Tectonic evolution of the Pacific margin of Antarctica 1. Late Cretaceous tectonic reconstructions

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[1] We present new Late Cretaceous tectonic reconstructions of the Pacific margin of Antarctica based on constraints from marine magnetic data and regional free-air gravity fields. Results from interpretation of new seismic reflection and gravity profiles collected in the Bellingshausen Sea are also incorporated in the reconstructions. The reconstructions show regional constraints on tectonic evolution of the Bellingshausen and Amundsen Seas following the breakup between New Zealand and West Antarctica. The breakup began at c. 90 Ma with the separation of Chatham Rise, probably accompanied by the opening of the Bounty Trough. Campbell Plateau separated from West Antarctica later, during chron 33r (83.0–79.1 Ma). A free-air gravity lineation northeast of Chatham Rise represents the trace of a triple junction that formed as a result of fragmentation of the Phoenix plate a few million years before Chatham Rise separated from West Antarctica. Remnants of the western fragment, the Charcot plate, are preserved in the Bellingshausen Sea. Subduction of the Charcot plate stopped before 83 Ma, and part of it became coupled to the Antarctic Peninsula across the stalled subduction zone. Subsequent convergence at the western margin of this captured ocean floor produced the structures that are the main cause of the Bellingshausen gravity anomaly. Part of a spreading ridge at the western boundary of the Phoenix plate (initially Charcot–Phoenix, evolving into Marie Byrd Land–Phoenix, and eventually Bellingshausen–Phoenix (BEL–PHO)) probably subducted obliquely beneath the southern Antarctic Peninsula during the Late Cretaceous. All of the Phoenix plate ocean floor subducted at the Antarctic Peninsula margin during the Late Cretaceous was probably <14 Myr old when it reached the trench. Several observations suggest that independent Bellingshausen plate motion began near the end of chron 33n (73.6 Ma). Reconstructions in which part of the West Antarctic continental margin, including Thurston Island, is assumed to have been within the Bellingshausen plate seem more plausible than ones in which the plate is assumed to have been entirely oceanic. *INDEX TERMS:* 8157 Tectonophysics: Evolution of the Earth: Plate motions—past (3040); 9310 Information Related to Geographic Region: Antarctica; 9609 Information Related to Geologic Time: Mesozoic; *KEYWORDS:* Pacific, New Zealand, Bellingshausen Sea, Cretaceous, gravity, magnetic anomaly

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1. Introduction

[2] The part of the Antarctic continental margin in the middle of the sector facing the Pacific Ocean is the most poorly studied, due to its remoteness and inaccessibility. However, the tectonic evolution of this sector of the margin, which lies in the Amundsen and Bellingshausen Seas (Figure 1), is important in several respects. It is arguably the most important sector to study in order to improve understanding of the Cretaceous–Tertiary development of the Antarctic plate [*Stock and Molnar*, 1987; *Mayes et al.*, 1990; *McCarron and Larter*, 1998; *Heinemann et al.*, 1999]. It also has potential to yield valuable insights into relationships between continental breakup processes and subduction dynamics [*Bradshaw*, 1989; *Luyendyk*, 1995; *Storey et al.*, 1999]. Furthermore, clarification of the complex plate tectonic evolution of this region is critical to reducing uncertainties in global plate circuit calculations linking the history of relative motions of the oceanic plates of the Pacific basin with the rest of

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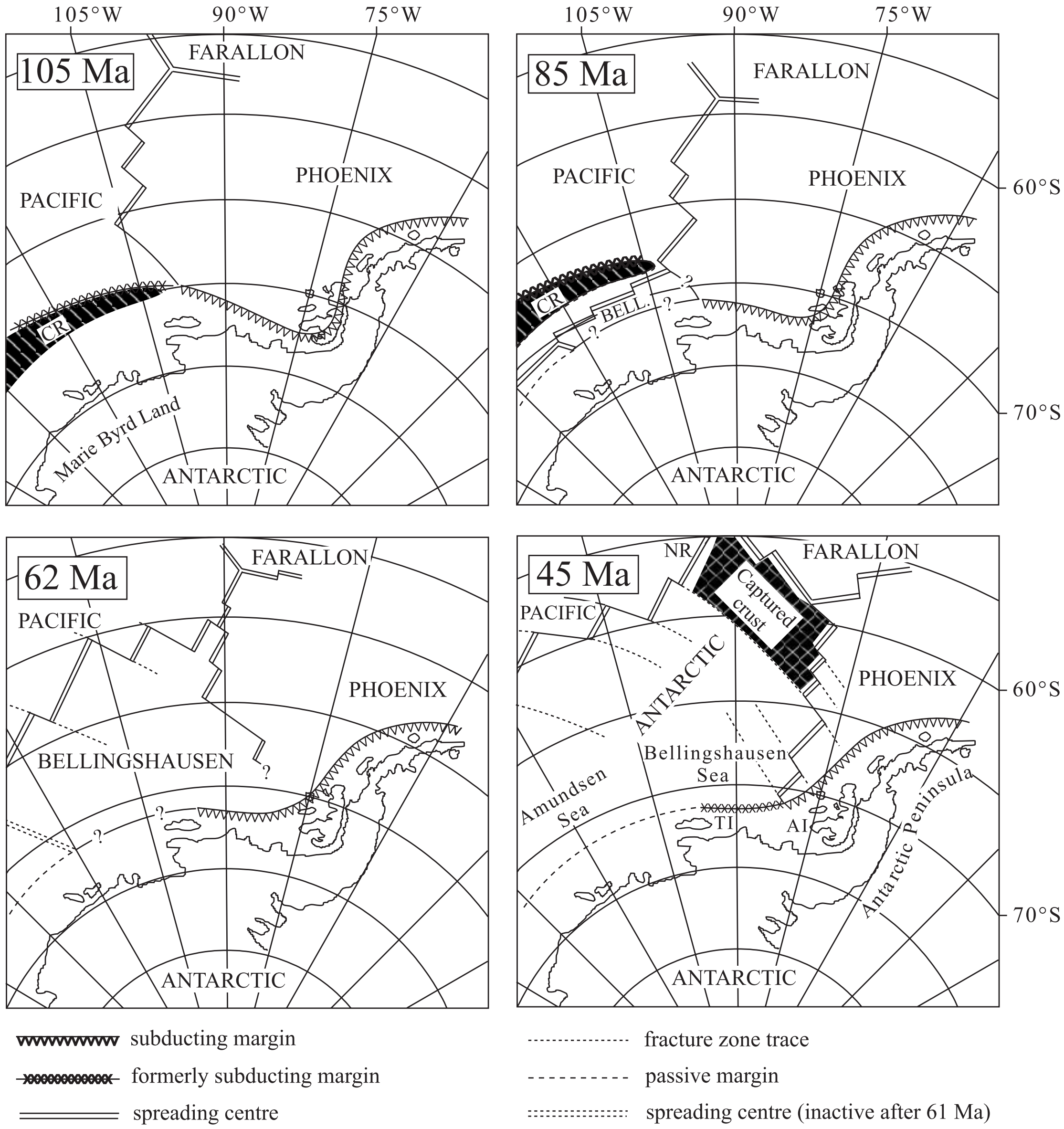


Figure 1. Late Cretaceous–early Tertiary reconstructions of the South Pacific in the Antarctic reference frame [after *McCarron and Larter*, 1998]. BELL, Bellingshausen plate; CR, Chatham Rise; NR, new ridge segment formed by propagation of the Pacific–Antarctic ridge to the Pacific–Farallon ridge at *c*. 47 Ma; AI, Alexander Island; TI, Thurston Island. Question marks indicate areas where the position and nature of plate boundaries are uncertain. Figure reproduced by permission of the Geological Society of London.

the world [*Pitman et al.*, 1968; *Molnar et al.*, 1975; *Cande et al.*, 1995, 2000].

1.1. Tectonic Reconstructions of the Pacific Margin of Antarctica

[3] Previous reconstructions have attempted to describe the tectonic evolution of the Pacific margin of Antarctica since the separation of New Zealand from West Antarctica [*Molnar et al.*, 1975; *Herron and Tucholke*, 1976; *Weissel et al.*, 1977; *Cande et al.*, 1982; *Stock and Molnar*, 1987; *Mayes et al.*, 1990; *McCarron and Larter*, 1998]. However, the Late Cretaceous finite rotations on which these reconstructions were based were poorly constrained because:(a) few magnetic profiles were available from the Bellingshausen and Amundsen Seas, (b) the ages of the oldest magnetic anomalies adjacent to Campbell Plateau (Figure 2a) were uncertain, and (c) the precise shape and position of the West Antarctic continental margin was poorly known. Recently *Stock et al.* [1996] (see also Stock et al., Updated history of the Bellingshausen plate, submitted to *Geology*, 1997, hereinafter referred to as Stock et al., submitted manuscript, 1997) have calculated new finite rotations for various times between chron 27 (61.1 Ma) and the young end of chron 33 (73.6 Ma) using new magnetic data from the Amundsen Sea. Furthermore, a consensus has emerged that the oldest ocean crust off Campbell Plateau formed during chron 33r

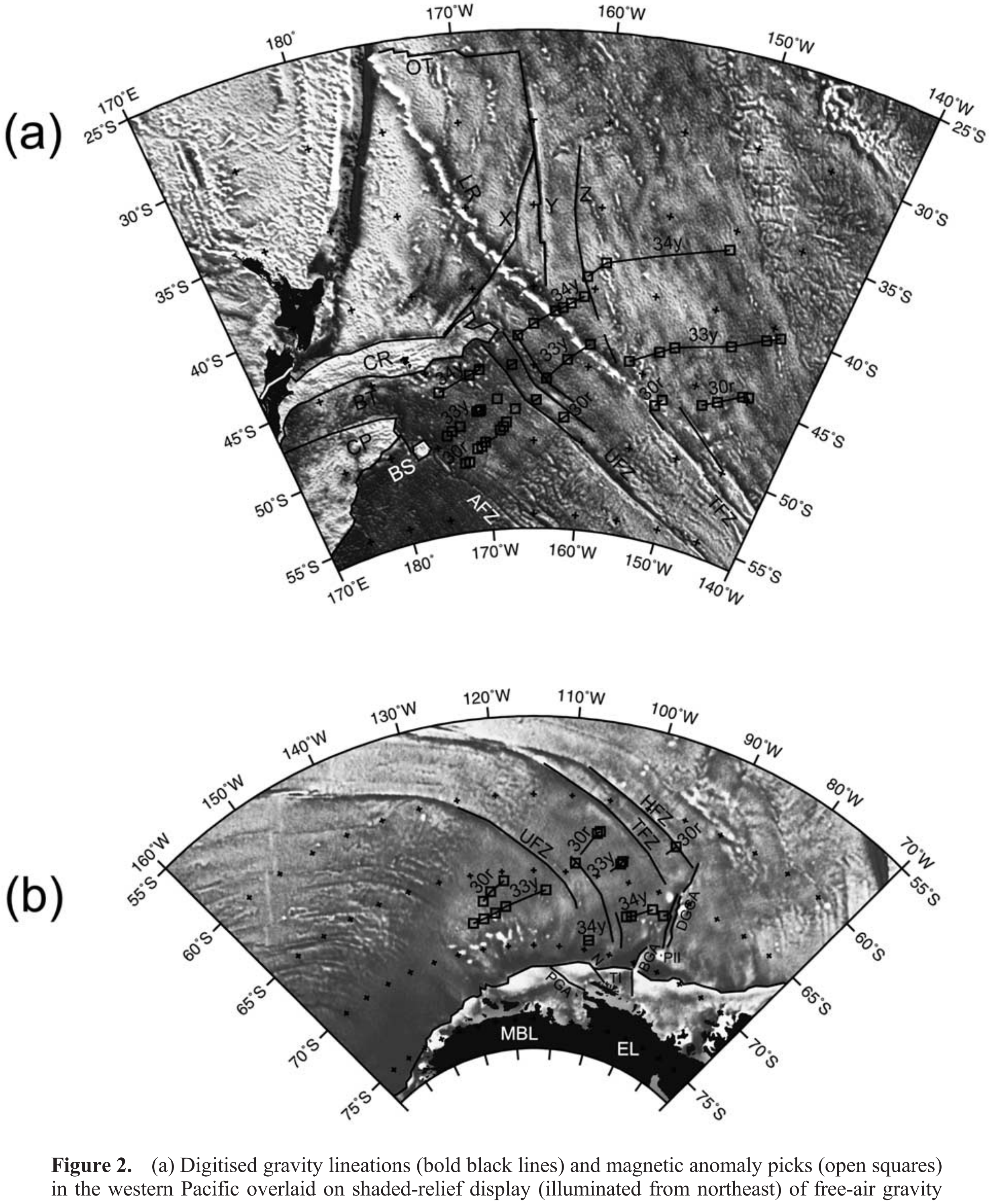


Figure 2. (a) Digitised gravity lineations (bold black lines) and magnetic anomaly picks (open squares) in the western Pacific overlaid on shaded-relief display (illuminated from northeast) of free-air gravity anomalies derived from satellite altimetry data [*Sandwell and Smith*, 1997]. Plotted on polar stereographic projection. CR, Chatham Rise; BT, Bounty Trough; CP, Campbell Plateau; BS, Bollons Seamount; LR, Louisville Ridge; AFZ, Antipodes Fracture Zone; UFZ Udintsev Fracture Zone; TFZ, Tharp Fracture Zone; OT, Osboum Trough; X, Y and Z, gravity lineations on Pacific Ocean floor formed during the Cretaceous Normal Superchron. (b) Digitised gravity lineations (bold black lines) and magnetic anomaly picks (open squares) in the Bellingshausen Sea overlaid on shaded-relief display (illuminated from northeast) of free-air gravity anomalies derived from satellite altimetry data [*McAdoo and Laxon*, 1997]. Plotted on polar stereographic projection. Abbreviations as for (a), plus HFZ, Heezen Fracture Zone; BGA, Bellingshausen gravity anomaly; DGGA, De Gerlache gravity anomaly; PGA, Peacock gravity anomaly; N, Noville gravity lineation; TI, Thurston Island; PII, Peter I Island; MBL, Marie Byrd Land; EL, Ellsworth Land.

(83.0–79.1 Ma) (Stock et al., submitted manuscript, 1997) [*Sutherland*, 1999], and a free-air gravity field derived using retracked ERS-1 satellite altimetry data has revealed the precise shape and position of the West Antarctic continental margin [*McAdoo and Laxon*, 1997] (Figure 2b).

[4] The oldest marine magnetic anomalies identified in the Bellingshausen Sea lie between the Udintsev and Tharp fracture zones (UFZ, TFZ), and record the northwestward migration of a spreading ridge in Late Cretaceous times (Figure 2b). This spreading took place in the wake of Chatham Rise as it migrated northwestward following its separation from West Antarctica *c*. 90 Ma ago (Figure 1). Farther northeast, magnetic anomalies record the northeastward propagation of this ridge during the early Tertiary, with the result that the Pacific–Phoenix (PAC–PHO) ridge was replaced by dual ridges separating the Pacific and Phoenix plates [*Cande et al.*, 1982] (Figure 1). Initially, the ocean floor between these two ridges was probably part of the Bellingshausen plate, but at about chron 27 (61.1 Ma), the Bellingshausen plate was incorporated into the Antarctic plate [*Cande et al.*, 1995]. At about chron 21 (47 Ma), northeastward propagation of the Pacific–Antarctic (PAC–ANT) ridge resulted in its connection to the Pacific–Farallon ridge, and the capture of an area of the Pacific plate by the Antarctic plate [*Cande et al.*, 1982] (Figure 1). Ages quoted for magnetic reversal chrons above, and throughout this paper, are from *Cande and Kent* [1995].

[5] Free-air gravity fields derived from satellite altimetry data [*McAdoo and Marks*, 1992; *McAdoo and Laxon*, 1997; *Sandwell and Smith*, 1997] show two prominent anomaly systems trending approximately N–S in the Bellingshausen Sea. The "Bellingshausen gravity anomaly" (BGA) consists of a paired gravity high and low that extend NNE from the margin between 94°W and 95°W to *c*. 68°S. The BGA also has a southern limb crossing the continental shelf. The "DeGerlache gravity anomaly" (DGGA), which consists of a central free-air gravity high with flanking lows along most of its length, lies between 90° and 92°W and extends from south of 68°S to *c*. 62°S (Figure 2b) [see also *Cunningham et al.*, 2002, Figure 2a]. Magnetic anomalies directly east of the DGGA record the southeastward migration of the Antarctic–Phoenix (ANT–PHO; also referred to by some authors as Antarctic–Aluk) ridge toward the Antarctic Peninsula margin [*Herron and Tucholke*, 1976; *Barker*, 1982; *Larter and Barker*, 1991], where left-stepping ANT–PHO ridge segments migrated into a trench at the margin during the Tertiary, first in the southwest, and progressively later to the northeast. *McCarron and Larter* [1998] showed that an ANT–PHO ridge segment arrived at the margin off southern Alexander Island during the Middle Eocene (Figure 1), and other ridge segments continued to migrate to the margin farther northeast until mid-Pliocene times [*Larter et al.*, 1997].

[6] In an analysis of marine magnetic anomalies southeast of New Zealand, *Stock and Molnar* [1987] found that Late Cretaceous and early Tertiary PAC–ANT finite rotations fail to reconstruct magnetic anomalies both east and west of the Campbell Plateau magnetic bight (near the Antipodes Fracture Zone, Figure 2a). They reconciled this with the existence of a previously unrecognised "Bellingshausen" plate, and proposed that it persisted as an independent plate until chron 18 (39 Ma). In later studies, *Mayes et al.* [1990] suggested independent Bellingshausen plate motion until chron 24 (53 Ma), and *Cande et al.* [1995] proposed that such independent motion stopped at about chron 27 (61.1 Ma). The existence of the Bellingshausen plate prior to chron 27 is supported by a recent reconstruction [*McAdoo and Laxon*, 1997], based on the chron 31 (67.7 Ma) PAC–ANT finite rotation pole of *Cande et al.* [1995], which shows misalignment of fracture zones on opposing flanks of the former Pacific–Bellingshausen (PAC–BEL) ridge. Hence, on the basis of recent reconstructions, the former Bellingshausen plate is thought to comprise mainly pre-chron 27 ocean floor east of about 130°W off Marie Byrd Land (Figures 1 and 2b).

[7] *Heinemann et al.* [1999] presented seismic reflection and magnetic profiles from the area around the western boundary of the former Bellingshausen plate, and interpreted a NNW trending graben in this area as part of the paleodivergent plate boundary between the Marie Byrd Land and Bellingshausen plates. The magnetic data presented by *Heinemann et al.* [1999] show a major discrepancy in spreading rates on either side of the former plate boundary between chrons 32n.1n and 27 (71.2–61.1 Ma), confirming the existence of an independent Bellingshausen plate during this interval. However, the southern and eastern extent of the Bellingshausen plate remains poorly defined, and it is unclear whether it included any part of continental West Antarctica. Furthermore, the age at which independent Bellingshausen plate motion began also remains uncertain. The magnetic data presented by *Heinemann et al.* [1999] show that it had started by chron C32n.1n (71.2 Ma). Stock et al. (submitted manuscript, 1997) and *Heinemann et al.* [1999] suggested that it had probably already begun by the start of chron 33n (i.e. before 79 Ma). In view of the uncertainty in the time of onset of independent Bellingshausen plate motion, we will refer to the ridge which generated ocean floor older than chron 27 between Chatham Rise and Antarctica as the Pacific–Marie Byrd Land/Pacific–Bellingshausen (PAC–MBL/PAC–BEL) ridge.

1.2. Objectives of This Study

[8] New Late Cretaceous tectonic reconstructions of the Pacific margin of Antarctica presented in this paper were produced to provide insight into regional constraints on the tectonic evolution of the Bellingshausen and Amundsen Sea regions following separation of New Zealand from West Antarctica. The reconstructions provide a context for interpretation of new marine geophysical data collected in the Bellingshausen Sea [*Cunningham et al.*, 2002]. Conversely, the new marine geophysical data provide constraints on details of the reconstructions in the Bellingshausen Sea region. In addition to these new marine geophysical data, the new reconstructions incorporate several other new sources of information as described in the previous section.

[9] Beyond providing a context for interpretation of new data collected in the Bellingshausen Sea, the new reconstructions were intended to: (a) reveal the regional tectonic setting at the times Chatham Rise and Campbell Plateau started to separate from West Antarctica, (b) provide a new perspective on the possible timing of the start of independent Bellingshausen plate motion, and (c) explore the

regional tectonic constraints on the position and nature of the southern boundary of the Bellingshausen plate.

2. Data Used in Reconstructions

2.1. Gravity Data

[10] The margins of Chatham Rise, Campbell Plateau and Bollons Seamount are sharply defined in the free-air gravity field derived from satellite altimetry data by *Sandwell and Smith* [1997] (Figure 2a). The gravity field also shows the traces of the UFZ, TFZ and other fracture zones, providing important constraints on reconstructions between the western Pacific and Bellingshausen Sea regions. The old end of the UFZ can be traced close to the tip of Chatham Rise. North and east of Chatham Rise there are three prominent gravity lineations which we refer to as X, Y and Z (Figure 2a). The northeastern end of X appears to be truncated by Y, and these two features have been referred to collectively as the Wishbone Scarp [*Billen and Stock*, 2000; *Sutherland and Hollis*, 2001]. Lineation Y continues northward to about 26°S, where it meets the E–W trending Osbourn Trough (Figure 2a).

[11] The Osbourn Trough has recently been shown to be an abandoned spreading center [*Billen and Stock*, 2000]. On the basis of models of magnetic profiles across the Osbourn Trough, *Billen and Stock* [2000] proposed that it had continued spreading at a full rate of 5 cm/yr until either 82 Ma or 71 Ma. However, despite these magnetic models, regional tectonic constraints suggest to us that the Osbourn Trough is unlikely to have continued spreading after subduction ceased along the New Zealand sector of the Antarctic margin at about 105 Ma [*Bradshaw*, 1989]. The Osbourn Trough could only have continued spreading after subduction stopped if the Pacific plate was migrating away from Antarctica. Paleomagnetic data do indicate that the Pacific plate was moving northward between 105 and 90 Ma at a rate in the range 20–40 km/Ma [*Larson et al.*, 1992]. However, an apparent polar wander path for East Antarctica suggests that Antarctica was moving toward the western Pacific at a rate at least as fast during the same interval [*DiVenere et al.*, 1994], making PAC–ANT spreading unlikely at this time. Thus we treat the Osbourn Trough as a dead ridge in our Late Cretaceous reconstructions.

[12] A prominent feature in the southwestern Pacific gravity field is the Louisville Ridge (Figure 2a). This is a seamount chain formed by northwestward migration of the Pacific plate across a hot spot since about 70 Ma [*Lonsdale*, 1988; *Watts et al.*, 1988].

[13] The West Antarctic continental margin is sharply defined in the free-air gravity field derived from retracked ERS-1 satellite altimetry data by *McAdoo and Laxon* [1997] (Figure 2b). This gravity field also shows the traces of the UFZ, TFZ, and other fracture zones, although they cannot be traced close to the Antarctic margin. This is probably a consequence of the thick and unevenly distributed sediments on the West Antarctic continental rise [*Nitsche et al.*, 2000].

[14] In addition to the BGA and DGGA (see section 1.1), gravity data also show two anomalies on the West Antarctic continental shelf described here as the "Noville gravity lineation" (NGL) and the "Peacock gravity anomaly" (PGA). The NGL consists of an elongated gravity high which extends 50 km northwest from Noville Peninsula, Thurston Island, and its projection to the continental margin, where it coincides with an offset in the margin near 103°W (labeled "N" in Figure 2b). Farther west, the PGA consists of a broad gravity high which emerges from the western end of Peacock Sound (between Thurston Island and the mainland), and trends WNW to reach the margin at about 113°W (Figure 2b) [see also *Cunningham et al.*, 2002, Figure 2a].

2.2. Marine Magnetic Data

[15] We have examined marine magnetic profiles from both the region east of Chatham Rise and the Bellingshausen Sea (Figures 3–6). After removal of the International Geomagnetic Reference Field [*Barton*, 1996] profiles were plotted along ship tracks, and positions of anomaly 30r (67.7 Ma), the young edge of anomaly 33 (33y; 73.6 Ma), and the young edge of anomaly 34 (34y; 83 Ma) were picked for inclusion in reconstructions. Selected profiles were projected onto lines parallel to fracture zone trends and compared to synthetic magnetic anomaly profiles to determine Late Cretaceous seafloor spreading rates (Figures 4 and 6).

[16] Magnetic profiles for the area east of Chatham Rise were extracted from the GEODAS database [*National Geophysical Data Center*, 1996]. Selected profiles, together with magnetic anomaly picks included in our reconstructions, are shown overlaid on the regional free-air gravity field in Figure 3. In selecting profiles we gave priority to those most closely aligned with fracture zone trends. Both for this region and the Bellingshausen Sea our reconstructions include some picks for anomalies 30r and 33y in the area west of the UFZ from Stock et al. (submitted manuscript, 1997). The patterns of anomalies identified in Figure 3 show that there was a large difference in half-spreading rate either side of gravity lineation Z between chrons 34y and 33y. This suggests that lineation Z represents the trace of a triple junction. After chron 32 the boundary between the two spreading regimes stepped eastward to the Heezen Fracture Zone (HFZ), but the separation between anomalies 33y and 32n.2n on profile L–L′ suggests that the boundary first stepped westward temporarily before stepping eastward (Figures 3 and 4). The projected profiles in Figure 4 show that the half-spreading rates on the two spreading systems differed by about a factor of two throughout the period from chron 34 to chron 27. The very fast spreading to the east of lineation Z and the HFZ occurred at the Pacific–Phoenix (PAC–PHO) ridge [*Weissel et al.*, 1977; *Cande et al.*, 1982], while the slower spreading to the west occurred at the ridge that formed when Chatham Rise separated from West Antarctica.

[17] On the basis of interpretation of radiolarians in sediment from near the base of DSDP Hole 595A (about 200 km north of the eastern end of the Osbourn Trough) as Early Cretaceous in age, and paleomagnetic data suggesting that the basalt basement at Site 595 formed at a paleolatitude of 63°S, *Sutherland and Hollis* [2001] proposed that an additional spreading ridge existed south of the PAC–PHO ridge in Early Cretaceous time. If *Sutherland and Hollis* [2001] are correct then it would have been this ridge, between the Phoenix plate and a previously unrecognised southern plate they named the Moa plate, which subse-

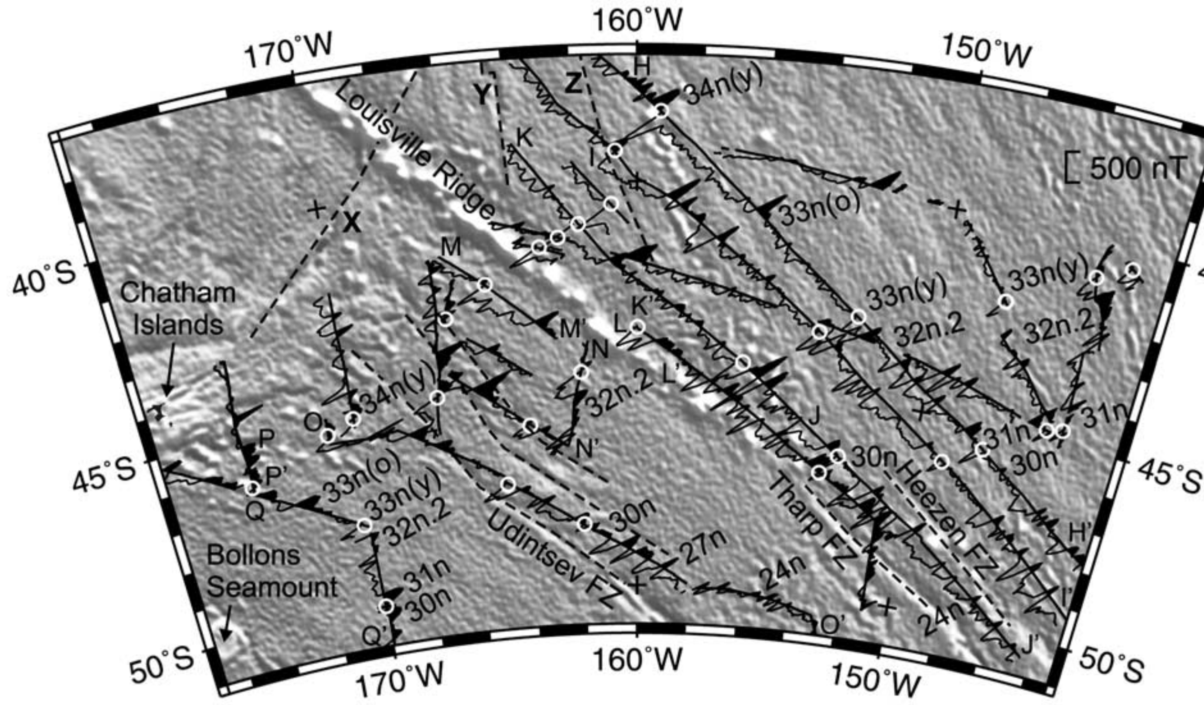


Figure 3. Selected Western Pacific marine magnetic profiles plotted along ship tracks and overlaid on shaded-relief display (illuminated from northeast) of the free-air gravity field derived by *Sandwell and Smith* [1997]. Plotted on polar stereographic projection. All profiles shown are from the GEODAS database [*National Geophysical Data Center*, 1996], and are residual magnetic anomalies following removal of the International Geomagnetic Reference Field. Profiles labeled H–H′ to Q–Q′ are compared to synthetic magnetic anomaly profiles in Figure 4. Anomalies on all profiles are projected in a direction 60° clockwise from the top of the page. Positive anomalies are filled in black. Magnetic anomaly labels conform to the geomagnetic polarity timescale nomenclature used by *Cande and Kent* [1995], with "(y)" or "(o)" appended to some labels to indicate the young and old edges of broad anomalies. White circles are anomaly picks shown in Figures 2, 7, and 8. Dashed lines are interpreted positions of fracture zones and other gravity lineations (i.e. lineations X, Y and Z).

quently produced the ocean crust now lying east of lineation Z during the Late Cretaceous. However, no M series (Early Cretaceous) marine magnetic lineations have been identified near Site 595. Moreover, if PAC–PHO spreading continued through the Cretaceous Normal Superchron (CNS, 118–83 Ma) at similar half rates to those measured before (77 mm/yr) [*Larson*, 1997] and after the CNS (92 mm/yr, Figure 4) then spreading on the northern flank of the ridge would account for the amount of ocean floor lacking magnetic lineations that exists between the Manihiki Plateau (8°–14°S, 161°–164°W) and anomaly 34y east of lineation Z. Unless or until additional evidence is found to support the model of *Sutherland and Hollis* [2001] we prefer the simple explanation that this area of ocean crust was produced by a single, fast spreading ridge, and hence we refer to the plate to the south of this ridge as the Phoenix plate.

[18] Four profiles show a positive anomaly about 200 km southeast of the eastern part of Chatham Rise which we interpret as anomaly 34y. Contrary to some earlier interpretations [e.g., *Mayes et al.*, 1990], anomaly 34y is now thought to be absent adjacent to Campbell Plateau [*Stock et al.*, 1996; *Sutherland*, 1999], so if our interpretation is correct it implies Chatham Rise separated from Marie Byrd Land before Campbell Plateau. Two profiles close to the UFZ and the two small fracture zones northeast of it show that a change in the fracture zone trends occurs close to anomaly 33y.

[19] New magnetic profiles collected in the Bellingshausen Sea by the British Antarctic Survey and the Alfred Wegener Institute were compiled with profiles from earlier cruises in the region [*Herron and Tucholke*, 1976; *Kimura*, 1982; *Larter and Barker*, 1991; *National Geophysical Data Center*, 1996]. Selected profiles, together with magnetic anomaly picks included in our reconstructions, are shown overlaid on the regional free-air gravity field in Figure 5. Once again, in selecting profiles we gave priority to those most closely aligned with fracture zone trends. On our new profiles we have identified two new anomaly 34y picks in the area to the west of the BGA and DGGA (Figure 5), providing additional constraints on reconstructions for this time. The patterns of anomalies identified reveal that the BGA and DGGA lie in an area that separates two distinct tectonic provinces: anomalies to the west record the northwestward migration of the ridge that formed when Chatham Rise separated from West Antarctica, whereas anomalies to the east record the southeastward migration of the ANT–PHO ridge toward the Antarctic Peninsula since chron 27 (61.1 Ma). However, the age and origin of a triangular area

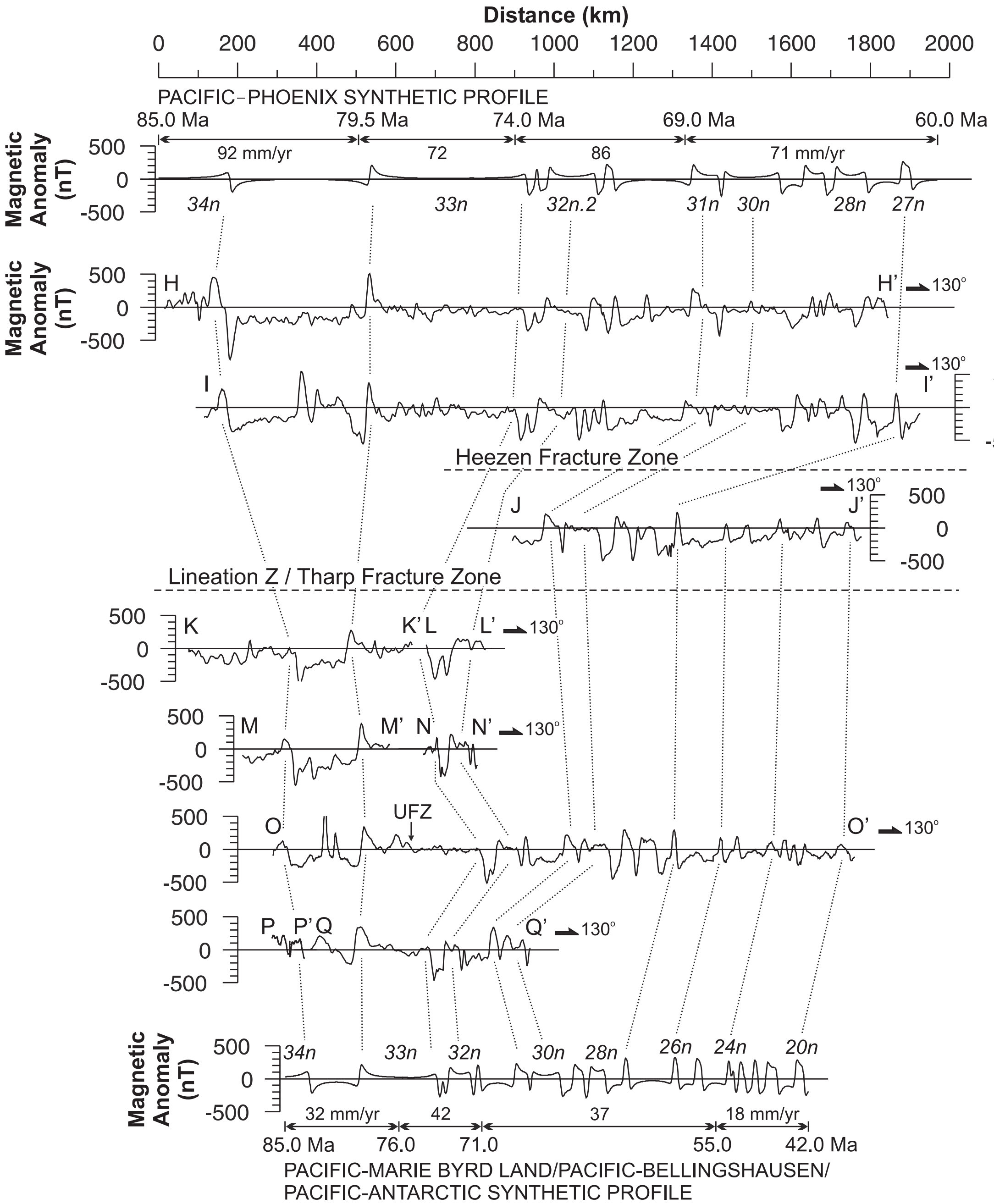


Figure 4. Selected Western Pacific marine magnetic profiles compared to synthetic magnetic anomaly profiles. Locations of profiles H–H′ to Q–Q′ are shown in Figure 3. All of the profiles are projected onto 130°. The synthetic profiles were calculated using the spreading rates shown, the geomagnetic polarity timescale of *Cande and Kent* [1995], the Definitive Geomagnetic Reference Field for 1980 [*Barton*, 1996], the age-depth relationship for oceanic crust of *Parsons and Sclater* [1977], a magnetic layer of 1 km thickness and susceptibility 0.02 (SI), and a remnant magnetisation vector with inclination −70° and declination 0°. UFZ indicates crossing of Udintsev Fracture Zone that causes repetition of anomaly 33n on profile O–O′.

of ocean floor, centered on Peter I Island, remain uncertain. The BGA together with the part of the DGGA south of 66°S, and the continental margin between 83°W and 95°W form two sides of this triangle [see *Cunningham et al.*, 2002, Figure 2b].

[20] The patterns of magnetic anomalies identified either side of the DGGA between 66°S and 62°S indicate an abrupt contrast in the age of oceanic crust across it, with the crust on both flanks younging away from the DGGA (Figure 5). The oceanic crust on the eastern flank of the DGGA is interpreted to be younger than that on the west, implying that the ANT–PHO ridge jumped to the position of the DGGA at about chron 27 (61.1 Ma). This coincides with a general plate reorganization in the South Pacific

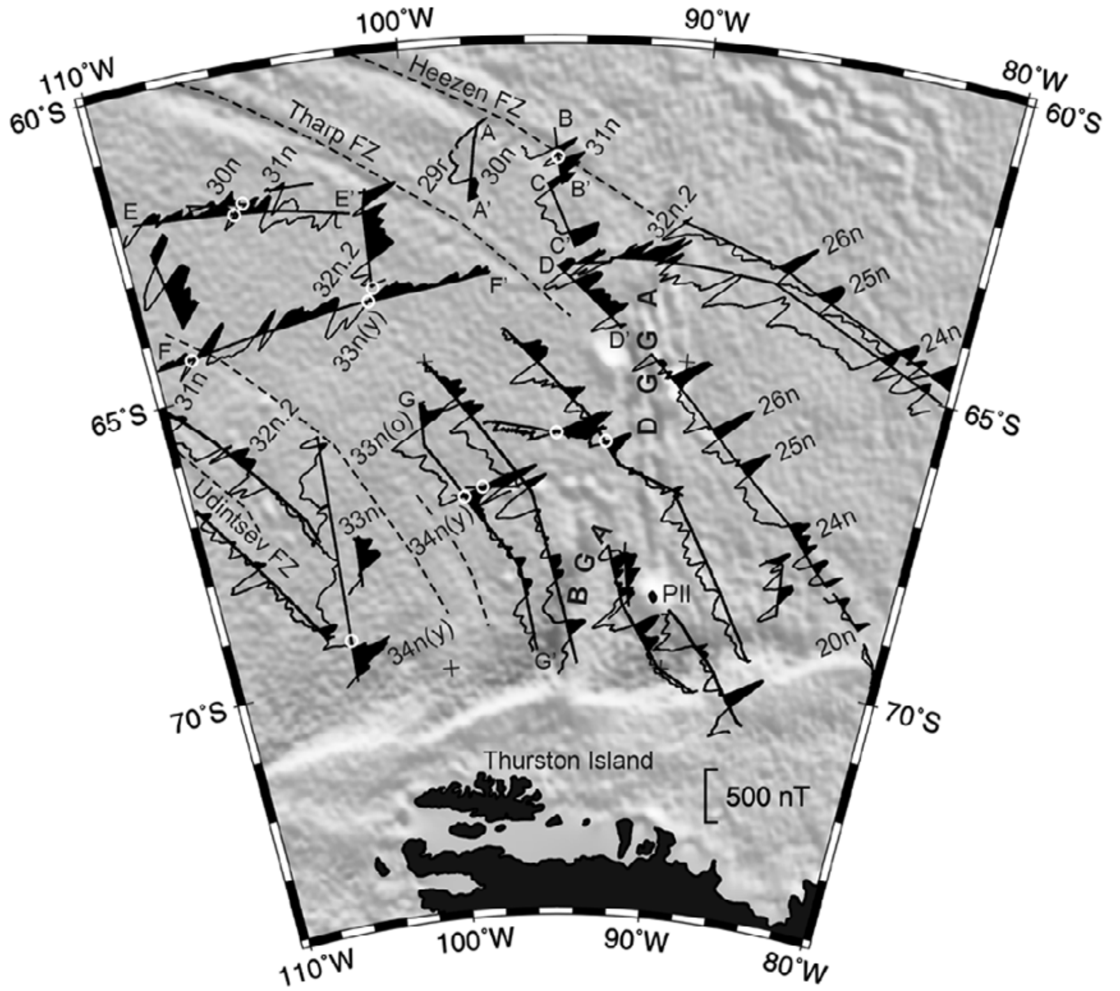


Figure 5. Selected Bellingshausen Sea marine magnetic profiles plotted along ship tracks and overlaid on shaded-relief display (illuminated from northeast) of the free-air gravity fields derived by *Sandwell and Smith* [1997] (north of 70°S) and *McAdoo and Laxon* [1997] (south of 70°S). Plotted on polar stereographic projection. New profiles collected by the British Antarctic Survey and the Alfred Wegener Institute are shown together with other profiles from the GEODAS database [*National Geophysical Data Center*, 1996], and one from *Kimura* [1982]. All profiles shown are residual magnetic anomalies following removal of the International Geomagnetic Reference Field. Profiles labeled A–A′ to G–G′ are compared to a synthetic magnetic anomaly profile in Figure 6. Anomalies on most profiles are projected in a direction 60° clockwise from the top of the page. The exceptions are profiles E–E′, F–F′, and three other short profiles near the northwest corner of the map, on which anomalies are projected in a direction 30° clockwise from the top of the page. Positive anomalies are filled in black. Magnetic anomaly labels conform to the geomagnetic polarity timescale nomenclature used by *Cande and Kent* [1995], with "(y)" or "(o)" appended to some labels to indicate the young and old edges of broad anomalies. White circles are anomaly picks shown in Figures 2, 7, and 8. Dashed lines are interpreted fracture zone positions. BGA, Bellingshausen gravity anomaly; DGGA, De Gerlache gravity anomaly; PII, Peter I Island.

which included the incorporation of the Bellingshausen plate into the Antarctic plate. Recognition of the abrupt contrast in ocean floor age across the northern part of the DGGA is a consequence of our reinterpretation of magnetic anomalies between the TFZ and HFZ to the west of the DGGA. We interpret these anomalies as a sequence younging to the northwest, starting from anomaly 32n.2n adjacent to the DGGA (profiles A–A′ to D–D′ in Figures 5 and 6). Previously *Cande et al.* [1982] interpreted the anomaly we identify as 32n.1n as anomaly 29n, and the anomaly we identify as 32n.2n as anomaly 28n, which suggested that ANT–PHO spreading had started earlier and farther west. This interpretation was adopted by *McCarron and Larter* [1998]. The continuity of the TFZ and HFZ to the west of the DGGA, and the absence of any major features in the gravity field between these two fracture zones, support our new interpretation.

[21] Comparison of magnetic anomaly profiles projected parallel to fracture zone trends with synthetic magnetic anomaly profiles (Figures 4 and 6) suggests that there was

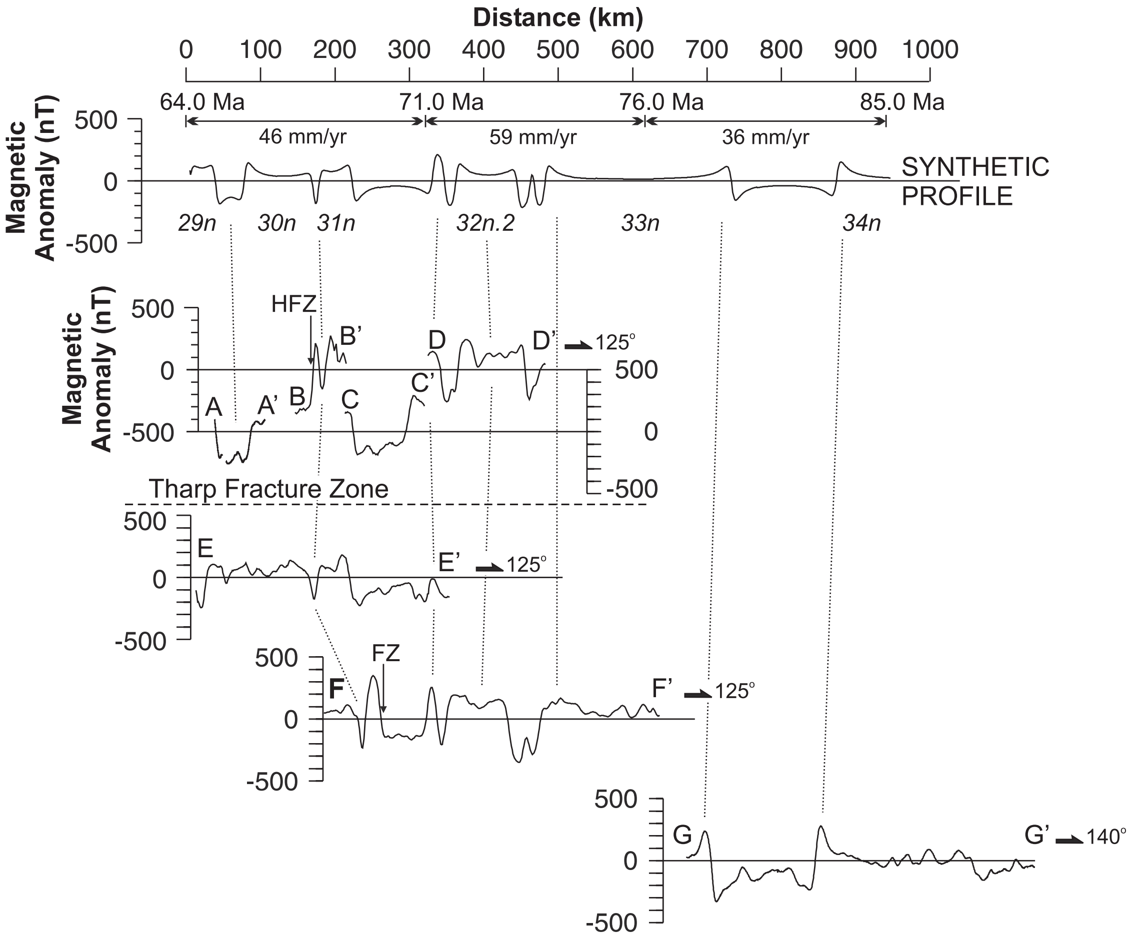


Figure 6. Selected Bellingshausen Sea marine magnetic profiles compared to a synthetic magnetic anomaly profile. Locations of profiles A–A′ to G–G′ are shown in Figure 5. All of the profiles except G–G′ are projected onto 125°. Profile G–G′ is projected onto 140°, reflecting an interpreted change in spreading direction. The magnetic anomaly scale for profiles B–B′ and D–D′ is offset by 500 nT from that for A–A′ and C–C′ so that the individual profiles can be clearly distinguished. The synthetic profile was calculated using the spreading rates shown, the geomagnetic polarity timescale of *Cande and Kent* [1995], the Definitive Geomagnetic Reference Field for 1980 [*Barton*, 1996], the age–depth relationship for oceanic crust of *Parsons and Sclater* [1977], a magnetic layer of 1 km thickness and susceptibility 0.02 (SI), and a remnant magnetisation vector with inclination −76° and declination 0°. HFZ indicates crossing of Heezen Fracture Zone that results in truncation of anomaly 30n on profile B–B′; FZ indicates crossing of small fracture zone that results in truncation of anomaly 31n on profile F–F′.

considerable asymmetry in spreading on the PAC–BEL ridge from chron 33y until at least chron 29 (74–64 Ma). On the profiles studied spreading rates were 40% faster on the south side of the ridge prior to 71 Ma, and remained 24% faster on the south side of the ridge from 71 to 64 Ma. However, our reconstructions show that the PAC–BEL ridge rotated anticlockwise during this period (see section 3.1), so our estimation of asymmetry may be a consequence of the distribution of the profiles available to us. The anomaly pattern interpreted by Stock et al. (submitted manuscript, 1997) suggests that profiles farther west show asymmetry favoring the opposite side of the ridge.

3. New Late Cretaceous Reconstructions

[22] We have produced a new set of Late Cretaceous tectonic reconstructions for the Pacific margin of Antarctica by digitizing tectonic features and magnetic anomalies identified in the southwest Pacific off New Zealand (Figure 2a) and in the Bellingshausen Sea (Figure 2b), and reconstructing them using finite rotations for chrons 30r, 33y, 34y, and *c*. 90 Ma (Table 1).

[23] The reconstructions (Figures 7 and 8) are shown in the reference frame of Marie Byrd Land because the most reliable constraints on the two most recent reconstructions (chrons 30r and 33y) are provided by finite rotations describing the motion between the Pacific plate and Marie Byrd Land (Stock et al., submitted manuscript, 1997). The most reliable constraint on the chron 34y reconstruction (Figures 7c and 8a) also comes from the Marie Byrd Land sector: we used the shape of the Marie Byrd Land continental margin revealed by the gravity field of *McAdoo and Laxon* [1997] and the outline of the Campbell Plateau margin digitized from the gravity field of *Sandwell*

Table 1. Finite Rotations Used in Reconstructions

	Plate Pair	Chron	Time	Latitude	Longitude	Angle	Source
1	PAC–MBL	30r	67.7	68.94	−55.52	49.6	Stock et al. (submitted manuscript, 1997)
2	PAC–BEL	30r	67.7	70.88	−51.01	52.48	Stock et al. (submitted manuscript, 1997)
3	BEL–MBL	30r	67.7	−72.46	−79.83	3.59	Sum of rotations no. 2 (reversed) and no. 1
4	PAC–MBL	33y	73.6	66.72	−55.04	53.74	Stock et al. (submitted manuscript, 1997)
5	PAC–BEL	33y	73.6	70.98	−41.28	62.7	Stock et al. (submitted manuscript, 1997)
6	BEL–MBL	33y	73.6	−73.08	−91.41	10.97	Sum of rotations no. 5 (reversed) and no. 4
7	PAC–MBL	34y	83	65.58	−52.38	63.07	This paper (CP fit)
8	PAC–MBL	CNS	90	66.51	−43.54	73.6	This paper (CR fit to present Antarctic margin)
9	PAC–MBL	CNS	90	64.06	−49.94	67.99	This paper (CR fit to adjusted Antarctic margin)
10	PAC–MBL	34y	83	66.72	−55.04	62	This paper (rotation no. 4 with increased angle)
11	PAC–MBL	CNS	90	64.03	−56.96	57.65	[*Mayes et al.*, 1990]

and Smith [1997] to determine a new finite rotation for the fit of Campbell Plateau to Marie Byrd Land (no. 7 in Table 1; Figure 9), where breakup occurred shortly after chron 34y [*Stock et al.*, 1996; *Sutherland*, 1999].

[24] Features digitized from the southwestern Pacific gravity field (Figure 2a) and Bellingshausen Sea fracture zones and magnetic anomalies (Figure 2b) are shown in Figures 7 and 8 in their reconstructed positions. However, the BGA and DGGA are shown in their present-day positions. In the case of the BGA this is because we believe that the basement structures associated with it formed as a result of convergence between the Marie Byrd Land (and subsequently Bellingshausen) plate and another plate to its east [*Gohl et al.*, 1997; *Cunningham et al.*, 2002]. In the case of the DGGA, we believe that the structures associated with it developed more recently than the times represented by the reconstructions (see section 2.2), but have indicated its present position in the most recent reconstruction (Figure 7a).

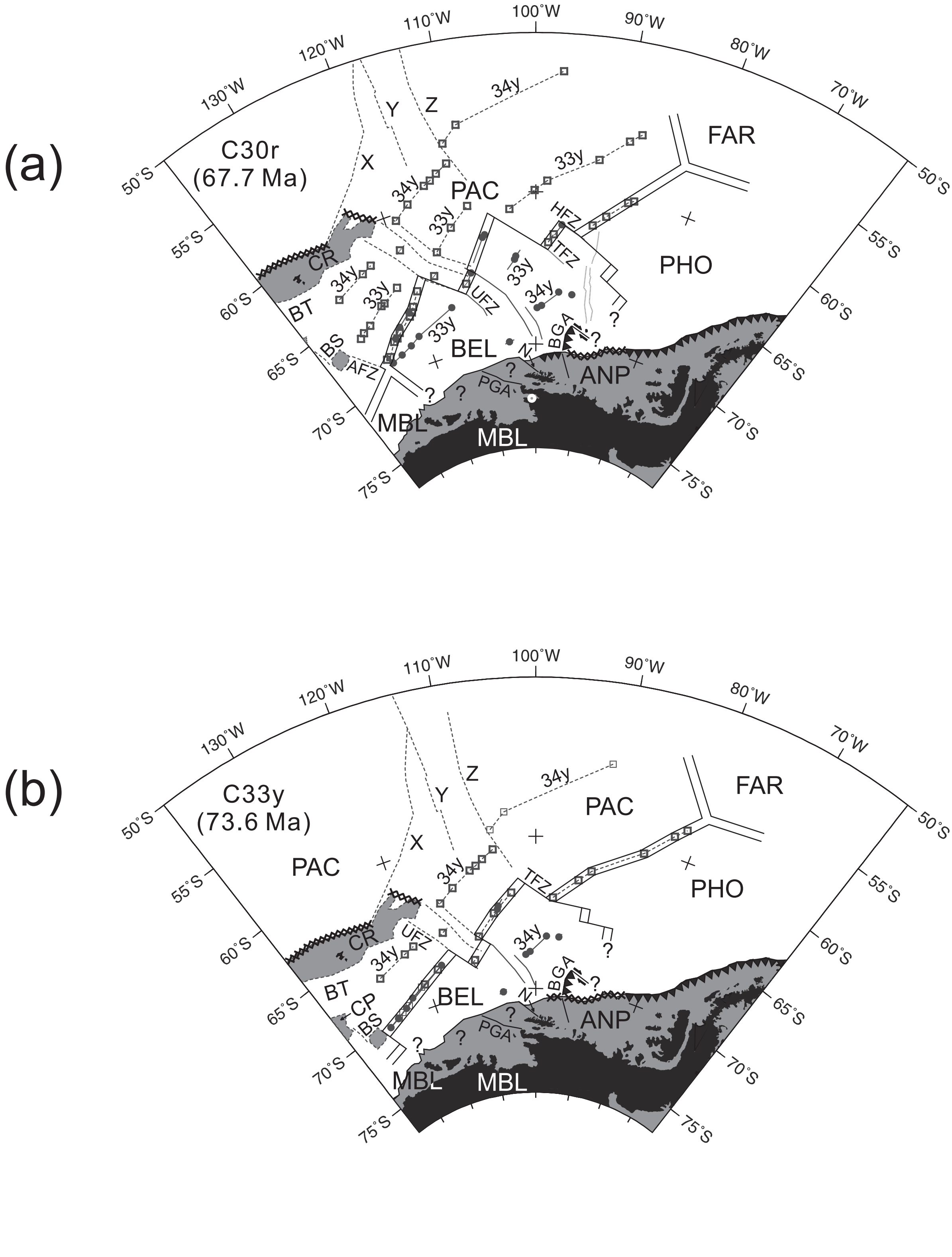
[25] The Antarctic continental margin, PGA and NGL are shown in Figure 7 in their present-day positions, on the assumption that there has been no relative motion between different parts of West Antarctica since the time of the earliest reconstruction (*c.* 90 Ma), and that the Bellingshausen plate did not include any part of West Antarctica (i.e. the southern boundary of Bellingshausen plate was situated along the West Antarctic continental margin, or within

Figure 7. (opposite) Late Cretaceous tectonic reconstructions of the Pacific margin of Antarctica in the Marie Byrd Land (MBL) reference frame, assuming that the Bellingshausen plate did not include any part of West Antarctica and that there has been no relative motion between different parts of West Antarctica since 90 Ma. All reconstructions plotted on polar stereographic projection. (a) Reconstruction for chron 30r (67.7 Ma). All Pacific features (magnetic lineations, gravity lineations and fracture zones shown with dashed lines) have been rotated using a chron 30r PAC–MBL finite rotation (no. 1, Table 1). All Bellingshausen features (magnetic lineations and fracture zones shown with solid lines) have been rotated using a chron 30r BEL–MBL finite rotation (no. 3, Table 1). The De Gerlache gravity anomaly (dotted lines) and Bellingshausen gravity anomaly (BGA) are shown in their present-day position relative to MBL, although the DGGA probably did not form until chron 27 (61.1 Ma). Existence of BEL–PHO ridge inferred from plate circuit calculations (see text). Open squares and filled circles are magnetic anomaly picks on the Pacific and Bellingshausen plates, respectively. Magnetic isochrons 33y and 34y are labeled. The BEL–MBL stage rotation pole for chrons 32n.1r-28r (71.5–63.8 Ma) is marked with a white circle at 73.64°S, 101.04°W (no. 19, Table 2). Solid barbs denoting subduction have been drawn along the present-day Antarctic Peninsula margin, although there has probably been considerable accretion along the southern part of the margin [*McCarron and Larter*, 1998], and subduction erosion farther northeast, since this time. Question marks indicate areas where the precise position and configuration of plate boundaries remain uncertain. BEL, Bellingshausen plate; MBL, Marie Byrd Land plate; ANP, Antarctic Peninsula plate; PAC, Pacific plate; PHO, Phoenix plate; FAR, Farallon plate; CR, Chatham Rise; BT, Bounty Trough; BS, Bollons Seamount; AFZ, Antipodes Fracture Zone; UFZ Udintsev Fracture Zone; TFZ, Tharp Facture Zone; HFZ, Heezen Fracture Zone; X, Y and Z, gravity lineations on Pacific ocean floor formed during the Cretaceous Normal Superchron; PGA, Peacock gravity anomaly; N, Noville gravity lineation. (b) Reconstruction for chron 33y (73.6 Ma). All Pacific features (open squares and dashed lines) have been rotated using a chron 33y PAC–MBL finite rotation (no. 4, Table 1). All Bellingshausen features (solid circles and lines) have been rotated using a chron 33y BEL–MBL finite rotation (no. 6, Table 1). The BGA is shown in its present-day position relative to MBL. Abbreviations as for (a), plus CP, Campbell Plateau (c) Reconstruction for chron 34y (83 Ma). All Pacific features (open squares and dashed lines), except Bollons Seamount (BS), have been rotated using a PAC–MBL finite rotation derived from tight fit of Campbell Plateau (CP) with MBL (no. 7, Table 1). BS has been reconstructed to the tip of CP. All Bellingshausen features (solid circles and lines) have been rotated using a chron 33y BEL–MBL finite rotation (no. 6, Table 1), with the implicit assumption that there was no BEL–MBL motion before chron 33y. The BGA is shown in its present-day position relative to MBL. Existence of slow spreading ridge on opposite side of PAC–PHO ridge from gravity lineation Z inferred on basis of interpretation of Z as a triple junction trace (see text). OT, Osbourn Trough, reconstructed assuming it has been inactive since before 90 Ma. Other abbreviations as in (a). (d) Reconstruction for Cretaceous Normal Superchron (90 Ma). All Pacific features (dashed lines), except CP and BS, have been rotated using a PAC–MBL finite rotation derived from tight fit of Chatham Rise with the part of the Antarctic continental margin between 120°W and 100°W (no. 8, Table 1). CP and BS are shown in the same positions as in (c). Annotations and abbreviations as for (c), plus CHA, Charcot plate; SI, part of South Island, New Zealand.

ocean floor to its north). A second assumption in Figure 7 is that Bellingshausen plate motion began at about chron 33y (see section 3.1 for justification of this interpretation). Alternative reconstructions for chron 34y (83 Ma) and *c*. 90 Ma (Figures 8a and 8b) show how the configuration of the continental margin would be expected to have differed if the Bellingshausen plate included part of the West Antarctic continental shelf (our preferred interpretation; see sections 3.5 and 3.6).

[26] In all of the reconstructions the Antarctic Peninsula is shown fixed in its present-day position relative to Marie Byrd Land. However, it is labeled as a separate plate (ANP) in recognition of the fact that we suspect that there was a small amount of relative motion between Marie Byrd Land and the Antarctic Peninsula during the interval covered by these reconstructions (see section 3.2).

[27] The reconstructions in Figure 7 are presented in order of increasing age because the position of Chatham Rise at final fit is based on consideration of the more recent reconstructions, and especially on reconstructed fracture zone trends in the chron 34y reconstructions (Figures 7c and 8a). In all reconstructions, spreading ridges drawn along



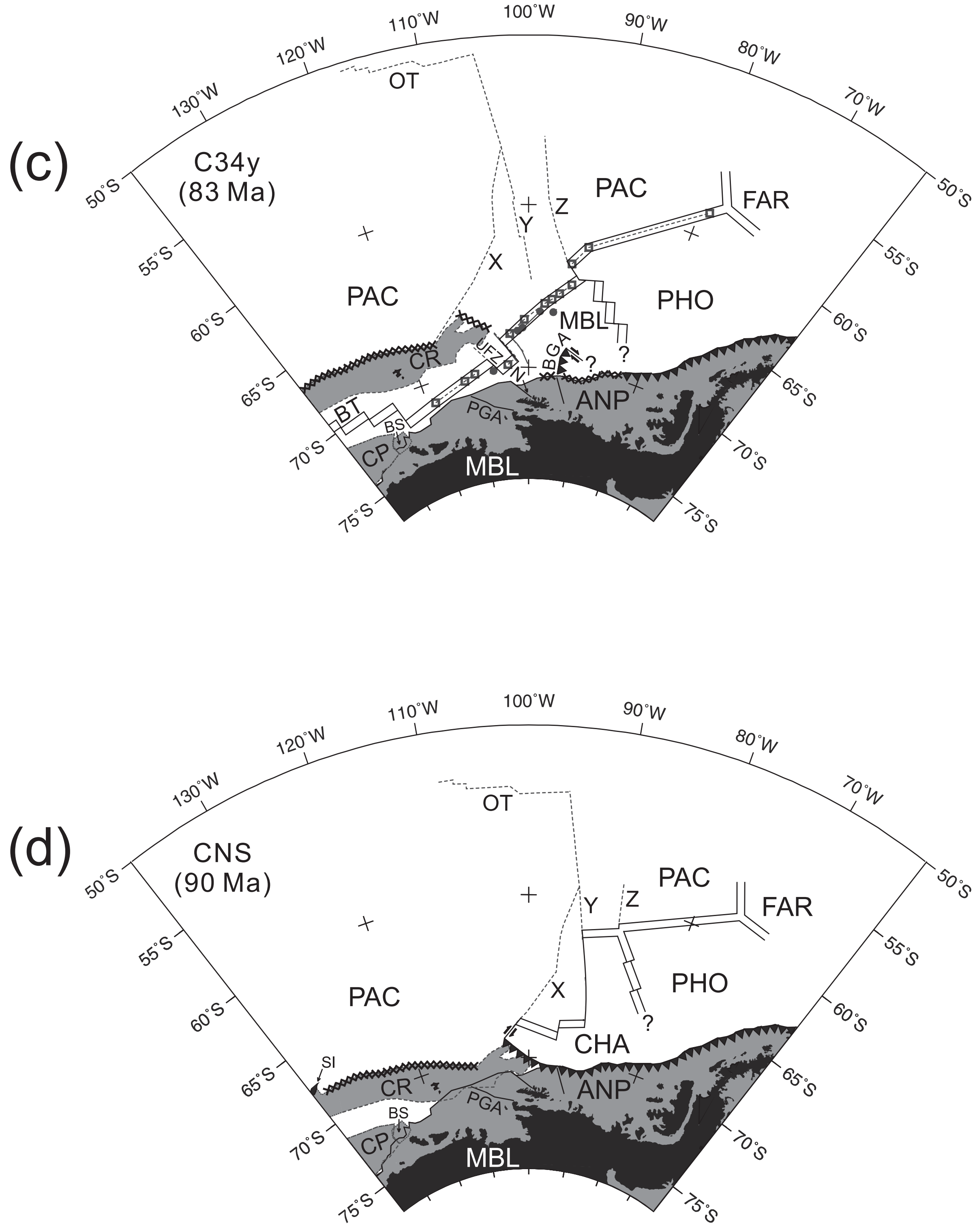


Figure 7. (continued)

magnetic anomaly picks are constrained by plate rotation calculations; ridges drawn without magnetic anomaly picks are schematic. Finite rotations used in this study are detailed in the figure captions and Table 1.

3.1. Chron 30r (67.7 Ma) Reconstruction

[28] Figure 7a shows that the PAC–BEL ridge during the latest Cretaceous included long-offset transform faults at the UFZ and TFZ. There is a marked difference between the trend of the ridge at this time and that of the flanking anomaly 33y trends, shown particularly clearly between 120° and 130°W (Stock et al., submitted manuscript, 1997). An anticlockwise rotation in fracture zone trends southeast from the tip of Chatham Rise also appears to date from chron 33y (Figures 7a and 7b). We interpret this as evidence that independent Bellingshausen plate motion began at

about chron 33y (73.6 Ma). This interpretation is reinforced by the fact that Bellingshausen plate features fit well in older reconstructions when rotated back to their chron 33y positions, but any further rotation would be difficult to accommodate in those reconstructions (see section 3.3, Figures 7c, 7d, 8a, and 8b).

[29] The Bellingshausen plate was probably bordered to the east by a Bellingshausen–Phoenix (BEL–PHO) ridge at this time. A quantitative estimate of Phoenix plate motion suggests that it was moving ESE at >100 mm/yr relative to Marie Byrd Land between chrons 34 and 31 (83–68 Ma) [*McCarron and Larter*, 1998]. By comparison Bellingshausen–Marie Byrd Land (BEL–MBL) motion was slow [*Cande et al.*, 1995; *Heinemann et al.*, 1999], so the motion of the Phoenix plate relative to the Bellingshausen plate would have been similar to its motion relative to Marie Byrd Land. This implies divergent BEL–PHO motion in the Bellingshausen Sea, and this divergence probably continued until independent Bellingshausen plate motion ceased as part of a widespread plate reorganization in the South Pacific at chron 27 (61.1 Ma) [*Cande et al.*, 1995]. At that time the BEL–PHO ridge was rendered inactive by a ridge jump westward to the DGGA, where ANT–PHO spreading was initiated (see section 2.2) [*Larter et al.*, 1999]. All of the ocean floor which lay to the east of the DGGA at chron 27, including the extinct BEL–PHO ridge, has since been subducted beneath the Antarctic Peninsula.

[30] Farther south, we consider that the BGA and the continental margin off Thurston Island probably accommodated convergent motion between the Bellingshausen and West Antarctic plates (MBL and ANP) at the time of this reconstruction, explaining the thick wedges of sediment and deformation structures observed on seismic reflection profiles across the BGA and across the margin [*Cunningham et al.*, 2002]. The location of the BEL–MBL stage rotation pole calculated for the interval between chrons 32n.1r and 28r (71.5–63.8 Ma; Table 2) is consistent with such motion (pole location marked by white circle in Figure 7a). It is also consistent with an extensional BEL–MBL plate boundary on the western side of the Bellingshausen plate, which appears to have been active at this time (near 126°W) [*Heinemann et al.*, 1999].

3.2. Chron 33y (73.6 Ma) Reconstruction

[31] Figure 7b shows a reconstruction for the time at about which we consider independent Bellingshausen plate motion began, within the seaway between Chatham Rise and Marie Byrd Land. At chron 33y, the PAC–BEL ridge had both right- and left-stepping offsets; the long transform offset at the UFZ shown in Figure 7a developed after this time as the ridge segments reorientated in response to the change in spreading direction associated with the onset of PAC–BEL motion. From interpretation of seismic profiles across the BGA, we suspect that convergent deformation across the BGA was already underway by this time, preceding the onset of independent Bellingshausen plate motion [*Cunningham et al.*, 2002]. In this case the earlier convergence represents slow relative motion between Marie Byrd Land and ocean floor attached to the Antarctic Peninsula.

[32] Two small fracture zones northeast of the UFZ appear to be misaligned in Figure 7b. This could indicate that the features digitized are not actually a pair of conjugate structures: the southwestern of the two fracture zones in the Bellingshausen Sea actually aligns well with the northeastern of the two near Chatham Rise. Alternatively the misalignment might indicate a small error in the chron 33y finite rotation used. As we do not have all the magnetic anomaly and fracture zone picks used in calculating this rotation we are not in a position to evaluate this possibility.

3.3. Chron 34y (83 Ma) Reconstruction With Fixed West Antarctic Margin

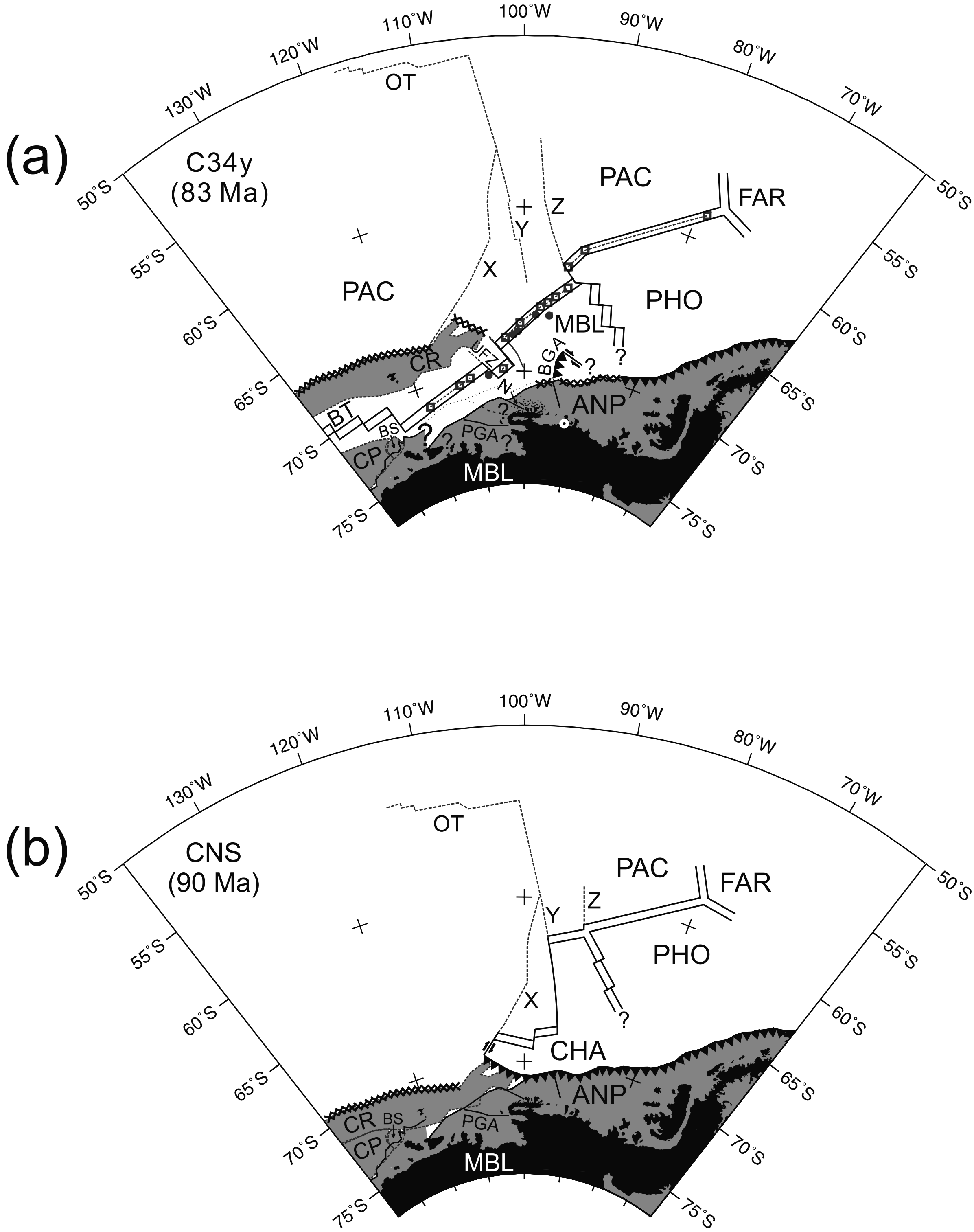
[33] Figure 7c shows an early stage in the development of the seaway between Chatham Rise and Marie Byrd Land, probably preceding the onset of independent Bellingshausen plate motion. It depicts a tectonic setting very similar to that around the modern Gulf of California. West of 126°W, Campbell Plateau and the Bollons Seamount are reconstructed to their prerift positions against Marie Byrd Land, as breakup occurred there shortly after chron 34y [*Stock et al.*, 1996; *Sutherland*, 1999]. The presence of anomaly 34y on marine magnetic profiles southeast of the Chatham Islands (Figures 3 and 4) indicates that organized seafloor spreading was established there by this time, and we suspect that the Late Cretaceous rifting of Bounty Trough to the east had finished [*Davy*, 1993; *Carter et al.*, 1994]. This reconstruction places the PAC–MBL ridge close to the southern margin of the seaway (e.g. near 115°W, Figure 7c). It is possible that such a situation could have resulted from highly asymmetric extension during the earliest stages of separation of Chatham Rise from Marie Byrd Land. However, we suspect that the asymmetric position of the ridge in this reconstruction is actually a consequence of the assumption that Bellingshausen plate motion did not affect the Marie Byrd Land margin being incorrect (see alternative reconstruction in Figure 8a).

[34] We used a PAC–MBL finite rotation derived from a tight fit of Campbell Plateau with Marie Byrd Land (no. 7, Table 1; Figure 9) to reconstruct Pacific plate features in Figure 7c, thereby making the implicit assumption that there was no relative motion between Campbell Plateau and Chatham Rise after chron 34y. If any subsequent relative motion did take place between these two blocks, then Chatham Rise and the spreading ridge to its south should be reconstructed to a position even closer to the West Antarctic margin than shown in Figure 7c. Magnetic anomaly picks and fracture zones in the Bellingshausen Sea have been reconstructed using a BEL–MBL finite rotation for chron 33y (no. 6, Table 1). Additional rotation about the same pole would place these features farther southwest. The fact that there is such a good fit between Pacific and Bellingshausen features on this reconstruction supports our interpretation that independent Bellingshausen plate motion began at about chron 33y.

[35] In this reconstruction lineament Z connects with a PAC–PHO–MBL triple junction and we interpret Z as a triple junction trace. If the rates of PAC–PHO and PAC–MBL spreading observed between anomalies 34y and 33y are extrapolated back into the CNS, the length of Z suggests that the triple junction developed a few million years before separation of Chatham Rise from Marie Byrd Land. In this case it probably originated by separation of the southwestern part of the Phoenix plate from the main body of that

plate during the latter part of the CNS. This is analogous to the way in which the Rivera and Cocos plates were formed by fragmentation of the Farallon plate during the late Tertiary [*Menard*, 1978; *Atwater*, 1989]. *McCarron and Larter* [1998] previously suggested the possibility of such fragmentation of the Phoenix plate during the Late Cretaceous or early Tertiary and proposed the name "Charcot" plate (CHA) for the southwestern, former Phoenix plate fragment.

[36] The easternmost segment of the PAC–MBL ridge in Figure 7c is considerably farther from the Antarctic continental margin than the other segments of this ridge. This ridge configuration suggests that the oldest ocean floor between this ridge segment and the margin formed before separation of Chatham Rise from Marie Byrd Land. Therefore our reconstructions imply that the ocean floor on both sides of the BGA probably formed at the PAC–CHA ridge during the latter part of the CNS (Figure 7d), and the



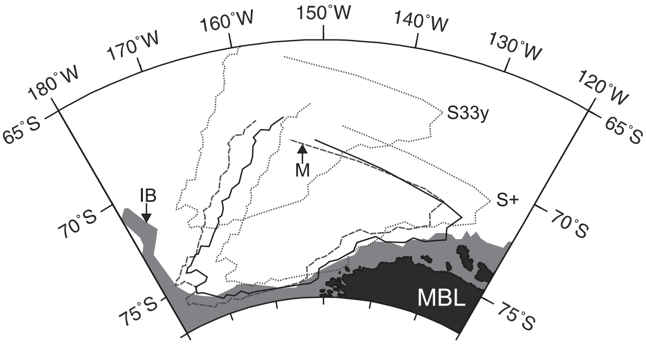


Figure 9. Reconstructed positions of Campbell Plateau (CP) in the Marie Byrd Land (MBL) reference frame using different PAC–MBL rotations, plotted on polar stereographic projection. The present-day position of the CP outline in shown in Figure 2a, and the MBL outline is the same as shown in Figure 2b. Dashed line "M" is the position resulting from the PAC–MBL "FIT" finite rotation of *Mayes et al.* [1990] (no. 11, Table 1). Dotted line "S33y" is the position resulting from a PAC–MBL finite rotation for chron 33y calculated by Stock et al. (submitted manuscript, 1997) (no. 4, Table 1). Dotted line "S+" is the position resulting from a finite rotation with the same pole position, but with the rotation angle increased to place the reconstructed position of the southeastern margin of CP approximately coincident with the MBL margin (no. 10, Table 1). The solid line shows the fit of CP to MBL proposed in this paper, which is the basis for the PAC–MBL finite rotation for chron 34y used in Figures 7 and 8 (no. 7, Table 1). IB, Iselin Bank; MBL, Marie Byrd Land.

western part of this ridge reorientated to become part of the PAC–MBL ridge as Chatham Rise separated from Marie Byrd Land.

3.4. Cretaceous Normal Superchron (90 Ma) Reconstruction With Fixed West Antarctic Margin

[37] Figure 7d shows a possible fit of Chatham Rise against the West Antarctic continental margin. This fit assumes that the part of Chatham Rise at the northern end of the UFZ reconstructs to the offset in the Antarctic margin at the NGL. Lineaments X, Y and Z on the Pacific plate have been reconstructed using the same PAC–MBL finite rotation determined for the fit of Chatham Rise (no. 8, Table 1). If the PAC–MBL half-spreading rate measured between anomalies 34 and 33 on profiles south of Chatham Rise (32 mm/yr) is extrapolated back to the margin, the estimated age of breakup is 90 Ma. By this time subduction along the northern margin of Chatham Rise had already ceased [*Bradshaw*, 1989], possibly as a result of the Hikurangi Plateau colliding with the margin. Based on the age distribution of calc-alkaline plutons in Marie Byrd Land, *Storey et al.* [1999] suggested that subduction ceased at *c*. 108 Ma in the west but persisted until *c*. 95 Ma along the eastern part of Chatham Rise.

[38] The PAC–PHO ridge position has been estimated by extrapolating the average half-spreading rates measured between chrons 34y and 33y east of lineation Z (80 mm/yr) back to 90 Ma. We interpret the northern part of lineament Z as the trace of a PAC–PHO–CHA triple junction (see section 3.3). The continuity of lineament Z implies that the ends of the PAC–PHO and PAC–CHA ridges must have remained close together during the formation of the triple junction trace and that there was no large ridge jump. The closest modern analogy is the Pacific–Nazca–Cocos triple junction. Migration of the PAC–CHA ridge segment between Y and Z southward to the position of the PAC–MBL ridge at chron 34y requires that this segment kept spreading at a fast rate similar to that of the PAC–PHO ridge until shortly before chron 34y. This in turn requires that subduction of the eastern part of the Charcot plate continued until shortly before chron 34y, in order to remove most of the large amount of ocean floor produced on the south flank of this fast spreading ridge segment. However, if the easternmost segment of the PAC–MBL ridge formed by reorientation of the western part of the PAC–CHA ridge as Chatham Rise separated from Marie Byrd Land at about 90 Ma, then the western part of the PAC–CHA ridge must already have been close to the eastern tip of Chatham Rise at that time. These considerations suggest to us that there was probably a long transform offset in line with lineament Y prior to 90 Ma, and the western part of the Charcot plate was captured by Marie Byrd Land at the time of breakup. In this case subduction along the part of the West Antarctic margin where the western part of the Charcot plate had been subducting would have stalled at the time of breakup. The youngest radiometric ages from calc-alkaline rocks from the

Figure 8. (opposite) Alternative (preferred) Late Cretaceous tectonic reconstructions of the Pacific margin of Antarctica in the Marie Byrd Land (MBL) reference frame, assuming that the Bellingshausen plate incorporated part of the Antarctic continental shelf in the Amundsen and Bellingshausen Seas, including Thurston Island. Reconstructions plotted on polar stereographic projection. Abbreviations as for Figure 7. (a) Reconstruction for chron 34y (83 Ma). All Pacific features (open squares and dashed lines), except Bollons Seamount (BS), have been rotated using a PAC–MBL finite rotation derived from tight fit of Campbell Plateau (CP) with MBL (no. 7, Table 1). BS has been reconstructed to the tip of CP. All Bellingshausen features (solid circles and lines) and the part of the Antarctic continental margin between about 125°W and 95°W (including the PGA, NGL and Thurston Island) have been rotated using a chron 33y BEL–MBL finite rotation (no. 6, Table 1), with the implicit assumption that there was no BEL–MBL motion before chron 33y. The unrotated continental margin (as in Figure 7) is shown by faint dotted lines. The chron 33y BEL–MBL finite rotation pole (no. 6, Table 1) is marked with a white circle at 73.08°S, 91.41°W. (b) Reconstruction for Cretaceous Normal Superchron (90 Ma). All Pacific features (dashed lines), except CP and BS, have been rotated using a PAC–MBL finite rotation derived from tight fit of Chatham Rise with the reconstructed position of the part of the Antarctic continental margin between 120°W and 100°W (no. 9, Table 1). CP and BS are shown in the same positions as in (a). The part of the Antarctic continental margin between about 125°W and 95°W (including the PGA, NGL and Thurston Island) has been reconstructed as in (a).

Table 2. Finite Rotations and Stage Rotations Used to Calculate BEL–MBL Stage Rotation for Chrons C32n.1r–C28r (71.5–63.8 Ma)

No.	Plate Pair	Reference Frame	Chrons	Latitude	Longitude	Angle	Comment
12	PAC–BEL	Finite	C28r	70.43	−56.55	46.35	(Stock et al., submitted manuscript, 1997)
13	PAC–BEL	Finite	C32n.1r	71.4	−42.69	59.57	(Stock et al., submitted manuscript, 1997)
14	BEL–PAC	PAC	C32n.1r–C28r	61.61	−12.38	−13.8	Sum of no. 12 and no.13 (reversed)
15	PAC–MBL	Finite	C28r	70.55	−55.72	47	(Stock et al., submitted manuscript, 1997)
16	PAC–MBL	Finite	C32n.1r	67.1	−57.4	50.48	(Stock et al., submitted manuscript, 1997)
17	PAC–MBL	MBL	C32n1.r–C28r	29.59	−46.08	4.52	Sum of no. 15 (reversed) and no. 16
18	BEL–PAC	MBL	C32n.1r–C28r	74.3	10.1	−13.8	No. 14 rotated to MBL ref. frame
19	BEL–MBL	MBL	C32n.1r–C28r	−73.64	−101.04	11.66	Sum of no. 18 and no. 17

corresponding sectors of Ellsworth Land (Figure 2b) are consistent with this scenario: these are 87 ± 2 Ma (K–Ar) and 89 ± 1 Ma (Ar–Ar) from a calcic granodiorite in the area southeast of the BGA [*Pankhurst et al.*, 1993]. A little farther west, the youngest ages from calc-alkaline rocks from the Jones Mountains (in the part of Ellsworth Land south of the eastern tip of Thurston Island) are 91 ± 1 Ma from silicic tuffs and agglomerates, and 89 ± 3 Ma from felsic dykes (both Rb–Sr) [*Pankhurst et al.*, 1993].

[39] In Figure 7d, the shape of Chatham Rise and the Marie Byrd Land margin does not permit complete closure of Bounty Trough at fit, which would imply that only *c*. 130 km of the *c*. 300 km width of the eastern part of the trough is a result of Late Cretaceous extension associated with breakup. However, an alternative reconstruction which permits the full width of the Bounty Trough to have formed by Late Cretaceous extension, and which we prefer, is shown in Figure 8b (see section 3.6).

3.5. Chron 34y (83 Ma) Reconstruction With Bellingshausen Plate Motion Affecting West Antarctic Margin

[40] Figure 8a shows an alternative reconstruction to Figure 7c for the southern Pacific Ocean at chron 34y. This is our preferred reconstruction and shows the effect of subsequent Bellingshausen plate motion on the West Antarctic continental margin, assuming that the plate included the part of the margin between 120° and 95°W. The PGA, NGL and Thurston Island have also been rotated with this part of the margin, using a BEL–MBL finite rotation for chron 33y (no. 6, Table 1). We think that these features moved northward relative to the rest of West Antarctica between chrons 33y and 27 (73.6–61.1 Ma) as part of the Bellingshausen plate. By chron 27 they reached their present-day positions, which are shown as dotted lines in Figure 8a. Reconstruction of the position of Thurston Island based on the assumption that it moved as part of the Bellingshausen plate results in near-perfect closure of Peacock Sound, the narrow strait between the island and the mainland.

[41] In contrast to Figure 7c, this reconstruction places the PAC–MBL ridge along the axis of the seaway, consistent with symmetric extension during the earliest stages of separation of Chatham Rise from Marie Byrd Land. The southern boundary of the Bellingshausen plate within West Antarctica remains poorly defined, and may have been diffuse. However, we speculate that tectonic strain between the Bellingshausen and Marie Byrd Land plates may have been partly accommodated by structures corresponding to the PGA and NGL. It may be more than coincidence that these two lineaments, and the part of the BGA crossing the continental shelf, radiate from the calculated position of the chron 33y BEL–MBL finite rotation pole (marked by a white circle in Figure 8a).

3.6. Cretaceous Normal Superchron (90 Ma) Reconstruction With Bellingshausen Plate Motion Affecting West Antarctic Margin

[42] Figure 8b shows an alternative reconstruction to Figure 7d for the fit of Chatham Rise to West Antarctica. This is our preferred reconstruction, allowing for the inferred effects of Bellingshausen plate motion on the West Antarctic continental margin as described above. The modified shape of the Antarctic margin now permits complete closure of Bounty Trough at fit, which is consistent with the full 300 km width of the eastern part of the Trough having formed by Late Cretaceous extension. Lineaments X, Y and Z on the Pacific plate have been reconstructed using the same PAC–MBL finite rotation determined for the revised fit of Chatham Rise (no. 9, Table 1). This places them slightly farther west and with their trends slightly rotated anticlockwise compared to their positions in Figure 7d. Other oceanic features have been placed in the same positions relative to these lineaments as in Figure 7d, and our interpretation of lineament Z and the history of PAC–CHA spreading is unaffected by the differences between these two reconstructions.

[43] The reconstruction in Figure 8b suggests that the BGA may have developed from a fracture zone conjugate to lineament Y. In section 3.4 we inferred that there was a long transform offset in line with Y prior to 90 Ma, and that subduction of the part of the Charcot plate to the west of this probably stalled at the time Chatham Rise separated from Marie Byrd Land. This scenario implies that the fracture zone conjugate to Y became a ridge-trench transform at the time of breakup. Subsequent changes in plate motions resulting in a small amount of convergence across this structure provide a viable explanation for features observed on seismic profiles across the BGA [*Cunningham et al.*, 2002].

4. Discussion

[44] The new reconstructions presented here show the regional constraints on the tectonic evolution of the Bellingshausen and Amundsen Sea regions during the Late Cretaceous. They provide some clues about the probable time of onset of independent Bellingshausen plate motion, and show the implications of different assumptions about the position and nature of the southern boundary of that plate. The earliest reconstructions also reveal the tectonic

framework in the southernmost Pacific Ocean during the breakup of the former Pacific margin of Gondwana.

4.1. The Ocean Basement Near the Bellingshausen Gravity Anomaly

[45] Marine magnetic profiles either side of the BGA do not define a clear pattern of lineations (Figure 5). The reconstructions in Figures 7 and 8 suggest that the ocean crust in this area is the oldest preserved in the Bellingshausen and Amundsen Seas. The absence of magnetic lineations is explained by the formation of this crust at the PAC–CHA ridge during the latter part of the CNS, prior to separation of Chatham Rise from Marie Byrd Land.

4.2. Late Cretaceous Subduction at the Antarctic Peninsula Pacific Margin

[46] The inferred existence of a slow-spreading ridge forming the western boundary of the Phoenix plate during the Late Cretaceous (Figures 7 and 8) is consistent with some geological observations from the southern part of the Antarctic Peninsula which suggest Late Cretaceous ridge subduction. On the basis of analyses of mafic dykes from the southern Antarctic Peninsula, *Scarrow et al.* [1997, 1998] interpreted a period of compositionally diverse magmatism between 95 and 65 Ma as resulting from spreading ridge subduction. Furthermore, high-Mg andesite lavas in southern Alexander Island, which probably erupted at *c*. 75 Ma [*McCarron and Millar*, 1997], have been interpreted as having been generated by partial melting of forearc mantle at shallow depth (<50 km) triggered by an increase in geothermal gradient associated with ridge subduction [*McCarron and Larter*, 1998; *McCarron and Smellie*, 1998].

[47] If PAC–PHO spreading during the CNS was as fast as between chrons 34y and 33y (an average of 80 mm/yr half rate), then our new reconstructions imply that, during the period they represent (90–67.7 Ma), Phoenix plate ocean floor generated at the PAC–PHO ridge was never older than 14 Myr when it was subducted at the Antarctic Peninsula margin. There are few places where it can be shown there has been subduction of such young ocean floor produced at such high spreading rates for such a long time interval, and therefore the Late Cretaceous subduction-related magmatic rocks of the Antarctic Peninsula provide a record of the magma compositions resulting from this kind of tectonic scenario.

4.3. Southern Boundary of the Bellingshausen Plate

[48] Previous studies have left the question of whether or not the Bellingshausen plate included any part of continental West Antarctica unresolved. Stock et al. (submitted manuscript, 1997) and *Heinemann et al.* [1999] speculated that the southern boundary of the Bellingshausen plate could have been located near the West Antarctic continental margin in the Amundsen Sea, or could have continued from the BEL–MBL divergent boundary at *c*. 126°W into the Amundsen Sea continental shelf.

[49] A seismic reflection profile (AWI-94042) that crosses the West Antarctic continental margin near 104°30′W does not show any evidence of tectonic structures [*Cunningham et al.*, 2002]. However, the profile does show a thick glacial-margin sediment wedge on this part of the margin, so it remains possible that tectonic structures lie buried and are obscured by seafloor multiple reverberations.

[50] Our new fit of Chatham Rise against the West Antarctic margin (Figure 8b) suggests to us that the Bellingshausen plate did incorporate part of the West Antarctic continental margin. We speculate that tectonic structures represented by the PGA and NGL, and the part of the continental margin north of Thurston Island, may have accommodated BEL–MBL motion. We offer two alternative explanations for development of these structures:

1. The southern boundary of the Bellingshausen plate could have been diffuse, so that BEL–MBL motion was distributed between several structures, including those along the PGA, the NGL, and the part of the margin north of Thurston Island.
2. The BEL–MBL boundary could have stepped from one site to another during the lifetime of the Bellingshausen plate, perhaps northward from a site near the coast of Marie Byrd Land, to the PGA, the NGL, and finally to the continental margin north of Thurston Island.

[51] On Thurston Island a mafic to silicic, mainly E–W striking, swarm of dykes intrude all other lithological groups on the island. No radiometric age data on these dykes have been published, but their emplacement has been assumed to be related to extensional stresses at the time of cessation of subduction and rifting of Chatham Rise from West Antarctica [*Storey et al.*, 1991; *Leat et al.*, 1993]. However, the observation that reconstructing the position of Thurston Island as part of the Bellingshausen plate results in near-perfect closure of Peacock Sound (Figure 8a) suggests an alternative possibility: the emplacement of the dykes may have been related to extensional stresses resulting from BEL–MBL motion between chrons 33y and 27 (73.6–61.1 Ma). This hypothesis can be tested by radiometric dating of the dykes.

4.4. Cenozoic Deformation in Antarctica

[52] *Cande et al.* [2000] proposed that there was relative motion between Marie Byrd Land and East Antarctica in Eocene and Oligocene time, resulting in roughly 180 km of separation in the western Ross Sea embayment. They did not attempt to define the eastern boundary of the Marie Byrd Land plate, but it seems to us doubtful that it included the Antarctic Peninsula, as there is no evidence of a tectonic boundary between the Antarctic Peninsula and East Antarctica during Cenozoic time, and Late Cretaceous paleomagnetic results from the Antarctic Peninsula are inconclusive [*DiVenere et al.*, 1994]. If the Antarctic Peninsula has remained fixed to East Antarctica during the Cenozoic, then the finite rotation estimated by *Cande et al.* [2000] to describe the full amount of Eocene and Oligocene extension in the western Ross Sea would place the reconstructed position of the Antarctic Peninsula 150–170 km northwest of where it is shown in Figures 7 and 8.

5. Conclusions

[53] New Late Cretaceous tectonic reconstructions, together with new marine geophysical data collected in the Bellingshausen Sea [*Cunningham et al.*, 2002], provide

insight into regional constraints on tectonic evolution of the Pacific margin of Antarctica since 90 Ma:

1. Chatham Rise started to separate from West Antarctica at about 90 Ma, and the Bounty Trough probably started to open at the same time. By chron 34y (83 Ma) organized seafloor spreading was established southeast of the Chatham Islands at the PAC–MBL/PAC–BEL ridge. Campbell Plateau started to separate from West Antarctica later, during chron 33r (83.0–79.1 Ma).

2. The ocean crust either side of the BGA is the oldest preserved in the Bellingshausen and Amundsen Seas, having formed at a ridge between the Pacific and Charcot plates prior to separation of Chatham Rise from West Antarctica. The Charcot plate originated as a fragment of the Phoenix plate a few million years before Chatham Rise separated from West Antarctica.

3. Subduction of the Charcot plate stopped before chron 34y (83 Ma), and the BGA trough developed at the western margin of ocean crust that became coupled to the Antarctic Peninsula across the stalled subduction zone. Initial development of the BGA trough probably exploited a fracture zone in the former Charcot plate.

4. A prominent gravity lineament ("Z") northeast of Chatham Rise is the trace of a triple junction which developed as a result of the separation of the Charcot plate from the Phoenix plate. It was a PAC–PHO–CHA triple junction until shortly before chron 34y (83 Ma), then became a PAC–PHO–MBL triple junction until about chron 33y (73.6 Ma), and continued as a PAC–PHO–BEL triple junction until chron 27 (61.1 Ma). The existence of a slow spreading ridge to the southeast of this triple junction is consistent with geological observations from the Antarctic Peninsula which suggest Late Cretaceous spreading ridge subduction.

5. Assuming PAC–PHO spreading prior to chron 34y was as fast as between chrons 34y and 33y (an average of 80 mm/yr half rate), the new reconstructions imply that the Phoenix plate ocean crust subducted at the Antarctic Peninsula margin during the Late Cretaceous was never older than 14 Myr when it reached the trench.

6. Several observations suggest that independent Bellingshausen plate motion began at about chron 33y (73.6 Ma): (i) the PAC–BEL ridge rotated rapidly anticlockwise after chron 33y, (ii) an anticlockwise rotation in fracture zone trends southeast from the tip of Chatham Rise also appears to date from chron 33y, and (iii) Bellingshausen plate features fit well in pre-chron 33y reconstructions when rotated back to their chron 33y positions.

7. The Bellingshausen plate probably did incorporate part of the West Antarctic continental margin. Reconstructions for chron 34y in which part of the West Antarctic margin is assumed to have moved with the Bellingshausen plate place the PAC–MBL/PAC–BEL ridge along the axis of the developing seaway between Chatham Rise and Marie Byrd Land, and permit complete closure of the Bounty Trough at fit. The southern edge of the Bellingshausen plate may have been a diffuse boundary, or the plate boundary may have stepped from one location to another during the lifetime of the plate. We suggest that tectonic structures represented by the PGA and NGL, and the part of the continental margin north of Thurston Island, accommodated components of BEL–MBL motion.

8. Tectonism at the BGA probably stopped with the cessation of independent Bellingshausen plate motion at chron 27 (61.1 Ma). At the same time a westward ridge jump from the former BEL–PHO spreading center initiated ANT–PHO spreading at the DGGA.

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References

Atwater, T., Plate tectonic history of the northeast Pacific and western North America, in *Eastern Pacific Ocean and Hawaii*, The Geology of North America, N, edited by E. L. Winterer, D. M. Hussong, and R. W. Decker, pp. 21–72, GSA, Boulder, Colo., 1989.

Barker, P. F., The Cenozoic subduction history of the Pacific margin of the Antarctic Peninsula: Ridge crest-trench interactions, *J. Geol. Soc. London*, *139*, 787–801, 1982.

Barton, C. E., Revision of International Geomagnetic Reference Field released, *Eos Trans. AGU Electron. Suppl.*, 16 April 1996. (Available as http://www.agu.org/eos_elec/95242e.html)

Billen, M. I., and J. Stock, Morphology and origin of the Osbourn Trough, *J. Geophys. Res.*, *105*, 13,481–13,489, 2000.

Bradshaw, J. D., Cretaceous geotectonic patterns in the New Zealand region, *Tectonics*, *8*, 803–820, 1989.

Cande, S. C., and D. V. Kent, Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic, *J. Geophys. Res.*, *100*, 6093–6096, 1995.

Cande, S. C., E. M. Herron, and B. R. Hall, The early Cenozoic tectonic history of the southeast Pacific, *Earth Planet. Sci. Lett.*, *57*, 63–74, 1982.

Cande, S. C., C. A. Raymond, J. Stock, and W. F. Haxby, Geophysics of the Pitman Fracture Zone and Pacific–Antarctic plate motions during the Cenozoic, *Science*, *270*, 947–953, 1995.

Cande, S. C., J. M. Stock, R. D. Müller, and T. Ishihara, Cenozoic motion between East and West Antarctica, *Nature*, *404*, 145–150, 2000.

Carter, R. M., L. Carter, and B. Davy, Seismic stratigraphy of the Bounty Trough, south-west Pacific Ocean, *Mar. Pet. Geol.*, *11*, 79–93, 1994.

Cunningham, A. P., R. D. Larter, P. F. Barker, K. Gohl, and F. O. Nitsche, Multichannel seismic investigation of the 'Bellingshausen Gravity Anomaly' and West Antarctic continental margin near 95°W, in *Proceedings of the 8th International Symposium on Antarctic Earth Sciences*, *Bull. R. Soc. N. Z.*, *35*, 201–206, 2002.

Cunningham, A. P., R. D. Larter, P. F. Barker, K. Gohl, and F. O. Nitsche, Tectonic evolution of the Pacific margin of Antarctica, 2, Structure of Late Cretaceous–early Tertiary plate boundaries in the Bellingshausen Sea from seismic reflection and gravity data, *J. Geophys. Res.*, *107*, 10.1029/2002JB001897, in press, 2002.

Davy, B., The Bounty Trough—Basement structure influences on sedimentary basin evolution, in *South Pacific Sedimentary Basins, Sedimentary Basins of the World*, vol. 2, edited by P. F. Ballance, pp. 69–92, Elsevier Sci., New York, 1993.

DiVenere, V. J., D. V. Kent, and I. W. D. Dalziel, Mid-Cretaceous paleomagnetic results from Marie Byrd Land, West Antarctica, *J. Geophys. Res.*, *99*, 15,115–15,139, 1994.

Gohl, K., F. Nitsche, and H. Miller, Seismic and gravity data reveal Tertiary interplate subduction in the Bellingshausen Sea, southeast Pacific, *Geology*, *25*, 371–374, 1997.

Heinemann, J., J. Stock, R. Clayton, K. Hafner, S. Cande, and C. Raymond, Constraints on the proposed Marie Byrd Land–Bellingshausen plate boundary from seismic reflection data, *J. Geophys. Res.*, *104*, 25,321–25,330, 1999.

Herron, E. M., and B. E. Tucholke, Sea-floor magnetic patterns and basement structure in the southeastern Pacific, *Initial Rep. Deep Sea Drill. Proj.*, *35*, 263–278, 1976.

Kimura, K., Geological and geophysical survey in the Bellingshausen Basin, off Antarctica, *Antarct. Rec.*, *75*, 12–24, 1982.

Larson, R. L., Superplumes and ridge interactions between Ontong Java and Manihiki Plateaus and the Nova-Canton Trough, *Geology*, *25*, 779–782, 1997.

Larson, R. L., M. B. Steiner, E. Erba, and Y. Lancelot, Paleolatitudes and tectonic reconstructions of the oldest portion of the Pacific plate: A comparative study, *Proc. Ocean Drill. Program Sci. Results*, *129*, 615–631, 1992.

Larter, R. D., and P. F. Barker, Effects of ridge crest-trench interaction on Antarctic–Phoenix spreading: Forces on a young subducting plate, *J. Geophys. Res.*, *96*, 19,583–19,607, 1991.

Larter, R. D., A. P. Cunningham, P. F. Barker, K. Gohl, and F. O. Nitsche, Structure and tectonic evolution of the West Antarctic continental margin and Bellingshausen Sea, *Korean J. Polar Res.*, *10*, 125–133, 1999.

Larter, R. D., M. Rebesco, L. E. Vanneste, L. A. P. Gambôa, and P. F. Barker, Cenozoic tectonic, sedimentary and glacial history of the continental shelf west of Graham Land, Antarctic Peninsula, in *Geology and Seismic Stratigraphy of the Antarctic Margin, 2, Antarctic Research Series*, vol. 71, edited by P. F. Barker and A. K. Cooper, pp. 1–27, AGU, Washinton D. C., 1997.

Leat, P. T., B. C. Storey, and R. J. Pankhurst, Geochemistry of Palaeozoic–Mesozoic Pacific rim orogenic magmatism, Thurston Island area, West Antarctica, *Antarct. Sci.*, *5*, 281–296, 1993.

Lonsdale, P., Geography and history of the Louisville hotspot chain in the southwest Pacific, *J. Geophys. Res.*, *93*, 3078–3104, 1988.

Luyendyk, B. P., Hypothesis for Cretaceous rifting of east Gondwana caused by subducted slab capture, *Geology*, *23*, 373–376, 1995.

Mayes, C. L., L. A. Lawver, and D. T. Sandwell, Tectonic history and new isochron chart of the South Pacific, *J. Geophys. Res.*, *95*, 8543–8567, 1990.

McAdoo, D. C., and S. Laxon, Antarctic tectonics: Constraints from an ERS-1 satellite marine gravity field, *Science*, *276*, 556–560, 1997.

McAdoo, D. C., and K. M. Marks, Gravity fields of the Southern Ocean from Geosat data, *J. Geophys. Res.*, *97*, 3247–3260, 1992.

McCarron, J. J., and R. D. Larter, Late Cretaceous to early Tertiary subduction history of the Antarctic Peninsula, *J. Geol. Soc. London*, *155*, 255–268, 1998.

McCarron, J. J., and I. L. Millar, The age and stratigraphy of forearc magmatism on Alexander Island, Antarctica, *Geol. Mag.*, *134*, 507–522, 1997.

McCarron, J. J., and J. L. Smellie, Tectonic implications of fore-arc magmatism and generation of high-magnesian andesites: Alexander Island, Antarctica, *J. Geol. Soc. London*, *155*, 269–280, 1998.

Menard, H. W., Fragmentation of the Farallon plate by pivoting subduction, *J. Geol.*, *86*, 99–110, 1978.

Molnar, P., T. Atwater, J. Mammerickx, and S. M. Smith, Magnetic anomalies, bathymetry, and tectonic evolution of the South Pacific since the Late Cretaceous, *Geophys. J. R. Astron. Soc.*, *49*, 383–420, 1975.

National Geophysical Data Center, *Marine Geophysical Trackline Data (GEODAS/TRACKDAS). Data Announcement 96-MGG-01*, National Oceanographic and Atmospheric Administration, Boulder, Colo., 1996.

Nitsche, F. O., A. P. Cunningham, R. D. Larter, and K. Gohl, Geometry and development of glacial continental margin depositional systems in the Bellingshausen Sea, *Mar. Geol.*, *162*, 277–302, 2000.

Pankhurst, J. R., I. L. Millar, A. M. Grunow, and B. C. Storey, The Pre-Cenozoic magmatic history of the Thurston Island crustal block, West Antarctica, *J. Geophys. Res.*, *98*, 11,835–11,849, 1993.

Parsons, B., and J. G. Sclater, An analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res.*, *82*, 803–827, 1977.

Pitman, W. C., III, E. M. Herron, and J. R. Heirtzler, Magnetic anomalies in the Pacific and sea-floor spreading, *J. Geophys. Res.*, *73*, 2069–2085, 1968.

Sandwell, D. T., and W. H. F. Smith, Marine gravity-anomaly from Geosat and ERS-1 satellite altimetry, *J. Geophys Res.*, *102*, 10,039–10,054, 1997.

Scarrow, J. H., P. T. Leat, C. D. Wareham, and I. L. Millar, Geochemistry of mafic dykes in the Antarctic Peninsula continental-margin batholith: A record of arc evolution, *Contrib. Mineral. Petrol.*, *131*, 289–305, 1998.

Scarrow, J. H., A. P. M. Vaughan, and P. T. Leat, Ridge-trench collision-induced switching of arc tectonics and magma sources: Clues from Antarctic Peninsula mafic dykes, *Terra Nova*, *9*, 255–259, 1997.

Stock, J., and P. M. Molnar, Revised history of early Tertiary plate motion in the south-west Pacific, *Nature*, *325*, 495–499, 1987.

Stock, J. M., S. C. Cande, and C. A. Raymond, Updated history of the Bellingshausen plate(abstract), *Eos Trans. AGU*, *77*(46), Fall Meet. Suppl., F647, 1996.

Storey, B. C., R. J. Pankhurst, I. L. Millar, I. W. D. Dalziel, and A. M. Grunow, A new look at the geology of Thurston Island, in *Geological Evolution of Antarctica*, edited by M. R. A. Thomson, J. A. Crame, and J. W. Thomson, pp. 399–403, Cambridge Univ. Press, New York, 1991.

Storey, B. C., P. T. Leat, S. D. Weaver, R. J. Pankhurst, J. D. Bradshaw, and S. Kelley, Mantle plumes and Antarctica-New Zealand rifting: Evidence from mid-Cretaceous mafic dykes, *J. Geol. Soc. London*, *155*, 659–671, 1999.

Sutherland, R., Basement geology and tectonic development of the greater New Zealand region: An interpretation from regional magnetic data, *Tectonophysics*, *308*, 341–362, 1999.

Sutherland, R., and C. Hollis, Cretaceous demise of the Moa plate and strike-slip motion at the Gondwana margin, *Geology*, *29*, 279–282, 2001.

Watts, A. B., J. K. Weissel, R. A. Duncan, and R. L. Larson, Origin of the Louisville Ridge and its relationship to the Eltanin Fracture Zone system, *J. Geophys. Res.*, *93*, 3051–3077, 1988.

Weissel, J. K., D. E. Hayes, and E. M. Herron, Plate tectonic synthesis: The displacements between Australia, New Zealand, and Antarctica since the Late Cretaceous, *Mar. Geol.*, *25*, 231–277, 1977.

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