Antarctic Tectonics: Constraints From an ERS-1 Satellite Marine Gravity Field

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A high-resolution gravity field of poorly charted and ice-covered ocean near West Antarctica, from the Ross Sea east to the Weddell Sea, has been derived with the use of satellite altimetry, including ERS-1 geodetic phase, wave-form data. This gravity field reveals regional tectonic fabric, such as gravity lineations, which are the expression of fracture zones left by early (65 to 83 million years ago) Pacific-Antarctic sea-floor spreading that separated the Campbell Plateau and New Zealand continent from West Antarctica. These lineations constrain plate motion history and confirm the hypothesis that Antarctica behaved as two distinct plates, separated from each other by an extensional Bellingshausen plate boundary active in the Amundsen Sea before about 61 million years ago.

The Ross, Weddell, Bellingshausen, and Amundsen seas lying offshore West Antarctica (Fig. 1) are the world's southernmost seas; they are also among the most poorly surveyed ocean basins on Earth. Large portions of them are perpetually covered with ice and hence are unexplored by ships, save for a few ice-breaker tracks. Much of the tectonic history of these seas and West Antarctica has been uncertain. We present a satellite gravity field that covers all of these seas and reveals important details about the tectonic history of this region. Details revealed include the traces of fracture zones (FZs) beneath the Amundsen Sea, such as FZ 8.5, the Endeavor, and the Pahemo. These traces allow us to reconstruct the position of the Campbell Plateau and New Zealand microcontinent relative to West Antarctica during Cretaceous time and to confirm Stock and Molnar's (*1*) hypothesis that this portion of West Antarctica behaved as more than one tectonic plate during the early stages of Pacific-Antarctic sea-floor spreading.

West Antarctic tectonics. West and East Antarctica were part of the supercontinent, Gondwanaland, before its early Mesozoic breakup 180 million years ago (Ma) (*2, 3*), as were India, Africa, South America, New Zealand, and Australia. Various models of the paths of the major continents during and after this breakup are in gross agreement (*2*). However, the plate tectonic behavior since 180 Ma of West Antarctica and the Campbell Plateau–New Zealand microcontinent, with which it was once joined, has remained a puzzle. Although today Antarctica is thought to behave as a single, rigid plate, it evidently consisted of multiple tectonic plates during much of the Cenozoic and Mesozoic (*2–5*). West Antarctica itself behaved (*3–5*) as four or more tectonic microplates (Fig. 2A), referred to collectively as Weddellia. Before the late Cretaceous (~83 Ma), the New Zealand microcontinent was also part of West Antarctica. Motion has clearly occurred between the Antarctic Peninsula and East Antarctica since 180 Ma; otherwise, plate reconstructions (*2, 6*) of Gondwana encounter the problem of overlap between the Antarctic Peninsula and the Falkland Plateau of South America. Paleomagnetic data resolve motion between West and East Antarctica after 100 Ma due to extension in the Marie Byrd Land and Ross Sea region (*5*). Other evidence of relative motion between West and East Antarctica include crustal deformation since 70 Ma in the Ross Sea and Transantarctic Mountains (*7–10*). Unmodeled motion between East and West Antarctica may help explain why global plate reconstructions for the Tertiary fail paleomagnetic tests of consistency (*7*).

The history of sea-floor spreading that accompanied the breakup of Gondwana is recorded in the ocean offshore West Antarctica, including the Ross, Weddell, and Amundsen seas. Weddell sea floor, for example, should contain some record of hypothesized Mesozoic rotational motion of the Antarctic Peninsula relative to East Antarctica (*2, 6, 11*). The sea floor of the southernmost Pacific was created after the Campbell Plateau separated from West Antarctica and might contain a record of West Antarctica behaving as multiple plates, including perhaps a Bellingshausen plate, which has been hypothesized (*1*) to have existed in the early Tertiary. Our gravity field allows us to view the sea floor of these areas and to test these various ideas about multiple-plate behavior of Antarctica.

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Gravity over sea ice and ocean from satellite altimetry. Satellite altimeters profile sea surface topography, and because this topography conforms, in the mean, to a level surface or geoid, accurate marine gravity fields and geoids can be derived. In principle, this technique is effective even where sea ice is present, because its dominant reflecting surface corresponds closely to the geoid. However, height trackers on board altimeter satellites become confused over sea ice and produce height errors of several meters or more. By reprocessing individual ERS-1 return echoes (*12*), using the technique of retracking (*13*), we significantly reduced these height errors (*14*) and have derived a detailed marine gravity field covering the entire Weddell, Ross, Bellingshausen, and Amundsen seas, including areas that are perpetually blanketed by sea ice. Coverage extends (Fig. 1) from 145° to 360°E and from 54°S to the edge of the Ross Ice Shelf at 79°S. This ERS-1 gravity field was derived with the use of techniques (*12, 15, 16*) comparable to those used to derive our Arctic Ocean field (*17*). In the southern oceans, unretracked satellite altimeter data have been used (*15, 16*) to derive detailed marine gravity fields, but these fields suffer large gaps and degradation in the southernmost seas because they are badly compromised by tracker errors in ice-covered areas such as the western Weddell, the Amundsen, and the northeastern Ross seas, and being derived primarily from Geosat data, they terminate at 72°S (Fig. 1).

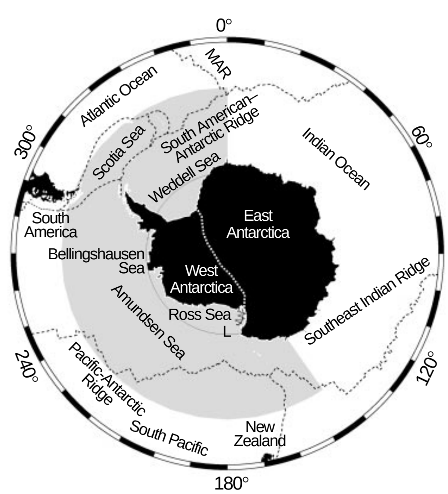

Fig. 1. Map of the Antarctic showing coverage (in gray) of the ERS-1 gravity field and location (dashed lines) of the active major tectonic plate boundaries. Solid line is 72°S latitude, the southern limit of Geosat data. Ship track for R/V *S. P. Lee* is shown in the Ross Sea (L). MAR, Mid-Atlantic Ridge.

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We used the entire ERS-1 Geodetic Mission (GM) data set, roughly 1 year's worth of observations, to compute the gravity field (Fig. 2A). The ERS-1/GM ground tracks are densely spaced, about 4 km apart at 60°S. Five 35-day cycles of ERS-1 data were also included in our analysis. In ice-free areas north of 68°S, we added densely spaced Geosat data (*18*) to improve the resolution of the gravity field. In the open ocean north of 70°S, comparisons with ship gravity (*19*) show that this field confidently resolves gravity anomalies of wavelengths as short as 25 to 30 km in good agreement with the resolution (*20*) of other altimetric fields (*15, 16, 18*). However, in permanently ice-covered Antarctic seas [for example, the western Weddell and southern Amundsen seas], sufficient, high-quality surface gravity data [for example, ice-breaker data or helicopter surveys, which have been used for the Arctic

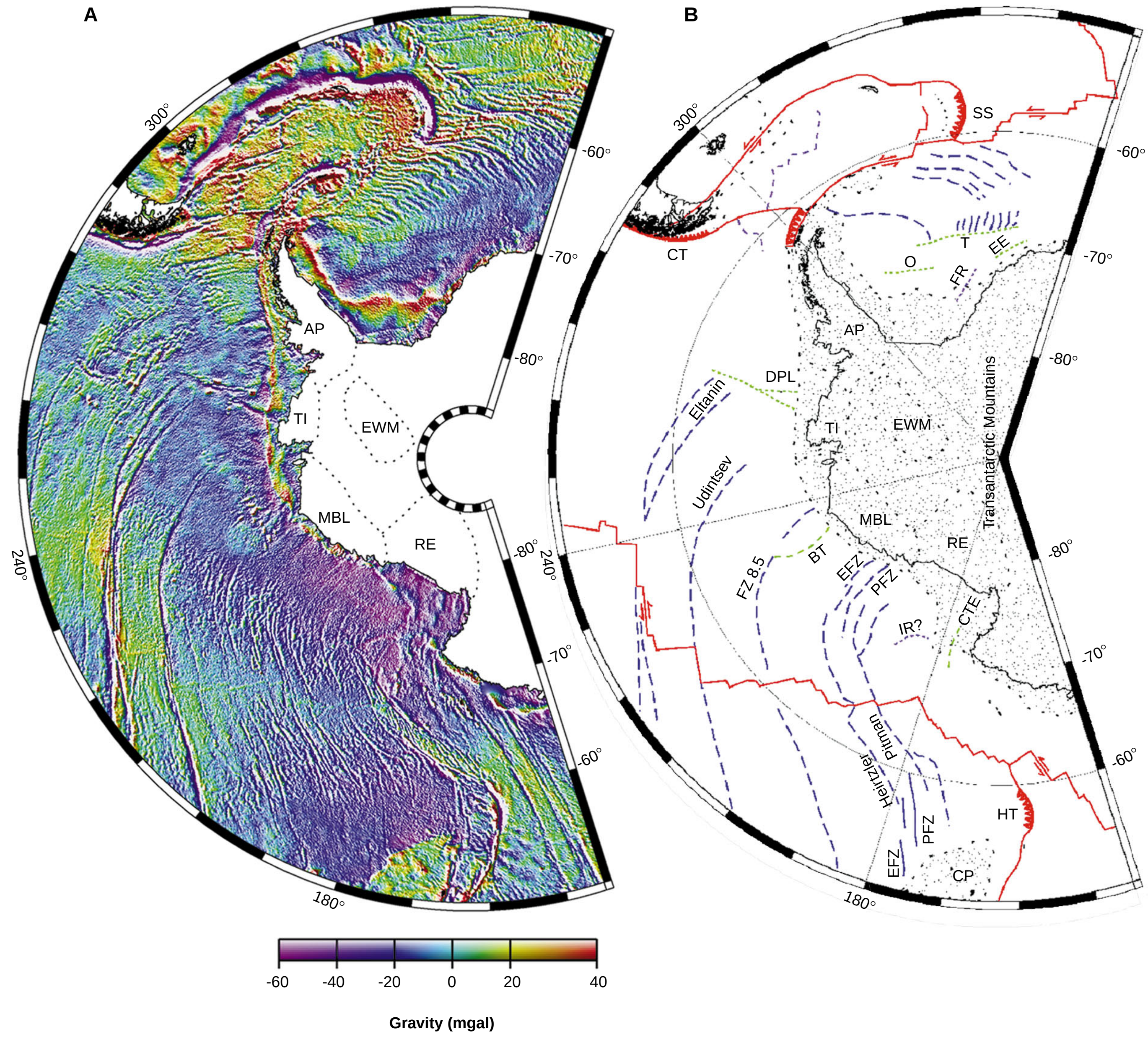

Fig. 2. (**A**) Gravity field of the ocean offshore West Antarctic derived from ERS-1 data over sea ice and open ocean. West Antarctic crustal blocks shown are Antarctic Peninsula (AP), Thurston Island (TI), Ellsworth-Whitmore Mountain (EWM), Marie Byrd Land (MBL), and the Ross Sea Embayment (RE). Gravity north of 54°S is a Geosat gravity field (*18*) that we spliced seamlessly onto our field to enable geophysical interpretation. Note the spurious, east-southeast–trending lineation, attributable to ice-ocean mode switching on board ERS-1, at 310°E, 76°S. Polar stereographic projection. The field is shown in milliGalileos: 1 mgal = 10^{-5} m/s^2. (**B**) Tectonic chart of ocean offshore West Antarctic. Tectonic features are "traced" from gravity shown in (A). Major FZ traces (blue dashed lines) include the Pahemo (PFZ), the Endeavor (EFZ), the Heirtzler, and the Pitman FZs. The Heirtzler and the Pitman are names newly proposed (*23*) for, respectively, FZ XI and FZ XII (*10*). Active plate boundaries are plotted (in red). They include the Hjort (HT), South Sandwich (SS), South Shetland, and Chile (CT) trenches or subduction zones (teeth on overriding plate). Also shown (red) are active mid-ocean ridges such the Pacific-Antarctic Ridge or the South American–Antarctic Ridge. Extinct or failed ridges are plotted (in purple) and include those in the Scotia Sea, a failed Weddell rift (FR) in the southeastern Weddell Sea, and the tentatively titled Iselin rift (IR). Other noteworthy or newly identified lineations (in green) include, in the Weddell Sea, the Orion anomaly (O), the Explora Escarpment (EE), and the T anomaly (T), plus in the southernmost Pacific, the Central Trough Extension (CTE), the Bellingshausen Trough (BT), and the DeGerlache–Peter I lineation (DPL). The Antarctic continental margin (black dotted line) follows approximately the 2000-m depth contour. Polar stereographic projection.

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(*17*)] are not available for such comparisons. Comparison with ship-track data in areas that are ice covered for most of the year, such as the western Ross Sea (Figs. 1 and 3), show that our field can confidently resolve gravity anomalies of wavelengths as short as 35 to 50 km (*21*).

Plate tectonic implications. This gravity field (Fig. 2A) shows known, active plate boundaries, including ridges, transforms, and trenches (Figs. 1 and 2B). Because gravity mimics topography at short (<400 km) wavelengths, lows are seen in our gravity field (Fig. 2) over deep ocean trenches such as the South Sandwich and Chile trenches, where plates converge and subduct. The axes of fast-spreading (rates > 6 cm/year) ridges such as the northern segment of the Pacific-Antarctic (PAC-ANT), generally appear as subtle, narrow (<60 km) gravity highs. However, slow-spreading and extinct ridges are usually marked by prominent, narrow axial troughs in gravity and bathymetry (*22*). Previously mapped extinct ridges are evident (Fig. 2) in the Scotia Sea and Drake Passage region; gravity troughs in the Ross and Amundsen seas perhaps also mark extinct ridges. Fracture zones, such as the Udintsev and Pitman FZs, can also be seen (Figs. 2 and 4). Fracture zones are the inactive scars of transform faults; they indicate direction of past plate motions.

The continental margin of West Antarctica is poorly surveyed by ships but is expressed clearly in our gravity field; it flanks the coastline and can be traced from Victoria Land at ~170°E roughly eastward around the Antarctic Peninsula to Coats Land at ~335°E, 74°S (Fig. 2). Large areas of the Marie Byrd Land margin located in the Amundsen Sea are uncharted by ships.

Possible Bellingshausen plate. In the western Amundsen Sea, two north-south–trending lineations between 72° and 76°S (at ~209° and 212°E) are the heretofore unmapped southern extensions of the Pahemo and Endeavor FZs (Figs. 2A and 4). Previous tracings of the Pahemo and Endeavor FZs terminated at 72° and 71°S, respectively (*23*), but the gravity lineations clearly continue south to the edge of the Antarctic continental shelf (Fig. 4). These lineations show that the Campbell Plateau and Marie Byrd Land crust must have fit together at about 83 Ma. Fracture zone FZ 8.5 seems to continue south, as Cande *et al.* (*23*) speculated it might (dashed line and "?" in Fig. 4), intersecting the West Antarctic continental margin at about 72°S, 239°E.

To test the hypothesis (*1*) of a tectonically distinct Bellingshausen plate, we used the finite PAC-ANT rotation pole (*23*) for chron C31 to rotate the gravity field of the Campbell Plateau and surroundings (including the Chatham Rise) back toward West Antarctica, which was kept fixed. The resulting paleogravity field (Fig. 5) reconstructs how the sea floor may have appeared at the end of the Cretaceous (67 Ma). The sea floor shown is from anomaly 31 time or older. In Fig. 5, the match between conjugate segments of the Pahemo and the Endeavor FZs is excellent, confirming that the rotation pole of Cande *et al.* (*23*) is correct. For example, a secondary offset in the Endeavor FZ just south of the Campbell Plateau has a matching offset on the conjugate portion of the Endeavor just north of Marie Byrd Land. However, as one moves eastward along the margin of Marie Byrd Land, the match between conjugate FZs deteriorates. For example, in Fig. 5, the Antarctic portion of FZ 8.5 is about 230 km east of the conjugate portion of FZ 8.5 to the north. Conjugate parts of the Tharp FZ (of the Eltanin system) and the Udintsev FZ are also offset by about 230 km. In Fig. 4, FZ 8.5 can be traced from the eastern edge of Bollons Tablemount (at 183°E, 50°S; south of Bounty Trough) to an intersection with the margin of West Antarctica at 239°E. We attribute this 230-km offset to east-west extension in the region offshore Marie Byrd Land in the vicinity of the western Amundsen ridges between the Endeavor and FZ 8.5. This extension occurred between 83 Ma and the time of anomaly 31 (67 Ma). It occurred by either (i) intraplate deformation within West Antarctica (*5*) or (ii) interplate motion, such as seafloor spreading, that caused West Antarctica to behave as two separate plates (*1*). In case (ii), the easternmost of these two plates—that is, the one bearing FZ 8.5, the Udintsev FZ, and the Tharp FZ—would be the Bellingshausen plate (Fig. 6), as hypothesized by Stock and Molnar (*1*). Our estimate of 230 km of extension may be low because we assumed that the conjugate Campbell Plateau behaved as a rigid plate, whereas evidence (9) indicates that the plateau may have undergone extension since 83 Ma. [Alternatively, this 230-km offset could be attributed to compression within the Campbell Plateau after 83 Ma, but this scenario is unlikely in view of studies suggesting extension in the Campbell Plateau (9).] This extension within Marie Byrd Land postdated its separation from the Campbell Plateau at 83 Ma and may have been localized along a north-south axis coin-

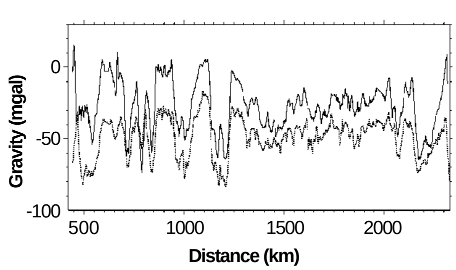

Fig. 3. Ship gravity for R/V *S. P. Lee* (United States, 1984) (solid line) and predicted along-track gravity from ERS-1 (dotted line). *Lee* gravity is offset from the ERS-1 by ~+30 mgal, which we ascribe to the different data used and errors in the ship data.

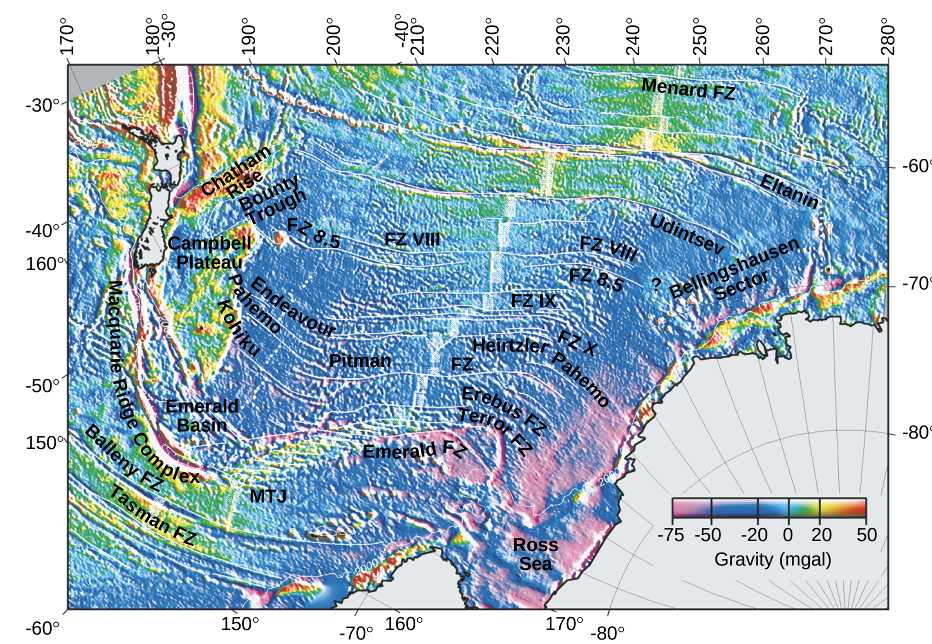

Fig. 4. ERS-1 gravity for the region of the Pacific-Antarctic Ridge overlain by white FZ traces, chron C31 (dots), and names, all from (*23*). Image made using the same oblique Mercator projection as (*23*), wherein the projection pole (274.2°E, 69.4°N) approximates the Euler pole of recent (chron C3a) relative rotation between the Pacific and Antarctic plates. Note, therefore, that ridge axis segments are nearly vertical, and relatively young (<40 Ma) FZs are horizontal.

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ciding with a gravity lineation that we call the Bellingshausen Trough (Fig. 2B). The Bellingshausen Trough appears (Figs. 2A and 4) to continue south across the Antarctic margin (at 232°E) and onto the continent. If this trough is indeed the extinct, divergent Bellingshausen plate boundary (Fig. 6), we can estimate from the location of the trough's northern terminus that spreading ceased at roughly the time of anomaly 27, 61 Ma, in agreement with Cande's estimate (*23*) and about 15 Ma earlier than that of Stock and Molnar (*1*). Alternately, this extension may have been diffuse or localized along another lineation such as the broad, north-northwest–south-southeast–striking trough that intersects the Antarctic margin at ~227°E. From gravity alone, we cannot pinpoint the site of extension or rifting. Detailed marine magnetic anomaly data are needed in this region.

Cande *et al.*'s (*23*) Cenozoic PAC-ANT rotation poles accurately describe relative motions between the Campbell Plateau and Marie Byrd Land back to, but not before, 65 Ma. Therefore, using the Pahemo and Endeavor FZ traces labeled in Fig. 5, we can extend the Cenozoic motion history (*23*) for the Campbell Plateau back into the Cretaceous. We will assume that PAC-ANT spreading began here at the time of anomaly 34 (83 Ma). By fitting small circles to the Pahemo and Endeavor traces, we derive, for the time interval from chron C31 through C34, a stage pole of 135° ± 15°W, 49° ± 25°S and a spreading rate of 2 cm/year. These estimates are preliminary and uncertain owing to the short FZ traces; they do not differ significantly from the rate estimated for the subsequent time period, chron C27 through C31 (*23*). Before we can precisely know this regional tectonic history, we must map exactly the extinct Bellingshausen plate boundary.

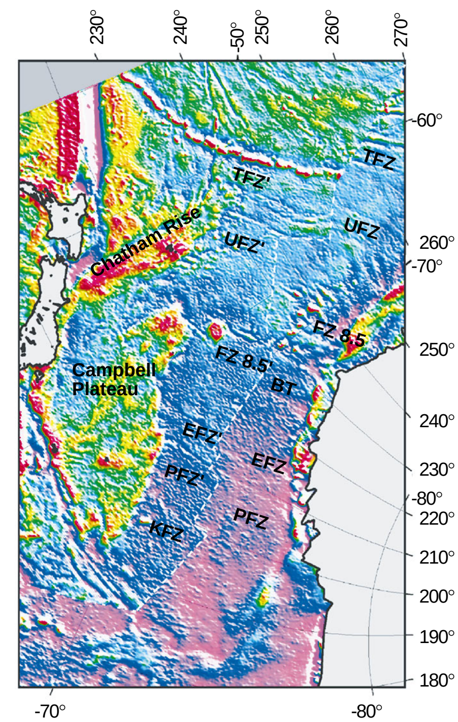

Fig. 5. Paleogravity reconstruction of Campbell Plateau relative to the Marie Byrd Land coast of West Antarctica at chron C31 (~68 Ma) based on Cande *et al.*'s (*23*) finite Pacific C31 rotation relative to Antarctica (fixed). Reconstruction was accomplished by using the 51.05° Euler rotation [see table 1 of (*23*)] about the C31 finite pole (69.33°N, 53.4°W) to rotate the gravity field of the Campbell Plateau region. We have removed sea floor younger than anomaly 31. This single image was constructed by first plotting our field using an oblique Mercator projection wherein the oblique pole matches the C31 Euler pole (*23*). Second, we translated, horizontally and to the right, the Campbell portion of the gravity field by an angular distance of 21.41° along the small circle (that is, a horizontal line in this projection) closest to the Endeavor FZ. This small circle intersects the present-day Pacific-Antarctic Ridge at 192.5°E, 63.4°S. A 21.41° translation along this small circle corresponds to the given 51.05° rotation about the Euler pole (*23*). With this oblique Mercator projection, scale is well preserved throughout the rotation. To isolate or cut out the Campbell Plateau portion of our gravity field (before rotation), we used the C31 isochron (white dotted line, compare with Fig. 4) on the Pacific side of the Pacific-Antarctic Ridge estimated (*23*) from magnetic anomaly data. Fracture zones shown are the Tharp (TFZ, part of the Eltanin system), the Udintsev (UFZ), FZ 8.5, the Endeavor (EFZ), the Pahemo (PFZ), and the Kohiku (KFZ). The FZs traced on the rotated Pacific plate are denoted by a prime. BT is the lineation tentatively entitled the Bellingshausen Trough. Note the consistent offset in the easterly FZs: FZ 8.5, UFZ, and TFZ.

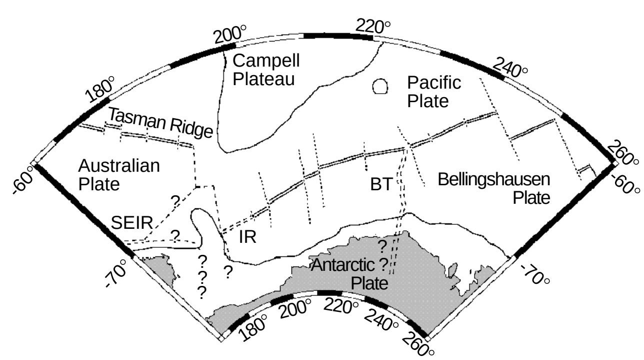

Fig. 6. Possible plate-boundary configurations in the Ross and Amundsen seas at about 60 Ma, that is, the time of anomalies 26 to 27, just before extinction of the proposed Bellingshausen plate boundary (dashed line, BT). IR denotes the Iselin rift. The Tasman spreading ridge was located after Molnar *et al.* (*10*). The Tasman continued spreading for only a few more million years, until about 53 Ma. Motion between the East Antarctic and Australian plates along the Southeast Indian Ridge (SEIR) was likely strike-slip at, and before, 60 Ma, so spreading was not yet under way here (*10, 24*). Two possible sites of interplate deformation between West and East Antarctica are shown (dashed lines with "?") in the Ross Sea; either one of these sites may have been active at this time.

Ross Sea tectonics. North-south–trending anomalies visible in the western Ross Sea area of our gravity field (Fig. 2A) are due to basins and grabens such as the Victoria Land Basin and the Central Trough. These structures result from Cretaceous-Tertiary crustal extension between West and East Antarctica since 105 Ma (*8, 24*). Other tectonic features that can be seen in this area of our gravity field (Figs. 2A and 4) include (Fig. 2B) the Iselin rift and the Central Trough Extension. We propose that both of these features represent more evidence that Antarctica did not behave as a single, rigid plate as the Campbell Plateau–New Zealand microcontinent separated from West Antarctica.

The Central Trough is an early rift basin associated with extension and thinning of continental crust beneath the western Ross Sea (*8*); it is overlain (see the north-south–trending high at ~176°E in Figs. 2A and 4) by a gravity high (*8*). It appears (Figs. 2A and 4) to extend north across the ocean-continent boundary into oceanic crust of uncertain age [presumably early Tertiary (*24*)]. This northern extension (the Central Trough Extension) suggests that some of the tectonic stretching that produced the Central Trough may be as recent as mid-Tertiary; that is, it may have occurred after the rifting of the South Tasman Rise from Antarctica (*24, 25*).

The Iselin rift (Fig. 2B) has no obvious conjugate expression on the northern side of the Pacific-Antarctic Ridge near Emerald Basin. We speculate that it might be an extinct or abandoned segment of the Pacific-Antarctic Ridge. The PAC-ANT reconstructions show the Iselin rift aligning with the rest of the Pacific-Antarctic Ridge at about the time of anomaly 20 or 21 (*26*). Molnar *et al.* [(*10*), see figure 21 therein)] suggested that at this time, about 45 Ma, a junction between three plates—the Pacific-Australian, the West Antarctic, and the East Antarctic plates—was active somewhere near Iselin Bank (now located near 184°E, 72°S). In this scenario, the western Ross Sea Embayment functioned as a plate boundary between West and East Antarctica (*9, 10*) and met the Pacific-Antarctic and the Southeast Indian ridges at the triple

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junction. If this scenario (*10*) is correct, the Iselin rift would have connected the Pacific-Antarctic Ridge to this triple junction. The Pacific and Australian plates are assumed to have been one between about 45 and 53 Ma because the Tasman Ridge (Fig. 6) is thought to have ceased spreading at 53 Ma, and Pacific-Australia spreading is thought not to have recommenced until 45 Ma, at which time it progressed along a new boundary through the South Island of New Zealand and the Macquarie Ridge to its south (*27*). Therefore, if the Iselin rift was a spreading ridge segment, it was likely abandoned at around 45 Ma when this new Australia-Pacific plate boundary began operating. At this time, the old triple junction died and a new one joining the Australia, Pacific, and Antarctic plates formed; this junction was the forerunner of the present-day Macquarie triple junction (Figs. 2B and 4). Our gravity field (Figs. 2A and 4) indicates possible locations for the old triple junction; it also suggests that the Ross Embayment paleo-plate boundary between West and East Antarctica might have, before 45 Ma, run south from the Iselin rift along the east margin of the Iselin Bank or south along the site of the Central Trough (Fig. 6). Even if the motion between West and East Antarctica in early Eocene time (45 to 55 Ma) was insignificant, the Iselin rift could have served, at that time, as a ridge segment connecting the Pacific-Antarctic Ridge to the nascent Southeast Indian Ridge (Fig. 6); before 53 Ma, it may have connected the Pacific-Antarctic Ridge to the Tasman Ridge by means of a long, now abandoned transform whose remnants are likely the old, north-south–trending portions of the Emerald FZ (Figs. 4 and 6). Ship surveys over the Iselin rift are nonexistent and are needed to test our speculation that it was an active spreading center during some or all of the time period from 83 to 45 Ma.

The Bellingshausen and other seas. In the Bellingshausen Sea, our gravity field (Fig. 2A) reveals an inverted Y-shaped, approximately north-south–trending lineation system, which we have labeled as the DeGerlache–Peter I Island lineation (Fig. 2B). At its northern end, near 62°S, this 1200 km-long lineation obliquely intersects the Heezen and Tharp FZs of the Eltanin system. Then, as it passes southward between the DeGerlache Seamounts (*16, 18*), it bifurcates into two branches: the eastern branch, which intersects Peter I Island at 69°S, and the western branch, which intersects and crosses the continental margin of West Antarctica at ~265°E, 70.5°S. This western branch extends south across the margin (Fig. 2A), which indicates it was produced by intraplate deformation after sea-floor spreading in this area. This lineation has been attributed to recent (~20 Ma), compressional tectonism or even intraplate subduction (*28*); it also has been deduced from plate reconstruction (*29*) to be a boundary between oceanic crust (to its west) formed at the Pacific-Antarctic Ridge and oceanic crust (to its east) formed at the Antarctic-Phoenix Ridge. The Antarctic-Phoenix Ridge was subducted during the Cenozoic, along the Pacific continental margin of the Antarctic Peninsula (*30*). It is likely that the DeGerlache lineation is both a crustal boundary and the result of compressional tectonism.

In the northeastern Weddell Sea, which is often free of ice, altimetric gravity fields (*16, 31*) displayed the same "herringbone" pattern of curvilinear anomalies we see in Fig. 2A. These anomalies are attributable (*32*) to FZs that appear to terminate along the T anomaly (Fig. 2B) at ~68°S, which has been ascribed to a dramatic slowing in spreading rate at about 125 Ma (*33*). Extensions of the FZ anomalies south across the T anomaly into presumably older sea floor are only vaguely discernible in our gravity (Fig. 2A). Other gravity features that can be seen (Fig. 2) in the perpetually ice-covered seas south and west of the T anomaly include the Polarstern Bank, the Orion anomaly, the Explora Escarpment, the Andenes Escarpment, and the failed Weddell rift (*3, 11, 14, 33*). To solve the tectonic puzzle of the Weddell and the other Antarctic seas, many more surface geophysical data are needed. Perhaps the first priority should be a detailed survey of the Bellingshausen Trough (*34*) in the Amundsen Sea.

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