24. R. Penrose, (1963) reprinted in *Gen. Rel. Grav.* **12**, 225 (1980).
25. H. Friedrich and J. M. Stewart, *Proc. R. Soc. London Ser. A* **385**, 345 (1983).
26. Because the crossover line is spacelike, the "bow-leggedness" of the diagram is to some extent due to our choice of coordinates. A different choice of simultaneity can change the qualitative shape but must leave invariant the smooth merger of the spacelike crossover line with the light ray lines leaving the cusps.
27. C. Misner, *Ann. Phys. NY* **24**, 102 (1963).
28. W.-M. Suen, paper presented at Grand Challenge Meeting, National Center for Supercomputing Applications (NCSA), University of Illinois at Urbana-Champaign, 6 to 8 November 1994 (lecture notes available from NCSA).
29. S. W. Hawking, in *Black Holes*, C. DeWitt and B. DeWitt, Eds. (Gordon and Breach, New York, 1973).
30. ______, *Commun. Math. Phys.* **25**, 152 (1972).
31. We thank D. Eardley, R. Geroch, R. Gómez, J. M. Stewart, K. Thorne, F. Tipler, and M. Visser for helpful comments on this work. We are especially grateful to J. Massó and P. Walker for producing Fig. 10 and for contributing significantly to the analysis in this paper. We also thank M. Blanton, M. Chia, S. Hughes, C. Keeton, P. Walker, and K. Walsh for participating in the computation and production of Figs. 3 and 4. This research was funded by the NSF Grand Challenge Grant PHY93-18152/ASC93-18152 (ARPA supplemented) and supported by the following individual grants: by NSF grant PHY83 10083, Texas TARP-085, and a Cray University Research Grant (R.A.M.); by NCSA and by NSF grant PHY 94-07882 (H.E.S. and L.S.); by NSF grants AST 91-19475 and PHY 94-08378 and National Aeronautics and Space Administration grant NAGW-2364 (S.L.S. and S.A.T.); by NSF grant PHY 94-04788 (W.-M.S.); and by NSF grant PHY92-08349 (J.W.). Computer time was made available by NCSA and the Pittsburgh Supercomputing Center (in part through MetaCenter grant MCA94P015), and by the Cornell Center for Theory and Simulation in Science and Engineering (supported in part by NSF, IBM Corporation, New York State, and the Cornell Research Institute).

RESEARCH ARTICLES

Geophysics of the Pitman Fracture Zone and Pacific-Antarctic Plate Motions During the Cenozoic

Steven C. Cande, Carol A. Raymond, Joann Stock, William F. Haxby

Multibeam bathymetry and magnetometer data from the Pitman fracture zone (FZ) permit construction of a plate motion history for the South Pacific over the past 65 million years. Reconstructions show that motion between the Antarctic and Bellingshausen plates was smaller than previously hypothesized and ended earlier, at chron C27 (61 million years ago). The fixed hot-spot hypothesis and published paleomagnetic data require additional motion elsewhere during the early Tertiary, either between East Antarctica and West Antarctica or between the North and South Pacific. A plate reorganization at chron C27 initiated the Pitman FZ and may have been responsible for the other right-stepping fracture zones along the ridge. An abrupt (8°) clockwise rotation in the abyssal hill fabric along the Pitman flowline near the young end of chron C3a (5.9 million years ago) dates the major change in Pacific-Antarctic relative motion in the late Neogene.

The Pacific-Antarctic Ridge is the key link in the global plate circuit tying the relative motion of the oceanic plates of the Pacific basin to the rest of the world (*1, 2*). For example, one of the more astounding consequences of rigid plate tectonics is that the accuracy of models of western North American deformation, including motion on the San Andreas fault, depends on how well magnetic anomalies and fracture zones (FZs) can be reconstructed in the far South Pacific (*3, 4*). Because key areas in the South Pacific are remote and poorly surveyed, circum-Pacific plate reconstructions have continued to have large uncertainties while uncertainties in other links in the global plate motion circuit have been progressively reduced. In this paper we describe a geophysical survey of an FZ near the southernmost end of the Pacific-Antarctic ridge that enables us to greatly reduce the uncertainties in the global plate circuit.

S. C. Cande is at the Scripps Institution of Oceanography, La Jolla, CA 92093-0215, USA. C. A. Raymond is at the Jet Propulsion Laboratory, Mail Stop 183-501, California Institute of Technology, Pasadena, CA 91109-8099, USA. J. Stock is at the Seismological Laboratory, Mail Stop 252-21, California Institute of Technology, Pasadena, CA 91125, USA. W. F. Haxby is at Lamont-Doherty Earth Observatory, Palisades, NY 10964, USA.

Plate motions and global tectonics. Several fundamental questions of circum-Pacific tectonics can be addressed by a better understanding of Pacific-Antarctic plate motions. For the South Pacific, some of the most important unresolved issues involve the timing and amount of early Tertiary relative motion between East and West Antarctica and between the Lord Howe Rise and Campbell Plateau, two of the links in the plate loop tying the Pacific, Australia, and Antarctic plates together (*2, 5*). A global hot-spot reference frame also depends on the accuracy of the Pacific-Antarctic link. Atlantic and Indian Ocean hot spots, when rotated back to the Pacific, do a poor job of predicting the track of the Hawaiian hot spot (*6–8*), raising questions of the fixity of hot spots (*9*). Non-Pacific paleomagnetic poles, when rotated back to the Pacific, do not agree with Pacific plate paleomagnetic poles. This misfit has led to the suggestion that there may be one or more missing plate boundaries between the North Pacific and East Antarctica (*10, 11*).

These unresolved questions have led to several hypotheses. Stock and Molnar (*9*) proposed that several puzzling aspects of early Tertiary Pacific tectonics could be explained if there was an undiscovered fossil spreading center in the Southeast Pacific that separated the region of the Antarctic plate near the Bellingshausen Basin (referred to as the Bellingshausen plate) from the part of the Antarctic plate adjacent to Marie Byrd Land (see Fig. 1). This scenario provided a better fit to magnetic anomaly data from chron C30 to chron C25 south of the Campbell Plateau; it reduced the amount of unexpected motion in the loop among the Australia, Antarctic, and Pacific plates in the early Tertiary; and it also helped to explain the failure of global reconstructions to predict the bend in the Hawaiian-Emperor chain (*12*).

Numerous tectonic issues can also be addressed by increasing the resolution of plate reconstructions. Several studies have proposed that there was a late Neogene change in the absolute motion of the Pacific plate, corresponding to a clockwise rotation in the separation direction of the Pacific and Antarctic plates (*13–16*). The age of this event, however, has been difficult to establish with the pre-existing data sets; estimates of its age vary from less than 9.8 Ma (million years ago) (*13*), 5 Ma (*14*), 5 to 3.2 Ma (*15*) to 3.86 to 3.4 Ma (*16*). Its exact age is of considerable interest because a number of late Neogene events around the Pacific, such as the onset of Pliocene compression along the San Andreas fault (*15, 17*), have been attributed to it.

Recent studies of the Pacific-Antarctic ridge have focused on interpreting satellite radar altimetry data collected by SEASAT and GEOSAT, which provide new data on the location of FZs (*18–20*). However, although images of the gravity field over the seafloor generated from satellite radar altimetry measurements have provided improved locations and trends of FZs and other tectonic features, without shipboard geophysical measurements in certain critical areas, uncertainties remain in Pacific-Antarctic reconstructions (*21, 22*). For example, a straightforward test of the Bellingshausen plate hypothesis of Stock and Molnar (9) would be to determine the location near Marie Byrd Land of the FZs conjugate to the early Tertiary fracture zones observed south of the Campbell Plateau (the Pahemo and Kohiku FZs in Fig. 1). However, GEOSAT observations alone have been insufficient to unambiguously trace the early Tertiary FZs across the ridge.

In order to better constrain Pacific-Antarctic plate motions we recently surveyed the Pitman FZ [previously referred to as FZ XII (*23*)], which runs from the base of the Campbell Plateau, across the axis of the Pacific-Antarctic ridge, to the continental rise of Marie Byrd Land (Fig. 1). We chose the Pitman FZ because (i) it clearly filled in a major gap in data coverage on the Antarctic side of the ridge, (ii) its proximity to the pole of opening results in accurate recordings of the various changes in the azimuth of plate motion, and (iii) the structure of the fracture zone near the ridge axis appeared relatively simple in the satellite radar altimetry data (Fig. 2).

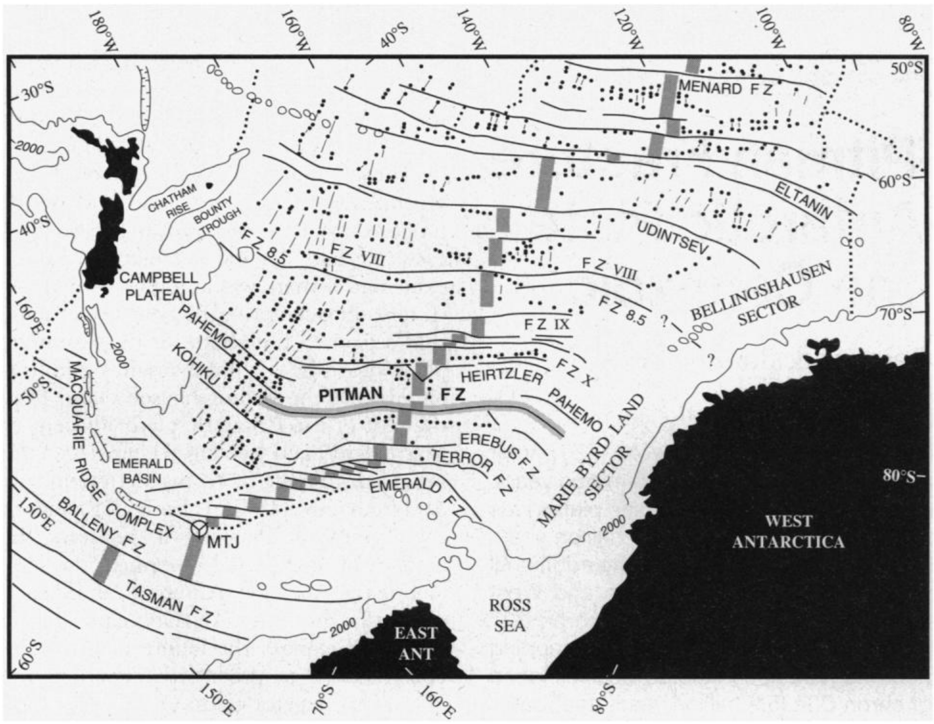

Fig. 1. Tectonic map of the Pacific-Antarctic ridge summarizing the location of magnetic anomaly data (filled circles) available before the recent cruises discussed in the text and demonstrating the sparsity of magnetic observations in the Marie Byrd Land sector of the Antarctic plate. The trace of the Pitman FZ, the focus of the survey, is highlighted. Map is an oblique Mercator projection about a pole at 69.4°N, 86.8°W, near the pole of rotation of Pacific to Antarctica at chron C3a.

Survey of the Pitman FZ. Our survey of the Pitman FZ was carried out on the R/V *Ewing* in January and February of 1992. This cruise mapped seafloor on the Antarctic plate back to magnetic anomaly 30 (66 Ma). We also include data from a 1990 cruise on the R/V *Polar Duke* (green track on Fig. 2) and a 1992 cruise on the R/VIB *Nathaniel B. Palmer* (*24*) that mapped early Tertiary and late Cretaceous magnetic anomalies and FZs along the margin of West Antarctica (east of the area of Fig. 2). We collected magnetic, gravity, and Hydrosweep multibeam data continuously during the cruise; single-channel seismic data were also collected except for a few days during a detailed swathmapping survey of the ridge axis region (Fig. 3). In addition, we made a Hydrosweep multibeam survey, with 100% areal coverage, of a 60 by 600 km section of the fracture zone straddling the ridge axis (Fig. 4).

Our analysis of plate motions is primarily based on fitting magnetic anomalies and FZ trends from conjugate sections of the ridge. However, the multibeam bathymetry by itself contains valuable information because the abyssal hill fabric generally forms perpendicular to the spreading direction (*25*) and can actually place tighter constraints on the timing of abrupt plate motion changes than is possible with the use of magnetic anomalies and FZ locations alone.

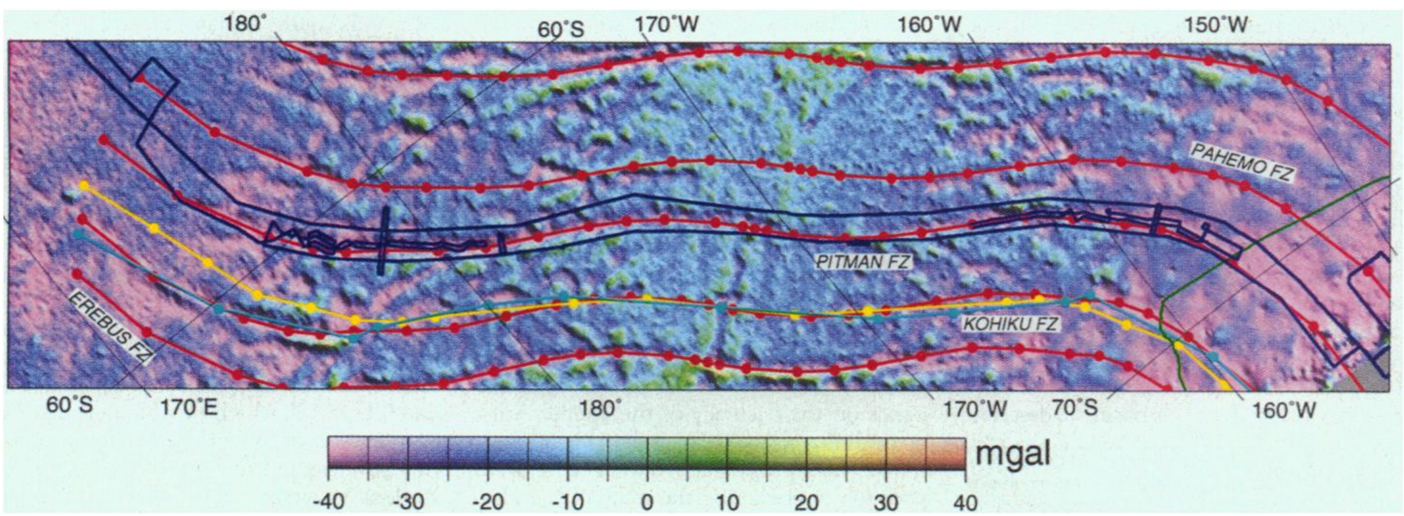

Fig. 2. The tracks of the R/V *Ewing* (dark blue) and the R/V *Polar Duke* (green) superimposed on an image of the satellite-derived, free-air gravity field of the southwest Pacific-Antarctic ridge. Synthetic flowline traces based on our new rotation parameters are shown in red and, for the Kohiku FZ, synthetic flowlines traces are also shown for the rotations of Molnar *et al.* (*2*) (light blue) and Mayes *et al.* (*21*) (yellow). The details of the R/V *Ewing* track near the ridge axis are omitted for clarity. Map projection same as for Fig. 1.

The Hydrosweep data from the Pitman FZ record an abrupt change in spreading direction in the late Neogene coincident with a rapid increase in spreading rate (*26*).

Implications for early Tertiary tectonics. The survey provides key data for understanding the early Tertiary evolution of the Pacific-Antarctic ridge. The survey reveals that the Pitman FZ does not link up with any of the early Tertiary fracture zones previously mapped south of the Campbell Plateau (Fig. 3). Instead, the Pitman FZ first appears abruptly as a right-stepping offset between the Pahemo and Kohiku FZs between anomalies 27 and 26. This abrupt appearance helps to explain the difficulty in tracing the FZs south of the Campbell across the ridge axis: the major FZs on the axis today are not continuous with the major FZs of the late Cretaceous and early Tertiary.

In the late Cretaceous and early Tertiary, the FZs south of the Campbell Plateau were all left-stepping, whereas on the present-day ridge axis the major FZs are all right-stepping (*2*, *27*). It has been a puzzle as to how and when the present day pattern formed. Our survey shows that at the Pitman FZ, a right-stepping fracture developed spontaneously, roughly midway between two left-stepping FZs. The right-stepping Pitman FZ may have developed in response to a major plate reorganization at chron C27, and many of the other right-stepping FZs may have been spawned by the same event.

The data also limit the motion of the Bellingshausen plate. This plate was proposed by Stock and Molnar (*9*) in order to explain differing FZ trends on the Pacific plate, northeast and southwest of FZ 8.5, from chron C31 to chron C25. Stock and Molnar (*9*) proposed that the northeast set of FZs were formed by spreading between the Pacific and Bellingshausen plates and that

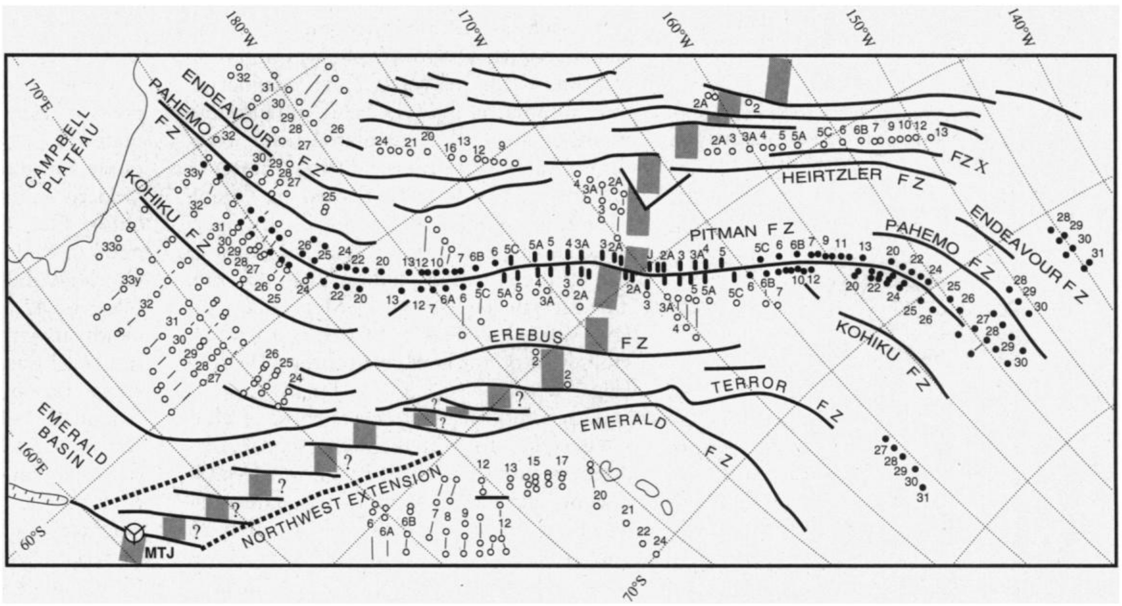

Fig. 3. Tectonic chart of the southwest Pacific-Antarctic ridge. These data show that the late Cretaceous FZs are not continuous with the major FZs on the modern ridge and that the Pitman FZ was initiated as an offset between the Pahemo FZ and Kohiku FZ around chron C27. Magnetic anomaly picks from the recent cruises are indicated by filled circles. Map projection same as in Figs. 1 and 2.

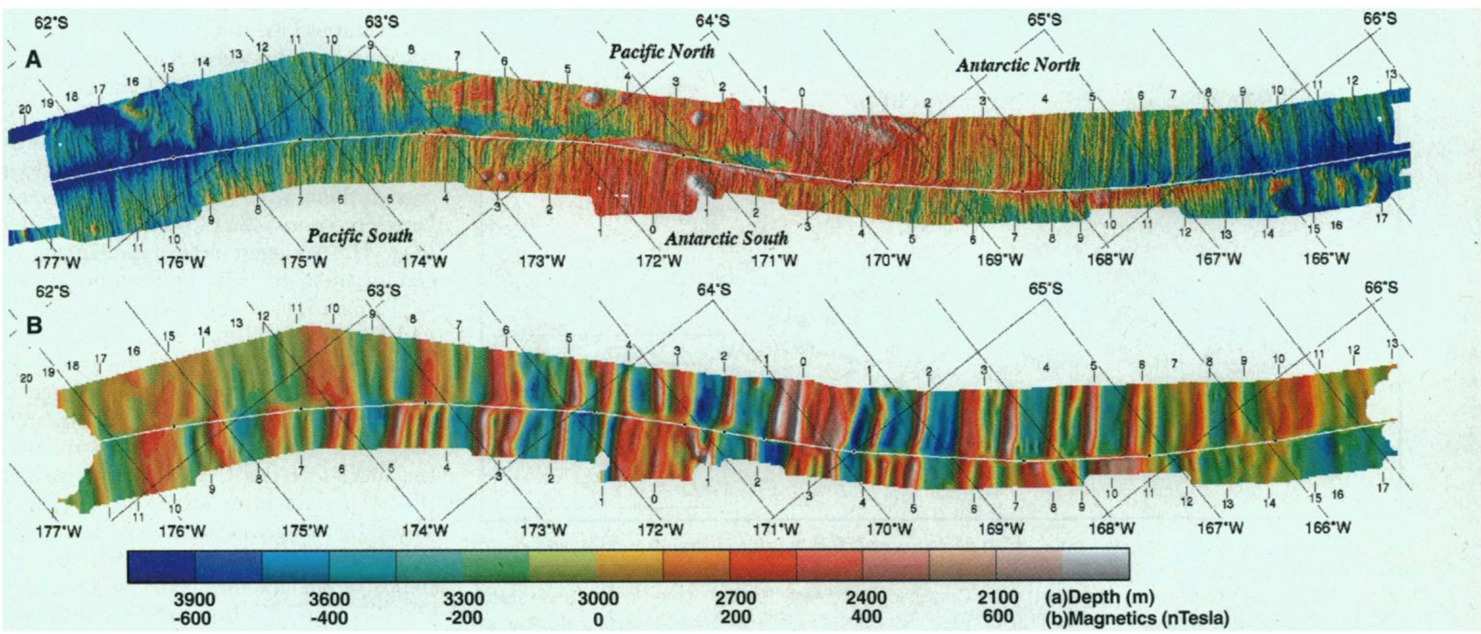

Fig. 4. Multibeam bathymetry (**A**) and magnetic anomaly data (**B**) from the area of the detailed ridge axis survey. Numbers above and below the images show crustal ages in millions of years ago based on the Cande and Kent (*52*) time scale. White lines are synthetic flowline traces based on our rotation parameters. Map projection same as in Figs. 1 to 3.

this spreading continued independently of Pacific-Antarctic spreading until chron C18; Mayes *et al.* (*21*) adopted a similar hypothesis but proposed that the Bellingshausen sector was only independent of Antarctica until about chron C24. Our survey of the Pitman FZ and the identification of the Pahemo FZ on both plates show that the Bellingshausen sector was only independent of Antarctica until about chron C27. Because the independent motion of the Bellingshausen plate ended sooner than originally envisioned by Stock and Molnar (*9*) or Mayes *et al.* (*21*), the early Tertiary reconstructions we derive are closer to those originally proposed by Molnar *et al.* (*2*) and Stock and Molnar (*13*).

Finite rotations. We combined the new geophysical data with a set of magnetic anomaly and FZ identifications from the rest of the Pacific-Antarctic ridge (*28*) in order to calculate a revised set of rotation parameters (poles plus angles). A total of 35 rotations describe the relative plate motion changes in great detail (*28*), although a subset of those rotations defines the major plate motion changes. Because the Bellingshausen plate northeast of FZ 8.5 (*24*) existed before chron C27, we have used only magnetic and FZ data from southwest of FZ 8.5 (Fig. 1) to derive the reconstruction parameters for anomaly 31.

Table 1. Finite rotations of the Pacific relative to Antarctica plates. Counterclockwise rotations are positive. Ages are from (*52*). An., anomaly.

Age (Ma)?	An.	Lat. (°N)	Long. (°E)	Angle
0.78	1	64.25	−79.06	0.68
2.58	2a	67.03	−73.72	2.42
5.89	3a	67.91	−77.93	5.42
8.86	4a	69.68	−77.06	7.95
12.29	5a	71.75	−73.77	10.92
17.47	5d	73.68	−69.85	15.17
24.06	6c	74.72	−67.28	19.55
28.28	10	74.55	−67.38	22.95
33.54	13	74.38	−64.74	27.34
42.54	20	74.90	−51.31	34.54
47.91	21	74.52	−50.19	37.64
53.35	24	73.62	−52.50	40.03
61.10	27	71.38	−55.57	44.90
67.67	31	69.33	−53.44	51.05

The magnetic anomalies were uniformly identified according to the scheme initiated by Atwater and Severinghaus (*29*) for the North Pacific. The FZ crossings were digitized from the detailed topographic data in the area of the Hydrosweep survey and from a combination of topography, magnetics, and minima in the GEOSAT gravity data in other areas. We calculated finite rotations (Table 1) using the fitting criteria of Hellinger (*30*) as implemented by Chang (*31*) and Royer and Chang (*32*). In Fig. 5 we compare our newly calculated poles to the results of earlier studies (*2*, *9*, *13*, *21*). The present day pole of DeMets *et al.* (*33*) (NUVEL-1) at 64.3°S, 96.0°E is a few degrees west of our youngest (chron C1) pole (Fig. 5).

Our rotations are closest to those of Molnar *et al.* (*2*). In particular, both sets of poles define a cusp near 75°S, 130°E in the mid-Eocene, and our anomaly 27 pole falls midway between Molnar *et al.*'s (*2*) anomaly 25 and 31 poles. The reconstructions of Mayes *et al.* (*21*), however, deviate considerably from all of the other results in the early Tertiary and late Cretaceous (between anomalies 31 and 18). This result is somewhat surprising because Mayes *et al.* (*21*) used GEOSAT-ERM satellite altimetry data to constrain the FZ trends. Mayes *et al.* (*21*), however, aligned the traces of the larger-offset FZs, which are now thought to be less reliable indicators of the directions of plate motion than medium and small offset FZs (*34*, *35*). This comparison shows the difficulty of trying to use the GEOSAT trends to constrain poles without sufficient constraints from magnetic anomalies, as well as underscoring the value of shipboard data.

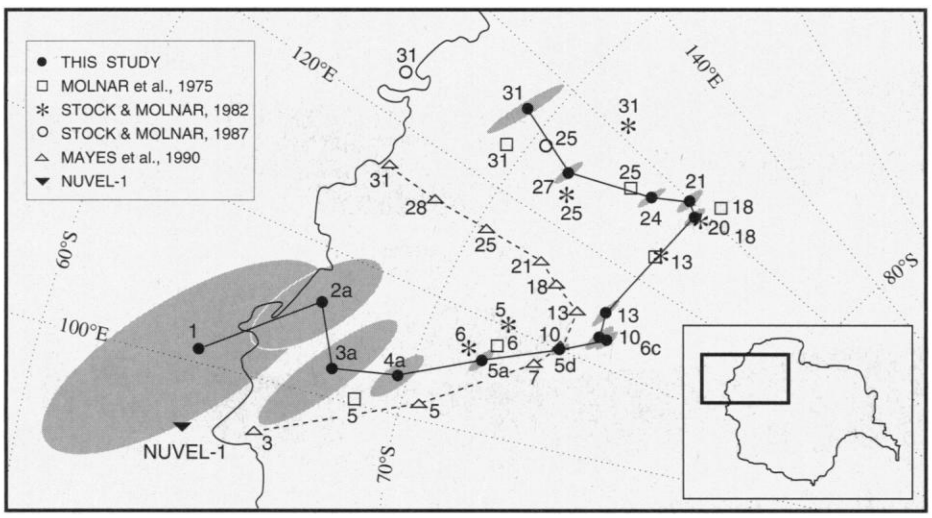

Fig. 5. Comparison of our rotation poles (filled circles connected by a solid line) to the rotation poles previously determined for the Pacific-Antarctic ridge. For clarity we also show the Mayes *et al.* (*21*) poles connected by a dashed line. Our poles for the late Cretaceous and early Tertiary come closest to the poles of Molnar *et al.* (*2*) and Stock and Molnar (*13*). Shaded ellipses show 95% confidence regions associated with the new poles. All pole positions are antipodal to those listed in Table I in order to show the spatial relationship to data in the region. Map projection is stereographic with a projection center at 70°S, 180°W.

Stage poles and synthetic flowlines. In order to evaluate the predictive quality of our finite rotations we calculated stage rotations and used these to generate synthetic flowlines. Tracks swept out by the stage poles relative to the Antarctic and Pacific plates (Fig. 6) indicate periods of slow to moderate motion separated by relatively sudden shifts. Between chron C31 and chron C21 (67.7 to 47.9 Ma) the stage poles moved away from the Pacific-Antarctic ridge. Between chrons C21 and C20 (47.9 to 42.5 Ma) the stage poles shifted rapidly to a position in the Ross Sea close to the southwesternmost end of the Pacific-Antarctic ridge. The stage poles apparently remained relatively stationary between chrons C20 and C13 (42.5 to 33.5 Ma) corresponding to a period of slow spreading (half rate of $<$ 10 mm/year) observed in the magnetic data along the Pitman flowline. Between chrons C13 and C10 (33.5 to 28.3 Ma) there was a rapid shift westward away from the ridge. Between chrons C10 and C6c (28.3 and 24.1 Ma) the stage poles moved toward the geographic south pole. From chrons C6c to C5a (24.1 to 12.3 Ma) the pole positions were relatively stationary.

Starting around chron C5a (12.3 Ma) the poles started to migrate relatively continuously towards the north-northwest, away from the Pacific-Antarctic ridge, although there was a distinct jump to the east between chrons C2a (2.6 Ma) and C1 (0.78 Ma). The youngest pole, representing the central anomaly, picks up the north-northwest migration of the pole started in the mid-Neogene, and may even reflect an acceleration in the motion of the pole.

We calculated synthetic flowlines for several FZs along the Pacific-Antarctic ridge (Fig. 6) and superimposed them on the images of the GEOSAT gravity field (Fig. 2) and the Hydrosweep survey (Fig. 4). These figures demonstrate an excellent fit between the synthetic flowlines and the trends of the fracture zones as imaged by GEOSAT and Hydrosweep. We also compared these synthetic flowlines to those based on the stage rotations of Molnar *et al.* (*2*) (in light blue) and Mayes *et al.* (*21*) for the Kohiku FZ (Fig. 2). The Molnar *et al.* (2) rotations do a fairly good job of matching the trace of the Kohiku FZ, whereas the Mayes *et al.* (21) rotations predict a trend about 75 km east of the Kohiku FZ in the early Tertiary on the Pacific plate.

Variations in spreading rates and spreading directions. Variations in spreading rate and spreading direction were much larger on the southwestern end of the ridge than to the northeast (Fig. 7). In particular, the Emerald FZ underwent dramatic changes in spreading direction and rate at the start and the end of the period between chrons C20 to C13 when the stage pole was nearby. Along this same southwesterly flowline there was a fairly continuous clockwise change in azimuth starting around chron C5a and continuing to the present day, reflecting the northerly trek of the stage poles. Overall there has been a 30° clockwise rotation in spreading direction in this period along this flowline.

Our rotation parameters predict relatively small variations in spreading directions along the Eltanin flowline (Fig. 7). In the mid-Cenozoic (between 43 Ma and 16 Ma) the flowline predicts a roughly 12° counterclockwise rotation, spread out uniformly over the entire time interval, while since 16 Ma the flowline predicts a 10° clockwise rotation, with about half of this (5°) occurring since 5 Ma. By comparison, Lonsdale (36) observed a 10° to 15° counter-clockwise rotation in the mid-Cenozoic, which is similar to our prediction, but concentrated around anomaly 7 (25 Ma), in an analysis of crustal fabric from swathmap bathymetry. Lons- dale's (37) observation of a 3° to 5° clockwise rotation in crustal fabric concentrated around 5 Ma is also compatible with our predictions. However, although there has been little change in spreading azimuth or rate along the Eltanin flowline in the last 3 Ma, it is clear that Pacific-Antarctic plate motion is still changing.

Late Neogene Pacific plate motion. The combination of detailed rotation poles and swathmapping control on abyssal hill azimuths reveals details of the late Neogene plate motion change. The late Neogene change in Pacific-Antarctic motion is the continuation of an apparently rather continuous change that started around 12 Ma. In particular, the azimuthal change is the result of a northwesterly movement of the stage poles, positioning them more distant from the region but at lower latitudes. Because the spreading rate gradually increased during this period, the difference has become especially noticeable over the last 6 million years as the curvature of the FZs decreased. The evolution of the southwesternmost segment of the Pacific-Antarctic ridge from a long transform joining the Pacific-Antarctic ridge to the Southeast Indian ridge to a series of short, en echelon spreading segments is another obvious result of the northerly motion of the stage poles in the late Neogene.

In addition to the gradual change, there was a particularly large and sudden rotation in spreading direction near the young end of chron C3a (5.9 Ma). This is shown in Fig. 8, which compares predictions of the spreading direction based on the stage poles (heavy line) to a compilation (38) of abyssal hill azimuths observed in the Hydrosweep data (filled circles). The predicted azimuths based on the stage poles document the overall nearly 20° rotation in strike in the last 12 million years; however, they are not capable of resolving the fine details of the change. The abyssal hill azimuths clearly show that the change in spreading direction was fairly smooth and continuous throughout the period except for a sharp, roughly 8° rotation around 5.9 Ma.

The chron C3a event is synchronous with several other Pacific basin events. In particular, it corresponds to the most recent resolvable spreading rate change (an in-

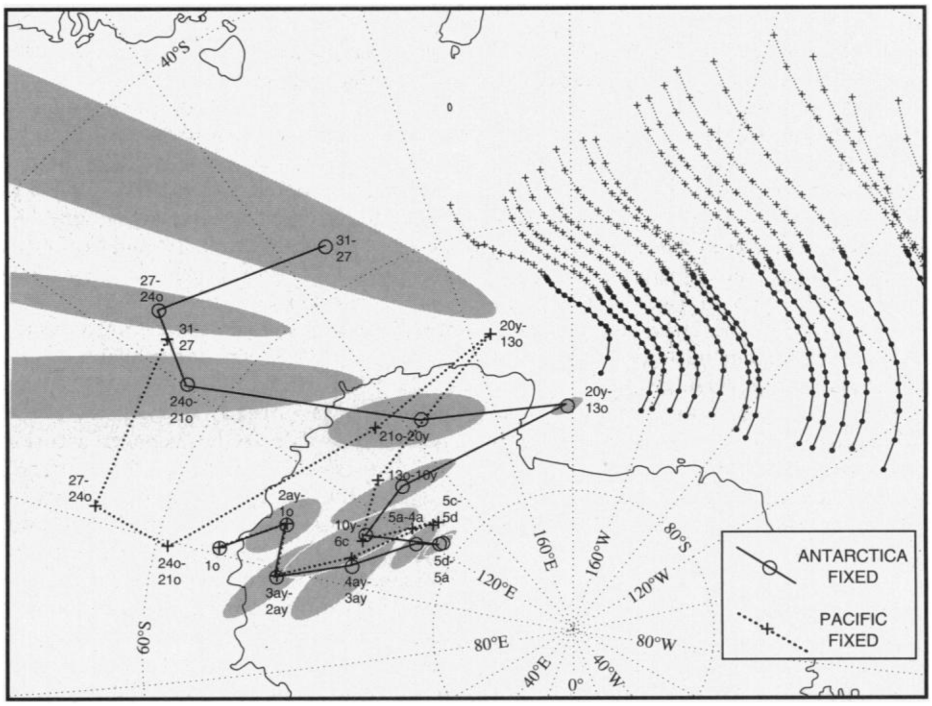

Fig. 6. Stage poles for Pacific-Antarctic relative displacements. Open circles are poles with respect to the Antarctic plate fixed; crosses are for the Pacific plate fixed. On the right, synthetic flowlines based on the poles are plotted for many of the present day ridge offsets with the symbols keyed to the respective (Pacific or Antarctic) sets of stage poles. 95% confidence regions are shown for the Antarctic-fixed stage poles; Pacific-fixed 95% confidence regions are similar in size but are omitted for clarity. Map projection same as for Fig. 5.

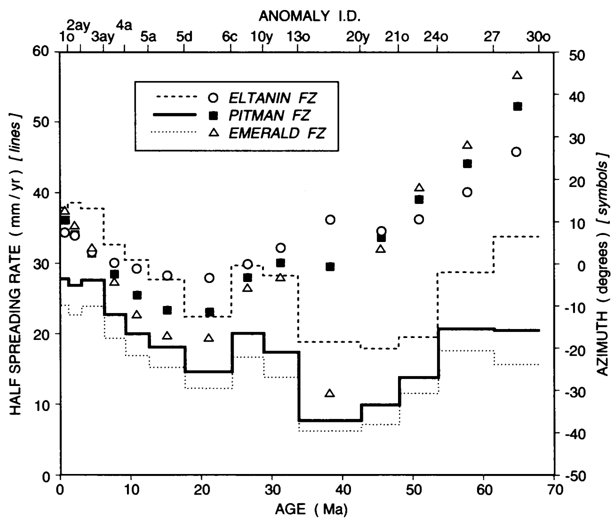

Fig. 7. Spreading rates (lines) and lineation azimuths (symbols) calculated from the rotation parameters along flowlines corresponding to the Eltanin FZ, Pitman FZ, and the Emerald FZ. The azimuths are relative to the oblique Mercator projection used for Figs. 1 to 4. Spreading rates are based on the time scale of Cande and Kent (52).

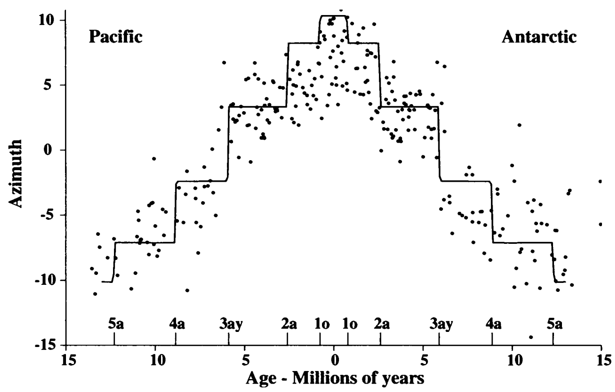

Fig. 8. Temporal variations of the azimuths of the ridge parallel abyssal hill fabric in the area of the detailed Hydrosweep survey. Individual observations (filled circles) are shown separately for the Pacific (**left**) and Antarctic (**right**) flanks. The abyssal high lineations reveal an abrupt clockwise change at 5.9 Ma (chron C3a). Predicted azimuths calculated from the rotation parameters are indicated by the heavy line. Azimuths are relative to the oblique Mercator projections used for Figs. 1 to 4.

crease of 20%) on the Pacific-Antarctic ridge (Fig. 7). Chron C3a was also the time of a sharp decrease in spreading rate on the Chile ridge (*39*). Bird and Naar (*40*) showed that the Easter and Juan Fernandez microplates both started to form about chron C3a. The onset of rifting in the Lau Basin has recently been dated at 6 Ma (*41*).

The detailed plate kinematics from our model should help in the determination (and isolation) of the causes and effects of the late Neogene circum-Pacific changes in plate motions. We speculate that the northwestward migration of the stage poles that started around 12 Ma was caused by a gradual change in the configuration of the convergent boundaries around the southwestern Pacific (*42*), while the sudden change in plate motion at chron C3a was caused by a more catastrophic event, perhaps the detachment of a piece of the downgoing slab beneath the New Hebrides arc and Fiji Plateau as suggested by Cox and Engebretson (*14*). Future studies of the causes and consequences of the late Neogene plate motion change need to consider both the gradual and abrupt aspects of the event.

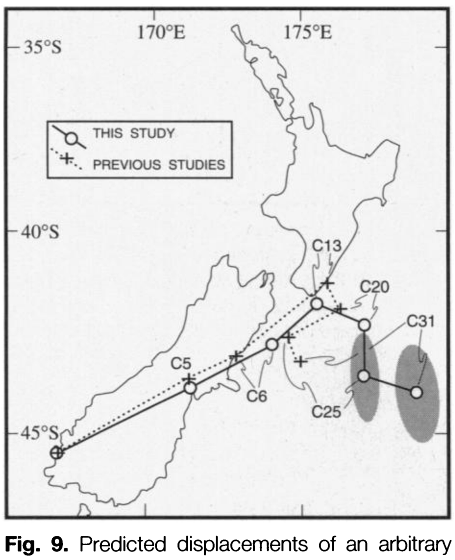

Fig. 9. Predicted displacements of an arbitrary point on the South Island of New Zealand relative to the (fixed) North Island of New Zealand from the present back to chron C31. The open circles (this study) are the predicted displacements using our revised Pacific-Antarctic rotations whereas the crosses (previous studies) show the displacements predicted by using Stock and Molnar's (*9*) rotations for Pacific-Antarctic motion. Our revised rotations predict 200 km of relative motion between chrons C31 and C20. In both cases, Pacific-Antarctic motions were combined with Royer and Sandwell's (*53*) Australia-Antarctic motion and Stock and Molnar's (*13*) Lord Howe Rise–Australia motion. 95% confidence regions are shown for the chrons C25 and C31 revised reconstructions.

Early Tertiary. The Antarctic plate from the Marie Byrd Land sector to the Bellingshausen sector has behaved as a single plate since chron C27. Before chron C27, we find [as in (*9*)] that we cannot fit the FZs in the two sectors with a single set of rotations. Because data from the Bellingshausen sector are representative of the entire West Antarctic plate for times younger than C27, it is not too surprising that our rotations for the early Tertiary, now constrained by satellite data and shipboard observations near Marie Byrd Land, are closer to those of Molnar *et al.* (*2*) and Stock and Molnar (*13*) than to those of Stock and Molnar (*9*) and Mayes *et al.* (*21*).

The effect of our revision to the early Tertiary reconstructions is that two tectonic problems that were thought to have been alleviated by the recognition of the Bellingshausen plate have to be reconsidered. One problem is that reconstructions of New Zealand that only consider motion on the Pacific-Antarctic ridge, on the Southeast Indian ridge and in the Tasman sea, predict on the order of 200 km of compression within New Zealand between chrons C31 and C20 (Fig. 9), a period of time characterized by post-rift subsidence and tectonic quiescence over the New Zealand region (*43*). The other effect of our revision to the early Tertiary poles is that predictions of the track of the Hawaiian hot spot based on global reconstructions fail, once again, to predict a large bend around 43 Ma as observed (Fig. 10).

The problem of apparent motion within New Zealand in the early Tertiary is particularly vexing because unaccounted for motion may have occurred at any number of locations along the plate circuit encompassing the Pacific, Antarctic, Australia, and Lord Howe Rise plates. For example, several sources of evidence suggest that there was late Cretaceous or early Tertiary motion between East and West Antarctica. The recent paleomagnetic results of DiVenere *et al.* (*44*) indicate that there has been 1100 ± 800 km of motion since 100 Ma. Geophysical work in the Ross Sea and along the Transantarctic mountains also indicates that there may have been considerable motion between East and West Antarctica (for example, *45*–*49*), although most of this may be before 85 Ma (*50*). Alternative locations for this missing plate motion in-

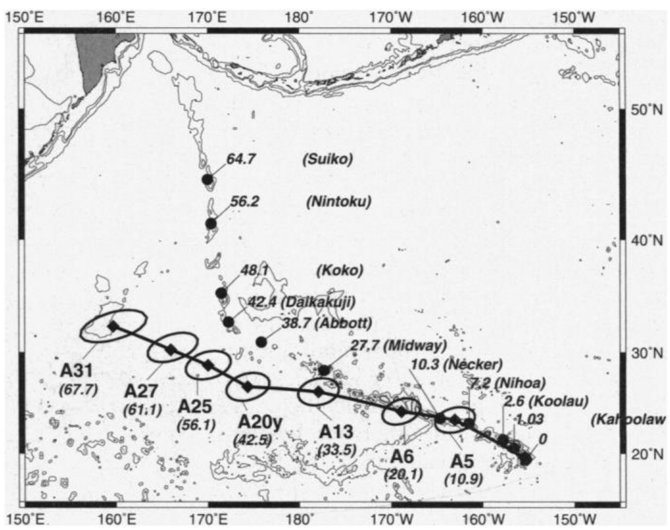

Fig. 10. Predicted track of the Hawaiian hot spot compared to isotopically dated edifices along the Hawaiian-Emperor chain. The predicted track fails to make the landmark bend at 43 Ma, and there is a significant misfit for all reconstructions older than chron C5. The predicted track was determined by rotating Müller *et al.*'s (*54*) hot spot reference frame for the Indo-Atlantic Oceans back to the Pacific using our Pacific-Antarctic rotations and the Africa-Antarctic rotations of Royer *et al.* (*55*). The age data for the Hawaiian-Emperor chain are from Clague and Dalrymple (*56*). Error ellipses are 95% confidence ellipses but include only estimated uncertainties in Müller *et al.*'s (*54*) rotation parameters.

clude the possibility of a missing plate boundary between the Lord Howe Rise and Challenger Plateau (50), or oblique, rather than orthogonal, rifting between Australia and Antarctica at this time (reconstructions of Antarctica-Australia motion before chron C18 lack good FZ constraints).

Similarly, the inability to predict a major bend in the Hawaiian-Emperor hot spot track (Fig. 10) can be the result of either missing boundaries in the plate circuit [for example, between East and West Antarctica, as suggested by many, or between the North and South Pacific (*11*)], or it may be due to the relative motion between hot spots (*12*). One consequence of our revised reconstructions is that, if the misfit between the Indo-Atlantic and Pacific hot spot reference frame is attributed entirely to drift between hot spots, then the rate of drift is on the order of 24 km per million years, compared to the 10 to 20 km per million years estimated by Molnar and Stock (*12*).

Our revised rotations also increase the discrepancy between Pacific plate paleomagnetic poles and non-Pacific paleomagnetic poles (*11*). The amount of apparent northward motion of the Pacific plate implied by Pacific plate paleomagnetic data is consistently larger than the amount of northward motion implied by global reconstructions of hot spots and non-Pacific paleomagnetic data, peaking at about 10° in the early Tertiary (*11*). Acton and Gordon (*11*) argued that several different sources could contribute to this discrepancy, including a large non-dipole geomagnetic field, drift between hot spots, motion between East and West Antarctica, and motion between the North and South Pacific, although no single cause appears to be large enough to explain the entire discrepancy. Our revised reconstructions increase this discrepancy by about 2° in the early Tertiary, adding to the difficulty in explaining it.

Changes in plate motion. An outcome of this high-resolution study, if we take the late Neogene as a guide, is that plate motion changes involve a mixture of gradual, and perhaps continuous, changes in direction interspersed with sudden, sharp changes. For example, the late Neogene change in Pacific-Antarctic spreading direction is characterized by a sharp change at chron C3a superimposed on a gradual clockwise rotation over the last 12 Ma. A similar pattern was described by Tucholke and Schouten (*51*) for the Kane FZ where the spreading direction seems to have slowly evolved such that the FZ stayed either in a condition of extension or compression for long periods of time interrupted by occasional sudden, abrupt shifts.

Similar high-resolution plate motion models are needed for the other plate pairs in the global circuits to study Pacific-Australia, Pacific-North America, and Farallon-North America interactions in great detail.

REFERENCES AND NOTES

1. W. C. Pitman III, E. M. Herron, J. R. Heirtzler, *J. Geophys. Res.* **73**, 2069 (1968).
2. P. Molnar, T. Atwater, J. Mammerickx, S. M. Smith, *Geophys. J. R. Astron. Soc.* **40**, 383 (1975).
3. T. Atwater and P. Molnar, in *Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System*, R. L. Kovach and A. Nur, Eds. (Stanford Univ. Publications in Geological Sciences, Stanford, CA, 1973), vol. 13, pp. 136–148.
4. J. Stock and P. Molnar, *Tectonics* **7**, 1339 (1988).
5. J. K. Weissel, D. E. Hayes, E. M. Herron, *Mar. Geol.* **25**, 231 (1977).
6. W. J. Morgan, in *Oceanic Lithosphere*, vol. 7 of *The Sea*, C. Emiliani, Ed. (Wiley-Interscience, New York, 1981), pp. 443–487.
7. ———, *Tectonophysics* **94**, 123 (1983).
8. R. A. Duncan, *ibid.* **74**, 29 (1981).
9. J. Stock and P. Molnar, *Nature* **325**, 495 (1987).
10. R. G. Gordon and A. Cox, *J. Geophys. Res.* **85**, 6534 (1980).
11. G. D. Acton and R. G. Gordon, *Science* **263**, 1246 (1994).
12. P. Molnar and J. M. Stock, *Nature* **327**, 587 (1987).
13. J. Stock and P. Molnar, *J. Geophys. Res.* **87**, 4697 (1982).
14. A. Cox and D. Engebretson, *Nature* **313**, 472 (1985).
15. F. Pollitz, *ibid.* **320**, 738 (1986).
16. W. Harbert and A. Cox, *J. Geophys. Res.* **94**, 3052 (1989).
17. W. Harbert, *Tectonics* **10**, 1 (1991).
18. W. F. Haxby, *Gravity Field of the World's Oceans* (National Geophysical Data Center, NOAA, Boulder, CO, 1987) (map).
19. K. M. Marks, D. C. McAdoo, D. T. Sandwell, *Eos* **72**, 145 (1991).
20. D. T. Sandwell and W. H. F. Smith, *Eos* (Fall Meeting Suppl.), **73**, 133 (1992).
21. C. L. Mayes, L. A. Lawver, D. T. Sandwell, *J. Geophys. Res.* **95**, 8543 (1990).
22. K. M. Marks and J. M. Stock, *ibid.* **99**, 531 (1994).
23. We have named FZ XII and FZ XI of Molnar *et al.* (*2*), the Pitman FZ and Heirtzler FZ, respectively, after W. C. Pitman III and J. R. Heirtzler [*Science* **154**, 1164 (1966)] who presented the first magnetic profiles that demonstrated unmistakable axial symmetry. These profiles still constitute a major part of the database used to constrain Pacific-Antarctic plate motions in this study. We use the names Pahemo and Kohiku for the two FZs that straddle the Pitman FZ as originally used by Falconer [R. H. K. Falconer, thesis, Victoria University of Wellington (1974)]. For the large fracture zone that marks the southwest boundary of the Pacific-Antarctic ridge for much of the Cenozoic, we use the name Emerald FZ after the vessel that discovered Emerald Island in these waters in 1821 [H. Stommel, *Lost Islands: The Story of Islands That Have Vanished from Nautical Charts* (Univ. of British Columbia Press, Vancouver, 1984), pp. 73–78]. We use the names Erebus FZ and Terror FZ, respectively, for Molnar *et al.*'s (*2*) FZ XIII and FZ XIV, after the ships of the Ross expedition of 1840–1843.
24. C. A. Raymond, J. Stock, S. C. Cande, in preparation.
25. K. C. Macdonald *et al.*, *Mar. Geophys. Res.* **14**, 299 (1992).
26. A. Macario *et al.*, *J. Geophys. Res.* **99**, 17921 (1994).
27. D. A. Christoffel and R. K. H. Falconer, in *Antarctic Oceanology II: The Australian-New Zealand Sector*, vol. 19 of Antarctic Research Series, D. E. Hayes, Ed. (American Geophysical Union, Washington, DC, 1972), pp. 197–209.
28. J. Stock *et al.*, in preparation.
29. T. Atwater and J. Severinghaus, in *The Eastern Pacific Ocean and Hawaii*, vol. N of *The Geology of North America*, E. L. Winterer, D. M. Hussong, R. W. Decker, Eds. (Geological Society of America, Boulder, CO, 1989), pp. 15–20.
30. S. J. Hellinger, *J. Geophys. Res.* **86**, 9312 (1981).
31. T. Chang, *ibid.* **92**, 6319 (1987).
32. J.-Y. Royer and T. Chang, *ibid.* **96**, 11779 (1991).
33. C. DeMets, R. G. Gordon, D. F. Argus, S. Stein, *Geophys. J. Int.* **101**, 425 (1990).
34. S. C. Cande, J. L. LaBrecque, W. F. Haxby, *J. Geophys. Res.* **93**, 13479 (1988).
35. R. D. Müller and W. R. Roest, *ibid.* **97**, 3337 (1992).
36. P. Lonsdale, *Mar. Geophys. Res.* **8**, 203 (1986).
37. ———, *ibid.* **16**, 105 (1994).
38. A. Macario, thesis, Columbia University (1995).
39. S. Tebbens, thesis, Columbia University (1994).
40. R. T. Bird and D. F. Naar, *Geology* **22**, 987 (1994).
41. J. W. Hawkins, *Proc. Ocean Drill. Proj. Init. Rep.* **135**, (1994).
42. L. W. Kroenke, *UN ESCAP, CCOP/SOPAC Tech. Bull.* **6**, 122 (1984).
43. P. F. Ballance, in *South Pacific Sedimentary Basins*, vol. 2 of *Sedimentary Basins of the World*, P. F. Ballance, Ed. (Elsevier, Amsterdam, 1993), pp. 93–110.
44. V. J. DiVenere, D. V. Kent, I. W. D. Dalziel, *J. Geophys. Res.* **99**, 15115 (1994).
45. A. K. Cooper, F. J. Davey, K. Hinz, in *Geological Evolution of Antarctica*, M. R. A. Thomson, J. A. Crame, J. W. Thomson, Eds. (Cambridge Univ. Press, New York, 1991), pp. 285–291.
46. P. G. Fitzgerald, P. J. Barrett, A. J. W. Gleadow, *Earth Planet. Sci. Lett.* **81**, 67 (1987).
47. T. J. Wilson, in *Antarctic Earth Science*, Y. Yoshida, K. Kaminuma, K. Shiraishi, Eds. (Terra Scientific, Tokyo, 1993), pp. 303–314.
48. ———, *Tectonics* **14**, 531 (1995).
49. J. C. Behrendt and A. Cooper, *Geology* **19**, 315 (1991).
50. L. A. Lawver and L. Gahagan, *Terra Antartica* **1**, 545 (1994).
51. B. E. Tucholke and H. Schouten, *Mar. Geophys. Res.* **10**, 1 (1988).
52. S. C. Cande and D. V. Kent, *J. Geophys. Res.* **100**, 6093 (1995).
53. J.-Y. Royer and D. T. Sandwell, *ibid.* **94**, 13755 (1989).
54. R. D. Müller, J.-Y. Royer, L. A. Lawver, *Geology* **21**, 275 (1993).
55. J.-Y. Royer, P. Patriat, H. Bergh, C. R. Scotese, *Tectonophysics* **155**, 235 (1988).
56. D. A. Clague and G. B. Dalrymple, in *The Eastern Pacific Ocean and Hawaii*, vol. N of *The Geology of North America*, E. L. Winterer, D. M. Hussong, R. W. Decker, Eds. (Geological Society of America, Boulder, CO, 1989), pp. 188–217.

57. We thank Captain J. O'Laughlin, the officers, crew, and scientific staff of the R/V *Ewing* for their efforts during the cruise. S. O'Hara contributed to processing the data at sea. Discussions with W. B. F. Ryan, T. Atwater, and many other colleagues have been greatly appreciated. A. Macario and two anonymous reviewers made many valuable comments. Drafting expertise was provided by B. Batchelder at Lamont and J. Griffith at Scripps. Funding was provided by NSF grants OPP-90-18742 and OCE-91-03573 to the Lamont-Doherty Earth Observatory, OCE-93-00945 to the Scripps Institution of Oceanography and EAR-92-96102 to Caltech. LDEO contribution #5419, Caltech contribution #5605.

26 May 1995; accepted 11 October 1995