.77	2.80								
E39	74°30'S	175°08'E	0.482	1.70	3.00	0.85	3.43	1.75								

v_0 = seafloor velocity; v_i, h_i are velocities and depths below seafloor at velocity-depth gradient changes.
The *Bowring* data have prefix B to sonobuoy number; recomputed *Eltanin* 52 data have prefix E to sonobuoy number.

Table 2 Sonobuoy solutions for Ross Sea—straight ray paths.

Sonobuoy	Location		Water Depth	v_0	z_0	v_1	z_1	v_2	z_2	v_3	z_3	v_4	z_4	Basement		
	Latitude	Longitude	km	km/s	km	km/s	km	km/s	km	km/s	km	km/s	km	v_B km/s	z_B km	$v_{B'}$ km/s
B10	77°30'S	161°46'W	0.622	1.9	0.25	2.6	0.26	3.1	0.50	3.6	1.2	4.7				
B22	74°43'S	166°41'E	1.052	3.0	0.48	3.9	0.87	4.5								
B23	74°19'S	165°29'E	0.425	2.5	0.56	3.2										
B24	73°50'S	169°19'E	0.458	2.0	0.32	2.4	0.18	2.9	1.10	4.48						
B25	73°14'S	170°38'E	0.472	2.0	0.41									6.1		
B26	75°24'S	169°33'E	0.540	1.9	0.52	3.9	1.84							6.0		
B28	76°35'S	165°52'E	0.705	2.0	0.09	2.3	0.74	3.4	0.26					5.1	2.04	6.2

v_i and z_i are velocities and thicknesses of the layered velocity models.
v_B and $v_{B'}$ are interpreted basement and sub-basement velocities respectively.

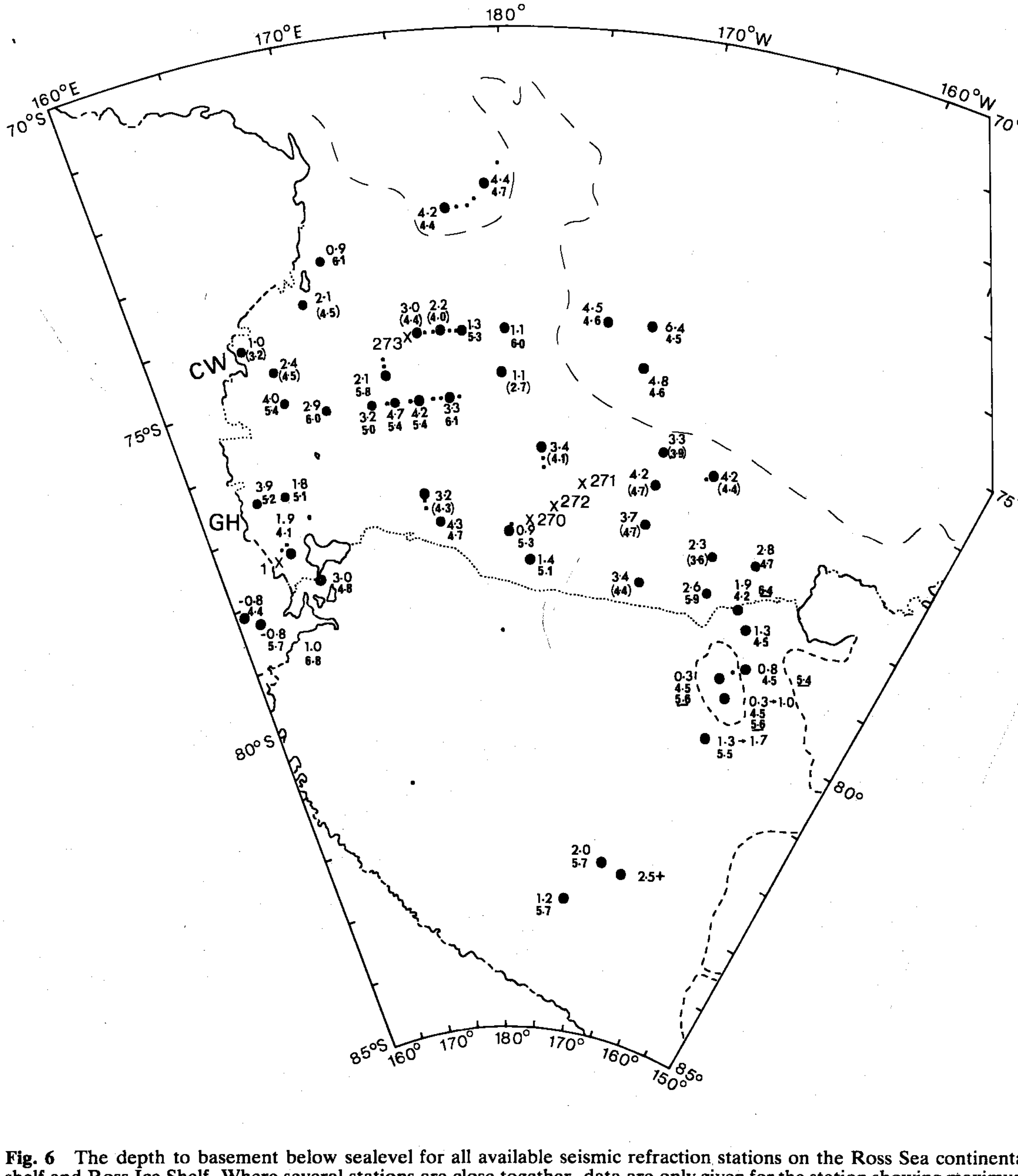

Fig. 6 The depth to basement below sealevel for all available seismic refraction stations on the Ross Sea continental shelf and Ross Ice Shelf. Where several stations are close together, data are only given for the station showing maximum depth to basement. These stations are marked by a large solid circle, others by small solid circle. The upper number gives depth (km) to basement (or to the highest velocity measured if not basement) below sealevel. The lower number is the highest velocity (km/s) measured (in brackets if not considered a basement velocity). DSDP drill sites 270–273 and MSSTS drill site 1 are numbered crosses. CW is Cape Washington, GH is Granite Harbour.

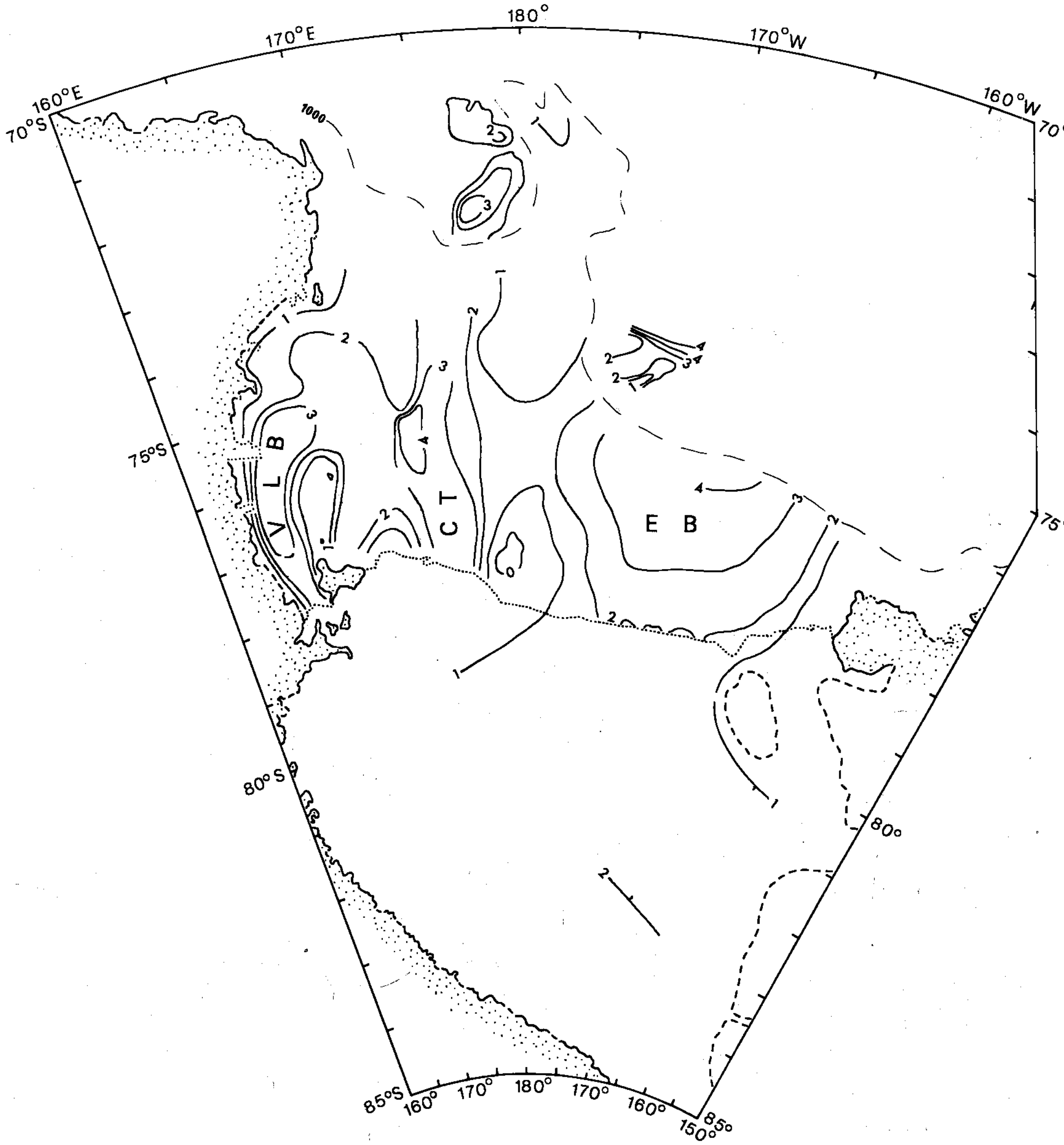

Fig. 7 Isopachs of total sediment thickness (km) for the Ross Sea continental shelf and for under the Ross Ice Shelf. VLB is Victoria Land Basin, CT is Central Trough, EB is Eastern Basin.

show thin subaerial or shallow-water sediments of Oligocene age overlying metamorphic basement. These sediments are overlain by Upper Oligocene and Miocene marine glacial sediments, indicating a depression of the region and the onset of continental glaciation. An interpreted seismic profile (Fig. 8) along the axis of the basin, from data recorded during the 1981 survey, and across the continental rise (Houtz & Davey 1973, fig. 11) suggest 1 possibility for the origin of the basin. The profile shows downfaulting of basement to the north along the lower continental rise. This brings basement down to about 2 km lower than basement further offshore. The depression of the rifted continental

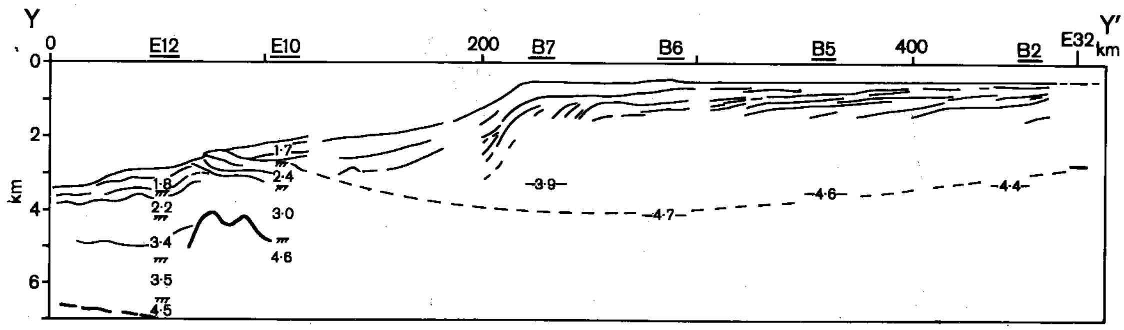

Fig. 8 A composite structural profile across the Eastern Basin and eastern Ross Sea continental slope, modified from Houtz & Davey (1973, fig. 11). Interpreted basement is shown by heavy line. Sonobuoy seismic refraction results are shown with velocities in km/s. For sonobuoys B2–7 the depth and highest velocity observed are plotted. Sonobuoys E10 and E12 are from Houtz & Davey (1973). E32 marks where *Eltanin* cruise 32 crosses the the profile. The profile is located in Fig. 1.

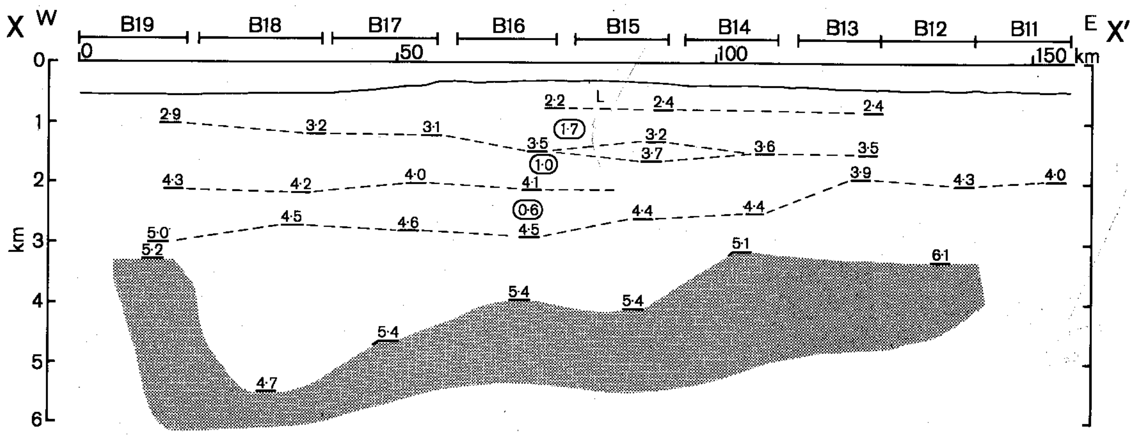

Fig. 9 West–east profile across the Central Trough. The depth and seismic velocity at changes in the velocity-depth gradient are marked. The average gradients for the zones are shown circled. The deepest sediment velocity observed is assumed to continue to basement. Basement is shown shaded. The profile is located in Fig. 1.

margin by 2 km could arise from subsequent loading of the crust by the prograding wedge of Oligocene and younger sediments. Houtz & Davey (1973) also note an outcropping sedimentary layer above the downfault in basement, and postulate that this layer may be pre-breakup (80 Ma) in age, suggesting that at least 2 km of section under the upper continental rise, and probably under part of the shelf, are at least Cretaceous in age. These sediments, if they exist, would only be under the central part of the basin, as no sediments older than Oligocene were sampled at the drill sites on the western margin. Furthermore, if the depression of basement is due to loading by Late and post-Oligocene sediments, a pre-existing trough is needed in which to deposit the sediments. This could well be a trough containing older sediments up to Cretaceous in age. The profile shows the thick sedimentary sequence in the basin. The simple velocity-depth profile suggests that the deepest refractors noted are part of the Cenozoic glacial sequence and that the basement seen on the profiler records from *Eltanin* cruise 32 along the edge of the Ross Ice Shelf (Houtz & Davey 1973), also shown on Fig. 8. where it crosses the profile, lies at the base of the late Cenozoic sediments. The upper surface of any early Tertiary–late Mesozoic sediments would thus lie at, or deeper than, the dashed line on Fig. 8.

The Central Trough

The Central Trough trends approximately north–south through the central Ross Sea along 175°E from the Ross Ice Shelf to at least 74°S. It may continue southwards under the Ross Ice Shelf. There is no evidence on the seismic reflection data for the presence of a deep trough (Houtz & Davey 1973) and its delineation is based primarily on sonobuoy seismic refraction measurements. The graben postulated by Hayes & Davey (1975), on the basis of gravity data and the seismic data of Houtz & Davey (1973), is shown by these new sonobuoy refraction data to be a simplification of the actual structure. The thickness of sediments on the margin of the trough exceeds 2 km in places and the graben would therefore appear to be primarily in the oldest sediments (Fig. 9). The seismic velocities for the sediments on this profile are similar at similar depths as are the velocity gradient changes (also indicated on Fig. 9). The age of the deeper sediments is unknown. Drilling results at DSDP site 273 showed sediments of possibly Early Miocene age at a depth of 365 m (Hayes et al. 1975b). Seismic reflection data extending to a greater depth do not reflect any of the graben structure at depth, especially on the profiles presented by Houtz & Davey (1973, fig. 8) where there are large offsets in basement at the graben margin. The sediments in the deeper part of the trough are thus probably much older than Miocene in age. Davey (1981) postulates an early Tertiary age, suggesting that the graben formed as a failed arm of the spreading centre which abutted the continental margin of western Ross Sea about 55 Ma (Weissel et al. 1977).

The Victoria Land Basin

The Victoria Land Basin lies along the Transantarctic Mountains from Coulman Island to McMurdo Sound, being apparently deepest off the Granite Harbour–Cape Washington region (Fig. 6). The thickest sequences are the high velocity (>3.8 km/s) sediments. Thick sedimentary sequences occur in the McMurdo Sound region (Northey et al. 1975, Wong & Christoffel 1981) where the basin is probably partially caused by loading of the crust by Ross Island, as is suggested by the bathymetric moat surrounding the island. In the isopach map (Fig. 7), a basement ridge is shown extending north from Ross Island through Beaufort and Franklin Islands. An alternative interpretation would be that these volcanic islands, probably at most 15 Ma old, sit on top of older sedimentary sequences which are thus continuous across this region. Seismic reflection data show sedimentary layers dipping into the basin (Houtz & Davey 1973, Northey et al. 1975, Wong & Christoffel 1981). A striking series of truncated dipping sedimentary layers occur off Granite Harbour and display a stratigraphic thickness of at least 1.3 km (D. J. Bennett pers. comm.). The upper part of the sedimentary sequence in McMurdo Sound was sampled by the MSSTS–1 drillhole (Barrett 1980) and found to be mostly Middle Miocene glacial sediments.

The basin lies alongside the Transantarctic Mountains in a region where the crustal thickness decreases sharply to the east. The seismic reflection data in McMurdo Sound (Northey et al. 1975, Wong & Christoffel 1981) indicate that this part of the basin has been rapidly downwarping during the late Cenozoic. The Transantarctic Mountains have been rising probably since the Jurassic, and at an increasing rate during the late Cenozoic. It is possible that the Victoria Land Basin has been downwarping in compensation for the uplifted load of the mountains. The tectonic problem is, then, the mechanism of uplift of the mountain range. Smithson (1972) and Herron & Tucholke (1975) have suggested convergence along the Transantarctic Mountains during the Cenozoic and this convergence may be being reflected by the uplifting of the Transantarctic Mountains and the corresponding downwarping of the western Ross Sea crust. Davey (1981) discounted convergence because of the existence of young tensional features such as grabens just west of the Central Trough and the late Cenozoic igneous centres along the western part of Ross Sea. However, these features may result from bending of the Ross Sea crust down into the Victoria Land Basin.

CONCLUSIONS

New seismic refraction data have helped define the total sedimentary cover of the Ross Sea in greater detail than previously known. The measurements confirm the presence of thick sediments contained in the Eastern Basin and in the Central Trough and demonstrate the existence of a thick sedimentary rock section east of the Transantarctic Mountains from McMurdo Sound to Coulman Island (the Victoria Land Basin). The data also demonstrate the different physical characteristics of the sediments in each of the basins, as reflected by their seismic velocity-depth profiles. The Eastern Basin shows a near-linear velocity-depth profile for the sedimentary section, suggesting a shale lithology. However, no basement velocities were obtained in the deeper part of this basin, so its total depth is unknown. The velocity-depth profiles for the sediments in the Central Trough generally show a more complex character and can be represented by a series of linear segments with decreasing gradient of velocity increase with depth, indicating, perhaps, a coarser sandstone lithology. Basement velocities are observed as distinct separate refractors from the curved alignment for the sediment refracted arrivals. The basement velocities are typical for metamorphic rocks, being in the range 5.0–5.5 km/s. One value of 6.0 km/s may correspond to higher velocity rocks, such as dolerites, but may also be an updip velocity as the dip of the refractor is not constrained. The Victoria Land Basin contains a more discretely layered sedimentary section. Velocities group around 2.0 km/s, 3.0 km/s, and 4.0 km/s. Basement velocities are variable in the range 4.9 km/s to 6.4 km/s, the latter possibly coming from Jurassic Ferrar Dolerites. In addition to, and perhaps causing, this difference in the sediment velocity structure characteristic of each basin, the tectonic history of each basin appears to be different. The Eastern Basin, or the upper few kilometres of it, appears to result from downwarping of the crust and concomitant onloading by late Cenozoic marine glacial sediments in a pre-existing trough, which perhaps contains Late Cretaceous–early Tertiary sediments. The Central Trough probably formed as a "failed" rift in the Eocene spreading episode in the southwest Pacific Ocean. The Victoria Land Basin appears to be intimately related to the uplift of the Transantarctic Mountains and may thus show greatest development in the late Cenozoic. The mechanism causing the uplift of the Transantarctic Mountains and the associated downwarping of the Victoria Land Basin may be associated with convergence between the Ross Sea lithosphere and the East Antarctic lithosphere.

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