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Geophysical studies in the Ross Sea region

F. J. Davey*

Geophysical studies in the Ross Sea and over the Ross Ice Shelf have defined the major structural features of this morphological depressed region (the Ross Embayment) between East and West Antarctica. Deep sedimentary basins or troughs containing over 2500 m of sediments occur either side of a basement ridge which runs north-south through central Ross Sea and apparently extends under the Ross Ice Shelf. This ridge marks the boundary zone between two regions which had a different late Cenozoic tectonic history. Under the Ross Ice Shelf the structural trends to the east of this boundary zone change to an approximately northwest-southeast direction, parallel to the Transantarctic Mountains.

The crust is thinner under this region than in either East Antarctica (40 km) or West Antarctica (30 km). This thinner crust suggests that the Ross Embayment may result from crustal rifting, and its formation and structural trends may be related to plate motions and changes in motion in the south Pacific Ocean during the late Cretaceous and Cenozoic.

The Transantarctic Mountains are one of the major morphological and geological features of Antarctica, coinciding with the large rapid change in crustal thickness from the Ross Embayment to East Antarctica. The history of the formation of this mountain belt remains one of the outstanding problems of the region.

INTRODUCTION

The Ross Sea region lies along the boundary zone between the old continental craton of East Antarctica and the geologically younger West Antarctica. The Ross Sea and Ross Ice Shelf, together called the Ross Embayment, coincide with a large morphological depression along this boundary zone (Fig. 1). In this paper we review geophysical studies of the structure and geological history of the crust of the Ross Embayment and its margins, dividing the region into three parts — Ross Sea, Ross Ice Shelf, Transantarctic Mountains and McMurdo Sound — as individual geophysical studies have tended to be restricted to one of these. Geophysical work in each of the subregions will be reviewed and related to the other studies.

THE ROSS SEA

Up to 1979 the most extensive geophysical surveys in the Ross Sea had been carried out by USNS 'Eltanin' between 1967 and 1972 (Houtz and Meijer, 1970; Houtz and Davey, 1973; Hayes and Davey, 1975). These surveys included bathymetric, gravity, magnetic, seismic airgun profiler and sonobuoy seismic refraction measurements and were all controlled by satellite navigator thus givinga significant improvement in positional control over previous work. The data give a good reconnaissance coverage, although there are gaps along the coasts of Marie Byrd Land and the Transantarctic Mountains.

The bathymetry of the Ross Sea (Fig. 2) may be divided into two parts, east and west of the 180° meridian. The eastern Ross Sea has a continental shelf at a depth of about 500 m with broad low ridges running north-south across it and with a simple continental slope and rise. The western Ross Sea has a continental shelf also at about 500 m but with

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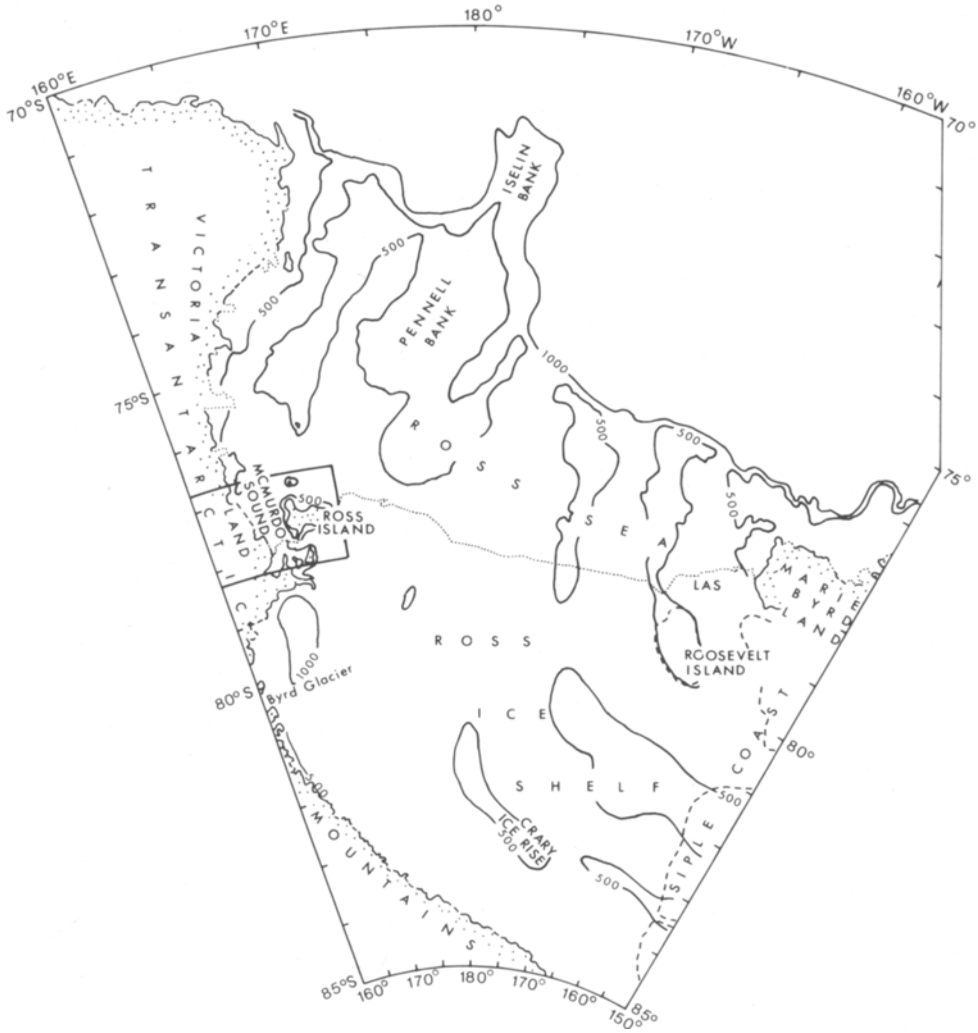

Fig. 1 — The Ross Sea region. 500-m and 100-m isobaths marked. Approximate outer limits of floating ice shelves = dotted lines; limits of grounded ice shelves = short dashed lines. LAS = Little America Station. The location of Fig. 6, the McMurdo Sound region, is outlined.

larger amplitude ridges running northeast-southwest across it and a morphologically complex continental slope and rise.

Seismic reflection profiling surveys (Houtz and Meijer, 1970; Houtz and Davey, 1973) show that the upper, approximately 500-1000 m of sediments on the continental shelf area of the Ross Sea consist of two main sequences. A well-bedded gently folded sequence is truncated in places by a widely occurring erosional surface at a depth of about 500 m below sea level; overlying this erosional surface, dated at about 4-5 m.y., are banks of younger unstratified sediments. The older sequence under the western Ross Sea is folded into broad anticlines and synclines, the anticlines coinciding with the morphological rises in the northwestern Ross Sea. These broad folds trend north-south and plunge gently to the north. In contrast, however, the north-south-trending rises in the eastern Ross Sea coincide with the younger banks of sediments. The dividing line between these two sub-regions coincides with a series of basement highs from the edge of the ice shelf to Iselin Bank (Fig. 1).

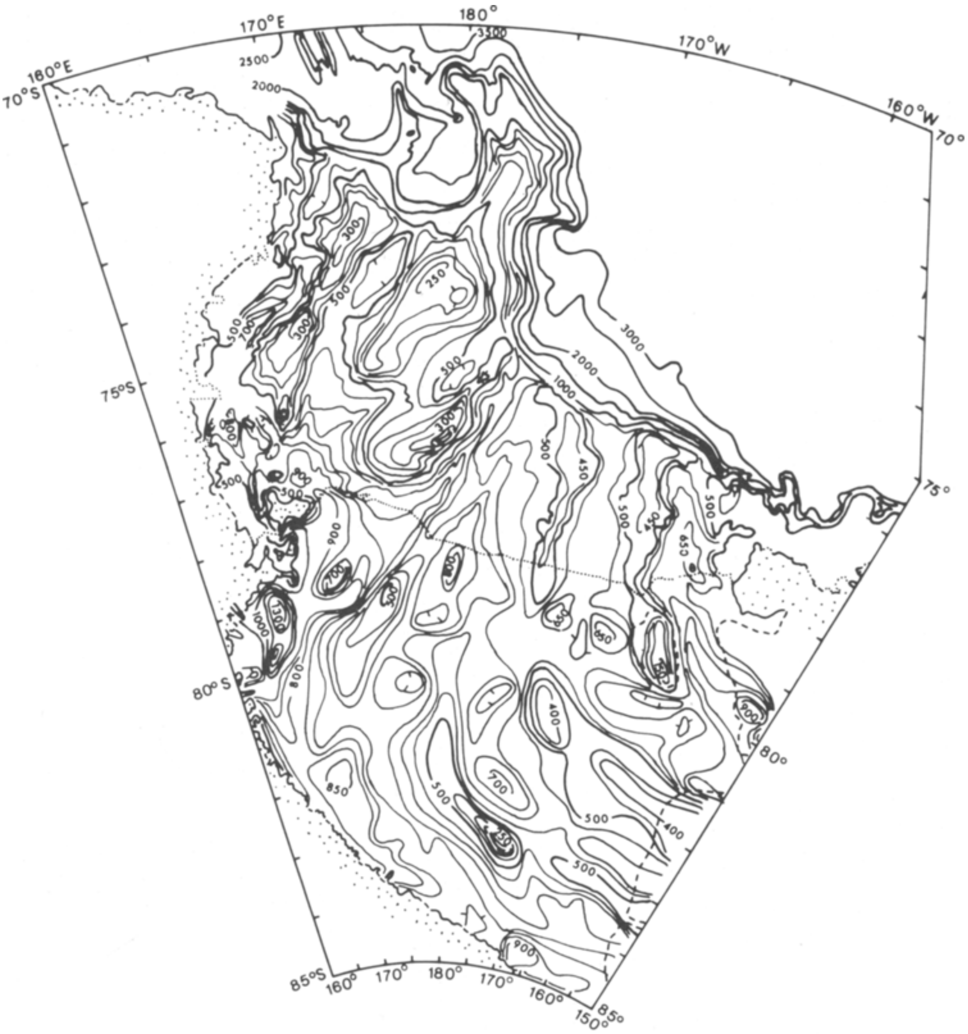

Fig. 2 — Bathymetry (m) of the Ross Sea region, after Hayes and Davey (1975) and Robertson *et al.* (in press).

The seismic profiler data rarely showed reflections from deeper than 1 km beneath the sea floor, at which depth the seafloor multiple occurred; information on the deeper geological structure is primarily from sonobuoy seismic refraction and variable angle reflection and gravity data. However basement at a depth of 2 to 3 km was detected on a reflection profile parallel to the ice shelf edge near Roosevelt Island. The profile showed deep basement valleys suggested by Houtz and Davey (1973) to be of glacial origin. The sonobuoy data defined two areas on the shelf where thick sedimentary sequences occurred (Fig. 3). Under the eastern Ross Sea up to 4 km of sediments was measured. The profiler data in the region showed reflectors continuously dipping towards the centre and shelf edge of the eastern Ross Sea and indicating a total sediment thickness of over 2000 m. This was interpreted by Houtz and Davey (1973) as defining a single large sedimentary basin underlying the whole of the eastern Ross Sea (Fig. 4), assuming that the dipping sedimentary layers did not thin under the basin. The Deep Sea Drilling Project (DSDP) sites 270 to 272 were on the western margin of the basin (Fig. 3). The sedimentary section consisted of thin mid to late Oligocene shallow-water sediments

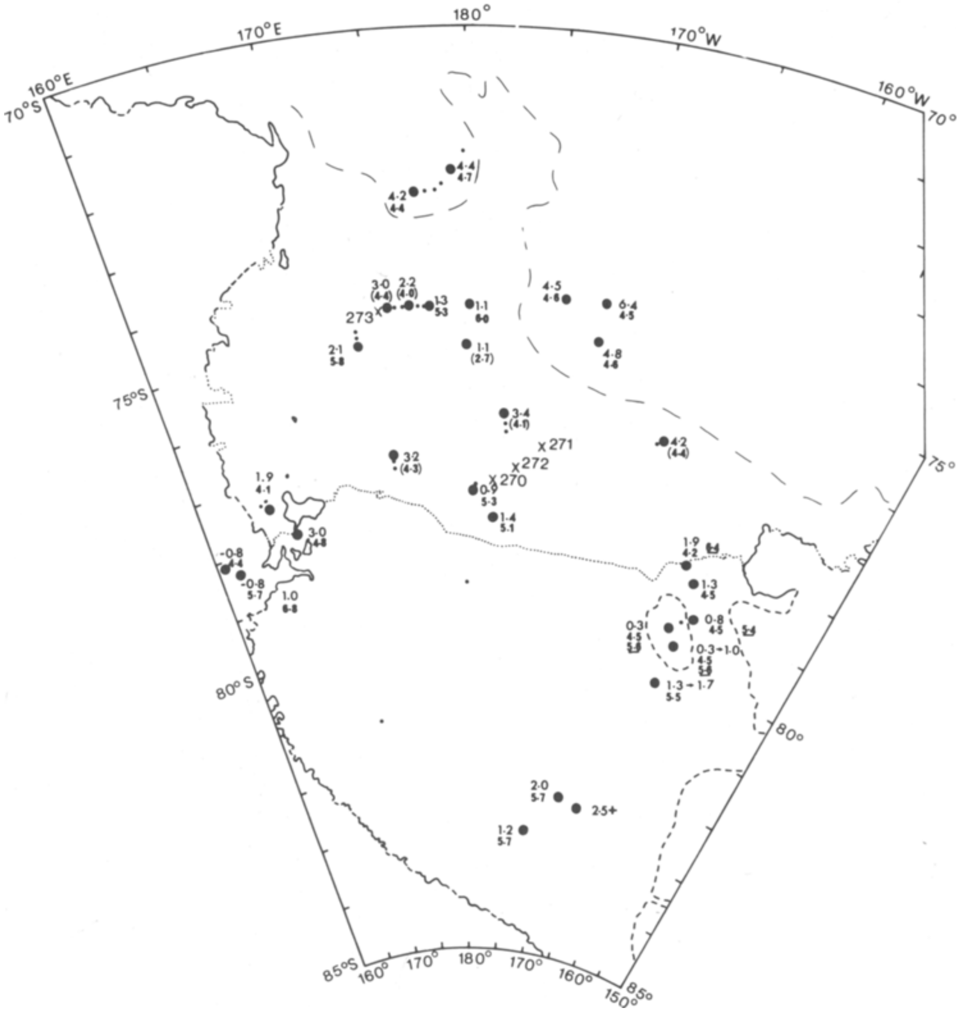

Fig. 3 — The location of seismic refraction measurements in the Ross Sea region. Pairs of numbers (upper, depth in km below sea level to basement; lower, basement seismic velocity (km/s) or, in brackets, highest seismic velocity measured if not basement) refer to each station marked by a large solid circle. Near Marie Byrd Land the third, underlined, number gives the seismic velocity of deeper basement rocks. Where several measurements are close together the data are given only for the measurements showing deepest basement. The position of the other measurements showing deepest basement. The position of the other measurements are shown by the small solid circles: DSDP sites 270-273 are marked by crosses and labelled.

overlain by early to middle Miocene marine glacial sediments. A hiatus at about 4-5 m.y., coinciding with the widespread unconformity seen on the seismic section, separated these sediments, which formed most of the section, from similar Pliocene to Recent marine glacial deposits. The consistent dip and total thickness of the sedimentary layers in the basin would suggest that Oligocene sediments would overlie basement in the vicinity of the fiords in basement near Roosevelt Island. These fiords may therefore reflect temperate glacier activity during the early Oligocene before the subsidence of the Ross Sea region and the onset of continental glaciation in the late Oligocene. The precise shape and total extent of the basin is not well defined by the data, however. Gravity observations over the area (Fig. 5) are interesting in that they do not show any significant gravity low over the basin (Hayes and Davey, 1975). This may arise in part from the

Fig. 4 — Isopachs (km) of sediment thickness under the Ross Sea after Houtz and Davey (1973) and Hayes and Davey (1975), and under the Ross Ice Shelf after Bennett (1964) and Robertson *et al.* (in press).

indurated nature of the sediments found during DSDP drilling, which is also indicated by the high seafloor sediment velocity of 2.25 km/s found in eastern Ross Sea by Houtz and Davey (1973); alternatively it may indicate a positive gravity contribution from a deeper high-density body, perhaps in the lower crust.

The deeper structure of the western Ross Sea appears more complex, perhaps because of the paucity of suitable seismic data. At least 2.5 km of sediments were measured under central western Ross Sea in a trough with a limited (125 km) east-west extent and a steep eastern boundary (Fig. 4). Gravity data over the region show a central high with marked peripheral lows over the thick sediments, in contrast to the data over eastern Ross Sea. Sea-floor seismic velocities (2.1 km/s) are lower here than in the eastern Ross Sea indicating lower density sediments. Hayes and Davey (1975) interpret the gravity and seismic data as defining a major north-south-trending graben underlying the central western Ross Sea and extending from the ice shelf to the continental margin. The central gravity high (Fig. 5) was interpreted in terms of a high density body emplaced at middle crustal depths under the rift. The graben does not affect the sedimentary layers defined

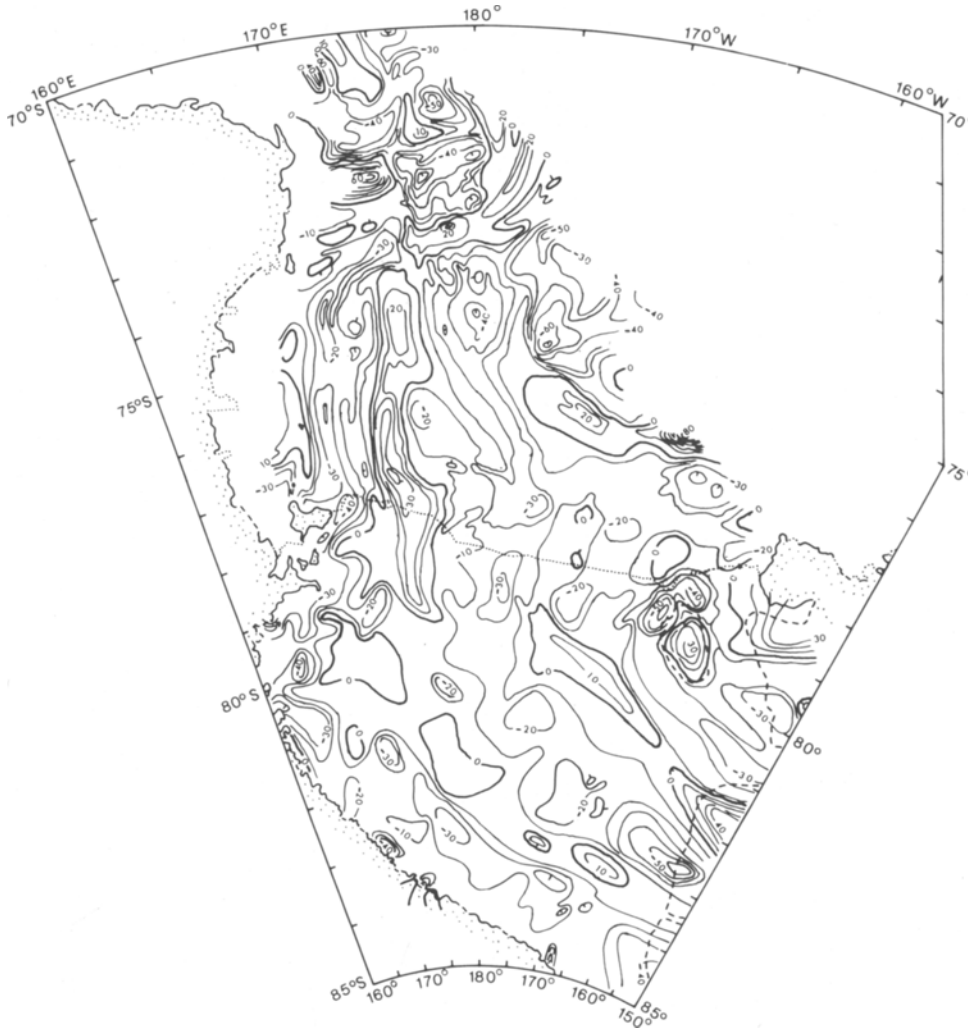

Fig. 5 — Free air gravity anomalies (10 μN/kg units) for the Ross Sea region after Hayes and Davey (1975) and Robertson *et al.* (in press). For anomalies based on IGSN71 gravity datum and the 1967 Geodetic Reference System see Greisher and Bentley (1980a).

by the seismic profiler data. DSDP site 273 was in this region (Fig. 3) and sampled sediments up to middle Miocene in age. As the drill hole only penetrated part of the sedimentary section seen on the seismic profiler data the graben must be a much older structure, at least early Tertiary. The sedimentary cover starts thickening again to the west of this structure, towards the Victoria Land coast, but data coverage stops well short of the coast.

The continental slope and rise along the northern margin of the Ross Sea can also be conveniently split into two sections, east and west of Iselin Bank. The eastern margin is steepest at its eastern end (Fig. 2). Seismic profiler data only cover the west part, where thick sediments underly the margin. Basement appears to be at a depth of 4 to 5 km beneath sea level under the upper continental slope but has a steep step down towards the north, midway down the slope, to a depth of about 7 km. This results in a marginal rift of limited extent and covered by up to 4 km of sediments at the edge of the continent. In contrast basement under the western continental margin lies at about 4.5 km (the depth of oceanic basement farther north), and no marginal rift is apparent. The western margin has a more complex basement, with sediments up to 3 km thick in the basins underlying the margin. Iselin Bank lies between the eastern and western Ross Sea continental margins. Hayes and Davey (1975) consider it to be probably continental in character. It is split at its northern end by a deep sediment filled rift.

The seismic velocities in the sedimentary sections over most of the Ross Sea increase steadily with depth, and, considered with the sequence of dipping reflectors underlying east Ross Sea, indicate that the seismic velocity of the sediments cannot be related to their age. Seafloor velocities, especially in the east, are high and are consistent with the indurated sediments in the area as noted in the DSDP studies. The difference in seafloor velocities between east and west Ross Sea suggests a different recent tectonic history for the two areas, the eastern part possibly undergoing greater uplift and erosion, the latter during the Pliocene maximum ice advance. The structural boundary between the east and west Ross Sea (the line of basement highs from the ice shelf to Iselin Bank), may also have existed in pre-Tertiary times as it coincides with the junction of the New Zealand and Australian continental blocks in Gondwana reconstructions (e.g. Grindley and Davey, in press).

The structural trends in basement rocks in Victoria Land and western Marie Byrd Land are similar, trending northwest-southeast, but diverge considerably from north-south structural trends obtained for Ross Sea which probably are younger. Information on the type of basement rocks underlying the Ross Sea is sparse. Seismic measurements show that the seismic velocities of basement rocks are greater than 5.1 km/s. Lower velocities which may correspond to velocities for Beacon group sediments (4-4.5 km/s) for example, are only recorded at depth in the deeper sedimentary sections where they are apparently related to the depth of burial of the sediments. The range of velocities recorded, 5.2 to 6.3 km/s, is that to be expected in metamorphic rocks. Seismic velocities measured on rock samples from Victoria Land (Barrett and Froggatt, 1978) give seismic values consistently lower (by 0.5-1.0 km/s) than seismic refraction measurements on apparently similar rock types. They consider this may be caused by depth of burial of the rocks examined in the field measurements. These uncertainties mean it is not possible to categorise basement rock type in detail on the basis of seismic velocity. For example, Barrett and Froggatt (1978) obtained a velocity of 4.5 km/s for the calcsilicate gneiss cored at DSDP site 270 (Ford and Barrett, 1975). By comparison, Houtz and Davey (1973) obtained basement seismic velocities of 5.2 and 5.3 km/s at two positions close to this site.

Low gravity anomaly values at the eastern side of the Ross Sea and along the median basement rise at about 74° S (Fig. 5) coincide with basement rises. They have been interpreted as caused by granitic bodies in basement and as being Cretaceous and Lower Palaeozoic, respectively (Hayes and Davey, 1975). Geomagnetic data define few anomalies of significance in the Ross Sea (Hayes and Davey, 1975). The anomalies found coincide, in general, with regions of known late Cenozoic volcanism in western Ross Sea or with shallow basement.

THE ROSS ICE SHELF

The early geophysical measurements over the Ross Ice Shelf were followed up by work concentrated at Roosevelt Island, largely glaciological and ice dynamics investigations (Clapp, 1965; Thomas *et al.,* 1980). A major systematic geophysical reconnaissance survey of the ice shelf only started in 1973 as part of the Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS) (Bentley, this volume). The gravity and seismic measurements, made systematically on a 50-km grid, were processed to give maps of sea-floor topography, free air and Bouguer gravity anomalies and seismic velocity columns (Robertson *et al.,* in press).

The sea floor (Fig. 2) under the ice shelf is characterised by a series of troughs and ridges lying subparallel to the Transantarctic Mountains (Robertson *et al.,* in press). As noted by Hayes and Davey (1975) the ridge and trough continue smoothly from the Ross Sea under the ice shelf edge with no major discontinuities. This can be traced under the

Ross Ice Shelf and for about 250 km under the grounded ice sheet of southern Marie Byrd Land, where it terminates at the deeper more rugged Byrd subglacial basin, to form a continuous morphological unit — the Ross Embayment (Albert *et al.*, 1978). The deepest troughs under the Ross Ice Shelf lie along the Transantarctic Mountains south of 74° S with local depressions more than 800 m deep lying off the mouths of the major glaciers. The maximum depth reached is 1300 m — the Discovery Deep — close to the mouths of the Byrd and Skelton glaciers. A possible extension of the morphological boundary mentioned earlier between the east and west Ross Sea can be traced south under the Ross Ice Shelf where it coincides approximately with the eastern margin of the Discovery Deep.

The distribution and structure of the sedimentary layers underlying the Ross Ice Shelf (Fig. 3) is poorly known, being based on few, mainly seismic, data (Robertson *et al.*, in press). It should be noted that the seismic interpretations are not well defined because the data are limited and few seismic profiles are reversed. Albert *et al.* (1978) consider that the low ridges under the central and eastern Ross Ice Shelf are probably depositional, as Houtz and Davey (1973) suggested for the eastern Ross Sea ridges into which they continue. Albert *et al.* (1978) note that the ridges tend to follow ice stream lines from Siple Coast and thus may be formed of glacial debris (see also Robertson 1975). Sub seafloor seismic reflection data at three stations on the Ross Ice Shelf (Robertson *et al.*, in press) from a reflector at depths of 40 to 150 m beneath the seafloor gave seafloor sediment velocities largely consistent with the high seafloor sediment velocities under the eastern Ross Sea. This reflector may correlate with the widespread shallow reflector in the eastern Ross Sea. The seismic refraction results show that sediments up to 2000 m thick underlie part of the Ross Ice Shelf (Fig. 3) and suggest that the deep sedimentary basins underlying the Ross Sea may continue southwards.

Basement seismic velocities include two main groups. Rocks with a velocity in the range 4.2 to 4.5 km/s are noted on the seismic data northeast of a line from the Byrd Subglacial Basin to Roosevelt Island, although they may occur but be missing on sections to the south if the rock layers are thin, as the velocity is very close to that of ice (3.8 km/s). Crary (1962) tentatively associates rocks with these seismic velocities with Beacon group sediments. However, if they only occur in the eastern part of the Ross Embayment they may well be associated with the low grade metasediments of western Marie Byrd Land. The higher seismic velocities of 5.4 to 5.9 km/s could be associated with any of the higher grade metamorphic basement rocks surrounding the Ross Ice Shelf (Robertson *et al.*, in press).

The few seismic measurements near the Transantarctic Mountains, in the vicinity of the Skelton Glacier and near the Horlick Mountains, show high seismic velocities ($>$6.0 km/s), typical of lower crustal rocks, within a few hundred kilometres either side of the Transantarctic Mountains at a shallow depth of 1 to 4 km below sealevel (Bentley and Clough, 1972; Bentley, 1973). The higher velocities are similar to those measured on the Ferrar dolerites of the Transantarctic Mountains, and Bentley and Clough (1972) and Bentley (1973) suggest that the sources of the dolerite extrusions are lower crustal basaltic rocks occurring unusually close to the surface. They also note that the occurrence of high velocity, and hence high density, rocks near to the surface on both sides of the Transantarctic Mountains would indicate that the source of the large Bouguer anomaly gradient over the Transantarctic Mountains is largely due to an abrupt change in crustal thickness.

Free-air gravity anomalies over the Ross Ice Shelf are shown in Fig. 5 (Robertson *et al.*, in press). The distinctive gravity anomaly trending north-south across the western Ross Sea can be traced across the ice shelf for 150 km. Over most of the remainder of the ice shelf the gravity anomaly trends are more northwest-southeast, parallel to the Transantarctic Mountains. Bouguer and isostatic anomalies show poor correlation with sediment thicknesses indicating deeper structural control of the gravity anomalies (as also found in the Ross Sea by Hayes and Davey, (1975)) and therefore deep structural control of the seafloor morphology as the morphology and gravity anomaly trends are closely parallel. The topography of the seafloor is not determined by the ice streams but *vice versa*.

The Crary Ice Rise, Roosevelt Island and Discovery Deep, however, appear to be compensated and in isostatic equilibrium. Bentley *et al.* (in press) and Greisher and Bentley (1980b) show that the regional isostatic gravity anomaly decreases from Ross Island and the Ross Sea continental shelf edge to the Siple Coast. This decrease can be interpreted in terms of incomplete isostatic rebound starting about 6000 years ago after glacial depression and recession. Greisher and Bentley (1980c) suggest that a further 100 m uplift is indicated before equilibrium is achieved.

THE TRANSANTARCTIC MOUNTAINS AND WESTERN ROSS SEA

The Transantarctic Mountains lie along the margin of the Ross Embayment where they form a remarkably smooth western boundary with the shape of two large arcs meeting in the vicinity of McMurdo Sound. The rocks exposed in the mountains are either Jurassic or older or are upper Tertiary volcanic and glacial tills; no Cretaceous or lower Tertiary rocks are exposed. The structure of the mountain chain has been interpreted both as a monclinal fold or as an upfaulted block showing an uplift of about 3000 m considered to be primarily late Cenozoic. Most geophysical work has been carried out in the McMurdo Sound region (Fig. 6) mainly because of its proximity to the bases on Ross Island but also because of a major investigation of the late Cenozoic history of the Dry Valley region of South Victoria Land, the Dry Valley Drilling Project (DVDP).

The early gravity surveys were extended by Smithson (1972), who made a regional survey over the Dry Valleys area. He interpreted an east-west profile from Ross Island to the Transantarctic Mountains (Fig. 6) in terms of crustal thinning, from 40 km under the Transantarctic Mountains to 27 km under McMurdo Sound. However to create the high gravity gradients along the coast a high density crustal intrusive under the McMurdo Sound region was necessary. He further postulated that this boundary between two different crustal structures may mark a collision zone between two continental masses. More recent gravity surveys by Hicks (1978) and Stern (1978) examine the thickness of ice and sediments in the Dry Valleys. Sissons (1980) extended the gravity measurements

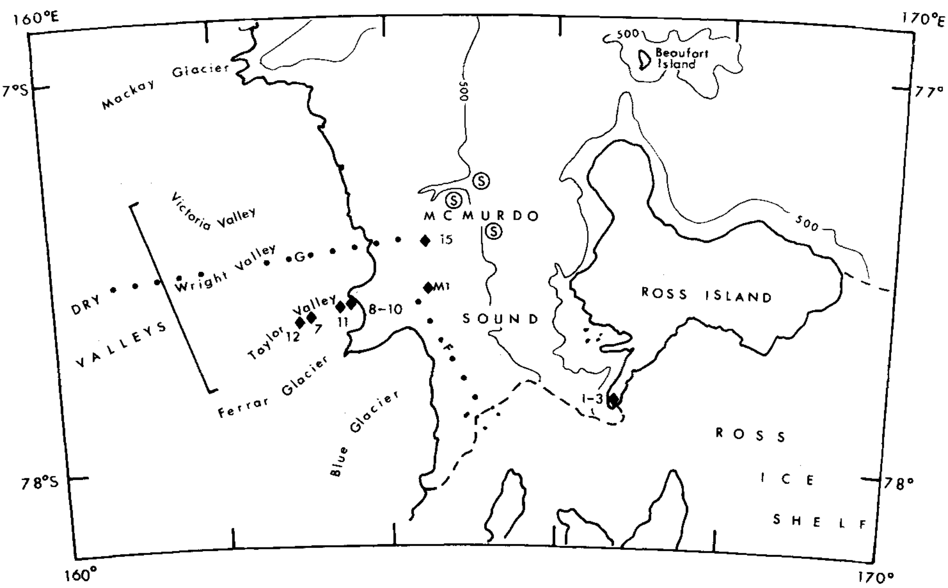

Fig. 6—The McMurdo Sound region. 500 m isobath is shown. Drilling sites (DVDP and MSSTS (M1)) = diamonds. Gravity profile of Smithson (1972) = dotted line G. Postulated fault of Sissons (1980) = dotted line F. Sonobuoy measurements of Wong and Christoffel (in press) = circled S.

offshore onto the sea ice to define the coastal gravity gradients more precisely and detected a possible fault with a throw of up to 1 km but of limited extent just offshore of the coast along the western margin of McMurdo Sound (Fig. 6).

Aeromagnetic data over the McMurdo Sound region showed strong local anomalies over and to the south of Ross Island (suggesting the extension of volcanics south of Ross Island), a smooth magnetic field over McMurdo Sound, medium amplitude anomalies associated with the dolerite sills and dykes of Victoria Land and a strong positive magnetic anomaly marking the western boundary of the Transantarctic Mountains.

Heat-flow measurements show generally high values in the McMurdo Sound region. On Ross Island heat-flow values of about 160 mW/m^2 (Risk and Hochstein, 1974) and 70 mW/m^2 (Decker, 1978) have been obtained. In McMurdo Sound, near Ross Island, heat flows of 160 to 250 mW/m^2 have been measured (Cousin and Christoffel, in Risk and Hochstein, 1974), and in the Dry Valleys, using DVDP drill holes, Decker (1978) measured heat flows of up to 150 mW/m^2. The temperature profiles for the DVDP drill holes can be used to derive probable thicknesses of the permafrost layer. A thickness of about 500 m is indicated on Ross Island, while in the Dry Valley the thickness derived varies from about 900 m at Lake Vida to 250 m at New Harbour (Decker and Bucher, 1977). The temperature gradient in the MSSTS-1 drill hole in New Harbour is 35-38° C (Sissons, 1980), suggesting a near normal heat flow of about 60 mW/m^2. The only other heat-flow values for the Ross Sea region are 50-70 mW/m^2 derived from Roosevelt Island by Thomas *et al.* (1980). Decker (1978) considers the heat-flow values of the McMurdo Sound region too high and extensive to be caused by volcanic activity on Ross Island (see also Risk and Hochstein, 1974) and compares them with those found in the Basin and Range province of the western USA, suggesting a deep-seated source, perhaps related to crustal rifting and extensional tectonics.

The early palaeomagnetic measurements on Jurassic rocks, primarily dolerites, of the Transantarctic Mountains have been supplemented by measurements on Ordovician lamprophyre dykes by Manzoni and Nanni (1979), which are consistent with results on rocks of similar age from other parts of East Antarctica. Palaeomagnetic measurements have been made on the younger volcanics of Ross Island (McMahon and Spall, 1974a, b) and on the magnetic stability of other older rock formations (Hunt and Mumme, 1977). In many cases palaeomagnetic data on older rocks have been overprinted by a Jurassic thermal event, the intrusion of the dolerite sills. It seems unlikely that the sediments have been heated enough to reset the remanent magnetisation, and extensive hydrothermal alteration is indicated. Palaeomagnetic data on DVDP drill hole cores and a core from DSDP site 270 show geomagnetic reversal stratigraphies which broadly confirm the ages of the sediments derived from microfaunal data (Allis *et al.*, 1975; Elston *et al.*, 1978). The data from DVDP cores show a change in the intensity of magnetisation of the sediments at about 5 m.y., indicating a change in the source of the sediments from the East Antarctic icecap to the McMurdo Sound region, presumably associated with an uplift of the Transantarctic Mountains.

McMurdo Sound has been surveyed fairly extensively by continuous seismic profiling, and some seismic refraction measurements have also been made (Northey *et al.*, 1975; Wong and Christoffel, in press). These data and bathymetric data show that the sound is a linear deep trending north-south with an asymmetric cross-section, deepest in the east near Ross Island. The seismic data define a well bedded sedimentary section dipping and thickening to a depth of 2 km in the east, a similar thickness to that found in the south (Robinson, 1963). An unconformity, probably about 5 m.y. (Northey *et al.*, 1975), overlies these reflectors and may correspond to the widespread unconformity of similar age in the Ross Sea. At the base of the trough this unconformity is overlain by flat-lying sediments, suggesting a major downwarp of the trough at about 5 m.y.; this is perhaps also related to loading of the crust by Ross Island the oldest volcanics of which are of this age. The results of the MSSTS-1 drill hole indicate that most of the sedimentary section seen on the seismic data is Miocene (Brady, 1980; Leckie and Ward, 1980) but this is not unequivocal as the drill site was about 5 km from the closest seismic profile. The refraction data in the sound gave seismic velocities of up to 4.1 km/s. This velocity is perhaps a little low for basement. Jackson *et al.* (1975), for example, obtained a minimum basement velocity of 4.9 km/s at shallow depth in the Dry Valleys. Kaminuma (1979) presents some vertical reflection data from explosions on Ross Island, which show reflectors at depths of up to 3.5 s two-way travel time; no velocity data, however, were derived. Kaminuma (1976) also confirmed the very low natural seismicity of the Ross Sea region (Adams, 1972a).

DISCUSSION

Geophysical data in the Ross Sea and over the Ross Ice Shelf have outlined the morphologically depressed region, the Ross Embayment, extending along the northeastern flank of the Transantarctic Mountains from the edge of the Ross Sea continental shelf to southern Marie Byrd Land. Data from farther to the east suggest that this feature extends to the Amundsen Sea and Bellinghausen Sea and may extend to the Weddell Sea (Bentley, 1972). Crustal thickness data for the Antarctic are sparse. Surface wave dispersion and gravity data demonstrate that the crustal thickness of west Antarctica is about 10 km thinner than east Antarctica and that the crustal thickness of east Antarctica is about 40 km (Adams, 1972b). This latter thickness is supported by crustal seismic measurements in Dronning Maud Land (Kogan, 1972). There is some evidence that the crust under the Ross Embayment may be thinner than either. Woollard (1962) using gravity and topographic data showed the thinnest crust to occur under the Ross Embayment, Byrd Basin and the Filchner Ice Shelf where he obtained a value of 25 to 30 km. Hochstein has derived a crustal thickness of 24 km under the Filchner Ice Shelf at 83° S 70° W (Bentley, 1973), which is apparently supported by the work of Masolov and Kurinin (1981). The thick sediments and possibly thin crust coinciding with the Ross Embayment suggests that it may be a major rift zone. Syntheses of plate movements during the past 100 m.y. have indicated rifting between east and west Antarctica (Molnar *et al.*, 1975; Herron and Tucholke, 1976), probably before 20 m.y.

If the Ross Embayment has formed by rifting of the Transantarctic Mountains from Marie Byrd Land then a structural grain parallel to the axis of rifting would be expected. The trend of the deeper structures controlling the morphology and gravity anomalies in the Ross Ice Shelf region (Robertson *et al.*, in press) would be consistent with this concept. These structures terminate abruptly along a zone running north from Byrd Glacier, suggesting that the postulated rifting stops there, possibly against a major transform fault stretching from Byrd Glacier along the eastern margin of Iselin Bank (Fig. 7) to link up with the late and post Cretaceous spreading on the Pacific-Antarctic ridge. This postulated transform coincides with the boundary dividing the Ross Sea into two structural regions mentioned earlier and with the western margin of the trough of thick low-density sediments under the Ross Ice Shelf noted by Bennett (1964). It may lie along an older line of weakness, as Grindley (this volume) notes an offset of the Lower Palaeozoic rocks at the Byrd Glacier.

The relationship of the west Ross Sea graben to this scheme is unclear. As noted earlier the graben is older than Miocene, perhaps considerably older. It was possibly formed as an aulocogen during a change in spreading direction south of New Zealand, a change which coincided with the separation of Australia from Antarctica at 55 m.y. (Weissel and Hayes, 1972). Weissel *et al.* (1977) show that the spreading ridge south of New Zealand abutted against a postulated strike-slip fault along the western Ross Sea margin at this time.

Two further problems arise if the Ross Embayment was part of a major crustal rift prior to about 20 m.y.. The eastern Ross Sea basin is considered from DSDP data to have been formed mostly in the Oligocene and early Miocene. This region would thus presumably have been at sea level in early Tertiary times and a mechanism and reason for its subsequent downwarping and then uplift relative to western Ross Sea must be sought. Perhaps it arose from a redistribution of stress associated with the major reorganisation of plate boundaries in the South Pacific at about 25 m.y. (Handschumacher, 1976; Weissel *et al.*, 1977).

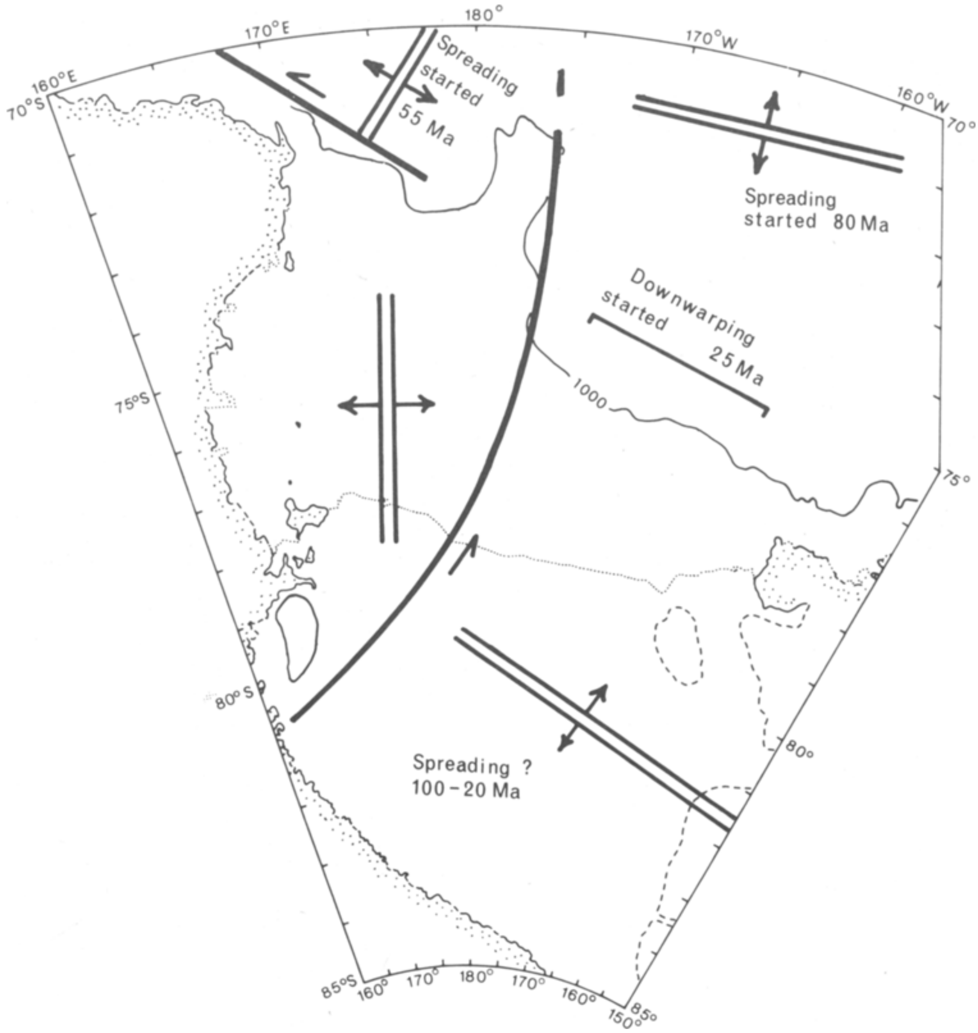

Fig. 7 — A schematic diagram for the opening of the Ross Embayment during the late Cretaceous and Cenozoic. Double thick line = rift centre. Single thick line = postulated transcurrent fault.

The Transantarctic Mountains are remarkable for the smooth curve of their eastern margin. If they coincide with the western margin of a rift zone for part of their length, an abrupt change in character or alignment may be expected along them. The offset north of Byrd Glacier, towards Ross Island, may mark this position. It should, however, be noted that no significant faults parallel to the postulated rifting are noted in the exposed land. The faulted margin presumably lies offshore and there is some gravity data in McMurdo Sound to support this (Sissons 1980). Smithson (1972) and Herron and Tucholke (1976) suggest that the boundary between the Transantarctic Mountains and the Ross Sea was a convergent margin, but the seismic results of Houtz and Davey (1973) and Hayes and Davey (1975) define graben features indicative of tensional stresses in western Ross Sea, probably until recent time, and the numerous late Cenozoic volcanic centres in western Ross Sea and high heat flow in McMurdo Sound region would also support this. However, the seismic data stop well short of the coast, and the eastern margin of the Transantarctic Mountains has not been studied adequately, especially next to the Ross

Ice Shelf, apart from in McMurdo Sound. The history and form of uplift of the Transantarctic Mountains is still poorly known.

The sedimentary basins and basement morphology underlying the Ross Sea and Ross Ice Shelf are poorly defined by existing data, especially in the latter region. The graben under the western Ross Sea is one of the major structural features on the shelf, but little is known of its true extent, age and relationship to other structures on the shelf. It is probable that it contains early Tertiary sediments. In contrast the basin under eastern Ross Sea is probably Oligocene or younger. It is also relatively poorly defined. The age of the basin is based on DSDP data long the western margin of the basin, whereas conceivably older sediments wedge out against basement under the central part of the basin and perhaps are seen as exposures on the continental slope. The solution to this problem awaits multichannel seismic data. In the region of the Ross Ice Shelf it is only possible to say that thick sediments probably occur under the eastern part of the ice shelf as the data are very sparse (Fig. 3). The thickness of the sediments in this region estimated by gravity data should be treated with caution in view of the lack of a gravity anomaly over the thick sediments of the eastern Ross Sea.

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