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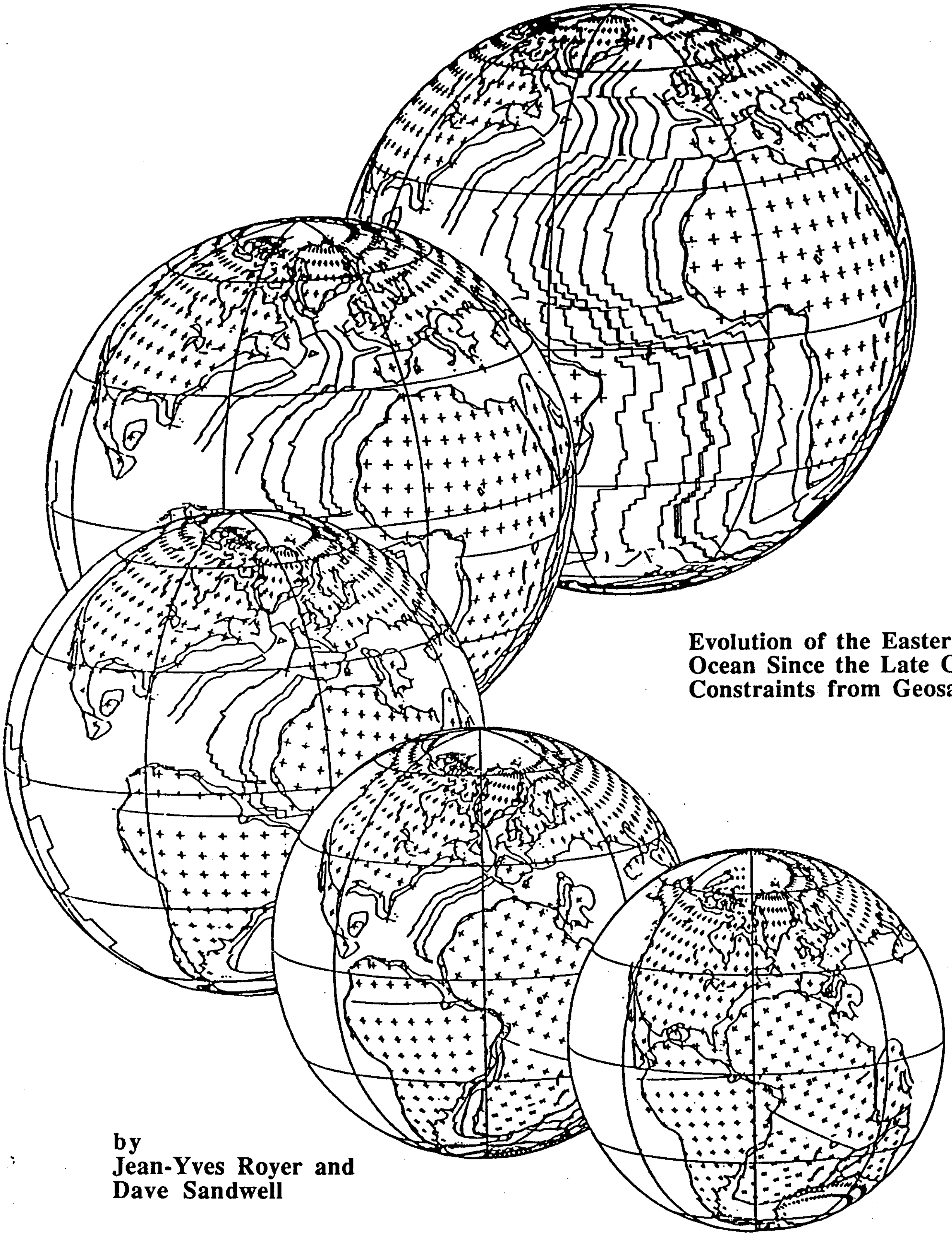

Evolution of the Eastern Indian Ocean Since the Late Cretaceous Constraints from Geosat Altimetry

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Evolution of the Eastern Indian Ocean Since the Late Cretaceous: Constraints from GEOSAT Altimetry

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Abstract

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, reinterpreted 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 paleo-spreading 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 the Broken Ridge at chron 20 (46 Ma). The opening of the Australian-Antarctic Basin from break-up to chron 24 requires a decoupling between the northern and southern provinces of the Kerguelen Plateau. Finally, the model for the relative motions of India, Australia and Antarctica is consistent with the emplacement of the Ninetyeast Ridge and the Kerguelen Plateau over a fixed hotspot.

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 now 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 morphology of the ocean floor between the continents is the site of the major aseismic Ninetyeast, Broken and Kerguelen ridges (Fig. 1).

Seafloor spreading among the major plates in the eastern Indian Ocean (India, Australia and Antarctica) occurred in three main phases. First, from the Late Jurassic to the Early Cretaceous, 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, 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, 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 divided by two periods of ocean-wide plate reorganization, the first during the Early/Middle Cretaceous (Cretaceous magnetic quiet zone) and the second during the Middle Eocene (magnetic anomaly 20 to 18). The reorganizations occurred by large 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 (Fig. 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 (an 22, 44 Ma) between Australia and Antarctica [*Weissel and Hayes*, 1972], resulted in an overlap between the two ridges at the Early Eocene [e.g. *Houtz et al.*, 1977; *Norton and Molnar*, 1977; *Konig*, 1980]. However, there is evidence that 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 DSDP site 255 [*Davies, Luyendyk et al.*, 1974], while piston cores on the Kerguelen Plateau show sediments of Cenomanian age [*Wicquart*, 1983]. The reinterpretation by *Cande and Mutter* [1982] of the chronology of the break-up of Australia and Antarctica at chron 34 (84 Ma) partially solves the problem of overlap [*Mutter and Cande*, 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 Wharton Basin was first interpreted as the symmetric limb of ocean floor being subducted under the Java-Sunda trench [*Sclater and Fisher*, 1974]. Interpretation of the east-west magnetic lineations indicates that the age of the Wharton Basin decreases from the Late Cretaceous (anomaly 33) in the south to the Late Eocene in the north. Reinterpretations of the magnetic data [*Liu et al.*, 1983; *Geller et al.*, 1983] revealed a Middle Eocene extinct spreading ridge (anomaly 19) that extends from the Sunda trench at the Equator to the Ninetyeast Ridge in a succession of right-lateral offset segments. Although most of the northern lineations have been subducted, a symmetric pattern of magnetic lineations can be identified on both sides of the fossil axis, the youngest corresponding to anomaly 20 and the oldest, to anomaly 31. This finding suggests that, prior to anomaly 20 time, the motions of India, Antarctica and Australia have to be consistent with one another. This is a stronger constraint than 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, anomaly 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/a (half rate) before anomaly 19 to 2.7 cm/a after anomaly 19 time. The question whether India and Australia have behaved as two different plates after seafloor spreading ceased in the Wharton Basin is another issue raised by these reinterpretations.

We have improved the reconstructions for the last two of the three phases of spreading in the eastern Indian Ocean by reinterpreting magnetic lineations in the Australian-Antarctic and Wharton basins and by incorporating fracture 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 oceanic seafloor [e.g. *Haxby*, 1985; *Gahagan et al.*, 1988]. In some areas, they are particularly suited for 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 the deflection of the vertical data or first derivative of the ocean-geoid signal along the satellite ground tracks (Fig. 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 since 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 in *Sandwell and McAdoo* [1988].

We present in Figure 4A 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 accurately 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 bears on the accurate location and extension of the fracture zones. Depending on the age offset, these features can be precisely mapped (Fig. 4B). The best illustration of such a feature is the Balleny Fracture Zone (Fig. 5) that lies between the South Tasman Rise and the Balleny Islands (Fig. 1) and has an age offset of about 10 Ma.

The tectonic features identified on the deflection fo the vertical charts place strong constraints on the closure of the Australian/Antarctic Basin. Going 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 (Fig. 5). The George V, Tasman and Balleny fracture zones tightly constrain the longitudinal motions of Australia relative to Antarctica at least from the Late Eocene (anomalies 18-13) to present.

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 (Fig.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. It corresponds in fact to the southern limit of the magnetic quiet zone bordering the south Australian continental margin. The COB correlates with the first positive peak of the deflection of the vertical on the descending passes (Fig. 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 shelf itself correlates with the deepest trough on the deflection of the vertical (or steepest descending slope of the geoid), parallel to the Australian coastline (Fig. 6). The width of the zone between the COB and the continental slope varies exactly with that of the magnetic quiet zone delineated by *Konig* [1980]. It becomes narrower east of 138°E as the two boundaries curve towards the south. While it seems reasonable that the steepest part of the continental shelf will produce the largest slope in the geoid, we do not yet understand why the deflection of the vertical is well correlated 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 (Fig. 7) to locate the Antarctic shelf edge. Like Australia, the continental margin approximates the coastline. East of Terre Adélie and off George V Land, East Antarctica, there appears to be a large basin. It is landward of what we interpret as the limit of the continental shelf, and so maybe underlain by continental crust. Nearly continuous ice-coverage causes it to still be a poorly surveyed areas around Antarctica [e.g. *Johnson et al.*, 1980]. Only the eastern part of this basin has been mapped at all [*Domack and Anderson*, 1983]. Using our reconstruction, we show that this previously uncharted basin was connected to the Bass Straight.

The Antarctic COB is delineated by the first negative peaks of the deviation of the vertical that lie seaward from the steep upward slope of the continental shelf (Fig. 7). From 120°E to 140°E, the peaks on the descending passes correlate well with the troughs of the ascending passes. They also match with seismic control point of *Konig* [1980] and *Veevers* [1986] at 132°E, but differs significantly from the tentative interpretation of Veevers [1986] further east. Our interpretation agrees with the limit of the magnetic quiet zone [*Konig*, 1980]. To the west the COB can tentatively be extended as far as 100°E, although the geoid signal does not show the same characteristic pattern. It is obscured further west by the southern tip of the Kerguelen Plateau. From 100°E to 133°E, the Antarctic COB and continental margin are about 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, recently investigated by *Bennett and Eittreim* [1987]. On the descending passes of the deflection of the vertical (Fig. 7), the COB probably corresponds to the large negative trough that curve 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. Further east, the COB does not look as straight as its Australian counterpart west of Tasmania, but apparently follows a stair-step pattern. Since the orbit 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 sections parallel to the continental shelf may correspond to areas of shear motions between Australia and Antarctica, and the perpendicular sections to areas of stretching.

The rifted margin of Kerguelen Plateau, clearly visible on the SEASAT data, has been interpreted as a basement offset [*Coffin et al.*, 1986]. The deflection of the vertical charts from GEOSAT permit us to extend by a few 100 km to the south this structural limit (Fig. 8). Extending along the northeastern edge of the Kerguelen Plateau, this limit shows a pronounced bend corresponding to the William's Ridge. This bend, which is exactly reproduced along the scarp of Broken Ridge (Fig. 6), puts a major 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 (Fig. 1), the northern counterpart, present the same peak and trough signature on the deflection of the vertical charts (Fig. 6 and 8), 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, Fig. 2) along the Southeast Indian Ridge. Some of them were already mapped in great detail from sea-surface ship's track in the Crozet Basin, the Central Indian Basin and in the area of the Australian-Antarctic Discordance [e.g. *Schlich*, 1975; *Sclater et al.*, 1976; *Patriat*, 1987; *Royer and Schlich*, 1988; *Vogt et al.*, 1983]. The new information bears mainly on the fracture zone pattern between Broken Ridge and Kerguelen Plateau (Fig. 2). The Kerguelen Fracture Zone, that runs NNE-SSW west of the Kerguelen Plateau (Fig. 2), is another major feature clearly delineated by the deflection of the vertical charts. The fracture zone fades away at about 62°S, which was not clear from the Seasat data, impaired by the ice coverage at these latitudes (e.g. *Haxby*'s map [1985]). In the Central Indian Basin and the Wharton Basin, the angle of incidence of the satellite ground tracks relative to the north-south fracture zones is too small for them to appear clearly. Furthermore, the basement undulations related to the deformation of the Central Indian Basin cause lineated geoid anomalies [*McAdoo and Sandwell*, 1985] that obscure the seafloor tectonic fabric. For instance, it is not possible to identify the northern counterpart of the Kerguelen Fracture Zone.

A REVISED TECTONIC CHART FOR THE EASTERN INDIAN OCEAN

The tectonic diagrams on Figure 9A and 9B 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 fabrics, 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 the Middle Eocene. 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). Their orientations range from N45°E west of the large offset Amsterdam and St Paul fracture zones, to north-south in the vicinity of the Australian-Antarctic Discordance and N10°W south of Tasmania. The fit of Broken Ridge with Kerguelen Plateau is now well constrained by the particular shape of their respective scarps, as identified on the deflection of the vertical charts. The direction of motions between India and Antarctica between the Late Cretaceous (anomaly 34) and the Middle Eocene (anomaly 20) 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/a, half rates), but is of less consequence in the areas of slow spreading rates, such as between Australia and Antarctica between the Late Cretaceous and the Middle Eocene (0.5 to 1.0 cm/a). 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, anomalies 5, 6, 13 and 18 identifications are from *Stock and Molnar* [1982] and *Vogt et al.* [1983]. Anomalies 20 to 34 are the *Veevers*' [1986] reinterpretation of the *Cande and Mutter*'s [1982] data. The anomaly 32/33 lineation from *Cande and Mutter* is reinterpreted as anomaly 33, the 27/31 lineation is reinterpreted as anomaly 31, and the 21/24 lineation is reinterpreted as anomaly 24. The only magnetic anomaly 34, identified by *Veevers* [1986], is located between 125°E and 132°E. In the Crozet and Central Indian basins, anomalies 5 and 6 identifications are from *Royer and Schlich* [1988], while anomalies 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] concerning the existence of a fossil spreading ridge of Middle Eocene age (~ anomaly 19/18). 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 were the magnetic data coverage is poor : the southern part of the Australian-Antarctic Basin between 85°E and 115°E, and the vicinities 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 backwards in time and with Australia fixed.

Past reconstructs of the Southeast Indian Ridge from the Rodriguez Triple Junction to the Macquarie Triple Junction have raised the question of whether this accreting plate boundary has behaved as a single plate boundary or not 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 anomalies 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 west of the Balleny Fracture Zone. However, at anomaly 18 time, data from the three sections cannot be fitted in a single plate boundary. When the central section and either one of the outer sections are reconstructed, a match cannot be achieved for the remaining section. From these results, *Stock and Molnar* [1982] suggest that some deformation took place within the Indo-Australian plate or within the region of the Macquarie Triple Junction between anomaly 18 and 13 times. More detailed reconstructions of the section of the Southeast Indian Ridge west of the Ninetyeast Ridge (i.e. west of Amsterdam Fracture Zone) at anomalies 5, 6, 13 and 18 [*Patriat*, 1987; *Molnar et al.*, 1988; *Royer and Schlich*, 1988] yield finite rotations inconsistent with 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].

Our reconstructions 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). Unlike the previous studies of the Southeast Indian Ridge, our data set extends from the Rodriguez Triple Junction to the Macquarie Triple Junction, that bound the Southeast Indian Ridge, and is uniformly dense and detailed all along the ridge.

The reconstructions at anomalies 5 and 6 times (Fig. 10A and 10B) 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 (Fig. 9), as well as the numerous magnetic anomaly identifications west of the Amsterdam Fracture Zone. Although the magnetic picks identified west of the Balleny Fracture Zone match, a clear mismatch of the two limbs of the Balleny Fracture Zone occurs at anomaly 5 (Fig. 10A).

The fit for anomaly 13 (35.5 Ma) is also well constrained (Fig. 10C). The anomaly 13 picks between Broken Ridge and Kerguelen Plateau reproduces exactly the shape of the "basement offsets" that delineates the scarps 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, ~250 km to the north, is estimated at about 38 Ma [*Duncan*, 1978] and the oldest sediment recovered are of Late Eocene/Oligocene age [*Davies, Luyendyk 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 Late Oligocene [*Nougier*, 1972]. 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 northern 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 Late Eocene [*Kenneth, Houtz 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 the Late Oligocene, in accordance with the sediment stratigraphy of the DSDP holes in this area [*Kenneth, Houtz et al.*, 1975]. To the southwest, the Balleny Islands and associated seamount chain starts overlapping the South Tasman Rise of continental origin according to DSDP site 281 [*Kenneth, Houtz 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 the Middle Eocene [*Kenneth, Houtz et al.*, 1975]. Such an age is compatible with our reconstruction.

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 (Fig. 10D) and some of those appear to be mislocated (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 [*LePichon and Heirtzler*, 1968; *McKenzie and Sclater*, 1971], further east anomaly 17 [*Houtz et al.*, 1977]; the first typical anomaly 18 is identified at 102°E (Fig.10D). 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 (Fig. 10C and 10D). 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 that 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 explains why the anomalies 5 and 6 lineations are not or less affected by such deformation. However, at chron 5 and 6 (Fig. 10A and 10B), the azimuth of the Balleny Fracture Zone is not compatible with the direction of motion between Australia and East Antarctica. *De Mets* [1988] synthesis of present-day plate motions in the Indian Ocean shows 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. Consistent with our results, it confirms that the Southeast Indian Ridge has behaved as a single plate boundary since the Late Eocene, while suggesting that deformation of the Australian or East Antarctic plates south of Tasmania have 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 the Late Cretaceous 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 towards 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 the Broken Ridge do not overlap after 84 Ma and possibly 100 Ma. So the question raised by reconstructions older than 43 Ma, is the amount of extension that the Kerguelen Plateau and Broken Ridge have undergone between 84 Ma and their breakup at 43 Ma. From the structural map of the Kerguelen Plateau by *Houtz et al.* [1977], three different tectonic trends are visible: 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 tectonics have been identified on Broken Ridge, narrower than its southern counterpart. According to *Munschy and Schlich* [1987], three phases of faulting can be identified within the northern province, between Kerguelen and Heard islands: a pre-rifting period that started 100 Ma ago, the breakup episode at about 45 Ma, and post-breakup faulting after 43 Ma. From their interpretations of the northern Kerguelen Plateau stratigraphy, we estimate an extension of about 1.6 given a rate of subsidence of ~20 m/Ma, a sediment thickness of ~2000m, and the initiation of subsidence at 100 Ma. Even if most of the extension for the northern part of the Kerguelen Plateau occurred before the break-up (from 100 Ma to 45 Ma), the total extension would be only 40 to 50 km which is small compared to the amount of oceanic crust produced in the Australian-Antarctic Basin between 84 and 43 Ma (~ 390 km at 125°E).

The northeastern margin of the southern province is flanked by the Labuan Basin (Fig. 1) which is characterized by a deep and rough oceanic basement [*Ramsay et al.*, 1986]. This basin is bounded to the northeast by the Kerguelen "basement offset" and to the northwest by the William's Ridge (Fig. 1 and 9A). Cenomanian sediments have been recovered by an R/V Eltanin piston core (EL 54-7) in this basin [*Kaharoeddin et al.*, 1973]. The Labuan Basin is thought to be the counterpart of the Diamantina Zone [*Mutter et al.*, 1985; *Ramsay et al.*, 1986; *Coffin et al.*, 1986]. The two areas have the same peak and trough signatures on the deflection of the vertical maps (Fig. 6 and 8). The rugged topography of these basins could result from the slow spreading episode (0.5 to 1.0 cm/a, half rate) between anomaly 34 and 18 time [*Cande and Mutter*, 1982; *Mutter et al.*, 1985]. However, no magnetic anomalies have been identified in these two basins. Taking into account their similar nature, the change in direction of the tectonic features between the northern and southern part of the Kerguelen Plateau and the impossibility of large extension on the Kerguelen Plateau or the Broken Ridge, we propose to solve the problem of the Late Cretaceous to Middle Eocene reconstructions by decoupling the northern and southern parts of Kerguelen Plateau (heavy dotted line on Fig. 9A). The northern part would have remained attached to the Broken Ridge (or the Australian Plate) until the Early Eocene, while the southern part, that would include the Elan and Banzare banks (Fig. 1), was transferred to the Antarctic plate much earlier, when Australia and Antarctica broke apart in the Early/Middle Cretaceous. This hypothesis would allow for the opening of the Labuan and Diamantina basins (Fig. 1) while avoiding large extension on the Un-Broken/Kerguelen Ridge after they built up in the Middle/Late Cretaceous. Consequently, it probably requires that some seafloor spreading occurred between the northern Kerguelen Plateau and the Elan Bank (Fig. 1) as it has been suggested by *Goslin and Patriat* [1984]. The different nature of the northern and southern sector of the Plateau [*Coffin et al.*, 1986] favors the decoupling hypothesis, rather than a detachment of Broken Ridge from the Australian Plate.

The closure of the Wharton Basin is constrained by the regular pattern of parallel N-S fracture zones (Fig. 9A). The major offset occurs along the Investigator Fracture Zone (at 98°E, Fig. 9A), which is the only one that curves into the Australian margin, recording the change of motion in the Middle Cretaceous. 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. However, because of the strike-slip motions along the northern part of Ninetyeast Ridge [e.g. *Sykes*, 1970; *Stein and Okal*, 1978], which are related to the intraplate deformation within the Indo-Australian plate since the Miocene [*Weissel et al.*, 1980], their actual location relative to the Central Indian Basin may have changed since the time they were generated. 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, which is generally true for the magnetic lineation pattern of the southern limb. Also we checked that the spreading rates deduced from the finite rotations were compatible with the observations that come mainly from the southern limb. Since we have assumed symmetrical spreading, we must also assume that the errors mentioned above, which result from ignoring the intraplate deformation of the Indo-Australian plate, are negligible. The same implicit assumptions have been made in the reconstructions based on the magnetic lineations (older than anomaly 26) that lie within the deformed area of the Central Indian Basin [e.g. *Patriat*, 1987; *Molnar et al.*, 1988].

For the last link of the circuit between India and Antarctica, finite rotation poles are derived from the reconstructions of *Patriat* [1987]. 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 less constrained. In particular, the reconstructions at anomaly 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 (anomaly 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 (Fig. 11A) brings the edges of the Kerguelen Plateau and Broken Ridge in contact. At that time, Kerguelen Plateau can be rotated in a single piece. It should be noted that DSDP site 255 on Broken Ridge and a piston core (noted PC on Fig. 11A) on Kerguelen Plateau recovered sediments of the same age (Santonian) face each other. The southernmost part of the Ninetyeast Ridge has been removed on Figure 11A according to the basement age of DSDP site 254 (~38 Ma [*Duncan*, 1978]). West of the Ninetyeast Ridge, the ridge axis is in the vicinity of DSDP site 253 where basement is older than 44 Ma [*Davies, Luyendyk et al.*, 1974]. East of the Ninetyeast Ridge, the position of the ridge axis can be deduced from the distance between chrons 20 and 28 (or 31) on the Australian Plate and from the location of chron 28 (or 31) in the first compartment east of the Ninetyeast Ridge (along 92°E on Fig. 9A) on the Indian Plate. This puts the ridge axis almost due east of the Osborn Knoll (Fig. 1). 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 amount of motion between chron 24 and chron 20 between the Australian and Antarctic plates requires either that the Kerguelen Plateau broke into two pieces or that Broken Ridge was detached from the Australian plate. We consider the first hypothesis. The anomaly 24 (56.1 Ma) reconstruction is one of the best controlled (Fig. 11B). 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 lineations on the Australian plate. The same 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 and a good match can be achieved given the previous constraints. Figure 11B shows that the South Tasman Rise slightly overlaps the Antarctic margin. This can be corrected by assuming Early Eocene rifting between Tasmania and the Tasman rise [*Houtz*, 1975]. Using the same reasoning as for the chron 20 reconstruction, the 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.

The reconstruction for anomaly 28 time (64.3 Ma; Fig. 11C) 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. 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, Sclater, et al.*, 1974] that is younger than chron 28. It appears from this reconstruction that the offset between the magnetic anomaly 32, 33 and 34 identified east and west of the Kerguelen Fracture Zone [*Schlich*, 1982] and on either side of the 84°E fracture zone is constant (~7°). The chron 28 reconstruction restores the magnetic lineation pattern west of the Ninetyeast Ridge.

The chron 31 reconstruction (Fig. 11D) is constrained by the numerous anomaly 31 identifications in the Central Indian Basin and Crozet Basin, as well as in the Australian-Antarctic Basin. There are also several anomaly 31 picks to locate the ridge axis throughout 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, Sclater, et al.*, 1974] while the basalts give a maximum isotopic age of 81 Ma [*Duncan*, 1978].

Chron 33 and 34 mark the beginning of seafloor spreading between Australia and Antarctica [*Cande and Mutter*, 1982]. From the magnetic lineations mapped south of Australia [*Konig*, 1980], it is apparent that seafloor spreading propagated eastward, as the length of the magnetic lineations increase eastward while their age decrease. *Mutter et al.*'s [1985] analyses of tectonic subsidence curves along the margin of Australia indicate that breakup propagated from 128°E to 140°E at a rate of 2 cm/a. Using these arguments, *Veevers* [1986] maps a diachronous COB along Australia and estimates its age at 96 Ma from 120°E to 132°E, at 80 Ma at 135°E and then even younger further east. Our reconstructions confirm this result. East of 140°E (on Fig. 12A) and to the way south of Tasmania, the Antarctic and Australian COBs fit almost synchronously at chron 33 (80 Ma). Between 130°E and 140°E, the anomaly 33 lineation and the COBs coincide, as noted by *Veevers* [1986]. West of 120°E, the conjugate COBs come in contact only at chron 34 (84 Ma; Fig. 12B). Accretion of oceanic crust at this time 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. Opening of the Red Sea occurs in a similar manner, with discontinuous areas of seafloor spreading and of stretched continental crust [*Cochran*, 1983].

Several models have been proposed for the Central Indian Ocean. *Patriat* [1987] match pairs of anomalies 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 those same picks with the ones identified north of Conrad Rise (between 74°and 77°E on Fig. 18) which 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 in the Central Indian Basin (Fig. 9A), 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 seen due east of the Crozet Plateau; the associated fracture zone is clearly visible on the deflection of the vertical charts (Fig. 3 and 9A). The reconstruction of *Patriat* [1987] infers that this fracture zone at anomaly 33 and 34 extends 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 a cusp in the isobaths north of Conrad Rise (at 50°E, Fig. 9A) and with a strong signature on the magnetics (see Figure 7 from *Goslin and Patriat* [1984]). 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/a and N54°E, computed, compared to 3.0 cm/a and N55°E, observed.

Finally Figures 13A and 13B 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 (Fig. 6 and 7). Seafloor spreading between Australia and Antarctica initiated in the Great Australian Bight where the oldest magnetic anomalies (34) are identified. While *Cande and Mutter* [1982] conclude an age of breakup and rifting ranging between 110 and 90 Ma, *Veevers* [1986] extrapolated seafloor spreading backwards to date the oldest part of the COB at 96 Ma . Our match of the COBs produce overlaps (stippled areas on Fig. 13 A) on either side of the Great Australian Bight and almost close the Labuan and Diamantina basins. Overlaps between the COB and the continental shelves (cross-hatched areas on Fig. 13A) appear where the deflection of the vertical charts show 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 eliminating some extension in the Bass Strait between Tasmania and the main Land. The new fit of Australia and Antarctica (Fig. 13 B) makes the George V Basin a direct continuation of the Bass Basin between Tasmania and the main land. The complete closure of the Bass Basin would eliminate the slight overlap of Tasmania with East Antarctica on Figure 13B.

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 hotspot 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 the Late Cretaceous and the Middle Eocene.

Figure 14 shows the evolution of the directions and (half) rates of spreading derived from the finite rotations (Table 2) with respect to different flowlines 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/a, 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 corresponds to a slight acceleration of spreading in the Australian-Antarctic Basin. This becomes even 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/a. East of the Ninetyeast Ridge, the same changes occur, but the large right-lateral transform offsets (~ N-S orientation) in the Wharton Basin (Fig. 11A) opposed to the change of motion (~ NE-SW direction). This may explain why seafloor spreading stalled in the Wharton Basin and jumped to the south into the slow spreading Diamantina and Labuan basins, causing the breakup of Kerguelen Plateau and Broken Ridge. *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. Their model suggests that the Ob trench at the foot of Broken Ridge was created this way. The Ob trench corresponds to the eastern part of the continuous and undulated tectonic feature identified on the deflection of the vertical charts as parallel to the scarp of Broken Ridge. Its conjugate, northeast of the Kerguelen Plateau, would correspond to the "basement offset line" identified by *Coffin et al.* [1986] along the scarps of the Kerguelen Plateau and clearly visible on the deflection of the vertical charts (Fig. 6). 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 happens at chron 5 and affects the whole ridge.

The ridge axes configurations at chron 33 and 34 (Fig. 12A and 12B) show that the location of the proto-Southeast Indian Ridge is asymmetrical relative to India and Antarctica-Australia, agreeing with the identifications of large westwards ridge jumps in the Mesozoic sequences of magnetic anomalies along the western Australian margin [*Larson et al.*, 1979; *Johnson et al.*, 1980]. The breakup between Madagascar and India in the Middle/Late Cretaceous 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 Quiet Zone and that these events coincided with the emplacement of the Conrad Rise. This reorganization caused the transform offsets on the India/Antarctica-Antarctica plate boundary 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-Antarctic boundary 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 chron 33 and 34 (Fig. 12A and 12B) 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 fracture zone east and parallel to the Ninetyeast Ridge (dotted lines on Fig. 11C and 11D). *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 further west and south of Kerguelen Plateau than we assume here. Whatever model is preferred, the motions along this boundary between chron 33 and 28 are very slow, since the Australian-Antarctic stage poles are located on the Broken and Kerguelen ridges (Table 2). In the mean time, the Kerguelen hotspot migrated westward relative to Australia, explaining the obliqueness of the Ninetyeast Ridge relative to the fracture zone pattern in the adjacent basins. It is not clear whether the Ninetyeast Ridge was generated during this time span in the vicinity of the Kerguelen hotspot or at the ridge axis further north, as the hotspot model of *Morgan* [1972] 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 hotspot (Fig. 15). The short distance (~ 300 km) between the ridge axis and the Kerguelen hotspot 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 (Fig. 15). 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]. 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, Luyendyk et al.*, 1974; *von der Borch, Sclater 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 further west in the Central Indian Basin. Magnetic anomaly identifications in the compartment adjacent to the 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) [*von der Borch, Sclater et al.*, 1974; *Pierce*, 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; *Pierce*, 1978]), and the age of site 214 (60 Ma). Our scenario is compatible with these results and predict that anomaly 31 lies in the vicinity of the Osborn Knoll and that this feature might represent the location of the propagating rift.

There is evidence that small ridge jumps to the south occurred afterward west of the Ninetyeast Ridge between chrons 26-25 and 24, 24 and 20, and 20 and 18 (Fig. 11B, 11A and 10D). For instance, west of the Kerguelen and 84°E Fracture Zones in the Crozet Basin or in the Central Indian Basin, the average distance between anomalies 20 and 33/34 is about 19° (Fig. 9A or 11A). The first anomaly 20 lineation identified east of the Kerguelen Plateau is at about 9° and 11° from the lineations 33 and 34, respectively, identified east of the Kerguelen Fracture Zone (Fig. 11A) while, 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°. The difference is bigger than the amount of crust transferred to the Indian plate at chron 25-26. The hotspot model of *Morgan* [1972] also predicts asymmetric spreading in the vicinity of the fixed hotspot. From our set of figures where we keep Australia fixed in its present-day position, it clearly appears that the Kerguelen hotspot remained almost fixed relative to Australia and Antarctica between the Late Cretaceous to the Middle Eocene (chron 20-18). From chron 31 to 26, the high spreading rates between India and Antarctica (~ 10 cm/a, half-rate) allowed the ridge to migrate northward, away from the hotspot. After the ridge jump at chron 26-25, the ridge axis is in 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/a between chron 24 and 20, 3 cm/a between chron 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 hotspot. Meanwhile, the transform boundary east and parallel to the Ninetyeast Ridge between the Indian and Australian plates increased drastically (Fig. 11A and 11B).

As demonstrated by the results from the drilling on the Ninetyeast Ridge (paleontology, basal sediments and isotopic dating), the age of this feature decreases from north to south as the magnetic anomaly pattern does immediately to the west. Our model agrees with the DSDP results, but predicts that the age may not decrease monotonically: the ages would decrease from 84 to 60 Ma between 10°N and 7°S (DSDP sites 217, 216, 215) then increase from 60 to 70 Ma between 7°S and about 16°S (DSDP site 214) and finally decrease with some discontinuity from 60 to 35 Ma between 16°S and 32°S (DSDP sites 253 and 254). From our kinematic reconstructions, India drifted away from the Kerguelen hotspot at an overall rate of 9.7 cm/a between 84 and 36 Ma, similar to the rate of 9.4±0.3 cm/a inferred by *Duncan*'s [1978] isotopic dating of the DSDP basalts from the Ninetyeast Ridge.

Our reconstructions show that in order to maintain the linearity of the Ninetyeast Ridge, the Kerguelen hotspot must slowly migrate westward relative to Australia and Antarctica at an estimated rate of 1.1 cm/a between chron 34 and chron 20 (Fig. 11A to 12B). The part of the Kerguelen Plateau created during this time span forms the mirror image of the Ninetyeast Ridge. At chrons 18 and 13, the Kerguelen hotspot built up the northwesternmost part of Kerguelen Plateau. From then, it remained practically fixed relative to Antarctica, while Australia drifted to the north. Since after the breakup of Gondwana, Antarctica is known to have little moved relative to the South pole [*McElhinny*, 1970], the paleolatitudes of the basalts created by the Kerguelen hotspot are expected to be close to 50°S, the present-day latitude of Kerguelen Island. This is what is observed [*Peirce*, 1978].

A unique and stationary source of volcanism for the Ninetyeast Ridge, for the Broken Ridge and for the Kerguelen Plateau seems the most simple and satisfactory model, as first suggested by *Morgan* [1972] and favored by *Peirce* [1978] and *Duncan* [1978, 1981]. It accounts simultaneously for a constant paleolatitude for the basalts of the Ninetyeast Ridge [Peirce, 1978], for the age progression along this lineament [*Duncan*, 1978] and agrees with the relative motions between India, Australia and Antarctica. Complex models have involved a combination of volcanic sources and leaky transform fault [*Sclater and Fisher*, 1974; *Luyendyk and Davies*, 1974; *Johnson et al.*, 1976] or a simultaneous occurrence of two hotspots [*Luyendyk and Rennick*, 1977].

The relative motion between the southern and northern Kerguelen Plateau can be considered in three periods (Table 3): north-south motion of 79 km between 100 Ma and 70 Ma (Chron 31), 124 km of motion along N140°E between 70 and 56 Ma (Chron 24), and 70 km of motion along N170°E until the breakup (Chron 20). The first period of motion may have taken place with some seafloor spreading south of the Kerguelen Plateau and/or with some extension occurring within the northern part of the Plateau. Figures 11D, 12A and 12B shows that the amount of seafloor spreading during this period is very small and that the presence of a spreading center south of Kerguelen Plateau is not really required by the decoupling hypothesis, between chron 34 and 31. Motion during the second period is oblique to the strike of the plateau (Fig. 11B) and is evidence for some shear motion and extension south of within the Northern Kerguelen Plateau, and consequently for extension between the northern and southern part of the plateau. The N-S horsts and grabens observed in the saddle between the two parts of the Plateau may have been generated at that time. The shear component of the motion also implies some compression in the western extremity of the Kerguelen Plateau (outlined by an overlap of the isochrons on Fig. 11A and 11B). Motion before the break-up of the Kerguelen Plateau and the Broken Ridge mostly involves extension on the northern Plateau. Although the predicted motions are consistent with the tectonic features observed on the Kerguelen Plateau, these results warrant a better chronology and accurate mapping of the tectonic events on the Plateau.

CONCLUSION

The accurate mapping of the seafloor tectonic fabrics from GEOSAT altimetry permitted us to reappraise and to improve previous plate tectonic models of the eastern Indian Ocean. Although it is difficult to interpret deflection of vertical profiles in term of precise location of the tectonic features, such as fracture zones, the trend and extension of these features can be accurately delineated. The uniform coverage of the satellite tracks and high signal to noise ratio of the stacked data make these type of data particularly useful for plate tectonic reconstructions. This is especially true for the poorly surveyed southern oceans. The only inconvenient is when tectonic features are subparallel to the satellite ground tracks, but generally the combination of the ascending and descending passes allows to overcome this difficulty.

A consistent model of evolution for the eastern Indian Ocean since the Late Cretaceous can be built from the reinterpretation of the seafloor spreading pattern in the Australian-Antarctic Basin [*Cande and Mutter*, 1982] and in the Wharton Basin [*Liu et al.*, 1983]. The main results from the reconstructions derived from our magnetic anomaly data compilation and the mapping of the seafloor tectonic fabrics are:

1) The Southeast Indian Ridge has behaved as a single plate boundary since the Middle Eocene (anomaly 18), with the exception of its easternmost segment in the vicinity of

the Macquarie Triple Junction where the poor match of the data is evidence of some deformation of the Australian or Antarctic plate since chron 18. This result is consistent with the conclusion of recent syntheses of present-day plate motions in the Indian Ocean [*Wiens et al.*, 1985, 1986; *De Mets*, 1988]. They show that in addition to the the Rodriguez Triple Junction where the plate boundaries of Africa, Antarctica and Australia meet together, the closure of the plate circuit requires another triple junction west of the Chagos-Laccadive Ridge where the Central Indian Ridge (Africa-Australia plate boundary), the Carlsberg Ridge (Africa-India plate boundary) and the diffuse plate boundary identified by *Wiens et al.* [1985] in the Central Indian Basin (India-Australia plate boundary) meet. Since the deformation of the Central Indian Ocean is occurring since Miocene [*Weissel et al.*, 1980] and is related to motions between India and Australia, it raises the question whether the conclusions from present-day plate motions would still be valid back in time. The closure of the Rodriguez Triple Junction has proven to be verified since the Late Cretaceous [*Tapscott et al.*, 1980; *Patriat*, 1987], but both models include a limited amount of data from the Central Indian Ridge. How good is the closure of the plate circuit when data from the Carlsberg Ridge are included in the model? Has the deformation of the Central Indian Basin started as early as chron 18, after seafloor spreading ceased in the Wharton Basin ?

2) The Kerguelen hotspot as unique source for the volcanism of the Ninetyeast Ridge and the Kerguelen Plateau appears to be consistent with the data from the Ninetyeast Ridge and the relative motion of India, Australia and Antarctica since the Late Cretaceous (chron 34). A portion of the crust lying west of the Ninetyeast Ridge, once on the Antarctic plate, has been transferred to the Indian Plate about 60 Ma ago (chron 26-25). The segment (~ 900 km) of the Ninetyeast Ridge trapped on this microplate (Fig. 15) may either be a part of the mirror image of the Ninetyeast Ridge on the Antarctic plate, or part of the trail left by the Kerguelen hotspot on the Antarctic plate while the India-Antarctic plate boundary was migrating northward. The former hypothesis implies that from 7°S to 16°S, the age of the Ninetyeast Ridge increases toward the south, while the latter implies that the age decreases southward as observed on the other parts of the Ninetyeast Ridge. Next drilling campaign on the Ninetyeast Ridge may answer this question. Our kinematic model also shows that in order to maintain the linearity of the Ninetyeast Ridge, which is oblique relative to the flowlines in the adjacent basins, the Kerguelen hotspot has migrated westward relative to Australia and Antarctica at a rate of 1.1 cm/a between chron 34 and 18.

3) Finally, the interpretation of the deflection of the vertical data allows for a better fit for the Kerguelen Plateau and the Broken Ridge. Break-up between these two features have propagated from east to west starting a little before chron 18 and ending before chron 13. The breakup 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 requires a decoupling between the northern and southern Kerguelen Plateau, in order to avoid the overlap of the Kerguelen Plateau and the Broken Ridge before these two features broke apart in the Middle Eocene (chron 24-20). The northern Kerguelen Plateau would have remained attached to Broken Ridge (or Australian plate) until chron 24-20, while the southern Kerguelen Plateau (Banzare Bank and Elan Bank) would have been transferred to the Antarctic Plate much earlier when seafloor spreading initiated between Australia and Antarctica in the Late Cretaceous (chron 34). The existence of a spreading center south of Kerguelen Plateau is possible but not required: until chron 24, the stage poles of motions between Australia and Antarctica are located in the vicinity of the combined Broken and Kerguelen ridges, allowing for slow seafloor spreading in the Australian-Antarctic Basin, very slow spreading in the Diamantina and Labuan basins and probably only extension within the Kerguelen Plateau.

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Table 1

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

y corresponds to the youngest boundary of the magnetic reversal. Ages are from the *Kent and Gradstein*'s [1985] reversal time scale.

Table 2

**** ANTARCTICA / INDIA ****

Finite rotations :

Chron	Age	Lat	Lon	Angle	
5	10.5	12.5	36.7	6.62	(IND = AUS)
6	20.5	14.5	32.8	11.98	(IND = AUS)
13	35.5	13.4	32.7	20.40	(IND = AUS)
18	42.7	16.6	29.9	23.62	(IND = AUS)
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	(1)
33	80.2	8.2	11.0	62.18	
34	84.0	7.8	10.9	65.10	

Stage poles, half rates and directions of spreading on the Indian Plate

CENTRAL INDIAN BASIN (2)

Chrons		Age	DT	Lat	Lon	Angle	Dist	V	Dir	Dist	V	Dir
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

Ages and **DT** are in Ma

Dist 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/a or km/Ma

Dir is the direction of spreading expressed in degrees from north

(1) From Patriat [1983]

(2) Flowlines passing through the Southeast Indian Ridge axis at 26°S, 71°E and 33°S, 78°E

Table 2 (continued)

**** ANTARCTICA / AUSTRALIA ****

Finite rotations :

Chron	Age	Lat	Lon	Angle	
5	10.5	12.5	36.7	6.62	(IND = AUS)
6	20.5	14.5	32.8	11.98	(IND = AUS)
13	35.5	13.4	32.7	20.40	(IND = AUS)
18	42.7	16.6	29.9	23.62	(IND = AUS)
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	Closure of COB Fit
160	160.0	-2.0	38.9	31.50	

Stage poles, half rates and directions of spreading on the Australian Plate

AUSTRALIAN-ANTARCTIC BASIN (3)

Chrons		Age	DT	Lat	Lon	Angle	Dist	V	Dir	Dist	V	Dir
0	5	.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
13	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

(3) Flowlines passing through the Southeast Indian Ridge axis at 47°S, 97°E and 50°S, 130°E

Table 2 (continued)

**** AUSTRALIA / INDIA ****

Finite rotations :

Chron	Age	Lat	Lon	Angle
17	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

Stage poles, half rates and directions of spreading on the Australian plate

WHARTON BASIN

Chrons		Age	DT	Lat	Lon	Angle	Dist	V	Dir	Dist	V	Dir
17	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

(4) Flowlines running east of the Ninetyeast Ridge and west of the Investigator Fracture Zone through Chron 20 at 15°S, 89°E and 0°N, 97°E, respectively

Table 3

**** southern Kerguelen Plateau / northern Kerguelen Plateau ****

Finite rotations :

Chron	Age	Lat	Lon	Angle
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

Stage poles, rates and direction of motion relative to the northern Kerguelen Plateau (1)

Chrons		Age	DT	Lat	Lon	Angle	Dist	Vt	Dir	Dist	Vt	Dir
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

(1) Calculations are made at 2 points located on the northern Kerguelen Plateau at 50°S, 72°E and in the Labuan Basin at 53°S, 80°E.

Ages and **DT** are in Ma
Dist is the distance in degrees between the stage pole of rotation and the point of measurement
Vt is the total rate of motion in mm/a or km/Ma
Dir is the direction of motion expressed in degrees from north

Figure Captions

Figure 1: General bathymetric map of the Indian Ocean (4000m and 2000m isobaths) and main structural features referenced in the text.

Figure 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 (bet. 60°E and 90°E), to N5°E in the vicinity of the Australian-Antarctic Discordance and N10°W east of 150°E.

Figure 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.

Figure 4: A) Signature of the deflection of the vertical or variation of sea surface slope over (a) a seamount, (b) a trough and (c) an offset in the basement.
B) Changes in the deflection of the vertical along a large offset fracture zone. The signal reverses at the mid-point of the transform section of the fracture zone.

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

Figure 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.

Figure 7: Conjugate margin and COB off Wilkes Land and George V Land, Antarctica.

Figure 8: Rifted margin of the Kerguelen Plateau (heavy dotted line) on the GEOSAT descending passes. Note the pick and trough signature of the Labuan Basin, that extends between the Plateau (outlined by the 3000m isobath) and the rifted margin of the Plateau.

Figure 9: Tectonic summary diagram of the Eastern Indian Ocean:

(A) type lines outline the fracture zones mapped from bathymetric and magnetic evidence. (B) through (E) type lines oultine 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 represent the magnetic anomaly picks identified in the Eastern Indian Ocean. Away from the ridge axis, they are represented in sequences of four different symbols: 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 segments in solid line 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]

9A) Seafloor tectonic fabirc map of the Central Indian Basin, the Crozet Basin and the western part of the Australian-Antarctic Basin;

9B) Seafloor tectonic fabtic of the Australian-Antarctic Basin.

Figure 10: Asterisks represent magnetic picks from the Antarctic Plate, squares from the Australian Plate, and triangles from the African Plate. Fracture zones are identified by dashed 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). 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 biger than at chron 13. The large right-lateral transform offsets in the Wharton Basin have opposed to the change of spreading direction that is occuring 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, living a fossil ridge axis in the

Labuan Basin.

Figure 11: 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 dotted area show the extension of the combined Broken and Kerguelen ridges.

A) Reconstruction at chron 20 (46 Ma). Note the coincidental match of DSDP site 255 and a piston core (PC) on the northeastern flank of the Kerguelen Plateau, that both recovered sediments of Santonian age [Davies, Luyendyk 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 hotspot, spreading rates after chron 31 are greater than 10 cm/a (half-rate).

D) Reconstruction at chron 31 (68.5 Ma).

Figure 12: 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.

Figure 13: 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. Stippled pattern shows the areas of overlap between the COBs, the cross-hatched pattern outlines the areas of overlap between the COBs and the continental shelves.

B) New fit of the margins of Australia and Antarctica based on the interpretation of the deflection of the vertical charts. Stippled pattern shows the areas of overlap between the continental shelves.

Figure 14: 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 plain and dashed lines show the evolution of the spreading parameters along two different flowlines: 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 Basin) and 130°E.

Figure 15: Schematic diagram showing the eastward propagation of the Indian/Antarctic plate boundary through the Kerguelen FZ at about chron 26 (60 Ma). The stippled area shows the portion of crust transferred from the Antarctic to the Indian Plate that may have behave as a microplate during a few Ma. 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, 1983].

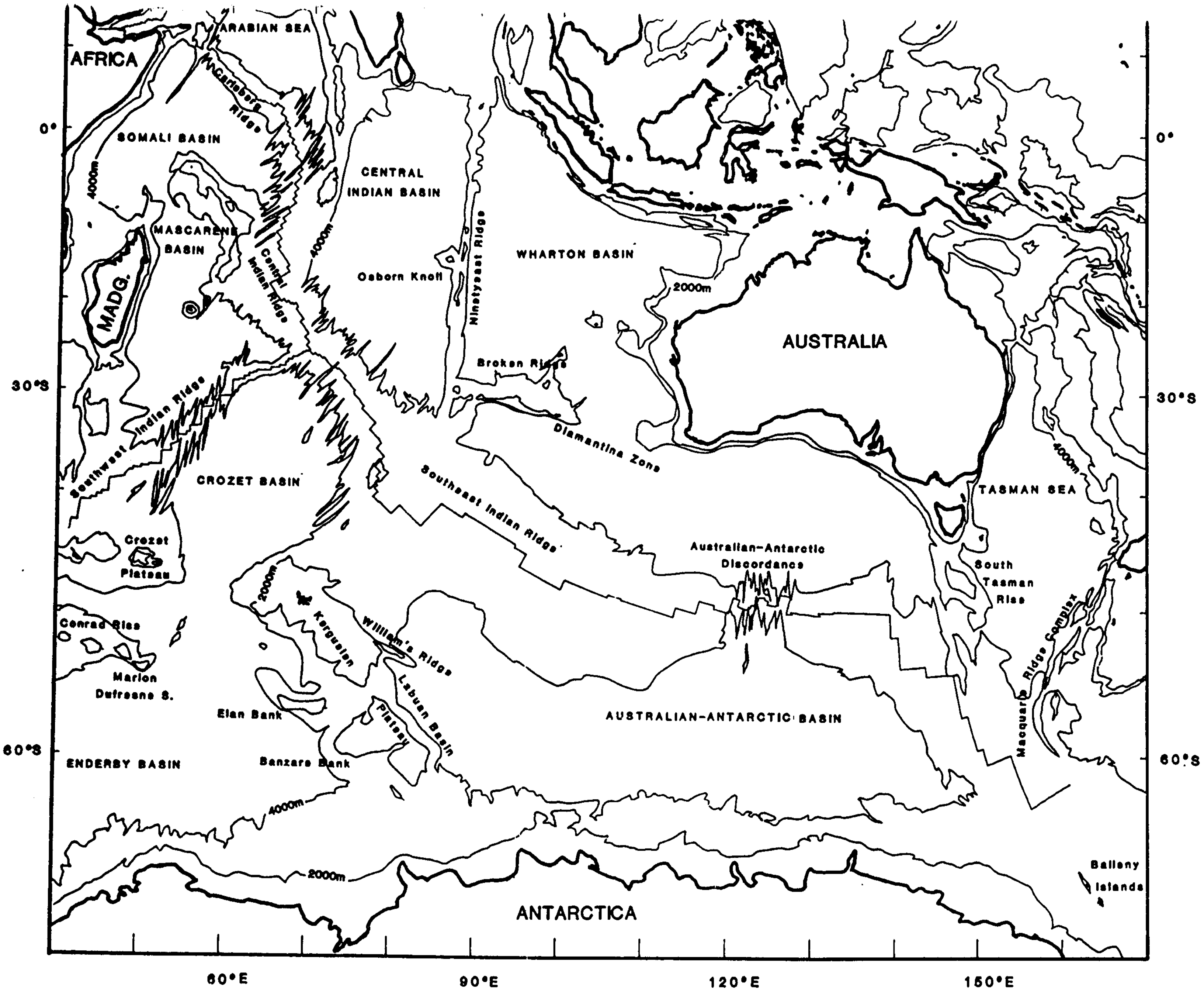

AFRICA
ARABIAN SEA
Carlsberg Ridge
SOMALI BASIN
4000m
MASCARENE BASIN
MADG.
Central Indian Ridge
CENTRAL INDIAN BASIN
4000m
Osborn Knoll
Ninetyeast Ridge
WHARTON BASIN
2000m
AUSTRALIA
Broken Ridge
Diamantina Zone
Southwest Indian Ridge
CROZET BASIN
Crozet Plateau
Southeast Indian Ridge
Australian-Antarctic Discordance
TASMAN SEA
4000m
South Tasman Rise
Macquarie Ridge Complex
Conrad Rise
Marion Dufresne S.
2000m
Kerguelen
William's Ridge
Labuan Basin
Plateau
Elan Bank
Banzare Bank
ENDERBY BASIN
AUSTRALIAN-ANTARCTIC BASIN
4000m
2000m
Balleny Islands
ANTARCTICA
0°
30°S
60°S
0°
30°S
60°S
60°E
90°E
120°E
150°E

Figure 1

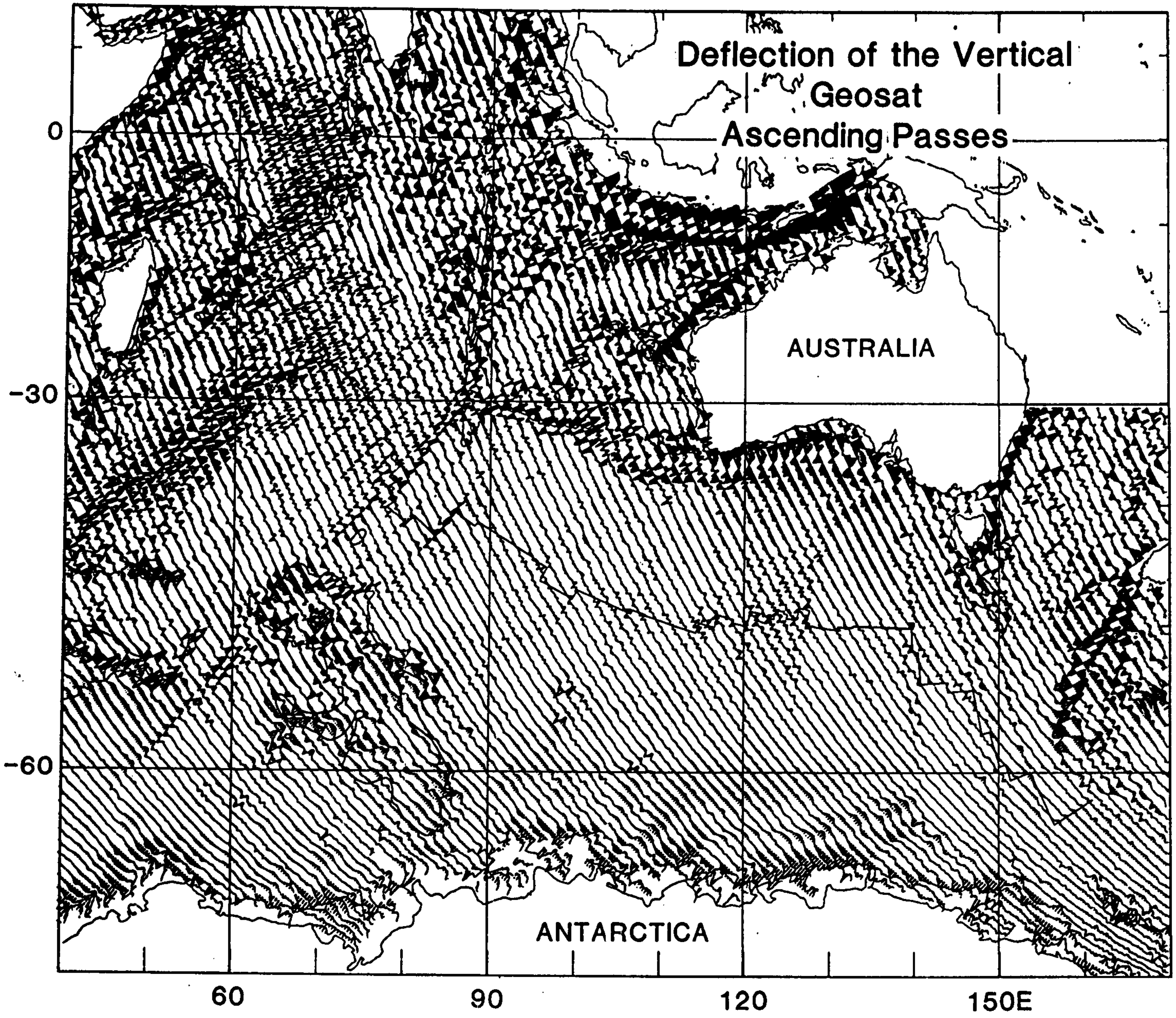

Deflection of the Vertical
Geosat
Ascending Passes
AUSTRALIA
ANTARCTICA
0
-30
-60
60
90
120
150E

Figure 2

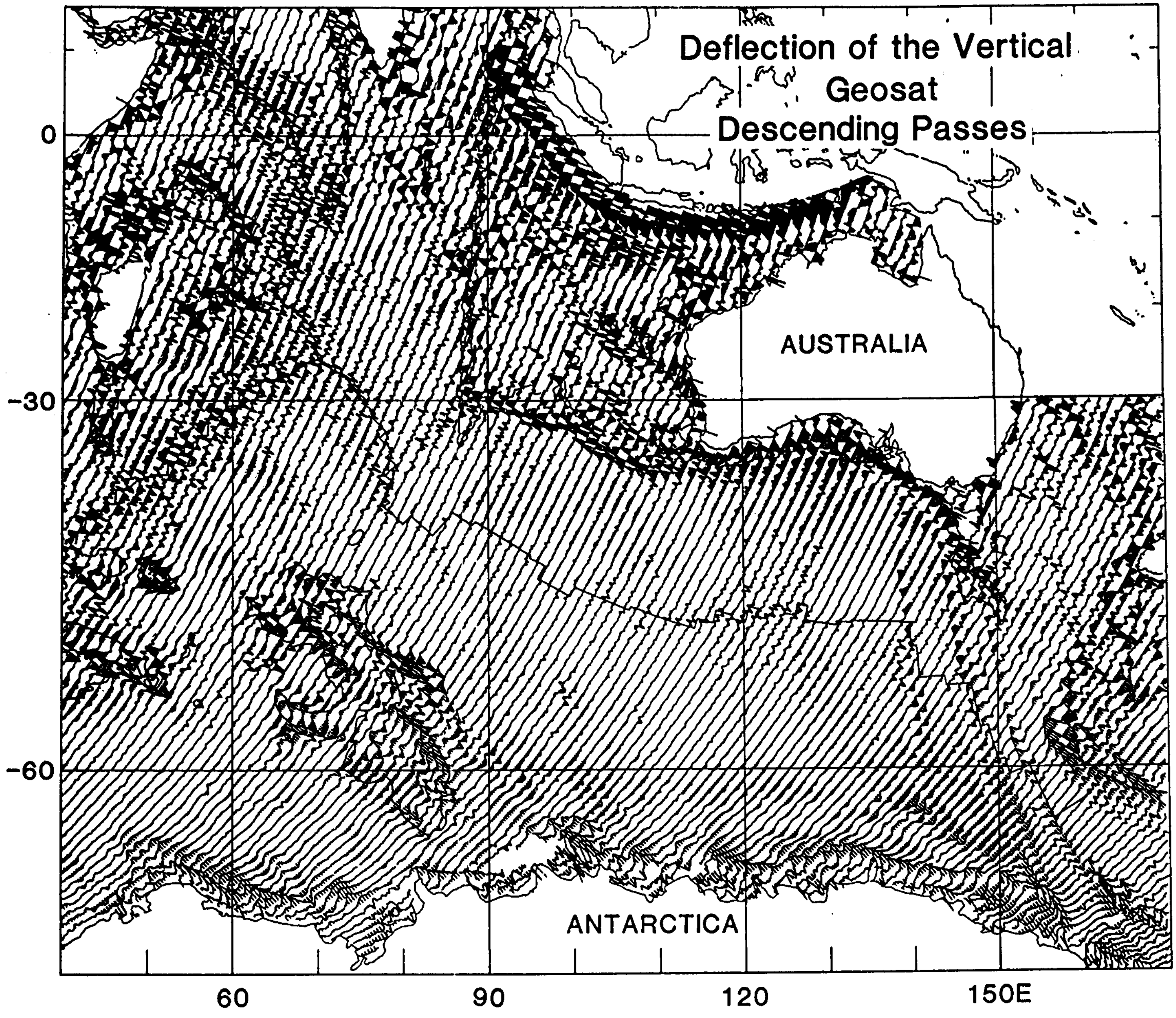
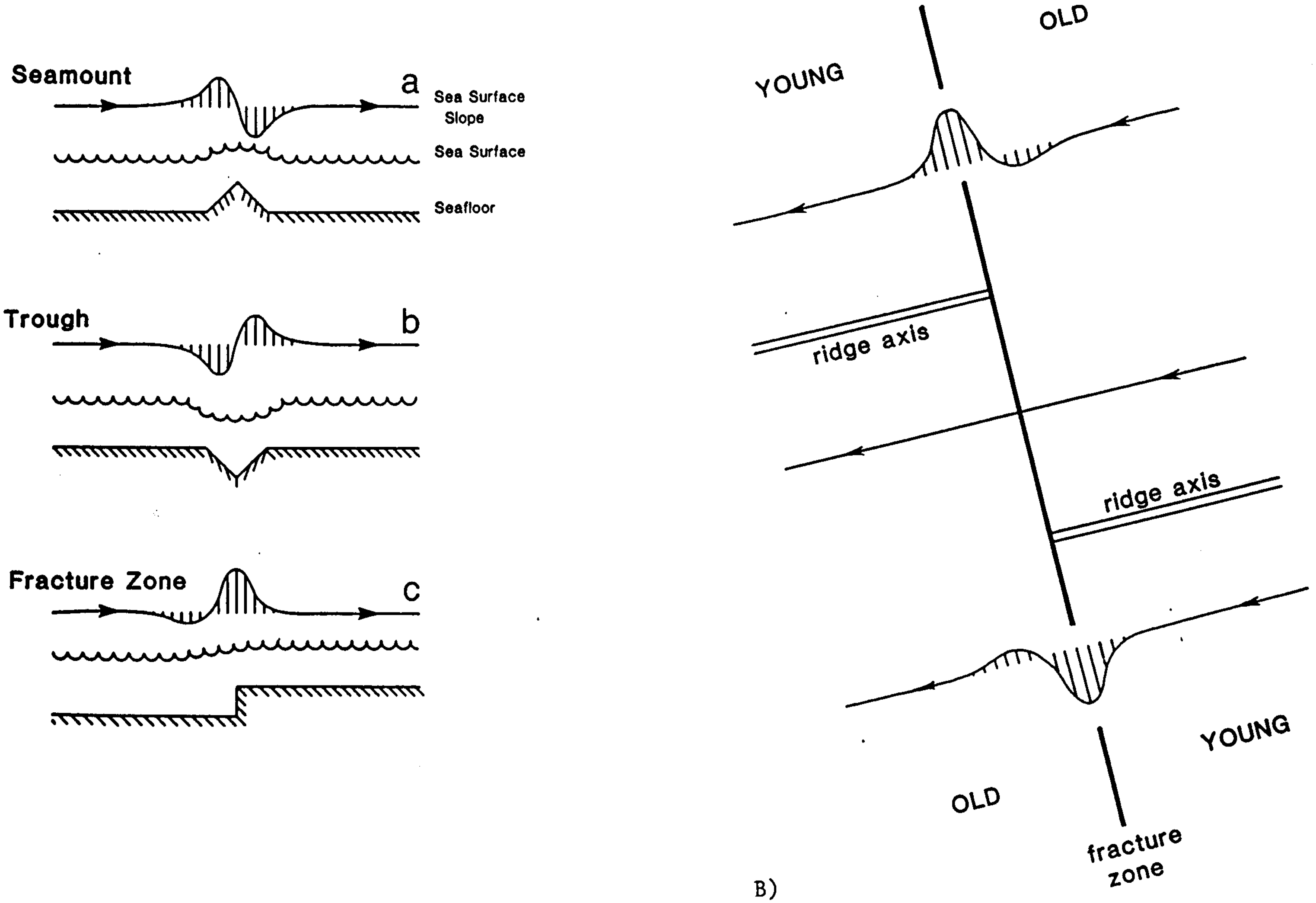

Deflection of the Vertical
Geosat
Descending Passes
AUSTRALIA
ANTARCTICA
0
-30
-60
60
90
120
150E

Figure 3


Seamount
a
Sea Surface Slope
Sea Surface
Seafloor
Trough
b
Fracture Zone
c
YOUNG
OLD
ridge axis
ridge axis
YOUNG
OLD
fracture zone

A)

B)

Figure 4

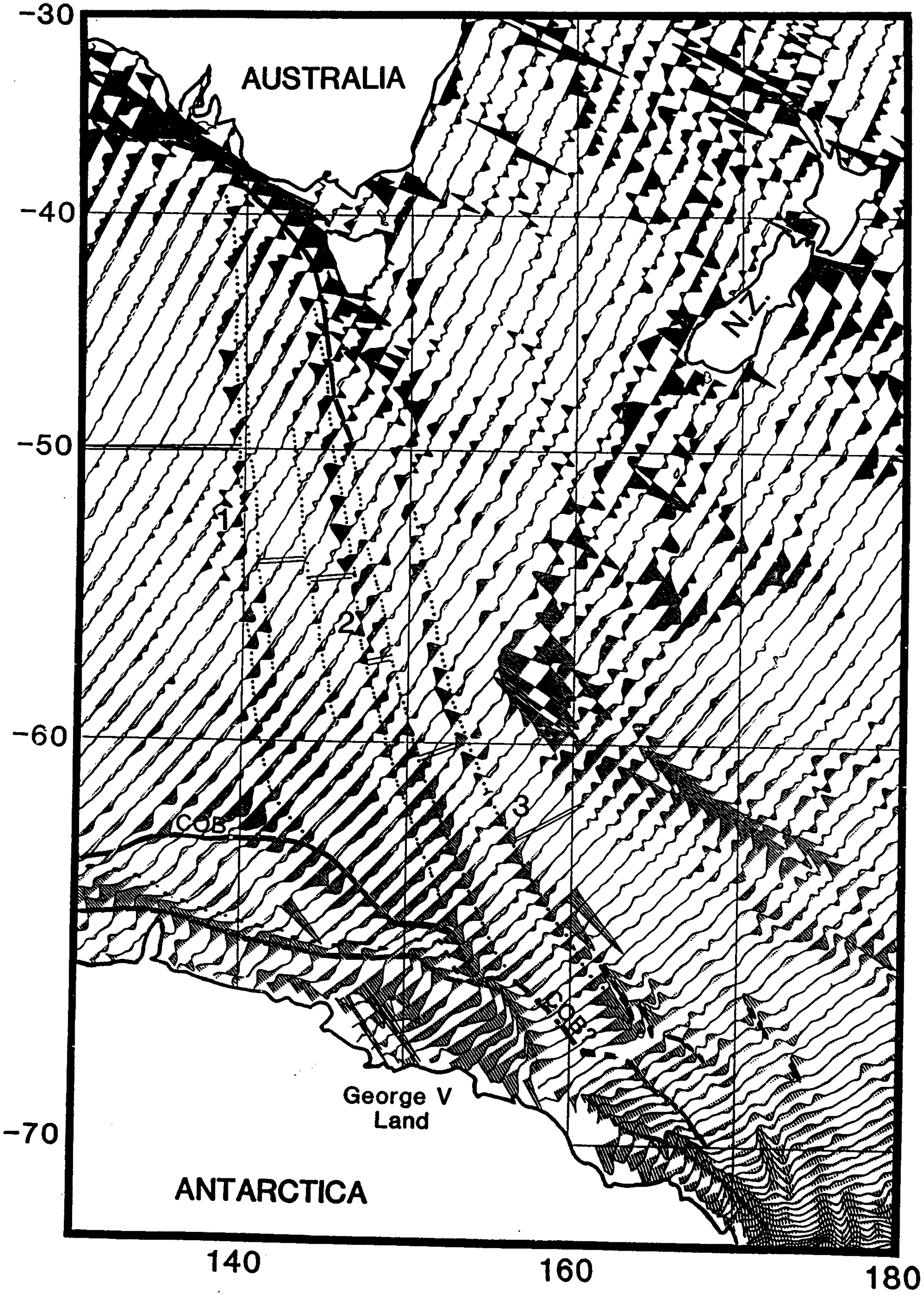

-30
-40
-50
-60
-70
140
160
180
AUSTRALIA
N.Z.
1
2
3
COB
COB
George V Land
ANTARCTICA

Figure 5

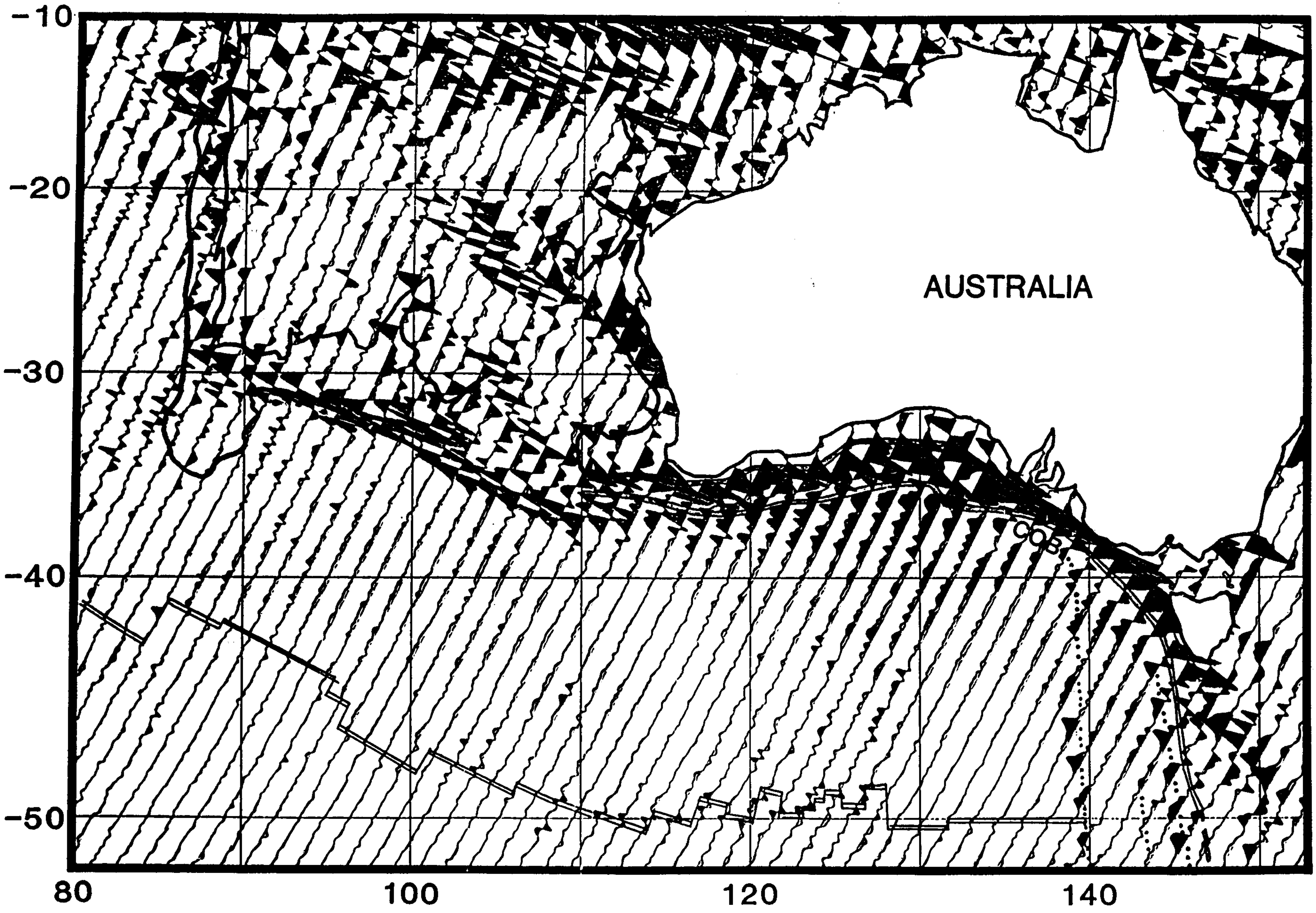


Figure 6

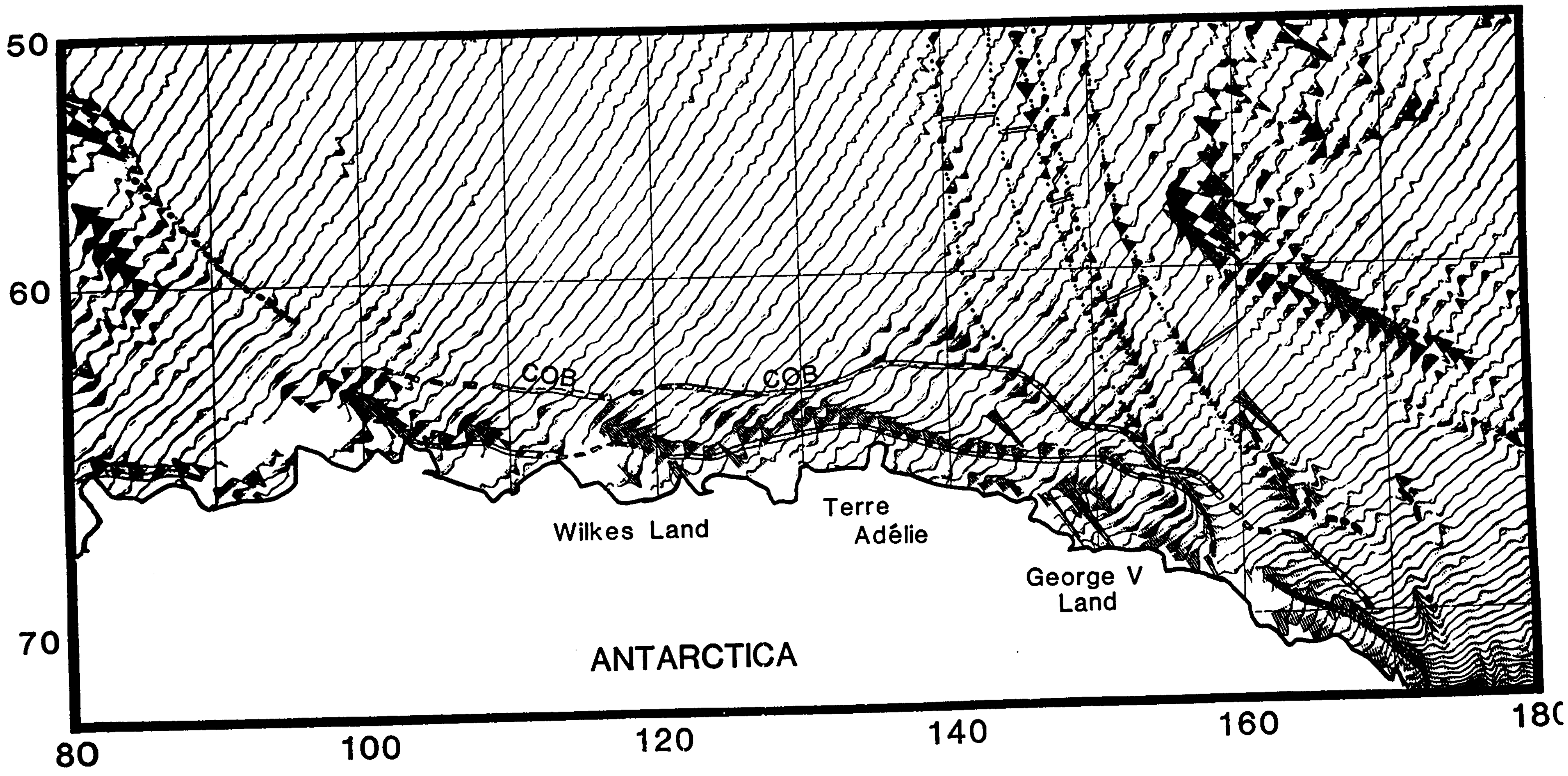

50
60
70
COB
COB
Wilkes Land
Terre
Adélie
George V
Land
ANTARCTICA
80
100
120
140
160
180

Figure 7

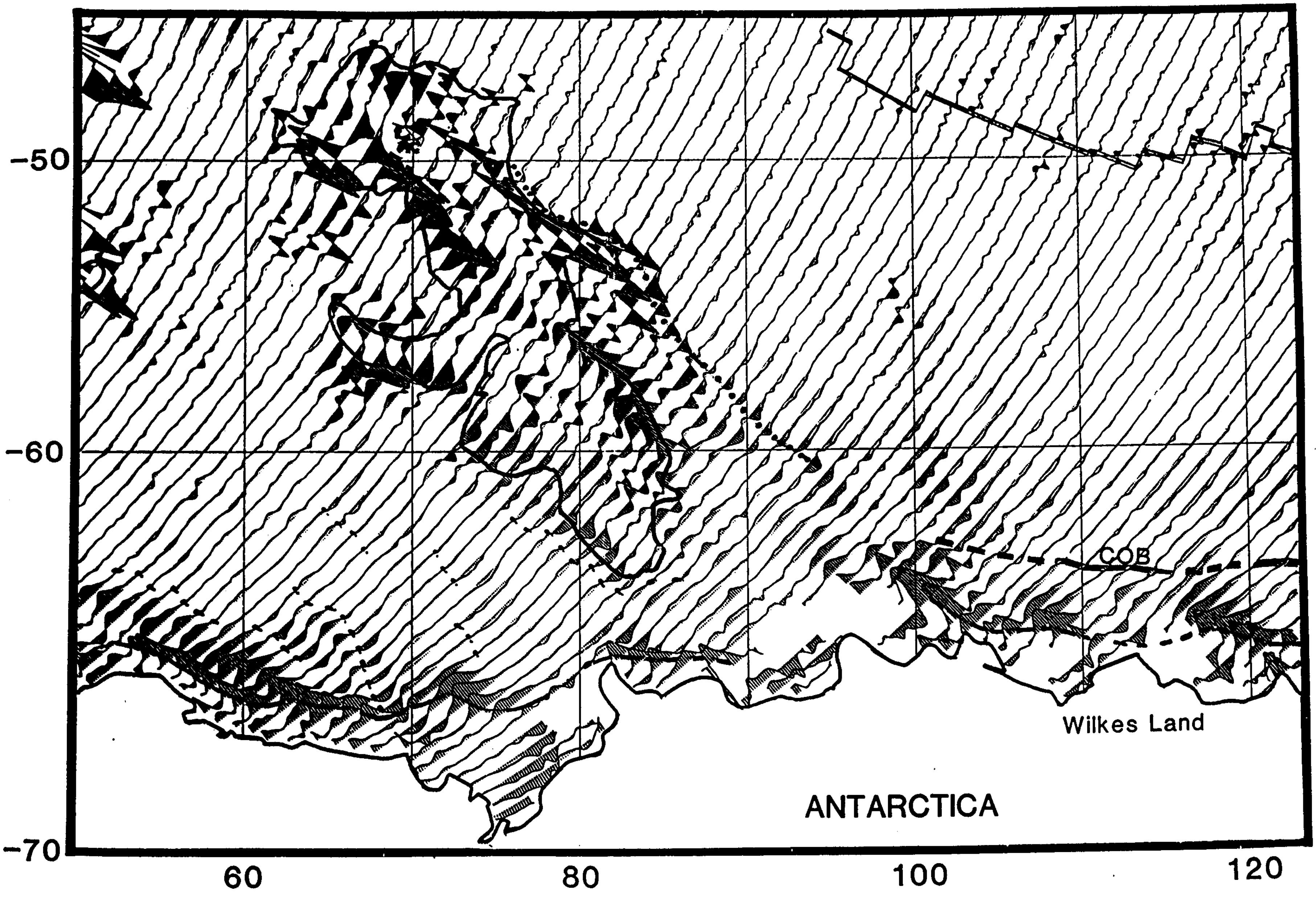
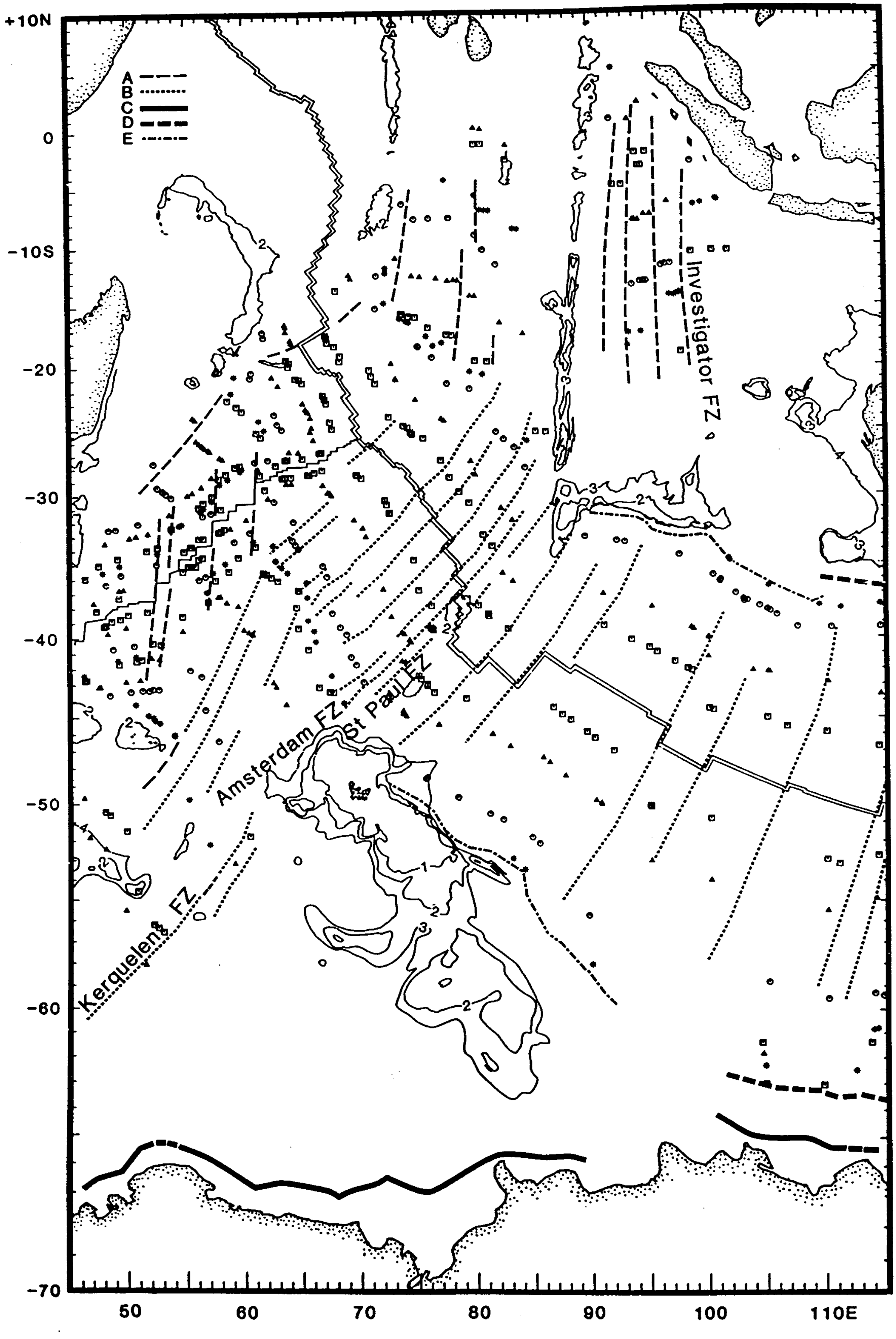


Figure 8



+10N
0
-10S
-20
-30
-40
-50
-60
-70
50
60
70
80
90
100
110E
A
B
C
D
E
Investigator FZ
Amsterdam FZ
St Paul FZ
Kerguelen FZ
1
2
3
4

Figure 9A

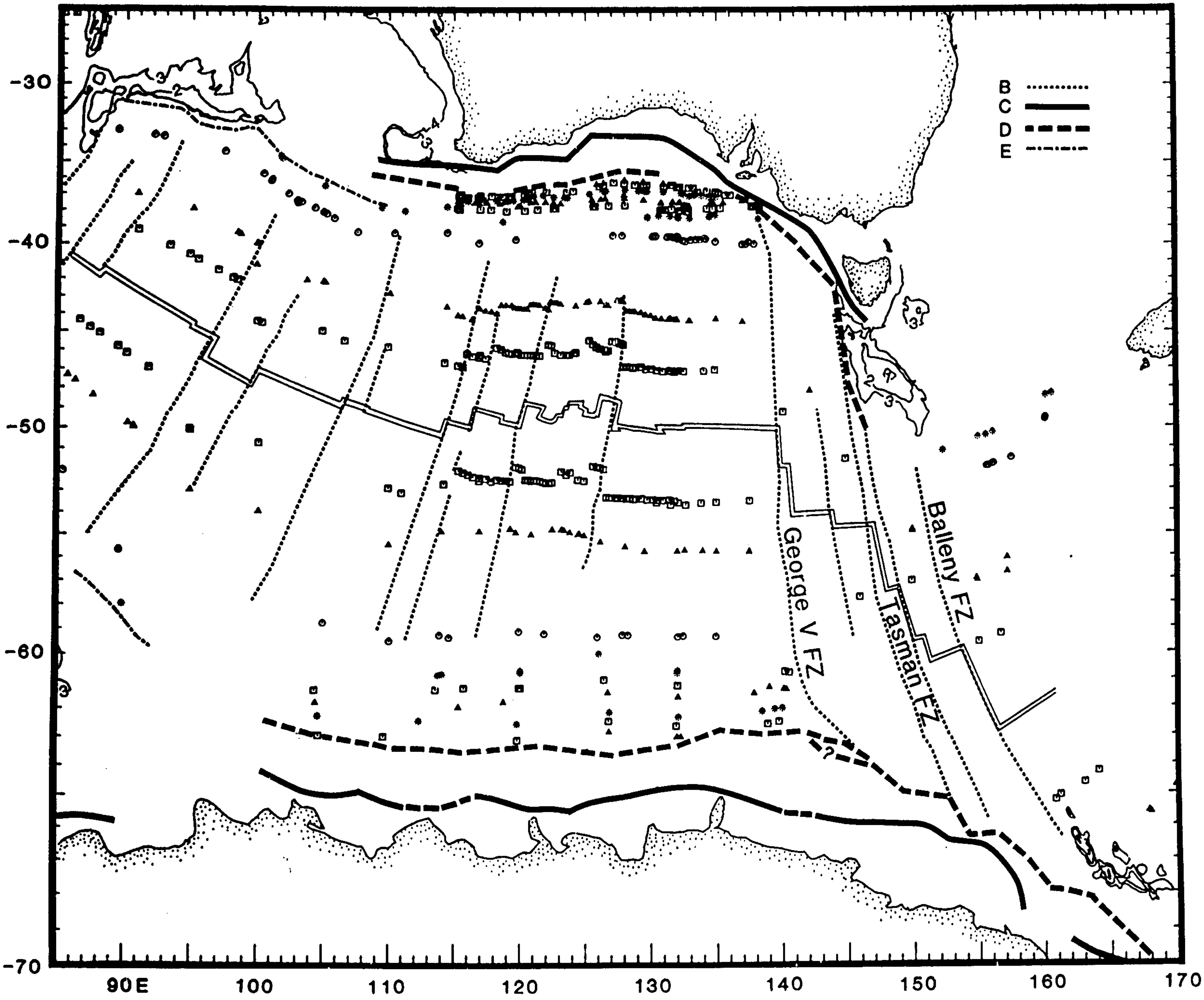

B
C
D
E
Balleny FZ
Tasman FZ
George V FZ
?
-30
-40
-50
-60
-70
90E
100
110
120
130
140
150
160
170

Figure 9B

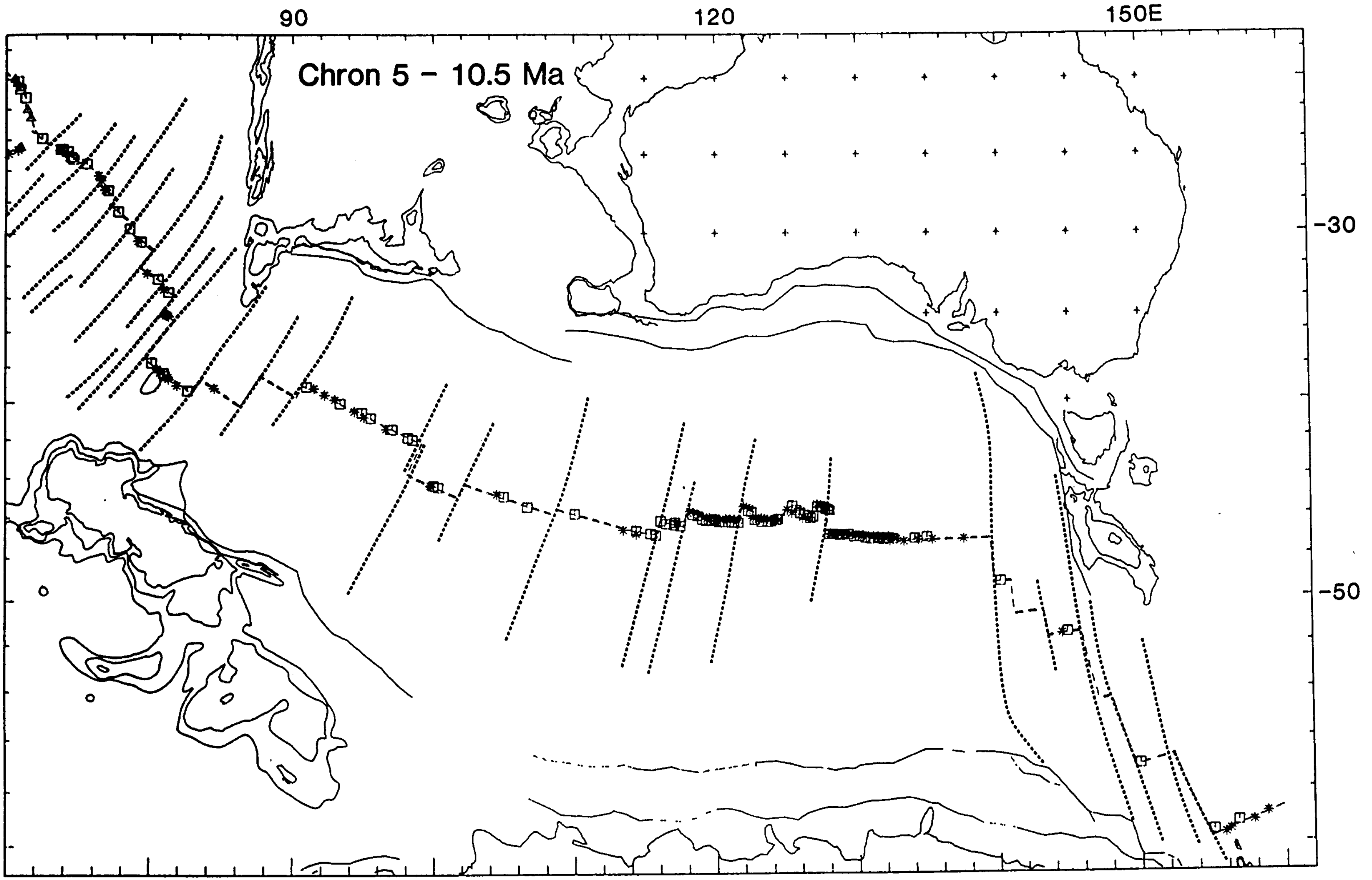


Figure 10A

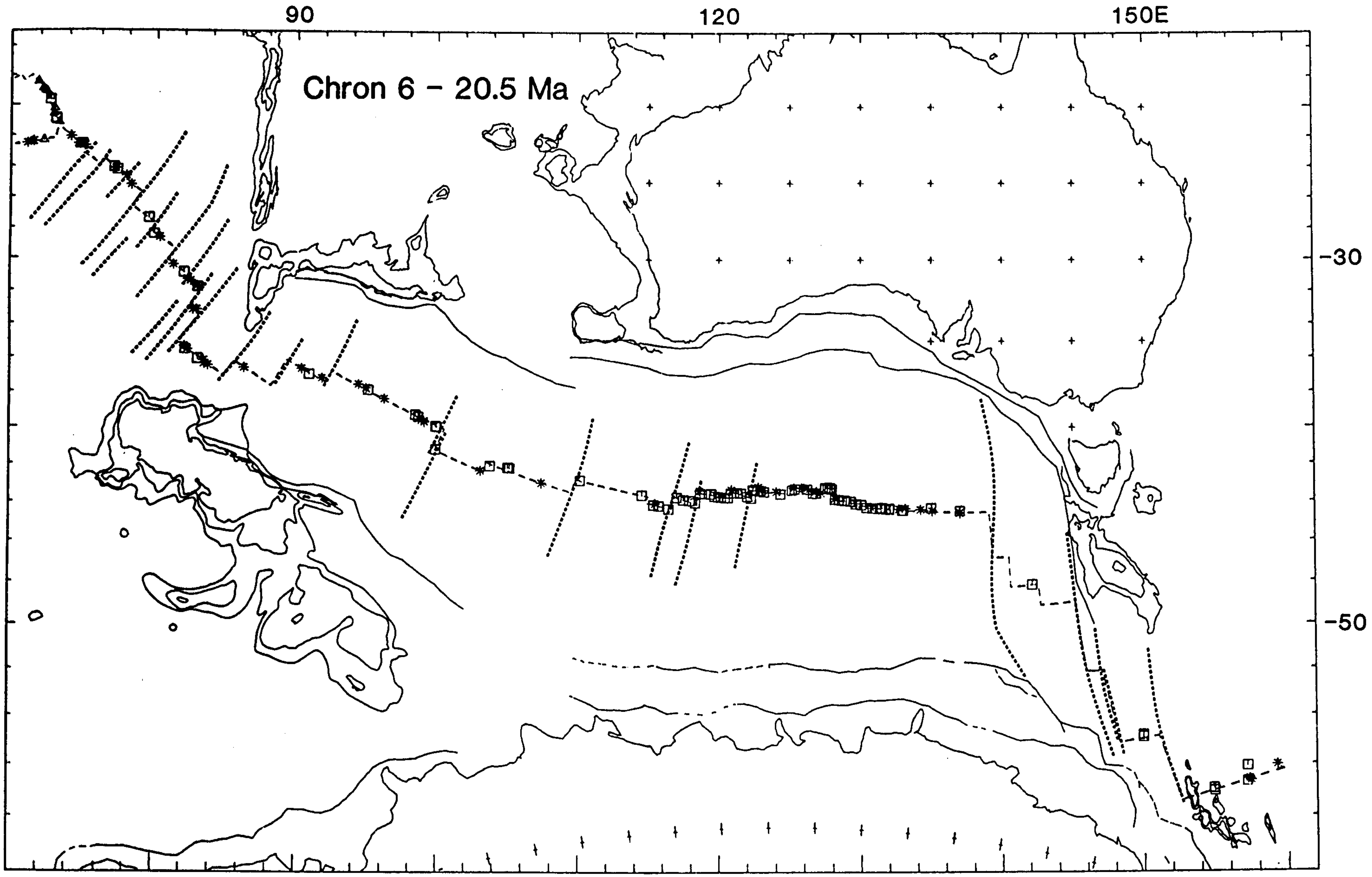


Figure 10B

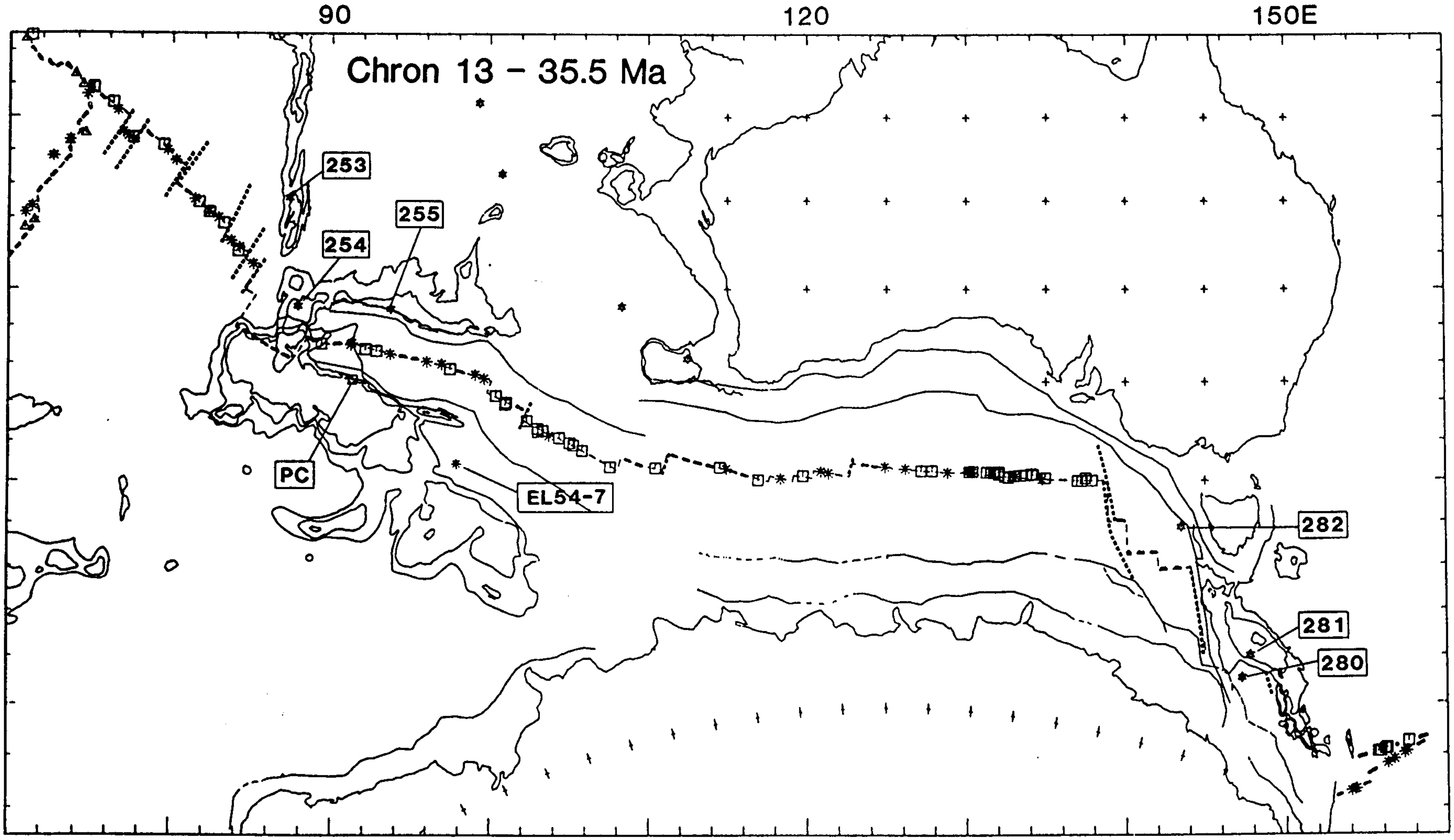

90
120
150E
-30
-50
Chron 13 - 35.5 Ma
253
254
255
PC
EL54-7
282
281
280

Figure 10C

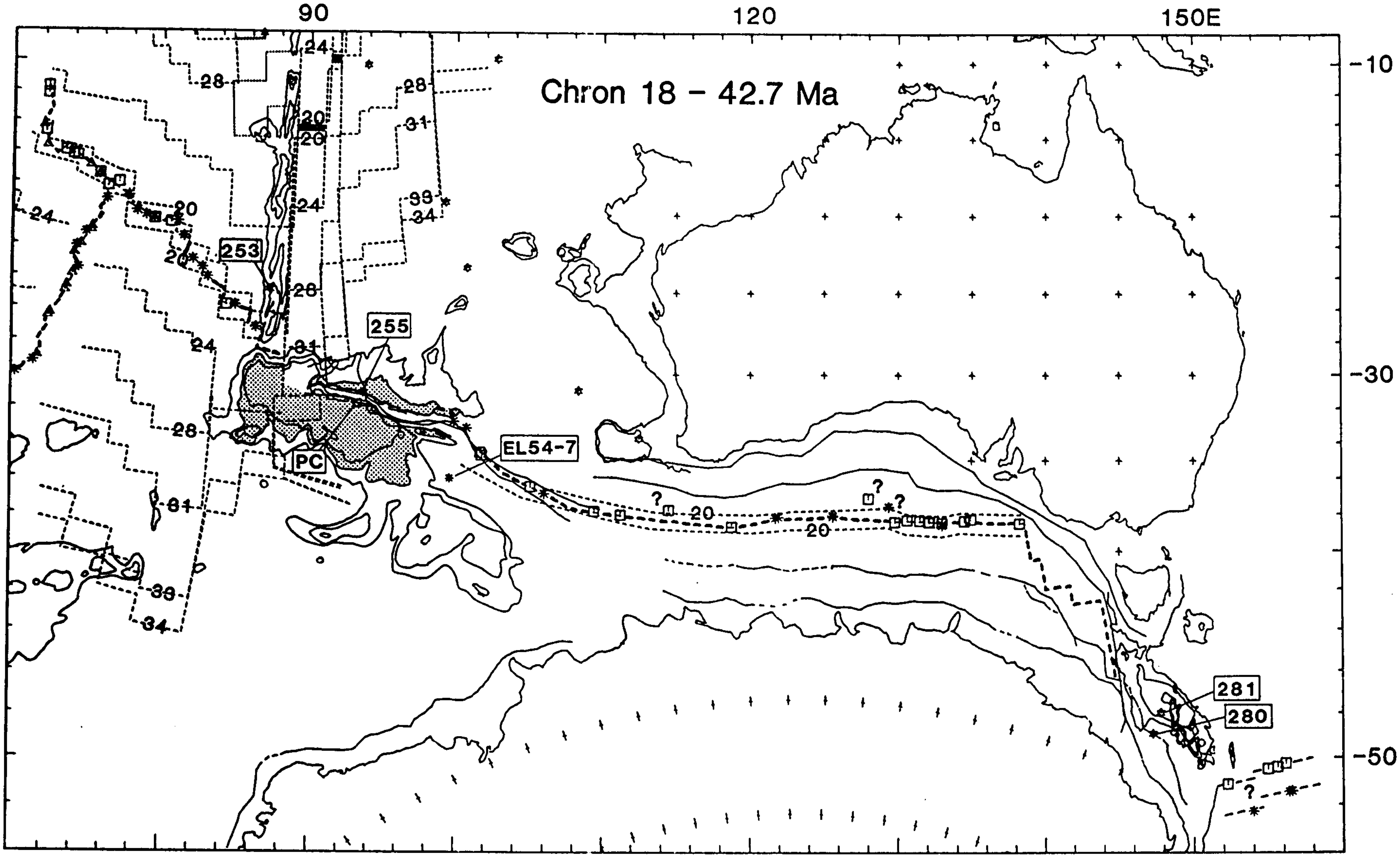

Chron 18 - 42.7 Ma
90
120
150E
-10
-30
-50
253
255
PC
EL54-7
281
280
20
24
28
31
33
34
?

Figure 10D

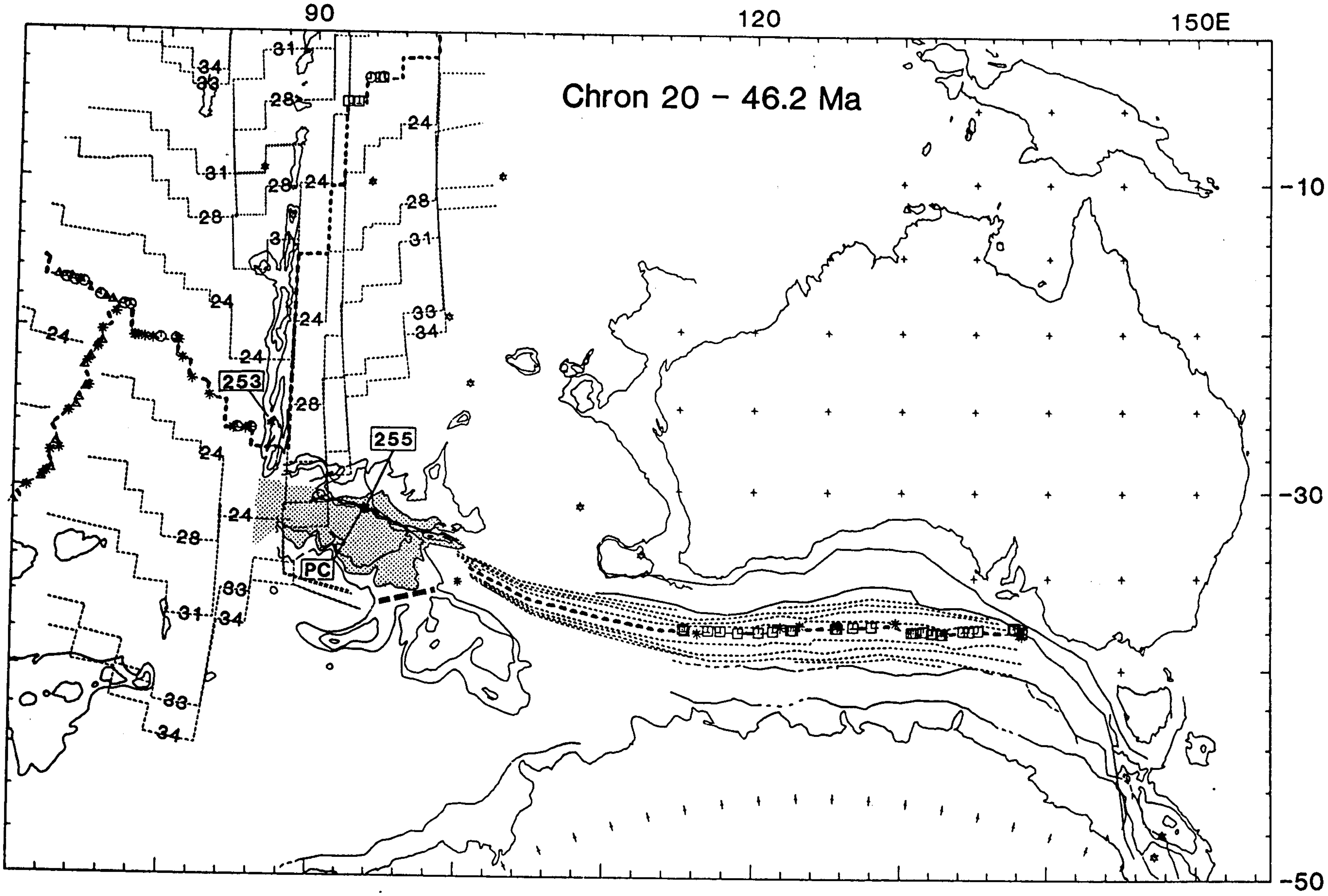

Chron 20 - 46.2 Ma
90
120
150E
-10
-30
-50
31
34
33
28
24
31
28
24
28
31
33
34
253
255
PC
24
28
31
33
34

Figure 11A

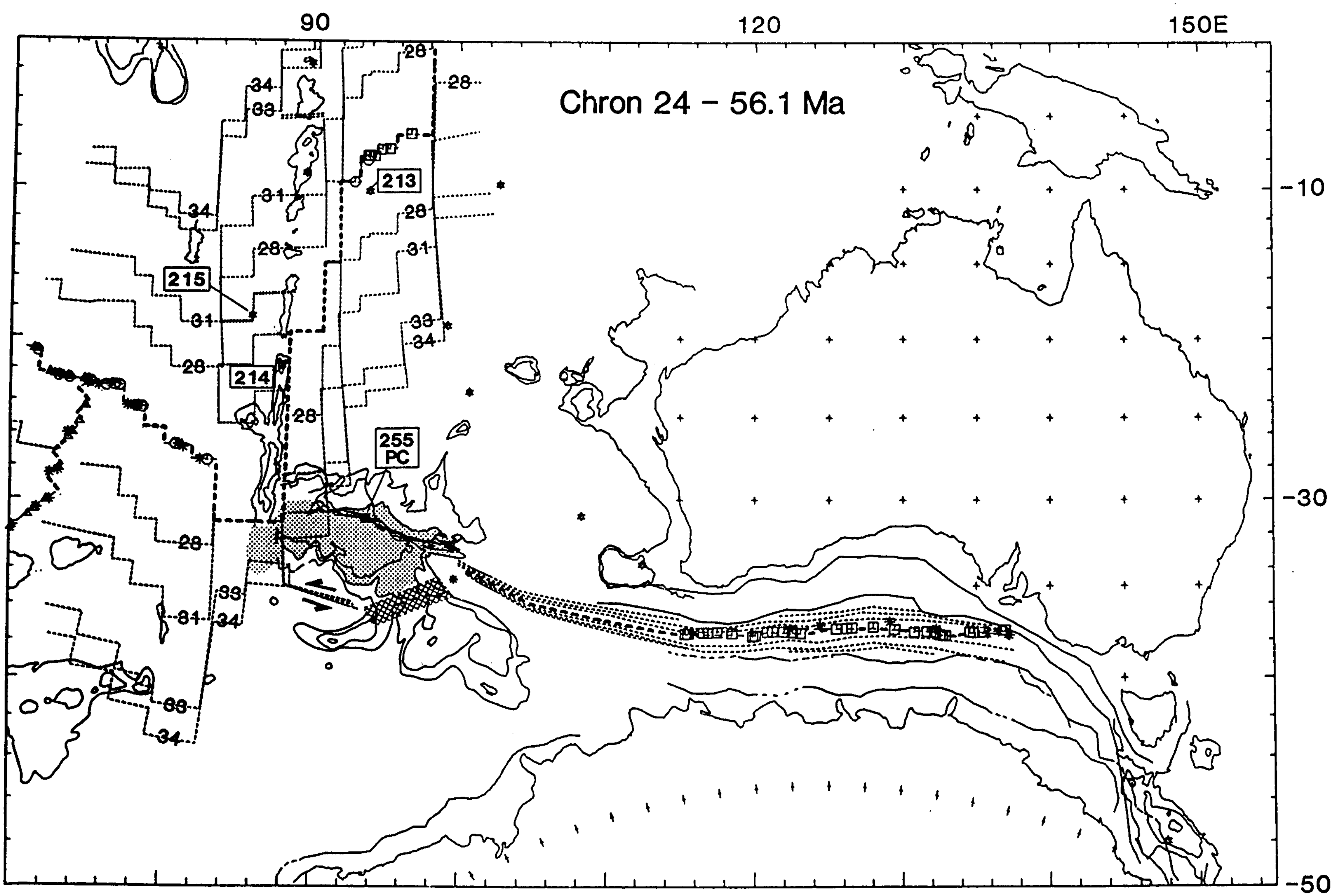

90
120
150E
-10
-30
-50
Chron 24 - 56.1 Ma
28
28
34
33
213
31
28
28
31
34
215
31
33
34
28
214
28
255
PC
28
33
31
34
33
34

Figure 11B

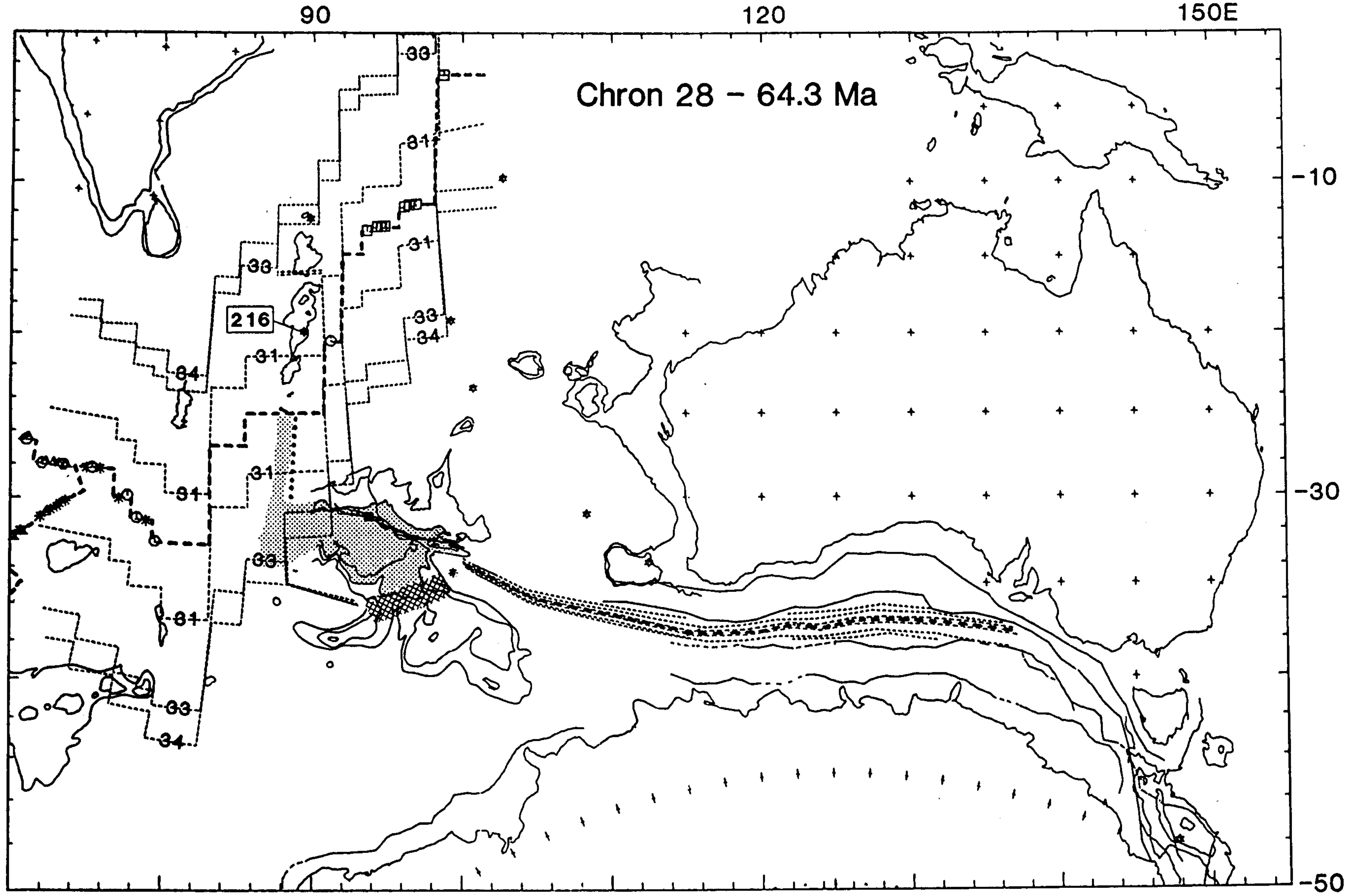


Figure 11C

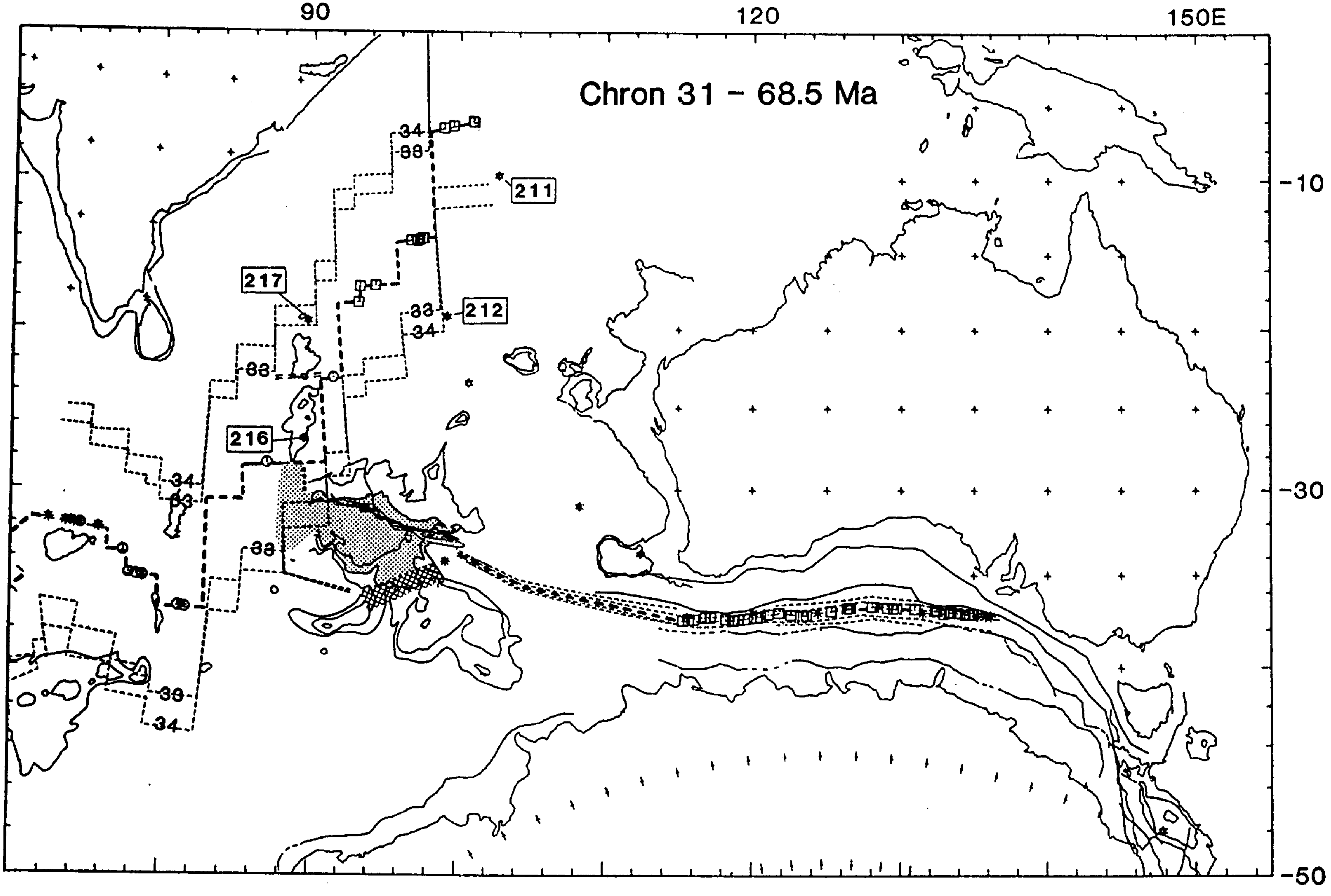

Chron 31 - 68.5 Ma
90
120
150E
-10
-30
-50
211
212
216
217
34
33
33
34
33
34
33
33
33
34

Figure 11D

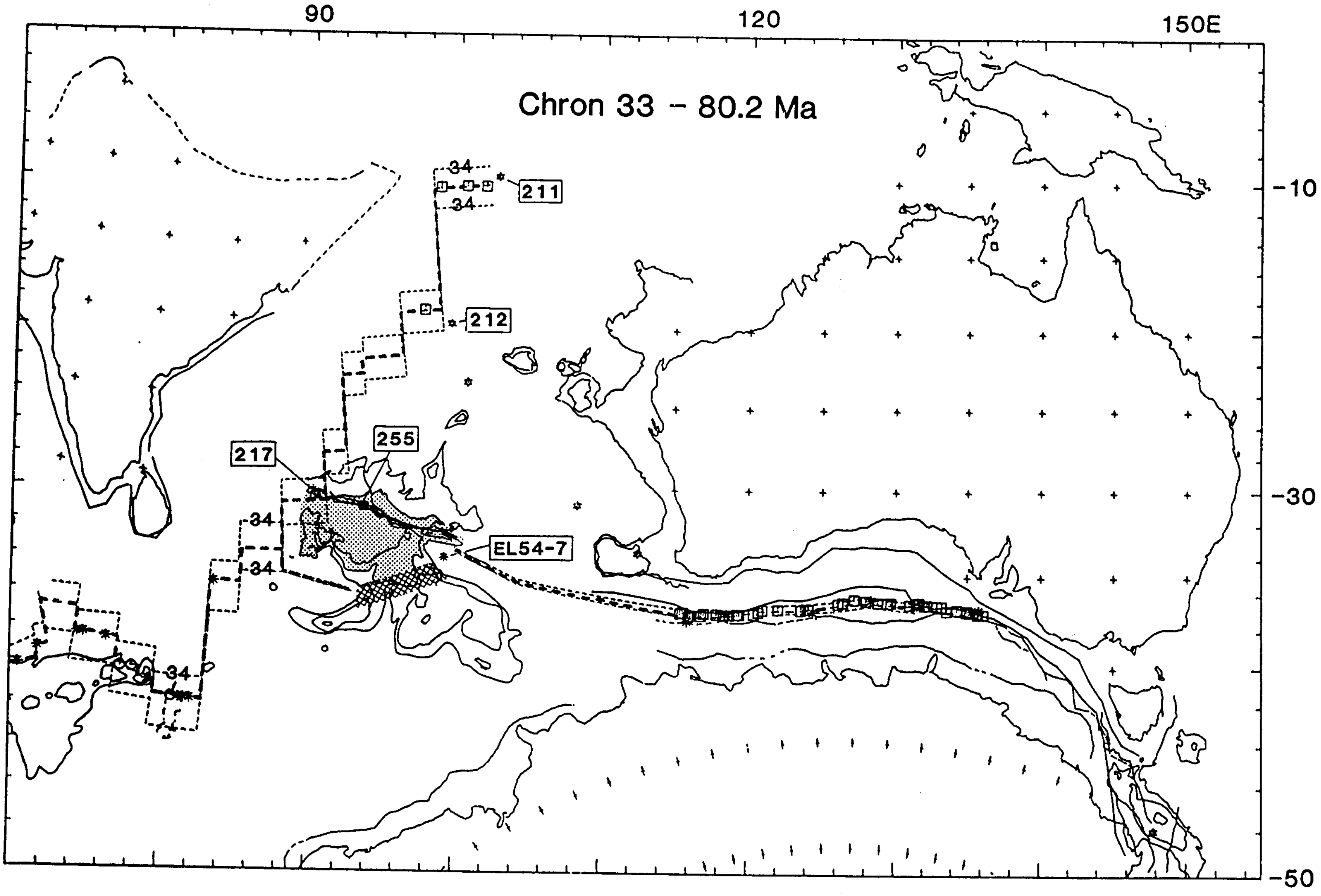

Chron 33 - 80.2 Ma
90
120
150E
-10
-30
-50
211
212
217
255
EL54-7
34
34
34
34
34

Figure 12A

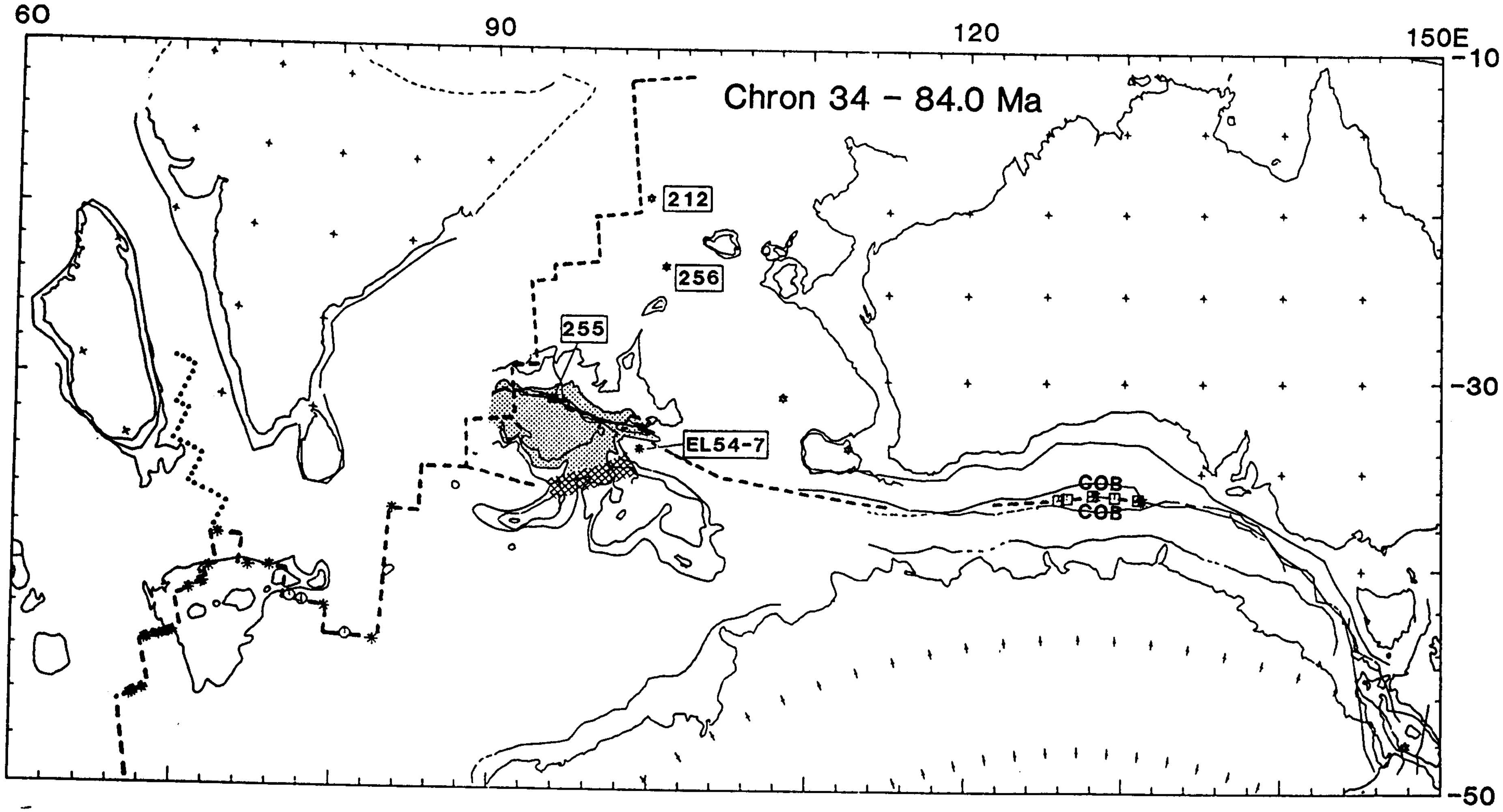
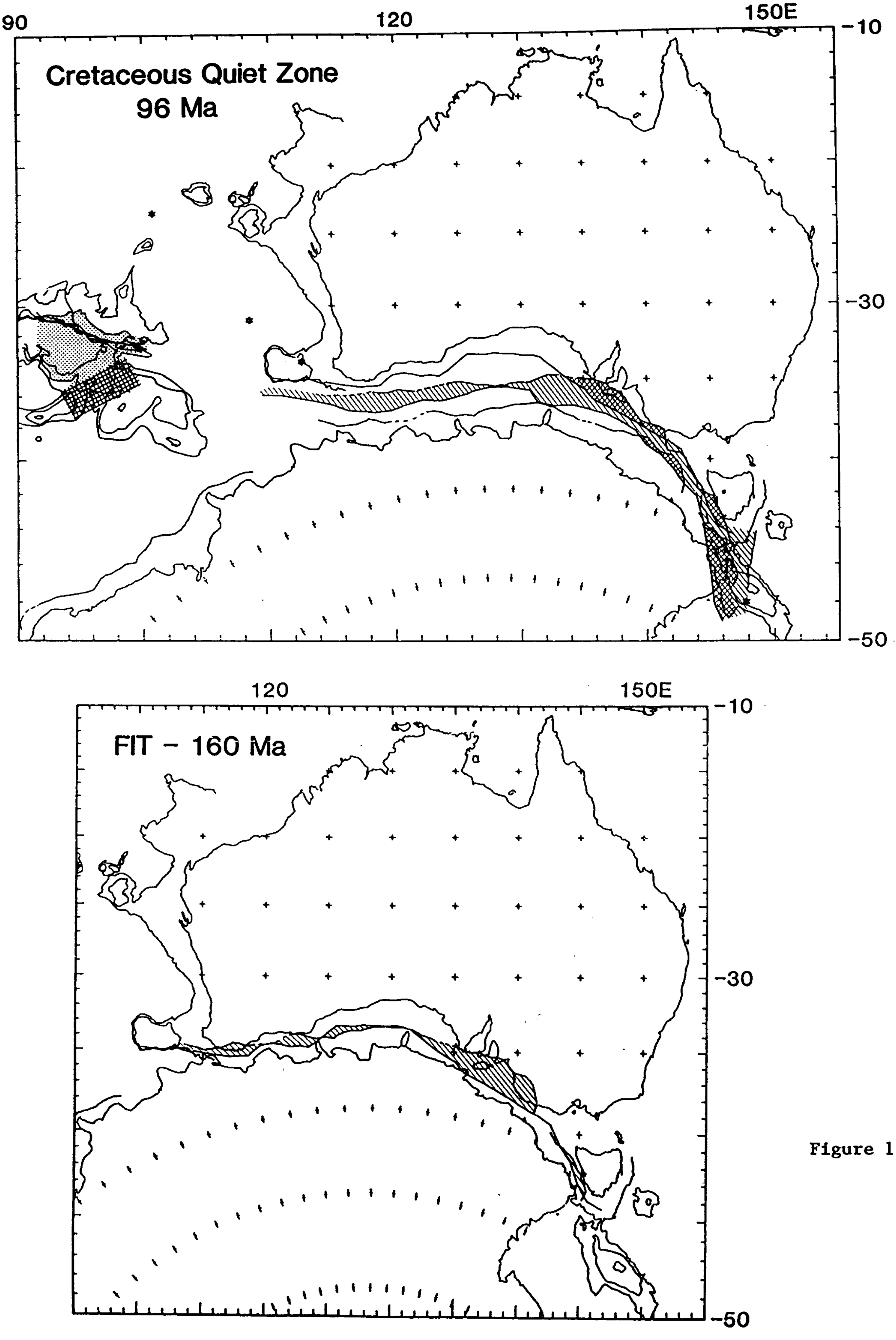


Figure 12B



90
120
150E
-10
-30
-50
Cretaceous Quiet Zone
96 Ma
120
150E
-10
-30
-50
FIT - 160 Ma

Figure 13

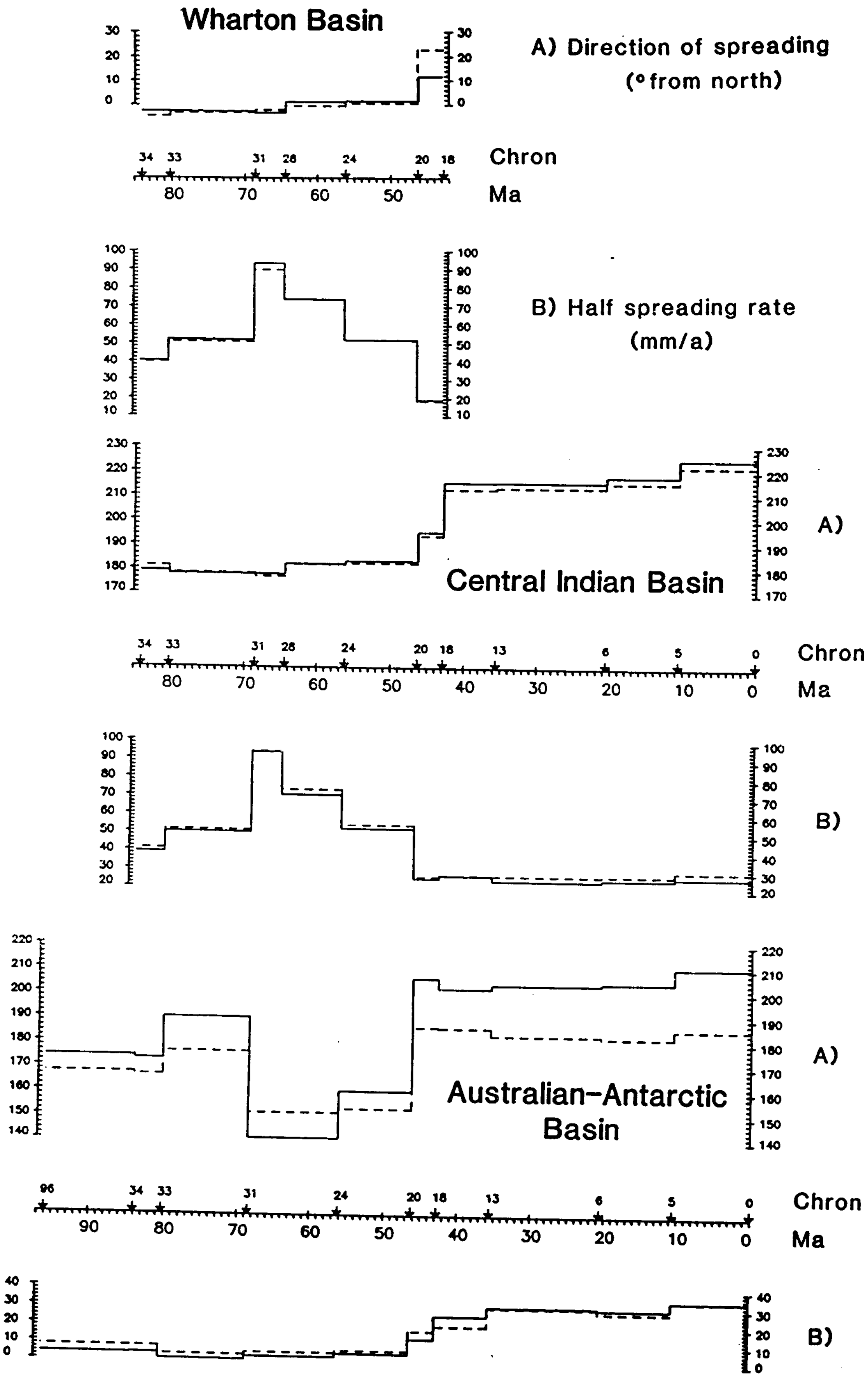
Wharton Basin
A) Direction of spreading
(° from north)
30
20
10
0
Chron
34 33 31 28 24 20 18
Ma
80 70 60 50
B) Half spreading rate
(mm/a)
100
90
80
70
60
50
40
30
20
10
230
220
210
200
190
180
170
A)
Central Indian Basin
Chron
34 33 31 28 24 20 18 13 6 5 0
Ma
80 70 60 50 40 30 20 10 0
B)
220
210
200
190
180
170
160
150
140
A)
Australian-Antarctic
Basin
Chron
96 34 33 31 24 20 18 13 6 5 0
Ma
90 80 70 60 50 40 30 20 10 0
40
30
20
10
0
B)

Figure 14

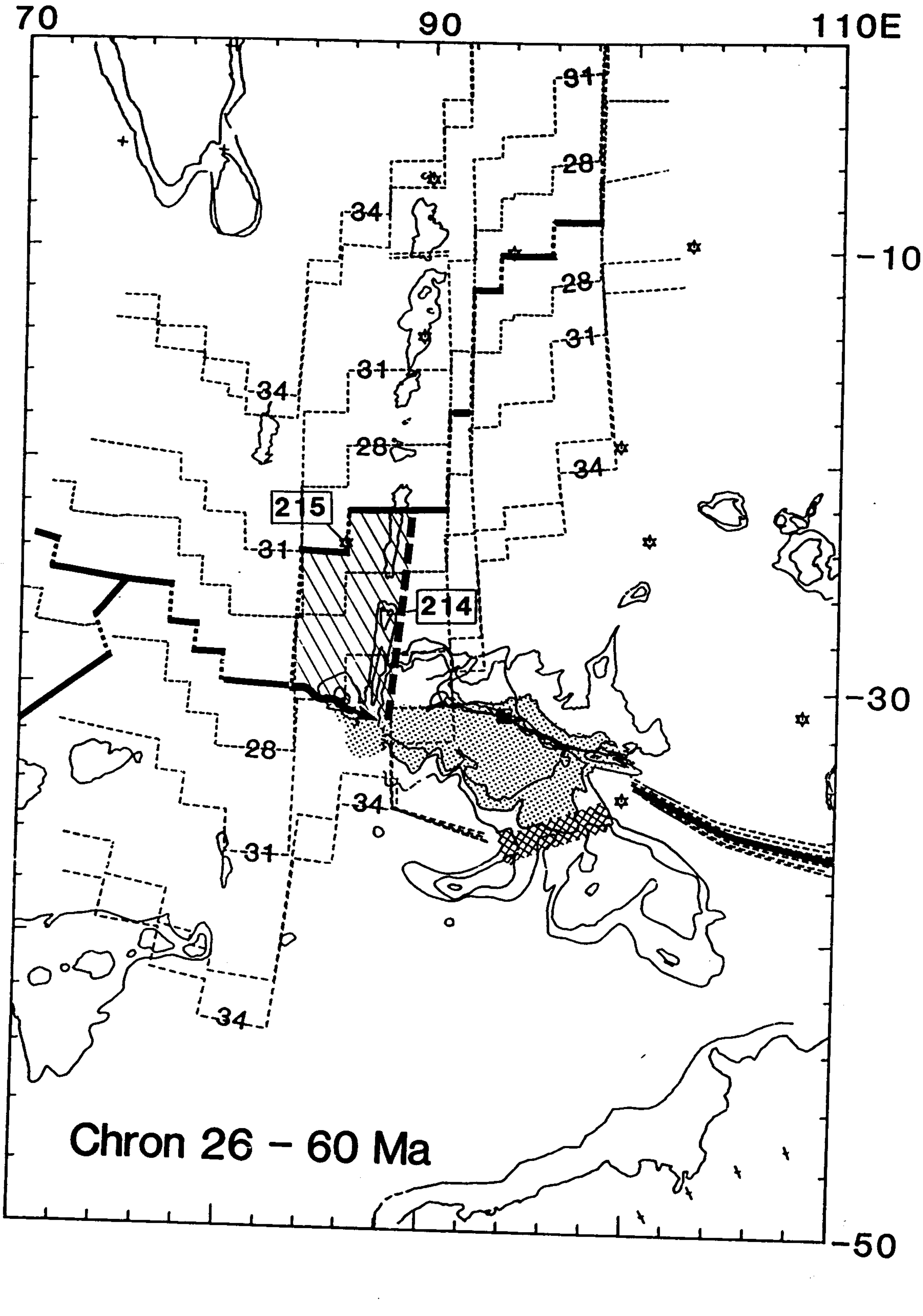

70
90
110E
-10
-30
-50
34
31
28
34
31
28
28
31
34
215
214
31
28
34
31
34
Chron 26 - 60 Ma

Figure 15