# Summary of palaeomagnetic results from West Antarctica: implications for the tectonic evolution of the Pacific margin of Gondwana during the Mesozoic

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**Abstract:** Marie Byrd Land (MBL) is the western keystone of West Antarctica. Recent palaeomagnetic results from Lower Cretaceous (*c.* 117 Ma) plutonic and volcanic rocks from MBL in conjunction with a previous palaeomagnetic result from New Zealand suggest that eastern MBL and the Eastern Province of New Zealand originated in a position adjacent to Weddellia (Antarctic Peninsula, Thurston Island, and Ellsworth–Whitmore Mountains blocks) as part of a continuous Pacific convergent margin. This is far from their previously assumed position adjacent to the Western Province of New Zealand and North Victoria Land. The 117 Ma palaeomagnetic pole for eastern MBL constrains the last movements of the Weddellia blocks related to spreading in the Weddell Sea to postdate the initial opening phase of the Weddell Sea. A *c.* 100 Ma pole for the amalgamated mid-Cretaceous MBL is consistent with like age poles from the Thurston Island and Antarctic Peninsula blocks but all are significantly offset from a newly constructed apparent polar wander path for East Antarctica. From this it is concluded that there has been palaeomagnetically resolvable post–100 Ma motion between East Antarctica and the Pacific-bordering blocks of West Antarctica as a result of extension in the Ross Sea, Ross embayment, and Byrd Subglacial Basin.

West Antarctica is composed of four major crustal blocks: Marie Byrd Land (MBL), Thurston Island (TI), Antarctic Peninsula (AP), and Ellsworth–Whitmore Mountains (EWM) (Dalziel & Elliott 1982) (Fig. 1). New Zealand was also part of West Antarctica before it separated from MBL at around 85 Ma (Weissel *et al.* 1977; Grindley & Davey 1982; Mayes *et al.* 1990). It has long been clear from Gondwana reconstructions (e.g., Smith & Hallam 1970; Dietz & Holden 1970; Norton & Sclater 1979) that West Antarctica (or at least AP) must have experienced significant displacements with respect to East Antarctica following the separation of East from West Gondwana. This is because AP cannot be maintained in its current position with respect to East Antarctica in the reconstructions without serious overlap with South America and the Falkland Plateau. The similarity of the stratigraphy of the Ellsworth Mountains to the Transantarctic Mountains and the Cape Mountains of South Africa, and the isolated position and truncated structures of the Ellsworth Mountains provided additional evidence for such displacements (Schopf 1969).

Much effort has been concentrated on understanding the evolution of West Antarctica following Gondwana break-up. Palaeomagnetic results from AP, TI, and EWM suggested that these three blocks constituted a tectonic entity termed 'Weddellia' (Grunow *et al.* 1987*b*) that was displaced more or less as a unit as a result of the opening of the Weddell Sea. Recent studies (Grunow *et al.* 1991; Grunow 1993) suggest more complicated (though not large), independent motions of these blocks. Nevertheless, Weddellia still seems an appropriate concept for the period of Gondwana break-up extending through the Early Cretaceous because the West Antarctic crustal motions during this period appear to be related to spreading in the Rocas Verdes-Weddell Sea basin (Barker *et al.* 1991; Dalziel 1992).

Previous studies have left several outstanding problems. Significant motions of Weddellia implied by palaeomagnetic studies postdate the

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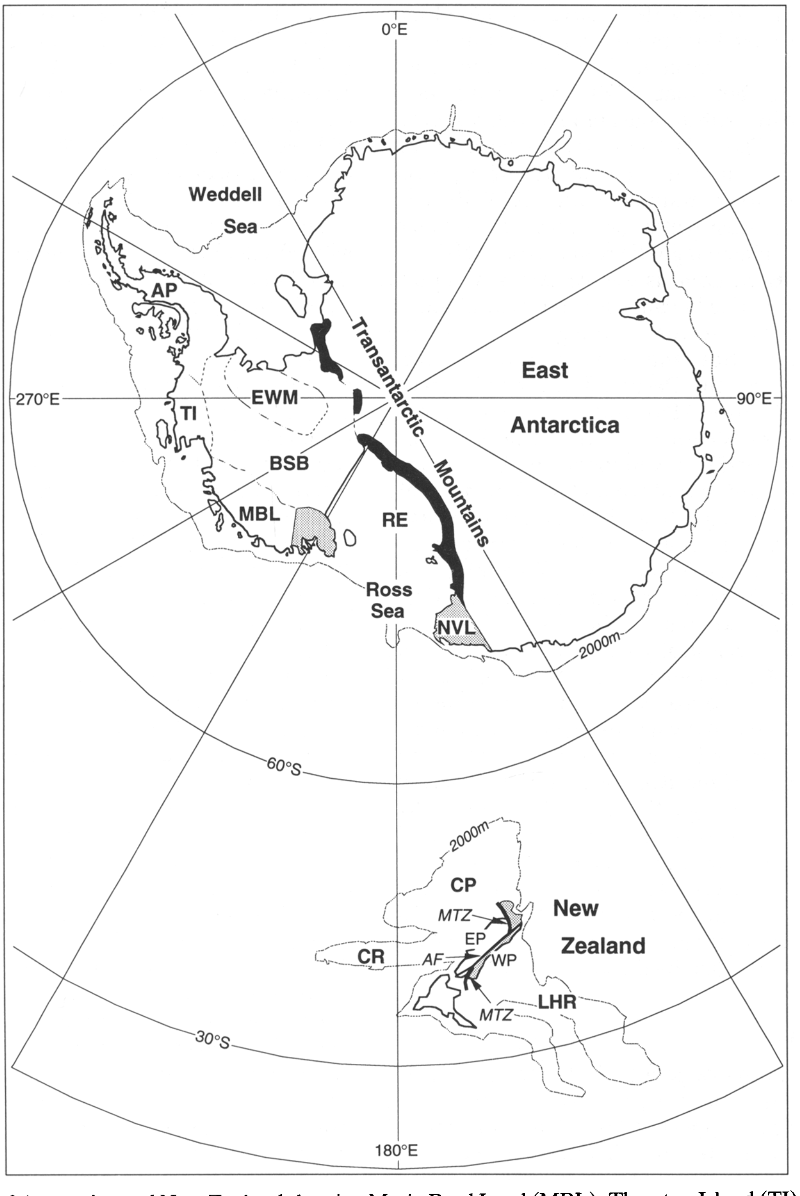


**Fig. 1.** Map of Antarctica and New Zealand showing Marie Byrd Land (MBL), Thurston Island (TI), Antarctic Peninsula (AP), and Ellsworth–Whitmore Mountains (EWM) crustal blocks of West Antarctica; Byrd Subglacial Basin (BSB) *sensu lato*, the entire area between MBL, TI, EWM, and the Transantarctic Mountains; Ross embayment (RE); North Victoria Land (NVL); the Eastern (EP) and Western (WP) provinces of New Zealand; Campbell Plateau (CP), Chatham Rise (CR), Lord Howe Rise (LHR), Median Tectonic Zone (MTZ; heavy black line), and the Alpine Fault (AF; medium black line). Stippled areas show areas of related lower Palaeozoic turbidites and Devonian granodiorites.

original opening of the Weddell Sea as interpreted from geophysical data in the Weddell Sea (LaBrecque & Barker 1981; LaBrecque 1986). Also, relatively little palaeomagnetic work has been focused on MBL and New Zealand and hence no clear relationship has been established between these blocks and AP, TI, and EWM prior to or in conjunction with these motions of Weddellia. Finally, previous palaeomagnetic comparisons (Grindley & Oliver 1983; Grunow *et al.* 1991; Grunow 1993) have concluded that there has been little or no relative motion of AP and TI with respect to East Antarctica since about 110 but that MBL may have been displaced by a substantial amount with respect to all three. These last conclusions were made, however, without the availability of a precise apparent polar wander path (APWP) constructed for East Antarctica and confirmation of the early palaeomagnetic results from MBL.

Marie Byrd Land is the western keystone of West Antarctica because it is the crucial link in the Ross Sea sector, relating motion among West Antarctica and East Antarctica, New Zealand, and the Pacific. Recent palaeomagnetic results from MBL and a newly constructed reference APWP for East Antarctica (DiVenere *et al.* 1994, 1995), in conjunction with a previous palaeomagnetic result from New Zealand, yield new insights regarding West Antarctic crustal motions. These results link the eastern portions of MBL and New Zealand with Weddellia since the Early Jurassic, confirm that major Early Cretaceous motions of the Weddellia blocks postdate geophysically based estimates for the time of original opening of the Weddell Sea, and reveal that there has been significant motion of MBL, TI, and AP with respect to East Antarctica since the mid-Cretaceous associated with the opening of the Ross Sea. In this paper, we review palaeomagnetic results from West Antarctica, the construction of the East Antarctic APWP, and our recent palaeomagnetic results from MBL. Reconstructions from our recent papers (DiVenere *et al.* 1994, 1995) highlight the interpretation of the tectonic evolution of West Antarctica implied by these new data.

## Problems

Interpretations of geophysical data in the Weddell Sea and palaeomagnetic data from AP, TI, and EWM support West Antarctic crustal displacements, but the detailed history of the opening of the Weddell Sea and the associated West Antarctic crustal motions is far from clear. Estimated ages for the oldest oceanic magnetic anomalies of around 160 to 156 Ma (M29 to M25; LaBrecque & Barker 1981; LaBrecque 1986) and northeast-trending linear gravity anomalies in the southern Weddell Sea (Bell *et al.* 1990) suggest that rotations of the Weddellia blocks should predate the Early Cretaceous age implied by palaeomagnetic data (e.g., Grunow *et al.* 1991). However, the interpretation of the incomplete marine geophysical data in the Weddell Sea is as yet uncertain and Martin & Hartnady (1986) indirectly inferred the initiation of spreading in the Weddell Sea as about 130 Ma (M10) from the spreading history in the SW Indian Ocean. Nevertheless, ophiolitic remnants of the Rocas Verdes basin on South Georgia Island have been dated at close to 150 Ma (Mukasa *et al.* 1988), showing that at least some oceanic crust was in existence in the region by the end of the Jurassic.

The relationship of MBL and New Zealand with Weddellia is poorly understood. Marie Byrd Land and New Zealand are normally left in a position adjacent to the Transantarctic Mountains and North Victoria Land in reconstructions. This is because lower Palaeozoic turbidites and Devonian granodiorites in western MBL, the Western Province of New Zealand, and North Victoria Land imply that MBL and New Zealand had been adjacent to North Victoria Land since these terranes were apparently sutured to East Antarctica in the late Palaeozoic (Borg & DePaolo 1991; Weaver *et al.* 1991). Until recently there have been no reliable palaeomagnetic results from MBL older than mid-Cretaceous to test the original position of MBL. This has created the impression that MBL and the New Zealand microcontinent have evolved separately from Weddellia, even though the Eastern Province of New Zealand appears to have been part of a continuous Gondwana convergent margin (arc, forearc, and accretionary prism) extending from Chile through the Antarctic Peninsula to New Zealand during the Permian to Early Cretaceous (Dalziel & Grunow 1985; Dalziel & Forsythe 1985; Bradshaw 1989; Tranter 1991). Dalziel (1992) and Dalziel & Grunow (1992), for example, separated Weddellia from MBL and New Zealand by a major transform fault.

The opening of the Weddell Sea was related to the earlier stages of Gondwana break-up with the separation (during the Mid-Jurassic) of Africa and South America (West Gondwana) from the rest of Gondwana (Barker *et al.* 1991; Royer & Coffin 1992). Break-up continued around the margin of the present East Antarctic craton with the separation of India in the Early Cretaceous (Royer & Coffin 1992) and eventually in the Ross Sea region as Australia separated and New Zealand rifted and separated in the mid- to Late Cretaceous (Weissel *et al.* 1977; Cande & Mutter 1982; Royer & Sandwell 1989). Cretaceous and Cenozoic extension in the Ross Sea and between East and West Antarctica has often been discussed but there has been much disagreement regarding the timing and amount of the motions. The suggestion, based on an interpretation of palaeomagnetic data (Grunow *et al.* 1991; Grunow 1993), that Weddellia and

East Antarctica have been stationary with respect to one another since about 110 Ma seems to contradict growing evidence that the Ross Sea, Ross embayment, and low-lying areas beneath the West Antarctic ice streams have been tectonically active during and since the Late Cretaceous and are still active (Behrendt & Cooper 1991; Cooper *et al.* 1991; Storey 1991; Fitzgerald 1992; Stump & Fitzgerald 1992; Blankenship *et al.* 1993; Behrendt *et al.* 1994). The palaeomagnetic poles from TI and AP have not been compared with a definitive APWP for East Antarctica. For example, the palaeomagnetic pole from the Lupata lavas of Africa (Gough & Opdyke 1963) is often included in pole lists but with the caveat that secular variation was probably not averaged and the pole therefore likely to be biased, as noted by the authors (see also treatment in Hargraves 1989). This pole, transferred to East Antarctica, was used by Grunow (1993) as the sole *c.* 110 Ma East Antarctic reference pole for comparison with AP and TI poles of similar age and formed one of the primary bases for concluding that there had been little or no post–110 Ma motion between AP/TI and East Antarctica. Advances in the quality of the global palaeomagnetic data base and plate kinematic models allow improvement of the East Antarctic APWP and reevaluation of post–110 Ma motion.

## East Antarctic APWP

Because only one palaeomagnetic reference pole (Mid-Jurassic) is available from East Antarctica for the Mesozoic and Cenozoic, it is necessary to transfer poles from other continents to evaluate tectonic motions of the West Antarctic crustal blocks with respect to East Antarctica for the remainder of this time. A new synthetic APWP was recently constructed for East Antarctica by transferring the most up to date and critically reviewed Cretaceous palaeomagnetic poles from Africa, North America, Australia, and India to East Antarctica using recent plate kinematic models (DiVenere *et al.* 1994). The individual Cretaceous poles in East Antarctic coordinates lie in a tight north-to-south swath through the western Ross Sea. The mean reference poles fall in the western Ross Sea adjacent to North Victoria Land in the Early Cretaceous, to the south of Ross Island at about 100 Ma, and pass by the geographic south pole on the Indian Ocean side by about 90 Ma. The Cretaceous APWP for East Antarctica is similar to the Besse & Courtillot (1991) APWP constructed from palaeomagnetic poles from the Atlantic-bordering continents (see DiVenere *et al.* 1994).

The Mid- Jurassic pole for East Antarctica is well defined by numerous palaeomagnetic studies of the Ferrar dolerites and Kirkpatrick basalts (Kellogg 1988). Poles for earlier times were selected from the palaeomagnetic database for Gondwana of Van der Voo (1993). There are relatively few high-quality poles in the global data set for the time between about 175 and 130 Ma, and there are contrasting interpretations of the poles that are available (Van Fossen & Kent 1990, 1992, 1993; Butler *et al.* 1992). This controversial period (Van der Voo, 1992; Courtillot *et al.* 1994) is omitted from the East Antarctic APWP. The relevant reference poles for East Antarctic are listed in Table 1.

## West Antarctic palaeomagnetic results

### *Ellsworth–Whitmore Mountains*

The only palaeomagnetic poles from EWM are of Cambrian and 175 Ma (Mid-Jurassic) age (Watts & Bramall 1981; Grunow *et al.* 1987*a*; Table 1). Comparing these poles with reference poles from East Antarctica, Grunow *et al.* (1987*a*) concluded that EWM rotated about 90° counterclockwise with respect to East Antarctica between the Cambrian and Mid-Jurassic, i.e., during a period of tectonic activity preceding the main opening of the Weddell Sea, and subsequently experienced a smaller but significant net clockwise rotation and poleward translation. There are no younger rocks exposed in EWM.

### *Thurston Island*

Grunow *et al.* (1987*b*, 1991) reported palaeomagnetic results for TI from rocks ranging in age from about 230 to 90 Ma. Based on a comparison of the two mid-Cretaceous (110 and 90 Ma) poles with selected poles from other Gondwana continents as proxies for East Antarctic reference poles, it was suggested that TI was at or near its present-day position with respect to East Antarctica by the mid-Cretaceous. However, the pre-110 Ma results were all found to be displaced from the reference poles in a sequence suggesting that TI had experienced a large clockwise followed by counterclockwise rotation with respect to East Antarctica during the Jurassic and Early Cretaceous.

### *Antarctic Peninsula*

A number of palaeomagnetic results exist from AP ranging in age from Mid-Jurassic to Ceno-

**Table 1.** *Palaeomagnetic poles*

| Block | Age | *N* | $A_{95}$ | Lon°E | Lat°N | Source |
|---|---|---|---|---|---|---|
| MBL | 117 | 6 | 8.7 | 185.6 | −56.8 | DiVenere *et al.* (1995) |
| MBL | 100 | 19 | 3.8 | 224.1 | −75.7 | DiVenere *et al.* (1994) |
| *TI* | *150* | 5 | 7 | 145 | −64 | Grunow *et al.* (1991) |
| TI | 125 | 5 | 7.9 | 232 | −49 | Grunow *et al.* (1987*a*) |
| TI | 110 | 7 | 7.6 | 210 | −73 | Grunow *et al.* (1991) |
| AP | 175 | 4[a] | 9.5 | 238 | −48 | Longshaw & Griffiths (1983) |
| *AP* | *160* | 10 | 7.1 | 124 | −64 | Grunow (1993) |
| *AP* | *140* | 4 | 9.5 | 50 | −60 | Grunow (1993) |
| *AP* | *130* | 6 | 5.9 | 182 | −74 | Grunow (1993) |
| AP | 106M | 29 | 6.2 | 203.8 | −74.3 | calculated in DiVenere *et al.* (1994) from site means of Kellogg (1980), Kellog & Rowley (1989), and Grunow (1993) |
| *EMW* | *Cambrian* | 5 | 11.2[b] | 296 | 4 | Watts & Bramall (1981) |
| EWM | 175 | 8 | 5.3 | 235.2 | −41.2 | Grunow *et al.* (1987*b*) |
| NZ | 207 | 24 | 10.6[b] | 162 | −24 | Grindley *et al.* (1981) with updated age from Graham *et al.* (1993) |
| EAnt | Tru/Jl (206) | 4[c] | 7.0 | 242.4 | −58.0 | Van der Voo (1993)[d,e] |
| EAnt | Jl (186) | 3[c] | 11.0 | 225.3 | −54.3 | Van der Voo (1993)[f,e] |
| EAnt | 175 | 17[g] | 4.4 | 220.4 | −52.7 | Kellogg (1988) |
| EAnt | 125 | 6[g] | 3.5 | 173.9 | −71.9 | DiVenere *et al.* (1994) |
| EAnt | 117 | 4[g] | 2.9 | 179.2 | −74.9 | DiVenere *et al.* (1994) |
| EAnt | 102 | 6[g] | 4.2 | 171.8 | −80.3 | DiVenere *et al.* (1994) |

MBL, Marie Byrd Land; TI, Thurston Island; AP, Antarctic Peninsula; FWM, Ellsworth–Whitmore Mountains; EAnt, East Antarctica; NZ, New Zealand; Lon and Lat are mean palaeomagnetic pole east longitude and north latitude (negative is south latitude); N is number of sites used to calculate mean; $A_{95}$ is the radius of the 95% cone of confidence about the mean pole; poles listed in italics were not used in reconstructions.

[a] $N = 4$ group means from 24 site means.

[b] $A_{95}$ conversatively estimated as the major axis of the confidence ellipse.

[c] $N =$ number of continent mean poles.

[d] Tru/Jl mean pole, 230 E/70 N in northwest African coordinates.

[e] Gondwana mean poles rotated to East Antarctic reference frame using Euler pole consistent with Van der Voo (1993) plate model (−12.36/−33.81/−53.29).

[f] Jl mean pole, 260 E/70 N in northwest African coordinates.

[g] $N =$ number of studies.

zoic. The Mid-Jurassic (*c.* 175 Ma) pole (Longshaw & Griffiths 1983; Table 1) is not significantly different from the 175 Ma pole for EWM, while both poles are offset from the 175 Ma reference pole for East Antarctica. This suggests that AP and EWM have experienced a similar post–175 Ma motion history (Grunow *et al.* 1987*a*, *b*). Several palaeomagnetic studies of mid-Cretaceous (*c.* 110–90 Ma) rocks (Kellogg & Reynolds 1978; Valencio *et al.* 1979; Watts *et al.* 1984; Kellogg & Rowley 1989; Grunow 1993) give somewhat conflicting results. Combining the most recent data from the southern AP (Kellogg & Rowley 1989) and northern AP (Grunow 1993) yields a *c.* 106 Ma mean pole (DiVenere *et al.* 1994; Table 1) that is consistent with the 110 Ma pole from TI (Grunow *et al.* 1991). For the period between 175 and about 110 Ma, Grunow (1993) reported results from Upper Jurassic/Lower Cretaceous rocks that are discordant, and results from Lower Cretaceous rocks that are concordant with the East Antarctic APWP. Accepting the AP poles at face value, it was concluded that AP had experienced a large clockwise rotation between about 175 and 160 Ma, a large counterclockwise rotation between about 160 and 130 Ma, and no significant motion with respect to East Antarctica since then (Grunow 1993).

## *Marie Byrd Land*

During the tripartite United States–United Kingdom–New Zealand 1990–1991 South Pacific Rim International Tectonics Expedition (SPRITE) to Marie Byrd Land, oriented samples were collected for palaeomagnetic analysis. Two major portions of the collection are from Lower Cretaceous (*c.* 117 Ma) volcanic rocks and granodiorite, and mid-Cretaceous (*c.* 100 Ma) alkali syenites, granites, and gabbro (Weaver *et al.* 1994). Unpublished Rb–Sr data have given *c.* 110–120 Ma ages for the volcanic units and 118 ± 2 Ma for the granodiorite suite (R. J. Pankhurst pers. comm. 1993). Unpublished zircon U–Pb data also give an age of about 117 Ma for the granodiorite at Mount Steinfeld (S. B. Mukasa pers. comm. 1993). The mid-Cretaceous units have all yielded Rb–Sr (R. J. Pankhurst pers. comm. 1993) and zircon U–Pb and $^{40}Ar/^{39}Ar$ (Palais *et al.* 1993; D. G. Palais & S. B. Mukasa pers. comm. 1993) dates of around 100 Ma. The 100 Ma rocks intrude the 117 Ma rocks across the Ruppert/Hobbs Coast. The Early and mid-Cretaceous poles from this study (DiVenere *et al.* 1994, 1995) supersede previous results of Scharnberger & Scharon (1972) and Grindley & Oliver (1983).

Although most of the Lower Cretaceous volcanic rocks collected have been thermally metamorphosed and remagnetized, palaeomagnetic results from six sites at Mount Vance in bedded, albeit hydrothermally altered, volcanic rocks are similar after tilt correction to results from a homogeneous *c.* 117 Ma granodiorite at Mount Steinfeld. The volcanic rocks at Mount Vance have evidently not been remagnetized at a much later time and the results are supported by a positive contact test (confirming a pre-100 Ma magnetization) and an indirect regional tilt (i.e., palaeohorizontal) test. The mean pole from the unremagnetized volcanic rocks (Table 1) is offset from the East Antarctic APWP, implying a clockwise rotation and southward translation between 117 and 100 Ma (DiVenere *et al.* 1995). This result is similar to the *c.* 125 Ma pole from TI (Grunow *et al.* 1991; Table 1) in that both call for Early Cretaceous clockwise rotations, suggesting that MBL and TI shared a common tectonic history.

Palaeomagnetic results from mid-Cretaceous alkali syenites and gabbro from 19 sites at six locations on the Ruppert/Hobbs Coast yield a *c.* 100 Ma mean pole that is supported by a regional tilt test and agreement across a wide area (approximately 300 km) of MBL (DiVenere *et al.* 1994; Table 1). This pole is consistent with the *c.* 110 and 106 Ma poles from TI and AP respectively (Table 1), from which it may be concluded that MBL has not experienced significant post-100 Ma motion with respect to AP and TI. The West Antarctic poles, however, are all significantly (95% confidence level) offset from the new East Antarctic reference APWP (DiVenere *et al.* 1994) indicating that the Pacific-bordering blocks of West Antarctica have in fact been displaced with respect to East Antarctica since the mid-Cretaceous (DiVenere *et al.* 1994).

Samples were also collected during the 1992–1993 SPRITE field season from a granite in the Kohler Range of easternmost MBL (DiVenere 1993), previously dated by K–Ar at about 100 Ma (Wade & Wilbanks 1972). These samples yielded stable palaeomagnetic results with a mean pole that is in excellent agreement with the *c.* 100 Ma mean pole from the Ruppert/Hobbs Coast. This extends the geographic baseline of mutually consistent mid-Cretaceous palaeomagnetic data to approximately 750 km.

## Tectonic synthesis

Adequate data now exist to propose the likely relationship of MBL and New Zealand with the Weddellia blocks. The new 117 Ma pole, which is based on results solely from east of 141°W (DiVenere *et al.* 1995), implies that MBL was far from North Victoria Land in the Early Cretaceous. This is contrary to the expected Early Cretaceous position of MBL adjacent to North Victoria Land based on the association of lower Palaeozoic turbidites and Devonian granodiorite found in western MBL, the western South Island of New Zealand, and the Robertson and Bowers Terranes of North Victoria Land (Fig. 1). These are thought to have comprised a terrane that accreted to the East Antarctic craton in the late Palaeozoic (Borg & DePaolo 1991; Weaver *et al.* 1991). However, the critical rock units are only found to the west of about 141°W in MBL, and the relationship between MBL and North Victoria Land is therefore only likely for this part of MBL. We have therefore distinguished an 'East MBL' and 'West MBL' now joined approximately along 141°W longitude (DiVenere *et al.* 1995). Likewise in New Zealand, an assemblage of Palaeozoic rocks, correlative with those in West MBL and North Victoria Land, is only found in the Western Province, west of the Median Tectonic Zone (Bradshaw 1989; Kimbrough *et al.* 1993; Bradshaw 1993). In contrast, the Eastern Province of New Zealand is made up of Permian through Early Cretaceous arc, forearc, and accretionary complexes and mid-Cretaceous alkaline volcanic rocks (Bradshaw 1989; Weaver & Pankhurst 1991). These are complementary with the Permian through Early Cretaceous calc-alkaline igneous rocks and mid-Cretaceous alkaline igneous rocks in East MBL. The relationship of the Eastern and Western Provinces of New Zealand across the Median Tectonic Zone is uncertain (Bradshaw 1993). The Eastern Province of New Zealand is made of a number of

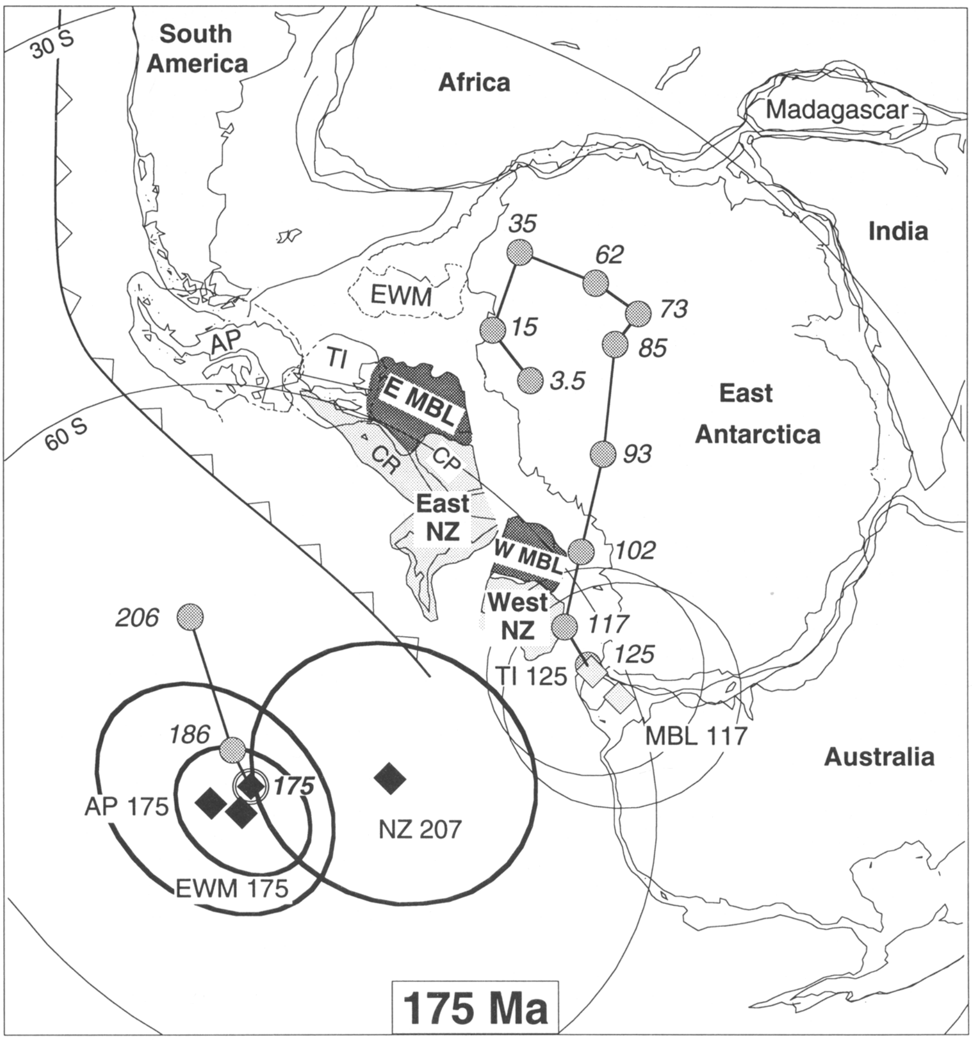


**Fig. 2.** Reconstruction of the West Antarctic and New Zealand crustal blocks within Gondwana for c. 175 Ma. Diamonds are palaeomagnetic poles from West Antarctic blocks and New Zealand with A95 circles of confidence shown in reconstructed positions. Connected grey circles are the East Antarctic APW path; Cretaceous to Cenozoic path is from DiVenere *et al.* (1994); 175 Ma pole is from Kellogg (1988); 186 and 206 Ma poles are Gondwana mean poles of Van der Voo (1993) transferred into the East Antarctic reference frame (DiVenere *et al.* 1995). Original poles are listed in Table 1. Crustal blocks: AP, Antarctic Peninsula; TI Thurston Island; EWM, Ellsworth–Whitmore Mountains; E MBL and W MBL, East and West Marie Byrd Land; NZ, East and West New Zealand; CR, Chatham Rise; CP, Campbell Plateau. East and West New Zealand are represented schematically since the position of the dividing line between them is uncertain.

terranes of uncertain relation (Bradshaw 1989) but we assume for the sake of simplicity in the reconstructions that Eastern Province was one integral crustal block. Given that the Eastern Province of New Zealand is known to have separated from MBL at about 85 Ma (Mayes *et al.* 1990), it is a reasonable assumption that East MBL and the Eastern Province of New Zealand may have shared a common history prior to that.

Previous reconstructions that had maintained all of MBL and New Zealand in a position adjacent to North Victoria Land based on the Palaeozoic geologic relations leave a gap between the forearc sequences of New Zealand and AP (Dalziel 1992; Dalziel & Grunow 1992). It is notable that if all of New Zealand is kept adjacent to North Victoria Land, then the earliest Jurassic palaeopole from the Murihiku

Terrane of the Eastern Province of New Zealand (Grindley *et al.* 1981) does not agree with the East Antarctic APWP, as noted by Grindley *et al.* (1981). We have instead proposed that East MBL and the Eastern Province of New Zealand were originally part of the Weddellia province, while West MBL and the Western Province of New Zealand were adjacent to North Victoria Land (DiVenere *et al.* 1995). This allows for a better interpretation of the Murihiku pole.

A new series of reconstructions for *c.* 175, 117, and 100 Ma that attempts to account for the palaeomagnetic data while maintaining reasonable geologic relationships has been presented by DiVenere *et al.* (1994, 1995). The major innovation in the Jurassic (175 Ma) and Early Cretaceous (117 Ma) reconstructions is the recognition of separate eastern and western provinces in both MBL and New Zealand. The 100 Ma reconstruction incorporates a tight fit in the Ross Sea region based on the now well-founded post 100 Ma extension in the Ross Sea.

The 175 Ma reconstruction (Fig. 2) maintains the continuity of the Permian through Early Cretaceous arc, forearc, and accretionary complex rocks extending from the Eastern Province of New Zealand through AP and into southern South America and places the magmatic arc terranes (East MBL and TI) behind these. It also maintains the diorites, quartz diorites, and granodiorites of easternmost MBL, with K–Ar (Lopatin *et al.* 1974) and Rb–Sr (Halpern 1972) ages ranging from 225 to 295 Ma, proximal to a gabbro–diorite suite on Thurston Island, with ages ranging from about 230 to 290 Ma ($^{40}$Ar/$^{39}$Ar, K–Ar, and Rb–Sr; Pankhurst *et al.* 1993).

Dalziel & Grunow (1992) proposed that the Ellsworth Mountains were displaced from a position between the Cape Fold Belt of South Africa and the Pensacola Mountains of East Antarctica in an early rifting episode between East and West Gondwana following Permo-Triassic folding and prior to the Mid-Jurassic. The Falkland Islands also appear to have been displaced and rotated from a similar position at about the same time (Taylor & Shaw 1989; Marshall 1994). The EWM block was rotated approximately 90° counterclockwise and displaced towards its present position with respect to East Antarctica. We place EWM in a position similar to that of previous reconstructions in the Jurassic and Early Cretaceous (e.g., Grunow *et al.* 1991; Dalziel & Grunow 1992), far from its present position with respect to East Antarctica. The palaeolatitude implied by the Mid-Jurassic pole for EWM combined with the reconstructed position implied by the Early Cretaceous pole for East MBL and the earliest Jurassic pole for the Eastern Province of New Zealand argue that EWM did not attain its current position with respect to East Antarctica until after about 117 Ma.

The Chatham Rise and Campbell Plateau of the Eastern Province of New Zealand are reconstructed to East MBL in their estimated mid-Cretaceous, pre-separation position. With this configuration, the earliest Jurassic (*c.* 207 Ma) pole from the Eastern Province of New Zealand (Grindley *et al.* 1981) remains offset from the East Antarctic APW path, but now the position of the Eastern Province of New Zealand is consistent with the palaeolatitude implied by the pole. The remaining offset implies either that the Eastern Province of New Zealand and East MBL rotated as a unit with respect to East Antarctica between about 207 and 117 Ma or that the Eastern Province of New Zealand (specifically, the Murihiku Terrane) rotated with respect to East MBL (and East Antarctica) between about 207 and 85 Ma.

It is interesting that this 175 Ma configuration (Fig. 2) is able to satisfy the Early Cretaceous poles for MBL and TI as well as the Mid-Jurassic poles for AP and EWM with respect to the East Antarctic APWP. However, the arrangement must have evolved somewhat during the separation of East and West Gondwana and the early opening of the Weddell Sea. In particular, AP must have been displaced following East–West Gondwana separation and approached near to its present position with respect to East Antarctica by the mid-Cretaceous. In arriving at the 117 Ma reconstruction (Fig. 3), we suggest that AP had moved with South America as Africa and South America separated from East Antarctica. The early opening of the Weddell Sea can be regarded as a passive result of East–West Gondwana separation and linked with back arc-extension in the Rocas Verdes basin (Barker *et al.* 1991). The compatibility of the pre-breakup and Early Cretaceous reconstructions (Figs 2 & 3) offers a less complicated alternative to the large linked rotations of AP and TI proposed by Grunow (1993) for the intervening period.

Whether or not AP and TI experienced the Late Jurassic/Early Cretaceous rotations suggested by Grunow (1993), the new 117 Ma pole from MBL places the constraint that the Weddellia blocks did not attain their mid-Cretaceous positions until after about 117 Ma, postdating the initial opening of the Weddell Sea. The post-117 (and pre-100 Ma) motions would have occurred during the Cretaceous Long Normal interval (*c.* 118–84 Ma), during which time no lineated magnetic anomalies were produced to

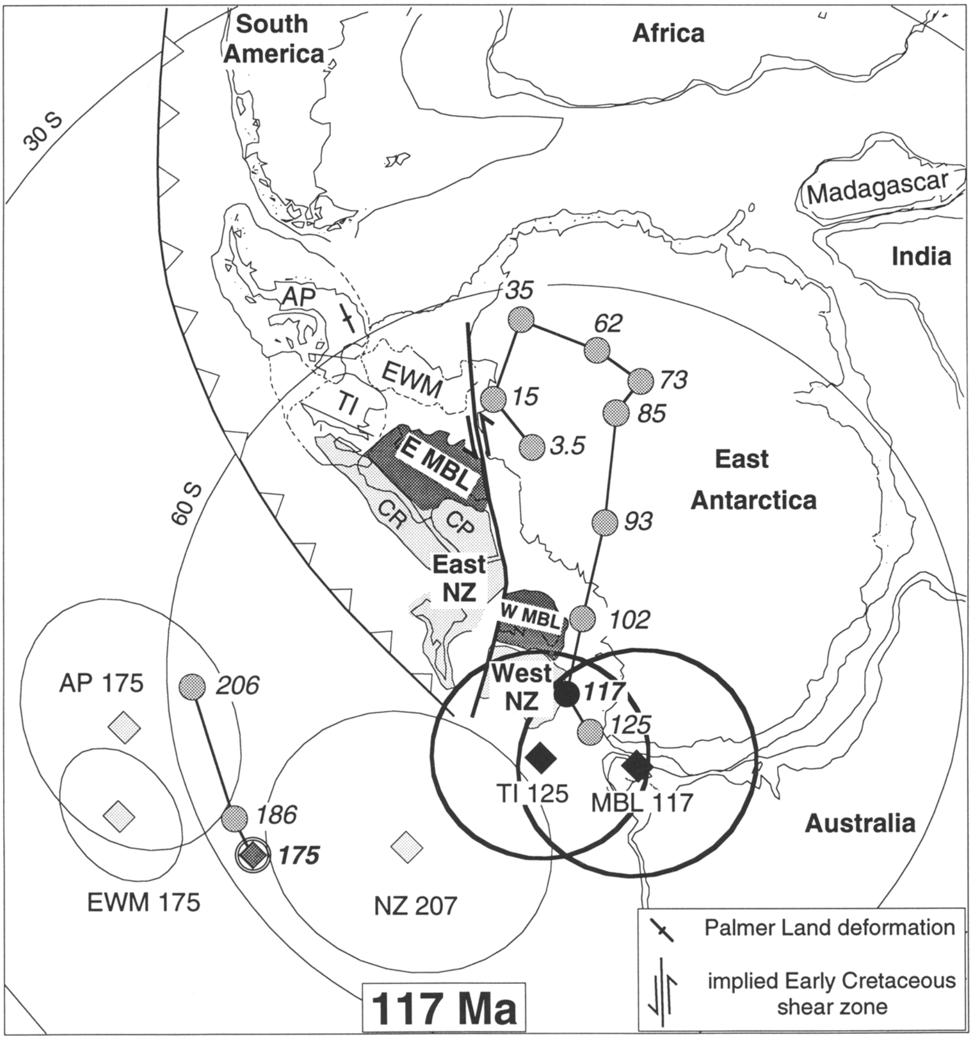


**Fig. 3.** Reconstruction of the West Antarctic and New Zealand crustal blocks within Gondwana for *c.* 117 Ma, with the Gondwana continents relative positions at magnetic anomaly M0 (DiVenere *et al.* 1995). Symbols as in Fig. 2.

serve as a record of motion in the Weddell Sea. However, Livermore & Woollett (1993) propose a change in spreading direction in the Weddell Sea as deduced from a bend in gravity lineaments (presumably fracture zones) within the Cretaceous Quiet Zone.

The *c.* 100 Ma mean palaeomagnetic pole from MBL, (produced from rocks from East MBL (DiVenere *et al.* 1994), implies that East MBL was at that time in a position nearer to the Transantarctic Mountains and North Victoria Land than it is at present. East and West MBL must therefore have been amalgamated by about 100 Ma. A formal statistical comparison of the *c.* 100 Ma pole for MBL with the newly constructed East Antarctic APWP (which includes reconstruction-based error estimates for the mean poles) shows that there has been significant (i.e., palaeomagnetically discernible) post-100 Ma extension in the Ross Sea (DiVenere *et al.* 1994). Mid-Cretaceous poles from TI and AP are also significantly offset from the East Antarctic APWP implying that these blocks have also experienced some motion relative to East Antarctica since the mid-Cretaceous. The *c.* 100 Ma reconstruction (Fig. 4) shows about 50% post-100 Ma extension in the Ross Sea, which is at the upper bound of

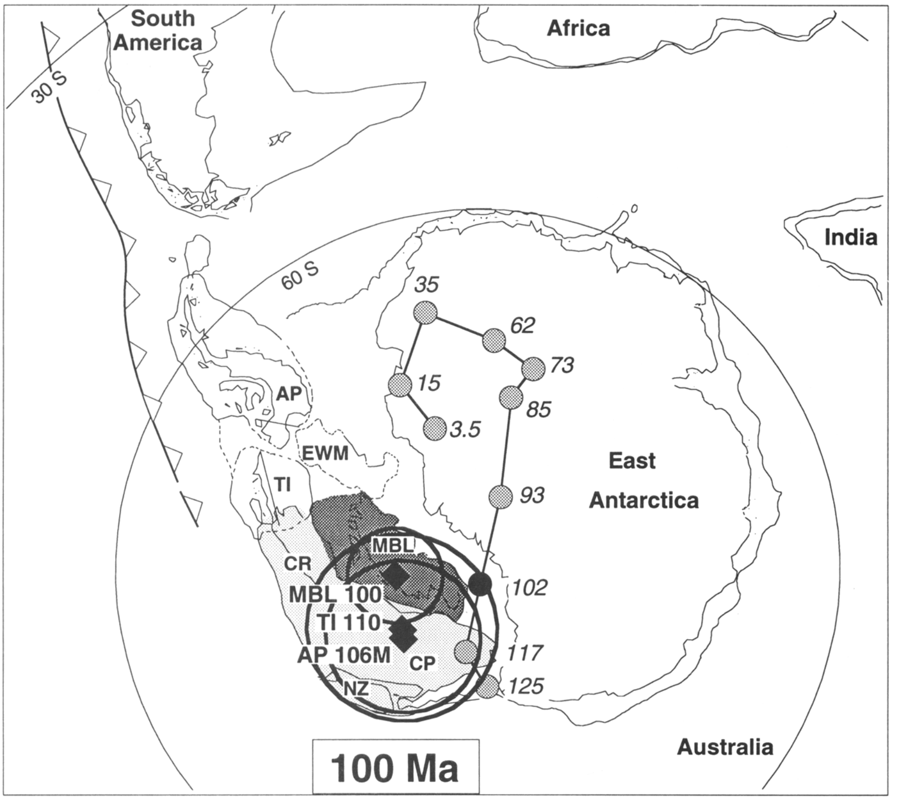


**Fig. 4.** Reconstruction of the West Antarctic and New Zealand crustal blocks within Gondwana for *c.* 100 Ma (DiVenere *et al.* 1994). MBL and NZ, Marie Byrd Land and New Zealand, each as a whole. All other symbols as in Fig. 2.

the proposed geological estimates based on crustal thickness arguments (Behrendt & Cooper 1991) and near the lower limit of the error bounds of the palaeomagnetic analysis (DiVenere *et al.* 1994). Given that the pole is from East MBL, it is possible that some of the total extension may be accounted for within West MBL.

Grunow (1993) related the Palmer Land deformation event in the southern AP, in which Middle and Upper Jurassic volcanic and sedimentary rocks were folded and thrusted prior to the emplacement of the Lassiter Coast intrusive suite between about 128 and 96 Ma (Kellogg & Rowley 1989; Pankhurst & Rowley 1991), to the subduction of ocean crust first created and then destroyed by the proposed large clockwise and ensuing counterclockwise rotations of AP and TI in the Late Jurassic and Early Cretaceous. The Palmer Land event could also be explained in our model by collision with EWM (as previously suggested by Grunow *et al.* 1987*a*, 1991) or intervening crust as AP moved with South America followed by expulsion of EWM, TI, and East MBL from the Weddell Sea sector in the Early Cretaceous.

The displacements of the Weddellia blocks eventually resulted in the suturing of East and West MBL and the Eastern and Western Provinces of New Zealand. We note that the timing of the implied displacements and suturing (between about 117 and 100 Ma) is approximately coeval with the last phase of the Rangitata II Orogeny in New Zealand (Bradshaw 1989). Though Bradshaw (1989) proposed that the Rangitata II deformation was caused by the approach and subduction of the Phoenix/Pacific Ridge, the MBL and New Zealand motions inferred from the palaeomagnetic results suggest that Eastern Province-Western Province amalgamation may have been at least partly responsible.

## Conclusions

Early Cretaceous palaeomagnetic data from East MBL and a reassessment of the earliest

Jurassic pole from New Zealand imply that East MBL and the Eastern Province of New Zealand were part of Weddellia from at least the Early Jurassic through the mid-Cretaceous. The Early Cretaceous pole from East MBL, in conjunction with the Early Cretaceous pole from TI, places the constraint that EWM, TI, East MBL, and the Eastern Province of NZ did not attain their mid-Cretaceous positions until after 117 Ma. This is after the estimated age of the initiation of spreading in the Weddell Sea. The post-117 Ma Weddellia block motions may therefore be the result of plate reorganization during the Cretaceous Long Normal interval rather than due to the initial opening of the Weddell Sea. The mid-Cretaceous poles from MBL, TI, and AP are all significantly offset from the East Antarctic APWP. From this we conclude that there has been palaeomagnetically resolvable displacement of the Pacific-bordering blocks of West Antarctica with respect to East Antarctica since about 100 Ma. This is compatible with geologic evidence for Cretaceous and Cenozoic extension in the Ross Sea, Ross embayment, and Byrd Subglacial Basin.

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