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Basement geology and tectonic development of the greater New Zealand region: an interpretation from regional magnetic data

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Abstract

The basement geology of New Zealand is composed of early Palaeozoic terranes of the Western Province, that are separated from late Palaeozoic–Mesozoic Eastern Province terranes by a suite of Carboniferous–Cretaceous arc-related igneous rocks (Median Tectonic Zone, MTZ). The Stokes Magnetic Anomaly System (SMAS) is associated with MTZ rocks and volcanogenic basement terranes of the Eastern Province. Offshore, it can be traced north along the northern margin of the New Caledonia Basin, and correlative Eastern Province rocks are found in New Caledonia. It can also be traced south across the Great South Basin, until a significant ENE-trending tectonic boundary is encountered on the central Campbell Plateau. This boundary is defined by linear gravity and magnetic anomalies (Campbell Magnetic Anomaly System, CMAS), and narrow fault-bounded sedimentary basins. If the sources of CMAS anomalies are correlative with those of the SMAS, then magnetic data require a ~400 km dextral offset of basement rocks by faults along the northern margin of the CMAS prior to 80 Ma. The geometry of correlative Western Province and MTZ rocks in Marie Byrd Land supports the hypothesis that CMAS anomalies are sourced by MTZ-correlative rocks. A NNE-trending boundary on the central Challenger Plateau marks a change from high amplitude magnetic anomalies to weakly magnetic basement, and appears to represent a fundamental change in crustal character. The western Challenger Plateau and Lord Howe Rise (south of 30ºS) are characterised by high amplitude magnetic and gravity anomalies with a NW-trending fabric, but the source of magnetic anomalies is unresolved. The magnetic character, combined with Cretaceous reconstruction, supports basement rock correlations with the east Lachlan Fold Belt or New England Fold Belt in Australia, rather than Western Province rocks in New Zealand. The magnetic signature of marginal ocean crust around New Zealand also offers clues into the region's tectonic history. Negative magnetic anomalies adjacent to the Campbell Plateau and Lord Howe Rise, and in the New Caledonia Basin, suggest that seafloor formation started during chron 33r (79–83 Ma). A linear positive magnetic anomaly in the outer Bounty Trough may be anomaly 33, which was isolated by a ridge-jump, and is consistent with separation of the Bollons Seamount continental fragment by ocean crust. Alternatively, it may be anomaly 34 and represent the earliest ocean crust formed between New Zealand and Marie Byrd Land. Magnetic lineations in the southern South Fiji Basin suggest that at least one ridge–ridge–ridge triple junction was active during its opening, and imply that Cenozoic ocean crust is younger in the east. At the southern edge of the South Fiji Basin, there is a significant tectonic boundary, named here the van der Linden Fault. It can be traced for ~500 km and may have been a leaky transform during basin formation.

Keywords: magnetic; basement; terranes; Australia; New Zealand; Antarctica; Gondwanaland; continental crust; ocean crust; Palaeozoic; Mesozoic; Cenozoic; backarc; subduction

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1. Introduction

The New Zealand continent extends over a large area in the South Pacific (~2,000,000 km^2) and is mainly submerged (Fig. 1). Direct sampling of basement rocks from the submerged continental region is restricted to a few islands, boreholes, and dredge sites (Fig. 2) (e.g. Beggs et al., 1990; Tulloch et al., 1991; Mortimer et al., 1997, 1998), but magnetic data are widely distributed and can place strong

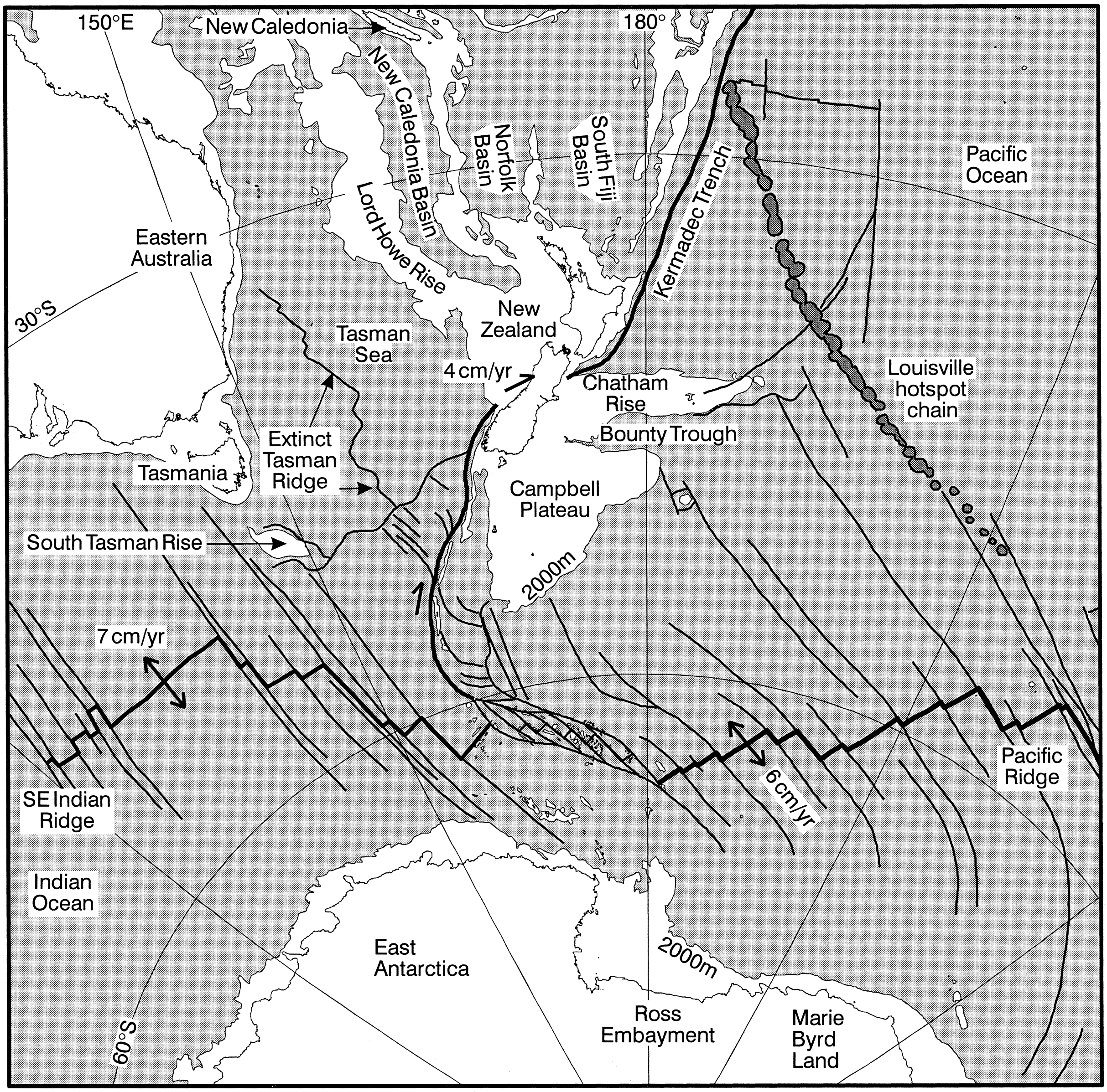


Fig. 1. Tectonic setting of the New Zealand region. Main tectonic features (e.g. fracture zones and spreading ridges) are shown as bold black lines and were traced from satellite-derived gravity anomaly maps (Sandwell and Smith, 1997). Water deeper than 2000 m is shown with a light shade. Azimuthal equidistant projection with centre at 60ºS, 180ºE.

constraints on the regional character and geometry of basement rocks (e.g. Wellman, 1959; Hatherton, 1967; Davey and Christoffel, 1978; Davy, 1991).

Recently compiled magnetic data (Sutherland, 1996) present the best opportunity for tracing offshore the extensions of basement terranes recognised onshore in New Zealand. When combined with plate reconstructions, the data help to provide constraints on the relationships of New Zealand rocks to correlatives found in Antarctica and Australia, and provide insight into the tectonic development of the region since the Palaeozoic.

2. Magnetic data

The first regional magnetic measurements in New Zealand were aeromagnetic surveys between 1949 and 1952 to assist geothermal power development and to provide information about regional geology (Gerard and Lawrie, 1995). These measurements, combined with aeromagnetic data collected later, formed the basis for the Magnetic map of New Zealand 150,000 series, which covered onshore New Zealand.

Since 1960, there have been more than 170 geophysical cruises in the New Zealand region that have made magnetic measurements. Marine magnetic data were combined with onshore data by Davey and Robinson (1978) and Robinson and Davey (1981) at a scale of 1 : 1,000,000, and the data were also combined for the Magnetic total force anomaly map: coastal series 150,000. Marine magnetic data were used to compile the Magnetic total force anomaly map: island series 100,000. Magnetic data from the Challenger Plateau were compiled by Wood (1994).

The regional compilation of Sutherland (1996) (Fig. 3) integrates marine magnetic data with onshore aeromagnetic data and a detailed aeromagnetic survey from north of the North Island (Malahoff et al., 1982). It is the first published compilation of magnetic data for the entire New Zealand continental region. The data grid computed by Sutherland (1996), which was used to produce the maps in this paper, was generated by fitting a minimum curvature surface through all the reliable data. It is thus totally objective, but may be geologically unrealistic in areas of sparse data coverage. Data reliability was assessed using a cross-over analysis, and data were rejected where cross-over values were consistently >100 nT (see Sutherland, 1996, for a full analysis). An interpretation of the magnetic data is shown in Fig. 4.

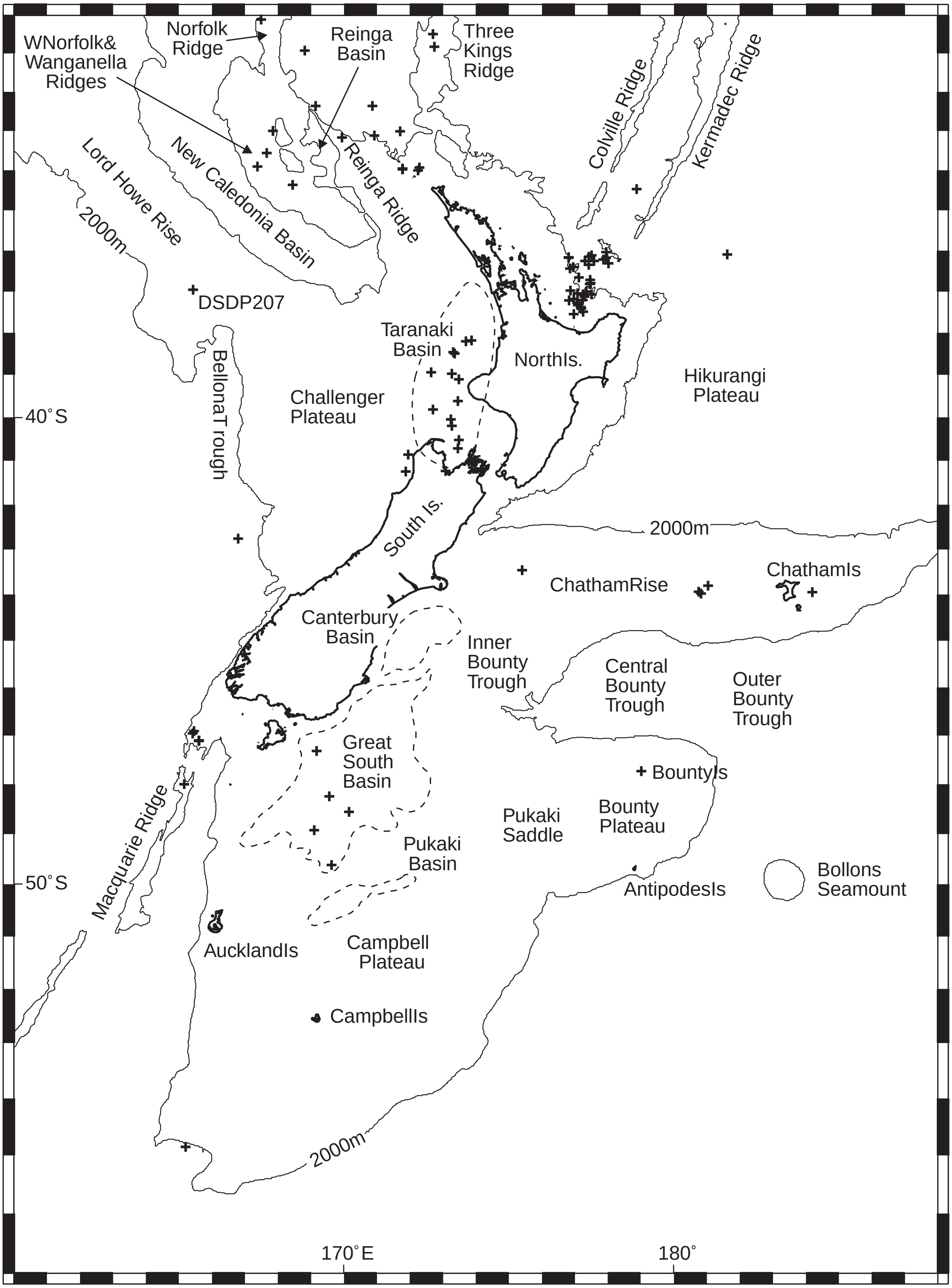
3. New Zealand geology

The basement geology of New Zealand has been described in terms of a number of tectonostratigraphic terranes and igneous suites (Coombs et al., 1976; Bishop et al., 1985; Bradshaw, 1989; Mortimer and Tulloch, 1996), which were accreted to the margin of the supercontinent Gondwanaland during late Palaeozoic and Mesozoic time.

The Western Province is dominated volumetrically by Late Cambrian–Late Ordovician quartzose greywacke sediments of the Buller Terrane, that are regionally metamorphosed and locally intruded by Palaeozoic granitoids (Nathan, 1976; Tulloch, 1983, 1988; Cooper and Tulloch, 1992). The Takaka Terrane is subordinate volumetrically, but composed of a diverse assemblage of deformed and metamorphosed Palaeozoic sedimentary and volcanic rocks (Bishop et al., 1985; Cooper and Tulloch, 1992).

Terranes of the Eastern Province are dominated by lithic and feldspathic metagreywackes, but include volcanic, intrusive, and ophiolitic assemblages (Coombs et al., 1976; MacKinnon, 1983; Bishop et al., 1985; Kimbrough et al., 1992; Ballance and Campbell, 1993; Roser et al., 1993; Mortimer, 1995). The Haast Schist separates weakly metamorphosed Caples and Torlesse terrane sediments, and represents a metamorphic overprint on at least these two terranes (Adams and Gabites, 1985; Graham and Mortimer, 1992).

The Median Tectonic Zone (Landis and Coombs, 1967) separates Western Province from Eastern Province rocks, and consists of a suite of subduction-related calc-alkaline plutons with subordinate volcanic and sedimentary rocks (Bradshaw, 1993; Kimbrough et al., 1994). Magmatic ages range from Carboniferous to Early Cretaceous, with apparent gaps in the Permian and Middle Jurassic (Kimbrough et al., 1994; Bradshaw et al., 1997). Carboniferous rocks are rare in the Median Tectonic Zone and their significance is still unclear (Kimbrough et al., 1994).


Norfolk
Ridge
WNorfolk&
Wanganella
Ridges
Reinga
Basin
Three
Kings
Ridge
Colville Ridge
Kermadec Ridge
Lord Howe Rise
New Caledonia Basin
Reinga Ridge
2000m
DSDP207
Taranaki
Basin
NorthIs.
Hikurangi
Plateau
BellonaT rough
Challenger
Plateau
40˚S
South Is.
2000m
ChathamRise
ChathamIs
Canterbury
Basin
Inner
Bounty
Trough
Central
Bounty
Trough
Outer
Bounty
Trough
Great
South
Basin
BountyIs
Pukaki
Saddle
Bounty
Plateau
Pukaki
Basin
Macquarie Ridge
50˚S
Bollons
Seamount
AntipodesIs
AucklandIs
Campbell
Plateau
CampbellIs
2000m
170˚E
180˚

The present shape of the New Zealand continent is mainly the result of Cretaceous–Cenozoic tectonics. During the period 130–80 Ma, there was a change from subduction-related processes to extension and widespread basin formation (Bradshaw, 1989), eventually culminating in seafloor spreading and formation of the Tasman Sea and South Pacific. During Late Cretaceous–Late Eocene time, the New Zealand continent had a passive margin setting and was relatively quiescent tectonically.

A new plate boundary propagated through New Zealand at ~45 Ma along the line of the Emerald fracture zones. Between 45 and 30 Ma, the instantaneous pole of Australia–Pacific rotation was close to New Zealand (Sutherland, 1995). The Resolution Rift Margin formed as a conjugate feature to the SW Campbell Rift Margin at this time (Fig. 4; Sutherland, 1995), and magnetic anomalies 18 to 11 have been identified south of New Zealand (Weissel et al., 1977; Wood et al., 1996; Fig. 4). In the vicinity of South Island, Cenozoic strike-slip faulting overprints earlier deformation, and is most clearly manifested by a 460 km apparent offset of the Maitai Terrane by the Alpine Fault (Fig. 5; Clark and Wellman, 1959). The total Eocene–Recent plate motion through South Island is well constrained as ~850 km (Sutherland, 1995). There is a record of calc-alkaline volcanism in North Island since earliest Miocene time (e.g. Herzer, 1995).

4. Magnetic character and extrapolation of basement geology

4.1. Onshore New Zealand

The most prominent feature of magnetic data from onshore is a zone of high amplitude positive anomalies associated with basement rocks located between the Median Tectonic Zone and Maitai Terrane (Fig. 5). This zone is called the Stokes Magnetic Anomaly System (SMAS) and its characteristics were reviewed by Hunt (1978). The northern anomaly within this system is called the Junction Magnetic Anomaly, and has a shallow source corresponding to mafic and ultramafic rocks of the Maitai Terrane (Davy, 1991). It is generally only about 20 km wide, but is well defined and extremely linear in the North and South Islands. The only significant (>20 km) offset of this anomaly is where it is cut by the Alpine Fault.

In contrast to the high amplitude anomalies of the SMAS, the Buller and Torlesse terranes have a subdued magnetic character, and local anomalies are typically associated with Cretaceous–Cenozoic volcanic and intrusive rocks. In the central North Island, late Cenozoic calc-alkaline volcanism is extensive and volcanic centres are conspicuous on magnetic maps of the region.

4.2. Offshore western New Zealand

The region west of the Alpine Fault, south of the Junction Magnetic Anomaly, and northwest onto the Lord Howe Rise is considered here (Fig. 4). The Lord Howe Rise is the continental extension of the Challenger Plateau (Fig. 4) and western New Zealand. The West Norfolk, Wanganella, and Reinga ridges are the continental extensions of northern North Island, and merge farther north with the Norfolk Ridge (Eade, 1988).

The Junction Magnetic Anomaly, which is associated with the Maitai Terrane, can be reliably traced as a continuous short wavelength feature through western North Island to just offshore from the northern tip of North Island. Eade (1988) proposed that the Junction Magnetic Anomaly can be followed along the Reinga Ridge, but it is offset in several places and the data distribution is too coarse for reliable correlation (Fig. 3).

Fig. 2. Location of basement sample sites (crosses), islands, and bathymetric features (2000 m isobath shown as solid line) referred to in the text. Outlines of the Taranaki, Canterbury, Great South, and Pukaki basins are shown dashed. Basement samples have been collected from: the Chatham Rise (Cullen, 1965; Herzer and Wood, 1988); southern Campbell Plateau (Challis et al., 1982); Great South Basin and Bounty Islands (Beggs et al., 1990); western Challenger Plateau (Tulloch et al., 1991); the region between North Island and the Kermadec Ridge (Gamble et al., 1993); northern Macquarie Ridge (Mortimer, 1994); northern margin of the Hikurangi Plateau (Mortimer and Parkinson, 1996); Taranaki Basin (Mortimer et al., 1997); the region between the West Norfolk and Three Kings Ridges (Mortimer et al., 1998).

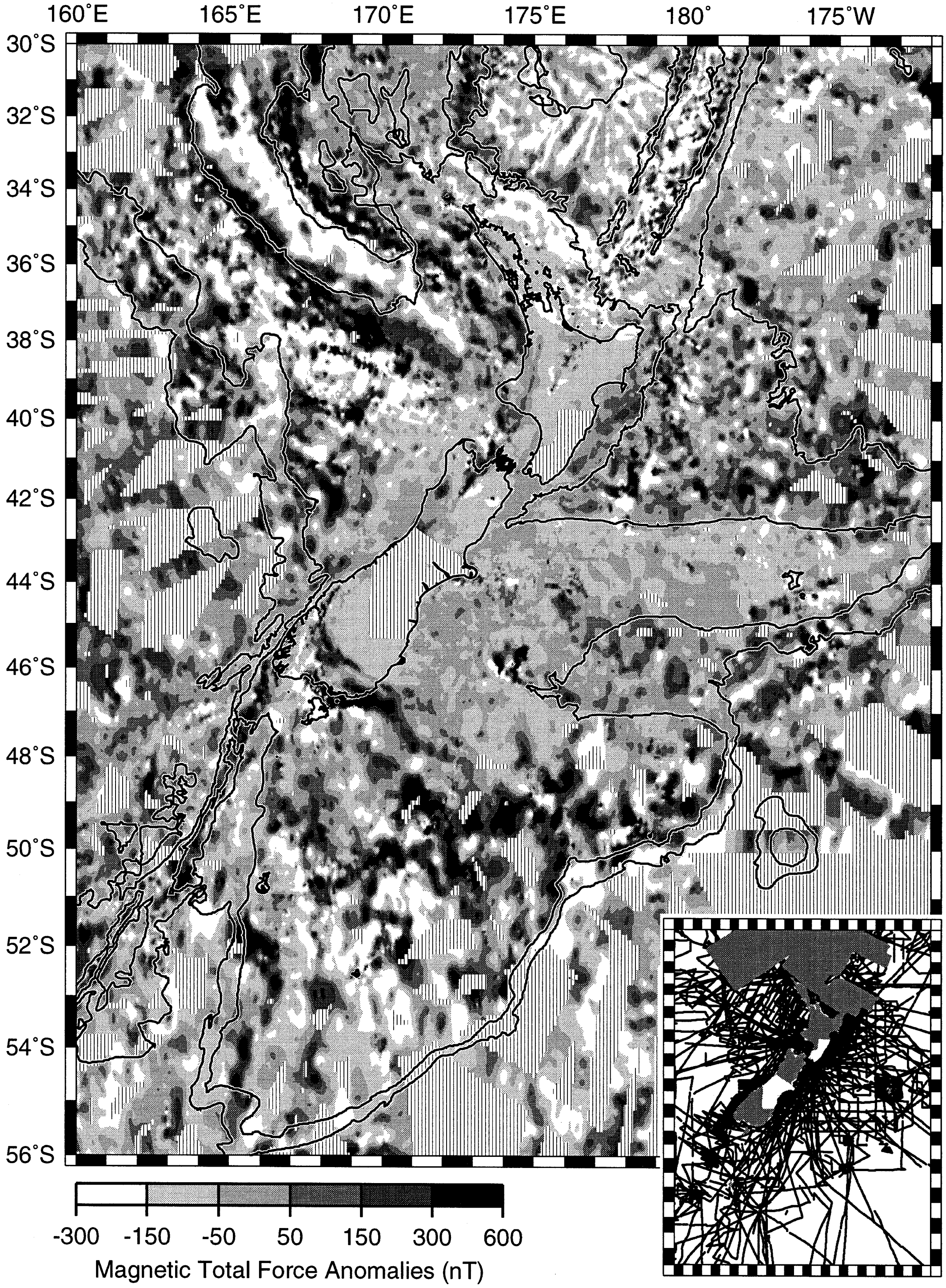


Fig. 3. Magnetic anomaly map of the New Zealand region after Sutherland (1996). 2000 m and 4000 m isobaths shown as solid black lines. Areas more than 50 km from magnetic data points are shown hatched (vertical lines). Inset shows distribution of aeromagnetic (shaded) and ship data used.

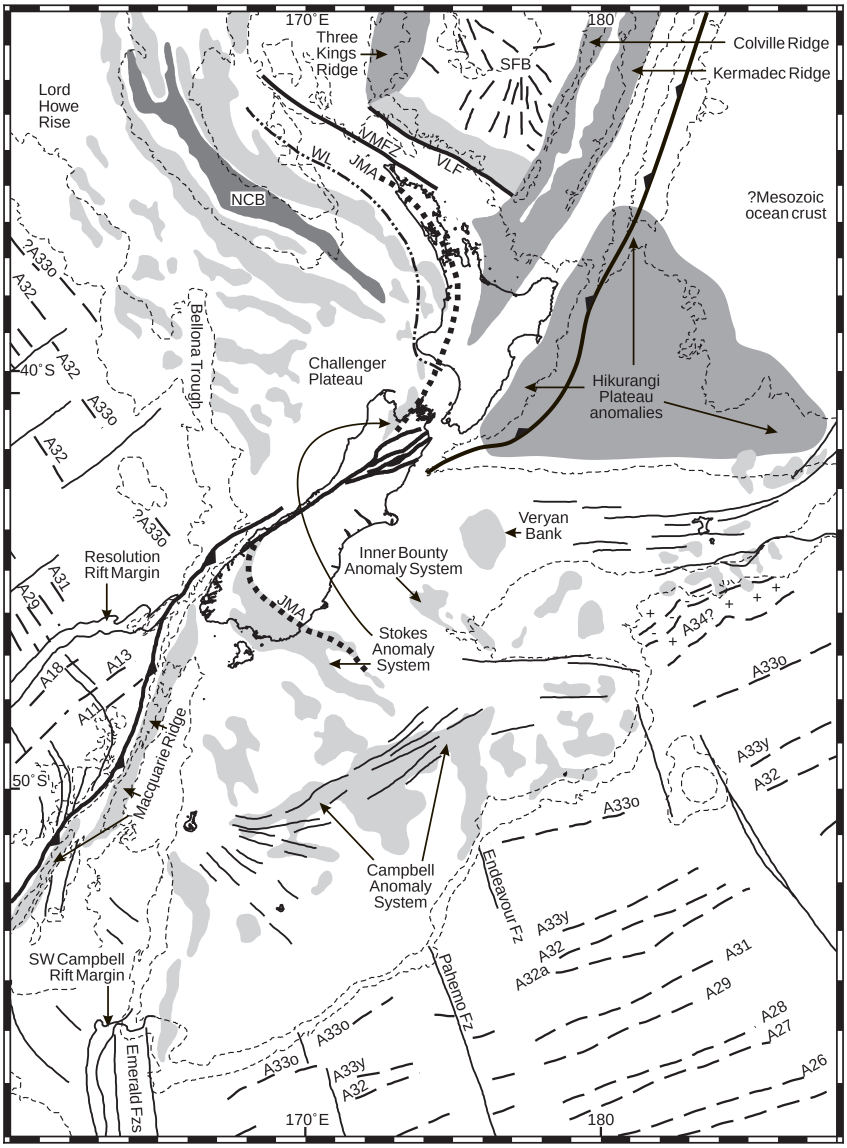


Fig. 4. Sketch map of the New Zealand region showing major magnetic features (shaded), seafloor spreading magnetic anomalies (modified after Cande et al., 1989), and the active plate boundary through New Zealand. *NCB* = New Caledonia Basin; *SFB* = South Fiji Basin; *VLF* = van der Linden Fault; *VMFZ* = Vening Meinesz Fracture Zone; *JMA* = Junction Magnetic Anomaly; *WL* = approximate western limit of Cenozoic arc magmatism. Features shown as black lines on the Campbell Plateau and Chatham Rise are gravity lineaments that are likely to be related to faults cutting basement.

The Reinga Ridge and North Island have been subjected to significant alkaline and calc-alkaline volcanism during the Cenozoic, and volcanic centres identified on seismic profiles have associated magnetic anomalies (e.g. Herzer, 1995). The western limit of Cenozoic arc-related volcanism is indicated on Fig. 4. Cenozoic arc and back-arc basin development is discussed later (below) in relation to the magnetic character of northern New Zealand.

The most prominent magnetic feature offshore western New Zealand is the linear negative anomaly associated with the New Caledonia Basin, and the

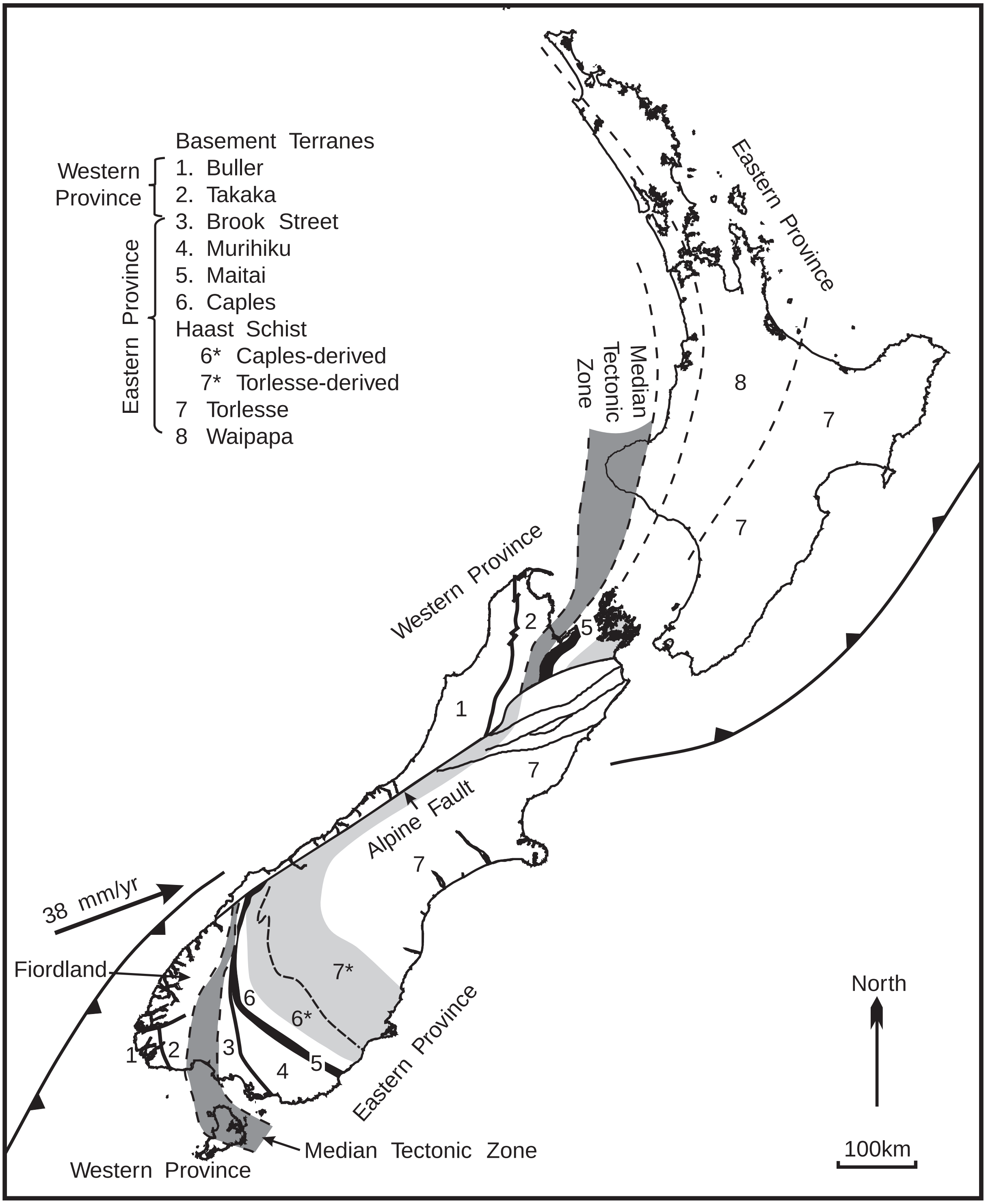


Fig. 5. Basement terranes of onshore New Zealand after Bishop et al. (1985), Kimbrough et al. (1994), Mortimer (1995), and Mortimer et al. (1997).

zone of strong positive anomalies along both its margins (Fig. 3; Davy, 1991). Samples collected from the northern zone of positive anomalies, which coincides geographically with the West Norfolk and Wanganella ridges, demonstrate that basement rocks are correlative with the Brook Street Terrane or Median Tectonic Zone found onshore in New Zealand (Mortimer et al., 1998). Thus, by correlation with onshore, it may be valid to include the zone of positive anomalies along the northern edge of the New Caledonia Basin as part of the SMAS.

An alternative hypothesis proposed by Davy (1991) is that the high amplitude magnetic anomalies associated with the New Caledonia Basin are related to igneous rocks formed during extension and basin formation. It may be that Late Cretaceous igneous rocks, and older rocks correlative to the Median Tectonic Zone, both contribute to the strong positive magnetic anomalies along the basin margins. The modelling of Davy (1991) suggests that the paired anomalies are not simply edge effects. If the New Caledonia Basin opened during the Cretaceous (Eade, 1988; Uruski and Wood, 1991), and the strong negative anomaly associated with the basin axis is caused by reversed polarity remanent magnetisation of Cretaceous igneous basement formed during extension, then the main phase of basin formation cannot have been entirely during the Cretaceous magnetic quiet period (~83–118 Ma; Cande and Kent, 1995). A hypothesis consistent with magnetic modelling (Davy, 1991) and known stratigraphy (Eade, 1988; Uruski and Wood, 1991) is that initial basin formation was during chron 34, and that extension and associated igneous activity continued during chron 33r.

Anomalies associated with the southern margin of the New Caledonia Basin and the basin axis can be followed to within about 100 km of the west coast of the North Island (Davy, 1991), where they become much weaker. No basement samples have been collected from this region of strong positive anomalies, so the source of the anomalies is unknown. Following the interpretation of Davy (1991), these anomalies could be related to Cretaceous igneous rocks. Alternatively, they could be associated with remnants of late Palaeozoic or Mesozoic volcanic arcs, possibly correlative with rocks found in the Median Tectonic Zone.

South of the New Caledonia Basin, the Lord Howe Rise and northwestern half of the Challenger Plateau are characterised by large amplitude, moderate wavelength (typically 30–80 km) magnetic anomalies. Individual anomalies are often elongate parallel to the axis of the Lord Howe Rise and define a NW–SE fabric. The only samples of basement rock from this region are Carboniferous 'S'-type granite dredged from the southwestern margin of the Challenger Plateau (Tulloch et al., 1991), and Cretaceous rhyolite drilled at the northern end of the Bellona Trough at DSDP site 207 (McDougall and van der Lingen, 1974). The Bellona Trough is characterised by moderate negative anomalies that cut across the dominant NW–SE magnetic fabric. These may be related to either Cretaceous or Eocene volcanic centres (Wood, 1991).

The eastern part of the Challenger Plateau, and western South Island, have a more subdued magnetic character than the western Challenger Plateau and Lord Howe Rise (Wood, 1994). The difference in magnetic character suggests that the two regions may have had significantly different geological histories, and that the geology found onshore in western New Zealand may be a poor analogue for the western Challenger Plateau and Lord Howe Rise.

4.3. Offshore northern New Zealand

The region between the Norfolk Ridge and Kermadec Trench, and north of the Junction Magnetic Anomaly, is considered here (Fig. 4). Development of this region has been dominated by Cenozoic tectonics associated with subduction and back-arc basin development (Malahoff et al., 1982; Davey, 1982; Herzer, 1995; Herzer and Mascle, 1996; Mortimer et al., 1998). The magnetic character of the region is relatively well known from aeromagnetic surveys conducted between 1977 and 1979 (Malahoff et al., 1982).

The Norfolk Ridge is the continental link between northern New Zealand and New Caledonia (Eade, 1988), where correlatives of the Murihiku Terrane and possibly the Brook Street Terrane are found (e.g. Black, 1997). The high amplitude positive magnetic anomalies associated with the southern end of the Norfolk Ridge are consistent with Brook Street or Murihiku Terrane basement, but would also be consistent with Cretaceous–Cenozoic intrusive or volcanic rocks. Late Oligocene volcanic rocks have been dredged from the southern Norfolk Ridge, and imply that subduction-related volcanism was occurring there at 26 Ma (Mortimer et al., 1998). Pliocene volcanic activity is also recorded on Norfolk and Philip Islands (Eade, 1988).

The South Norfolk Basin has typical water depths in the range 2500–4300 m. It was interpreted by Herzer and Mascle (1996) and Mortimer et al. (1998) as an Early Miocene back-arc basin on the basis of seismic data, dredge samples, and the regional deformation history. However, it has a relatively subdued magnetic character, and linear magnetic anomalies are not recognised. If the South Norfolk Basin is of Cenozoic age, its magnetic character suggests that normal seafloor spreading processes were not well developed during its formation.

The South Fiji Basin lies between the Three Kings Ridge, an extinct east-facing Early Miocene volcanic arc (Mortimer et al., 1998), and the Colville Ridge, which is probably an extinct Late Miocene volcanic arc (Herzer, 1995; Wright et al., 1996). The southern part of the South Fiji Basin contains well defined linear magnetic anomalies, which have been correlated with a sequence from anomaly 7 in the west to anomaly 12 in the east (Malahoff et al., 1982; Davey, 1982). However, alternative correlations are possible (e.g. Davey, 1982), and Herzer (1997) has recently reinterpreted the anomalies as an eastward-younging Miocene sequence.

However, the geometry of magnetic lineations in the southern part of the South Fiji Basin is complex (Figs. 3 and 6) and appears to require at least one ridge–ridge–ridge triple junction to have been active during formation of the basin. The chevron pattern of anomalies in the southwestern part of the basin is suggestive of a triple junction migrating east-northeast, and the radial lineations around 177.5°E, 31.5°S may be the fossil triple junction. If this interpretation (Fig. 6) is correct, it would require that lineations in the southwestern part of the basin young towards the east, which is not consistent with initial correlations (Malahoff et al., 1982; Davey, 1982).

A major NW-trending tectonic boundary along the southern margin of the South Fiji Basin is clearly defined by a change from moderate positive magnetic anomalies in the north ($\sim$200–300 nT), to moderate negative anomalies farther south. This linear boundary is well defined by magnetic data between the southern end of the Three Kings Ridge and the Colville Ridge, a distance of $\sim$500 km. The boundary is located in 2000–2500 m water depth and is north of the Northland Plateau. It is distinct from the Vening Meinesz Fracture Zone, which meets the Northland continental shelf $\sim$100 km farther south (Herzer and Mascle, 1996). The prominent magnetic boundary is coincident with a lineament observed on gravity maps (Sandwell and Smith, 1997), a sudden change in water depth, possibly associated with major faults (Davey, 1977; R.H. Herzer, pers. commun., 1998), and a linear chain of seamounts. The boundary is referred to here as the van der Linden Fault.

Previous interpretations of South Fiji Basin formation rely on the Vening Meinesz Fracture Zone as the major tectonic boundary at the south end of the basin (e.g. Davey, 1982; Malahoff et al., 1982; Herzer, 1995). However, the term Vening Meinesz Fracture Zone was loosely defined before the detailed mapping of Herzer and Mascle (1996), and its location south of the South Fiji Basin was poorly understood. Continuity of the Vening Meinesz Fracture Zone across the Northland continental shelf is undemonstrated, but it is now clear that the van der Linden Fault is a distinct feature and separated by $\sim$100 km from the Vening Meinesz Fracture Zone.

The magnetic data (Fig. 3) suggest that South Fiji Basin seafloor terminates at the van der Linden Fault. A preliminary tectonic interpretation of the van der Linden Fault is that it was a leaky transform during formation of the South Fiji Basin (cf. Brothers and Delaloye, 1982). This is based on its geometry perpendicular to magnetic lineations in the southern South Fiji Basin (Fig. 6), and the associated seamounts along its length. An alternative hypothesis is that it represents a fossil subduction margin, where South Fiji Basin crust was subducted beneath Northland (cf. Herzer, 1995).

The zone of high amplitude magnetic anomalies associated with the Colville Ridge and Kermadec Ridge extends south into central North Island, where there is active calc-alkaline volcanism (Fig. 6). The Kermadec Ridge is the active volcanic arc associated with subduction at the Kermadec Trench, and is thought to have migrated from the Colville Ridge by

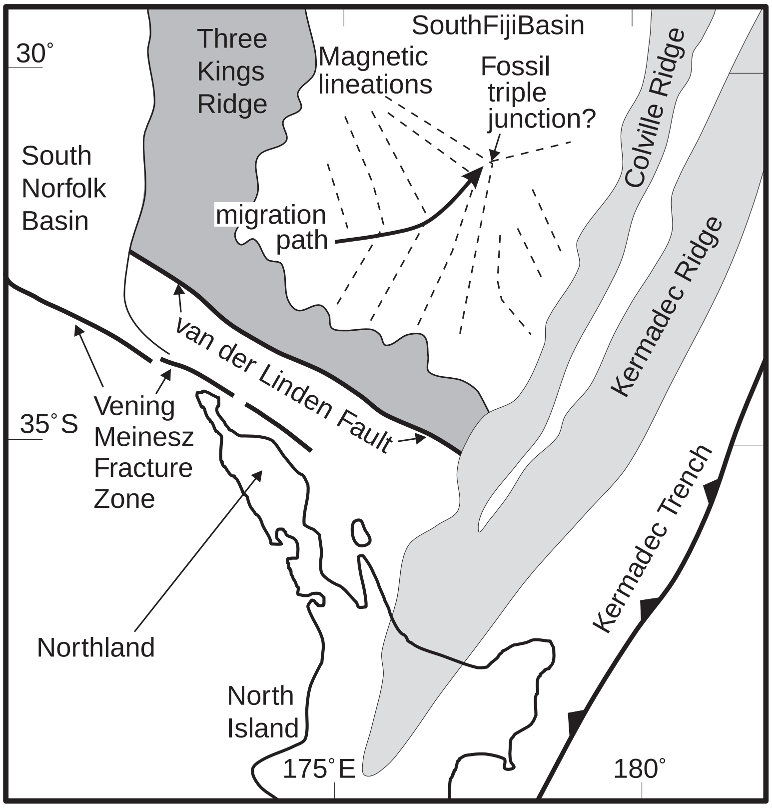


Fig. 6. Sketch interpretation of magnetic data from the South Fiji Basin region. Patterned areas are characterised by high amplitude (200–500 nT), moderate wavelength (5–50 km) magnetic anomalies. Kinks in South Fiji Basin magnetic lineations suggest that ocean crust youngs east, and they define the migration path of a possible triple junction. A pattern of radial lineations farther east may be the fossil triple junction. The southern edge of the South Fiji Basin is prominent on gravity and magnetic maps, and is interpreted as a fault. It is named here the van der Linden Fault, and may have been a leaky transform during formation of the South Fiji Basin.

a process of back-arc rifting since 5 Ma (Wright et al., 1996).

4.4. Offshore eastern New Zealand

The major structural features of eastern New Zealand are the Hikurangi Plateau, the Chatham Rise, the Bounty Trough, and the Campbell Plateau. The Chatham Rise and Campbell Plateau are continental extensions of eastern South Island (Fig. 2) that were modified by significant Cretaceous extension and crustal thinning in the Great South Basin and Bounty Trough (e.g. Davey, 1977; Beggs, 1993; Davy, 1993).

The Hikurangi Plateau lies mostly at depths of 2500–3500 m, and is thought to be a Mesozoic igneous province comprising thickened oceanic crust, similar to the Ontong Java Plateau and Manihiki Plateau (Wood and Davy, 1994; Mortimer and Parkinson, 1996). It is characterised by discontinuous high amplitude magnetic anomalies, which are related to the many volcanic centres observed on seismic reflection data (Davy and Wood, 1994; Wood and Davy, 1994). Because surrounding crust has a more subdued magnetic character, the extent of the Hikurangi Plateau is evident from the distribution of high amplitude magnetic anomalies (Figs. 3 and 4). Magnetic anomalies associated with Hikurangi Plateau crust that has been subducted at the Hikurangi Trough are evident as far west as the east coast of North Island.

The Chatham Rise has a structural fabric defined by east–west trending fault-bounded basins filled with Cretaceous–Cenozoic sediment (Wood and Herzer, 1993). It has a subdued magnetic character consistent with deformed and metamorphosed Torlesse Terrane basement, which has been dredged from the crest of the Chatham Rise and is found on the Chatham Islands (Wood and Herzer, 1993). Short wavelength magnetic anomalies in the Veryan Bank region (Fig. 4) are associated with Cenozoic volcanic centres, and are also found intermittently farther west to the South Island coast (Herzer et al., 1989). Prominent magnetic anomalies immediately south of the Chatham Islands are related to Cretaceous–Cenozoic volcanic centres associated with fault-bounded basins (Wood and Herzer, 1993).

The southern portion of the SMAS can be traced from southeastern South Island offshore to the Great South Basin (Davey and Christoffel, 1978; Cook et al., 1999). The SMAS is continuous through the Great South Basin, but anomalies decrease in amplitude to the southeast and become indistinct near 48.3ºS, 173.0ºE.

The region northeast of the SMAS is characterised by relatively few magnetic anomalies, consistent with greywacke and schist basement rocks found onshore. Davy (1993) collectively referred to magnetic anomalies between the South Island coast and the outer Bounty Trough as the Bounty Magnetic Anomaly System, and interpreted a linear pattern of symmetric anomalies centred along the axis of the Bounty Trough. The linear nature of individual anomalies within the Bounty Magnetic Anomaly System is not apparent on the new magnetic map (Fig. 3), but the weakly defined magnetic fabric is similar to that described by Davy (1993). The area around 46ºS, 174.5ºE (Fig. 4) of high amplitude magnetic anomalies with moderately well-defined northwest trend is referred to here as the Inner Bounty Magnetic Anomaly System.

The parallel trend and similar amplitude of the SMAS suggests that the Inner Bounty Magnetic Anomaly System is also related to structurally controlled igneous basement. The origin of magnetic anomalies in the central Bounty Trough is unknown and data coverage is barely adequate to define their geometry. Davy (1993) suggests that they are related to underlying Permian ocean crust, but an alternative explanation is that they are related to Cretaceous igneous activity. The magnetic anomaly symmetry is neither perfect nor obvious on most profiles (Davy, 1993), and does not provide conclusive evidence for an oceanic crust origin. The highly deformed nature of Permian rocks found onshore in South Island also suggests that it is unlikely a symmetric anomaly pattern could be preserved.

One of the most prominent features on the magnetic map (Figs. 3 and 4) is the zone of high amplitude positive anomalies trending northeast across the central part of the Campbell Plateau. These anomalies were named the Campbell Magnetic Anomaly System (CMAS) by Davey and Christoffel (1978). The CMAS coincides geographically with a linear series of gravity anomalies (Sandwell and Smith, 1997), which reconnaissance seismic measurements (Davey, 1977) indicate, in some cases, may be related to narrow fault-bounded basins and basement highs. The system of well-defined gravity lineaments following the CMAS suggests that more detailed magnetic surveying may reveal the CMAS to be significantly more linear and have more internal fabric than the sparse available data show.

Davey and Christoffel (1978) postulated that the SMAS was the offset equivalent of the CMAS, but few basement rock samples have been collected from the region (see Beggs et al., 1990) and the cause of magnetic anomalies on the Campbell Plateau remains unknown. It is clear, however, that there probably exists a major structural discontinuity along the northwestern edge of the CMAS. Basement rocks north of this discontinuity have a northwest trending magnetic fabric, and to the south there is a northeast trending gravity and magnetic fabric.

5. The continent–ocean boundary and marginal ocean crust

Cretaceous–Cenozoic seafloor spreading in the Tasman and Pacific oceans has been discussed previously by many authors (e.g. Molnar et al., 1975; Weissel et al., 1977; Stock and Molnar, 1982), but details of the earliest stage of spreading (chrons 33–34) in the Tasman and South Pacific remain poorly known.

Plate motions during the transition from continental extension to seafloor spreading are difficult to quantify because there were many regions of distributed deformation before and during the early stages of seafloor spreading. Added to this are complications such as the possibility that initial seafloor spreading may have been oblique or asymmetric, fractures zones were not yet well developed, and the magnetic signature associated with initial ocean crust is partly obscured by factors such as extrusive and intrusive activity at the continental margin, and edge effects related to magnetic sources at the nearby continental margin.

Ocean crust along the southwestern margin of the Lord Howe Rise and Challenger Plateau, and adjacent to the Campbell Plateau, typically has an associated negative magnetic anomaly. I suggest that the most likely reason for this is that initial seafloor spreading was during chron 33r (79–83 Ma) and the anomalies are associated with remanent magnetisation of ocean crust. Modelling is required to rule out the possibility that negative anomalies are an edge effect associated with strong positive magnetic anomalies at the continental margin. If volcanism was extensive just prior to the onset of seafloor spreading during chron 33r (i.e. during chron 34), then strong positive anomalies would be expected to be associated with the continental margin, and negative anomalies with the oldest ocean crust. If the New Caledonia Basin formed at this time, then the strong central negative anomaly and marginal positive anomalies may have a similar explanation. Davy (1991) has shown by magnetic modelling that the central negative anomaly in the southeastern New Caledonia Basin cannot simply be explained by edge effects.

Immediately south of the Chatham Islands (at approximately 46ºS), there exists a linear positive magnetic anomaly trending ∼050º (Fig. 4), with negative anomalies on either side. The linear anomaly occurs in water depths of ∼4500 m, with a typical sediment thickness of 500–1000 m (Davy, 1993). The water depth and seismic reflection character of basement (Davy, 1993) suggest that the linear anomaly is associated with ocean crust, but it is not clear at what age the crust formed.

One possibility is that the linear positive anomaly is part of anomaly 34 (118–83 Ma), and that it represents the earliest seafloor spreading on the South Pacific Ridge, contemporaneous with mid-Cretaceous extension in the Bounty Trough and Great South Basin. An alternative explanation is that the positive anomaly is anomaly 33, and that there was a ridge jump to the south during chron 33. A ridge jump in the region at about chron 33 is required to produce the observed separation of Bollons Seamount from the Chatham Rise.

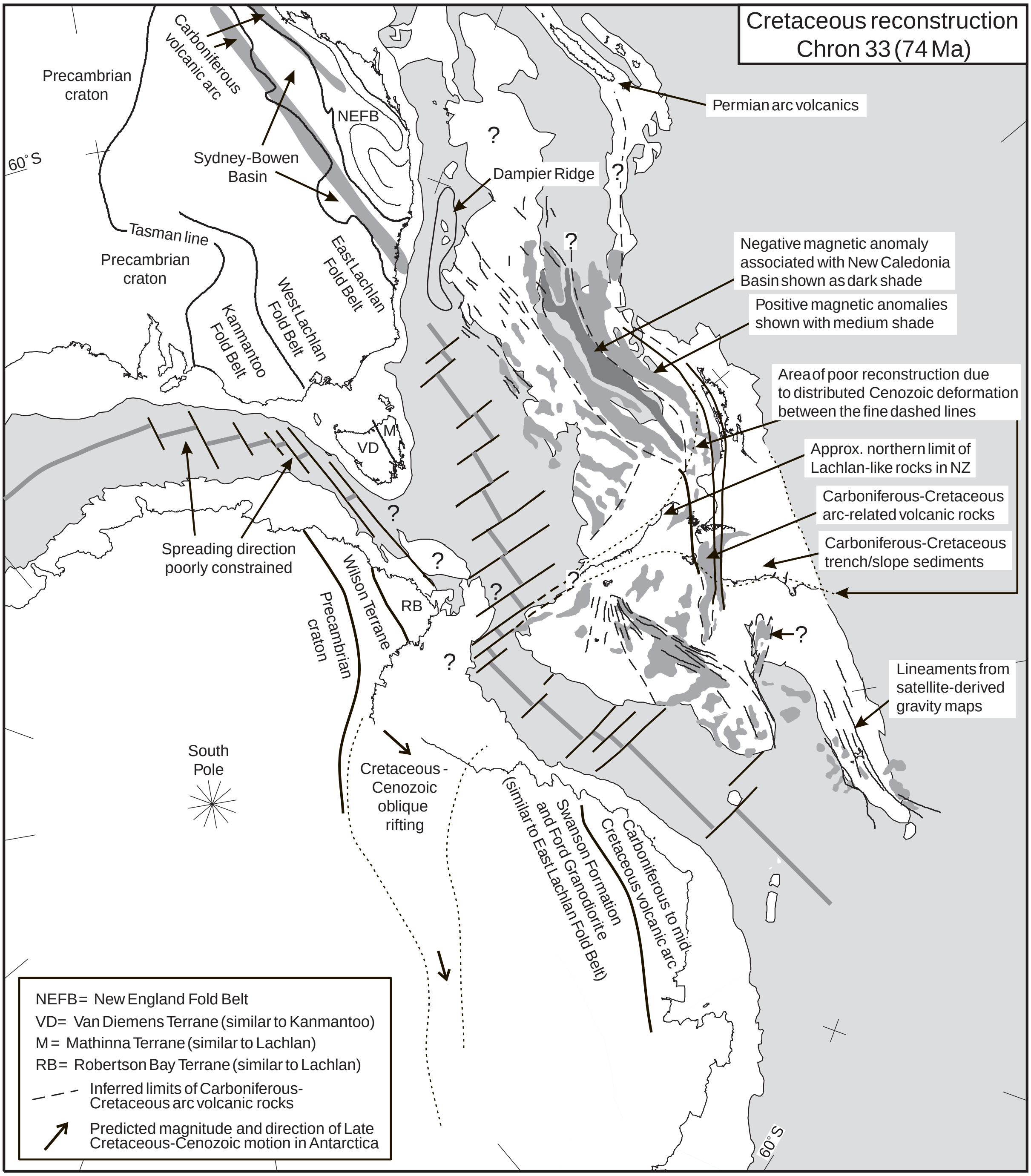
6. Cretaceous reconstruction

Seafloor spreading histories of the southeast Indian Ocean, Tasman Sea, and South Pacific are moderately well constrained back to chron 33 (74–79 Ma). In particular, anomaly 32r is distinctive and means that the locations of anomaly 33y can be well determined. A reconstruction for this time is shown in Fig. 7. Closure of the Australia–New Zealand–Antarctica plate circuit for this time implies oblique rifting in the Ross Embayment since chron 33y, with lesser degrees of rifting farther south. This is in good agreement with the known geology and crustal structure of the region, and indicates that first order geological constraints are satisfied at all boundaries in the plate circuit.

The 90 Ma reconstruction (Fig. 8) is less well constrained because it is based on fitting continental margins, which are sometimes poorly defined, and requires that continental deformation be accounted for. Fitting the Campbell Plateau to Marie Byrd Land is one exception, because the Pahemo and Endeavour fracture zones can be recognised adjacent to both continental margins, and both margins are defined well by gravity data (McAdoo and Laxon, 1997). Allowance was made for stretching in the New Caledonia Basin, Bellona Trough, Bounty Trough, and along the western edge of Lord Howe Rise. It was assumed that extension was approximately perpendicular to the axes of basins, and bathymetry was used as a proxy for crustal thickness.

To fit the Tasman Sea conjugate boundaries, and the Campbell Plateau with Marie Byrd Land, requires some deformation through New Zealand if the above procedure is used. This can be defined by a Lord Howe Rise–Campbell Plateau finite rotation with a pole close to where the MTZ–Eastern Province boundary crosses the Marie Byrd Land continental margin, and a clockwise rotation of ∼8º. The precise finite rotation is sensitive to geological estimates of stretching along the various margins. More rigorous estimates of continental extension may place quite strong constraints on Late Cretaceous motion through New Zealand and Antarctica.

The 90 Ma reconstruction presented here (Fig. 8) is broadly similar to earlier reconstructions (e.g. Molnar et al., 1975; Crook and Belbin, 1978; Cooper et al., 1982; Grindley and Davey, 1982; Kamp, 1986;



Gray and Norton, 1988; Lawver and Gahagan, 1994) because the seafloor spreading history of the Tasman, Indian, and Pacific oceans has been moderately well known for several decades. Differences with previous reconstructions are mostly due to how continental deformation has been accounted for, and this deformation can be subdivided into three main categories: Eocene–Recent deformation through New Zealand and Antarctica; the location and magnitude of Cretaceous extension; any additional deformation.

Eocene–Recent plate motion through New Zealand has previously been estimated using geological arguments (e.g. Kamp, 1986; Bradshaw, 1989), or from closure of plate circuits (e.g. Molnar et al., 1975; Stock and Molnar, 1982). However, it is now well constrained by seafloor formed at the Australia–Pacific boundary (Sutherland, 1995). Although details of Eocene–Recent deformation in New Zealand remain uncertain, the known plate motion provides a significant improvement over earlier reconstructions and means that the Eocene position of the Challenger Plateau with respect to the Campbell Plateau is well constrained.

It is significant that the 90 Ma reconstruction cannot be constructed by simply taking the chron 33 reconstruction and closing the remaining Tasman, Indian, and Pacific oceans. This implies that there has been some Cretaceous–Eocene deformation other than simple extension at the continental margins. The reconstruction presented here shows about 200 km of Cretaceous dextral strike-slip along the eastern margin of the Campbell Plateau, but this may in fact have been accommodated by more complex kinematics such as contemporaneous extension and block rotation over a wide region (see e.g. Gray and Norton, 1988). It is emphasised that this reconstruction is only one possible solution and that deformation elsewhere in the plate circuit (e.g. within Antarctica) would alter the estimated Cretaceous plate motion through New Zealand.

7. Structural discontinuity on the Campbell Plateau

One of the most striking features on Fig. 8 is the apparent 400 km dextral offset of MTZ correlative rocks on the Campbell Plateau. There are several possible interpretations for this feature.

(1) 400 km of dextral offset occurred along the northern margin of the CMAS between 130 and 80 Ma. MTZ volcanism ended at ca. 130 Ma in New Zealand (Kimbrough et al., 1994). This is a similar interpretation to that of Davey and Christoffel (1978), but with the structures following the northern margin of the CMAS as equivalent to their 'Campbell Fault', which has been shown not to exist in the location they suggested (Beggs, 1993). However, the interpretation requires that arc-related rocks aged 130 Ma are partly responsible for the CMAS on the western Campbell Plateau, and that the volcanic arc at 130 Ma was continuous. This has not been demonstrated and basement rock samples are required to test the hypothesis.

(2) 400 km of dextral offset occurred along the northern margin of the CMAS at some time between Late Carboniferous time and 90 Ma. It is possible that the CMAS is related to late Palaeozoic or early Mesozoic arc-related rocks. If this is true then the offset may be much older than Early Cretaceous. An analogous feature in the New England Fold Belt of northeast Australia, with a similar dextral offset of

Fig. 7. Late Cretaceous reconstruction (chron 33; 74 Ma). Areas deeper than 2000 m water depth (present day) are shown as light shade. Magnetic features (after Sutherland, 1996) are shown as medium and dark shade. Basement geology of eastern Australia shown after Veevers et al. (1994), eastern Antarctica after Collinson et al. (1994), Marie Byrd Land after Bradshaw et al. (1997). New Zealand basement terrane boundaries (see text) have been reconstructed to take account of distributed Cenozoic deformation, but the coastline and magnetic features have simply been cut along the line of the Alpine Fault and are hence not properly reconstructed. The plate circuit and finite rotations used: eastern Antarctica–Australia (Royer and Sandwell, 1989); Australia–Lord Howe Rise (Stock and Molnar, 1982); Lord Howe Rise–Campbell Plateau (Sutherland, 1995); Campbell Plateau–Marie Byrd Land (J. Stock, pers. commun., 1996). A free boundary was allowed in Antarctica, and the resulting plate closure (shown by open arrows) implies oblique rifting in the Ross Embayment, which is in good agreement with the known geology and crustal structure of the region (see text). The ridge positions are shown after Cande et al. (1989). Fracture zones and gravity lineaments were traced from satellite-derived gravity data (Sandwell and Smith, 1997). The map is in the Australian palaeomagnetic reference frame of Veevers and Li (1991), and drawn using a south polar azimuthal equidistant projection.

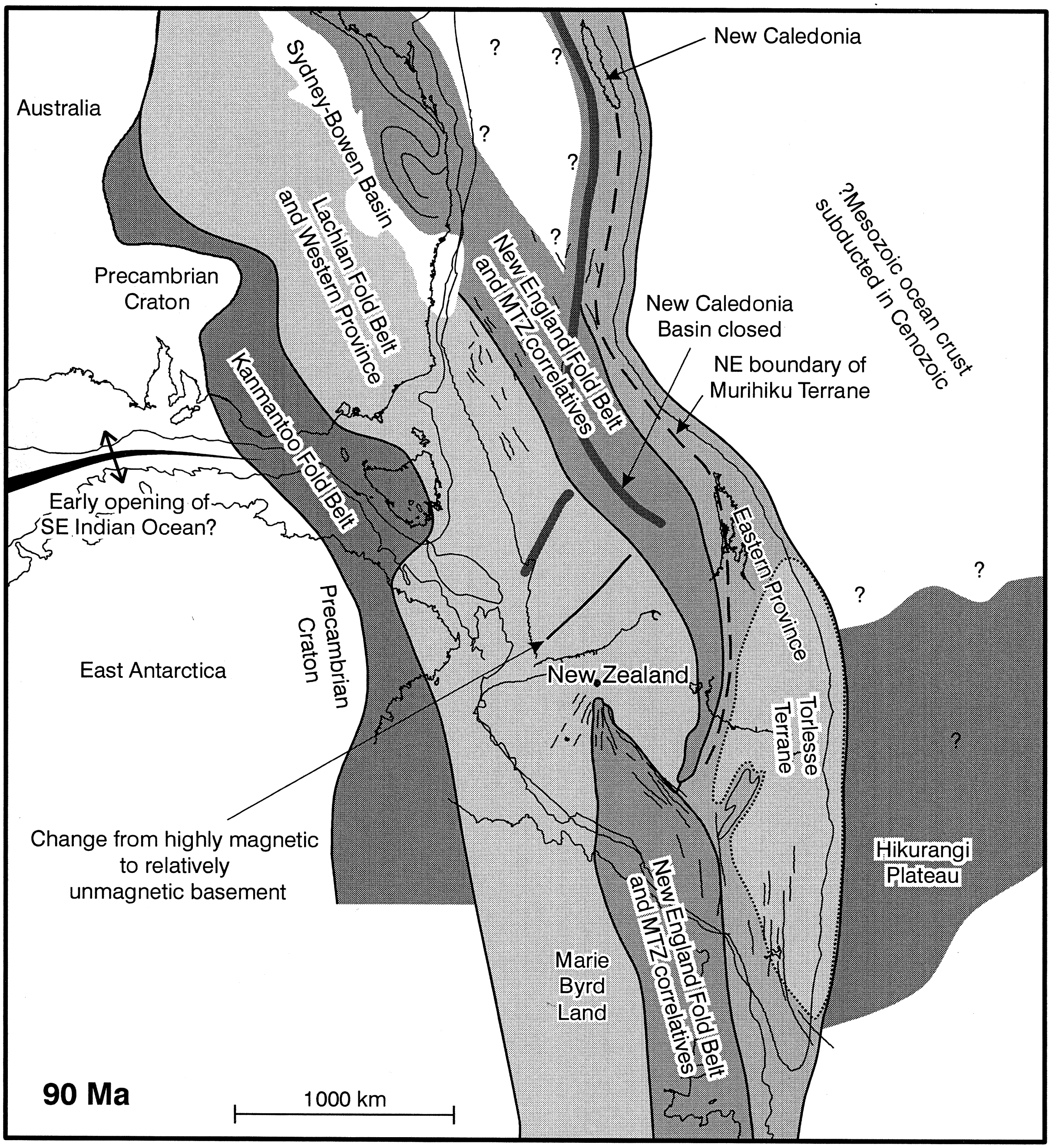


Fig. 8. Mid-Cretaceous (90 Ma) reconstruction showing major basement provinces prior to the onset of seafloor spreading in the Tasman and Pacific oceans. Present-day coastline is included for reference, and 2000 m bathymetry as a proxy for the continental margin. The continental margins for the Lord Howe Rise, Norfolk Ridge and Chatham Rise were estimated after allowance was made for distributed extensional deformation in the Bounty Trough, New Caledonia Basin and Bellona Trough. The Australia–Antarctica finite rotation was interpolated from Royer and Sandwell (1989). Faults interpreted from gravity anomaly maps and major geological boundaries are shown as black lines.

about 400 km, is thought to have been active during the late Palaeozoic (e.g. Korsch et al., 1990; Veevers et al., 1994). The New England Orocline, which is one manifestation of this displacement, is the feature outlined in Fig. 8 (after Veevers et al., 1994).

(3) The generalisation and geometry of basement rock provinces shown in Fig. 8. is misleading or incorrect. Because there are so few rock samples from offshore, we must treat the proposed geometry of basement provinces as highly speculative. The gravity and magnetic anomalies clearly suggest a major geological feature in the region of the CMAS, but it has not yet been demonstrated that the associated rocks are correlative with the MTZ. It is quite possible that they may be associated with igneous activity unrelated to arc-volcanism along the Gondwanaland margin. The rapid narrowing of the SMAS and CMAS on the Campbell Plateau, and the anomalous nature of the Torlesse Terrane in relation to the narrowness of the Eastern Province farther along strike, may also be related to an anomalous Mesozoic tectonic setting that we do not yet understand.

8. Geological relationships between New Zealand, Antarctica, and Australia

There are close similarities in geological history between the Western Province and Median Tectonic Zone found in New Zealand, and rocks found in western Marie Byrd Land (Bradshaw et al., 1997). Distinct pulses of late Palaeozoic–Early Cretaceous intrusive activity are recognised in both regions and there is a close correlation between the timing of magmatic pulses in the two areas (Kimbrough et al., 1994; Bradshaw et al., 1997). Combined with Cretaceous reconstruction (Fig. 8), the similarities add strength to the hypothesis that MTZ-correlative rocks are the source of the CMAS.

The boundaries of the MTZ can be delineated northwestward from New Zealand using borehole data from the Taranaki Basin and magnetic anomalies (Mortimer et al., 1997). Permian–Early Cretaceous intrusive rocks dredged from the West Norfolk and Wanganella ridges also have chemistry and ages consistent with being part the Median Tectonic Zone and allow the known distribution of MTZ rocks to be extended along the northern margin of the New Caledonia Basin (Mortimer et al., 1998). Correlatives of the Murihiku Terrane and Brook Street Terrane of the Eastern Province are found in New Caledonia and it is reasonable to assume that these terranes are continuous along the Norfolk Ridge (Fig. 7).

The closest correlatives of MTZ rocks found in Australia are in the New England Fold Belt, which experienced a pulse of Late Carboniferous–Permian calc-alkaline volcanism and deformation, including dextral strike-slip faulting (Coney et al., 1990; Veevers et al., 1994). Calc-alkaline volcanism migrated east during Triassic time, and by Jurassic time the volcanic arc was located northeast of the present Australian coast (Williams and Korsch, 1991). The Sydney–Bowen Basin overlies the boundary between the New England Fold Belt and Lachlan Fold Belt and shows that they were amalgamated by Permian time (Veevers et al., 1994). Dredge samples from the Dampier Ridge (Fig. 7) are composed of sandstone and Permian volcanic arc-related intrusive rocks (McDougall et al., 1994), supporting the hypothesis that some magnetic anomalies on the Lord Howe Rise may be related to sources correlative with the New England Fold Belt, or an older part of the MTZ.

Close correlatives of Western Province rocks are widely distributed and are described from the Lachlan Fold Belt of Australia, the Mathinna Terrane in Tasmania, the Robertson Bay Terrane in East Antarctica, and the Swanson Formation in Marie Byrd Land (Coney et al., 1990; Cooper and Tulloch, 1992; Bradshaw et al., 1997) (Fig. 7). However, the Western Province of New Zealand is characterised by mainly S-type granites, in contrast to the common occurrence of I-type granites in the east Lachlan Fold Belt (Chappell et al., 1988; Tulloch, 1989; Cooper and Tulloch, 1992). If the chemistry of granites in the Lachlan Fold Belt is related to the type of lower crust present (Chappell et al., 1988), then this suggests a major difference between Western Province crust and that found in the east Lachlan Fold Belt.

The Lord Howe Rise and western Challenger Plateau are characterised by large amplitude magnetic anomalies, similar to the east Lachlan Fold Belt, but the eastern Challenger Plateau and western New Zealand are magnetically relatively quiet (Fig. 3). The sudden change in magnetic character on the central Challenger Plateau suggests that a significant crustal boundary trending north-northeast exists in the region. Undeformed Late Cretaceous sediments overlie the feature (Wood, 1991), thus constraining the minimum age of activity on the boundary.

The lack of samples from the region west of this boundary leaves a number of possible sources for the high amplitude magnetic anomalies observed.

(1) I-type granitoid plutons of a similar age to those found in the east Lachlan Fold Belt. Following the suggestion of Chappell et al. (1988), this may imply that the Challenger Plateau discontinuity predates granite emplacement (370–310 Ma; Cooper and Tulloch, 1992), and could be related to a difference in lower crustal characteristics.

(2) Palaeozoic metamorphic complexes, which are known to exist and are highly magnetic in parts of the Lachlan Fold Belt (e.g. Scheibner and Basden, 1996). If this is the case, then the boundary must post-date formation of (early Palaeozoic?) metamorphic complexes.

(3) Correlative rocks to the New England Fold Belt or MTZ.

(4) Cretaceous igneous rocks associated with the early opening history of the Tasman Sea.

(5) There are no correlative rocks in either Australia or New Zealand.

The geology of the western Challenger Plateau and Lord Howe Rise remains unknown, but magnetic data indicate that correlations with eastern Australia may be more likely than with western New Zealand.

9. Permian–Cretaceous accretion and strike-slip along the Gondwanaland margin

A striking observation that can be made from the 90 Ma reconstruction (Fig. 8) is the relative width of the New England Fold Belt and its continuation offshore, compared to the narrowness of the MTZ in New Zealand. The equivalent of the MTZ in Antarctica is also much wider (e.g. Bradshaw et al., 1997). This is probably related to different rates of accretion along the Gondwanaland convergent margin, and varying amounts of removal or addition of material by lateral movement along the margin.

Adams and Kelley (1998) suggest a New England Fold Belt source in northeast Australia for Torlesse Terrane sediments (Fig. 5) on the basis of isotopic evidence and detrital mineral ages. He proposes 2000 km of Jurassic–Cretaceous dextral strike-slip motion along the margin to produce the observed provenance and palaeontological characteristics. This requires an average Jurassic–Cretaceous strike-slip rate of about 2 cm/yr, or a slip rate of 4 cm/yr if all the strike-slip motion occurred during the period 130–80 Ma.

There is evidence in the New England Fold Belt of northeast Australia for at least 400 km of dextral offset in Late Carboniferous–Permian time (e.g. Williams and Korsch, 1991; Veevers et al., 1994), and evidence for about 400 km of dextral offset across the Campbell Plateau (above). There is also evidence for an early Mesozoic dextral shearing event in West Antarctica that has extensively deformed rocks found in the Ellsworth Mountains (Curtis, 1997). If strike-slip motion was parallel to the major basement terranes then much more could be hidden because of a lack of obvious piercing points.

We have a very incomplete knowledge of offshore basement rock, and the region was an active plate margin for most of the >200 Ma between Late Carboniferous and Early Cretaceous time. There is evidence for both convergent margin volcanism and strike-slip motion during this time, and there are significant differences in the width and histories of geological provinces along the margin. These must be explained by the accretion and deformation history, but at present there are insufficient samples from the region to constrain it adequately.

10. Summary

(1) The Stokes Magnetic Anomaly System can be traced south across the Great South Basin and north along the northern margin of the New Caledonia Basin (Davey and Christoffel, 1978; Mortimer et al., 1998; Cook et al., 1999).

(2) There is a major tectonic boundary on the central Campbell Plateau. Gravity and magnetic anomalies suggest a NNE-trending fault zone bounding the northern edge of the Campbell Magnetic Anomaly System. The first order geometry of magnetic anomalies suggests a dextral offset of basement rocks by $\sim$400 km.

(3) The western Challenger Plateau and Lord Howe Rise (south of 30ºS) are characterised by high amplitude magnetic and gravity anomalies with a NW-trending fabric.

(4) A NNE-trending boundary on the central Challenger Plateau marks a change from high amplitude magnetic anomalies to weakly magnetic basement, and probably represents a fundamental change in crustal character.

(5) Negative magnetic anomalies adjacent to the Campbell Plateau and Lord Howe Rise, and in the New Caledonia Basin suggest that seafloor formation started during chron 33r (79–83 Ma).

(6) A linear positive magnetic anomaly in the outer Bounty Trough may be anomaly 33, which was isolated by a ridge-jump and is consistent with separation of Bollons Seamount by ocean crust. Alternatively, it may be anomaly 34 and represent the earliest ocean crust formed between New Zealand and Marie Byrd Land.

(7) At the southern edge of the South Fiji Basin, there is a tectonic boundary, named here the van der Linden Fault, that can be traced for ~500 km and lies ~100 km north of the Vening Meinesz Fracture Zone (Fig. 6).

(8) Magnetic lineations suggest that at least one ridge–ridge–ridge triple junction was active during opening of the South Fiji Basin, and imply that crust is younger in the east (Fig. 6).

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