Cenozoic motion between East and West Antarctica

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The West Antarctic rift system is the result of late Mesozoic and Cenozoic extension between East and West Antarctica, and represents one of the largest active continental rift systems on Earth. But the timing and magnitude of the plate motions leading to the development of this rift system remain poorly known, because of a lack of magnetic anomaly and fracture zone constraints on seafloor spreading. Here we report on magnetic data, gravity data and swath bathymetry collected in several areas of the south Tasman Sea and northern Ross Sea. These results enable us to calculate mid-Cenozoic rotation parameters for East and West Antarctica. These rotations show that there was roughly 180 km of separation in the western Ross Sea embayment in Eocene and Oligocene time. This episode of extension provides a tectonic setting for several significant Cenozoic tectonic events in the Ross Sea embayment including the uplift of the Transantarctic Mountains and the deposition of large thicknesses of Oligocene sediments. Inclusion of this East–West Antarctic motion in the plate circuit linking the Australia, Antarctic and Pacific plates removes a puzzling gap between the Lord Howe rise and Campbell plateau found in previous early Tertiary reconstructions of the New Zealand region. Determination of this East–West Antarctic motion also resolves a long standing controversy regarding the contribution of deformation in this region to the global plate circuit linking the Pacific to the rest of the world.

West Antarctica has long occupied an enigmatic position in plate reconstructions. Unlike the East Antarctic craton, which is treated as a coherent block in reconstructions of Gondwanaland, West Antarctica consists of several smaller pieces that have moved relative to each other and to East Antarctica[1]. Palaeomagnetic data indicate that there has been at least 300 km of displacement and perhaps 40° to 90° of relative rotation between East Antarctica and West Antarctica since 100 Myr ago[2,3,4]. The evidence that there has been significant Cenozoic (post 65 Myr) extension is more controversial. Reconstructions have suggested that there has been little (< 50 km) extension in the last 85 Myr (ref. 5). However, if there has been an important episode of Cenozoic extension, it is likely to have occurred in the Ross Sea embayment, separating Marie Byrd Land from East Antarctica. Basins filled with late Cretaceous and younger sediments are found in both the eastern and western parts of the embayment. These basins form part of the West Antarctic rift system which, although largely aseismic, is considered active on the basis of abundant late Cenozoic volcanism and tectonism in the region[6]. Evidence for large amounts of Cenozoic extension include the episodic uplift of the Transantarctic Mountains, starting 50–55 Myr ago[7,8], and the development of sedimentary basins with more than 7 km of Cenozoic sediments[9,10] in the western part of the embayment. Recent drilling near Cape Roberts, Antarctica, has shown that greater amounts of sediments in these basins than previously thought are Oligocene in age[11], adding to the evidence for a large Cenozoic extensional event.

Plate tectonic constraints on East–West Antarctica motion since chron 34 (83 Myr; all chron ages are from ref. 12) come from seafloor spreading anomalies and fracture zones generated by Australia–East Antarctica spreading on the southeast Indian ridge (SEIR)[13,14], Pacific–West Antarctica spreading on the Pacific–Antarctic ridge[15,16] and, for the short time between chron 20 (43 Myr) and chron 8 (26 Myr), Australia–Pacific spreading in the Emerald and south Tasman ocean crust (STOC) basins that now straddle and are offset by the Macquarie ridge[17,18] (Fig. 1). For a plate reconstruction of this region to be considered accurate, plate motions calculated by adding the motion of Australia–East Antarctica, East Antarctica–West Antarctica and Pacific–West Antarctica

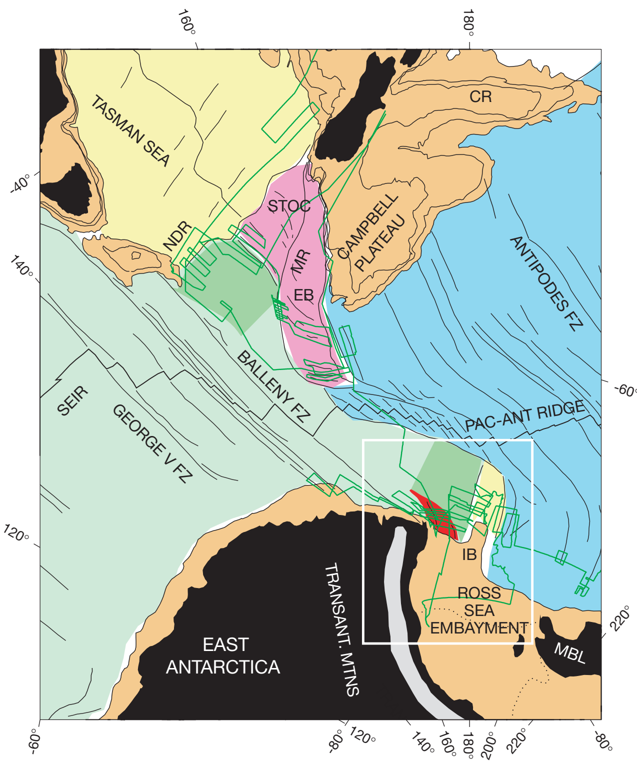

Figure 1 Classification of regions of southwest Pacific ocean crust by the spreading ridge at which they were formed. The two dark green regions east of the Balleny fracture zone were generated by Australia–West Antarctic spreading before chron 8. The red region was generated by East–West Antarctic spreading and the pink region by Australia–Pacific spreading, both between chrons 20 and 8. Light green, blue and yellow indicate regions generated by Australia–East Antarctic, Pacific–West Antarctic and Australia–Lord Howe rise (Tasman Sea) spreading, respectively. Dark green lines show the tracks of the RV *Ewing* cruise 9513 and RVIB *Palmer* cruises 9602 and 9702. Abbreviations: CR, Chatham rise; EB, Emerald basin; IB, Iselin bank; MR, Macquarie ridge; NDR, Nella Dan rift; MBL, Marie Byrd Land; SEIR, southeast Indian ridge. The white box shows the location of Fig. 3.

should predict a reasonable plate tectonic history for the Australia–Pacific boundary, and in particular, for the section of that boundary that runs through New Zealand and continues on to the southwest along the Macquarie ridge.

The best evidence for some relative motion between East and West Antarctica in Cenozoic time has been the observation of large misfits in Southwest Pacific reconstructions that do not include motion between East and West Antarctica. The original plate reconstructions for the early Tertiary predicted a large gap between the North and South islands of New Zealand which could only be eliminated by including 500 km of motion between East and West Antarctica[15]. Various modifications to the plate tectonic circuit have reduced the amount of this misfit[19,20], but the most recent rotation parameters for the SEIR and Pacific–Antarctic ridge still predict a gap of the order of 150 km between the Pacific and Australia plates south of New Zealand in the early Tertiary (Fig. 2a). Sutherland[18] derived a rotation for East–West Antarctica motion by assuming that this gap should be closed. However, his rotation was not well constrained and predicted highly oblique dextral extension in the Ross Sea embayment. Here we present new marine geophysical data from the region north of the Ross Sea and in the South Tasman Sea that allows us to directly calculate East–West Antarctic motion since the early Tertiary period. This motion is tightly constrained by a set of linear seafloor spreading magnetic anomalies, formed in Eocene and Oligocene time, that straddle a fossil spreading centre north of the western Ross Sea embayment.

Balleny fracture zone corridor

We constrained East–West Antarctic motion using the corridor of the southeast Indian ridge east of the Balleny fracture zone. Previous analyses[14,19] of magnetic and fracture zone data from the SEIR indicated that early Tertiary spreading east of the Balleny fracture zone may have occurred at a slightly faster rate than along the rest of the SEIR (dark green areas in Fig. 1). It was proposed that this discrepancy reflected relative motion between East and West Antarctica, as early Tertiary magnetic anomalies east of the Balleny fracture zone are found north of the Iselin bank, which, in turn, lies to the east of the axes of the Cenozoic basins in the western Ross Sea embayment. More recently, satellite-derived free-air gravity data[21] revealed the full extent of a graben structure, the Adare trough, north of the western Ross Sea, that had only been partially mapped by conventional methods[22] (Fig. 3). This structure was aligned with the western Ross Sea sedimentary basins and seemed likely to be related to East–West Antarctica extension.

Magnetics, gravity, swathmap bathymetry and seismic reflection data were collected in several important areas on the RV *Ewing* cruise 9513 and on the RVIB *Palmer* cruises 9602 and 9702. In addition, several magnetic profiles were collected east of the Balleny fracture zone on transits between Australia and Antarctica by the RV *Hakurei Maru* operated by the Japan National Oil Corporation[23,24]. Together, these data enable us to quantify the discrepancy in spreading rates and directions across the Balleny fracture zone and to calculate an Euler pole for mid-Cenozoic motion between East and West Antarctica.

Profiles collected on RVIB *Palmer* 9702 across the Adare trough show that a set of magnetic lineations straddles the trough and parallels the graben structure (Fig. 4a). Two profiles (C and D) are characterized by a double peak on the eastern rift flank followed further off axis by a prominent single peak. We identify this sequence as anomalies 11 to 13 and, based on the constant spreading rate model in Fig. 4a, infer that spreading was active between anomalies 18 and 9. The model profile in Fig. 4a indicates that spreading took place at the constant rate of 12.5 mm yr^{-1}, with a slight asymmetry in spreading rate: 5.5 mm yr^{-1} on the west flank, 7 mm yr^{-1} on the east flank.

The existence of this anomaly pattern suggests that the Adare trough was one limb of a ridge–ridge–ridge triple junction, and that the Adare trough, not the Balleny fracture zone, was the boundary between East and West Antarctica in Eocene and Oligocene time. To test this idea we analysed the misfits of the SEIR anomalies east of

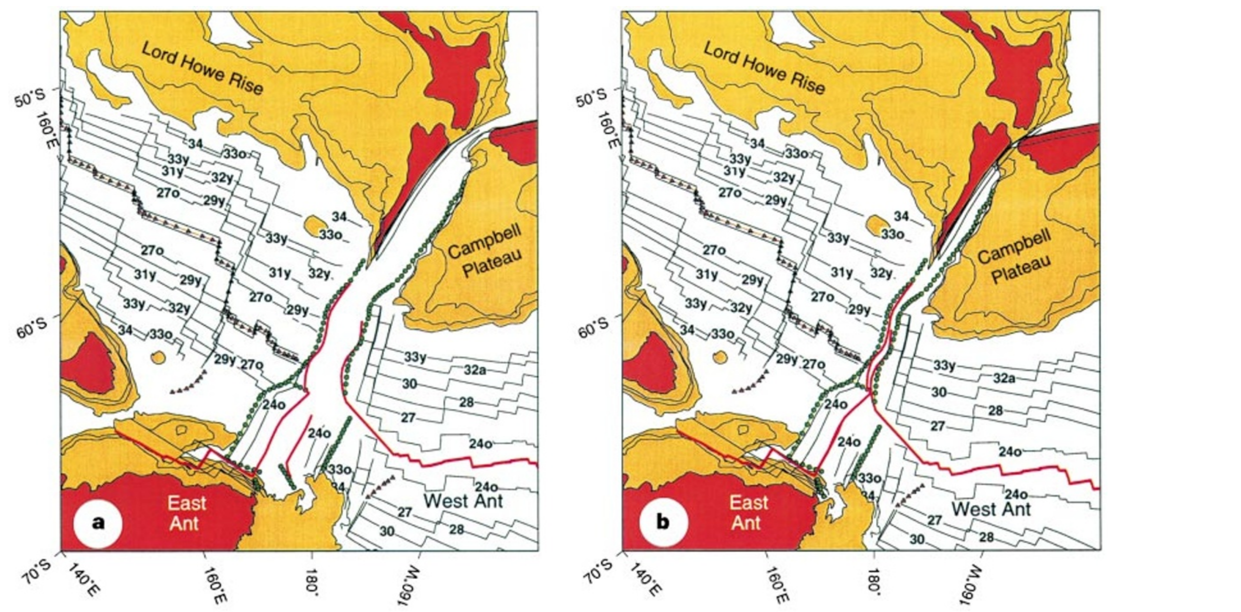

Figure 2 Two reconstructions of the Southwest Pacific for chron 20 constructed by restoring motion along the Pacific–Antarctica–Australia plate circuit. **a**, The plate circuit does not include any East–West Antarctic motion. There is a 150-km gap between the Campbell plateau and Lord Howe rise as well as in the anomaly 20o isochrons (red lines) north of the Ross Sea. **b**, The plate circuit includes an anomaly 20o rotation for East–West Antarctic motion calculated by extrapolating the anomaly 13o rotation as described. The addition of East–West Antarctic motion eliminates the gap in the Pacific–Australia plate boundary, indicating that the Adare trough is a critical missing plate boundary in the global plate circuit. **a**, **b**, Australia is restored to East Antarctica by a rotation of −24.55° about a pole at 15.07° N, 31.78° E (ref. 25) and the Pacific plate is restored to West Antarctica by a rotation of 35.32° about a pole at 74.78° N, 51.55° W (based in part on unpublished data of S. C. C. and J. M. S). East Antarctica is fixed. Red lines indicate the active plate boundary, brown triangles connected by brown lines indicate fossil spreading centres and green dots show tectonic discontinuities such as triple junction traces and ridge jumps.

the Adare trough that were caused by using rotations based on Australia–East Antarctica anomalies from the SEIR west of the Balleny fracture zone. Revised rotations for the SEIR have recently been calculated for anomalies 20o and 24o (ref. 25) and for anomalies 6o, 8o, 10o and 13o (Cande *et al.*, manuscript in preparation), where the suffix 'o' refers to the old end of the anomaly. Unlike previous studies, the revised rotations for anomalies 6o, 8o, 10o and 13o are based on data solely between the Amsterdam–St Paul fracture zone (at 75° E) and the George V fracture zone (at 140° E), thus avoiding potential errors associated with the existence, since at least chron 5, of a distinct Capricorn plate on the north side of the SEIR west of 75° E (ref. 26).

The revised SEIR rotations were used to rotate the anomaly locations from the Australian plate east of the Balleny fracture zone back to the Antarctica plate. These rotations confirm the result of a study[19] that found a misfit in anomalies 13o and 20o east of the Balleny fracture zone (Fig. 5). The rotated position of a small fracture zone that offsets anomaly 13, Fracture Zone A, when compared to its position on the Antarctic plate, indicates that there is a large oblique component to the misfit (Fig. 5). We find that the anomaly 10o and anomaly 13o locations east of the Adare trough are misfit by about 20 km and 75 km, respectively, whereas anomaly 20o locations are misfit by 180 km. Younger anomalies (6o and 8o) show no misfit and nor do the anomaly 10o and 13o identifications between the Balleny fracture zone and the Adare trough.

The most important aspect of Fig. 5 is that the size of the misfit in anomaly 13o is the same as the distance between the anomaly 13o locations across the axis of the Adare trough, confirming our identifications of the Adare trough anomaly sequence. We conclude that the Adare trough anomalies were formed by spreading on the third limb of a ridge–ridge–ridge triple junction between the Australia, East Antarctic and West Antarctic plates that started some time before chron 20 (43 Myr), spread uniformly between chrons 20 and 10 (28 Myr) and had ended by chron 8 (26 Myr). The Adare trough is a fossil rift valley that lay at the axis of the spreading centre when spreading ceased. Because the Adare trough is aligned with the Cenozoic basins of the western Ross Sea, we also conclude that the Adare trough anomalies directly record East–West Antarctic spreading.

The onset of this episode of East–West Antarctic motion can be constrained by analysing the misfit in anomalies older than chron 20. Unfortunately, ambiguity in the identification of anomaly 24 (53 Myr) and older anomalies north of the Iselin bank makes it difficult to determine when this motion started. In Fig. 4b we show magnetic and bathymetric profiles that cross the Nella Dan and Scott rifts, the tectonic boundaries bordering the south Tasman rise and the Iselin bank, respectively, where spreading on the SEIR initiated east of the Balleny fracture zone. Anomalies 21, 24 and 26 are relatively straightforward to identify on the young side of the Nella Dan rift (profiles N1 and N2). A model based on these identifications ('Model' in Fig. 4b) indicates that spreading on this section of the SEIR started around chron 29 (64 Myr). On the young side of the Scott rift side, north of the Iselin bank, anomalies 21, 24 and 26 can be identified that have the same spacing as on the Nella Dan rift (profiles S1 and S2); these are our preferred identifications of these anomalies. However, the character of anomalies 24 and 26 on the young side of the Scott rift is not as consistent as on the Nella Dan rift profiles and an alternative interpretation ('24?' in Fig. 4b) would move anomaly 24 closer to the Scott rift.

The ambiguity in the anomaly 24 identification affects the calculation of the onset of rifting between East and West Antarctica. With our preferred anomaly 24o identification, the misfit does not increase between anomalies 20o and 24o (Fig. 5), implying that East–West Antarctic motion started around chron 20. With the alternative anomaly 24o identification, there is an additional 25 km of misfit before chron 20, implying that there was extension in the 10-Myr interval between chrons 24 and 20. However, even with the alternative anomaly identification, the rate of opening between East and West Antarctic before chron 20 (roughly 2.5 mm yr^{-1}) is much slower than in the period between chrons 20 and 8.

East–West Antarctic Motion

We would have liked to determine an Euler pole for East–West Antarctica motion directly from the data on the Adare trough, but it is too short a feature and has no fracture offsets to constrain rotation parameters. However, anomaly 13o locations from the SEIR west and east of the Adare trough constrain Australia–East Antarctic and Australia–West Antarctic motions, respectively, and, when combined with the anomaly 13o locations from the Adare trough, they form a three-plate configuration (Fig. 6) that can be quantitatively solved for East–West Antarctic motion. We assume that no other active plate boundaries have disrupted the anomaly 13 isochrons since they were formed. Deformation of the southeast corner of the Australian plate[27] would add to the uncertainty of our calculation, but the lack of a misfit in anomaly 8 and younger anomalies suggests that such deformation has been minor. We used the fitting criteria of ref. 28 and the statistical algorithms of refs 29 and 30 to determine best-fit rotation parameters and 95% confidence limits for all three limbs of the triple junction. The anomaly 13o locations and fracture-zone crossings that constrain this geometry are shown in

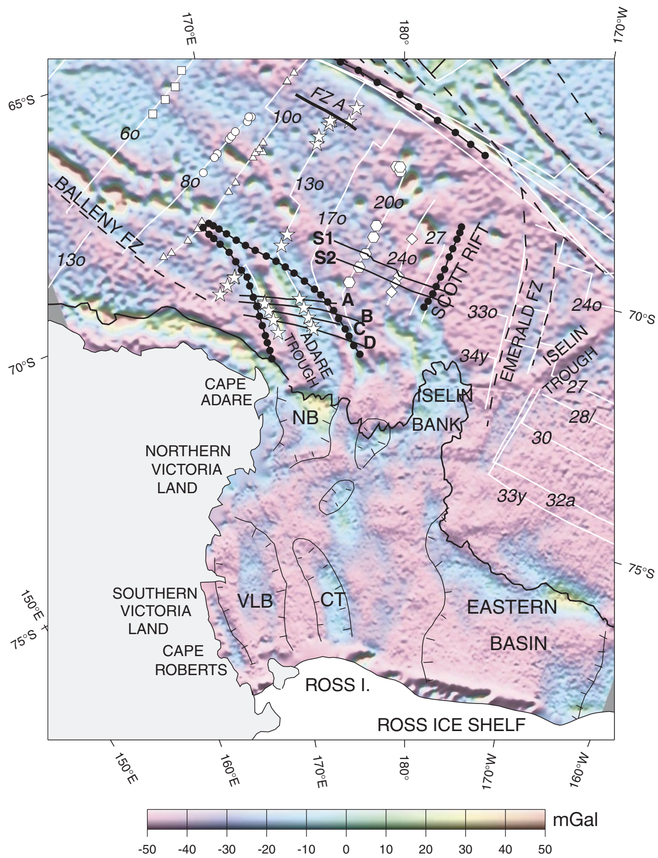

Figure 3 Tectonic features of the western Ross Sea region superimposed on the satellite-derived free-air gravity field. White lines denote isochrons; heavy black line shows 1,000-m contour; black dots indicate tectonic discontinuities. Boundaries of sedimentary basins in Ross Sea are from ref. 10. White filled symbols show control for magnetic isochrons from the Antarctic plate: square, anomaly 6o; circle, 8o; triangle, 10o; star, 13o; hexagon, 20o; diamond, 24o. VLB, Victoria Land Basin; NB, Northern Basin; CT, Central Trough. mGal, milligal. Gravity data are from ref. 21 (north of 72° S) and ref. 37 (south of 72° S).

Table 1 Finite rotations for anomaly 13o three-plate solution

Plate pair	Latitude (+°N)	Longitude (+°E)	Angle (degrees)
Australia & East Antarctica	−13.696	−146.025	20.485
Australia & West Antarctica	−12.600	−147.298	20.848
East Antarctica & West Antarctica	−18.146	−17.847	−0.696

Table 2 Covariance matrices for rotations in Table 1

Plate pair	*a*	*b*	*c*	*d*	*e*	*f*	*g*
Australia & East Antarctica	3.64	−4.09	2.03	6.16	−3.30	7.78	7
Australia & West Antarctica	5.06	−2.02	7.57	0.835	−2.99	11.4	5
East Antarctica & West Antarctica	2.19	0.0039	5.74	0.0041	0.0083	15.1	5

The covariance matrix is given by the formula

$$\frac{1}{\hat{\kappa}} * \begin{pmatrix} a & b & c \\ b & d & e \\ c & e & f \end{pmatrix} \times 10^{-g}$$

where the values a–f are given in radians squared.

Fig. 6. The fracture-zone crossings were digitized from plots of the satellite-derived free-air gravity field except for Fracture Zone A east of the Balleny fracture zone which is constrained by offsets in shipboard magnetic anomaly data.

Following the statistical method of ref. 30, uncertainties were assigned to the individual anomaly locations and fracture zone crossings. The anomaly locations and fracture zone crossings west of the Balleny fracture zone, which were digitized from Mercator plots, were assigned uncertainties of 7 km and 14 km, respectively. Anomaly locations from east of the Balleny fracture zone, which were digitized using an interactive computer program in which magnetic data points are directly associated with navigation data, were assigned uncertainties of 3 km. The points marking the location of Fracture Zone A were assigned an uncertainty of 9 km. The best-fit rotation parameters for the three plate boundaries are given in Table 1 and the associated covariance matrices constraining the 95% confidence limits are given in Table 2. The value of $\hat{\kappa}$, a parameter that indicates whether the uncertainties are relatively correct, was 0.63. This indicates that the uncertainties assigned to the data points are slightly underestimated. As a check, we note that applying the Australia–West Antarctic rotation to the anomaly 13o locations from the Australian plate east of the Adare trough eliminates the misfit in these anomalies (Fig. 5).

The 95% confidence region associated with the East–West Antarctica rotation is shown in the inset in Fig. 7. Although this confidence region is large, the rotation provides valuable constraints on the motion between East and West Antarctica. The shape of the confidence region indicates that the geometry of the anomaly 13o locations places a strong constraint on the direction to the Euler pole. A rotation anywhere within the 95% confidence region predicts large east–west extension in the Ross Sea embayment. In Fig. 7 we show the predicted amount of extension, and corresponding 95% confidence ellipses, at several positions in the Ross Sea. There would have been 75 km of extension in a roughly east–west direction for an active plate boundary anywhere in this region with 95% confidence limits on the order of ± 15 km in the northern end of the region and ±40 km in the southern end of the region. As anomaly 13o is less than 200 kyr younger than the Eocene/

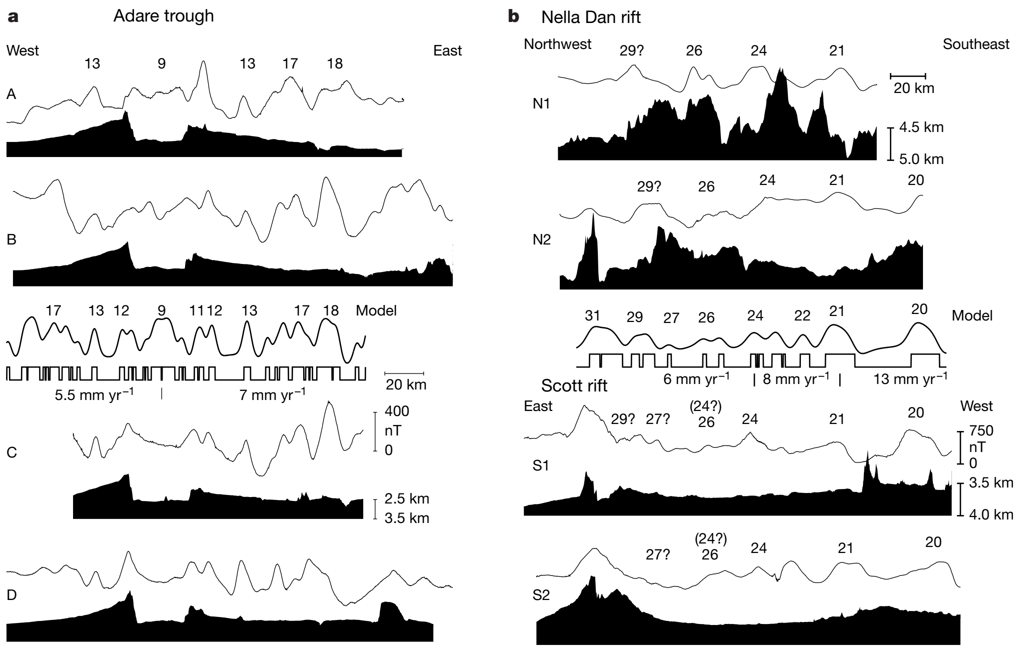

Figure 4 Projected bathymetric and magnetic profiles compared to magnetic models. **a**, Adare trough profiles (A, B, C, D). These data directly constrain the time of East–West Antarctic separation. The model indicates that spreading started around chron 20 and stopped near the end of chron 9. Spreading rates (mm yr^{-1}) are shown beneath the reversal pattern. The model assumes a flat layer between depths of 3.0 and 3.5 km. Other model parameters: present inclination (I_0) = −84°; present declination (D_0) = −87°; remanent inclination (I_r) = −70°; remanent declination (D_r) = 0°; azimuth = 80°; magnetization = 7 amps m^{-1}; gaussian smoothing (σ) = 0.5 km. Location of profiles is shown in Fig. 3. **b**, Nella Dan rift (N1, N2) and Scott rift (S1, S2) profiles. These data constrain the onset of SEIR spreading east of the Balleny fracture zone. Anomaly 26 is the oldest easily identified anomaly, but spreading clearly started earlier, probably around chron 29. The model assumes a flat layer between depths of 5.0 and 5.5 km. Other model parameters: I_0 = −76°; D_0 = 21°; I_r = −70°; D_r = 0°; azimuth = 160°; magnetization = 7 amps m^{-1} and σ = 1.5 km. Location of Scott rift profiles is shown in Fig. 3, Nella Dan rift profiles in Fig. 6.

Oligocene boundary[12] we take this as a measure of the total Oligocene extension.

The Euler pole seems to be applicable to East–West Antarctic motion back to chron 20o. We estimated a rotation for chron 20o by taking the best-fit East–West Antarctic anomaly 13o pole and gradually increasing the rotation angle in 0.05° increments. At each step we added the new rotation to the Australia–East Antarctic rotation for anomaly 20o (ref. 25) in order to calculate an Australia–West Antarctic anomaly 20o rotation. We found that the anomaly 20o locations from the Australia plate were rotated back to their Antarctic-plate counterparts when the East–West Antarctic rotation angle was 1.70° (Fig. 5). Repeating this exercise for anomaly 24o, we found that no additional increase in the angle was needed to remove the misfits in the preferred anomaly 24o locations, reinforcing our earlier conclusion that the period of spreading started around chron 20o. Although we cannot calculate an uncertainty region for this earlier phase of extension, these observations indicate that there was probably an additional 105 km of separation in Eocene time in the western Ross Sea, to make a total of 180 km of separation in Eocene and Oligocene time.

Implications for the Global Plate Circuit

These results have important implications for the tectonics of Antarctica. The roughly 180 km of Eocene and Oligocene separation provides a tectonic framework for understanding the uplift of the Transantarctic Mountains, the development of the Victoria Land and Northern basins in the western Ross Sea and the abundant rift-related plutonic and intrusive activity that was occurring simultaneously in Northern Victoria Land[31]. The continuing uplift of the Transantarctic mountains in mid-Cenozoic time can be correlated to motion recorded in the opening of the Adare trough. However, it is less certain whether the onset of Cenozoic uplift at 55–50 Myr, as dated by fission track analyses[7,8], is directly related to the axis of extension through the Adare trough region. As we noted, the main episode of extension near the Adare trough seems to have started around chron 20 (43 Myr), 7–12 Myr younger than the onset of uplift. However, as the misfits of anomalies older than anomaly 20 are poorly constrained, it is possible that slow extension between Northern Victoria Land and the Iselin bank started earlier than 43 Myr. If this is the case, then the uplift of the Transantarctic Mountains after 55 Myr might be related to the initiation phase of Adare trough rifting.

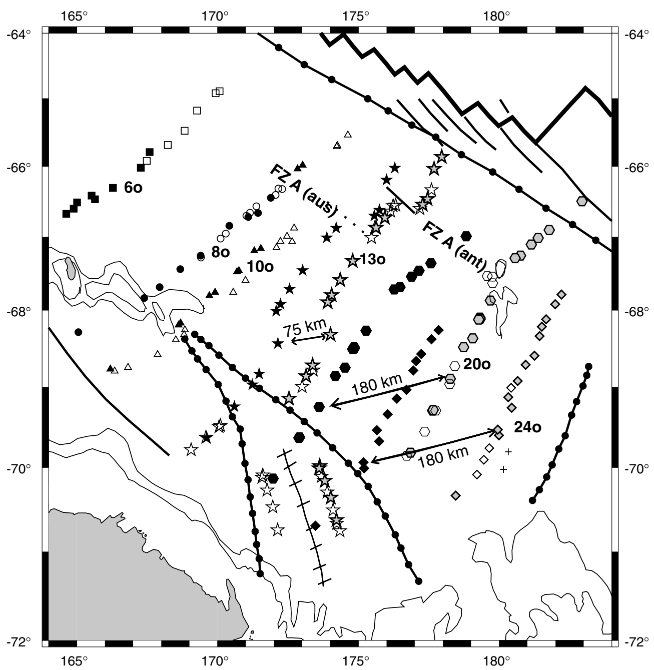

Figure 5 Misfit of anomalies east of the Balleny fracture zone caused by East–West Antarctic motion. Anomalies from the Australian plate (filled symbols) are rotated to the Antarctic plate using Australia–East Antarctic rotations and are compared to the position of Antarctic plate anomalies (open symbols). Australian plate anomalies 10o, 13o and 20o are underrotated by 20, 75 and 180 km, respectively. Shaded anomaly 13o locations have been rotated by the Australia–West Antarctic rotation in Table 1. Shaded anomaly 20o and 24o locations were rotated by Australia–West Antarctic rotations, described in the text. Magnetic anomaly symbols are the same as in Fig. 3 except that the + symbols on the old side of anomaly 24o show the alternative anomaly 24o locations discussed in the text.

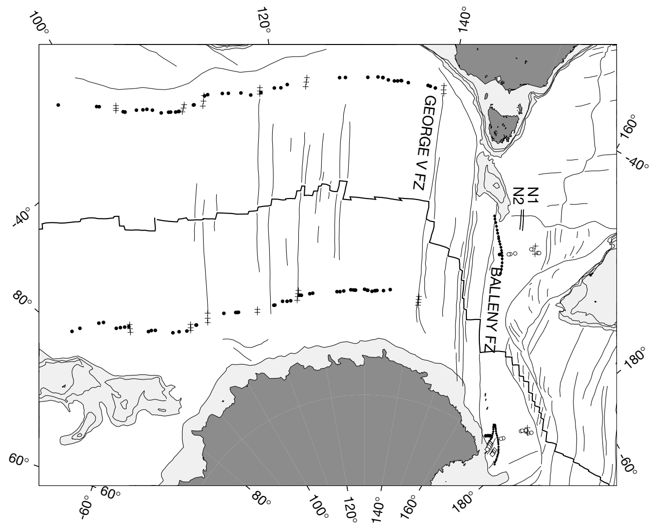

Figure 6 Data constraining the three-plate solution for the Adare triple junction at chron 13o. Anomaly 13o locations for Australia–East Antarctica motion (west of the Adare trough) are shown by filled circles, Australia–West Antarctic motion (east of the Adare trough) by open circles and East–West Antarctic (Adare trough) motion by open diamonds. Fracture zone constraints are shown by + symbols. Profile locations as in Fig. 4. FZ, fracture zone.

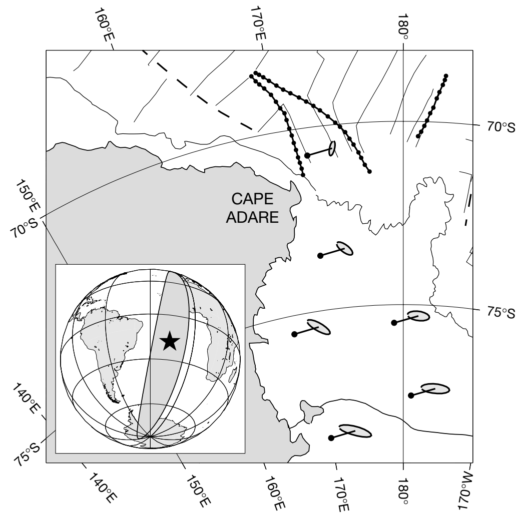

Figure 7 Amount of extension in the western Ross Sea embayment between chrons 13o and 8o (33–26 Myr). Predicted displacements and their 95% confidence ellipses are calculated for points on East Antarctica relative to a fixed West Antarctica. The total amount of mid-Cenozoic extension was probably more than twice this amount, as discussed. Inset, the best-fit East–West Antarctica (Adare trough) anomaly 13o pole (star) and its 95% confidence region.

There is also the possibility of an alternative axis of rifting between East and West Antarctica before chron 24 (53 Myr). The Iselin trough located to the northeast of the Iselin bank (Fig. 3) accommodated up to 50 km of extension between chrons 27 and 24 (Cande *et al*., manuscript in preparation). If this motion extended to the southwest across the Ross sea to the Transantarctic mountains, there would have been motion between East and West Antarctica associated with it. However, the Iselin trough is nearly at right angles to the Adare trough and the motion along the Transantarctic mountains would probably have been in a NW–SE direction and very oblique. Although there is evidence for a period of oblique motion in South Victoria Land[32], this direction of motion seems unlikely to have been capable of generating large extensional uplift.

The termination of Adare trough spreading between chrons 10 and 8 (28 and 26 Myr) corresponds to an important change in southwest Pacific tectonics. In the West Antarctic region, this time marks the onset of widespread volcanism across Marie Byrd Land[33]. In the Ross Sea region, it has been proposed[34] that 30 Myr corresponds to a fundamental change in the axis of tectonic extension from ENE–WSW to WNW–ESE. South of New Zealand, this time marks the termination of extension between the STOC and Emerald Basins straddling the Pacific–Australia plate boundary[18] and the onset of the current regime of oblique transform motion along the Macquarie ridge.

The recognition of this episode of East–West Antarctic extension has important implications for the tectonics of the entire southwest Pacific plate circuit and, indeed, the global plate circuit. As noted above, a significant tectonic puzzle of the southwest Pacific has been that previous reconstructions for the early Tertiary have predicted a gap between the Lord Howe rise and Campbell plateau. The reconstruction for chron 20 in Fig. 2a, which does not include motion between East and West Antarctica, shows that the gap between the Australia and Pacific plates is comparable to a gap in the anomaly 20o isochrons east of the Balleny fracture zone. Figure 2b is a reconstruction for chron 20 that restores motion between East and West Antarctica using the anomaly 13o best-fit pole with the 1.70° angle we found necessary to eliminate the anomaly 20 misfit east of the Balleny fracture zone. The gap between the Pacific and Australia plates southwest of New Zealand is eliminated, indicating that the Adare trough region is the final critical missing plate boundary in the Southwest Pacific. The inclusion of motion across the Adare trough in the plate circuit will modify the plate motion history associated with the Alpine Fault in New Zealand and also affect global issues such as the motion between hotspots in the Pacific and Indo-Atlantic Oceans[35,36]. □

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