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THE LATE MESOZOIC AND CENOZOIC STRUCTURAL SETTING OF THE ROSS SEA REGION

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A review of the tectonic events over the past 120 m.y. in the Ross Sea region, and adjacent areas in Gondwana times, indicates that four major tectonic events have affected the region. The first event started in the Early Cretaceous with the development of rift basins and half grabens, and accompanied by minor uplift of the Transantarctic Mountains. The major extension of the Ross Sea region was probably associated with this event, which had an extensional trend approximately normal to the Gondwana margin in the region and followed subduction of the Pacific-Phoenix spreading ridge at the margin. Major extension recommenced about 85 Ma with the onset of sea-floor spreading between Antarctica and New Zealand and very slow spreading between Antarctica and Australia, and was followed by thermal subsidence. A major period of uplift and denudation of the Transantarctic Mountains started at 55 Ma, following the cessation of Tasman Sea spreading. It was rapid until about 45 Ma, when sea-floor spreading commenced between the South Tasman Rise and western Ross Sea and greatly increased between Australia and Antarctica further to the west. This uplift of the Transantarctic Mountains probably was accompanied and followed by further subsidence of the Ross embayment. The latest tectonic event commenced about 30 Ma, and gave rise to the volcanic and igneous bodies of western Ross Sea and Marie Byrd Land. Existing faults are inferred to have been reactivated in a transtensional mode, allowing the emplacement of igneous rocks. The major magnetic anomalies and inferred associated igneous centers are oriented at a high angle to the stress direction, and may have acted as transfer systems for extensional strain. The eastern and western Ross Sea are separated by a sharp change in crustal thickness, and appear to have different morphology and structure. Estimates of the amount and timing of the major extension across the Ross Sea are inconsistent, and further work is needed.

INTRODUCTION

The Ross Sea forms the Pacific segment of the morphological depression along the boundary between Precambrian and Paleozoic craton of East Antarctica and the younger orogenic belt of West Antarctica (Figure 1). East Antarctica and West Antarctica are so called because they lie respectively to the east and west of the Greenwich meridian (0° longitude). However, in the Ross Sea region, at about longitude 180°, East Antarctica will be on the geographic western side of the Ross Sea and West Antarctica lies on its eastern side. The Ross Sea lies along the Pacific margin of the Jurassic rift (JR - Figure 1) [*Schmidt and Rowley*, 1986] that is delineated by the extensive dolerite sills of the Ferrar Group in the Transantarctic Mountains, and coincides in part with the active, Cenozoic, West Antarctic Rift System (WRS - Figure 1) [*LeMasurier*, 1978; *Behrendt et al.*, 1991], considered to be caused by a mantle plume [*Hole and LeMasurier*, 1994; *Behrendt et al.*, 1992]. The Transantarctic Mountains, one of the world's great mountain chains, forms, for a large part of its length, the rift shoulder of the West Antarctic Rift System. It is over 4000 km long, reaches elevations of over 4000 m, and is block faulted and backtilted to the west (craton). The complementary rift shoulder in Edward VII Peninsula and western Marie Byrd Land is far more subdued and has more of a horst and graben (basin and range) style of morphology [*LeMasurier and Rex*, 1983] that is mostly ice covered

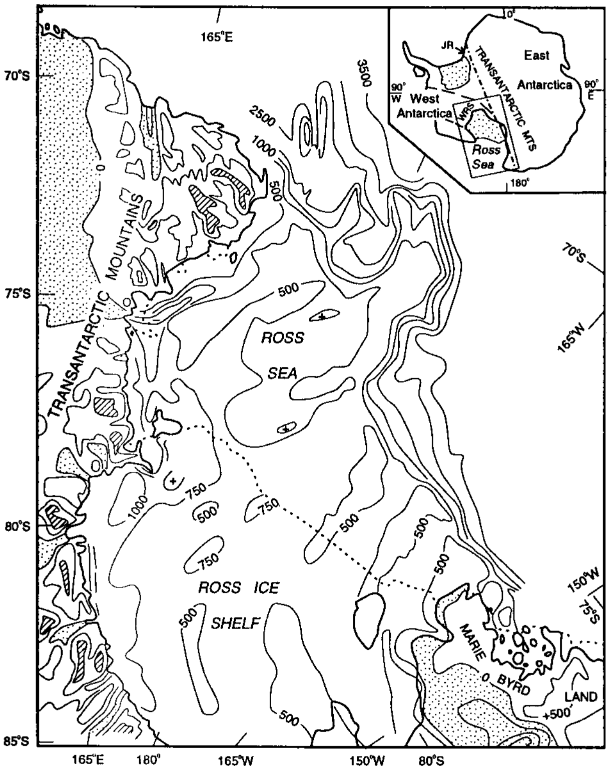


Fig. 1. Location and morphology of the Ross Sea region. Bathymetric contours are at 500 m intervals with 250 m interval contours on the shelf [after *Davey,* 1981]. On land or under grounded ice: in Marie Byrd Land, contours are at 500 m intervals and areas below sea level have a dot shading, for the Transantarctic Mountains, contours are at 0, 1000 m and 2000 m elevation, with elevations over 2000 m shown by a diagonal shading and areas below sea level by a dot shading [after *Drewry,* 1983]. The edge of the ice shelves or floating glaciers delineated by the dotted line. On inset map, JR marks the Jurassic rift and WRS the West Antarctic Rift System.

and extends about 1000 m above and below sea level [*Drewry,* 1983]. The different flexural rigidity for the lithosphere of the two rift margins, an old craton and a younger orogenic belt [e.g., *Stern and ten Brink,* 1989], may give rise to this difference in character [e.g., *Behrendt et al.,* 1991].

The Ross Sea and its southern continuation under the Ross Ice Shelf form the Ross Embayment, which is about 500 m deep and generally has a gentle ridge and valley morphology (Figure 1). Maximum depths (1200 m) are along the western margin, adjacent to the Transantarctic Mountains. As the deeps coincide with the major glacier outlets and trend north to northeast, along the line of ice flow, they probably result from associated with the initial sea-floor spreading between glacial erosion during times of ice-sheet expansion by major glaciers which pass through the Transantarctic Mountains. Tectonic subsidence may also contribute but bathymetric deeps are found where no marginal grabens have been detected. The depth of the Ross Sea is significantly deeper than is normal for a continental shelf (50-200 m). This is considered to arise largely by crustal thinning [*Fitzgerald et al.,* 1986; *Stern et al.,* 1992] but glacial erosion, which over deepened the inner shelf, and sediment loading on the continental rise during the time of a more extensive ice sheet, may also contribute, as proposed by *ten Brink and Cooper* [1992] for the Antarctic continental shelf in general. The sea-floor topography also shows features (e.g., broad flat bottom valleys) inferred to be of glacial origin, and the approximately north-south oriented valleys on the shelf are considered to coincide with past ice streams in the ice sheet when it was more extensive [*Hayes and Davey,* 1975]

The sedimentary basins in the Ross Sea (Figure 2) were probably formed largely by rifting processes during and since the break-up of this part of Gondwana in the Late Cretaceous [e.g., *Davey,* 1981]. *Cooper and Davey* [1985] and *Cooper et al.* [1987, 1991] noted two phases to the basin formation: i) an initial regional extension phase related to the Gondwana break-up episode and ii) a possibly mid-Cenozoic phase, which was localized in the western Ross Sea. *Elliot* [1992] suggested that the earliest extensional event in the formation of the basins and the morphologically depressed Ross Sea - Ross Ice Shelf region was the poorly defined rifting episode associated with the intrusion of the Ferrar dolerites at about 180 Ma. The subsequent tectonic development of the region resulted from the development of the West Antarctic Rift System in the late Mesozoic [*Behrendt et al.,* 1991], New Zealand, Australia and Antarctica [e.g., *Weissel et al.,* 1977] and with the presumed concurrent development of a mantle plume [*Weaver et al.,* 1994]. *Hole and LeMasurier* [1994], however, associate the beginning of plume activity with the onset of active volcanism in the region and uplift in western Marie Byrd Land at about 30 Ma. Uplift of the adjacent Transantarctic Mountains appears to have occurred in several phases commencing about 115 Ma [*Fitzgerald,* 1994].

In this paper, we collate data on the faulting, vertical and horizontal deformation and inferred extension of the region, and attempt to define the evolution of the crust of the Ross Sea in response to stresses during the past 120 m.y.

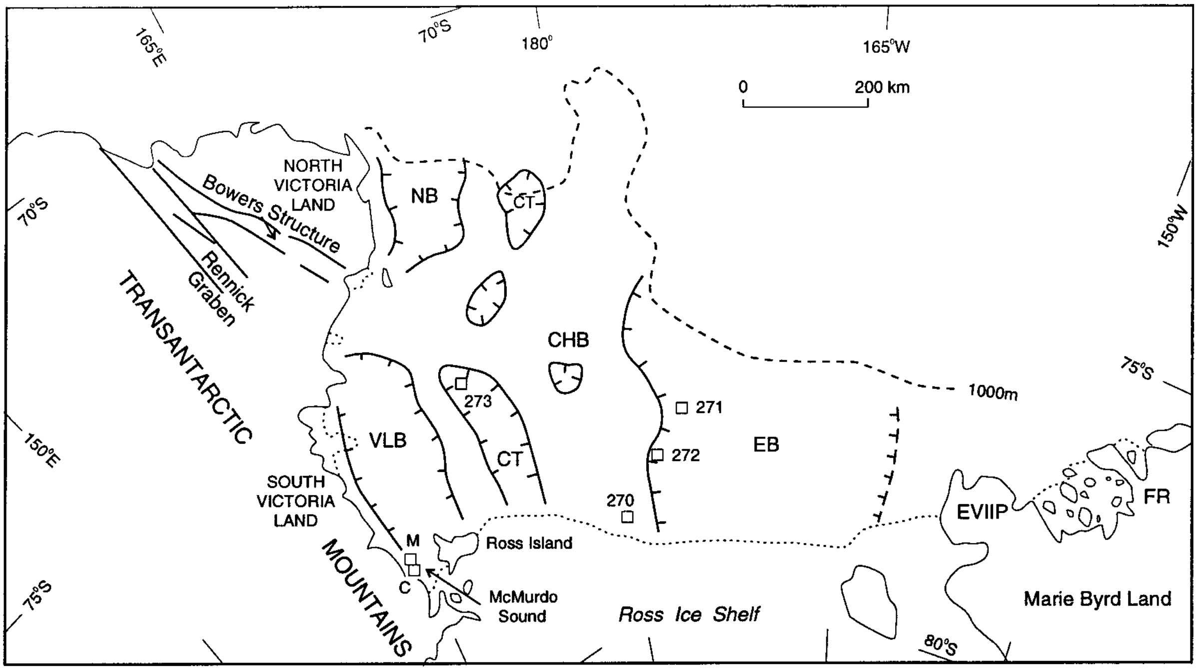


Fig. 2. The major sedimentary basins of the Ross Sea region [after *ANTOSTRAT*, this volume]. NB - Northern basin, VLB - Victoria Land basin, CT - Central trough, CHB - Central High basin, EB - Eastern basin, EVIIP - Edward VII peninsula, FR - Ford Ranges. Squares marked 270 - 273 locate the DSDP drill sites 270 - 273, M and C refer to the MSSTS-1 and CIROS-1 drill sites.

PLATE TECTONIC SETTING

Prior to the fragmentation of Gondwana in the Jurassic [*Lawver et al.*, 1992], the Ross Sea region lay inland of the active convergent plate boundary of Gondwana (paleo New Zealand) with the Pacific and Phoenix plates (Figure 3). Extensional rifting started in this region in the Jurassic (180 Ma) with, over a very short time interval (5 m.y.) [*Elliot*, 1992], the intrusion of the Ferrar dolerites and the extrusion of the Kirkpatrick volcanics. Early crustal extension in the Ross Sea region may have commenced at this time [*Elliot*, 1992]. This early rifting was coeval with, and probably related to, rift processes giving rise to the Karroo Formation in South Africa, the Dundas Group in Tasmania and the Kirnoo dolerites in New Zealand [*Mortimer et al.*, 1995].

The break-up of Gondwana and the generation of new oceanic lithosphere commenced in Early Jurassic (Africa) and took place sequentially around Antarctica [*Lawver et al.*, 1991]. Rifting of Australia started at about 125 to 100 Ma [*Cande and Mutter*, 1982], and very slow sea-floor spreading possibly started at the same time, but was certainly underway by 70 Ma, with a change to a much faster spreading at about 45 Ma. At 105 Ma, the Pacific-Phoenix spreading center north of New Zealand subducted at the convergent margin and continental extension commenced throughout New Zealand and the adjacent Ross Sea region [*Bradshaw*, 1989; *Lawver et al.*, 1992]. The South Tasman Rise, a stretched continental fragment [*Hinz et al.*, 1990], was originally located against the western margin of Ross Sea, to the west of Iselin Bank. It possibly commenced rifting in a westerly direction, along a transcurrent fault along the west Ross Sea - northern Victoria Land margin, at about 100 Ma [*Lawver et al.*, 1992], but marine magnetic data indicates that sea-floor spreading commenced here only at about 45 Ma [*Weissel et al.*, 1977].

The generation of new oceanic lithosphere between New Zealand and Antarctica commenced at 84 Ma with the rifting of Campbell Plateau from the eastern margin of Ross Sea and western Marie Byrd Land [*Christoffel and Falconer*, 1972]. The initial motion between the two is considered to have been transtension [*Houtz and Davey*, 1973; *Lawver et al.*, 1991; *Wilson*, 1992; *Luyendyk et al.*, 1992]. Prior to rifting, Campbell Plateau was close to Eastern basin (Figure

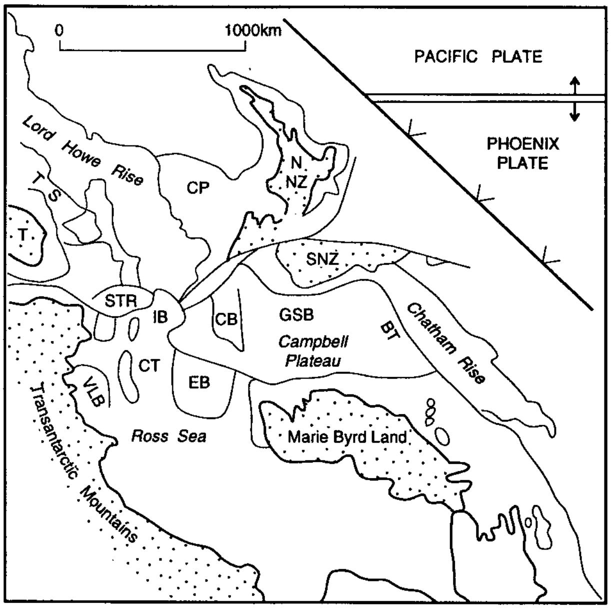


Fig. 3. The Ross Sea region prior to breakup of Gondwana [after *Lawver et al.*, 1992]. NNZ - northern New Zealand, SNZ - southern New Zealand, CP - Challenger Plateau, T - Tasmania, TS - future Tasman Sea, STR - South Tasman Rise, BT - future Bounty Trough, GSB - future Great South basin, CB - future Campbell basin, IB - Iselin Bank, others as in Figure 2.

3). Continuity of structures (e.g., the alignment of the Campbell basin with the Eastern basin) across the rift (Figure 3) has been used to constrain a pre-breakup reconstruction [*Davey and Houtz*, 1977; *Lawver et al.*, 1994], but the linkage is equivocal.

Major changes in plate tectonic movements in the region occurred at about 50 Ma and comprised the cessation of spreading of the Tasman Sea about 55 Ma [*Weissel and Hayes*, 1977] and the onset of fast spreading between Antarctica and Australia at about 45 Ma [*Cande and Mutter*, 1982]. This latter event coincided with the start of sea-floor spreading off the western Ross Sea - North Victoria Land margin [*Weissel et al.*, 1977]. A major re-organization of the plate boundaries forming the eastern and south Pacific occurred at about 25 Ma [*Handschumacher*, 1976; *Weissel et al.*, 1977], and changes in plate motion occurred in the southwest Pacific and possibly affected the Antarctic plate between about 20-35 Ma [*Stock and Molnar*, 1987]. More recent analysis and geological evidence in New Zealand indicates that a major change in plate motion occurred at about 25 Ma [*Lawver et al.*, 1992; *Walcott*, 1989; *Ballance*, 1988] and was associated with the development of the plate boundary through New Zealand and the Macquarie triple junction.

TECTONIC EVENTS IN THE ROSS SEA REGION

The deformation of the crust and the major tectonic events for the Ross Sea and its present and past margins are summarized in the following four sections. The information is discussed by area. Several events can be noted which effect two or more areas, and these are discussed subsequently.

3.1. *The Eastern Margin of Ross Sea*

The eastern margin of Ross Sea (western Marie Byrd Land and Edward VII Peninsula) forms the present continental margin of western Antarctica. In general terms, the limited geological outcrop in Marie Byrd Land shows a Paleozoic crystalline basement overlain by young, Cenozoic basaltic volcanics with a major erosion surface of Late Cretaceous to early Cenozoic age (80 Ma to 28 Ma) separating the two [*LeMasurier and Rex*, 1994]. Mid-Cretaceous to Late Cretaceous mafic dikes occur parallel to the coast in Marie Byrd Land, and granitoids of same age have been intruded [*LeMasurier and Rex*, 1994]. Extensive basaltic hyaloclastite deposits, less then 28 Ma, overlie the erosion surface and are overlain by felsic shield volcanoes of less than 16 Ma [*LeMasurier*, 1990]. The uniformity of alkaline basalt composition throughout the West Antarctic rift is interpreted to indicate a mantle plume and uniformly minimal crustal extension during the late Cenozoic by *Hole and LeMasurier* [1994].

In the Ford Ranges (Figure 2) of western Marie Byrd Land, Ar-Ar, U-Pb and apatite fission track data show several episodes of heating and denudation [*Luyendyk et al.*, 1992; *Luyendyk*, 1993; *Richard et al.*, 1994]. The subduction of the Phoenix-Antarctic spreading center beneath Marie Byrd Land resulted in the elevation of the geothermal gradient by magmatic advection, and high-temperature low-pressure metamorphism of the middle crustal rocks by about 104 Ma. Between about 104 and 100 Ma, granites were intruded into the metamorphic rocks (the present Fosdick metamorphic complex), and was followed by rapid exhumation (about 1.5 mm/yr) and cooling over 6 m.y. (100-94 Ma), (Figure 5) [*Richard et al.*, 1994]. This uplift, possibly involving removal of up to 15 km of overburden, was accompanied by N to NNE exten-

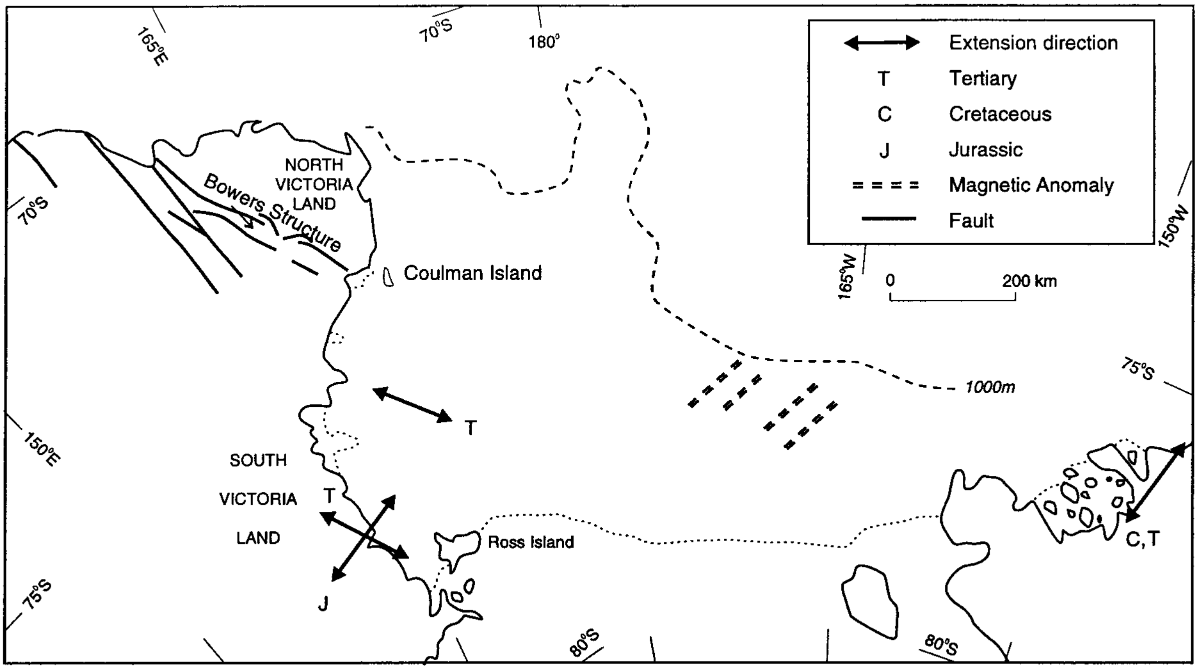


Fig. 4. Inferred regional extension directions [after *Luyedyk et al.*, 1992; *Wilson*, 1992; *Bosum et al.*, 1989]. Linear magnetic anomalies in eastern Ross Sea after *Coren and Rebesco* [1994].

sion (Figure 4), consistent with dextral transcurrent rifting at the coast [*Luyendyk et al.*, 1992].

The geology of the Alexandra Mountains in the Edward VII Peninsula is similar to the Fosdick metamorphic complex of the Ford Ranges and a similar history may be expected. In the Alexandra Mountains, *Weaver et al.* [1992] give an age of 95-100 Ma for extensional processes (anorogenic granites), and K-Ar biotite and zircon-apatite fission track ages indicate commencement of regional uplift at about 100 Ma, immediately after granite emplacement [*Adams et al.*, in press]. *Weaver et al.* [1994] identify two suites of granites - I type dated at 108-124 Ma and A-type dated at 95-120 Ma, indicating a rapid change from subduction related magmatism (I type) to rift related magmatism (A-type).

Between about 94 Ma and 80 Ma, the cooling and denudation rate in the Ford Ranges slowed significantly. A period of rapid cooling of crustal rocks from 80 to 70 Ma, nearly coeval with the initiation of seafloor spreading between New Zealand and West Antarctica, can be related to further exhumation, possibly associated with faulting and N-S extension [*Richard et al.*, 1994]. Since 70 Ma, slow cooling and exhumation (about 3 km), with possibly minor faulting, has occurred [*Richard et al.*, 1994]. This prolonged stability led to the development of a widespread Late Cretaceous to early Tertiary erosion surface of very low relief over most of West Antarctica [*LeMasurier and Rex*, 1994]. Post 50 Ma changes in the trend of the glacial striations have been interpreted by *Luyendyk* [1993] to indicate a late Cenozoic trend of extension of about N-S to NE-SW (Figure 4). At 28-30 Ma, volcanic activity started in the Marie Byrd Land volcanic province [*LeMasurier*, 1990], with peaks of activity at 8-12 Ma and 0-1 Ma, contemporaneous with block faulting and uplift. Significant post-Eocene vertical tectonics have occurred, similar to basin and range tectonics [*Luyendyk et al.*, 1992] with up to 1.5 km vertical movement in western Marie Byrd Land. Uplift rates, derived from displacements of the erosion surface associated with volcanic activity, average about 100 m/m.y. for the past 25 Ma [*LeMasurier and Rex*, 1989].

3.2. *The Western Margin of the Ross Sea*

The Transantarctic Mountains form the western margin of the Ross Sea. Indicators of horizontal deformation since Jurassic time are few. *Wilson* [1992], from a study of fracture and dike orientations, has derived a NE trend for Jurassic extension and a SE

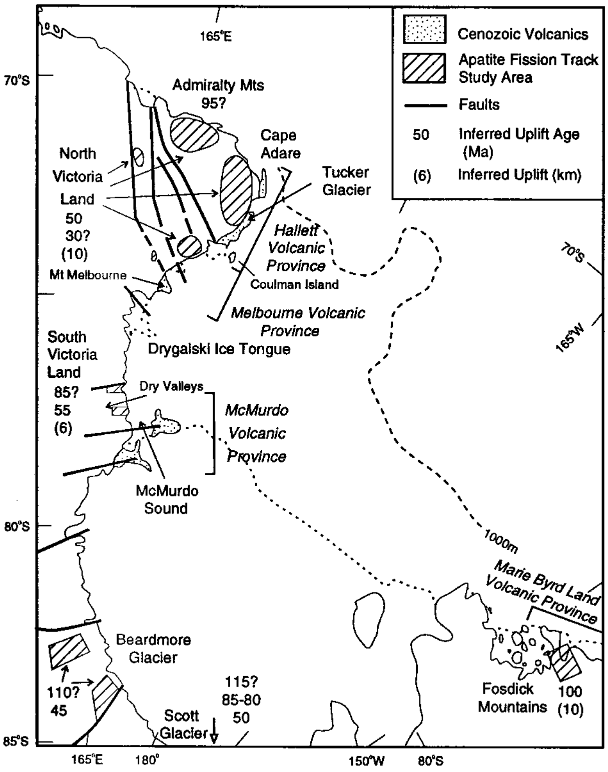


Fig. 5. Location of apatite fission track ages and times of uplift (after references in text), Cenozoic volcanics [after *LeMasurier and Thomson*, 1990], faults delineating crustal blocks [after *Tessensohn*, 1994].

trend for Cenozoic extension in South Victoria Land (Figure 4).

The uplift of the Transantarctic Mountains has been estimated from apatite fission track data [*Gleadow and Fitzgerald*, 1987]. Fission track data are able to constrain the magnitude, rates and timing of denudation and inferred uplift. Data (Figure 5) have been derived for several sites in North Victoria Land [*Fitzgerald and Gleadow*, 1988], in the Granite Harbour and Wilson Piedmont Glacier area of South Victoria Land [*Fitzgerald*, 1992], in the Beardmore Glacier area of the central Transantarctic Mountains [*Fitzgerald*, 1994] and in the Scott Glacier area [*Stump and Fitzgerald*, 1992]. All data sets show an onset of rapid denudation beginning at about 50-55 Ma with an indication of rapid denudation in the early Cretaceous (115 Ma) at Scott Glacier and in the Beardmore Glacier region [*Fitzgerald*, 1994]. Rapid denudation in the Late Cretaceous (about 85 Ma) is suggested at Scott Glacier and possibly at Admiralty Mountains in North Victoria Land and in South Victoria Land, and in the latest Cenozoic in lower Tucker Glacier region of North Victoria Land [*Fitzgerald and Gleadow*, 1988]. Uplift rates reach at least 200 m/m.y. for about 10 to 15 m.y. after uplift commenced at 55 Ma in South Victoria Land [*Fitzgerald*, 1992].

The uplift rates of the Transantarctic Mountains are also estimated from other evidence. The present elevation of sub-aerial volcanics indicate a maximum uplift of 209 m since 2.57 Ma in the Dry Valleys of South Victoria Land [*Wilch et al.*, 1993]. Uplift rates derived from drill hole information in the Dry Valleys and McMurdo Sound region, based on microfossils, give 150 m/m.y. [*Wrenn and Webb*, 1982], and *Ishman and Webb* [1988] derived a rate of 125 m/m.y. since 3 Ma. *McKelvey et al.* [1991] and *Webb et al.* [1994] have demonstrated that, at the Beardmore Glacier, the Sirius Group is essentially terrestrial strandline deposits which have been uplifted by about 1300 m to 1700 m since Pliocene time. A detailed study of the Cenozoic glacial geology of North Victoria Land [*van der Wateren and Verbers*, 1992] has suggested uplift of the Transantarctic Mountains with rates of about 100 m/m.y. in the early Pliocene rising to about 1000 m/m.y. in the Pleistocene to present. *Behrendt and Cooper* [1991] also suggest that high uplift at a rate of about 1000 m/m.y. since mid-Pliocene is possible. Rapid uplift could be still continuing [*van der Wateren and Verbers*, 1992].

The segmentation of the Transantarctic Mountains into several crustal blocks (Figure 5) is indicated by the differing amounts of uplift between major crustal blocks [*Fitzgerald*, 1994] and within the same crustal block (e.g., within South Victoria Land and the Scott Glacier region) [*Fitzgerald*, 1992; *Stump and Fitzgerald*, 1992]. Uplifts of 6 km are inferred for South Victoria Land and 10 km for the lower Tucker Glacier of North Victoria Land during the mid-Cenozoic. Differential uplift of North Victoria Land is suggested by Cenozoic glacial geology [*van der Wateren and Verbers*, 1992], and inferred major cross range faults along the major outlet glaciers through the Transantarctic Mountains also supports segmentation of the Transantarctic Mountains [*Tessensohn*, 1994; *Tessensohn and Woerner*, 1991; *Redfield and Behrendt*, 1992; *van der Wateren et al.*, 1994].

The tectonic history of the Transantarctic Mountains is also reflected in its Cenozoic igneous history [*LeMasurier and Thomson*, 1990]. Alkali basaltic volcanism of the McMurdo Volcanic Group commenced between 25 and 18 Ma in three elongate (N-S) provinces along the Ross Sea margin (Figure 5): Hallett (Cape Adare to Coulman Island, 0 to 13 Ma), Melbourne (0 to 26 Ma) and Erebus (0 to 19 Ma). Most of the volcanics are younger than 10 Ma. Volcanic sediments, interpreted to be derived from the McMurdo Volcanic Group, were sampled throughout the CIROS-1 drillhole in western McMurdo Sound [*George*, 1989]. The interpretation of the age of the oldest sediments in CIROS-1 as middle Eocene [*Hannah*, 1994] suggested that late Cenozoic volcanism commenced in this region about middle Eocene times (about 45 Ma).

3.3. *The Ross Sea Continental Shelf and Slope*

The structural and depositional framework of the Ross Sea is formed by four main depocenters, trending approximately north-south across the continental shelf: the Victoria Land basin, the Northern basin, the Central trough and the Eastern basin, [*Houtz and Davey*, 1973; *Davey*, 1981, 1983; *Hinz and Block*, 1984; *Cooper et al.*, 1987, 1994].

The crustal thinning processes in the Ross Sea that formed these major basins are probably related to the separation of Antarctica, Australia and New Zealand [*Davey*, 1981; *Cooper et al.*, 1987, 1991; *Behrendt et al.*, 1991]. Two main rifting episodes have been proposed: i) an early, essentially non-magmatic, rifting event throughout the Ross Sea which formed all the main depocenters, and ii) a late rifting event, with associated bimodal alkali basalt volcanics, which was localized in the western sectors and formed the Terror Rift in the Victoria Land basin in western Ross Sea.

The ages of these two events are not well constrained. A late Mesozoic age has been suggested for the early rifting, associated with Gondwana breakup, and an Eocene and younger age for the later rifting event [*Cooper et al.*, 1987, 1991].

An early compilation of structure in the region [*Hinz and Kristofferson*, 1987] delineated the major features of the main basins of the Ross Sea and identified a structural trend across the western Ross Sea aligned with the onshore Bowers structure of North Victoria Land (Figure 2). *Davey* [1981] proposed that a major transform fault zone divided the Ross Sea into eastern and western parts, linking up with Late Cretaceous and post-Cretaceous spreading on the Pacific-Antarctic ridge. *Cooper et al.* [1987] noted major normal faulting in the western Ross Sea of two ages: faults forming basement half grabens, which frequently terminated within the sedimentary section, and more recent Cenozoic faulting which, in places, reached the sea floor. Some of the recent faulting is associated with Cenozoic volcanism. The trend of faulting is largely north-south. Transverse structures are also mapped across the Ross Sea, and deform late Cenozoic strata *[Cooper et al.*, 1994].

Aeromagnetic data over the western Ross Sea margin show a north-south fabric in the magnetic anomalies over the western Ross Sea and a major magnetic anomaly, the Polar 3 anomaly, between Coulman Island and Mount Melbourne [*Bosum et al.*, 1989] (Figure 5). *Bosum et al.* [1989] interpreted the magnetic data in terms of basic igneous bodies and inferred an extensional direction for the formation of these features (Figure 4). Recent magnetic data [*Damaske et al.*, 1994] delineate a highly magnetic province east of Ross Island. *Damaske et al.* [1994] inferred that this anomaly group and the Polar 3 anomaly correspond to transfer faults between the extensional systems giving rise to the volcanic provinces along the western Ross Sea margin and the Victoria Land basin. In the eastern Ross Sea, marine magnetic anomaly data over the outer shelf of the Eastern basin delineate a group of linear magnetic anomalies with a northeast-southwest alignment [*Coren and Rebesco*, 1994] suggesting NW-SE extension, orthogonal to the lineations (Figure 4).

Crustal structure studies of the Ross Sea [*Smithson*, 1972; *Davey and Cooper*, 1987; *McGinnis et al.*, 1985; *Behrendt et al.*, 1991; *Trehu et al.*, 1993] indicate a crustal thinning from between 30 and 40 km to about 20 km, indicating 100% extension or a beta factor of 2. Under the Central trough, the extension is far higher with the crystalline crust thinned to about 5 km in places and an associated beta factor of 5-8 [*Trehu et al.*, 1993]. Here the stretching has been modeled for associated crustal/mantle decompression melting, and is consistent with thin (1 km) volcanics at the base of the basin and a high velocity wedge of mantle melt, now inferred to be incorporated into the lower crust under the basin [*Trehu et al.*, 1993]. We have computed the thickness of crystalline crust for the Ross Sea (Figure 6) by subtracting basement depths of *ANTOSTRAT* [this volume] from Moho depths [*Coren et al.*, in press] derived from gravity data controlled by seismic data. Crustal thicknesses vary from 4 km (under Victoria Land basin) to 20 km (under Central high), with the crust underlying the Eastern basin showing as a distinct unit at 12-16 km thick. Assuming a normal crustal thickness of 30-40 km, these crustal

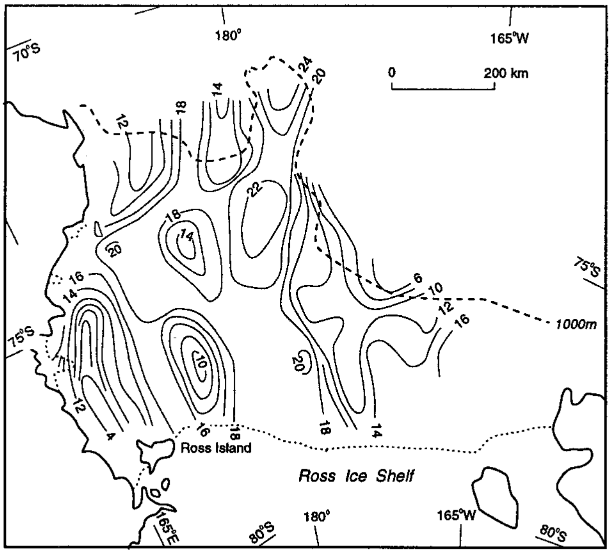


Fig. 6. Thickness of crystalline crust for the Ross Sea, based on moho thickness derived from seismic and gravity data [after *Coren and Zanolla*, 1994] and basement depth [after *ANTOSTRAT*, this volume]. Depths are in km.

thicknesses indicate an average extension of about 100 to 140% (beta = 2-3) over the width (900 km) of the Ross Sea, or 350 to 450 km of extension. This compares with previous estimates of 350 km by *Behrendt and Cooper* [1991] and the post 100 Ma extension of 1130±690 km derived by *DiVenere et al.* [1994] from paleomagnetic data in Marie Byrd Land.

Seismic data linked to drillhole information has shown that some thousands of meters of sediments are present in the deepest part of the Ross Sea depocenters [*ANTOSTRAT*, this volume]. The sediments form two major sequences. In the upper sequence, 6 major unconformities, U1-U6, have been identified [*Hinz and Block*, 1984] and the intervening units mapped [*Busetti and Zayatz*, 1994; *ANTOSTRAT*, this volume]. Unconformity U6 separates these sediments from the underlying sediments, which are probably early Eocene and Paleocene to early Mesozoic in age, and perhaps older [*Cooper et al.*, 1987]. However the history in the basins is not well defined because of the lack of age control.

The significance of unconformities recognized on the seismic data in terms of vertical deformation may vary considerably. Unconformities may arise from tectonic or sea-level changes. They may also be caused by the action of ice erosion associated with an expansion of the Antarctic Ice Sheet that can erode to depths several hundred meters below sea level [*Barnes and Lien*, 1988; *Bartek et al.*, 1991]. Differential erosion may result from the differential flexural response of the continental shelf to ice loading or unloading [*ten Brink and Schneider*, 1994].

The identification of significant tectonic events or eustatic events, and estimates of the rates of subsidence for the Eocene and younger sediments, may be deduced at the drill sites in the region. The correlation of the drillcore ages with the identified unconformities is not well constrained, and extrapolation of these ages to other areas depends on the unconformities not being time transgressive with respect to the sediments above or below [*ANTOSTRAT*, this volume]. Subsidence rates for the older sedimentary section (Eocene and older) depend on the assumption of the age of these sediments. Drill hole data (Figure 2) are available from the eastern and central Ross Sea: on the western margin of the Eastern basin (DSDP site 270, 271 and 272 [*Hayes et al.*, 1975]), from the central Ross Sea - over the Central trough (DSDP site 273 [Hayes et al 1975]) and from the western Ross Sea (McMurdo Sound), where the section sampled may be affected by local tectonic and glacial events (MSSTS-1 and CIROS-1 & -2 [*Barrett*, 1986, 1989] and DVDP sites 8 to 15 [*McGinnis*, 1981]).

Major changes in sedimentation rate may result from tectonic events. Rates of several tens of meters per million years are indicated by the drillhole data. *Savage and Ciesielski* [1983] recognize an extremely high sedimentation rate (over 150 m/m.y.) at site 272 and 273 suggesting an increase in subsidence rate for the early and middle Miocene. Cores from CIROS-1, initially, were also interpreted to show sedimentation rates which differed greatly downhole: 40 m/m.y. for the upper sequence and 200 m/m.y. for the lower sequence [*Barrett*, 1989]. However, the recent reassessment of the age of the deepest sediments in CIROS-1 as middle Eocene [*Hannah*, 1994], suggests a rate of about 40 m/m.y. or less for the whole sequence, and reassessment, based on better age control on diatom biostratigraphic events from recent Southern Ocean drilling, indicates lower sedimentation (and subsidence) rates for the DSDP sites than previous published [D. Harwood, pers. comm.]. The very high sedimentation rate derived for site 273 is critically dependent on the short time range inferred for the lower sedimentary unit.

3.4. *New Zealand Plateau*

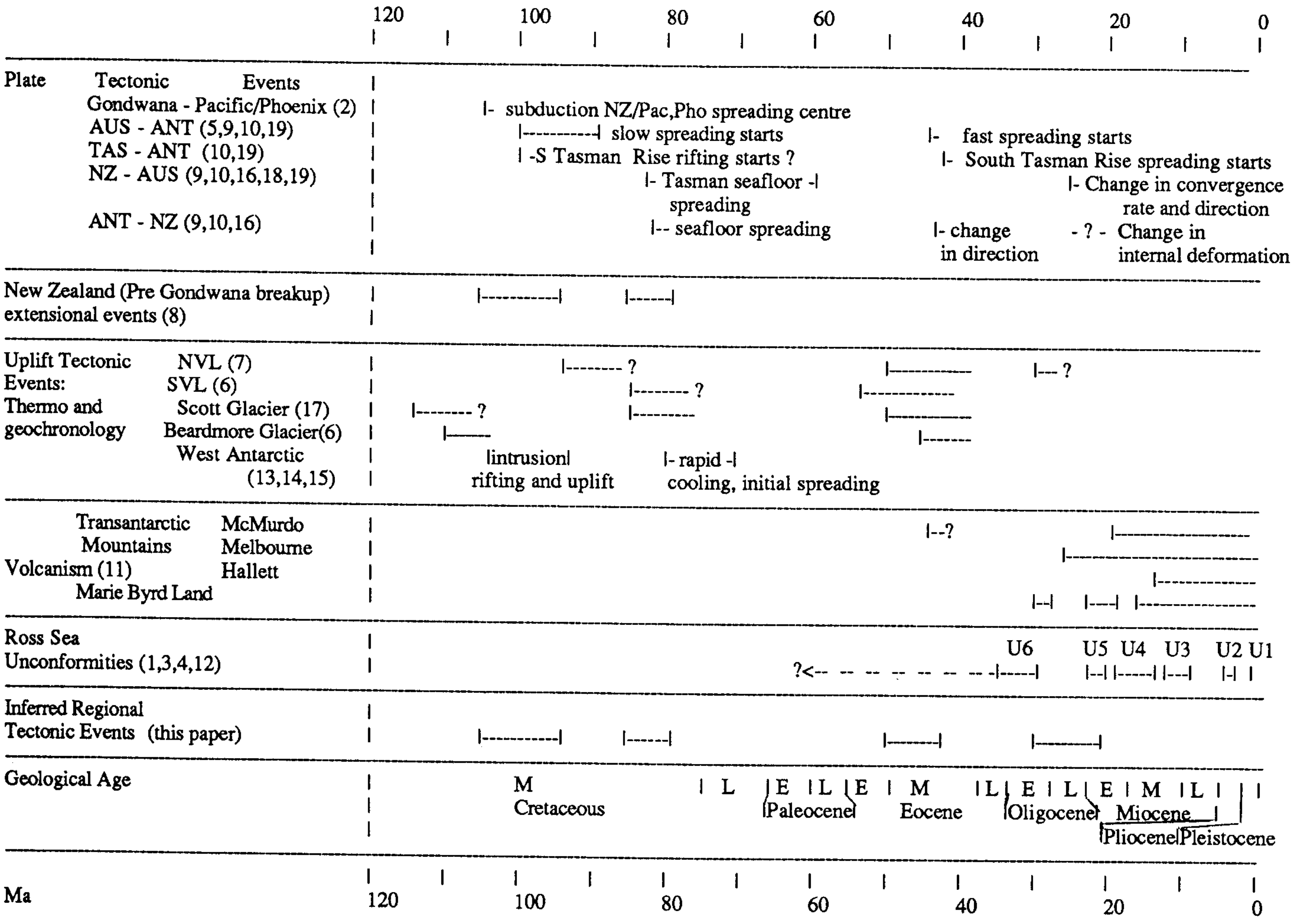
The New Zealand Plateau was adjacent to eastern Ross Sea and Iselin Bank prior to rifting (Figure 3), and may be expected to have been affected by the same tectonic events prior to breakup. Two major periods of extension occurred in the Mesozoic [*Laird*, 1993]: i) a rifting stage starting at 105±5 Ma, considered to be caused by the subduction of the Phoenix-Pacific spreading ridge along the northern margin of New Zealand (Figure 3) [*Bradshaw*, 1989], and ii) a sea-floor spreading related stage from 80-84 Ma, corresponding to the sea-floor spreading episode south of New Zealand. A possible separate extensional episode with associated magmatism occurred at about 95-100 Ma and is represented by 97 Ma intraplate alkali basalt flows and sills in South Island, New Zealand, a 96 Ma rhyolite at DSDP site 207 on Lord Howe Rise, and a Challenger Plateau granite dated at 94.5 Ma [*Laird*, 1993]. The mid-Cretaceous (100 Ma to 105 Ma) faults occur to the west and east of New Zealand, and are presently aligned WNW (parallel to Tasman Sea spreading). They are associated throughout much of New Zealand and its offshore region with half grabens containing mainly non-marine sediments and controlled by listric faulting. Late Cretaceous faults occur to the west and south of New Zealand, and, at present, trend NNE to NE, perpendicular to the older trend but parallel to the Tasman fracture zones. They may be a reactivation of older features [*Laird*, 1993].

DISCUSSION

Early extension of the Ross Sea region is represented by the massive intrusion of the Ferrar dolerites and the associated Kirkpatrick basalts at about 180 Ma and now exposed along the Transantarctic Mountains [*Elliot*, 1992]. No equivalent rocks are known from the Ross Embayment or further east and may indicate that the Jurassic Antarctic Rift (*Schmidt and Rowley*, 1986) corresponded with the present rift margin in this area (Figure 1, inset). However, rocks of this age may lie under the present ice cover or have been eroded at an earlier time. The Jurassic extensional episode corresponds to the stretching between East and West Gondwana (i.e., between Africa-South America and India-Antarctica) prior to onset of break-up of Gondwana by sea-floor spreading later in the Jurassic [*Lawver et al.*, 1991]. Subsequent to this event, the geological and geophysical information, summarized in the earlier sections for western Marie Byrd Land, Transantarctic Mountains, Ross Sea and New Zealand, show a number of periods when there was active tectonism in some or all of these areas (Table 1). Extensional deformation can be documented for the periods 105-95 Ma, 84-80 Ma, 55-50 Ma and 30-25 Ma (Figure 7). These deformational episodes are coeval with plate tectonic events in the region which must provide constraints for the detailed deformational history of the Ross Sea.

At about 105 Ma, the Phoenix-Pacific spreading center subducted along the northern New Zealand margin, resulting in the cessation of subduction and the development of a passive margin. The present WNW aligned rift grabens and half grabens developed extensively in the New Zealand region [*Laird*, 1993]. In Figure 7, we show the reconstruction for this part of Gondwana at 100 Ma [after *Lawver et al.*, 1992]. The reconstruction shows that at about 100 Ma the direction of extension indicated by the grabens in the eastern and western New Zealand region was similar to that inferred from geological evidence in South Victoria Land and Marie Byrd Land [*Wilson*, 1992; *Luyendyk et al.*, 1992]. Seismic data show a consistent (present) north-south trend to the fault controlled rifts forming the basal parts of the Ross Sea basins and the early half graben in the Ross Sea [*Cooper et al.*, 1987, 1991]. This trend on the plate reconstruction lies at a high angle to the direction of extension noted above, and we suggest that these rift basins initially were formed, possibly as transtensional basins, in the early extensional-rifting phase of this part of the Gondwana margin, prior to the onset of sea-floor spreading. The initiation of the rift basins would be Early Cretaceous in age. This period is coeval with a change in the chemistry of Marie Byrd Land granites, reflecting a rapid change from subduction-related to rift-related magmatism [*Weaver et al.*, 1994], and the onset of rapid uplift and denudation in coastal western Marie Byrd Land. In the Transantarctic Mountains, fission track data gives some indications of uplift at this time. This period also coincides broadly with the rifting of Australia from Antarctica, with the initial slow sea-floor spreading between the two commencing about 95 Ma.

Extension may have commenced during the Early Jurassic rifting episode but there is no information to confirm this. *Lawver et al.* [1994] infer, from matching of continental boundaries, that most extension must have been completed before New Zealand rifted from Antarctica at about 84 Ma. *Hole and LeMasurier* [1994] suggest minimal extension since the start of the late Cenozoic. *Grindley and Oliver* [1983] suggest an extension of between 200 and 500 km since about 100 Ma on the basis of paleomagnetic data. *DiVenere et al.* [1994] infer, also from paleomagnetic data, an



( ):- Data after (1)Anderson and Bartek [1992], (2)Bradshaw [1989], (3)Busetti and Cooper [1994], (4)Busetti and Zayatz [1994], (5)Cande and Mutter [1982,] (6)Fitzgerald [1992, 1994], (7)Fitzgerald and Gleadow [1988], (8)Laird [1993], (9)Lawver et al. [1991], (10)Lawver et al. [1992], (11)LeMasurier and Thomson [1990], (12)Hinz and Block [1984], (13)Luyendyk [1993], (14)Luyendyk et al [1992], (15)Richard et al. [1994], (16)Stock and Molnar [1987], (17)Stump and Fitzgerald [1992], (18)Weissel and Hayes [1977], (19)Weissel, Hayes and Herron [1977].

Table 1

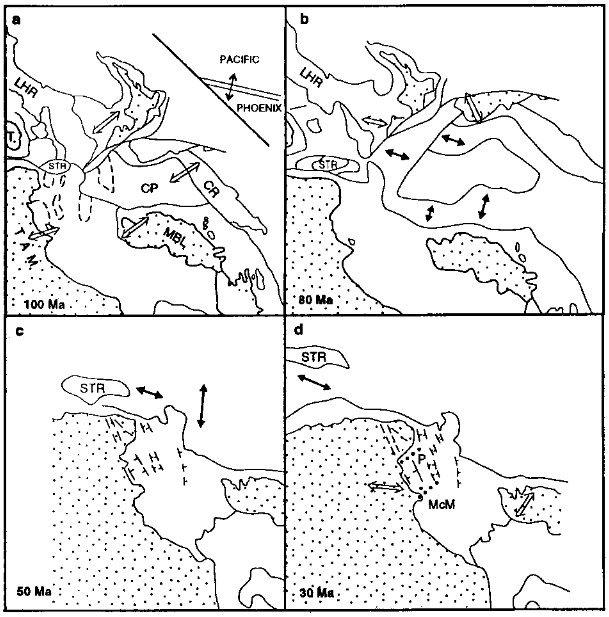


Fig. 7. Evolution of the Ross Sea region since 120 Ma. Base maps after *Lawver et al.* [1992]. Solid double head arrows indicate extension direction based on magnetic anomaly trends and plate reconstructions, open double head arrows indicate extension directions based on geological and geophysical features (Figure 4), dashed lines (7a) and ticked lines (7c, 7d) define pre-Eocene Ross Sea basins, solid circles - the major magnetic anomaly belts near Coulman Island (Polar 3 anomaly) and near Ross Island. Abbreviations as for Figure 3 plus MBL - Marie Byrd Land, TAM - Transantarctic Mountains.

extension of about 1150 km since 100 Ma. This suggests that the major extension must have been between 100 Ma and 84 Ma. The amount of extension is not well defined. Estimates based on crustal thinning give extensional factors of about 100% or about 400 km, but paleomagnetic data indicates almost three times that amount. Further work is needed.

A major regional plate tectonic event occurred at 84 Ma, with the onset of sea-floor spreading between New Zealand and Antarctica and between Australia and New Zealand. In the New Zealand region, the extensional processes gave rise to Late Cretaceous NNE to NE (present directions) trending faults and grabens south and west of New Zealand, followed by slow subsidence and quiescence. In western Marie Byrd Land, the onset of sea-floor spreading was followed by rapid cooling of crustal rocks for about 10 m.y. and then prolonged stability and the development of an extensive erosion surface. Uplift at about 80-85 Ma is indicated by fission track data in the Transantarctic Mountains. The eastern part of Ross Sea is largely affected by the rifting of New Zealand (Campbell Plateau) from Antarctica, but *Lawver et al.* [1994] noted the close fit of Campbell Plateau to the inferred continental boundary for the Ross Sea and proposed no crustal extension in this area since sea-floor spreading started (see above). The rifting and spreading in the sector are fairly simple and the extensional stress directions inferred for this area for the Cretaceous are consistent with a dextral transtension movement between New Zealand and eastern Ross Sea - Marie Byrd Land.

The period between about 55 Ma and 45 Ma coincided with significant changes in the regional plate tectonic situation. Tasman Sea spreading ceased at about 55 Ma. At about 45 Ma, sea-floor spreading of southeast Australia (Tasmania and South Tasman Rise) from western Ross Sea commenced [*Weissel et al.*, 1977], with the spreading center abutting the Ross Sea margin and a transform fault developing along the margin. There was an associated rapid increase in spreading rate between Australia and Antarctica. No events of this age have been documented in western Marie Byrd Land, and evidence for tectonic activity is only found now in the western part of the Ross Sea region. Fission track data record the onset of significant denudation and inferred rapid uplift all along the Transantarctic Mountains at about 55 Ma. Data from South Victoria Land indicates that the high rate continued for about 10-15 m.y. [*Fitzgerald*, 1992]. The coeval nature of the above events suggest that they may be cogenetic.

In the western Ross Sea, basement structures, particular the Central trough, are apparently dextrally offset along a northwest trend. As noted by *Hinz and Kristofferson* [1987], this trend is reflected in the Bowers structure in North Victoria Land, which is co-linear with the offshore transform faults of Australian-Antarctic sea-floor spreading, but no age has been ascribed for the offset. *Davey* [1981] and *Cooper et al.* [1991] suggest that the late rift phase of deformation, defined by the seismic data in the western Ross Sea, is coeval with the cessation of Tasman Sea spreading and the onset of fast spreading between Australia and Antarctica, and directly related to spreading between South Tasman Rise and western Ross Sea [*Davey*, 1981]. Extension in the basins may take place by pull apart mechanisms, as suggested by *Tessensohn* [1994]. The major vertical deformation along the western margin of the Ross Sea, and the inferred extensional deformation in the Ross Sea associated with the onset of spreading north of western Ross Sea, would be expected to give a significant unconformity in the Ross Sea sedimentary section. This unconformity may be the regional unconformity, U6.

At about 30-25 Ma, the relative plate motion changed markedly along the boundary through New Zealand between the Pacific and Australian plates, and the final departure of the South Tasman Rise from coastal North Victoria Land occurred [*Lawver et al.*, 1992]. The direction of extension in South Victoria Land, based on geological indicators, was approximately NW-SE [*Wilson*, 1992]. In western Marie Byrd Land, extensive basaltic volcanism and block faulting and uplift commenced at 28 Ma, and limited data indicates that the trend of extension had become N-S to NE-SW. This period also corresponded to the onset of extensive volcanism along the Transantarctic Mountain front, from North Victoria Land to McMurdo Sound [*LeMasurier and Thomson*, 1990]. There is some indication of increased uplift rates for the Transantarctic Mountains in North Victoria Land [*Fitzgerald and Gleadow*, 1988]. If the regional uplift along the Transantarctic Mountains was accompanied by extension and downwarp of the Ross Sea [*Davey*, 1983; *Stern and ten Brink*, 1989], then the series of angular unconformities detected in the Victoria Land basin by seismic data would indicate episodic uplift of the mountains [*Cooper et al.*, 1994]. The relative orientation of the extension direction and the trend of existing fault controlled basins indicates a transtensional reactivation of the Ross Sea basins [*Wilson*, 1992]. Extensive deformation along NW-SE and NE-SW trends is documented throughout the Ross Sea at this time and at younger times [*Cooper et al.*, 1994], and is inferred to be related to reactivation of transform faults during regional plate deformation.

The latest deformation is focused on the margins of the Ross Sea, and is manifest in the recent and active volcanic centers in western Marie Byrd Land and along the western Ross Sea margin (Ross Island, Terror rift of Victoria Land basin, Mt. Melbourne). Seismicity is generally associated with volcanic activity and ice quakes. Few tectonic earthquakes have been recorded with magnitudes over 3 and activity must be at a very low level. *Kaminuma* [1994] notes that only 11 earthquakes with a magnitude of 4.3 or more have been reported for the Antarctic continent since IGY. The seismograph network at Mt. Melbourne [*Privitera et al.*, 1992] detected about 20 microearthquakes over a period of 3 months at ranges of 90 - 160 km, possibly off the Drygalski Ice Tongue. These microearthquakes may correspond to active rifting processes in the Victoria Land basin, but the level of activity is low and the magnitudes of the events small. Several explanations have been put forward for this low level of activity: the temporal low level of activity after a very high level of activity associated with glacial unloading [*Muir Wood*, 1989], a suppression of the build up of stress by the high strength lithosphere because of the thermal regime resulting from the low surface temperature [*Johnston*, 1987], the suppression of seismicity by magma overpressure in some areas [*LeMasurier et al.*, 1994], or the lack of stress build-up because Antarctica is located within a plate surrounded by spreading ridges, and is more or less stationary in the mantle (hot-spot) reference frame.

CONCLUSIONS

A review of the tectonic events over the past 120 Ma in the Ross Sea region, and adjacent areas in Gondwana times, suggests that the major extension of the Ross Sea region started in the Early Cretaceous, about 105-95 Ma, coeval with, and perhaps triggered by, the subduction of the Pacific-Phoenix spreading center along this part of the Gondwana margin and the cessation of convergent plate processes there. These events led to the initiation of the major rift basins and half grabens in the Ross Sea, accompanied by major uplift and erosion in Marie Byrd Land and minor uplift of the Transantarctic Mountains. The trend of the Ross Sea basins and faulting is consistent with that of similar features in the New Zealand region and in the Transantarctic Mountains and Marie Byrd Land, and indicates an extension direction orthogonal to the Gondwana margin. The major extension of the Ross Sea may have occurred at this time.

A major extensional event commenced at about 85 Ma with the onset of sea-floor spreading between Antarctica, New Zealand and Australia, and was followed by thermal subsidence. The close fit of plate reconstructions indicates that little extension occurred at or after this time in the eastern Ross Sea. Uplift and tilting is indicated for this period in western Marie Byrd Land, and uplift may have occurred in the Transantarctic Mountains.

Major uplift and denudation of the Transantarctic Mountains started at about 55 Ma and was most rapid up to about 45 Ma. This period corresponds closely to plate tectonic changes from the cessation of Tasman Sea spreading to spreading commencing between western Ross Sea and the South Tasman Rise and the onset of the faster Australian-Antarctic spreading. This readjustment of plate motion was probably followed closely by further subsidence over the whole width of the Ross embayment. Gravity anomaly patterns for the Ross Sea and the offset of basins indicate an apparent dextral offset through western Ross Sea on a NW-SE trend from the onshore Bowers trend, but no age can be ascribed to this.

The latest tectonic event commenced about 30 Ma and gave rise to the volcanic and igneous bodies of western Ross Sea and Marie Byrd Land. The tectonic activity is continuing to the present and may have increased in the last few m.y., based on volcanism and uplift. The extension direction in the Transantarctic Mountains was about NW-SE and some existing faults were reactivated in a transtensional mode allowing the extrusion of igneous rocks along the western margin of the Ross Sea and the eastern margin of the Transantarctic Mountains. The Polar 3 and Ross Island transfer systems arc oriented more normal to the extension direction than the volcanic provinces along the western Ross Sea and are the sites of larger intrusions. Limited data indicates that the extension direction in Marie Byrd Land at this time was approximately N-S, significantly different to that for the Transantarctic Mountains.

The crust underlying the eastern and western Ross Sea shows a marked change in crustal thickness at the boundary between the two. This change probably arose during early rifting in the mid- to Late-Cretaceous, since when the two regions have apparently had different Cenozoic deformational histories. Estimates of the amount and timing of the major extension across the Ross Sea are inconsistent and further work is needed.

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