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Evolution of the Eastern Indian Ocean Since the Late Cretaceous: Constraints From Geosat Altimetry

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We propose a new model for the tectonic evolution of the eastern Indian Ocean from the Late Cretaceous to the present. Two types of data are used to improve previously published reconstructions. First, recent reinterpretations of seafloor magnetic anomalies, between Australia and Antarctica and in the Wharton Basin, provide new constraints on spreading rates and the timing of major reorganizations. Second, vertical deflection profiles (i.e., horizontal gravity anomaly), derived from 22 repeat cycles of Geosat altimeter data, reveal the tectonic fabric associated with fracture zones. These new Geosat data provide tight constraints on paleospreading directions. For example, three prominent fracture zones can be traced from south of Tasmania to the George V Basin, Antarctica, providing an important constraint on the relative motions of Australia and Antarctica through the Late Eocene. In addition, the Geosat profiles are used to locate the conjugate continental margins and continent-ocean boundaries of Australia and Antarctica, as well as the conjugate rifted margins of Kerguelen Plateau and Broken Ridge. Based on a compilation of magnetic anomaly data from the Crozet Basin, the Central Indian Basin, the Wharton Basin and the Australian-Antarctic Basin, ten plate tectonic reconstructions are proposed. Reconstructions at chrons 5 (11 Ma), 6 (21 Ma), 13 (36 Ma) and 18 (43 Ma) confirm that the Southeast Indian Ridge behaved as a single plate boundary since chron 18. The constraints from the Geosat data provide an improvement in the fit of the Kerguelen Plateau and Broken Ridge at chron 20 (46 Ma). To avoid overlaps between Broken Ridge and the Kerguelen Plateau prior to their breakup, our model includes relative motions between the northern and southern provinces of the Kerguelen Plateau. Finally, we examine the implications of our model for the relative motions of India, Australia and Antarctica on the tectonic evolution of the Kerguelen Plateau and Broken Ridge, and the adjacent Labuan Basin and Diamantina Zone, as well as the emplacement of the Ninetyeast Ridge and the Kerguelen Plateau over a fixed hot spot.

INTRODUCTION

Many authors [e.g., *McKenzie and Sclater*, 1971; *Sclater and Fisher*, 1974; *Johnson et al.*, 1976; *Duncan*, 1978; *Norton and Sclater*, 1979; *Curray et al.*, 1982] have used the theory of plate tectonics to reconstruct the tectonic history of the eastern Indian Ocean and the past position of the continents surrounding this basin. Particularly enigmatic has been the history of the Southeast Indian Ridge which extends from the Rodriguez Triple Junction at 25°S, 70°E to the Macquarie Triple Junction south of New Zealand at 61°S, 162°E. This spreading center separates the Indian and Australian continents from Antarctica. In addition, the eastern Indian Ocean floor is the site of uncommonly large submarine plateaus such as the Ninetyeast and Broken ridges, and the Kerguelen Plateau (Figure 1).

Seafloor spreading among the major plates (India, Australia and Antarctica) in the eastern Indian Ocean occurred in three main phases. First, from Late Jurassic to Early Cretaceous times, Greater India separated from Antarctica/Australia resulting in the Mesozoic basins along the western Australian margin [*Markl*, 1974, 1978; *Larson et al.*, 1979; *Veevers et al.*, 1985]. Second, from Early Cretaceous to Middle Eocene times, the rapid northward motion of India created the Central Indian Basin and the Crozet Basin [*McKenzie and Sclater*, 1971; *Schlich*, 1975, 1982]. The Wharton Basin also opened during this period [*Sclater and Fisher*, 1974; *Liu et al.*, 1983] and spreading initiated between Australia and Antarctica [*Cande and Mutter*, 1982]. Finally, from Eocene to present time, the Australian-Antarctic Basin [*Weissel and Hayes*, 1972], the northern Crozet Basin and southern Central Indian Basin [*Schlich*, 1975; *Sclater et al.*, 1976] opened along the Southeast Indian Ridge. These three phases of spreading were separated by two periods of oceanwide plate reorganization, the first during Early/mid-Cretaceous time (Cretaceous magnetic quiet zone) and the second during Middle Eocene time (magnetic anomaly 20 to 18). The reorganizations occurred by ridge jumps, changes in spreading direction and spreading rate.

The reinterpretation of the seafloor magnetic pattern in the Australian-Antarctic Basin [*Cande and Mutter*, 1982] has important consequences for the breakup of Australia and Antarctica, and for the fit of the Kerguelen Plateau and Broken Ridge (Figure 1). Broken Ridge is a shallow (~1000 m), east-west trending plateau with a steep scarp facing the Australian-Antarctic Basin and a gentle slope facing the Wharton Basin. The conjugate Kerguelen Plateau faces Broken Ridge and extends in a NNW-SSE direction for more than 2,000 km. The original interpretation of the oldest magnetic anomaly (anomaly 22, 44 Ma) between Australia and Antarctica [*Weissel and Hayes*, 1972], resulted in an overlap between the two ridges at Early Eocene time [e.g., *Houtz et al.*, 1977; *Norton and Molnar*, 1977; *König*, 1980]. However, both Broken Ridge and the Kerguelen Plateau existed in the Late Cretaceous and thus could not overlap. On Broken Ridge, Santonian sediments have been recovered at Deep Sea Drilling Project (DSDP) site 255 [*Davies et al.*, 1974], while samples from the Kerguelen Plateau include sediments of Cenomanian age [*Wicquart*, 1983] and Lower Cretaceous basalts [*Leclaire et al.*, 1987]. Ocean Drilling Program (ODP) Legs 119, 120 and 121 have recently provided further evidence that Broken Ridge and the Kerguelen Plateau formed more than 90 million years ago [*ODP Leg 119 Scientific Drilling Party*, 1988; *ODP Leg 119 Shipboard Scientific Party*, 1988; *ODP Leg 120 Scientific Drilling Party*, 1988; *ODP Leg 120 Shipboard Scientific Party*, 1988; *ODP Leg 121 Scientific Drilling Party*, 1988; *ODP Leg 121 Shipboard Scientific Party*, 1988]. The reinterpretation by *Cande and Mutter* [1982] for the chronology of the breakup of Australia and Antarctica at chron 34 (84 Ma) partially solves the problem of overlap [*Mutter and Cande*,

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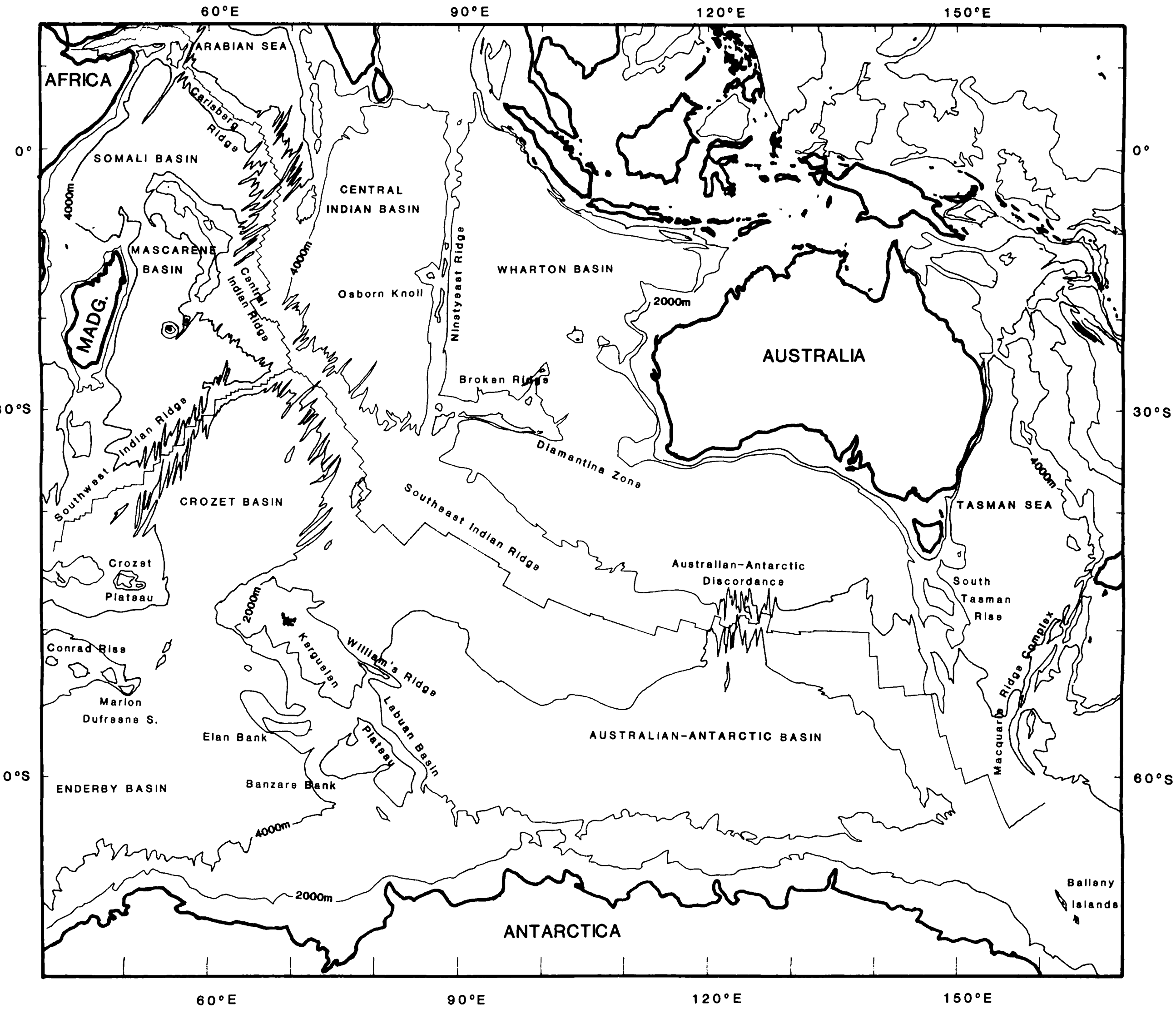

Fig. 1. General bathymetric map of the Indian Ocean (4000-m and 2000-m isobaths) and main structural features (after General Bathymetric Chart of the Oceans (GEBCO) summary chart 5·00).

1983], but no attempt has yet been made to include these results in a larger framework.

The existence of a Middle Eocene fossil spreading ridge in the Wharton Basin [*Liu et al.*, 1983; *Geller et al.*, 1983] is evidence that the Indian and Australian plates shared a divergent plate boundary until chron 19, and that the relative motions between India, Australia and Antarctica are coupled. The magnetic anomaly pattern identified by *Sclater and Fisher* [1974] in the Wharton Basin shows east-west magnetic lineations with ages decreasing from Late Cretaceous (anomaly 33) in the south to Late Eocene in the north. The youngest anomalies they identified are anomalies 19, 20 and 22, with a more questionable anomaly 17 identification. They postulated that the magnetic anomaly pattern continued northward to anomaly 11 before the Wharton Basin subducted under the Java-Sunda trench. Using additional magnetic profiles, *Liu et al.* [1983] were able to identify remnants of an extinct spreading ridge, extending from the Sunda trench at the equator to the Ninetyeast Ridge in a succession of right-lateral offset segments. Magnetic data reinterpretations [*Liu et al.*, 1983; *Geller et al.*, 1983] show that seafloor spreading ceased during Middle Eocene time (~chron 19), and that, in addition to the magnetic anomalies identified by *Sclater and Fisher* [1974], a symmetric pattern of magnetic lineations can be identified north of the fossil ridge axis, the youngest corresponding to anomaly 20 and the oldest, to anomaly 31. The Wharton Basin also appears more segmented than initially proposed. The new interpretation provides a stronger constraint on plate motions than was available when only a transform plate boundary between India and Australia was considered [e.g., *Sclater and Fisher*, 1974; *Johnson et al.*, 1976; *Duncan*, 1978; *Norton and Sclater*, 1979]. Furthermore, chron 19 is about the time when Broken Ridge and Kerguelen Plateau separated, and when spreading rates in the Australian-Antarctic Basin [*Cande and Mutter*, 1982] drastically increased from 0.5 cm/yr (half rate) before anomaly 19, to 2.7 cm/yr after anomaly 19 time. The question of whether India and Australia behaved as two different plates after seafloor spreading ceased in the Wharton Basin is another issue raised by these reinterpretations.

We present here an improved reconstruction for the last two of the three phases of spreading in the eastern Indian Ocean using the reinterpretations of the magnetic anomaly pattern in the Australian-Antarctic [*Cande and Mutter*, 1982] and Wharton [*Liu et al.*, 1983] basins, a compilation of magnetic anomalies in the Central Indian Basin and Crozet Basin, and fracture zone lineations derived from Geosat altimeter data. We have not yet attempted to model the earliest phase of evolution because of the absence of symmetric Mesozoic basins in the eastern Indian Ocean.

GEOSAT ALTIMETER DATA

Satellite altimetry data have now been widely used for locating topographic features of the ocean floor [e.g., *Haxby*, 1985; *Gahagan et al.*, 1988]. In some areas, they are particularly suited to outlining tectonic fabrics on the seafloor and have provided evidence to reappraise or improve plate reconstruction models [e.g., *Royer et al.*, 1988; *Cande et al.*, 1988]. The recent release of the Geosat data [*Sandwell and McAdoo*, 1988] significantly improves the amount of information on the poorly charted oceans south of 60°S. In this paper, the seafloor tectonic fabrics and the main structural features of the ocean floor are derived from data on the deflection of the vertical which is the first derivative of the ocean-geoid signal along the satellite passes (Figures 2 and 3). To improve the accuracy and coverage of the data, 22 Geosat repeat cycles were averaged. Coverage is nearly complete between 72°N and 72°S because Geosat has operated for more than one seasonal cycle. In addition, the uncertainty in the average of the 22 repeat profiles is generally less than 1 μrad (1 μrad ≈ 1 mgal). The data processing procedure is described by *Sandwell and McAdoo* [1988].

We present in Figure 4*a* some examples of interpretations of the deflection of the vertical signal. The combination of the information from the ascending and descending passes permits us to delineate prominent features on the ocean floor such as fracture zones, seamounts and the continental shelf. For the purpose of plate tectonic reconstructions, the most useful information is the accurate location and extension of the fracture zones. Depending on the age offset and the spreading rates which control the topographic and geoid signature of a fracture zone, these features can be precisely mapped (Figure 4*b*). The best illustration of such a feature is the Balleny Fracture Zone (trace 3 in Figure 5) that lies between the South Tasman Rise and the Balleny Islands (Figure 1) and has an age offset of about 10 Ma.

The tectonic features identified on the deflection of the vertical charts place strong constraints on the closure of the Australian/Antarctic Basin. From east to west, the major constraints are the fracture zones between Tasmania and Antarctica, the continent-ocean boundaries of Australia and Antarctica, and the margins of Broken Ridge and the Kerguelen Plateau. The prominent offset fracture zones south of Tasmania can be traced all the way south into the Antarctic margin (Figure 5). The George V, Tasman and Balleny fracture zones tightly constrain the longitudinal motions of Australia relative to Antarctica at least from Late Eocene (anomalies 18-13) to present time.

The location of the continental slope and the continent-ocean boundary (COB) along the south coast of Australia can be identified on the deflection of the vertical charts (Figure 6). On the Australian margin, *Talwani et al.* [1979] and more recently *Veevers* [1986] mapped the COB by correlating seismic data with what *Weissel and Hayes* [1972] recognized as magnetic anomaly 22, and *Cande and Mutter* [1982] as magnetic anomaly 34. *Veevers* [1986] interpreted the magnetic anomaly marking the southern limit of the magnetic

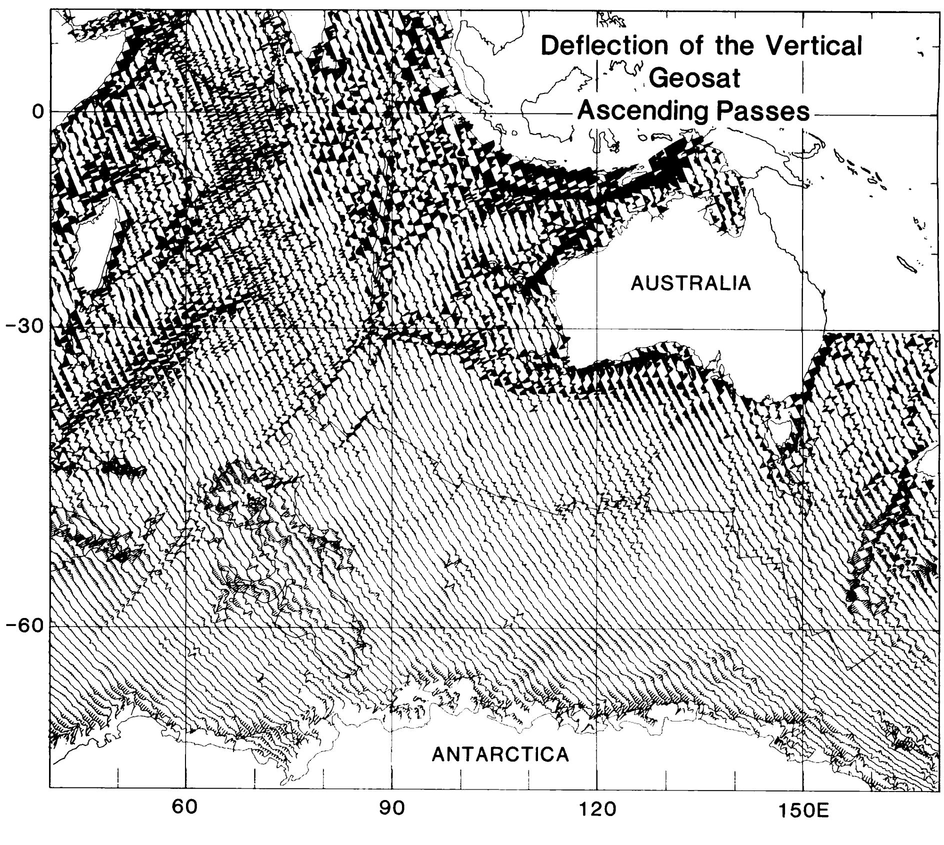

Fig. 2. Deflection of the vertical plotted along the Geosat ascending ground tracks. Note the pattern of linear fracture zones perpendicular to the Southeast Indian Ridge. Their orientation progressively shifts from N45°E in the Crozet Basin (between 60°E and 90°E), to N5°E in the vicinity of the Australian-Antarctic Discordance and N10°W east of 150°E.

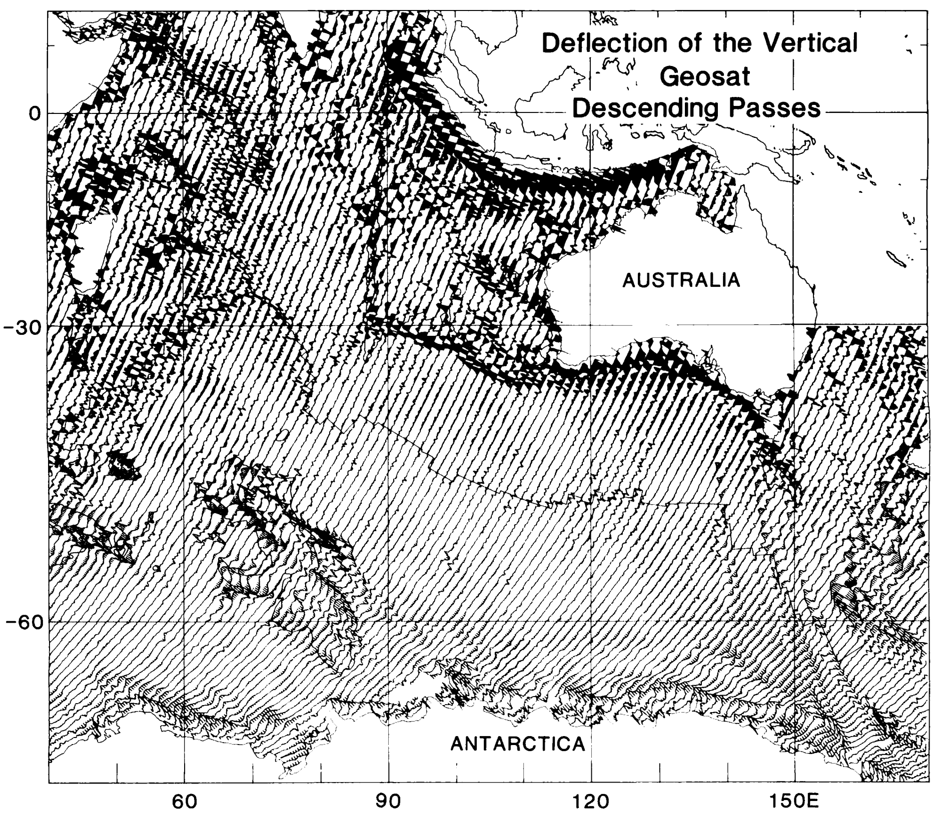

Fig. 3. Deflection of the vertical plotted along the Geosat descending ground tracks. The descending passes mostly outline the Southeast Indian Ridge axis, the fracture zones southeast of Australia and the margins of Australia and Antarctica, and the rifted margins of Broken Ridge and the Kerguelen Plateau.

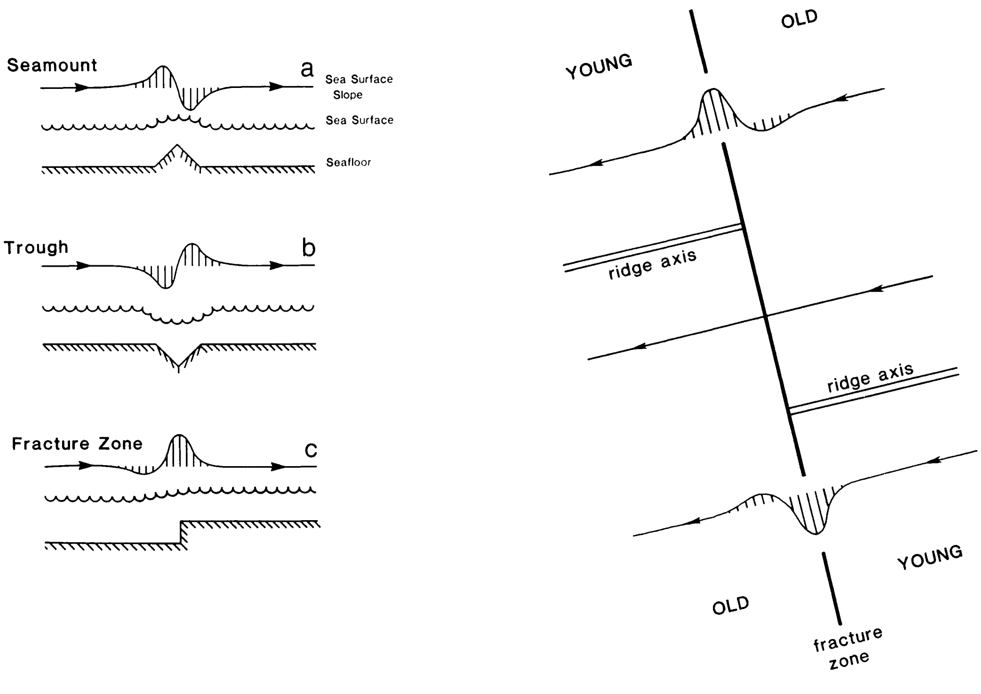

Fig. 4. (*a*) Signature of the deflection of the vertical or variation of sea surface slope over (top) a seamount, (middle) a trough and (bottom) an offset in the basement. (*b*) Changes in the deflection of the vertical along a large offset fracture zone. The signal reverses at the midpoint of the transform section of the fracture zone.

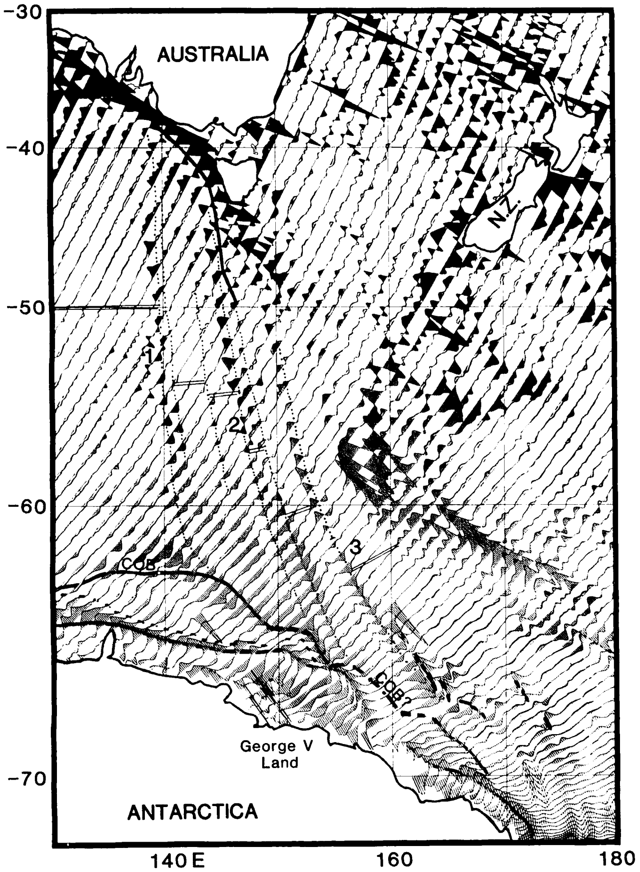

Fig. 5. Interpretation of the deflection of the vertical on the Geosat descending passes (20 μrad/degree of longitude): 1, George V Fracture Zone; 2, Tasman Fracture Zone; 3, Balleny Fracture Zone. The Southeast Indian Ridge axis outlined by a double line is located from magnetic and bathymetric data.

quiet zone along the south Australian continental margin as the combined effect of oceanic crust against continental crust with the anomaly 34 polarity reversal. The COB correlates with the first positive peak of the deflection of the vertical on the descending passes (Figure 6). It can be followed from the foot of the Naturaliste Plateau (110°E) to the south of Tasmania (145°E). The steepest part of the continental slope itself correlates with the deepest trough on the deflection of the vertical (or steepest descending slope of the geoid), parallel to the Australian coastline (Figure 6). Except in the Great Australian Bight, the width of the zone defined by the COB and the continental slope varies exactly with that of the magnetic quiet zone delineated by *König* [1980] (Figure 7). It becomes narrower east of 138°E as the two boundaries curve toward the south. While it seems reasonable that the steepest part of the continental slope will produce the largest slope in the geoid, we do not yet understand why the deflection of the vertical correlates well with the COB.

In order to identify the continental slope and the COB along the conjugate margin of Antarctica, where the bathymetric, seismic and magnetic data are more limited, the same criteria as for the Australian margin have been applied. We used the first high peak of the deflection of the vertical (or steepest slope of the geoid) off the coastlines (Figure 8) to locate the Antarctic shelf edge. As is the case with Australia, the continental margin parallels the coastline. East of Terre Adélie and off George V Land, East Antarctica, there appears to be a large basin landward of what we interpret as the limit of the continental shelf, indicating that it is perhaps underlain by continental crust. Nearly continuous ice coverage causes it to be a poorly surveyed area around Antarctica [e.g., *G. L. Johnson et al.*, 1980]. Only the eastern part of this basin has been mapped [*Domack and Anderson*, 1983; *Chase et al.*, 1987]. Using our reconstruction, we show that this previously uncharted basin was once connected to the Bass Strait (Figure 7).

The Antarctic COB is delineated by the first negative peaks of the deflection of the vertical that lie seaward from the steep upward slope of the continental shelf (Figure 8). From 120°E to 140°E, the peaks on the descending passes correlate well with the troughs of the

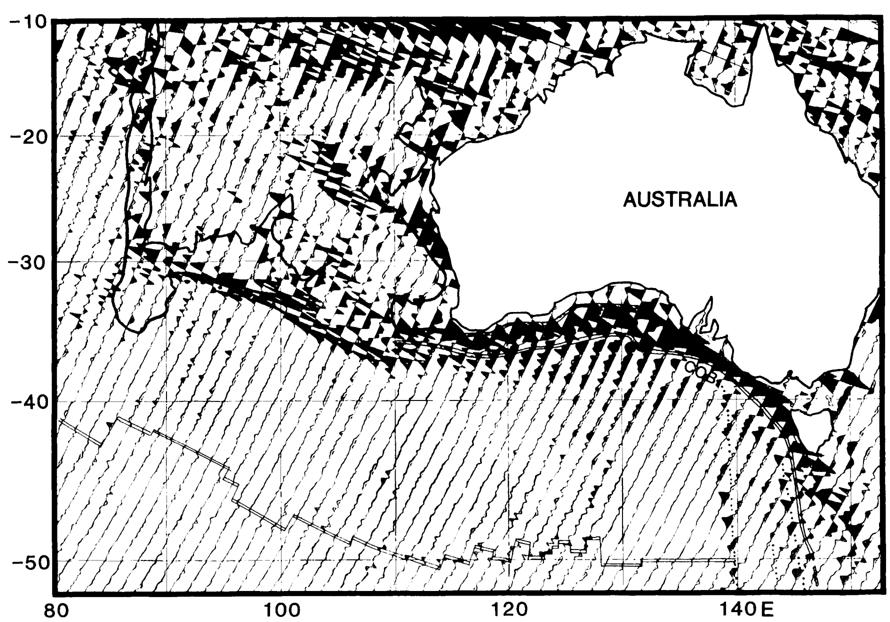

Fig. 6. Identification of the rifted margin of Broken Ridge, the shelf edge of Australia (first thick line seaward) and the continent-ocean boundary (COB) on the Geosat descending passes.

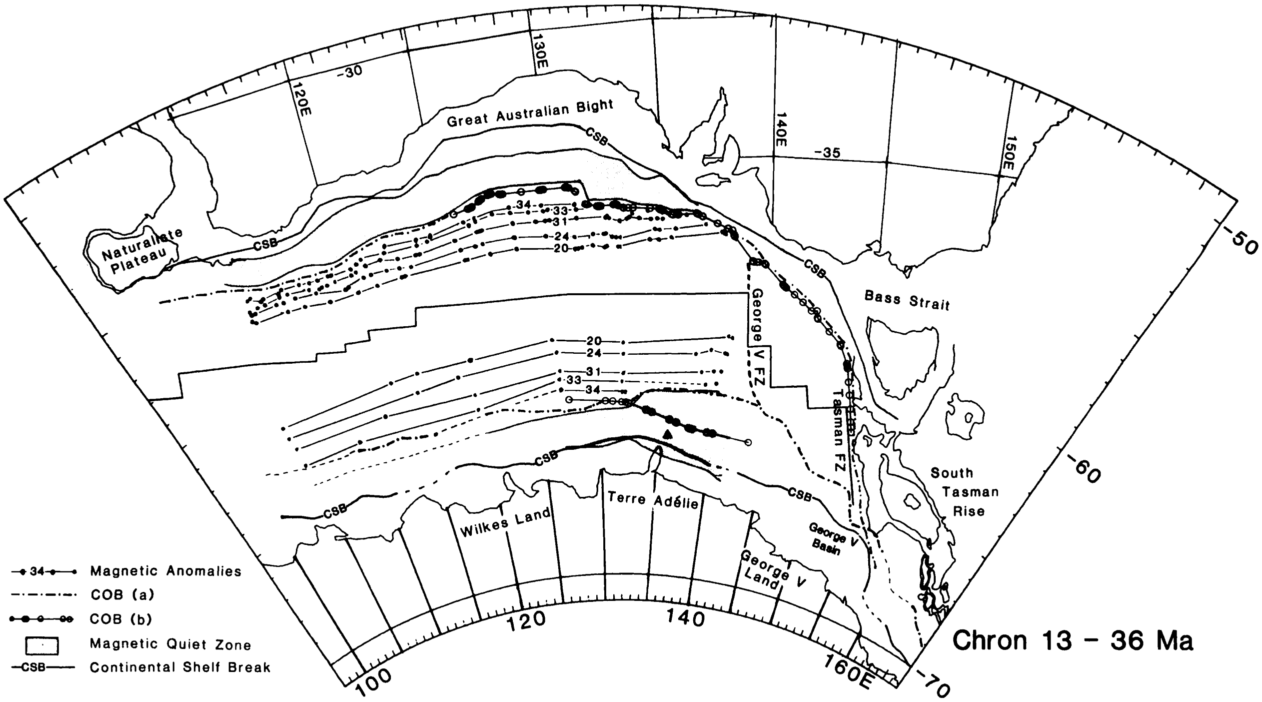

Fig. 7. Comparison on the conjugate Australian and Antarctic margins of the continent-ocean boundary (COB) derived from the deflection of the vertical data (COB a) and from magnetic and seismic data (COB b). South of Australia, the southern limit of the magnetic quiet zone (shaded area [after *König*, 1980]) matches the COB interpreted by *Veevers* [1986, 1987] from magnetic and seismic data (open circles). The deflection of the vertical data (Figure 6) displays a broad negative zone corresponding to the limit of the shelf break (CSB) and the continental slope. The first seaward positive peak correlates with the COB. These criteria are then used to identify the conjugate shelf break (CSB) and COB (dot-dashed line) on the Antarctic margin (Figure 8). For easy comparison of the conjugate margins, we use the chron 13 reconstruction (this paper) keeping Antarctica fixed in its present-day coordinates (polar stereographic projection). Note the good agreement of the COB a with the limit of the magnetic quiet zone [*König*, 1980] and the seismic control points between 130°E and 133°E [*Eittreim and Smith*, 1987]. The location of the COB after *Wannesson et al.* [1985] is located by a triangle off Terre Adélie.

ascending passes. To the west, the COB can tentatively be extended as far as 100°E, although the vertical deflection signal does not show the same characteristic pattern. It is obscured farther west by the southern tip of the Kerguelen Plateau. From 100°E to 133°E, the Antarctic COB and continental margin are roughly parallel to one another and separated by only 120 to 170 km. East of 133°E, the assumed COB and continental margin diverge, forming a broader zone of "transitional" crust more than 200 km wide. On the descending Geosat passes showing deflection of the vertical (Figure 8), the COB probably corresponds to the large negative trough that curves into the continental slope at 150°E. The eastern boundary of this zone seems to coincide with the termination of the George V Fracture Zone. Farther east, the COB is not as straight as its Australian counterpart west of Tasmania, but apparently follows a stair-step pattern which may correspond to a succession of pull-apart basins created during the breakup of Australia and Antarctica. Since

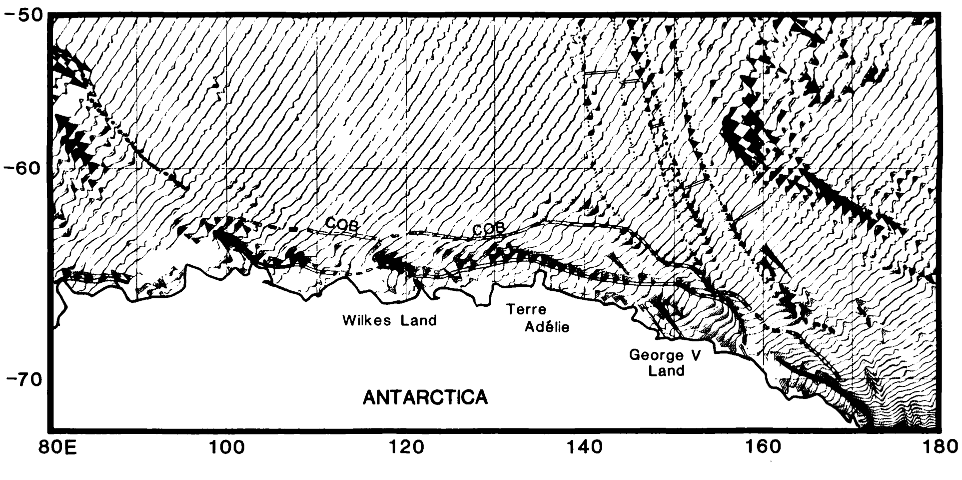

Fig. 8. Conjugate margin and COB off Wilkes Land and George V Land, Antarctica.

the orbits of the satellite are tangent to the 72°S parallel, the data are about twice as dense along the Antarctic margin as along the Australian margin.

The comparison of our interpretation with previous mapping of the Antarctic COB is shown on Figure 7. Our COB, based on the deflection of the vertical, agrees fairly well with the northern limit of the magnetic quiet zone as mapped by *König* [1980]. It also correlates with the seismic control points located between 130°E and 134°E of *König* [1980], *Veevers* [1986] and *Eittreim and Smith* [1987]. The latter authors show consistent line-to-line correlations of the continent-ocean boundary along with the limit of the magnetic quiet zone. *Wannesson et al.'s* [1985] identification of the COB off Terre Adélie (Figure 7) appears to be inconsistent with the results from *Eittreim and Smith* [1987], *Veevers* [1986, 1987] and our interpretation. Their point lies too close to the continental shelf break compared to the location of the COB in adjacent areas. Farther east between 134°E and 145°E, our interpretation as well as *König's* [1980] differs significantly from that of *Veevers* [1986, 1987]. Seismic coverage in this area is poor, and according to *Eittreim and Smith* [1987], the available data do not show a tectonic pattern as characteristic as west of 134°E. *Veevers* [1986, 1987] determined the COB using magnetic anomaly profiles which have low amplitudes and do not exhibit a characteristic "COB" magnetic anomaly that is observed west of 134°E or south of Australia [e.g., *Veevers*, 1987, Figure 11*a*]. This discrepancy in interpretation raises the question whether the breakup of Australia and Antarctica was synchronous [*Veevers*, 1986, 1987] or whether it propagated from west to east [*König*, 1980, 1987].

South of Australia, magnetic lineations lengthen eastward as their age become younger [*König*, 1980; *Cande and Mutter*, 1982], which is a clear evidence that seafloor spreading propagated eastward. This is in agreement with *Veevers'* [1986, 1987] interpretations, where the Australian COB becomes younger toward the east. *Mutter et al.* [1985] looking at subsidence curves along the Australian margin reached the same conclusion that breakup propagated from 128°E to 140°E at a rate of 2 cm/yr. Our interpretation is consistent with *König's* [1980] model where the conjugate COBs converge to the east. A kink in the COB similar to that observed at 131°E south of Australia can be mapped at about 134°E off Antarctica from the deflection of the vertical profiles. In general, we note that continental breakup and initiation of seafloor spreading are not synchronous (in the South Atlantic [e.g., *Rabinowitz and LaBrecque*, 1979], in the Central Atlantic [e.g., *Dunbar*, 1988], or in the Red Sea [*Cochran*, 1983]).

The basement offset that delineates the rifted margin of Kerguelen Plateau [*Coffin et al.*, 1986] is clearly visible on the Seasat data. The deflection of the vertical charts from Geosat permit us to extend this structural limit by a few 100 km to the south (Figure 9). The northeastern edge of the Kerguelen Plateau shows a pronounced bend corresponding to William's Ridge (Figure 10). This bend, which is exactly reproduced along the scarp of Broken Ridge (Figures 6 and 10), is a constraint on the relative position of the two ridges at the time when they broke apart. The Labuan Basin between 90° and 105°E and the Diamantina Zone (Figure 10), its northern counterpart, have similar deflection of the vertical signatures (Figures 6 and 9), corresponding to the rugged topography associated with the slow spreading episode between anomaly 34 (84 Ma) and anomaly 20 time (46 Ma) [*Cande and Mutter*, 1982].

In addition to the features described above, numerous fracture zones appear on the deflection of the vertical charts (ascending lines mostly, Figure 2) along the Southeast Indian Ridge. While many of these fracture zones were already mapped in great detail [e.g., *Schlich*, 1975; *Sclater et al.*, 1976; *Patriat*, 1987; *Royer and Schlich*, 1988; *Vogt et al.*, 1983], new fracture zones appear in the vertical deflection profiles (Figure 2) between Broken Ridge and Kerguelen Plateau. The Kerguelen Fracture Zone, which runs NNE-SSW west of the Kerguelen Plateau (Figure 2), is another major feature clearly delineated by the deflection of the vertical charts. This fracture zone disappears at about 62°S. In the Central Indian Basin and the Wharton Basin, the wide spacing and low angle of incidence of Geosat profiles are not suitable for mapping the north-south fracture zones. Furthermore, the basement undulations related to the deformation of the Central Indian Basin cause east-west lineated geoid anomalies [*McAdoo and Sandwell*, 1985] which obscure the seafloor tectonic fabric. For instance, it is not possible to identify the northern counterpart of the Kerguelen Fracture Zone.

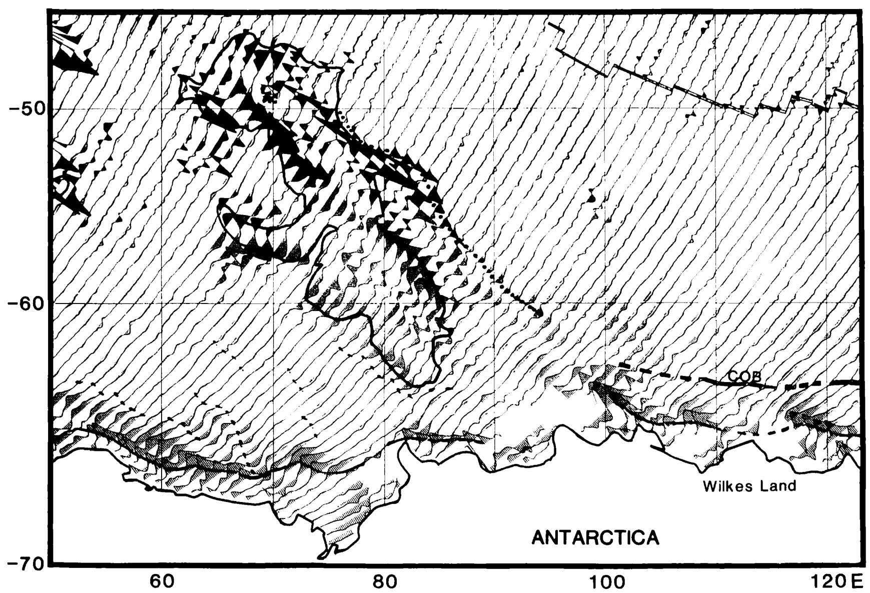

Fig. 9. Rifted margin of the Kerguelen Plateau (heavy dotted line) on the Geosat descending passes. Note the peak and trough signature of the Labuan Basin, which extends between the Plateau (outlined by the 3000-m isobath) and the rifted margin of the Plateau.

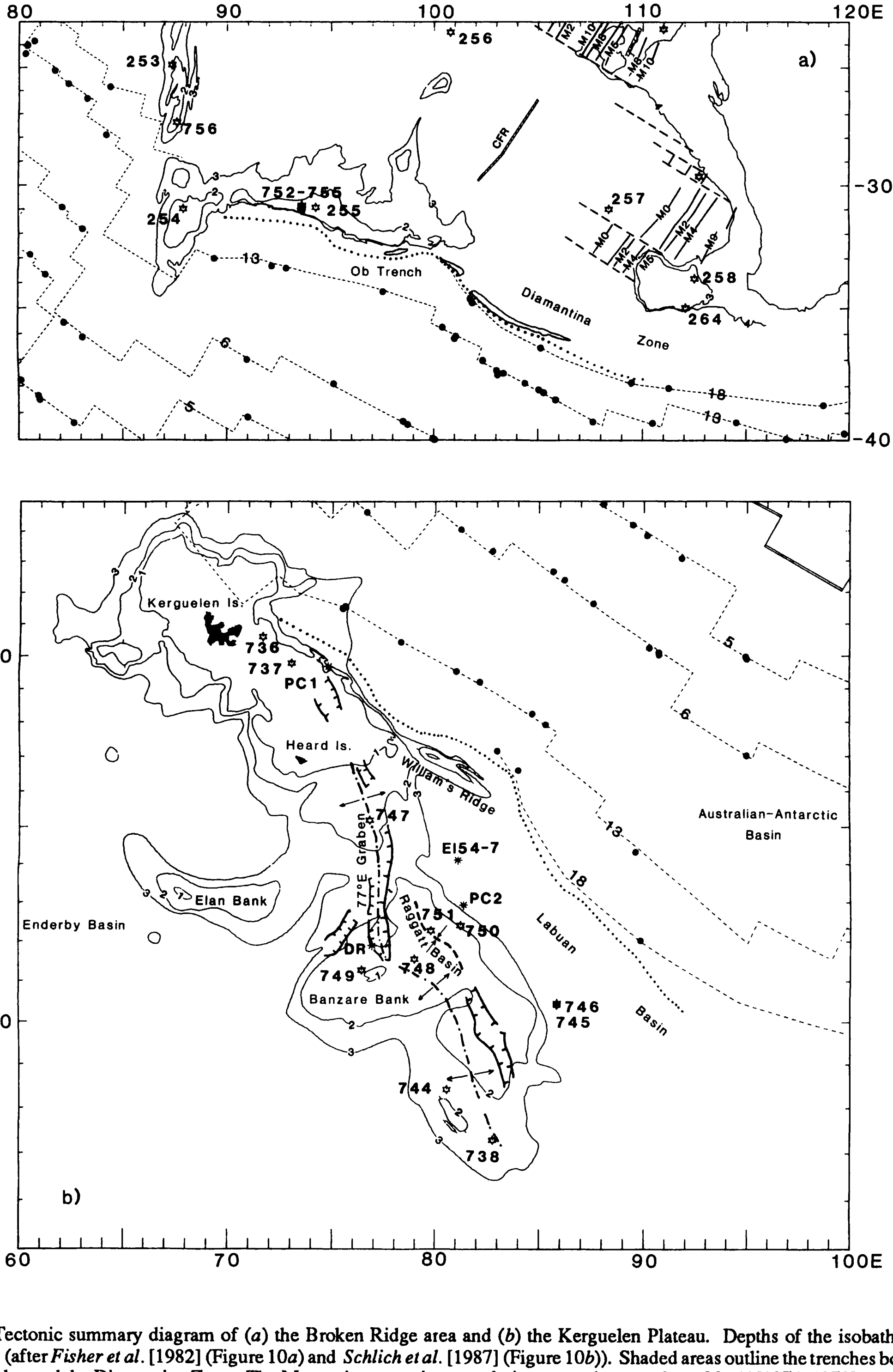

Fig. 10. Tectonic summary diagram of (*a*) the Broken Ridge area and (*b*) the Kerguelen Plateau. Depths of the isobaths are in kilometers (after *Fisher et al.* [1982] (Figure 10*a*) and *Schlich et al.* [1987] (Figure 10*b*)). Shaded areas outline the trenches bordering Broken Ridge and the Diamantina Zone. The Mesozoic magnetic anomaly interpretations are from *Markl* [1974, 1978] and *Veevers et al.* [1985]. CFR (Cretaceous fossil ridge) shows the location of a mid-Cretaceous extinct spreading axis [*Markl*, 1974; *Powell et al.*, 1988]. DSDP and ODP drilling sites (bold numbers) are located by stars. Piston cores (PC) and dredges (DR) are indicated by asterisks. The light dashed lines are isochrons and the solid circles along them are the magnetic picks. The dotted line corresponds to the conjugate rifted margin of Broken Ridge and Kerguelen Plateau as identified on the deflection of the vertical data (Figures 6 and 9). The dot-dashed line with anticline symbols corresponds to a broad arch of the southern Kerguelen province and the dashed line with syncline symbols to the axis of the Raggatt Basin [after *Coffin et al.*, 1986]. The oldest date on Broken Ridge is early Turonian (site 755 [*ODP Leg 121 Scientific Drilling Party*, 1988; *ODP Leg 121 Shipboard Scientific Party*, 1988]). The oldest date on the northern Kerguelen Plateau is Cenomanian (PC1 [*Wicquart*, 1983]), and on the southern province 114 Ma (DR [*Leclaire et al.*, 1987]) and Cenomanian (site 748, 750 [*ODP Leg 120 Scientific Drilling Party*, 1988; *ODP Leg 120 Shipboard Scientific Party*, 1988]; EL54-7 [*Quilty*, 1973]).

A REVISED TECTONIC CHART FOR THE EASTERN INDIAN OCEAN

The tectonic diagrams on Figures 11*a* and 11*b* summarize the seafloor tectonic fabric derived from the deflection of the vertical charts, the magnetic anomaly pattern since the Late Cretaceous and the main structural features identified in the eastern Indian Ocean. With regard to the seafloor tectonic fabric, the best documented period in the evolution of the eastern Indian Ocean corresponds to the last stage of evolution that follows the major reorganization of the spreading centers in Middle Eocene time. From anomaly 18 time (43 Ma) to present day, the closure of the Central Indian Basin, the Crozet Basin, and the Australian-Antarctic Basin is tightly constrained by the numerous fracture zones identified between the Rodriguez Triple Junction (25°S, 70°E) and the Macquarie Triple Junction (61°S, 162°E). The fit of Broken Ridge with Kerguelen Plateau is now well constrained by the distinctive shape of their respective scarps, as identified on the deflection of the vertical charts. The direction of motions between India and Antarctica between Late Cretaceous (anomaly 34) and Middle Eocene (anomaly 20) time are constrained by the fracture zone pattern in the Crozet Basin and in particular by the Kerguelen Fracture Zone, while the motions of India relative to Australia are determined by the north-south fracture zones in the Wharton Basin, and in particular by the large offset Investigator Fracture Zone. Finally, a new reconstruction of Australia and Antarctica can be proposed on the basis of the revised contours of their respective COBs and continental margins.

The magnetic anomaly identifications used in this study are based on earlier data compilations. However, for the purpose of making reconstructions, we have standardized the locations of the picks with respect to the magnetic anomaly signatures. This standardization is critical for reconstructing areas of fast spreading rates such as the Wharton Basin, the Central Indian Basin or the Crozet Basin (11 to 4 cm/yr, half rates), but is of less consequence in the areas of slow spreading rates, such as between Australia and Antarctica between Late Cretaceous and Middle Eocene time (0.5 to 1.0 cm/yr). The reversal boundaries that we selected and their ages (*Kent and Gradstein*'s [1986] reversal time scale) are shown in Table 1.

Between Australia and Antarctica, anomaly 5, 6, 13 and 18 identifications are from *Stock and Molnar* [1982] and *Vogt et al.* [1983]. Anomaly 20 to 33 interpretations are from *Cande and Mutter*'s [1982]. Anomaly 34 is from *Veevers* [1986], who attributes the positive anomaly identified as anomaly 34 by *Cande and Mutter*'s [1982] to an edge effect of the COB combined with the anomaly 34 polarity reversal. Similarly, east of 131°E, anomaly 33 becomes part of the COB anomaly. In the Crozet and Central Indian basins, anomaly 5 and 6 identifications are from *Royer and Schlich* [1988], while anomaly 13 through 34 identifications are from *Patriat* [1987]. Additional identifications (anomalies 5, 6, 13 and 18) between Kerguelen and Broken Ridge have been made from data published by *Tilbury* [1981]. In the Wharton Basin, profiles of total intensity magnetic anomaly have been reinterpreted in the interest of consistency of the data set. We favor the interpretation of *Liu et al.* [1983] and *Geller et al.* [1983]. New evidence for the existence of a fossil spreading ridge of Middle Eocene age (~ anomaly 19/18) will be presented elsewhere (J.-Y. Royer et al., manuscript in preparation). The oldest magnetic anomalies recognized in the northern Wharton Basin are anomalies 28 and 31 (at 92°E). Finally, magnetic data along the Southwest Indian Ridge and the Central Indian Ridge are from *Patriat* [1987]. There are two areas where the magnetic data coverage is poor: the southern part of the Australian-Antarctic Basin between 85°E and 115°E, and in the vicinity of the Ninetyeast Ridge where there are very few magnetic profiles parallel to this feature.

RECONSTRUCTIONS AT CHRONS 5, 6, 13 AND 18

As a result of combining the deflection of the vertical charts and the magnetic anomaly compilation, the best documented period of evolution of the Southeast Indian Ridge is the Late Eocene to present time span. Our confidence in the reconstructions decreases as we go back further in the past. All the reconstructions are presented backward in time and with Australia fixed.

Past reconstructions of the Southeast Indian Ridge from the Rodriguez Triple Junction to the Macquarie Triple Junction have raised the question of whether or not this accreting plate boundary has behaved as a single plate boundary since motions may have occurred between India and Australia after seafloor spreading ceased in the Wharton Basin, at Middle Eocene time (~anomaly 19 [*Liu et al.*, 1983]). Plate tectonic reconstructions along the Southeast Indian Ridge [*Stock and Molnar*, 1982] show that, at anomaly 5, 6 and 13 times (11, 20 and 36 Ma, respectively), different finite poles are not required to simultaneously match magnetic anomaly data from the three main segments of the ridge: between India and Antarctica (i.e., west of the Ninetyeast Ridge), between Australia and Antarctica, and east of the Balleny Fracture Zone. Between anomaly 18 and 13 times, however, when the central section and either one of the outer sections are reconstructed, a match cannot be achieved for the remaining section. Because of this discrepancy, *Stock and Molnar* [1982] proposed that either the Indo-Australian plate was deforming or deformation occurred in the region of the Macquarie Triple Junction. More detailed reconstructions of the section of the Southeast Indian Ridge west of the Ninetyeast Ridge at anomalies 5, 6, 13 and 18 [*Patriat*, 1987; *Molnar et al.*, 1988; *Royer and Schlich*, 1988] yield finite rotations different from those proposed by *Stock and Molnar* [1982], which mainly rely upon data from the Australian-Antarctic Basin (east of the Ninetyeast Ridge). The combinations of the different solutions for the India/Antarctica motions with the Australia/Antarctica motions lead to India/Australia motions different from the solutions derived from recent global models for present-day plate motions [*Stein and Gordon*, 1984; *Wiens et al.*, 1985, 1986; R. G. Gordon et al., Present-day motion between the Australian and Indian plates: Kinematic constraints on distributed lithospheric deformation in the equatorial Indian Ocean, submitted to *Tectonics*, 1989 (hereinafter Gordon et al. (1989))]. Our reconstructions show that two different rotations are not required to match the data along the entire Southeast Indian Ridge, and confirm that the Southeast Indian Ridge has behaved as a single plate boundary at least since anomaly 13 time (36 Ma), and probably since anomaly 18 time (43 Ma). This conclusion is well supported by our data set which extends between the two extremities of the Southeast Indian Ridge, from the Rodriguez Triple Junction to the Macquarie Triple Junction, and is uniformly dense and detailed all along the ridge.

The reconstructions at anomaly 5 and 6 times (Figures 12*a* and 12*b*) are well constrained by the crenelate shape of the ridge between Australia and Antarctica (Australian-Antarctic Discordance), the large offset Amsterdam, Saint-Paul, George V, and Tasman fracture zones (Figure 11), as well as the numerous magnetic anomaly identifications west of the Amsterdam Fracture Zone. Although the magnetic picks identified east of the Balleny Fracture Zone agree, there is a clear mismatch of the two limbs of the Balleny Fracture Zone at chron 5 (Figure 12*a*).

The fit for anomaly 13 (35.5 Ma) is also well constrained (Figure 12*c*). In particular, the anomaly 13 picks between Broken Ridge and Kerguelen Plateau reproduce the shape of the "basement offsets" of the ridges on either side. To the west, this lineation disappears under the northwesternmost part of the Kerguelen Plateau and the southern tip of the Ninetyeast Ridge. The basement reached at DSDP site 254,

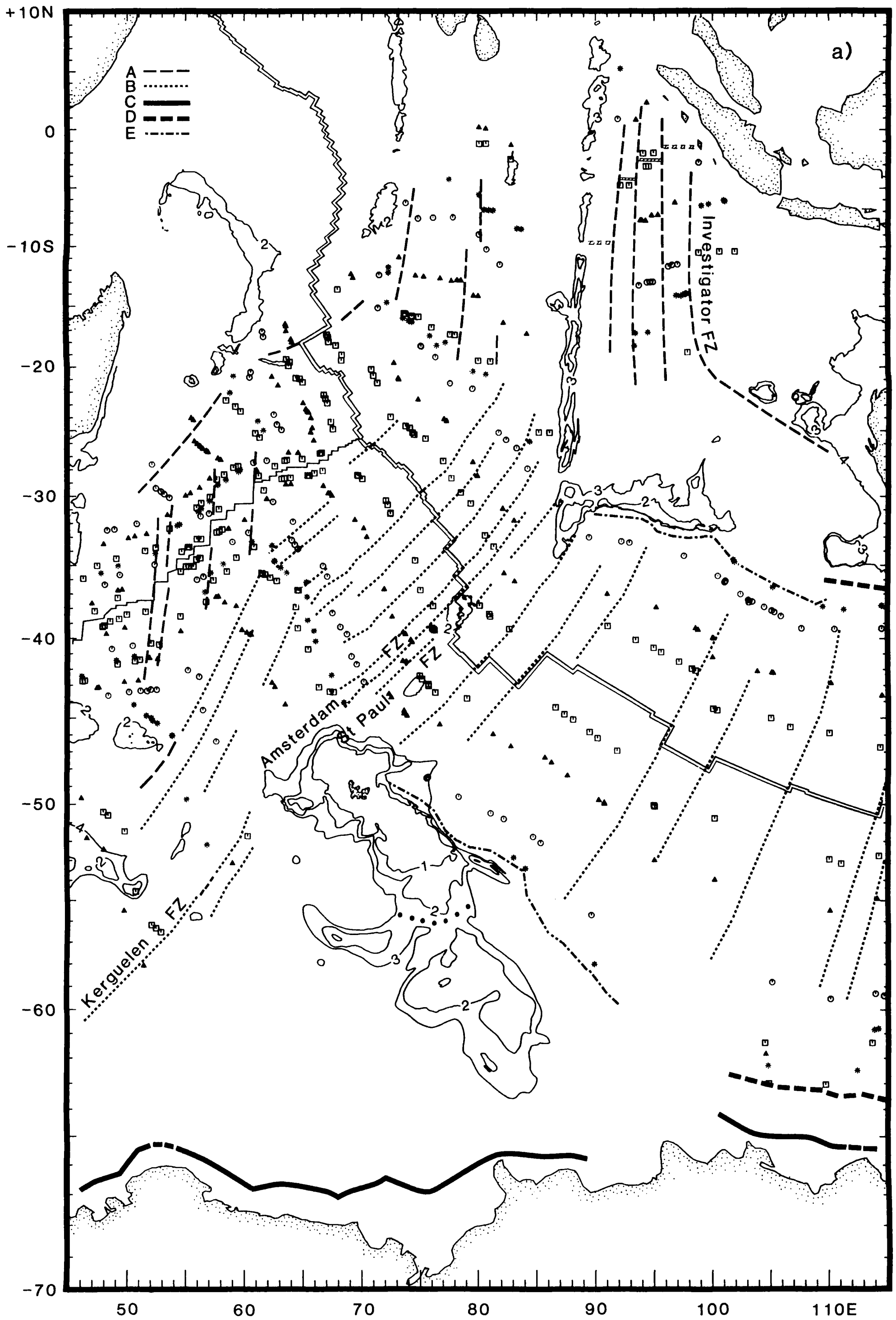

Fig. 11. Tectonic summary diagram of the Eastern Indian Ocean: long-dashed lines A outline the fracture zones mapped from bathymetric and magnetic evidence; line types B through E outline the seafloor tectonic fabrics mapped from the deflection of the vertical charts. They are, respectively, B, the fracture zones; C, the limit of the continental shelf; D, the continent/ocean boundary; and E, the rifted margin of Broken Ridge and the Kerguelen Plateau. The ridge axes are shown by a double line. Symbols (by sequences of four) represent the magnetic anomaly picks identified in the Eastern Indian Ocean: squares (magnetic anomalies 5, 20 and 33), triangles (anomalies 6, 24 and 34), circles (anomalies 13 and 28) and asterisks (anomalies 18 and 31). In the Wharton Basin, the double-lined segments locate the fossil ridge axis; the youngest magnetic anomaly on either side is anomaly 20 (square). The bathymetric contours are in kilometers and are taken from the GEBCO overlays [*Laughton*, 1975; *Falconer and Tharp*, 1981; *Fisher et al.*, 1982; *Monahan et al.*, 1982]. The contours of the Kerguelen Plateau are from *Schlich et al.* [1987].

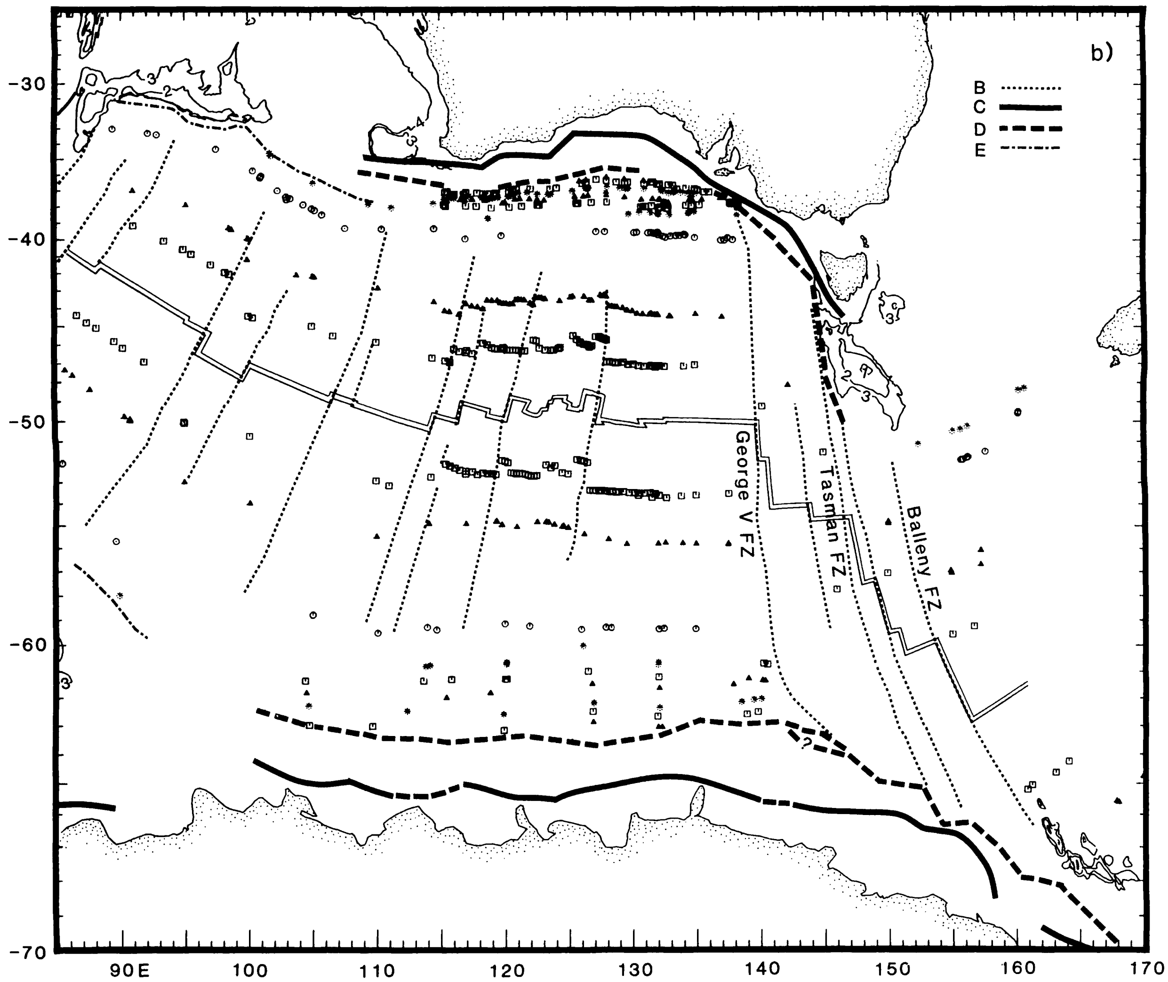

Fig. 11. (continued)

TABLE 1. Ages of the Selected Magnetic Anomalies.

Anomaly	Age, Ma
5	10.5
6	20.5
13y	35.5
18	42.7
20	46.2
24	56.1
28y	64.3
31y	68.5
33	80.2
34y	84.0

Here, y refers to the youngest boundary of the magnetic reversal. Ages are from *Kent and Gradstein*'s [1986] reversal time scale.

~250 km to the north, is estimated at about 38 Ma [*Duncan*, 1978] and the oldest sediment recovered is of Late Eocene/Oligocene age [*Davies et al.*, 1974]. The northwesternmost part of the Kerguelen Plateau might be of the same age or even younger. The oldest age determined by isotopic dating for the volcanism of the Kerguelen Islands is Middle Eocene; a K-Ar date of 39 Ma was obtained from igneous rocks [*Giret and Lameyre*, 1983]. Our anomaly 13 reconstruction indicates that the conjugate to the westernmost magnetic pick identified south of Broken Ridge has been covered by the Kerguelen Plateau. Consequently, the northwestern part of the Kerguelen Plateau, which supports the Kerguelen Islands, would be underlain by Late Eocene/Early Oligocene oceanic crust. This hypothesis agrees with the location of the oldest magnetic anomaly recognized north of this portion of the Kerguelen Plateau, that is Early/Late Oligocene (anomaly 11 [*Schlich and Patriat*, 1971]). Between Australia and Antarctica, except the George V Fracture Zone (at 138°E), there are no observable major transform offsets. East of George V Fracture Zone, the lineament that we identified as the COB along the Tasman Rise lines up with the George V Land continental shelf. The oldest sediments recovered at DSDP site 282 are of Late Eocene age [*Kennett et al.*, 1975]. At that time, Australia and Antarctica were still connected south of Tasmania, so deep sea water circulation between the Indian Ocean and the Pacific Ocean initiated only in Late Oligocene time, in accordance with the sediment stratigraphy of the DSDP holes in this area [*Kennett et al.*, 1975]. To the southwest, the Balleny Islands and associated seamount chain start overlapping the South Tasman Rise of continental origin according to DSDP site 281 [*Kennett et al.*, 1975], suggesting an oceanic origin and a Late Eocene age limit for these seamounts. According to the position of DSDP site 280, the crust lying west of the Balleny Island chain is probably older than Middle Eocene [*Kennett et al.*, 1975]. Such an age is compatible with our reconstruction.

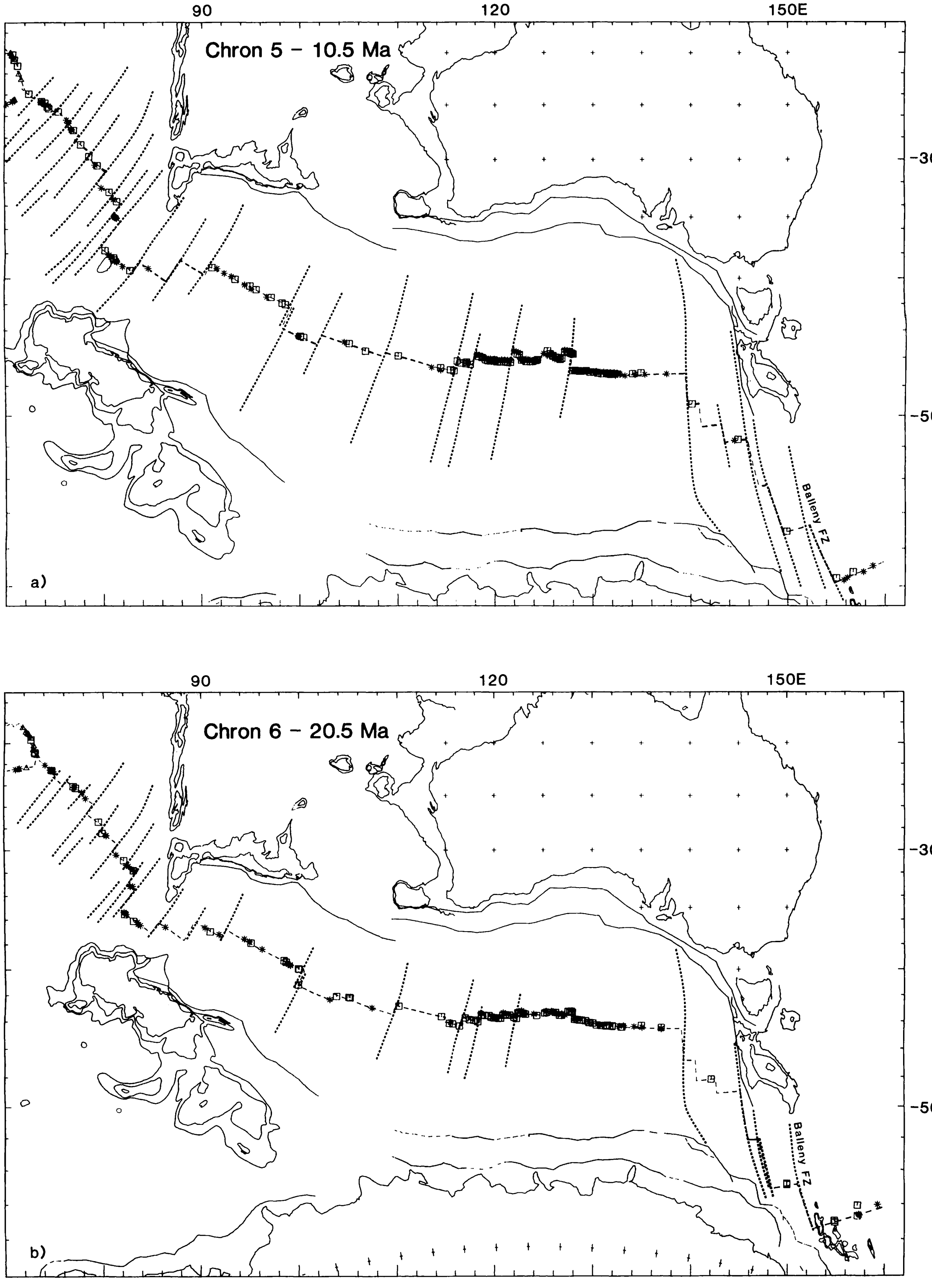

Fig. 12. Reconstructions at chrons 5, 6, 13 and 18. Asterisks represent magnetic picks from the Antarctic Plate, squares from the Australian Plate, and triangles from the African Plate. Fracture zones are identified by dotted lines. (*a*) Reconstruction at chron 5 (10.5 Ma). Note the mismatch of the two limbs of the Balleny Fracture Zone at 150°E. (*b*) Reconstruction at chron 6 (20.5 Ma). (*c*) Reconstruction at chron 13 (35.5 Ma). Note the perfect correspondence between the shape of the anomaly 13 lineation and of the rifted margins of Broken Ridge and the Kerguelen Plateau as identified on the deflection of the vertical charts. (*d*) Reconstruction at chron 18 (42.7 Ma). DSDP site 255 and a piston core (PC) on the northeastern flank of the Kerguelen Plateau both contain sediments of Santonian age [*Davies et al.*, 1974; *Wicquart*, 1983]. The overlap of the rifted margins of Broken Ridge and the Kerguelen Plateau is evidence for a diachronous breakup. The mismatch of the magnetic picks southeast of Tasmania is larger than at chron 13. The large right-lateral transform offsets in the Wharton Basin are opposed to the change of spreading direction that is occurring in the Central Indian Basin and in the Crozet Basin. Consequently, seafloor spreading in the Wharton ceased and jumped southward in the Diamantina and Labuan basins, leaving a fossil ridge axis in the Labuan Basin.

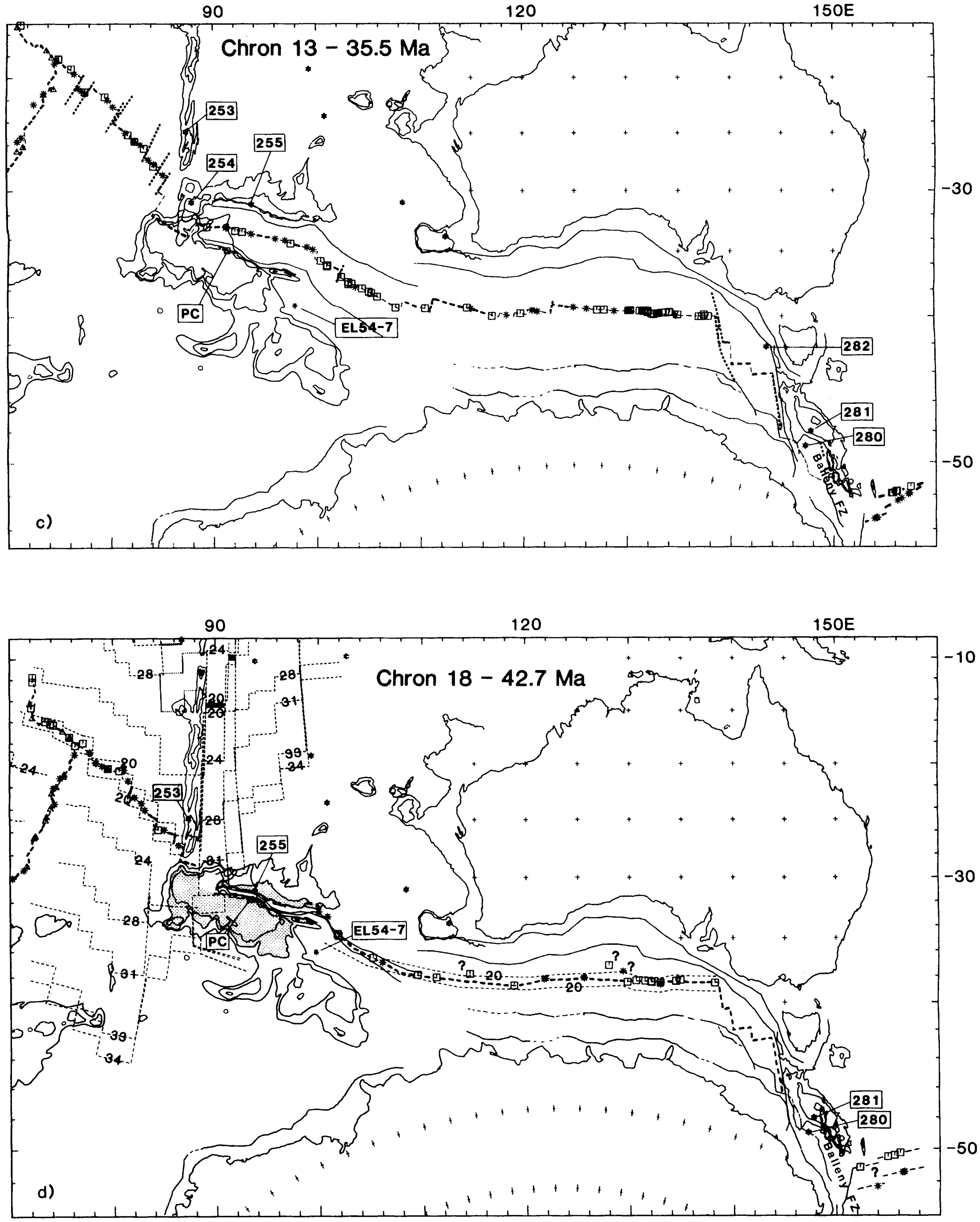

Fig. 12. (continued)

The anomaly 18 reconstruction is probably the least constrained in this series. There are only a few conjugate pairs of picks in the Australian-Antarctic Basin (Figure 12*d*) and some of those appear to be misplaced (at 115°E, 128°E and 130°E). The principal constraint comes from the match of the "basement offsets" north of the Kerguelen Plateau and south of Broken Ridge. The use of a single finite pole for this reconstruction inevitably produces some misfit of the two lines. A perfect match causes the older magnetic anomalies to overlap in the Australian-Antarctic Basin and creates large gaps west of the Ninetyeast Ridge. Our reconstruction suggests that the rifting of Kerguelen Plateau and Broken Ridge was not synchronous and propagated from east to west between anomaly 18 and 13. The increasing ages of the magnetic anomaly identified between the two ridges support this hypothesis. To the west the oldest anomaly clearly identifiable is anomaly 13 [*Le Pichon and Heirtzler*, 1968; *McKenzie and Sclater*, 1971], farther east anomaly 17 [*Houtz et al.*, 1977]; the first typical anomaly 18 is identified at 102°E (Figure 12*d*). Although a single finite rotation is consistent with the data along the Southeast Indian Ridge, it is possible that some differential motion between India and Australia may have continued at that time along the Ninetyeast Ridge, since seafloor spreading in the Wharton Basin may have not ceased at once along 1000 km of spreading ridge.

In agreement with *Stock and Molnar*'s [1982] results, we are unable to match the few anomaly 13 and 18 picks lying east of the Balleny Fracture Zone (Figures 12*c* and 12*d*). There is a gap of about 40 km at anomaly 13 time that increases to 100 km at anomaly 18 time. The rotation that makes these data coincide degrades the closure of the Australian-Antarctic Basin and the fit of Kerguelen Plateau and Broken Ridge. Several models can explain this discrepancy. First, another plate boundary east of the Tasman Rise and the present-day Balleny Islands existed before anomaly 13 time and until shortly thereafter. This interpretation is favored by the respective position of the continent/ocean boundaries and margins of Australia and Antarctica which were in contact at that time. Some extension between East and West Antarctica in the Ross Sea would be sufficient to explain the observed gaps on anomaly 13 and 18 reconstructions. Similar ideas have been proposed to solve problems in reconstructing the south Pacific [*Molnar et al.*, 1975; *Stock and Molnar*, 1982], since extension in the Ross Sea is relevant for the period of time involved. We note that *Cooper and Davey* [1985] relate Late Cenozoic volcanism within the Ross Sea with extensional tectonic events. An alternative model is that the misfits reflect some deformation of the Australian Plate resulting from the convergence between the Pacific and Australian plates. The initiation of subduction along the Macquarie Trench might explain why the anomaly 5 and 6 lineations are not affected or less affected by such deformation. However, at chrons 5 and 6 (Figures 12*a* and 12*b*), the azimuth of the Balleny Fracture Zone is not compatible with the direction of motion between Australia and East Antarctica. The *DeMets et al.* [1988] and Gordon et al. (1989) syntheses of present-day plate motions in the Indian Ocean show that the India-Africa-Antarctica-Australia motions are consistent with circuit closure, with the exception of the data (transform azimuths and spreading rates) in the vicinity of the Macquarie Triple Junction. These results confirm that the Southeast Indian Ridge has behaved as a single plate boundary since Late Eocene time, while suggesting that deformation of the Australian or East Antarctic plates south of Tasmania has occurred since then and continues presently.

RECONSTRUCTIONS AT CHRONS 20, 24, 28, 31, 33 AND 34, AND CLOSURE OF THE AUSTRALIAN-ANTARCTIC BASIN

Anomaly 20 (46 Ma) is the youngest magnetic anomaly recorded before seafloor spreading ceased in the Wharton Basin. From Late Cretaceous time until then, there were three accreting plate boundaries and three interacting plates in the Eastern Indian Ocean: the Indian, Australian and Antarctic plates. However, because seafloor spreading was extremely slow between Australia and Antarctica, the main plate motion corresponded to the rapid northward drift of India toward Asia.

In the Australian-Antarctic Basin, the observed magnetic lineations are very linear with almost no fracture zones. To the east, the only constraint for closing this basin is the shear margin between George V Land and the Tasman Rise. To the west, the constraint is that the Kerguelen Plateau and Broken Ridge cannot overlap. The question is where the plate boundary between Australia and Antarctica extended to the west. Tectonic elements older than chron 18 in the area are Broken Ridge, the Kerguelen Plateau, the Labuan Basin and the Diamantina Zone (Figure 10). The Labuan basin is bounded to the northeast by the Kerguelen "basement offset", to the north by William's Ridge, and to the southwest by the northeastern flank of the southern Kerguelen Plateau. The Diamantina Zone, characterized by an extremely rugged topography, stretches from south of the Naturaliste Plateau to the eastern limit of Broken Ridge where it abruptly ends. *Houtz et al.* [1977] identified three different tectonic trends on the Kerguelen Plateau: NW-SE horsts and grabens between Kerguelen and Heard islands, N-S trending grabens between the northern and southern Kerguelen Plateau, where the bathymetry deepens and forms a saddle, and NW-SE horsts and grabens on the southern and easternmost part of the plateau. No such tectonic features have been identified on Broken Ridge. Multichannel surveys in a basin south of Kerguelen Island [*Munschy and Schlich*, 1987] and in the Raggatt Basin [*Ramsay et al.*, 1986; *Schlich et al.*, 1988], which tops the southern Kerguelen Plateau (Figure 10*b*), show no evidence for a major faulting in the basement, indicating that the subsidence of these basins is not caused by extensional tectonics (M. F. Coffin et al., Seismic stratigraphy of the Raggatt Basin, southern Kerguelen Plateau: Tectonic and paleoceanographic implications, submitted to *Geological Society of America Bulletin*, 1989). Most of the faulting in the northern province is related to the breakup of Kerguelen and Broken Ridge at 43 Ma (chron 18). Several hypotheses have been proposed to relate these features.

Mutter and Cande [1983] and *Mutter et al.* [1985] proposed that the horst and graben zone on the northern province is the western termination of the Diamantina Zone and that the rough topography in the Diamantina Zone resulted from extremely slow seafloor spreading between anomaly 34 and 18 [*Cande and Mutter*, 1982]. In this model, the Australian-Antarctic plate boundary would extend through the Diamantina Zone and Labuan Basin and through the northern Kerguelen Plateau. However, the basement offset that limits the Labuan Basin and matches the trenches along Broken Ridge and the Diamantina Zone at chron 18 is evidence for a discontinuity in seafloor spreading.

Analyzing Seasat altimetry data and seismic reflection data, *Coffin et al.* [1986] and *Ramsay et al.* [1986] prefer to distinguish three different structural provinces: a northern sector including the Kerguelen and Heard islands, a southern sector comprising the southern plateau, and an eastern sector including the Labuan Basin. Their data show that the Labuan Basin has a structural style (rough basement topography) that is similar to the Diamantina Zone, suggesting that the Labuan Basin represents the former western extension of the Diamantina Zone or its conjugate. In this scheme, the Australian-Antarctic plate boundary would extend through the Labuan Basin and Diamantina Zone; farther to the west, it must extend either to the north of Broken Ridge, or to the south of the Kerguelen Plateau. However, north of Broken Ridge, magnetic lineations are oriented NE-SW (Figure 10*a*) and are related to seafloor spreading between Australia and Greater India during Early and Late Cretaceous time [*Markl*, 1974, 1978]. Furthermore, there is no evidence either in the bathymetry or the deflection of the vertical profiles for the Australian/Antarctic plate boundary; one would expect such a boundary to be at right angles to the Cretaceous magnetic anomaly pattern, with a SW-NE connection with the spreading center located in the Diamantina/Labuan zone. Thus in the absence of significant extension within the northern and southern Kerguelen Plateau, the only observed tectonic feature that could represent a plate boundary is the N-S oriented grabens recognized by *Houtz et al.* [1977] between the two provinces, referred to as the 75°E and 77°E grabens. *Coffin et al.* [1986] suggested that the 75°E graben is a minor feature compared to the 77°E graben (e.g., Figure 10*b*) and M. F. Coffin et al. (A Cretaceous to Eocene tectonic history of the Kerguelen Plateau province and Diamantina Zone, manuscript in preparation, 1989; hereinafter Coffin et al. (1989)) provide seismic evidence that the 77°E graben was created by predominantly strike-slip motion.

Taking into account these observations, we consider that the northern and southern provinces of the Kerguelen Plateau behaved as a single entity before the breakup of Australia and Antarctica. After the breakup and until chron 18, they were on two different plates. The northern part of the Kerguelen Plateau would have remained attached to Broken Ridge (i.e., the Australian Plate) until the Early Eocene, while the southern part, which would include the Elan and Banzare banks (Figure 10*b*), remained attached to the Antarctic plate. This hypothesis would allow for the opening of the Labuan Basin and Diamantina Zone while avoiding large extension on the Broken/Kerguelen Ridge. This model predicts that seafloor spreading occurred south of the northern Kerguelen Plateau and perhaps north of the Elan Bank (Figure 10*b*) as suggested by *Goslin and Patriat* [1984]. Implications of our model on the development of the Kerguelen Plateau will be examined in the discussion section.

The closure of the Wharton Basin is constrained by the regular pattern of parallel N-S fracture zones (Figure 11*a*). The major offset occurs along the Investigator Fracture Zone (at 98°E, Figure 11*a*), which curves into the Australian margin and records the change of motion in mid-Cretaceous time. We consider the magnetic lineations located north of the fossil ridge axis as part of the Indian Plate, i.e., fixed relative to the magnetic lineations in the Central Indian Basin. Subsequent intraplate deformation of the Indo-Australian plate since the Miocene is not accounted for in our model. There are only a few anomalies for which we have picks on both sides of the fossil spreading ridge (anomalies 20, 22, 23 and 24). For the older anomalies, we assumed that the offsets along the fracture zones remained roughly constant through time and that spreading was symmetric. We then made sure that the spreading rates deduced from the finite rotations were compatible with the observations.

For the last link of the circuit between India and Antarctica, finite rotation poles are derived from the reconstructions of *Patriat* [1987], which are similar to those presented by *Molnar et al.* [1988]. After anomaly 29 time, the reconstructions along the Southeast Indian Ridge are required to agree with the reconstructions along the Southwest and Central Indian ridges in order to maintain the coherency of the Central Indian Triple Junction [e.g., *Patriat and Ségoufin*, 1988]. Prior to that time, the motions of India relative to Antarctica are not well constrained. In particular, the reconstructions at anomalies 33 and 34 between India and Antarctica may differ substantially depending on how the data from the Crozet and Central Indian Basins are matched. It is not possible to constrain these assemblages by solving the plate circuit Antarctica —> Africa+Madagascar —> India. Although the Africa/Antarctica reconstructions are well determined [*Royer et al.*, 1988], the occurrence of a Paleocene fossil ridge (anomalies 27-28) in the Mascarene Basin [*Schlich*, 1982] prevents any direct determination of the relative motions between Madagascar and India prior to that time.

The anomaly 20 (46.2 Ma) reconstruction (Figure 13*a*) brings the edges of the Kerguelen Plateau and Broken Ridge in contact. DSDP site 255 on Broken Ridge and a piston core [*Wicquart*, 1983] (noted PC on Figures 12*d* and 13*a*) on Kerguelen Plateau, where sediments of Santonian age have been recovered, appear to be almost conjugate points. At that time, Kerguelen Plateau can be rotated in a unit. At that time (Figure 13*a*), the southernmost part of the Ninetyeast Ridge did not exist according to the basement age of DSDP site 254 (~38 Ma [*Duncan*, 1978]). West of the Ninetyeast Ridge, the anomaly 20 ridge axis occurs in the vicinity of DSDP site 253 where basement is older than 44 Ma [*Davies et al.*, 1974]. In the first compartment east of the Ninetyeast Ridge, the position of the ridge axis can be deduced from the distance between chrons 20 and 28 (or 31) observed on the Australian Plate at 95°E and from the location of chron 28 (or 31) at 92°E on the Indian Plate. This puts the ridge axis almost due east of the Osborn Knoll. From this, the transform boundary along the eastern side of the Ninetyeast Ridge can be estimated to be 1700 to 1800 km long. The India-Australia-Antarctica or Eastern Indian Ocean Triple Junction would be located somewhere between DSDP site 253 and Broken Ridge.

The anomaly 24 (56.1 Ma) reconstruction is one of the best controlled (Figure 13*b*). In the Wharton Basin, there are two magnetic picks for anomaly 24 from the Indian Plate on both sides of a 200-km transform offset that match with well defined anomalies on the Australian plate. The reconstruction of the Central Indian Ocean Triple Junction is also consistent [*Patriat*, 1987; *Royer et al.*, 1988]. Finally, the anomaly 24 identifications in the Australian-Antarctic Basin are numerous so a good match can be achieved. Figure 13*b* shows that the South Tasman Rise slightly overlaps the Antarctic margin. This can be accommodated by assuming Early Eocene stretching between Tasmania and the Tasman rise [*Houtz*, 1975]. Using the same reasoning as for the chron 20 reconstruction, the major transform boundary between the Indian and Australian plates can be estimated at 1400 km, with the triple junction remaining in the vicinity of the combined Broken and Kerguelen ridges. Chron 24 is also the time when problems of overlap between the northern Kerguelen Plateau and Broken Ridge arise. In order to avoid these problems, while accounting for the relative motions of Australia and Antarctica before chron 24, we consider that relative motions between the Kerguelen provinces, with the northern part attached to Broken Ridge (i.e., Australia) and the southern part to Antarctica, lasted until chrons 20-24.

The reconstruction for anomaly 28 time (64.3 Ma; Figure 13*c*) is not as well constrained as the anomaly 24 reconstruction. The rotation between Australia and Antarctica is interpolated between the finite rotations for chrons 24 and 31 (56.1 and 68.5 Ma, respectively). The ridge axis configuration is inherited from the chron 31 configuration and is significantly different from that at chron 24 in the area immediately west of the Ninetyeast Ridge. The location of the ridge axis west of the Ninetyeast Ridge is compatible with the position of the anomalies 30 and 31 identified to the north [*Sclater and Fisher*, 1974; *Peirce*, 1978] and with the location of DSDP sites 214 and 215, where basal sediments are 60 Ma old [*von der Borch et al.*, 1974], that is, younger than chron 28. The chron 28 reconstruction also restores the symmetry of the magnetic anomaly pattern between the Ninetyeast Ridge and the Kerguelen and 84°E fracture zones. The transform fault east of the Ninetyeast Ridge probably did not exist at that time.

The chron 31 reconstruction (Figure 13*d*) is constrained by the numerous anomaly identifications in the Central Indian Basin and Crozet Basin, as well as in the Australian-Antarctic Basin. There are also several anomaly picks in the Wharton Basin. This reconstruction rotates two anomaly 31 picks from the Indian Plate with the northern part of the Ninetyeast Ridge. Those picks are offset by 5° on either side of the ridge. We believe that the transform offset was located east of the Ninetyeast Ridge in order to put DSDP site 216 north of the ridge axis. Age of the basal sediments recovered at site 216 range from 65 to 80 Ma [*von der Borch et al.*, 1974] while the basalts give a maximum isotopic age of 81 Ma [*Duncan*, 1978].

Several models have been proposed for the Central Indian Ocean at chrons 33 and 34. *Patriat* [1987] matches pairs of anomaly 33 and 34 picks located at 80°E in the Central Indian Basin with conjugate picks identified south of the Marion Dufresne Seamount. *Molnar et al.* [1988] matched the picks from the Central Indian Basin with the picks identified north of Conrad Rise (between 74°and 77°E on Figure 18). This brings India closer to Madagascar. We prefer a slight modification of the model of *Patriat* [1987]. The lineations for anomalies 31, 32, 33 and 34 that intersect 80°E between 0° and 7°S

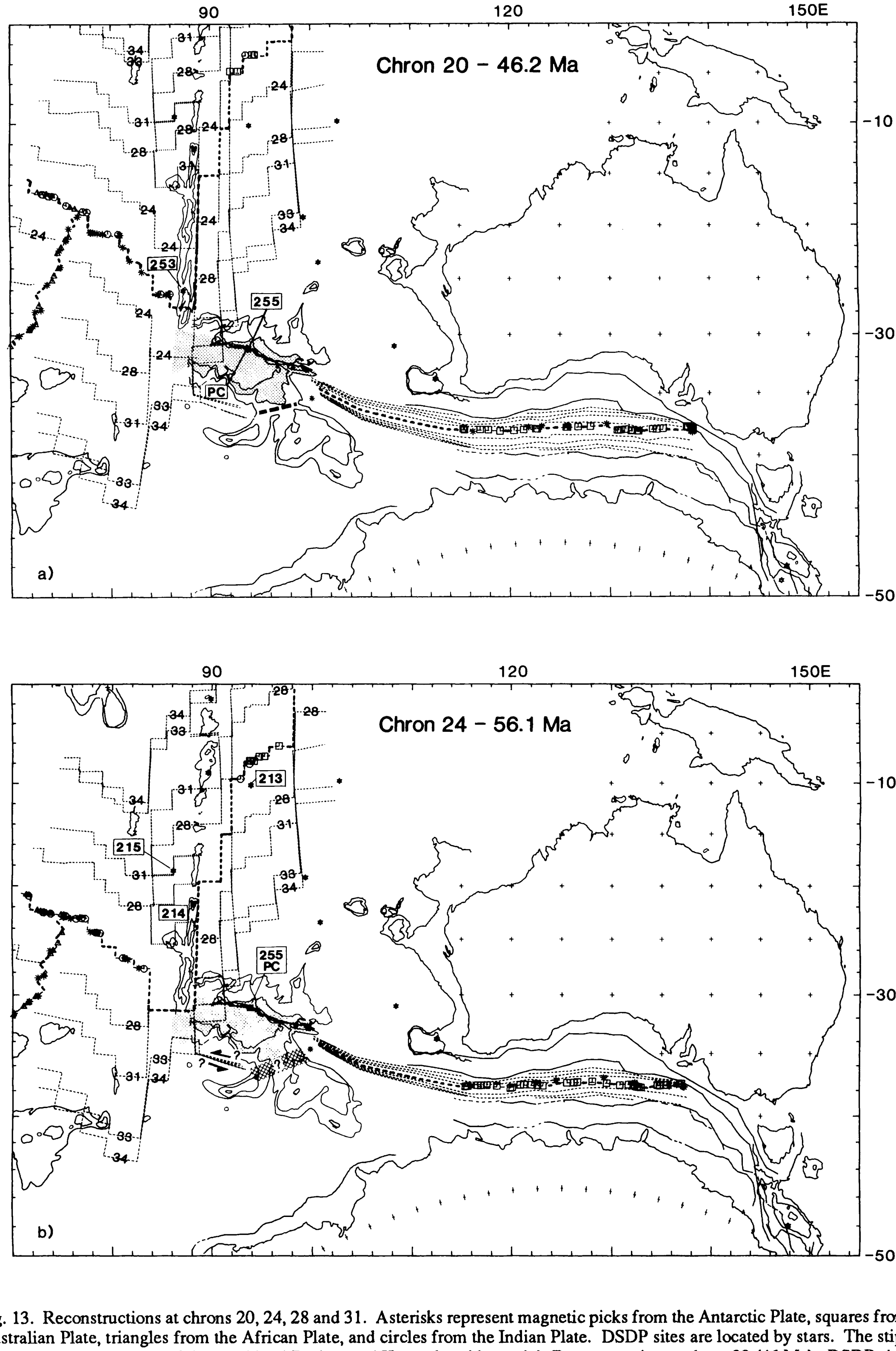

Fig. 13. Reconstructions at chrons 20, 24, 28 and 31. Asterisks represent magnetic picks from the Antarctic Plate, squares from the Australian Plate, triangles from the African Plate, and circles from the Indian Plate. DSDP sites are located by stars. The stippled areas show the extension of the combined Broken and Kerguelen ridges. (*a*) Reconstruction at chron 20 (46 Ma). DSDP site 255 and a piston core (PC) on the northeastern flank of the Kerguelen Plateau both contain sediments of Santonian age [*Davies et al.*, 1974; *Wicquart*, 1983]. (*b*) Reconstruction at chron 24 (56.1 Ma). Configuration of the ridge after a large ridge jump to the south, west of the Ninetyeast Ridge. (*c*) Reconstruction at chron 28 (64.3 Ma). The ridge axis immediately west of the Ninetyeast Ridge is migrating away from the Kerguelen hot spot; spreading rates after chron 31 are greater than 10 cm/yr (half rate). (*d*) Reconstruction at chron 31 (68.5 Ma).

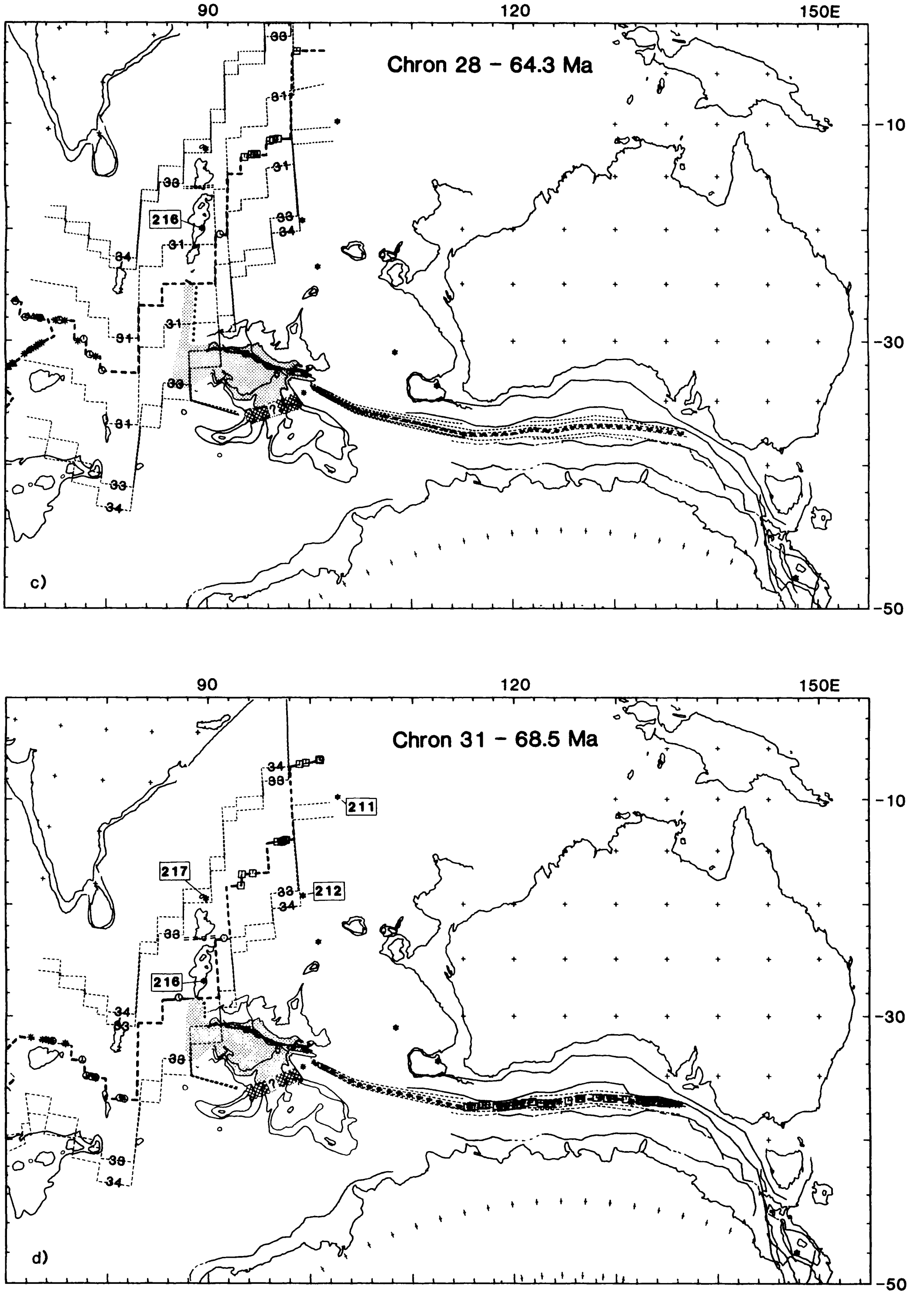

Fig. 13. (continued)

in the Central Indian Basin (Figure 11*a*), are limited to the west by a fracture zone that has a left-lateral offset of ~200 km at anomaly 31 time. A similar offset is apparent on the deflection of the vertical charts (Figures 3 and 11*a*) due east of the Crozet Plateau. The reconstruction of *Patriat* [1987] places this fracture zone between the two easternmost seamounts of the Conrad Rise. We think that it in fact corresponds to a linear tectonic feature, 60 km to the west, outlined as a cusp in the isobaths north of Conrad Rise (at 50°E, Figure 11*a*) and with a strong signature on the magnetics [*Goslin and Patriat*, 1984, Figure 7]. This solution implies a more continuous spreading direction between anomalies 31 and 34 and also avoids overlaps of the northernmost and oldest part of the Ninetyeast Ridge (DSDP site 217) with the combined Broken and Kerguelen ridges. Furthermore, the directions of motion between anomalies 34, 33 and 31 agree much better than Patriat's model does with the trend of the large offset Kerguelen Fracture Zone. Finally, the combination of the India-Antarctica finite rotations with the Antarctica-Africa rotations [*Royer et al.*, 1988] leads to a direction and amount of motion between Madagascar and India compatible with the spreading rates and fracture zone trends observed in the Mascarene Basin between anomalies 31 and 34 [*Schlich*, 1982]: 3.2 cm/yr and N54°E, computed, compared to 3.0 cm/yr and N55°E, observed.

Chrons 33 and 34 mark the beginning of seafloor spreading between Australia and Antarctica [*Cande and Mutter*, 1982]. Between 131°E and 140°E, the anomaly 33 lineation and the COBs coincide, as noted by *Veevers* [1986]. Although the COBs are expected to be younger farther east [*Veevers*, 1986, 1987], our reconstruction at chron 33 (80 Ma; Figure 14*a*) fits almost synchronously the Antarctic and Australian COBs from 132°E down to Tasmania. Using *Veevers'* [1986, 1987] interpretation of the COB off Antarctica, east of 134°E (Figure 7), some oceanic crust would still remain south of the Australian COB dated as 80 Ma old. At chron

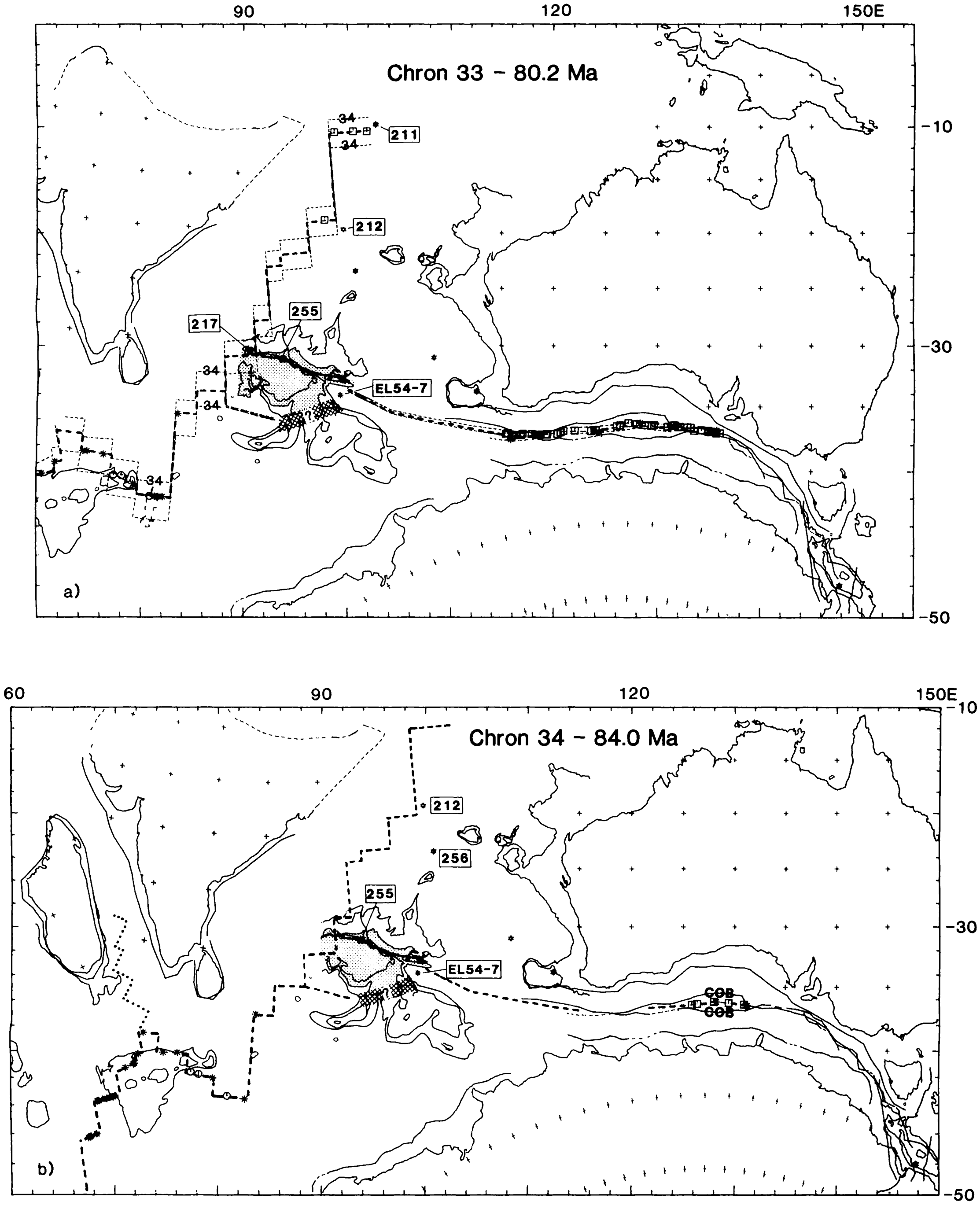

Fig. 14. Reconstructions at chrons 33 and 34. Asterisks represent magnetic picks from the Antarctic Plate, squares from the Australian Plate, triangles from the African Plate, and circles from the Indian Plate. DSDP sites are located by stars. (*a*) Reconstruction at chron 33 (80.2 Ma). Note the change of orientation of the transform offsets east and west of the Kerguelen Fracture Zone, resulting from a ridge jump of the African/Antarctic and Indian/Antarctic spreading ridges north of the Conrad Rise, during the Cretaceous Quiet Zone [*Goslin and Patriat*, 1984]. (*b*) Reconstruction at chron 34 (84.0 Ma). Note the discontinuity of seafloor spreading along south of Australia.

34 (84 Ma; Figure 14*b*), the conjugate COBs west of 120°E come in contact, indicating that accretion of oceanic crust at this time only occurred within a restricted area in the Great Australian Bight and also possibly south of the Naturaliste Plateau, in the Diamantina Zone and the Labuan Basin.

Finally, Figures 15*a* and 15*b* present a possible fit for the COBs and the continental shelves of Australia and Antarctica. These reconstructions (in the absence of magnetic lineations) are extrapolated from the reconstruction at chron 34 and rely on a visual match of the COBs and continental shelf edges identified on the deflection of the vertical charts (Figures 6 and 8). Seafloor spreading between Australia and Antarctica initiated in the Great Australian Bight where the oldest magnetic anomalies (34) are identified. Our match of the oldest portion of the COBs, dated at 96 Ma [*Veevers*, 1986], produces overlaps (cross-hatched areas on Figure 15*a*) on either side of the Great Australian Bight. The Labuan and Diamantina basins are almost closed. Overlaps between the COB and the continental shelves (cross-hatched areas on Figure 15*a*) appear where the deflec-

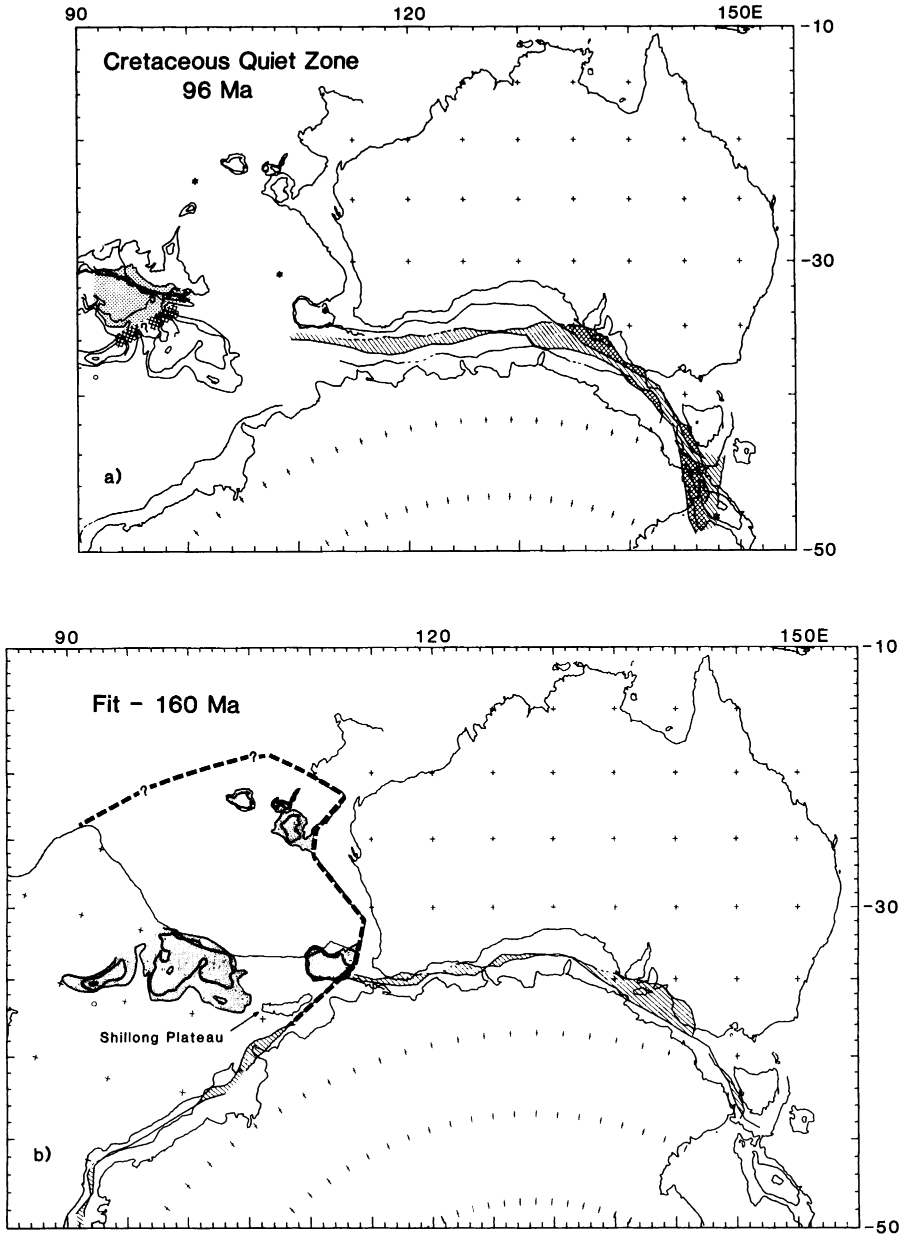

Fig. 15. (*a*) Closure of the Australian-Antarctic Basin at 96 Ma by matching the conjugate continent/ocean boundaries mapped on the deflection of the vertical charts. Hatched areas show overlaps between the COBs; the cross-hatched pattern outlines the areas of overlap between the COBs and the continental shelves. Our pole of rotation for the closure of the COB is similar to that proposed by *König* [1980] (1.5°N, 37.0°E), and the angle agrees with that of *Veevers* [1987] (angle=27.85°). (*b*) New fit of the margins of Australia and Antarctica based on the interpretation of the deflection of the vertical charts. Hatched areas show overlaps between the continental shelves. Rotation of India relative to Antarctica is from *Lawver and Scotese* [1987] (4.4°S, 16.7°E, angle=-92.77°). The Shillong Plateau is a Precambrian outcrop that marks the eastern limit of the Indian Shield. The heavy dashed line represents the possible extent of Greater India. Possible oceanic plateaus are shaded. Note that little room is left between India and Antarctica to fit even a small fragment of the Kerguelen Plateau.

tion of the vertical charts shows evidence for stretched continental crust (George V Basin) and between the Tasman Rise and the Antarctic margin. As mentioned earlier, this latter overlap can be avoided first by closing the Early Eocene rift between Tasmania and the Tasman Rise [*Houtz*, 1975] and second by restoring some extension in the Bass Strait between Tasmania and the mainland. The new fit of Australia and Antarctica (Figure 15*b*) indicates that the George V Basin is a continuation of the Bass Basin between Tasmania and the mainland. The complete restoration of extension in the Bass Basin [e.g., *Etheridge et al.*, 1987] would eliminate the slight overlap of Tasmania with East Antarctica.

DISCUSSION

This section discusses some aspects and implications of our new plate reconstructions: the interactions between the relative motions of the Indian, Antarctic and Australian plates, the influence of the Kerguelen hot spot on the evolution of the plate boundary between India and Australia-Antarctica and the tectonic setting of the Ninetyeast Ridge, and the motion between the southern and northern Kerguelen Plateaus between Late Cretaceous and Middle Eocene time.

Figure 16 shows the evolution of the directions and (half) rates of spreading derived from the finite rotations (Table 2) with respect to different flow lines in the Central Indian Basin, in the Wharton Basin and in the Australian-Antarctic Basin. The parameters of rotation between India and Australia are determined by adding the rotations between India and Antarctica, and Antarctica and Australia. Since the relative motions between India, Australia and Antarctica are dependent, it is not surprising that the rates and direction of spreading along the three shared plate boundaries present a coherent evolution. At chron 31, the drastic increase of the spreading rates between India and the two other plates corresponds to a change of spreading direction between Australia and Antarctica. This important change in the spreading rates (from 5 to 10 cm/yr, half rates) is observed in the Crozet and Madagascar basins [*Schlich*, 1975], in the Central Indian Basin [*McKenzie and Sclater*, 1971; *Patriat*, 1987], in the Wharton Basin [*Sclater and Fisher*, 1974; *Liu et al.*, 1983] and also in the Mascarene Basin [*Schlich*, 1982]. This major change also corresponds to seafloor spreading reorganizations along the Southwest Indian Ridge [*Royer et al.*, 1988], and in the South Atlantic [*Barker*, 1979; *LaBrecque and Hayes*, 1979; *Cande et al.*, 1988]. At chron 24, the slowing in spreading recorded in the Central Indian, Crozet and Wharton basins coincides with a slight acceleration of spreading in the Australian-Antarctic Basin. This becomes more apparent at the time of anomaly 20 and 18. West of the Ninetyeast Ridge the change of motion is abrupt, with the direction of spreading shifting by more than 30° while the spreading rates drop from 5.0 to 2.5 cm/yr. East of the Ninetyeast Ridge, the same changes occur, but the large right-lateral transform offsets (~ N-S orientation) in the Wharton Basin (Figure 13*a*) opposed the change of motion (~ NE-SW direction). This change in regional spreading directions may explain why seafloor spreading stalled in the Wharton Basin. Between Australia and Antarctica, the change of motion occurs abruptly between chron 24 and 20, a little earlier than in the contiguous basins. The last noticeable change of motion along the Southeast Indian Ridge occurs at chron 5.

The ridge axis configurations at chrons 33 and 34 (Figures 14*a* and 14*b*) show that the location of the proto-Southeast Indian Ridge is asymmetrical relative to India and Antarctica-Australia, in agreement with the identifications of large westward ridge jumps in the Mesozoic sequences of magnetic anomalies along the western Australian margin [*Larson et al.*, 1979; *B. D. Johnson et al.*, 1980]. The breakup between Madagascar and India in mid- to Late Cretaceous time coincides with the propagation of the Southwest and Southeast Indian Ridges north of the Conrad Rise. *Goslin and Patriat* [1984] suggest that the northward propagation of these ridges resulted from a ridge jump during the Cretaceous magnetic quiet zone and that these events coincided with the emplacement of the Conrad Rise. This reorganization caused the transform offsets on the Indian/Antarctic and Indian/Australian plate boundaries to become left-lateral west of the Kerguelen Fracture Zone, while they all remained right-lateral from the Kerguelen Fracture Zone up to the Investigator Fracture Zone.

From chron 34 to 28, the Indian/Australian and Indian/Antarctic plate boundaries migrated away from Australia and Antarctica. As a result, the triple junction between India, Australia and Antarctica moved from the combined Broken and Kerguelen ridges at chrons 33 and 34 (Figures 14*a* and 14*b*) to about 200 km northward at chron 31 and 500 km at chron 28. Two branches of the triple junction were the mid-oceanic ridges in the Central Indian Basin and in the Wharton Basin, and the third branch or Antarctica/Australia plate boundary was at this time a transform fault east and parallel to the Ninetyeast Ridge (dotted lines on Figures 13*c* and 13*d*). Although such Ridge-Ridge-Fault geometry would not be stable, we believe that this plate boundary configuration is regionally correct. *Liu et al.* [1983] propose a different model where the triple junction at chron 28 is located along the "86°E Fracture Zone" (actually at 84°E) of *Sclater and Fisher* [1974]. Their model would require the westernmost segment of the Australian-Antarctic ridge to lie farther west and south of Kerguelen Plateau than we assume here. Whatever model is preferred, the motions along the transform boundary east of the Ninetyeast Ridge were very slow between chrons 33 and 28; the Australian-Antarctic stage poles are located on the Broken and Kerguelen ridges (Table 2). During this period, the Kerguelen hot spot migrated westward relative to Australia. This can explain the obliqueness of the Ninetyeast Ridge relative to the fracture zone pattern in the adjacent basins. The only way the Kerguelen hot spot could have generated the Ninetyeast Ridge during the chron 33 to 28 interval would be through a resurgence of volcanic material at the ridge axis itself, as the hot spot model of *Morgan* [1978] would predict.

Between chron 28 (64.3 Ma) and chron 26 (58 Ma), the ridge axis west of the Kerguelen Fracture Zone reached the latitude of the Kerguelen hot spot (Figure 17). The short distance (~ 300 km) between the ridge axis and the Kerguelen hot spot across the Kerguelen Fracture Zone, combined with the weakness of the lithosphere due the thermal perturbation of the Kerguelen plume, may have caused the Indian/Antarctic boundary to propagate eastward through the Kerguelen Fracture Zone. For a short period of time, since the spreading center 900 km to the north was still active, it created a microplate bounded to the east by the Ninetyeast Ridge and to the west by the 84°E and northern termination of the Kerguelen Fracture Zone (Figure 17). The magnetics in this area are too sparse to observe any fanned anomaly pattern, as observed elsewhere on present [e.g., *Hey et al.*, 1985] or past [e.g., *Tamaki and Larson*, 1988] microplates. Later on, when spreading ceased on the northern ridge segment (chron 25?; 59 Ma), this microplate transferred to the Indian plate. This scenario best explains the 11° southward ridge jump documented by *Sclater and Fisher* [1974] and *Peirce* [1978].

Drilling results on the Ninetyeast Ridge (DSDP Leg 22 and 26) show a close correspondence between the ages of the Ninetyeast Ridge and of the adjacent oceanic crust to the west [*Davies et al.*, 1974; *von der Borch et al.*, 1974; *Duncan*, 1978]. However, the ages along the ridge do not decrease regularly from north to south (site 217 to 254) as expected from the ages of the magnetic lineations farther

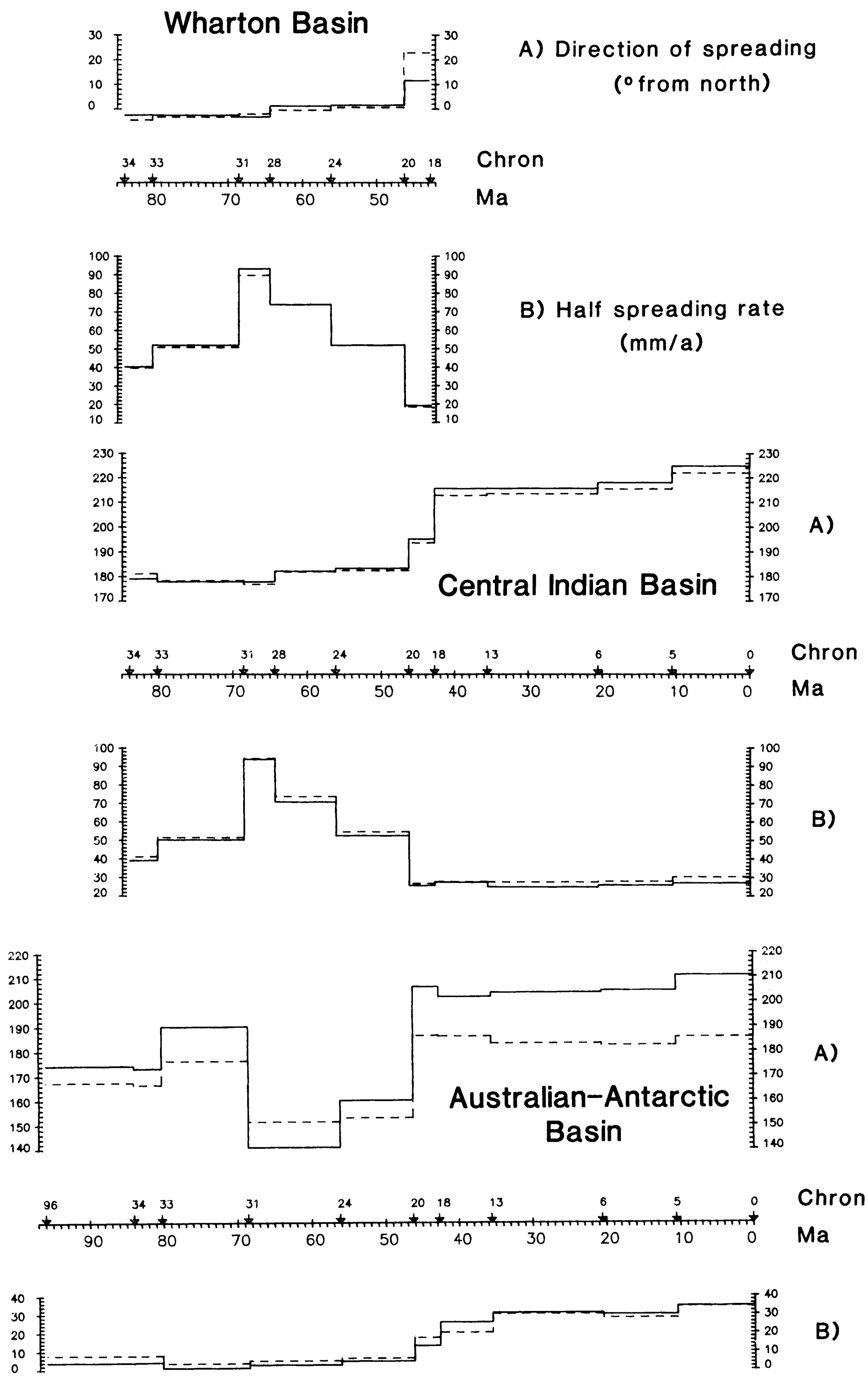

Fig. 16. Evolution of the direction and half rate of spreading in the Wharton Basin (Australian Plate), in the Central Indian Basin (Indian Plate) and in the Australian-Antarctic Basin (Australian Plate). Derived from the finite rotations and stage rotations on Table 2. The solid and dashed lines show the evolution of the spreading parameters along two different flow lines: in the Wharton Basin, they are located respectively along the Ninetyeast Ridge and the Investigator FZ; in the Central Indian Basin, one is passing through the Rodriguez Triple Junction and the other northwest of the Amsterdam FZ, respectively; in the Australian-Antarctic Basin, they are respectively located at 97°E (Diamantina Zone) and 130°E.

west in the Central Indian Basin. Magnetic anomaly identifications in the compartment adjacent to the Ninetyeast Ridge and the basement ages at site 214 and 216 suggest that a ridge jump to the south of about 11° occurred at about anomaly 25-26 time (~58 Ma) [*Sclater and Fisher*, 1974; *Peirce*, 1978]. The position of the fossil ridge axis would be in the vicinity of site 215, as inferred from the position of the magnetic anomalies (30 and 31) identified to the north (between the fracture zone at 86°E and the Ninetyeast Ridge [*Sclater and Fisher*, 1974; *Peirce*, 1978]), and the age of site 214 (60 Ma). Our scenario is compatible with these results and predicts that anomaly 31 lies in the vicinity of the Osborn Knoll and that this feature might represent the location of the fossil propagating rift.

There is evidence of small southward ridge jumps, west of the Ninetyeast Ridge, between chrons 26-25 and 24, 24 and 20, and 20 and 18 (Figures 13*b*, 13*a* and 12*d*). For instance, west of the Kerguelen and 84°E fracture zones, the average distance between anomalies 20 and 33/34 is about 19 degrees (Figures 11*a* or 13*a*). In contrast, the first anomaly 20 lineation identified east of the Kerguelen Plateau is at about 9 and 11 degrees from the lineations 33 and 34 (Figure 13*a*), respectively. Moreover, east of the 84°E Fracture Zone in the Central Indian Basin, anomaly 20 lineation is separated from the anomalies 33 and 34 by a distance greater than 24 degrees. The difference is greater than the amount of crust transferred to the Indian plate at chrons 25-26. From our analysis, assuming Australia fixed in its present-day position, the Kerguelen hot spot has remained almost stationary relative to Australia and Antarctica between the Late Cretaceous to the Middle Eocene (chrons 20-18). From chron 31 to 26, when spreading rates between India and Antarctica were high (~ 10 cm/yr, half-rate), the spreading ridge migrated northward, away from the hot spot. After the ridge jump at chrons 26-25, the ridge axis returned to the vicinity of the plume. From chron 25 to 18, the India/Antarctica boundary kept migrating northward, but at a much slower rate (~ 5 cm/yr between chrons 24 and 20, 3 cm/yr between chrons 20 and 18, Table 2). The influence of the thermal plume may then have predominated, causing the easternmost extremity of the India/Antarctica plate boundary to remain in the vicinity of the Kerguelen hot spot. Meanwhile, the transform boundary east and parallel to the Ninetyeast Ridge between the Indian and Australian plates lengthened drastically (Figures 13*a* and 13*b*).

A variety of sources have been proposed for the volcanism that created the Ninetyeast Ridge: a fixed hot spot [*Morgan*, 1972, 1981; *Duncan*, 1978, 1981; *Peirce*, 1978], a leaky transform-spreading ridge junction [*Sclater and Fisher*, 1974], a combination of the two processes [*Luyendyk and Davies*, 1974; *Johnson et al.*, 1976], and two hot spots [*Luyendyk and Rennick*, 1977]. Most of the evidence favors the hot spot hypothesis, which postulates that the Ninetyeast Ridge was created as the Indian plate drifted away from Antarctica over the Kerguelen hot spot, fixed relative to the spin axis. The ages (paleontology, basal sediments and isotopic dating) at the drilling sites along the Ninetyeast Ridge decrease from north to south [*Davies et al.*, 1974; *von der Borch et al.*, 1974; *Duncan*, 1978; *ODP Leg 121 Scientific Drilling Party*, 1988; *ODP Leg 121 Shipboard Scientific Party*, 1988]. Basalts from the Ninetyeast Ridge display a constant paleolatitude [*Peirce*, 1978] which is close to the present latitude of Kerguelen Island (~ 50°S). However, a linear age progression of the Ninetyeast Ridge is not compatible with the ages of the oceanic crust lying east of the ridge which record several southward ridge jumps, as discussed earlier. Models involving several sources of volcanism [e.g., *Sclater and Fisher*, 1974; *Luyendyk and Davies*, 1974; *Johnson et al.*, 1976; *Luyendyk and Rennick*, 1977], although more complicated, palliate this difficulty. Our model, which includes a large ridge jump at chron 26 and a succession of ridge jumps later on, agrees with the ages of the DSDP and ODP drilling sites. However, it predicts that the ages may not decrease monotonically: the ages would decrease from 84 to 60 Ma between 10°N and 7°S (drilling sites 217, 758, 216, 215), then increase from 60 to 70 Ma between 7°S and about 16°S (site 214), and finally decrease with some discontinuity from 60 to 35 Ma between 16°S and 32°S (sites 757, 253, 756 and 254). This assumes that, between chrons 33 and 26, while the Indian-Antarctic spreading center was migrating northward away from the Kerguelen hot spot, the Ninetyeast Ridge was still being generated at the ridge axis. An alternative to our model would be that the ridge jumps west of the Ninetyeast Ridge were continuous allowing the spreading center to remain in the vicinity of the plume.

Using our model for the relative motions among India, Australia and Antarctica, we further examine the fixed hot spot hypothesis (Figure 18). India drifted away from the Kerguelen hot spot at an overall rate of 9.7 cm/yr between 84 and 36 Ma, similar to the rate of 9.4±0.3 cm/yr inferred by *Duncan*'s [1978] isotopic dating of the DSDP basalts from the Ninetyeast Ridge. From simple geometric considerations (i.e., the linearity of the Ninetyeast Ridge), the Kerguelen hot spot slowly migrated westward relative to Australia

TABLE 2*a*. Finite Rotations

Chron	Age, Ma	Latitude, +°N	Longitude, +°E	Angle, deg	Comments
		Antarctica Relative to India			
5	10.5	12.5	36.7	6.62	1
6	20.5	14.5	32.8	11.98	1
13	35.5	13.4	32.7	20.40	1
18	42.7	16.6	29.9	23.62	1
20	46.2	16.3	28.5	25.24	
24	56.1	12.3	21.5	34.40	
28	64.3	9.7	17.4	45.12	
31	68.5	9.4	13.7	51.59	2
33	80.2	8.2	11.0	62.18	
34	84.0	7.8	10.9	65.10	
		Antarctica Relative to Australia			
5	10.5	12.5	36.7	6.62	3
6	20.5	14.5	32.8	11.98	3
13	35.5	13.4	32.7	20.40	3
18	42.7	16.6	29.9	23.62	3
2	46.2	15.1	31.3	24.50	
24	56.1	12.5	31.7	25.24	
31	68.5	8.7	33.2	25.83	
33	80.2	6.2	35.1	26.37	
34	84.0	4.9	35.8	26.81	
96	96.0	1.0	38.0	28.30	4
160	160.0	-2.0	38.9	31.50	5
		Australia Relative to India			
18	42.7	90.0	0.0	0.00	
20	46.2	17.6	-32.8	1.47	
24	56.1	3.4	-1.5	10.47	
28	64.3	1.8	1.0	21.39	
31	68.5	1.7	-2.1	28.43	
33	80.2	0.6	-3.1	39.43	
34	84.0	0.4	-3.1	42.16	

Angles are positive counterclockwise. Comments are as follows: 1, same rotations as Antarctica relative to Australia; 2, from *Patriat* [1987]; 3, same rotations as Antarctica relative to India; 4, closure of the Australian and Antarctic COBs; 5, fit.

TABLE 2*b*. Stage Poles, Half Rates and Directions of Spreading between India, Australia and Antarctica.

						Flow Line 1			Flow Line 2		
Chrons	Age, Ma	DT, Ma	Latitude, +°N	Longitude, +°E	Angle, deg	Distance, deg	V, mm/yr	Direction, deg	Distance, deg	V, mm/yr	Direction, deg
Relative Motions Between Antarctica and India (Indian Plate Fixed) in the Central Indian Basin a											
0 - 5	0.0	10.5	12.5	36.7	6.62	51	27	225	60	31	222
5 - 6	10.5	10.0	16.4	27.7	5.40	60	26	218	69	28	215
6 - 13	20.5	15.0	11.8	32.8	8.43	53	25	216	62	28	213
13 - 18	35.5	7.2	30.1	7.7	3.59	83	23	216	92	28	213
18 - 20	42.7	3.5	7.5	11.2	1.72	70	26	195	79	27	194
20 - 24	46.2	9.9	-3.0	8.3	10.00	70	53	183	77	55	182
24 - 28	56.1	8.2	-2.5	9.2	11.20	69	71	182	76	74	182
28 - 31	64.3	4.2	-2.8	-6.1	7.13	84	94	178	91	95	177
31 - 33	68.5	11.7	-2.9	3.4	10.95	75	50	178	82	52	178
33 - 34	80.2	3.8	-0.1	13.5	2.95	65	39	179	72	41	181
Relative Motions Between Antarctica and Australia (Australian Plate Fixed) in the Australian-Antarctic Basin b											
0 - 5	0.0	10.5	12.5	36.7	6.62	80	35	211	102	35	186
5 - 6	10.5	10.0	16.4	27.7	5.40	89	30	204	111	28	182
6 - 13	20.5	15.0	11.8	32.8	8.43	82	31	204	104	31	183
1 - 18	35.5	7.2	30.1	7.7	3.59	112	26	202	133	20	186
18 - 20	42.7	3.5	-11.2	65.3	1.22	43	13	206	64	18	186
20 - 24	46.2	9.9	-39.0	54.1	1.35	39	4	160	58	7	153
24 - 31	56.1	12.4	-45.8	82.1	1.90	19	3	141	37	5	151
31 - 33	68.5	11.7	-33.3	93.1	1.51	9	1	190	31	4	176
33 - 34	80.2	3.8	-35.0	78.1	0.81	21	4	173	42	8	166
34 - 96	84.0	12.0	-34.6	79.8	2.60	19	4	174	41	8	167
96 - 160	96.0	64.0	-23.1	53.3	3.58	45	2	181	66	3	168
Relative Motions Between India and Australia (Australian Plate Fixed) in the Wharton Basin c											
18 - 20	42.7	3.5	17.6	-32.8	1.47	124	20	12	128	19	23
20 - 24	46.2	9.9	0.7	2.8	9.28	87	52	2	94	52	1
24 - 28	56.1	8.2	-0.1	3.1	10.95	86	74	1	94	74	0
28 - 31	64.3	4.2	3.6	-11.1	7.16	100	93	-1	109	90	0
31 - 33	68.5	11.7	-1.2	-6.5	11.03	94	53	-4	103	51	-4
33 - 34	80.2	3.8	-2.2	-4.1	2.73	92	40	-4	100	40	-6

Age corresponds to the youngest chron and DT is the time span between the two chrons. Distance is the distance in degrees between the stage pole of rotation and the point of measurement. V is the half rate of motion in mm/yr or km/Ma. Direction is the direction of spreading expressed in degrees from north.

a Along two flow lines passing through the Southeast Indian Ridge axis at 26°S, 71°E (flow line 1) and 33°S, 78°E (flow line 2).

b Along two flowlines passing through the Southeast Indian Ridge axis at 47°S, 97°E (flow line 1) and 50°S, 130°E (flow line 2).

c Along two flow lines running east of the Ninetyeast Ridge (flow line 1) and west of the Investigator FZ (flow line 2) through Chron 20 at 15°S, 89°E and 0°N, 97°E, respectively.

and Antarctica at a rate of 1.4 cm/yr between chron 34 and chron 24 (~390 km for 28 Ma). The northwesternmost part of the Kerguelen Plateau was created during this time span and forms the mirror image of the Ninetyeast Ridge. While longitudinal positions of the hot spot are well constrained, the latitudinal positions can tentatively be inferred from the ages at the drilling sites. The location of the hot spot at chrons 34 (84 Ma) and 33 (80 Ma) is constrained by the presence of a late Cretaceous sedimentary basin on the northern Kerguelen Plateau [*Munschy and Schlich*, 1987]. Whether or not our prediction agrees with the hot spot models of *Morgan* [1981] or *Duncan* [1981] is beyond the scope of this paper. However, we note that neither model uses the revised ages for the seafloor spreading between Australia and Antarctica to derive the relative motions between India and Australia (via Antarctica), to which the Kerguelen Plateau, at least its northern part, remained attached until chron 24.

The relative motions between the southern and northern Kerguelen plateaus can be considered in three intervals (Table 3): 96 Ma to chron 31 (70 Ma), chron 31 to chron 24 (56 Ma), and chron 24 to chron 20 (46 Ma). For these three intervals, the amount and direction of relative motions at 80°E are respectively: 110 km along N180°, 62 km along N145°E, and 79 km along N170°E. Overall, 240 km of north-south relative motion and 50 km of east-west motion are predicted. We have raised the hypothesis that since limited extension occurred within the northern and southern Kerguelen plateaus prior to the Middle Eocene, the 77°E graben may represent a former plate boundary between the two Kerguelen provinces. Consistent with Coffin et al. (1989) observations, our kinematic model predicts that from 96 Ma to the Middle Eocene the 77°E graben has behaved primarily as a strike-slip fault (~ 240 km of strike-slip) and has undergone relatively minor extension (~ 50 km). We note that the 2000-m isobaths on either side of the 77°E graben (Figure 10) reconstruct at 84 and 96 Ma (e.g., Figures 14*b* and 15*a*). Extension would have mostly occurred during the Early and Middle Eocene (chron 28 to 20). However, east-west extension between the northern and southern provinces implies some compression in the western extremity of the Kerguelen Plateau (outlined by an overlap of the

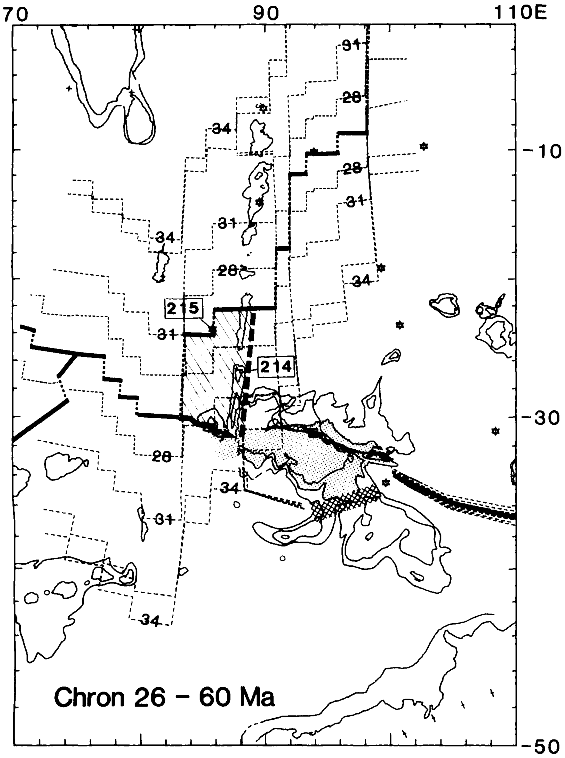

Fig. 17. Schematic diagram showing the eastward propagation of the Indian/Antarctic plate boundary through the Kerguelen FZ at about chron 26 (60 Ma). The hatched area shows the portion of crust transferred from the Antarctic to the Indian Plate that may have behaved as a microplate during a few million years. The magnetic anomaly pattern immediately west of Kerguelen FZ and its northern counterpart, is severely disturbed both in the Crozet Basin and the Central Indian Basin; there are no recognizable magnetic anomalies from anomaly 28 to 24 in this area [*Patriat*, 1987].

isochrons on Figures 13*a* and 13*b*); but no compressional tectonic features have yet been documented in this area. Seafloor spreading south of the northern Kerguelen Plateau would have been limited, which results from proximity to the poles of relative motions (Table 3). Between 96 Ma and 46 Ma the overall spreading rate (full) is 2 mm/yr at 65°E and 4 mm/yr at 75°E, with most of the spreading taking place between chrons 28 and 20.

Mutter and Cande [1983] suggested that rifting between Broken Ridge and Kerguelen Plateau resulted from a ridge jump from the south at chron 24. We question this age for the ridge jump, since it relies mainly upon a reconstruction that brings the edges of Kerguelen Plateau and Broken Ridge in contact. This reconstruction is interpolated from previous reconstructions [*König*, 1980] to which the authors have assigned the revised ages of *Cande and Mutter* [1982]. Furthermore no magnetic anomalies older than anomaly 18 have been identified between the two ridges. Recent drilling on Broken Ridge [*ODP Leg 121 Scientific Drilling Party*, 1988; *ODP Leg 121 Shipboard Scientific Party*, 1988] has confirmed that the stratigraphic unconformity, erosional in nature as observed at DSDP site 255 [*Davies et al.*, 1974] and related to the rifting episode between Broken Ridge and Kerguelen Plateau, is not much older than chron 18 (Upper Eocene, ~42 Ma). Regarding the nature of the basement offsets along these two ridges, *Mammerickx and Sandwell* [1986] observed that deep troughs generally appear at the location of new spreading centers resulting from ridge jumps in old oceanic lithosphere. The trenches at the foot of Broken Ridge and south of the Diamantina Zone (Figure 10*a*) would have been created this way.

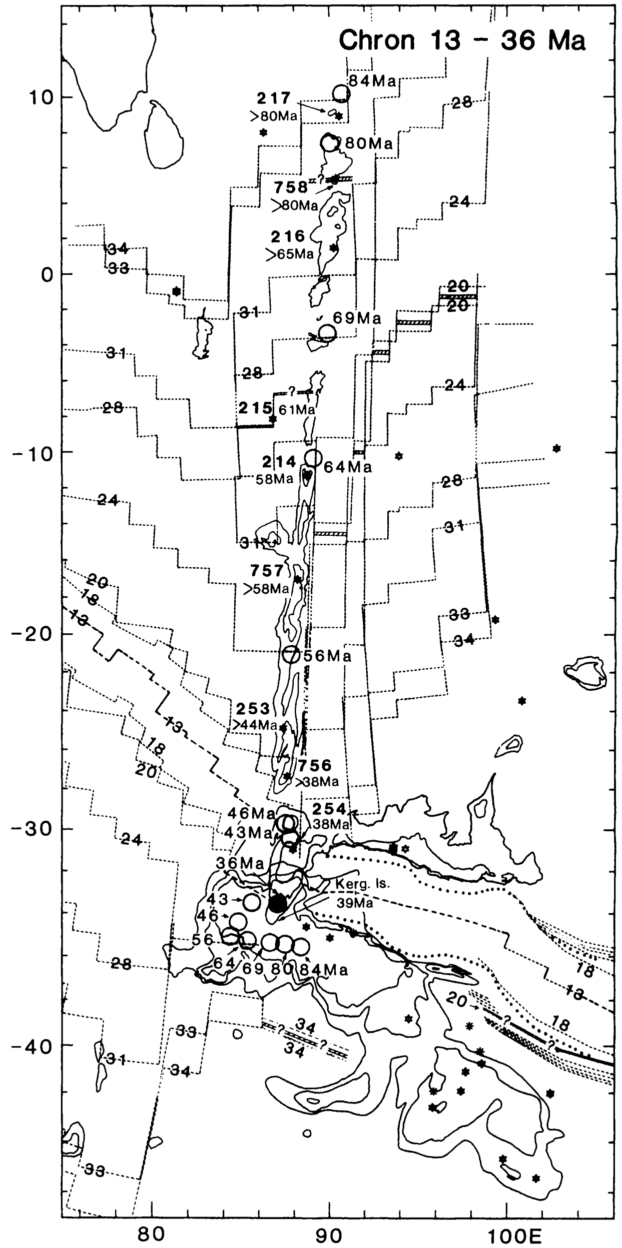

Fig. 18. Reconstruction at chron 13 (36 Ma) showing the location of the Kerguelen hot spot (shaded circles) at chrons 34 (84 Ma), 33 (80 Ma), 31 (69 Ma), 28 (64 Ma), 24 (56 Ma), 20 (46 Ma), 18 (43 Ma) and 13 (36 Ma; solid circle). The Indian and Australian plates are fixed relative to their present-day coordinates. DSDP sites [*Davies et al.*, 1974; *von der Borch et al.*, 1974; *Duncan*, 1978] and ODP sites [*ODP Leg 121 Scientific Drilling Party*, 1988; *ODP Leg 121 Shipboard Scientific Party*, 1988] are located by stars with their corresponding ages below. Between 84 and 56 Ma, a westward migration (~390 km) of the Kerguelen hot spot relative to Australia is required to maintain the linearity of the Ninetyeast Ridge. The predicted ages do not contradict the observed ages; however, between 7°S and 14°S, the age progression does not match the ages of the ocean floor west of the Ninetyeast Ridge. West of the Ninetyeast Ridge, the distance between the ridge axis and the hot spot increased from chrons 31 to 26.

Their conjugate, northeast of the Kerguelen Plateau, would correspond to the basement offset observed by *Coffin et al.* [1986] along the scarps of the Kerguelen Plateau and clearly visible on the deflection of the vertical charts (Figure 6). The question of whether the ridge jumped from the north (Wharton Basin) or from the south (south of Kerguelen Plateau) can be long debated. However, it is clear that two major tectonic events are concomitant at chron 18 in the eastern Indian Ocean: the demise of spreading in the Wharton Basin and the initiation of seafloor spreading between Broken Ridge and Kerguelen Plateau.

The extension of the basement offsets along the eastern scarp of the Kerguelen Plateau and the extension of the deep troughs along Broken Ridge and the western Diamantina Zone are evidence that the breakup of Kerguelen and Broken Ridge at chron 18 also affected the Labuan Basin and Diamantina Zone. East of 95°E, the Kerguelen basement offset becomes more gradual [*Coffin et al.*, 1986]. The amplitudes of the associated deflection of the vertical signal decrease from west to east (Figure 9) and the deep trenches (in some places deeper than 6000 m) bordering the Diamantina Zone (Figure 10*a*) disappear east of 110°E. If one assumes that these features correspond to the scars left by the anomaly 18 ridge jump, as inferred by the *Mammerickx and Sandwell* [1986] model, then the age offsets decrease toward the east, and consequently the newly emplaced spreading ridge merged with the Australian-Antarctic spreading ridge. In our attempt to define the plate boundaries in the Kerguelen/Broken Ridge area, we have assumed continuous seafloor spreading from chron 34 until chron 20 (Figures 14*a*, 13*d*, 13*c*, 13*b*, 13*a*) in the Labuan Basin and Diamantina Zone. The location of the spreading center north of the southern Kerguelen Province is constrained at chron 34 (Figure 14*b*) by the position of the piston core EL54-7 where Cenomanian sediments were recovered [*Quilty*, 1973]. We propose that at chron 18 the new ridge axis cut obliquely the magnetic anomaly pattern in the Labuan Basin and left remnants of a fossil spreading axis in the Labuan Basin, south of the basement offset (as in Figure 12*d*). This hypothesis does not preclude the possibility that part of the Labuan Basin and Diamantina Zone was generated in the Early Cretaceous during the separation of Greater India from Australia. This has to be considered to account for the occurrence of Cenomanian sediments in the Labuan Basin. A more detailed account of the Labuan Basin and Diamantina Zone will appear in the work by Coffin et al. (1989). A puzzling question remains: if a slow spreading ridge was active south of the Kerguelen Plateau and in the Labuan and Diamantina Zone basins with the 77°E graben acting as a transform fault, why would a ridge jump occur through the Kerguelen/Broken Ridge?

TABLE 3*a*. Finite Rotations Between the Northern and Southern Provinces of the Kerguelen Plateau

Chron	Age, Ma	Latitude, +°N	Longitude, +°E	Angle, deg
20	46.2	90.0	0.0	0.00
24	56.1	-46.6	26.5	1.30
28	64.3	-53.7	35.7	2.52
31	68.5	-55.0	38.1	3.16
33	80.2	-55.4	49.7	4.60
34	84.0	-54.4	50.4	5.41
96	96.0	-52.8	52.5	8.00
130	130.0	-48.2	48.6	9.73

SUMMARY

The accurate mapping of the tectonic fabrics from Geosat altimetry enabled us to reappraise and to improve previous plate tectonic models of the eastern Indian Ocean. Trends and extension of tectonic features such as fracture zones can be accurately delineated because of the uniform coverage and high signal to noise ratio obtained by averaging 22 Geosat repeat cycles.

A consistent model of evolution for the eastern Indian Ocean since the Late Cretaceous was developed using fracture zone trends from Geosat along with reinterpreted magnetic anomalies in the Australian-Antarctic Basin [*Cande and Mutter*, 1982] and in the Wharton Basin [*Liu et al.*, 1983]. Our model is compatible with the results from the recent drilling on the Ninetyeast Ridge, Broken Ridge and the Kerguelen Plateau (ODP Legs 119, 120 and 121). The main tectonic results are as follows.

1. The Southeast Indian Ridge has behaved as a single plate boundary since the Middle Eocene (anomaly 18). This is consistent with the conclusion of recent syntheses of present-day plate motions in the Indian Ocean [*Wiens et al.*, 1985, 1986; *DeMets et al.*, 1988; Gordon et al., 1989].

2. The Kerguelen hot spot could be the unique source for the volcanism of the Ninetyeast Ridge and the Kerguelen Plateau. To maintain the linearity of the Ninetyeast Ridge, which is oblique relative to the flow lines in the adjacent basins, we propose that the Kerguelen hot spot has migrated westward relative to Australia and Antarctica at a rate of 1.4 cm/yr between chrons 34 and 24.

3. Finally, the interpretation of the deflection of the vertical profiles allows for a better fit of the Kerguelen Plateau and the Broken Ridge. Breakup between these two features propagated from east to west between chron 18 (43 Ma) and chron 13 (36 Ma). The breakup possibly resulted from a ridge jump to the south and the demise of seafloor spreading in the Wharton Basin at anomaly 19-18 time. The closure of the Australian-Antarctic Basin with motion between the northern and southern Kerguelen Plateau avoids the overlap of the Kerguelen Plateau and the Broken Ridge before these two features broke apart in Middle Eocene time. The northern Kerguelen Plateau may have remained attached to Broken Ridge (or Australian plate) until chron 24-20, while the southern Kerguelen Plateau (Banzare Bank and Elan Bank) transferred to the Antarctic

TABLE 3*b*. Relative Motions Between the Northern and Southern Provinces of the Kerguelen Plateau

						Western Point			Eastern Point		
Chrons	Age, Ma	DT, Ma	Latitude, +°N	Longitude, +°E	Angle, deg	Distance, deg	Vt, mm/yr	Direction, deg	Distance, deg	Vt, mm/yr	Direction, deg
20 - 24	46.2	9.9	-46.6	26.5	1.30	30	7	169	34	8	169
24 - 28	56.1	8.2	-59.9	49.1	1.25	16	5	133	18	5	145
28 - 31	64.3	4.2	-59.4	49.3	0.65	16	5	134	18	5	146
31 - 33	68.5	11.7	-52.1	72.9	1.51	3	1	163	4	1	181
33 - 34	80.2	3.8	-48.6	53.4	0.82	12	5	178	17	7	182
34 - 96	84.0	12.0	-49.2	56.0	2.60	10	4	175	15	6	182

Calculations are made for two points located on the northern Kerguelen Plateau at 50°S, 72°E (western point) and in the Labuan Basin at 53°S, 80°E (eastern point). Ages, DT, distance and direction same as in Table 2*b*. Vt is the total rate of motion in millimeters per year.

Plate when Australia and Antarctica broke apart in the mid-Cretaceous. From the Late Cretaceous to the Middle Eocene, the 77°E graben may have been a transform fault separating the north and south Kerguelen provinces. The overall motion between the two provinces is 240 km N-S and 50 km E-W. Seafloor spreading from 96 Ma to 46 Ma (chron 20) south of the Kerguelen Plateau may have been extremely slow.

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