Crustal extension and origin of sedimentary basins beneath the Ross Sea and Ross Ice Shelf, Antarctica

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Abstract

The Ross Sea is underlain by basement grabens filled with up to 8 km of high-velocity, (?)Mesozoic strata that are unconformably overlain by up to 6 km of flat-lying Cenozoic rocks. The 2–14 km thick sedimentary section is strongly deformed only in the Terror rift of the western Ross Sea. S–SE-trending positive gravity anomalies, probably marking locally thinner crust, coincide with the three major Ross Sea basement grabens, and continue over 1000 km beneath Ross embayment. Offsets in gravity anomalies, structures and physiographic features of the Ross embayment region suggest that major transverse basement faults have controlled locations of horizontal and vertical displacements due to rifting. Crustal extension in the Ross embayment includes: (1) an early rift period ((?)late Mesozoic) of widespread graben downfaulting, crustal thinning, and later sediment infilling; and (2) a late rift period (Cenozoic) of more localized deformation, principally along the Transantarctic Mountains, Terror rift and in Marie Byrd Land. The change from widespread to more localized deformation may coincide with the documented Eocene change in oceanic plate motions.

Introduction

The Ross embayment (Ross Sea and Ross Ice Shelf) has been cited as a major zone of crustal extension between East and West Antarctica, based on regional mapping (Elliot, 1975; Hayes & Davey, 1975; Davey, 1981; Bentley, 1983; Kadmina *et al.*, 1983; McGinnis *et al.*, 1985; Schmidt & Rowley, 1986; Tessensohn & Wörner, this volume, p. 273) and global plate-motion studies (Molnar *et al.*, 1975; Jurdy, 1978; Gordon & Cox, 1980; Lawver & Scotese, 1987; Stock & Molnar, 1987). However, the nature and extent of subsurface rift structures has only been clearly imaged by post-1980 multichannel seismic-reflection (MCS) surveys of the Ross Sea (Hinz & Block, 1984; Sato *et al.*, 1984; Kim, McGinnis & Bower, 1986; Cooper, Davey & Behrendt, 1987a; Hinz & Kristoffersen, 1987). The MCS data reveal up to 14 km of sedimentary strata lying within the three major depositional centres of the Ross Sea: the Victoria Land basin (VLB), the Central trough and the Eastern basin (Fig. 1).

Herein, we describe the major subcrustal features of the Ross Sea region, and relate them to episodes of crustal extension since late Mesozoic time.

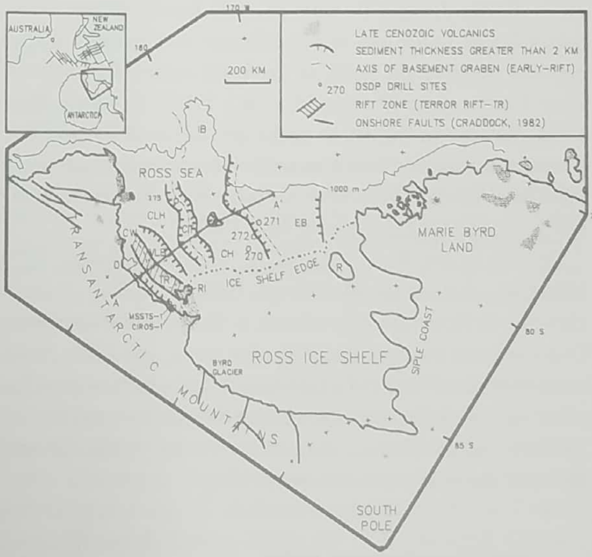

Fig. 1. Index map of the Ross Sea showing the major sedimentary basins, early rift basement grabens and the active Terror rift; basin outlines from Hinz & Block (1984) and Cooper *et al.* (1987a). CP, Campbell Plateau; CH, Central high; CLH, Coulman high; CT, Central trough; CW, Cape Washington; D, Drygalski Ice Tonge; EB, Eastern basin; IB, Iselin Bank; M, McMurdo Sound; TR, Terror rift; R, Roosevelt Island; RI, Ross Island; VLB, Victoria Land basin.

Regional setting

The Ross embayment is bordered by the Transantarctic Mountains (TAM) on the west and Marie Byrd Land on the

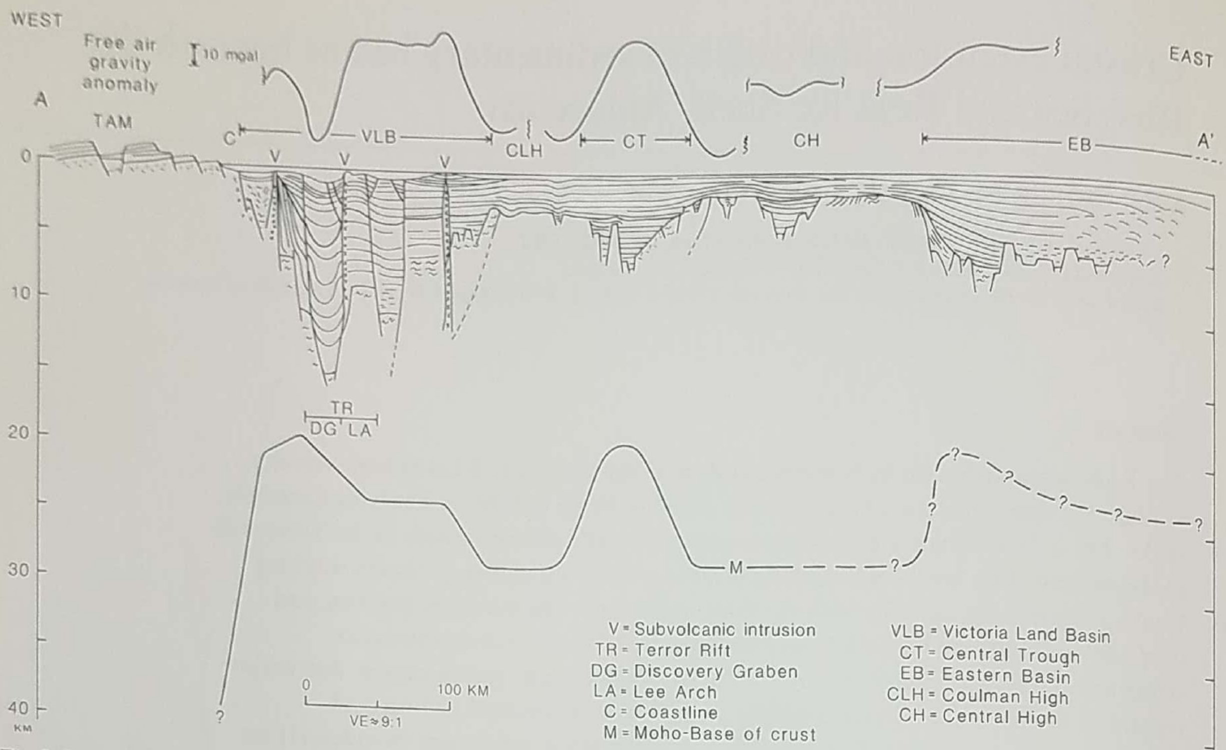

Fig. 2. Generalized profile across the Ross Sea, based in part on offshore multichannel seismic-reflection data (Hinz & Block, 1984; Cooper *et al.*, 1987a) and gravity-model studies (Davey & Cooper, 1987). Early rift grabens, delineated by positive free-air gravity anomalies and thin crust, lie beneath a buried regional unconformity (heavy line). Late-rift faults and intrusive rocks deform the Victoria Land basin and some small basement grabens.

east (Fig. 1). In the TAM, Precambrian and Early Palaeozoic basement rocks are unconformably overlain by gently dipping Devonian–Jurassic strata of the Beacon Supergroup (Davey, 1987). Rocks younger than Jurassic are limited to late Cenozoic volcanic rocks and minor Pliocene and younger glacial deposits. Asymmetric uplift of the TAM occurred principally since Eocene time (Fitzgerald *et al.*, 1987). In Marie Byrd Land, Palaeozoic basement rocks are intruded by mid–late Cretaceous plutons. Late Cenozoic volcanic rocks rest on an uplifted erosional platform of probable early Tertiary or Late Cretaceous age (LeMasurier & Rex, 1983).

Drilling in the Ross Sea (DSDP, Hayes & Frakes, 1975; MSSTS-1, Barrett & McKelvey, 1986; CIROS-1, Barrett, Hambrey & Robinson, this volume, p. 651) has recovered early Oligocene and younger glacial-marine strata, and Early Palaeozoic basement. Rocks of Late Cretaceous and Palaeogene age occur only as glacial erratics, and are thought to underline the offshore basins (Davey, Bennett & Houtz, 1982; Cooper, Davey & Behrendt, this volume, p. 279).

Ross Sea sedimentary basins

Crustal structure deduced from seismic data

Herein, we refer to basement as the acoustic basement in offshore seismic-reflection records. Acoustic basement may, in places, be younger than onshore Precambrian and Early Palaeozoic basement rocks (Hinz & Block, 1984; Cooper *et al.*, 1987a, b).

The Ross Sea is underlain by three asymmetrical basement grabens, up to 175 km wide, that contain up to 8 km of layered high-velocity (4.2–6.0 km/s) strata (Fig. 2). A buried regional unconformity cuts the high-velocity strata and intervening basement platforms. The unconformity is covered by up to 6 km of nearly flat-lying rocks that generally are thickest in the seaward prograding deposits at the continental shelf edge of the eastern Ross Sea. The total sedimentary thickness in the Ross Sea is up to 14 km in the VLB, decreasing to the south.

Small grabens lie beneath basement platforms and the flanks of the major grabens. Commonly, some small grabens contain deformed strata, and their bounding faults do not displace the eroded basement or overlying sediment. Other grabens, however, downwarp the eroded basement and overlying sedimentary section. The two graben types suggest two periods of deformation.

The major basement grabens of the Ross Sea trend N–S (Fig. 1). In the west and central Ross Sea, the 2-km isopach delineates the grabens. In the east, however, a major basement graben lies beneath only the west side of the Eastern basin (Fig. 2), which principally comprises thick seaward-prograding shelf deposits burying the major graben (Hinz & Block, 1984).

The VLB, unlike other Ross Sea basins, is underlain by an active axial rift zone, 50–60 km wide, extending from active volcanoes at Cape Washington to those at Ross Island (Terror rift; Cooper *et al.*, 1987a). The rift is defined by an axial graben (Discovery graben, coincident with the axis of the basement graben), and an adjacent subvolcanically-intruded basement horst (Lee arch, Fig. 2; Cooper *et al.*, 1987a).

Basement grabens can be traced seismically more than 450 km from seaward of the continental shelf edge to the Ross

Ice Shelf edge (Fig. 1; Hinz & Block, 1984; Davey & Cooper, 1987). The VLB ends abruptly at Cape Washington, about 300 km south of the continental shelf edge (Cooper *et al.*, 1987a). All three basins may extend several hundred kilometres S–SE beneath the Ross Ice Shelf.

Most normal faults parallel the basin axes. The basement faults, along which the grabens have been downfaulted, commonly do not disrupt overlying strata, with the exception of the Terror rift where faults extend upward through the entire sedimentary section. Along the front of the TAM, basement faults are steep and planar to depths of 1–2 km, but may flatten at depth. Seismic evidence for low-angle basement faulting, such as is seen in other highly extended regions (Allmendinger *et al.*, 1983) is poor, but weak intrabasement reflections at the eastern edge of the VLB may be from a fault that extends beneath the entire basin (Fig. 2).

Volcanic rocks and shallow subvolcanic intrusions are apparently associated with faulting and rifting in the VLB, as these rocks occur in the southern half of the basin, along the Terror rift and near the eastern and western edges of the basin (Fig. 2; Cooper *et al.*, 1987a). Jurassic and Cenozoic volcanic deposits, which are common onshore, are likely offshore but may not comprise a major part of the sedimentary section, except near Ross Island (late Cenozoic). (?)Cenozoic magmatic rocks may also locally intrude the shallow basement platform directly north of the VLB (Behrendt, Cooper & Yuan, 1987).

Crustal thickness has been measured seismically only beneath the VLB in McMurdo Sound, where it is 21 km (McGinnis *et al.*, 1985). Layered reflections from 16 to 22 km depths are seen in sonobuoy and multichannel seismic-reflection data from the Terror rift and Coulman basement high (McGinnis & Kim, 1986; Cooper *et al.*, 1987b), and are interpreted as coming from a magma chamber or layered intrusion. High heat flow values support this interpretation.

Aeromagnetic data over the VLB show a distinct long-wavelength magnetic low that contrasts with the irregular pattern of anomalies over the Central trough. This broad magnetic low can be explained either by a 10–14 km thick sedimentary section, consistent with seismic data (Behrendt *et al.*, this volume, p. 299), or by a thinner sedimentary section and a rise in the Curie isotherm, consistent with higher heat flow (Behrendt *et al.*, 1987).

Crustal structure deduced from gravity and bathymetric data

Free-air gravity anomalies in the Ross Sea (Davey & Cooper, 1987) and over the Ross Ice Shelf (Davey, 1981; Robertson *et al.*, 1982) are nearly linear and continuous over large distances from seaward of the Ross Sea continental shelf edge to the southern limit of the data at about 86° S (Fig. 3). Gravity anomalies trend N–S in the Ross Sea and NW–SE beneath the Ross Ice Shelf, south of a line connecting Byrd Glacier and Roosevelt Island (Fig. 1). In the Ross Sea, gravity trends commonly cut across bathymetric trends. Beneath the Ross Ice Shelf, the two trends converge to the south-east and finally coincide (bathymetric ridges and positive gravity anomalies) at the head of the ice shelf (Fig. 3; Robertson *et al.*, 1982).

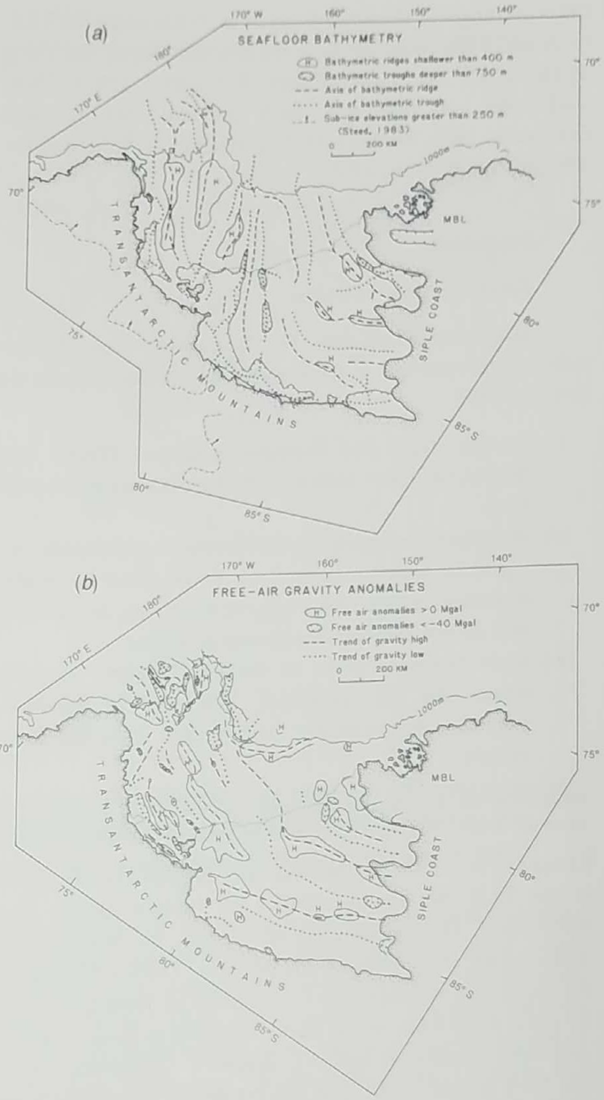

Fig. 3. Geophysical maps of the Ross embayment: (*a*) Seafloor bathymetry (Robertson *et al.*, 1982; Davey & Cooper, 1987) and subice elevation under the Transantarctic Mountains; (*b*) free-air gravity anomalies (Robertson *et al.*, 1982; Davey & Cooper, 1987). Gravity and bathymetry trends differ in most areas indicating tectonic (rather than ice erosion) control on gravity anomalies, with the exception of ice-stream erosion near the Siple Coast.

The three major basement grabens beneath the Ross Sea are marked by relatively positive gravity anomalies (Figs 2 & 3). This uncommon inverse relation can be explained by either crustal thinning or possible deep crustal intrusions, bringing high density rocks to shallow depths beneath the Central trough (Hayes & Davey, 1975), the VLB (Davey & Cooper, 1987), and the Eastern basin (Fig. 2). Small basement grabens, however, apparently are not compensated by thinner crust, as they are marked by negative anomalies (Fig. 2).

A narrow, large-amplitude, negative gravity anomaly coincides with the Discovery graben (Fig. 2), and is superimposed on the broad positive anomaly covering most of the VLB. The gravity low results from the deep bathymetric depression and low density strata at the top of the 12–14 km thick sedimentary section (Davey & Cooper, 1987). Gravity models indicate that the crust ranges in thickness from 19 to 23 km under the VLB, to about 27 km under the Ross Sea basement highs, and about 40 km under the TAM (Davey & Cooper, 1987). These thicknesses are consistent with previous interpretations (Smithson, 1972; Bentley, 1973; Robinson & Splettstoesser, 1984; McGinnis *et al.*, 1985).

Discussion

Episodic crustal extension

Seismic-reflection data (Fig. 2) provide evidence for episodic crustal extension in the Ross Sea and probably under the Ross Ice Shelf:

(i) younger fault and intrusive structures (Terror rift) deform the older sediment-filled graben underlying the VLB
(ii) two types (and ages) of small basement grabens are seen – grabens with bounding faults that displace the eroded basement surface and overlying sediments, and grabens that do not displace this basement surface
(iii) some basement faults of the VLB displace overlying strata and are associated with shallow intrusions whereas other basement faults do not show this deformation
(iv) more than one basement unconformity exists indicating at least two periods of uplift and erosion (and rifting).

Cooper *et al.* (1987a) recognized early rift and late rift periods in the VLB. We suggest similar rift periods for the Ross embayment. During the early rift period, the basement was downfaulted in a series of rift grabens. Crustal thinning by extension was accompanied by elevation of dense mantle and by rapid subsidence of the basin, resulting in positive gravity anomalies. Sediment infilling following subsidence formed flat-lying graben strata. The late rift period was characterized by widespread uplift, initial erosion of the regional unconformity that cuts across basement beneath the Coulman and Central highs, development of the Terror rift and uplift of the TAM.

Age of crustal extension

The age of the two rift periods is ill-defined because the layered sedimentary sections filling the basement grabens have not been sampled. Evidence for late Mesozoic and younger crustal extension from the regional geologic record, includes:

(i) emplacement of Jurassic rift-related tholeiitic dolerite dykes, sills and volcanic rocks throughout the TAM (Elliot, 1975)
(ii) downfaulting of the Rennick graben of northern Victoria Land in post-Early Cretaceous time (Grindley & Oliver, 1983a)
(iii) emplacement of mid-Cretaceous mafic dykes in Marie Byrd Land (90–110 Ma; Grindley & Oliver, 1983b)
(iv) uplift and (?)Late Cretaceous erosion of a regional peneplain (now at 500–2700 m elevation) in Marie Byrd Land (LeMasurier & Rex, 1983)
(v) initial Eocene uplift of the TAM (50 Ma; Fitzgerald *et al.*, 1987), and downfaulting of axial grabens along the central TAM in Tertiary time (Katz, 1982)
(vi) eruption of alkalic volcanic rocks in Victoria Land since probably early Oligocene time (38 Ma; Barrett *et al.*, this volume, p. 651) and Marie Byrd Land since about 27 Ma (LeMasurier & Rex, 1983)
(vii) uplift and erosion of a now-buried regional basement unconformity beneath the Ross Sea before the late Oligocene (26 Ma at DSSDP site 270; Hayes & Frakes, 1975; Fig. 2).

Our proposed ages for the two rift periods are based on: (1) the above-listed events; (2) the relative ages from seismic stratigraphy for the Ross Sea (Hinz & Block, 1984; Cooper *et al.*, 1987a, this volume, p. 279); and (3) the Jurassic and younger ages for rocks drilled from formerly nearby rift basin areas of Australia–Tasmania (Veevers, 1982; Williamson *et al.*, 1987) and New Zealand (Cooper *et al.*, 1982; Shirley, 1983). We suggest that early rifting was mostly Cretaceous (rapid graben subsidence), but commenced in the Jurassic. Infilling of the three grabens may have been principally during the Late Cretaceous and Palaeogene. Late rifting probably began in the Eocene (initial uplift of TAM and development of Terror rift) but was more intense in the late Cenozoic (areally extensive alkalic volcanism).

We tentatively relate the early rifting and late rifting periods to widely recognized periods of major plate motions and plate re-organizations. The early rift period may correspond with a pre-80 Ma episode of slow continental rifting between Australia and Tasmania, and with the post-80 Ma opening of the Tasman Basin and the initial separation of New Zealand and Antarctica. The late rift period probably commenced during the Eocene re-organization of plate motions, marked by a 40° change in magnetic anomaly trend south of New Zealand (50–42 Ma; Stock & Molnar, 1987) and by increased spreading rates in the Indian Ocean (43 Ma; Cande & Mutter, 1982).

Crustal extension beneath the Ross Ice Shelf

Crustal extension beneath ice-covered areas south-east of the Ross Sea, such as the Ross Ice Shelf, Byrd Subglacial Basin, Marie Byrd Land and areas farther south-east, has been postulated principally on geophysical evidence for thin crust (25–30 km thick) and block-faulted bedrock ridges (Jankowski & Drewry, 1981; Bentley, 1983; Jankowski, Drewry & Behrendt, 1983; LeMasurier & Rex, 1983; Robinson & Splettstoesser, 1984; McGinnis *et al.*, 1985). We suspect that the linear positive-gravity anomalies of the Ross embayment (Fig. 3), which correspond with deeply buried rift grabens in the Ross Sea, may delineate similar early rift grabens beneath the Ross Ice Shelf.

Aeromagnetic data (Behrendt, 1983) indicate that 8 km of non-magnetic strata lie beneath the head (south-eastern end) of the Ross Ice Shelf. The bathymetric troughs in this areas are aligned with the major ice streams (Jankowski & Drewry, 1981), but Robertson *et al.* (1982) postulated, from gravity data, that the troughs and ridges have 'deep structural control'.

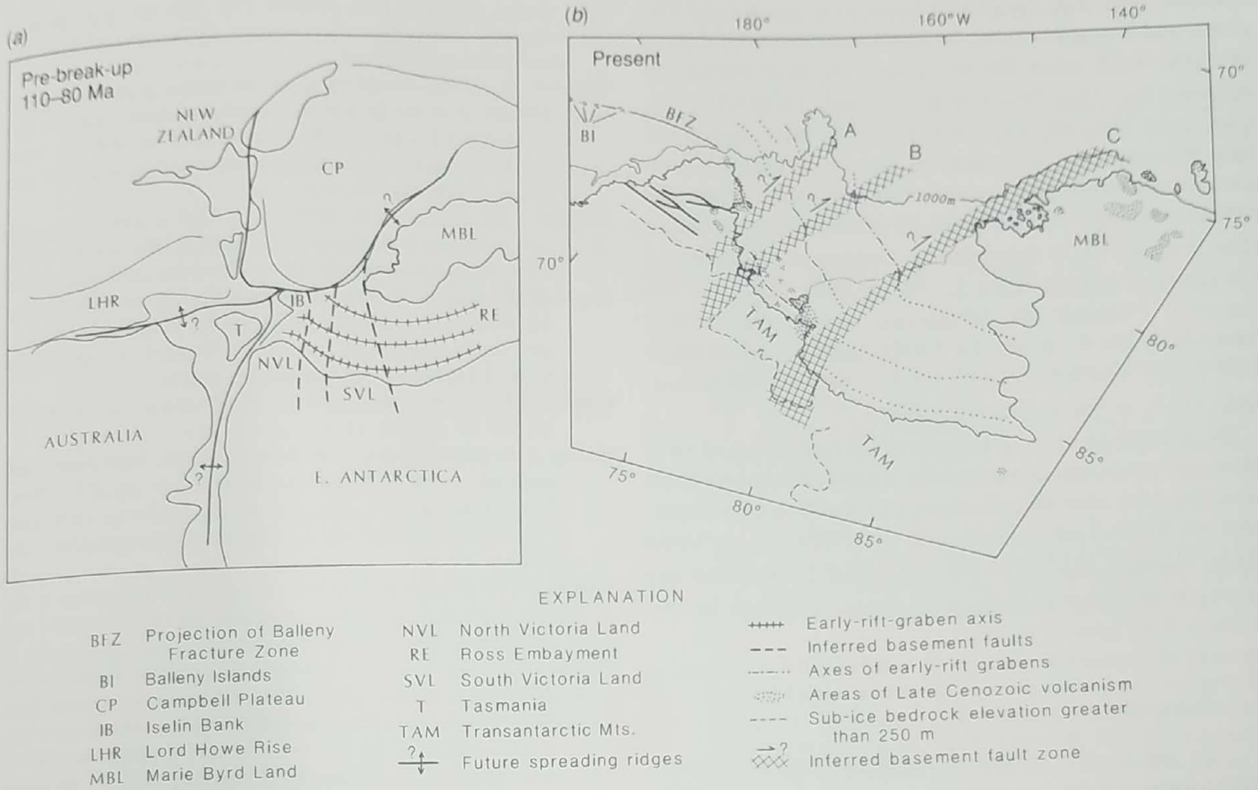

Fig. 4. Models for the Ross embayment: (*a*) 110–80 Ma (modified from Lawver & Scotese, 1987), showing early rift development of the three major graben systems beneath the Ross embayment, which is one-half its present width; (*b*) present-day, showing offset and (?) rotated position of the early rift grabens. Horizontal and vertical displacements on transverse basement faults is likely to have occurred in Mesozoic and Cenozoic times.

The poor correlation between bathymetric highs and positive free-air gravity anomalies, except near the head of the ice shelf, suggests to us that parts of the Ross Ice Shelf may be underlain by high-density sedimentary strata. The positive gravity anomalies may also be due, in part, to thinner crust.

Limited seismic-refraction data near the head of the Ross Ice Shelf (Robertson *et al.*, 1982; Rooney, Blackenship & Bentley, 1987) show < 1.5 km of rocks above a 5.7 km/s basement. This basement velocity falls in the 4.8–6.0 km/s range of velocities measured for early rift strata beneath the Ross Sea (Cooper *et al.*, 1987a, this volume, p. 279), thus leading to an uncertain interpretation for the 5.7 km/s rocks. Seismic-reflection data are needed to resolve the nature of these basement rocks (see Rooney *et al.*, this volume, p. 261). Similar basement velocities, and interpretational uncertainties, occur farther south-east beneath the Byrd Subglacial Basin, which is an area attributed to dissection by initial rifting in middle–late Mesozoic time and by further Cenozoic rifting (Jankowski *et al.*, 1983).

Transverse fault zones beneath the Ross embayment

At several locations in the Ross embayment region, major structural and physiographic features exhibit large horizontal offsets. These offsets are aligned along three subparallel zones (A, B, C, Fig. 4*b*), which we interpret as major transverse basement faults. Zone C, possibly the most significant, trends SW–NE, along the major topographic trough beneath Byrd Glacier, along the points where gravity and bathymetric trends change direction by 40° beneath the Ross Ice Shelf, and along the 400 km long bathymetric scarp in Marie Byrd Land. Horizontal offsets along zone C occur in the subice elevation contours for the TAM, the coastline of southern Victoria Land, and the linear gravity anomalies (and early rift grabens?) of the Ross embayment. Additionally, zone C marks the southernmost termination of major Cenozoic volcanism along the Transantarctic Mountains (with the exception of two localities in the central TAM) and the westernmost location in Marie Byrd Land (González-Ferrán, 1982; LeMasurier & Rex, 1982; Figs 1 & 4*b*).

Two basement fault zones (A & B, Fig. 4*b*) lie beneath the Ross Sea. Zone B lies along the deep trough beneath the Drygalski Ice Tongue and along points where horizontal offsets occur in elevation contours of the TAM and in the axes of the three Ross Sea early rift grabens. Additionally, zone B marks the northernmost extents of offshore (?)Neogene subvolcanic intrusions in the VLB and of short-wavelength linear magnetic anomalies that characterize the south-western Ross Sea (see Behrendt *et al.*, this volume, p. 299). The northernmost zone (A, Fig. 4*b*) is more tentative. Zone A lies, W–E, along a small horizontal offset in TAM elevation contours, along the major Polar 3 magnetic anomaly (Behrendt *et al.*, this volume, p. 299), and near the abrupt terminations of the VLB structure (Fig. 1) and the Central trough gravity anomaly (Fig. 3*b*).

The transverse fault zones are basement structures with a Cenozoic history of movement as they offset late Mesozoic rift-graben axes and post-Eocene mountain topography and coastlines, and they apparently control the location of Oligocene and younger volcanic centres. Based on limited seismic data, the fault zones do not appear to have extensively deformed the (?)late Mesozoic and younger sedimentary sections under (through) which they pass. The fault zones could have initiated either in Palaeozoic time as structural boundaries between different basement terranes, or in Mesozoic time as fractures delineating the break-up of Gondwana. In places, these faults appear to determine the location of: (1) horizontal continental break-up (zone C: Marie Byrd Land and the Campbell Plateau); (2) differential, vertical displacement (zones A, B and C: across the TAM); and (3) possible large-scale crustal rotation (zone C: rotation between rift grabens under the Ross Sea and Ross Ice Shelf).

The orientation of the transverse faults may reflect an early rift stress regime that controlled the initial trend and (?)offsets of the late Mesozoic rift grabens beneath the Ross embayment. With the Eocene reorganization of plate motions, the stress regime changed, leading to late rift crustal deformation and volcanism located principally along the western Ross Sea and in Marie Byrd Land (Fig. 4*b*).

Summary

In the Ross embayment, significant crustal extension (100%, Lawver & Scotese, 1987) has probably occurred episodically in response to motions of surrounding major plates. We think that most regional extension occurred during a late Mesozoic, early rift period marked by downfaulting of the major and minor graben systems. A late rift period, commencing with a major Eocene change in plate motions, resulted in crustal deformation localized principally in the western Ross Sea and Marie Byrd Land. Major transverse basement faults, newly mapped at three sites across the Ross embayment region, appear to be long-active (?post-Palaeozoic) features controlling horizontal (possibly strike-slip and rotation) and vertical displacements associated with the early rift and late rift periods.

Although we propose two distinct rift periods, crustal extension beneath the Ross embayment may have been more or less continuous since the initial break-up of Gondwana.

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