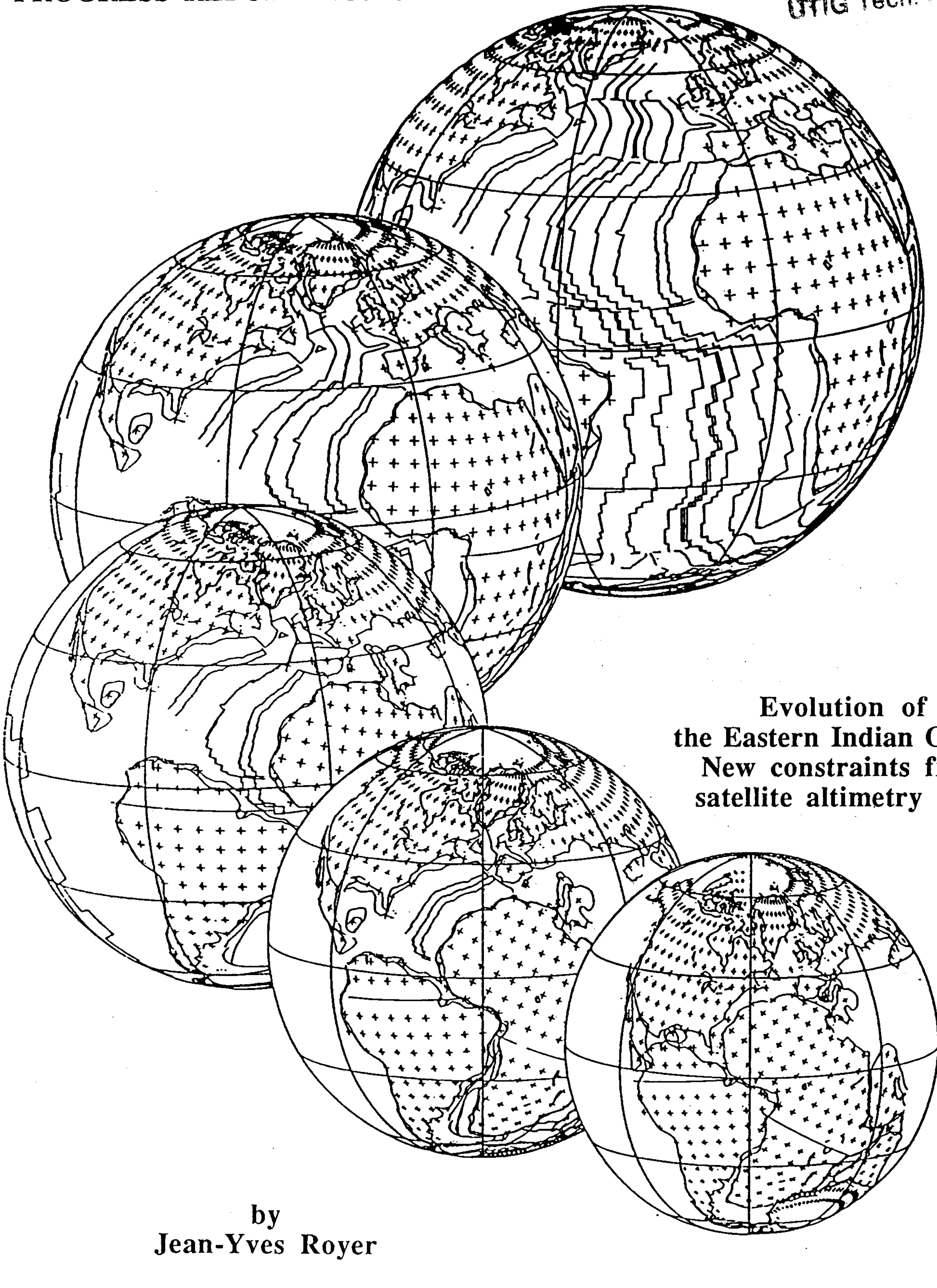
PALEOCEANOGRAPHIC MAPPING PROJECT
PROGRESS REPORT NO. 29-1287



Evolution of the Eastern Indian Ocean: New constraints from satellite altimetry data

by
Jean-Yves Royer

Evolution of the Eastern Indian Ocean since the Late Cretaceous: New constraints from satellite altimetry data.

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Introduction

The opening of the Eastern Indian Ocean resulted in the dispersal of the three main pieces of Eastern Gondwana: India, Australia and East Antarctica. Based on the seafloor magnetic anomaly pattern recognized in the Central Indian Basin, the Crozet Basin, the Wharton Basin and the Australian-Antarctic Basin (Fig. 1), the evolution of the Eastern Indian Ocean can be summarized in three main phases :

- from Late Jurassic to Early Cretaceous: early separation of Antarctica+Australia from Greater India and creation of the Mesozoic Basins along the western Australian margin [Markl, 1974, 1978; Larson et al., 1979; Veevers et al., 1985];
- from Early Cretaceous to Middle Eocene: fast northward drift of India corresponding to the creation of the symmetric Central Indian Basin and Crozet Basin [McKenzie and Sclater, 1971; Schlich, 1982] , opening of the Wharton Basin [Sclater and Fisher, 1974; Liu et al, 1983] and initiation of spreading between Australia and Antarctica [Cande and Mutter, 1982];
- and from Eocene to present: opening of the Australian-Antarctic Basin [Weissel and Hayes, 1972] and of the northern Crozet and southern Central Indian Basins [Schlich, 1975; Sclater et al., 1976] along the Southeast Indian Ridge.

The transition periods, during the Early/Middle Cretaceous (Cretaceous magnetic quiet zone) and Middle Eocene (magnetic anomaly 20 to 18), correspond to important reorganizations of the plate boundaries within the whole Indian Ocean, that are implemented by large ridge jumps and/or drastic changes in the spreading directions and spreading rates.

Evidence of the early evolution of the Eastern Indian Ocean are only documented on the western margins of Australia and are too sparse to build any valid model. To answer this question, one would also need to consider the constraints from the Mesozoic basins in the western Indian

Ocean and the interactions between the other plates involved in the breakup of Gondwana. The next two stages of evolution, from the Late Cretaceous to present day, can be examined independently, and several models have already attempted to describe the relative motions between India, Australia and Antarctica [e.g. McKenzie and Sclater, 1971; Sclater and Fisher, 1974; Duncan, 1978; Norton and Sclater, 1979 ...]. These models, however, can be revised in the light of recent reinterpretations of the ages of the Australian-Antarctic Basin and the northern Wharton Basin, and from new constraints from satellite altimetry data.

Reinterpretations of seafloor magnetic pattern in the Eastern Indian Ocean Basins

The reinterpretation of the seafloor magnetic pattern in the Australian-Antarctic Basin [Cande and Mutter, 1982] has shown that the initiation of seafloor spreading between Australia and Antarctica, previously thought to be of Eocene age [Weissel and Hayes, 1972], actually occurred earlier, in the Late Cretaceous. It has important consequence on the relationship between the Australian-Antarctic Basin and the adjacent basins to the west, and on the fit of the Broken Ridge and Kerguelen Plateau (Fig. 1). Broken Ridge is an east-west plateau that strikes at right angle to the southern tip of the Ninetyeast Ridge and culminates at 1,000 m below sea-level. It is bordered by a steep scarp to the south, facing the Australian-Antarctic Basin and by more gentle slopes to the north, towards the Wharton Basin. The Kerguelen Plateau faces Broken Ridge south of the Southeast Indian Ridge axis and separates the Australian-Antarctic Basin from the Enderby Basin. The very broad relief of the Kerguelen Plateau is capped by the Kerguelen and Heard islands. It extends over more than 2,000 km in a NNW-SSE direction and is about 600 km wide. Without getting into the discussion about the age and nature of these two ridges, several pieces of evidence suggest that both of them were existing in the Late Cretaceous and therefore cannot be overlapped until then. On Broken Ridge, Santonian sediments have been recovered at DSDP site 255 [Davies, Luyendyk et al., 1974]. Several piston cores on the Kerguelen Plateau [Wicquart, 1983] showed sediments of Cenomanian age. The reinterpretation of the chronology of the break-up of Australia and Antarctica partially solves the major problem of overlap between these two ridges [Mutter and Cande, 1983], that resulted from the fit of Australia with Antarctica at the Eocene instead of the Late Cretaceous. However, no attempt has yet been made to include these results in a larger framework.

The Wharton Basin was first interpreted as being the symmetric limb of a basin that subducted under the Java-Sumatra trench [Sclater and Fisher, 1974]. The east-west magnetic lineations decrease in age from the Late Cretaceous (anomaly 33) to the Late Eocene, from south to north towards the trench. Reinterpretations of the magnetic data [Liu et al., 1983] reveal the existence of a Middle Eocene extinct spreading ridge (anomaly 19) that extends southward from the trench to the Ninetyeast Ridge in a succession of offset segments. Although most of the northern lineations have disappeared under the trench, a symmetric pattern of lineations can be identified on either side of the fossil axis, the youngest corresponding to anomaly 20 and the oldest, tentatively, to anomaly 31. The major implication of this pattern is that, prior to anomaly 20 time, the amounts of motion between India, Antarctica and Australia are not independent from one another. This was not the case when only a transform plate boundary was considered between India and Australia. Furthermore, anomaly 19 is about the time when Broken Ridge and Kerguelen Plateau separated and when spreading rates in the Australian-Antarctic Basin drastically increased from 0.5 cm/a (half rate) since anomaly 34 to 2.7 cm/a after anomaly 19 time [Cande and Mutter, 1982].

New constraints from satellite altimetry 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 adequate for outlining the seafloor tectonic fabrics and have provided new constraints to reappraise or improve plate tectonic models [e.g. Royer et al., 1988; Cande et al., 1988]. The recent release of the Geosat data [Sandwell and McAdoo, 1988] significantly increases the amount of information on the poorly charted oceans south of 60°S, since this satellite completed its mission mostly during the ice-free austral summer. The seafloor tectonic fabrics and the main structural features of the ocean floor are here derived from the deviation of the vertical data or first derivative of the ocean-geoid signal (Fig. 2 and 3).

Figure 4A presents some examples of interpretation of the deflection of the vertical. The combination of the information from the ascending and descending passes permits the accurate delineation of the most prominent features of the ocean floor such as fracture zones, seamounts, 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, these features can be precisely mapped (Fig. 4B). The best illustration of the schematic diagram of Figure 4B is the Balleny Fracture Zone that runs from the South Tasman Rise to the Balleny Islands (Fig. 1, 3 and 5) .

The tectonic features outlined by the Geosat data provide new and strong constraints on plate tectonic reconstructions and closure of the Australian/Antarctic Basin. Theses features are from east to west:

1) The large offset fracture zones south of Tasmania that can now be traced all the way south into the Antarctic margin (Fig. 5). The long and continuous George V, Tasman and Balleny fracture zones tightly constrain the longitudinal motions of Australia relative to Antarctica at least until the Middle Eocene (anomaly 18-20).

2) The possible location of the Antarctic continent-ocean boundary (COB). On the Australian margin, Veevers [1986] mapped the COB by correlating seismic data with what Cande and Mutter [1982] recognized as magnetic anomaly 34. It corresponds to the magnetic anomaly peak that bound the magnetic quiet zone bordering the Australian continental margin. This limit corresponds to 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 (100°E) to the south of Tasmania (145°E). The slope of the continental shelf itself is expressed on Figure 6 by the deepest trough on the deflection of the vertical (or steepest descending slope of the geoid), parallel to the Australian coastlines. It also matches with the rapid deepening of the bathymetry [GEBCO chart 5·10, Monahan et al., 1982]. The width of the zone between the COB and the continental slope varies exactly with that of the magnetic quiet zone (figure 1 from Cande and Mutter [1982]). This zone narrows east of 138°E as the two boundaries curve towards the south. On the conjugate Antarctic margin, the seismic control points as well as the magnetic evidence are more limited. Nevertheless, the same criteria that characterizes the Australian COB on the deflection of the vertical data can be applied; the COB is defined by the first negative peak of the deviation of the vertical that lies 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 Veevers [1986] seismic control point at 132°E, but differs significantly from his tentative interpretation further east. Our interpretation agrees with the limit of the magnetic quiet zone presented in Cande and Mutter [1982] paper. West of 120°E, although the geoid signal does not show the same systematic and characteristic pattern, the COB can tentatively be extended as far as 100°E, and is obscured further west by the rise associated with the Southern Kerguelen Plateau. The Antarctic shelf edge can be located the same way as for Australia, by following the first highest peak of the deflection of the vertical (or steepest slope of the geoid) off the coastlines (Fig. 7). Similarly to Australia, the limit of the continental shelf runs parallel to the coastlines. However, east of Terre Adélie and off George V Land, the two boundaries diverge and a large basin is clearly visible behind the steep slope interpreted as the limit of the continental shelf.

This strongly favors the hypothesis that this deep basin is underlain by continental crust. Due to the ice-coverage, this area is still poorly surveyed [e.g. GEBCO chart 5·14, Falconer and Tharp, 1981], and only the eastern part of this basin has yet been mapped [Domack and Anderson, 1983]. Going east from 100°E, the Antarctic COB and continental margin are nearly parallel to one another and 120 to 170 km apart. East of 133°E, the two lines diverge and outline a broader zone of "transitional" crust stretched over more than 200 km. On the descending passes (Fig. 7), the COB probably corresponds to the large negative trough of the deflection of the vertical and seems to curve into the continental slope at 150°E. The eastern boundary of this zone lines up with the termination of George V Fracture Zone. Further east, the COB does not look as straight as its counterpart west of Tasmania, but apparently follows a kind of stair-shaped curve. It is emphasized that due to the orbit of the satellite which is tangent to the 72°S Parallel, the data are about twice as dense along the Antarctic margin than along the Australian margin. The sections of COB parallel to the continental shelf may correspond to areas of shear motions between Australia and Antarctica, and the perpendicular sections to areas of stretching.

3) The rifted margin of Kerguelen Plateau that was already clearly visible on the Seasat data [Coffin et al., 1986]. The Geosat data permit the extension, by a few 100 km to the south, of what Coffin et al. [1986] have identified as a "basement offset" (Fig. 8). The particular shape of the northeastern edge of the Kerguelen Plateau, which shows a pronounced bend corresponding to the William's Ridge, is exactly reproduced along the Broken Ridge scarp (Fig. 6). This puts a major constraint on the relative position of the two ridges at the time when they broke apart.

4) The counterpart of the Diamantina Zone between 93° and 105°E (Fig. 1 and 8) that presents the same rugged topography associated with the slow spreading episode between anomaly 34 (84 Ma) and anomaly 20 time (46 Ma) [Cande and Mutter, 1982].

Finally, numerous fracture zones show on the Geosat data (ascending lines mostly, Fig. 2) along the Southeast Indian Ridge. Some of them were already mapped with great detail from sea-surface ship tracks, such as in the Crozet Basin, the southern Central Indian Basin or in the area of the Australian-Antarctic Discordance [e.g. Schlich, 1975; Sclater et al., 1976; Patriat, 1983; 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. 3).

Preliminary reconstructions of the Eastern Indian Ocean

From the above results, new reconstructions of the Eastern Indian Ocean can be proposed. These reconstructions are mainly based on magnetic anomaly identifications presented in earlier compilations regarding the Eastern Indian Ocean (Fig. 9). However, a special concern has been borne in homogenizing the magnetic anomaly picking relative to time. This is particularly important when the spreading rates are fast as in the Wharton Basin (11 to 4 cm/a), but is of less consequence in the case of slow spreading rates, such as between Australia and Antarctica from the Late Cretaceous to the Middle Eocene (0.5 to 1.0 cm/a).

In the Crozet and Central Indian basins, magnetic anomaly picks are from Patriat [1983] and Royer and Schlich [1988]. In the Wharton Basin, the profiles of total intensity magnetic anomaly have been reinterpreted in the interest of maintaining consistency within the data set. In the Australian-Antarctic Basin magnetic data are from Stock and Molnar [1982], Cande and Mutter [1982], Vogt et al. [1983] and Veevers [1986]. Additional identifications of magnetic anomalies between Kerguelen and Broken Ridge have been made from data published by Tilbury [1981].

Figures 10 to 18 illustrate the configurations of the Eastern Indian Ocean at chron 18 (43 Ma), chron 20 (46 Ma), chron 24 (56 Ma), chron 28 (64 Ma), chron 31 (69 Ma), chron 33 (80 Ma), chron 34 (84 Ma), and the closure of the continent/ocean boundary along with a revised fit of Australia and Antarctica. Parameters of the finite rotations are given in Table 1. Anomaly 18 time (43 ma) is the time when seafloor spreading between the Kerguelen Plateau and Broken Ridge initiated (Fig. 10). A tighter and still reasonable fit (Fig. 11) of these two ridges can be obtained when considering the Southeast Indian Ridge as a single plate boundary at chron 20 (46 Ma), although the spreading ridge in the Wharton Basin was still active at that time (seafloor spreading ceased at anomaly 19/18 time). Motions between Australia and Antarctica prior to anomaly 20 require the splitting of the Kerguelen Plateau in two pieces: one attached to Broken Ridge, or the Australian Plate, and the other moving with the Antarctic plate. Gravity and seismic studies [Houtz et al., 1977; Ramsay et al., 1986; Coffin et al., 1986] show that three different provinces can be recognized on the Kerguelen Plateau: a northern province lying between the Kerguelen and Heard islands with NW-SE horsts and grabens, an intermediate province with N-S oriented grabens and a southern province comprising the Elan and Banzare banks (Fig. 1), and characterized by another set of NW-SE horsts and grabens and a different gravity signature from that of the northern province. According to seismic stratigraphy interpretations of the northern Kerguelen Plateau [Munschy and Schlich, 1987], faulting in the northern province started 100 Ma ago (Middle Cretaceous) and lasted until the break-up of Kerguelen Plateau and Broken Ridge (43 Ma, Middle

Eocene). The boundary inferred by the reconstruction model may correspond to the intermediate province, where tectonic trends contrast with those from the northern and southern Kerguelen Plateau, which are parallel to the eastern scarps of the plateau and to the seafloor magnetic anomaly pattern. Furthermore, the decoupling between the northern and the southern Kerguelen Plateau allows for the closure of the conjugate Labuan and Diamantina basins (Fig. 1).

Reconstructions at chron 33 (Fig. 15) and 34 (Fig. 16) confirm that the continent/ocean boundaries (COB) along the Australian and Antarctic margins are not isochrons as Veevers [1986] suggested. East of 140°E and all way south of Tasmania, the COBs fit almost synchronously at anomaly 33 time (80 Ma). Between 130° and 140°E, the anomaly 33 lineation and the COB coincide. West of 120°E, the COBs come in contact only at chron 34 (84 Ma). Accretion of oceanic crust between Australia and Antarctica initiated in the Great Australian Bight where the oldest magnetic anomalies (34) are identified, and probably propagated first to the west and then to the east. Veevers [1986] extrapolated the age of anomaly 34 to date the oldest part of the COB in the Great Australian Bight at 96 Ma. Figures 17 and 18 show possible fit of the COBs and continental margins that have been derived from the Geosat data (Fig. 6 and 7). Since the COBs are not isochrons, it is not surprising that the reconstruction of Figure 17 produces overlaps on either side of the Great Australian Bight, and it almost closes the Labuan/Diamantina basin. On Figure 18, overlaps between the COB and the continental shelves appear where the Geosat data show evidence for stretched crust (e.g. George V Basin). It is worth noting that the new fit of Australia and Antarctica put the George V Basin delineated on the Geosat data in the direct prolongement of the Bass Basin between Tasmania and the main land.

Conclusion

The reinterpretation of the age of break-up of Australia and Antarctica, along with the reidentification of the magnetic anomalies in the northern Wharton Basin and the interpretation of the Geosat satellite altimetry data in the Southern Ocean have led to a more consistent model of evolution for the Eastern Indian Ocean since the Late Cretaceous. The fit of Kerguelen Plateau and Broken Ridge is especially improved in this model, as well as the closure of the Australian-Antarctic Basin which requires that from the Late Cretaceous to the Middle Eocene (chron 24/20) the northern and southern province of the Kerguelen Plateau were two different entities. It is of interest to note the vicinity of these two features and the Naturaliste Plateau in the Late Cretaceous, indicating that they may be related genetically and may have the same age. The synthesis of this new model with the models for the Central Indian Ocean [Patriat and Ségoufin, 1988] and the

Southwestern Indian Ocean [Royer et al., 1988 or POMP report #25] will now provide a strong and new basis from which to address the question of the early evolution of the Indian Ocean.

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Table 1: FINITE ROTATIONS

***** ANTARCTICA/INDIA *****

Chron	Age	Lat.	Lon.	Angle	
5	10.50	12.50	36.70	6.62	AUS=IND
6	20.50	14.50	32.80	11.98	AUS=IND
13	35.50	13.40	32.70	20.40	AUS=IND
18	42.70	16.60	29.90	23.62	AUS=IND
20	46.20	15.20	28.90	25.27	
24	56.10	12.80	21.90	34.48	(1)
28	64.30	11.10	15.40	44.24	(1)
31	68.50	9.40	13.70	51.59	(1)
33	80.20	9.30	9.30	61.55	
34	84.00	8.00	9.90	64.74	

(1) from Patriat [1983]

***** ANTARCTICA/AUSTRALIA *****

Chron	Age	Lat.	Lon.	Angle	
5	10.50	12.50	36.70	6.62	
6	20.50	14.50	32.80	11.98	
13	35.50	13.40	32.70	20.40	
18	42.70	16.60	29.90	23.62	
20	46.20	14.80	30.90	24.33	
24	56.10	13.80	30.50	25.32	
31	68.50	9.00	33.50	25.83	
33	80.20	6.10	35.20	26.37	
34	84.00	4.80	35.90	26.81	
COB	96.00	1.00	38.00	28.30	closure of COB
FIT	160.00	-2.20	38.90	31.50	

***** AUSTRALIA/INDIA *****

Chron	Age	Lat.	Lon.	Angle
19	45.00	90.00	.00	.00
20	46.20	10.60	-13.00	1.27
24	56.10	3.20	2.60	10.12
28	64.30	2.90	-3.70	20.99
31	68.50	1.30	-2.10	28.50
33	80.20	1.60	-6.20	39.37
34	84.00	.40	-4.70	42.14

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 profiles plotted along the Geosat ascending passes.

Figure 3: Deflection of the vertical profiles plotted along the Geosat descending passes.

Figure 4: A) Signature of the deflection of the vertical 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 Zone, 3) Balleny Fracture Zone.

Figure 6: Identification of the rifted margin of Broken Ridge, the continent-ocean boundary and the shelf-edge of Australia on the Geosat descending passes.

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

Figure 8: Rifted margin of the Kerguelen Plateau and counterpart of the Diamantina Zone on the Geosat descending passes. 1) Labuan Basin, 1) + 2) counterpart of the Diamantina Zone.

Figure 9: Summary tectonic diagram of the Eastern Indian Ocean.

Figure 10: Reconstruction at chron 18 (43 Ma). 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.

Figure 11: Reconstruction at chron 20 (46 Ma). Same symbols as Fig. 10. DSDP sites are located by stars.

Figure 12: Reconstruction at chron 24 (56 Ma). See Fig. 10 for symbols.

Figure 13: Reconstruction at chron 28 (64 Ma). See Fig. 10 for symbols.

Figure 14: Reconstruction at chron 31 (69 Ma). See Fig. 10 for symbols.

Figure 15: Reconstruction at chron 33 (80 Ma). See Fig. 10 for symbols.

Figure 16: Reconstruction at chron 34 (84 Ma). See Fig. 10 for symbols.

Figure 17: Closure of the Australian-Antarctic Basin at 96 Ma (oldest part of the continent/ocean boundary).

Figure 18: New fit of the continental margins of Australia and Antarctica based on the Geosat data interpretation.

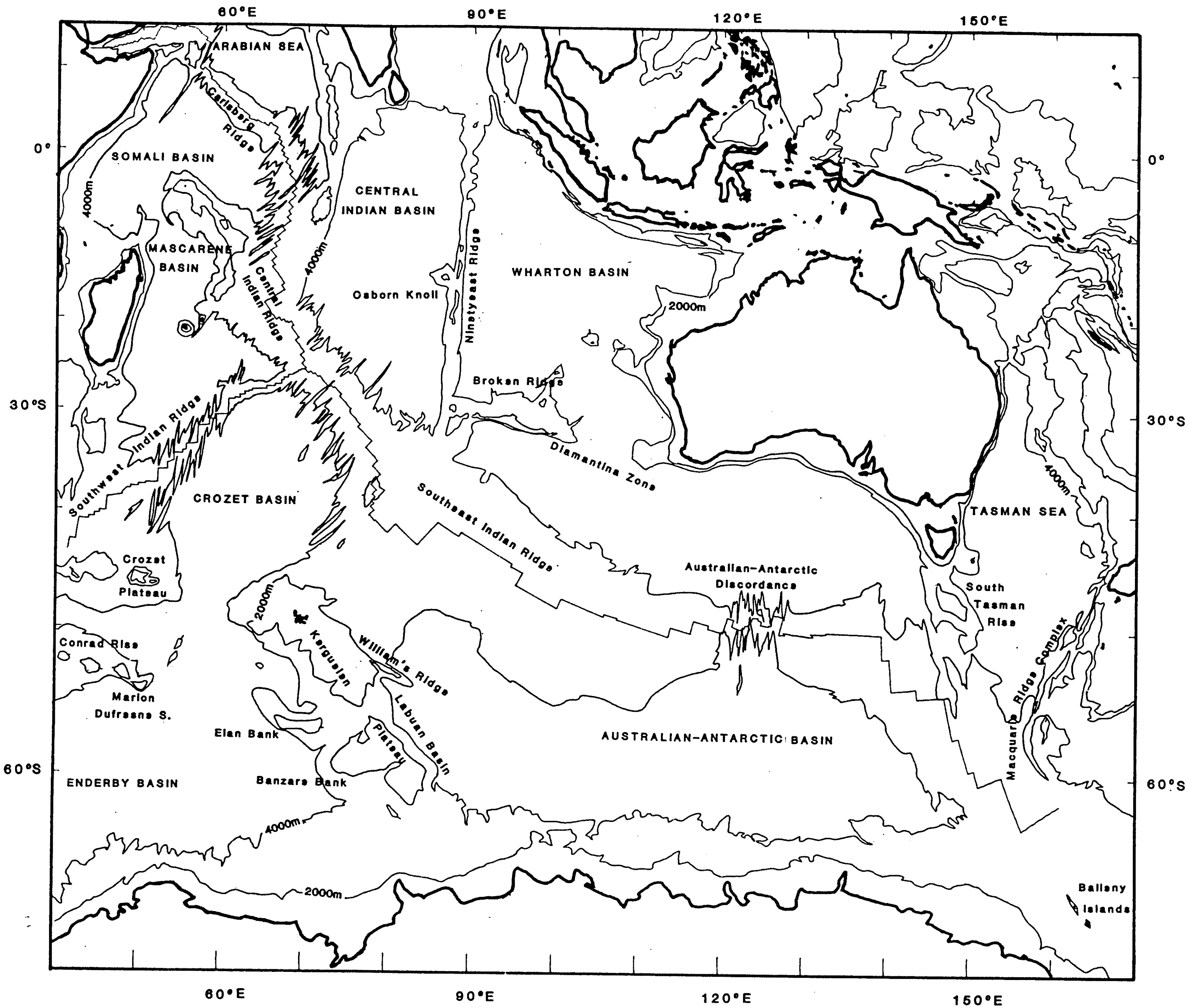

60°E
90°E
120°E
150°E
0°
30°S
60°S
ARABIAN SEA
Carlsberg Ridge
SOMALI BASIN
4000m
MASCARENE BASIN
Central Indian Ridge
CENTRAL INDIAN BASIN
4000m
Osborn Knoll
Ninetyeast Ridge
WHARTON BASIN
2000m
Broken Ridge
Diamantina Zone
Southwest Indian Ridge
CROZET BASIN
Southeast Indian Ridge
Crozet Plateau
Conrad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

Figure 1

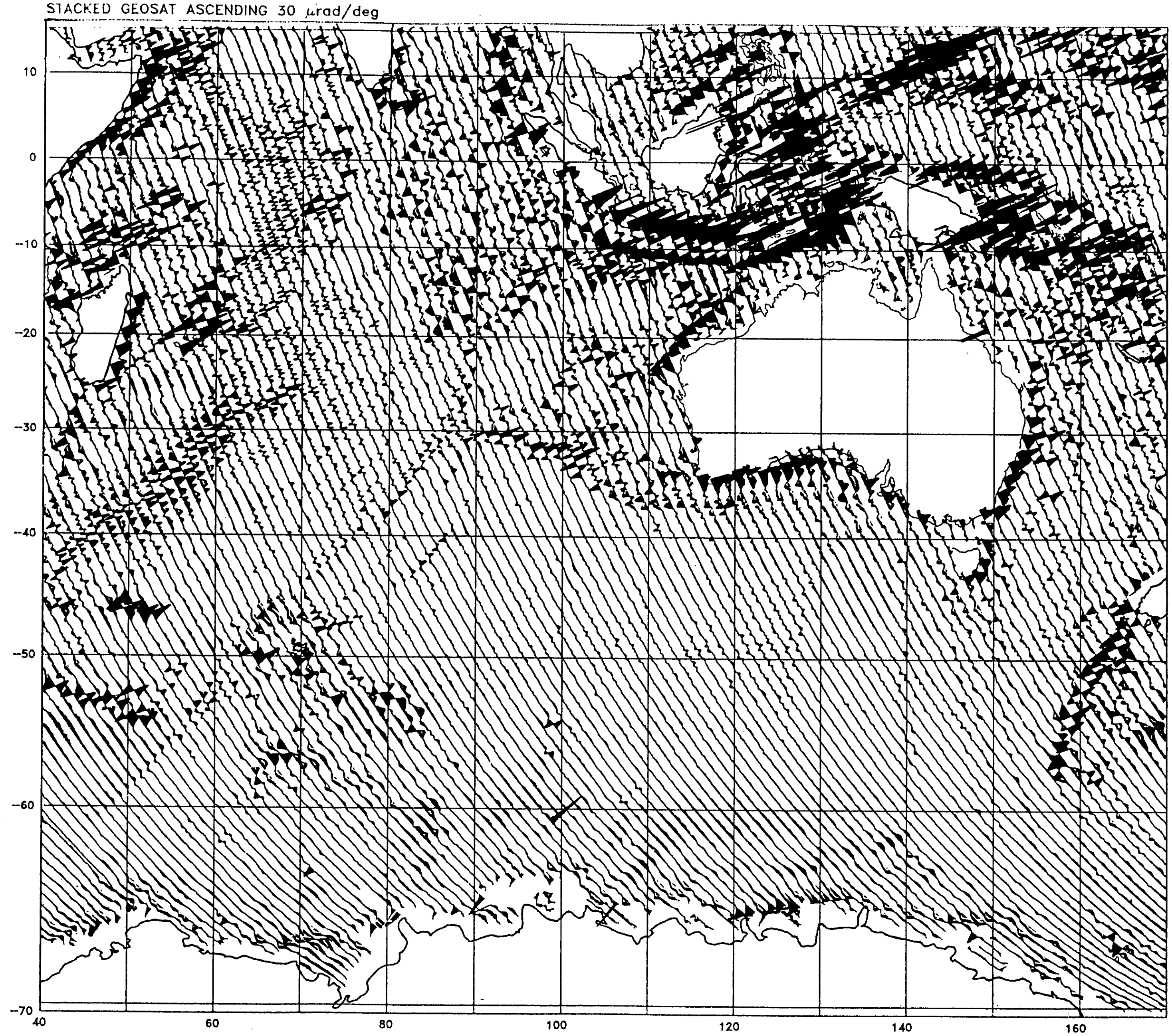

STACKED GEOSAT ASCENDING 30 μrad/deg
10
0
-10
-20
-30
-40
-50
-60
-70
40
60
80
100
120
140
160

Figure 2

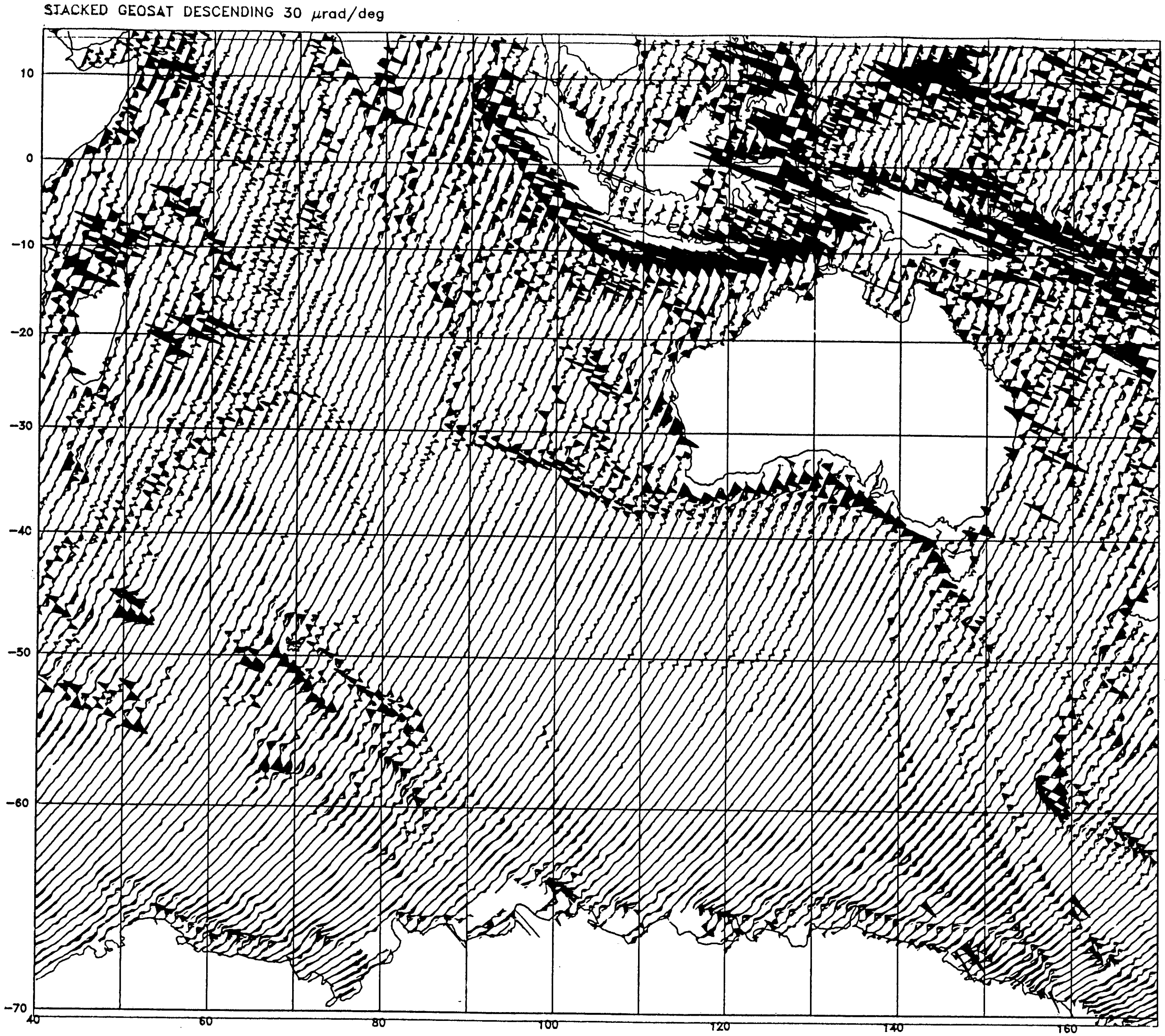

STACKED GEOSAT DESCENDING 30 µrad/deg
10
0
-10
-20
-30
-40
-50
-60
-70
40
60
80
100
120
140
160

Figure 3

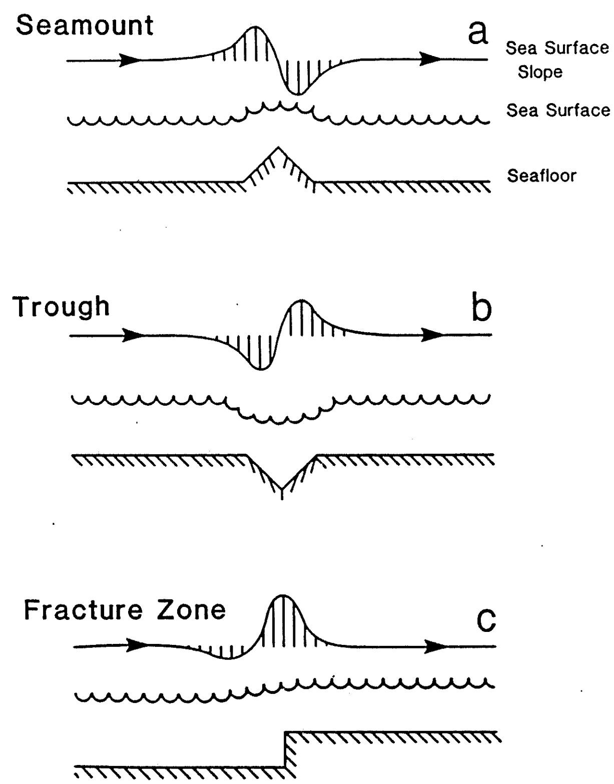


Figure 4A

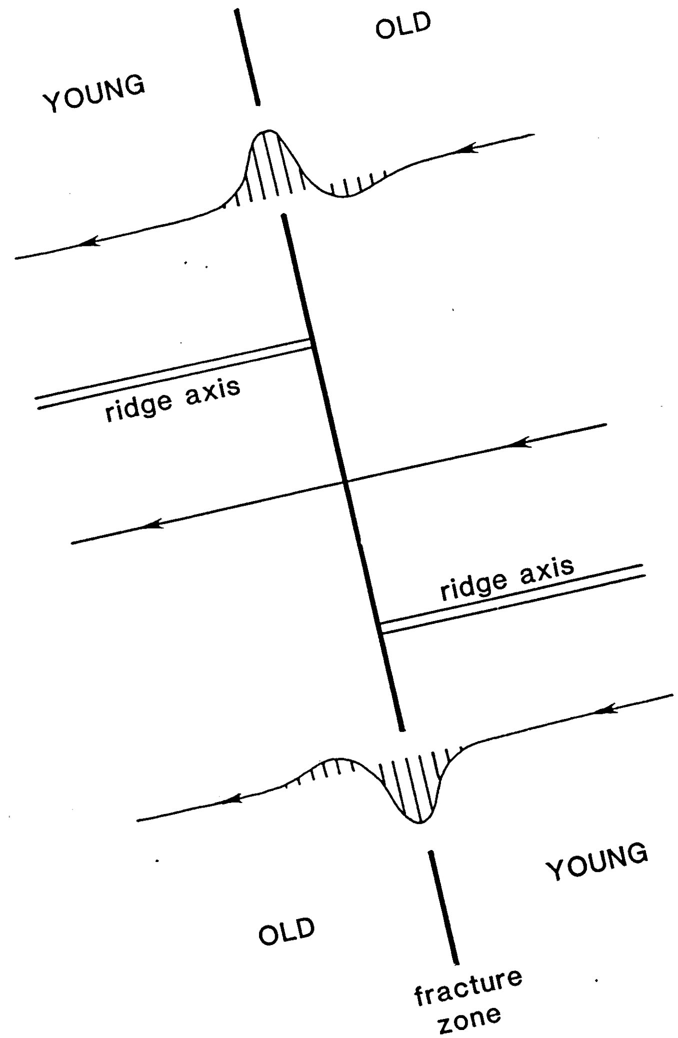


Figure 4B

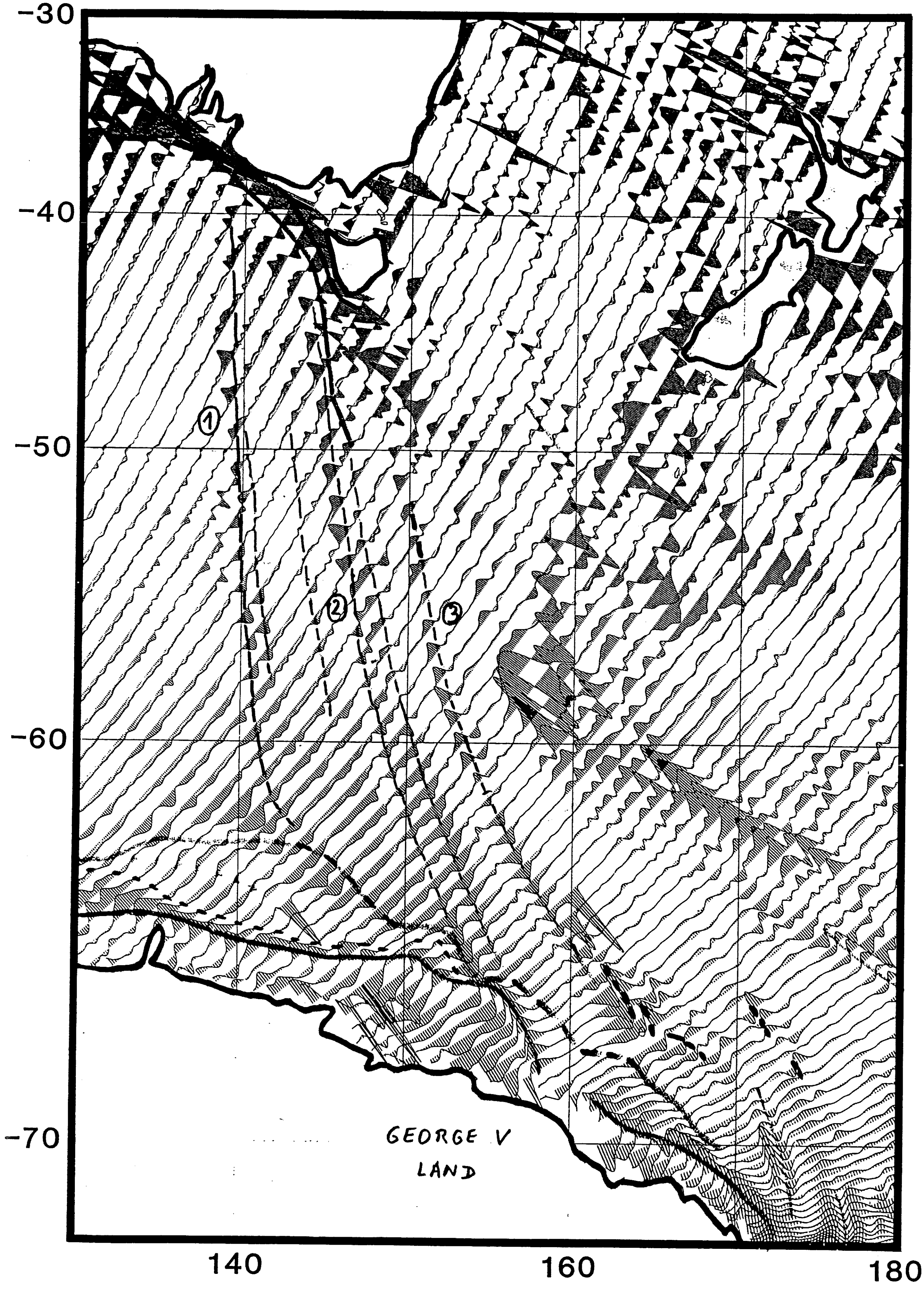


Figure 5

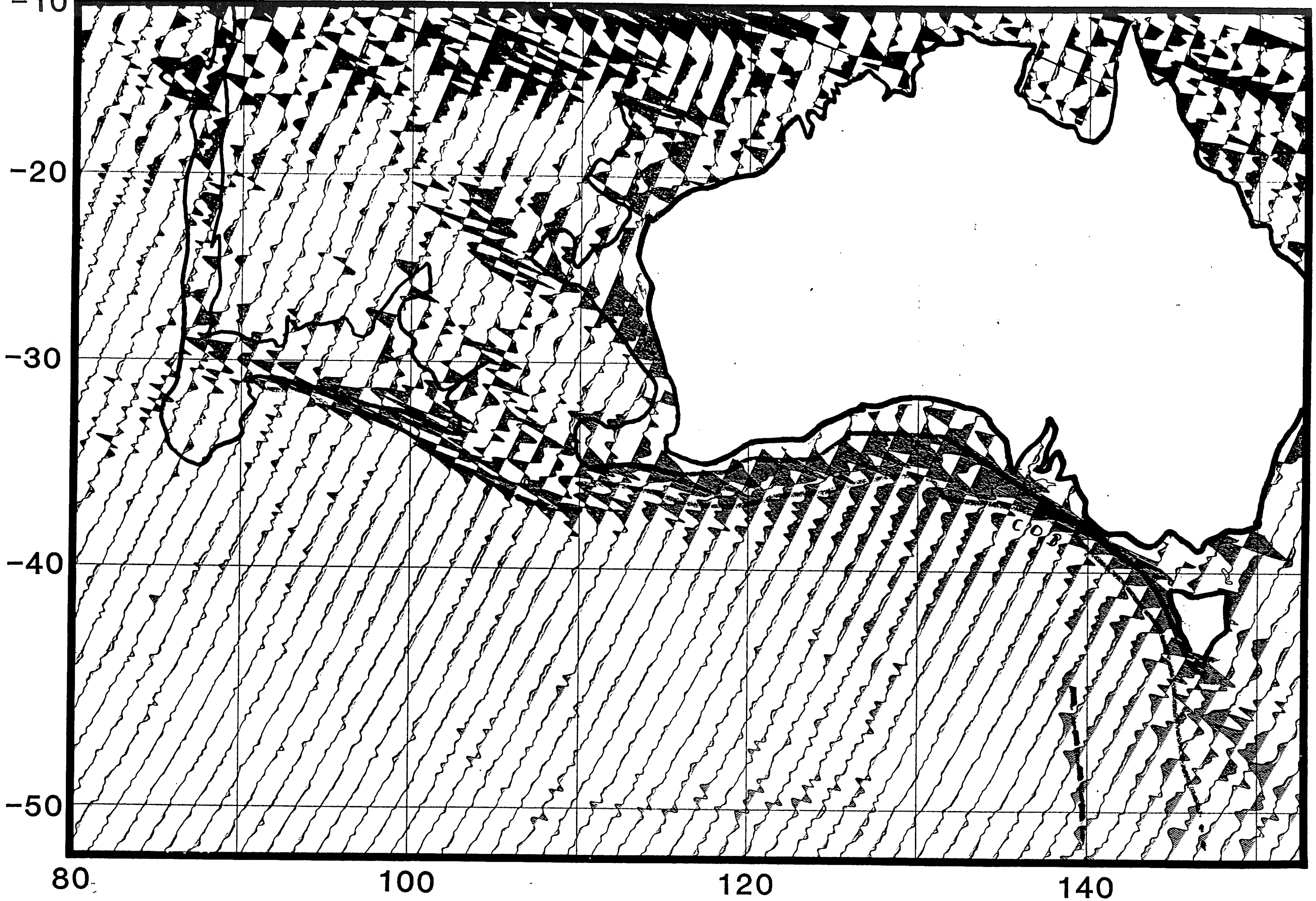


Figure 6

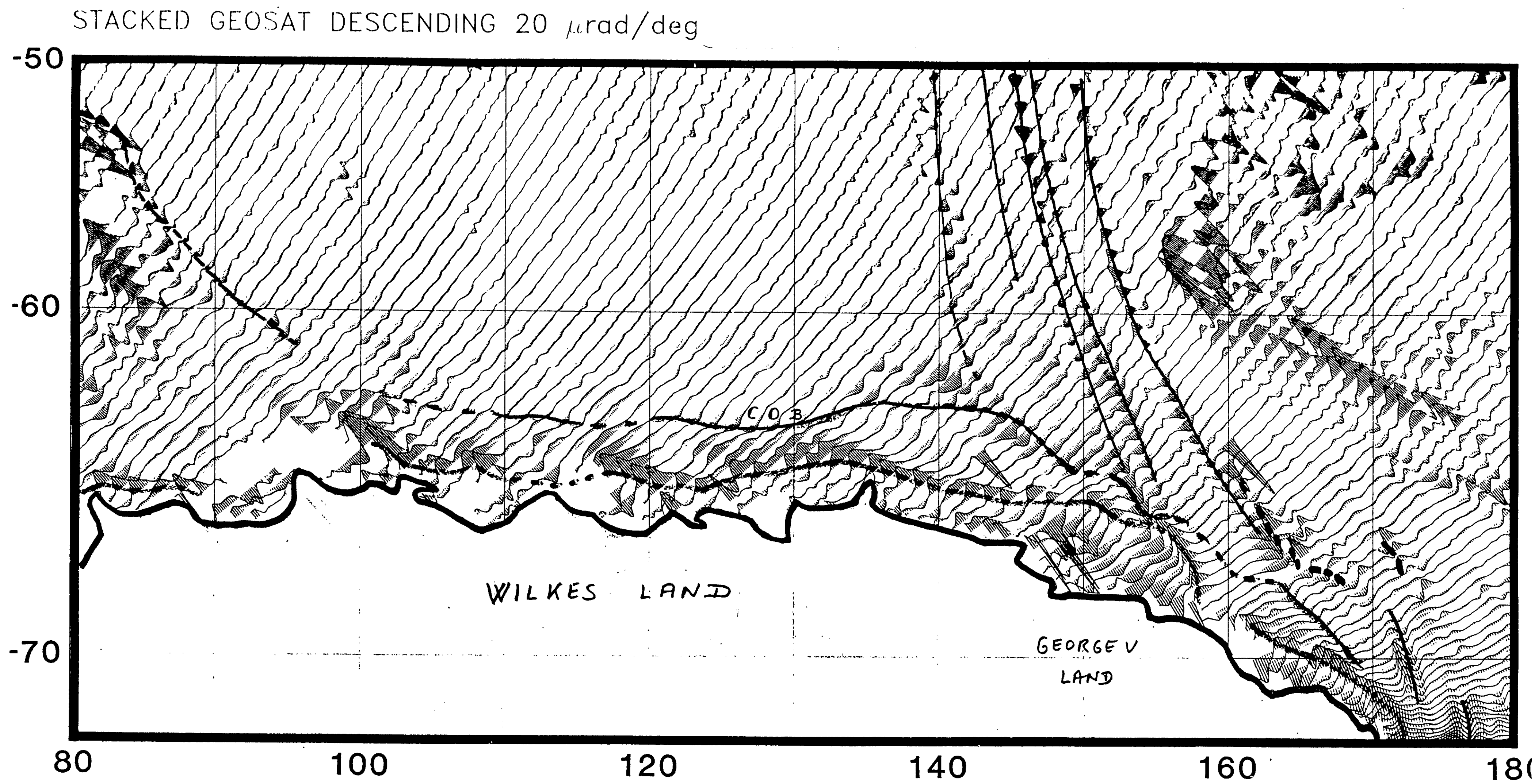

STACKED GEOSAT DESCENDING 20 µrad/deg
-50
-60
-70
80
100
120
140
160
180
COB
WILKES LAND
GEORGE V
LAND

Figure 7

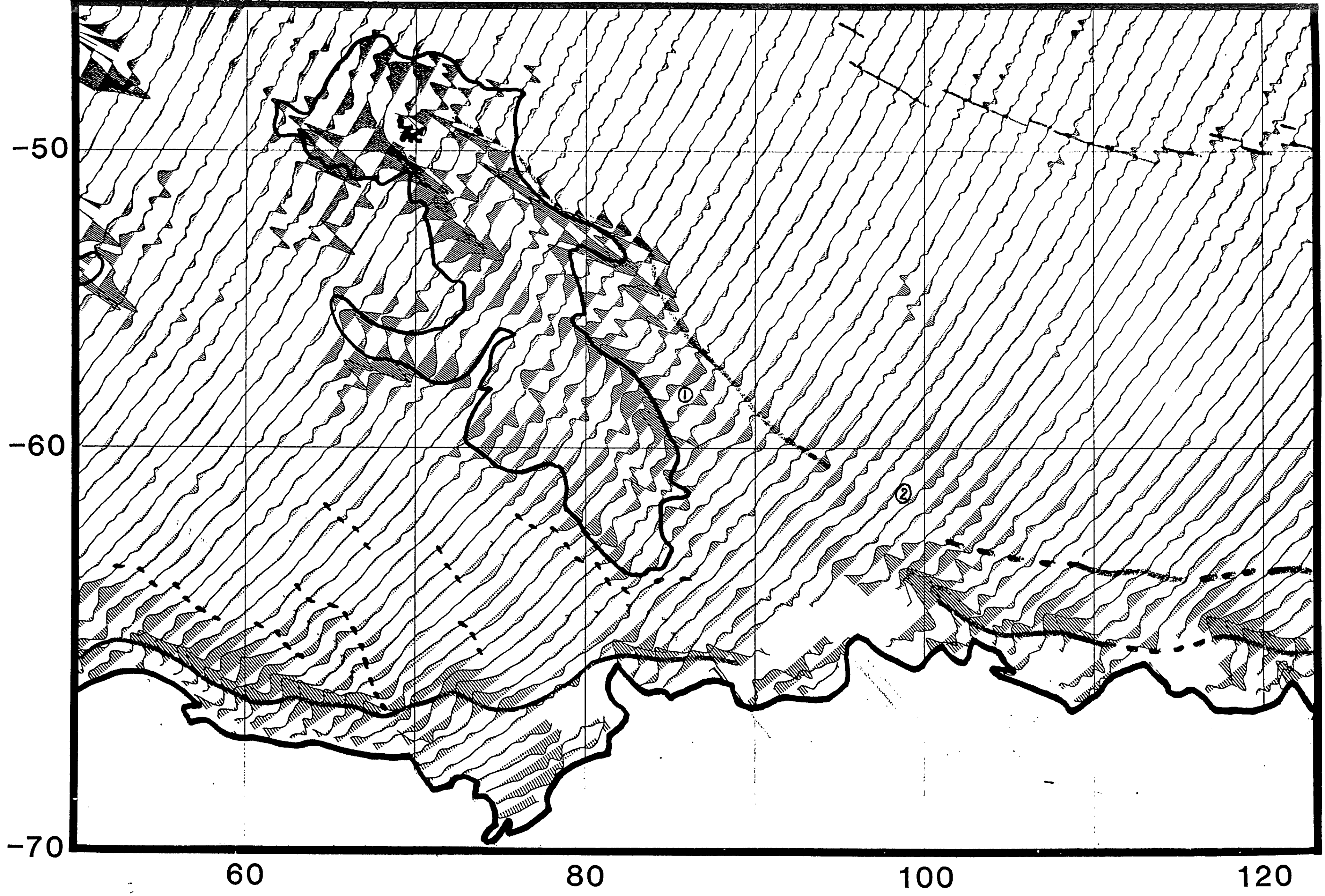


Figure 8

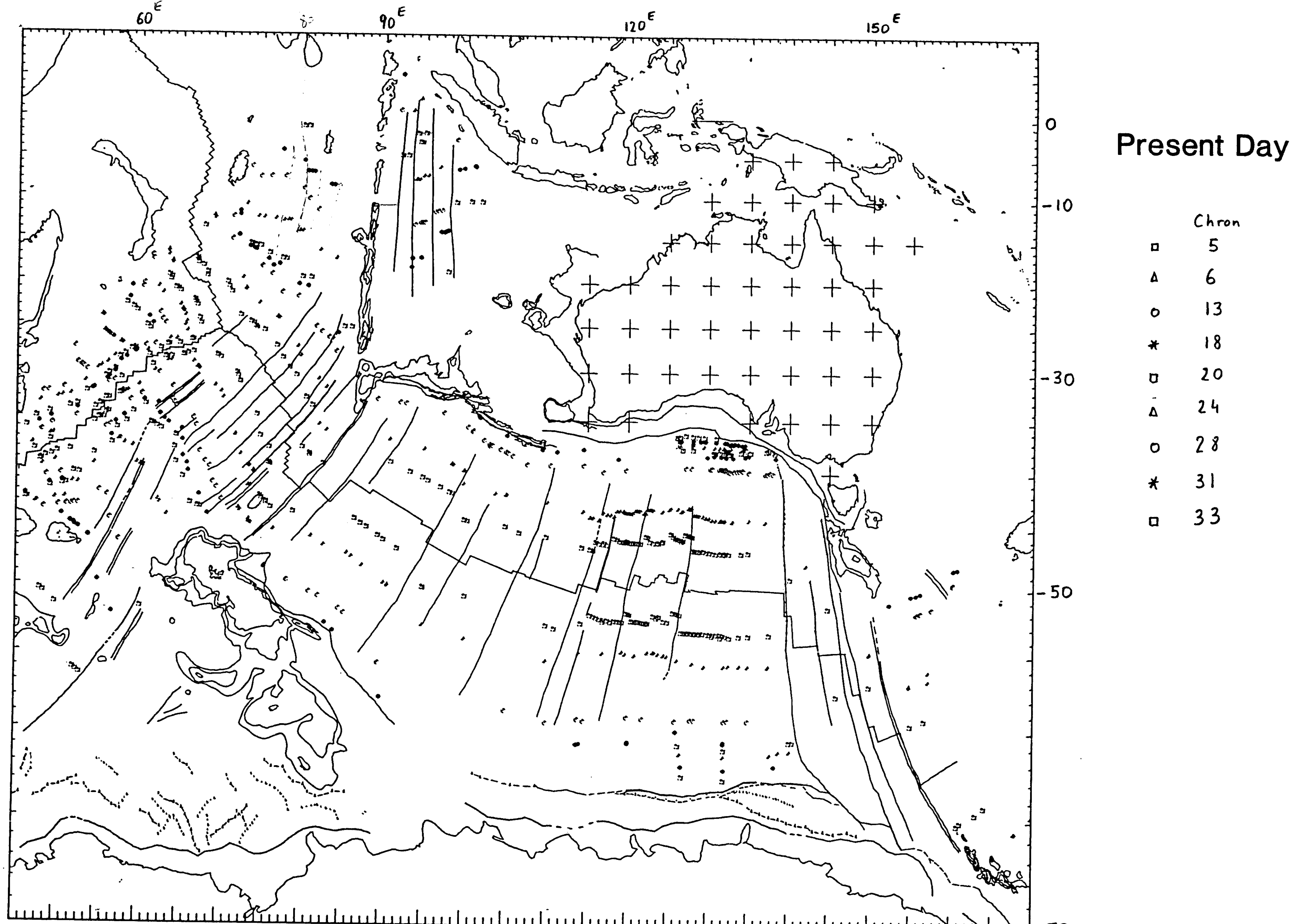

60 E
90 E
120 E
150 E
0
-10
-30
-50
-70
Present Day
Chron
5
6
13
18
20
24
28
31
33

Figure 9

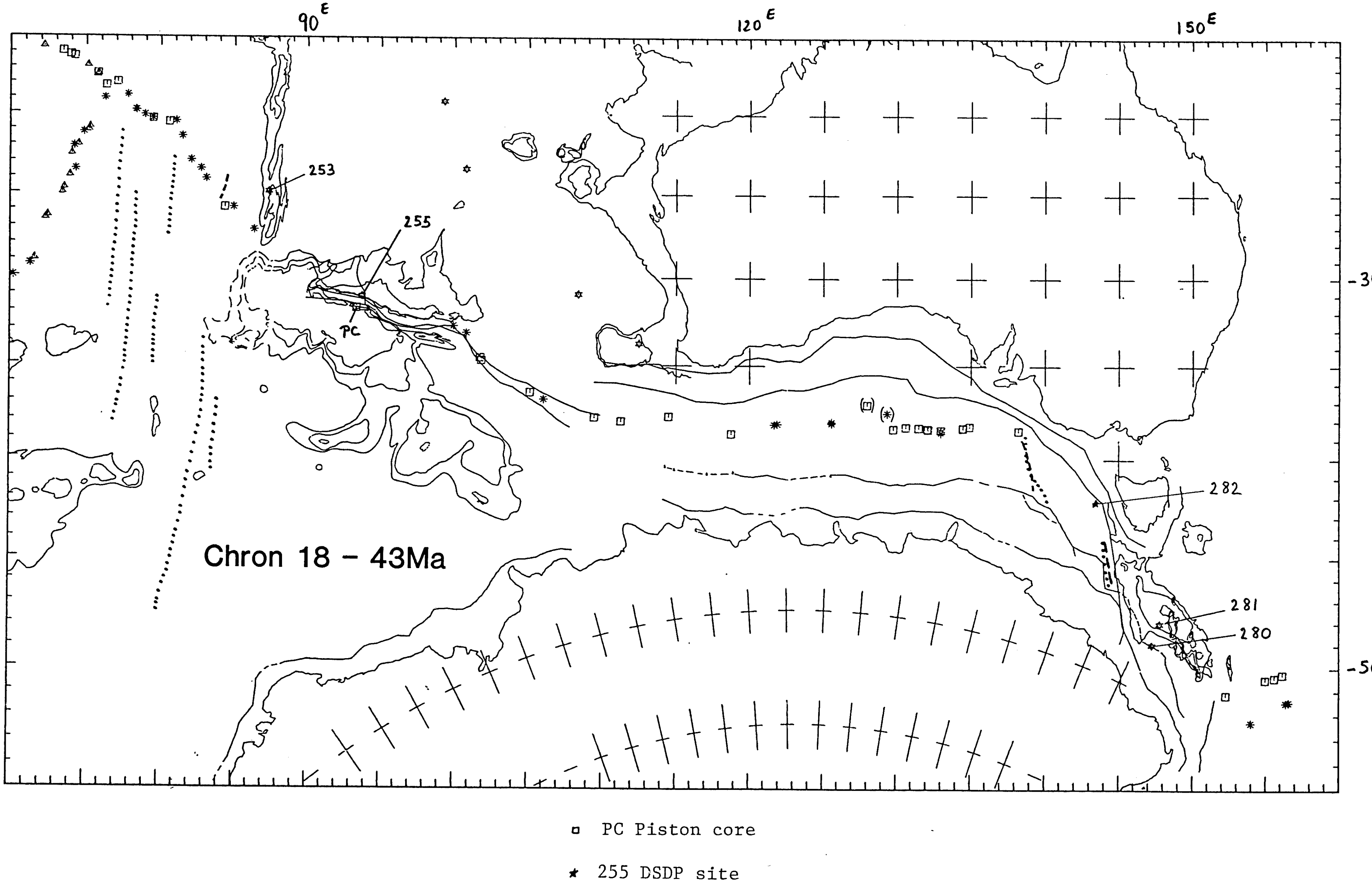
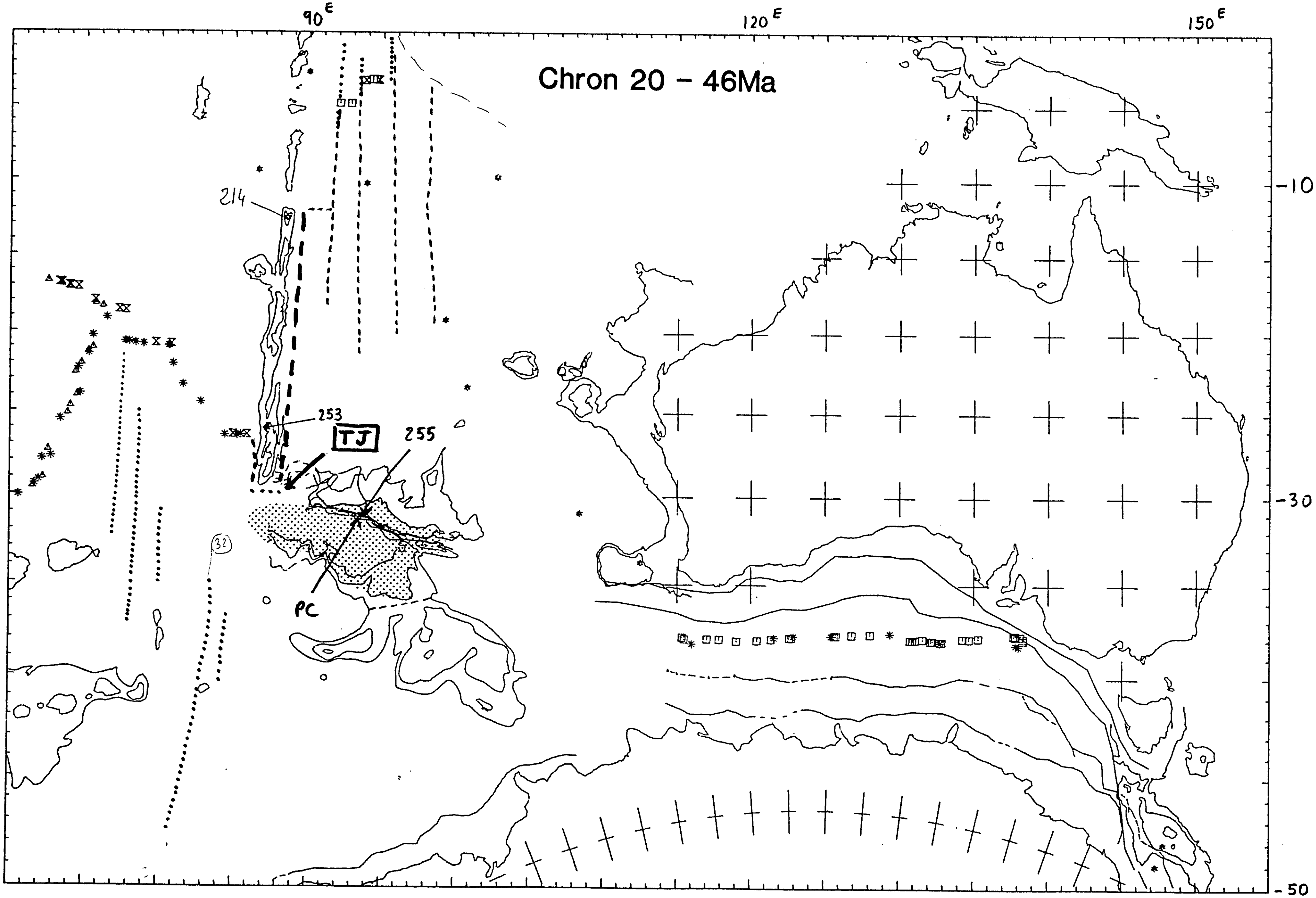

90E
120E
150E
-30
-50
253
255
PC
282
281
280
Chron 18 - 43Ma
PC Piston core
255 DSDP site

Figure 10



TJ = Triple Junction

Figure 11

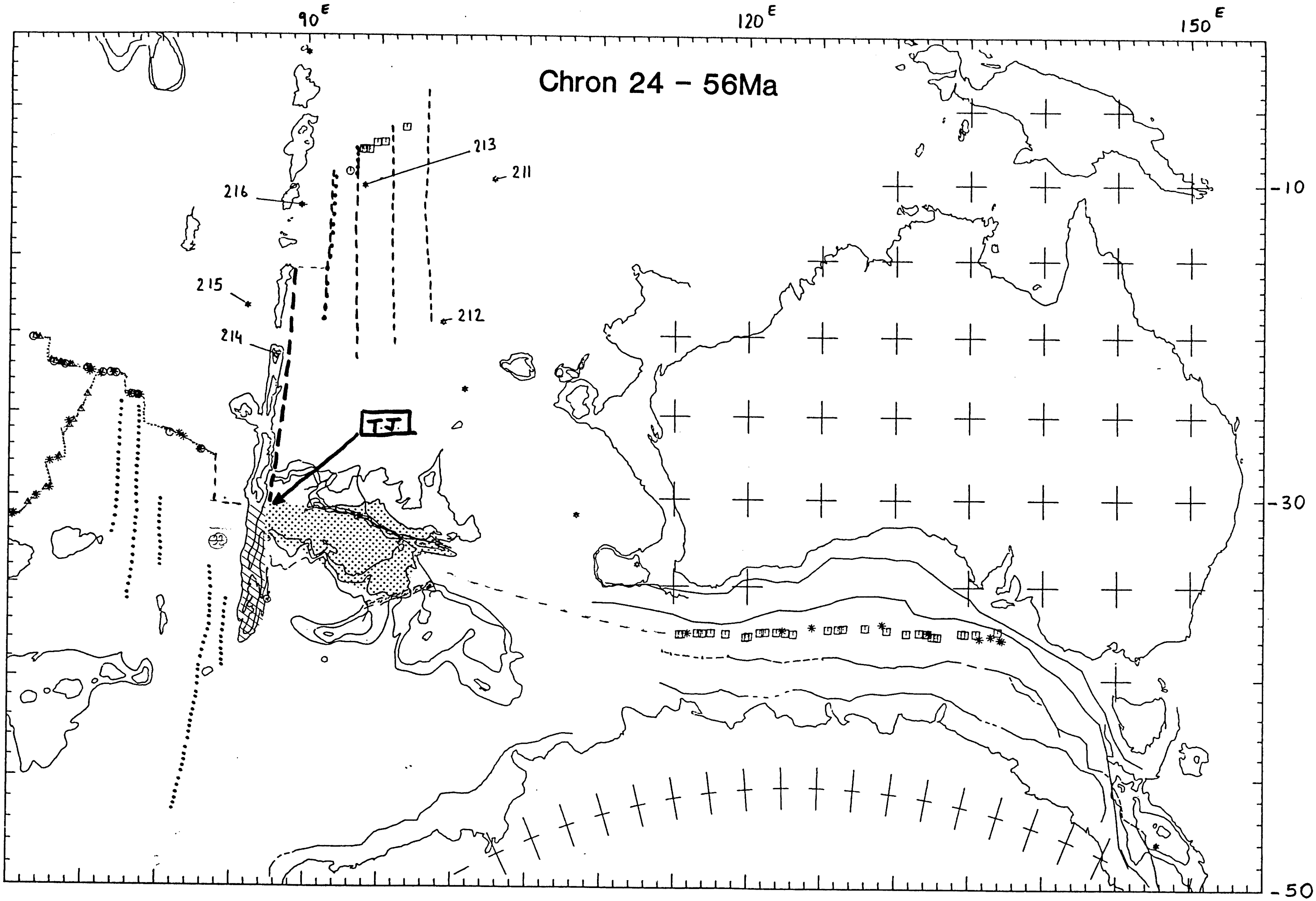
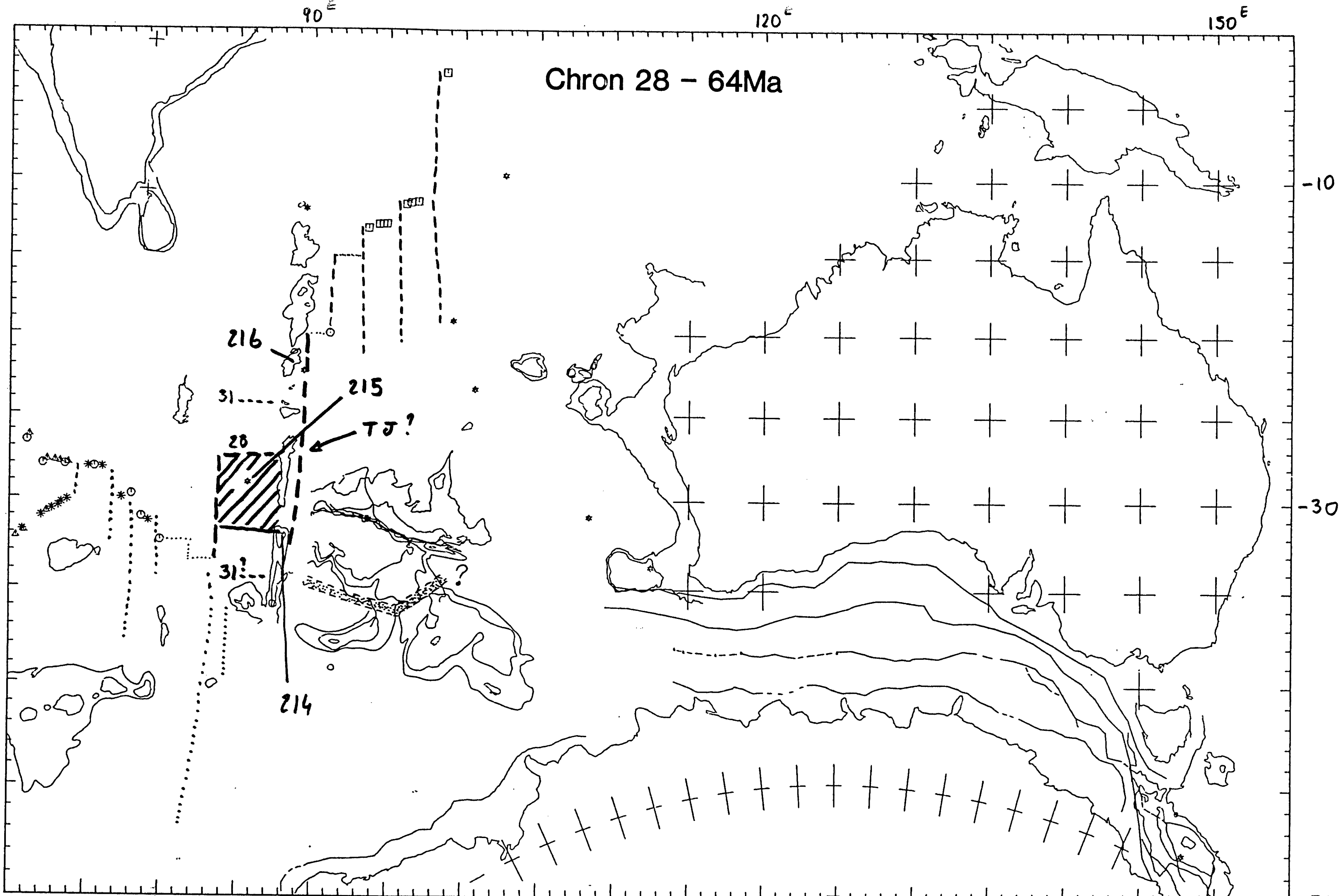


Figure 12



Crust younger than Chron 28 -

Figure 13

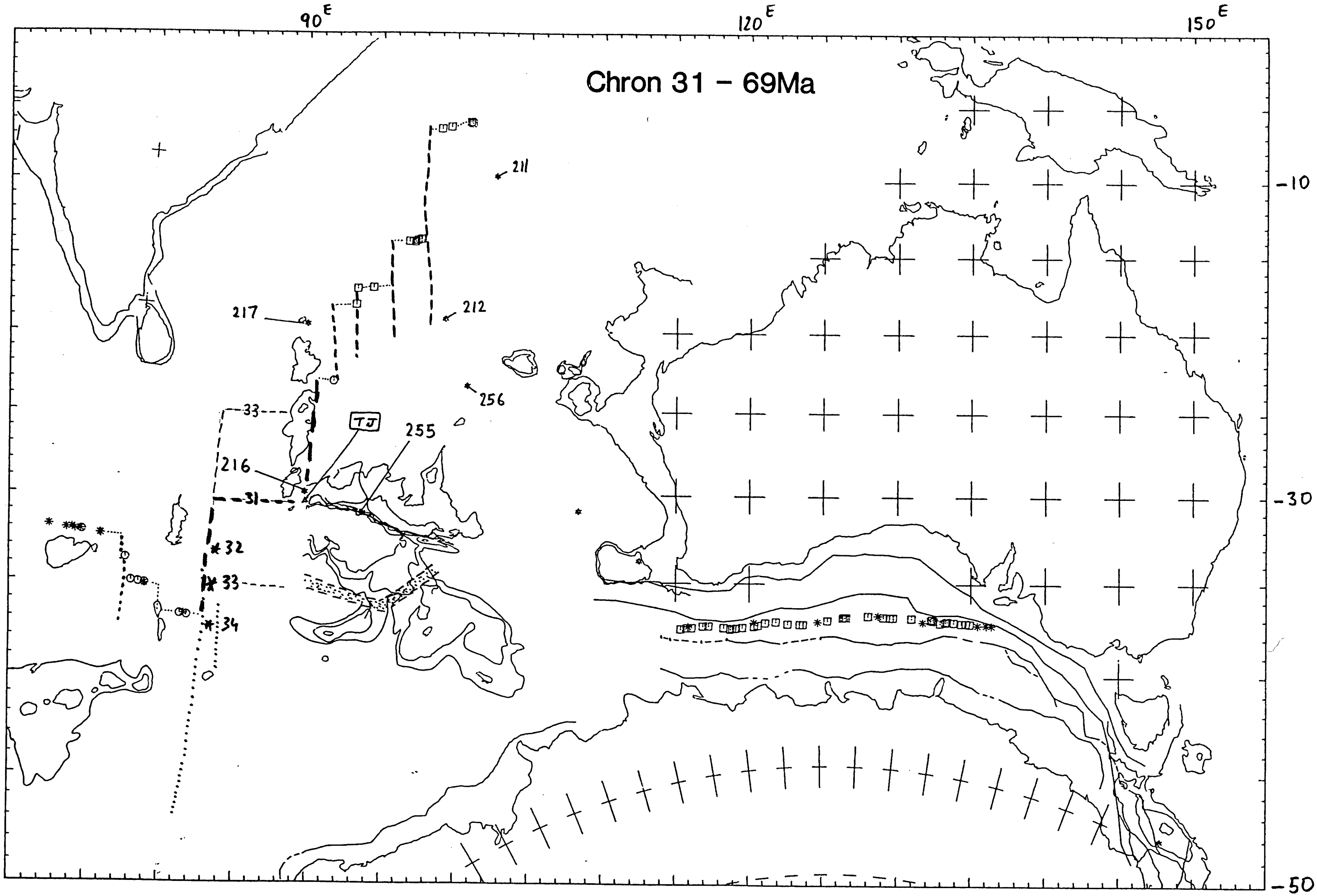
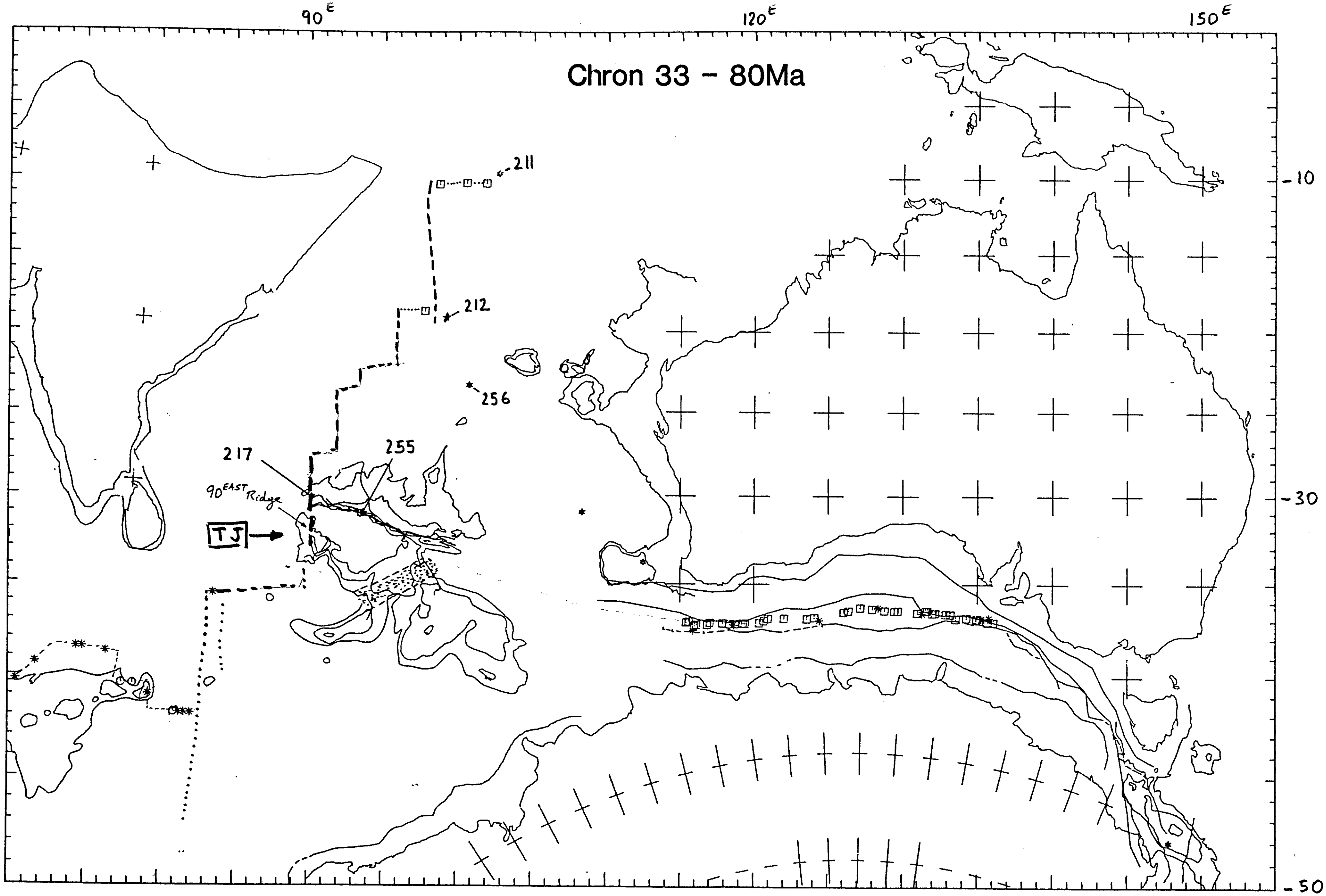

Chron 31 - 69Ma
90^E
120^E
150^E
-10
-30
-50
211
212
217
256
255
TJ
216
33
31
32
33
34

Figure 14



90^E
120^E
150^E
Chron 33 - 80Ma
211
212
256
217
255
90^EAST Ridge
TJ
-10
-30
-50

Figure 15

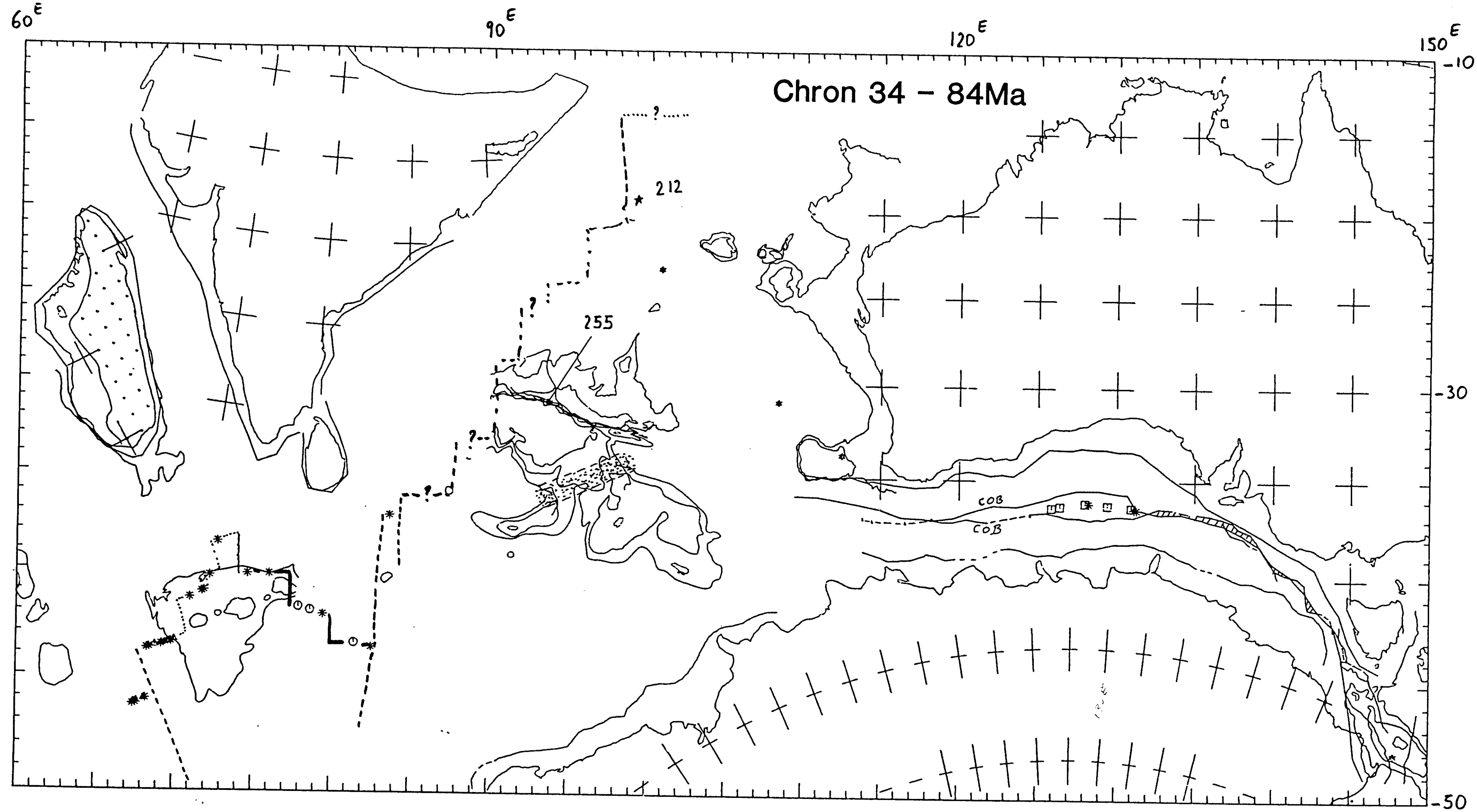


Figure 16

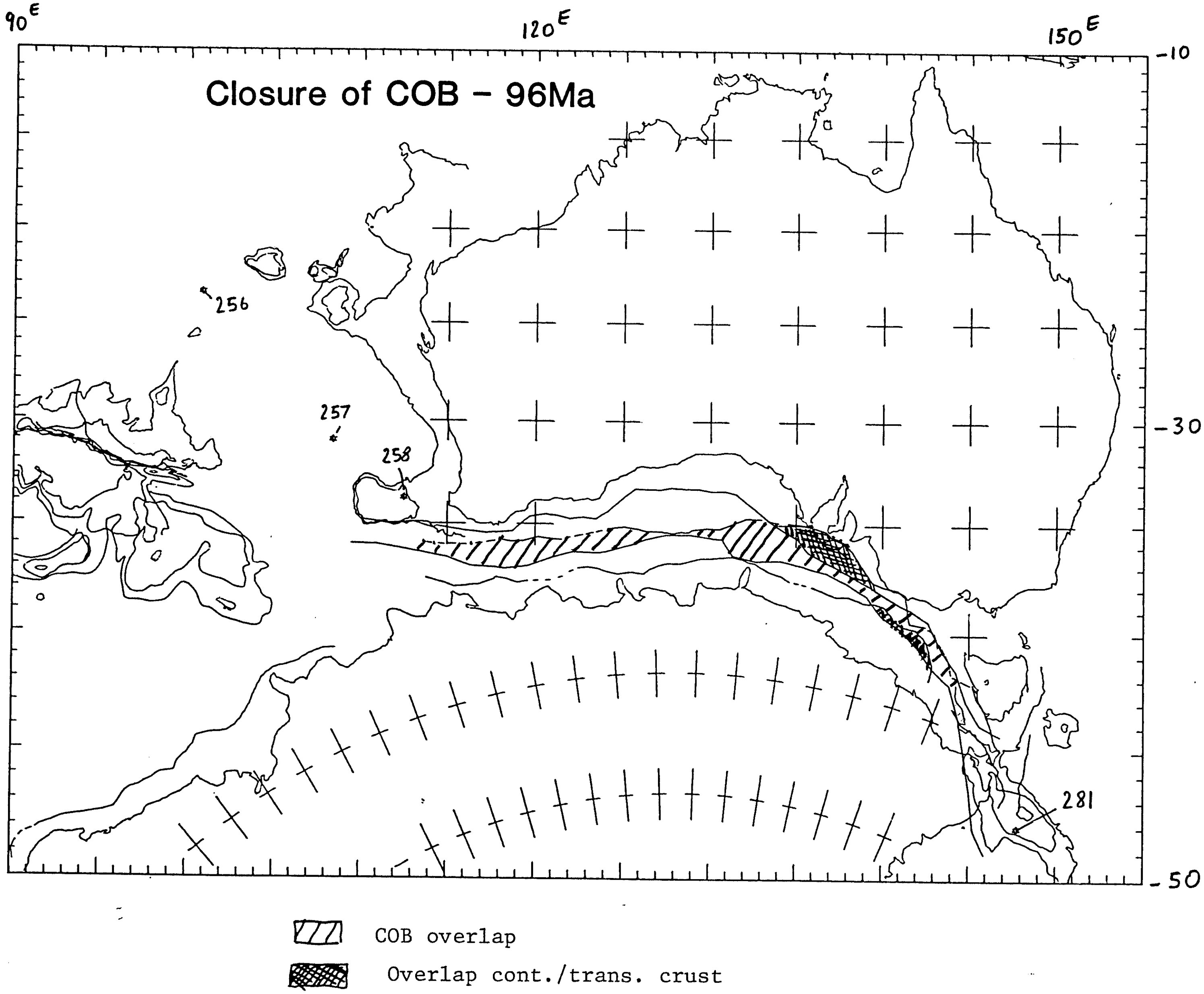

Closure of COB - 96Ma
90E
120E
150E
-10
-30
-50
256
257
258
281
COB overlap
Overlap cont./trans. crust

Figure 17

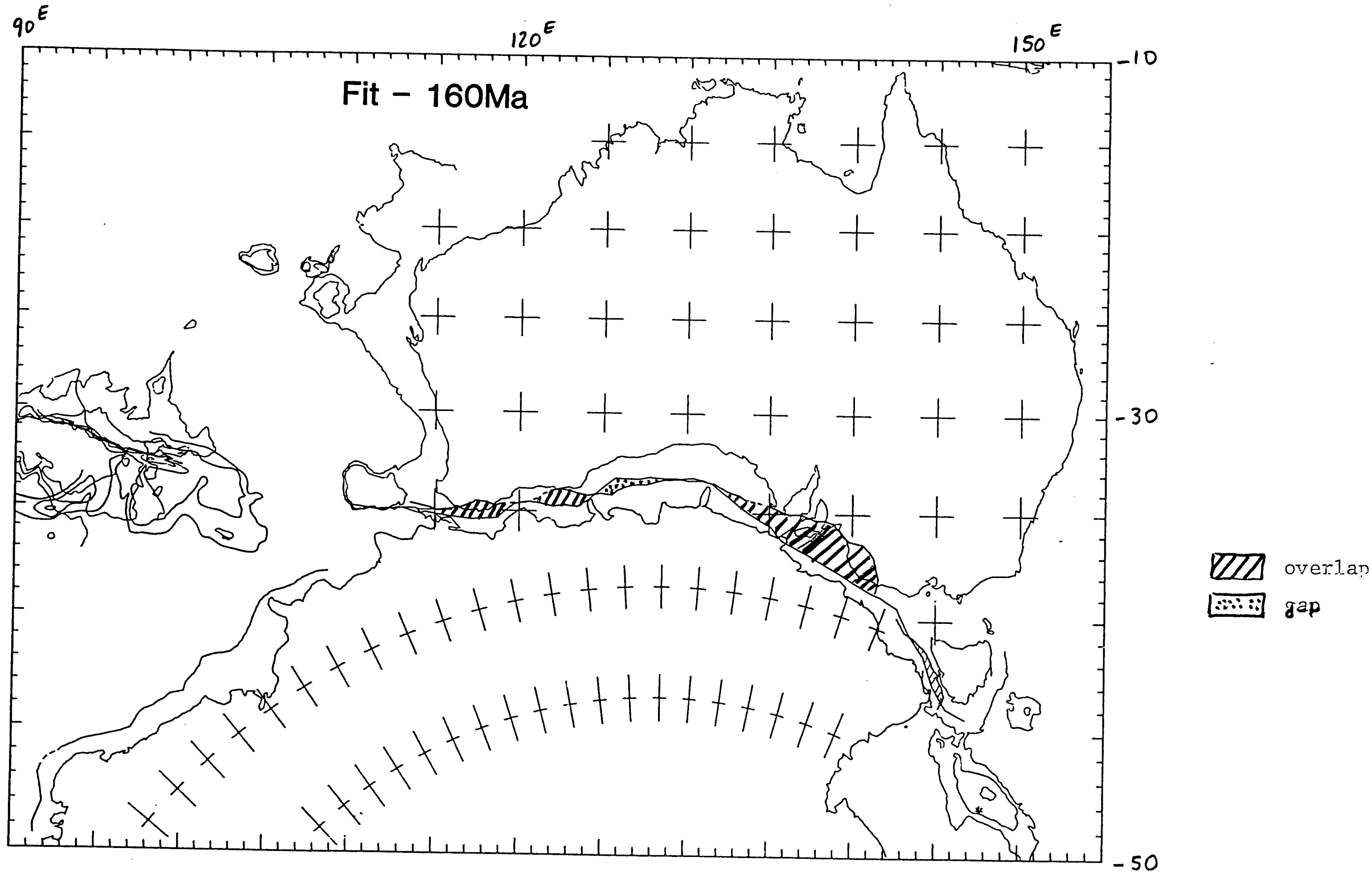
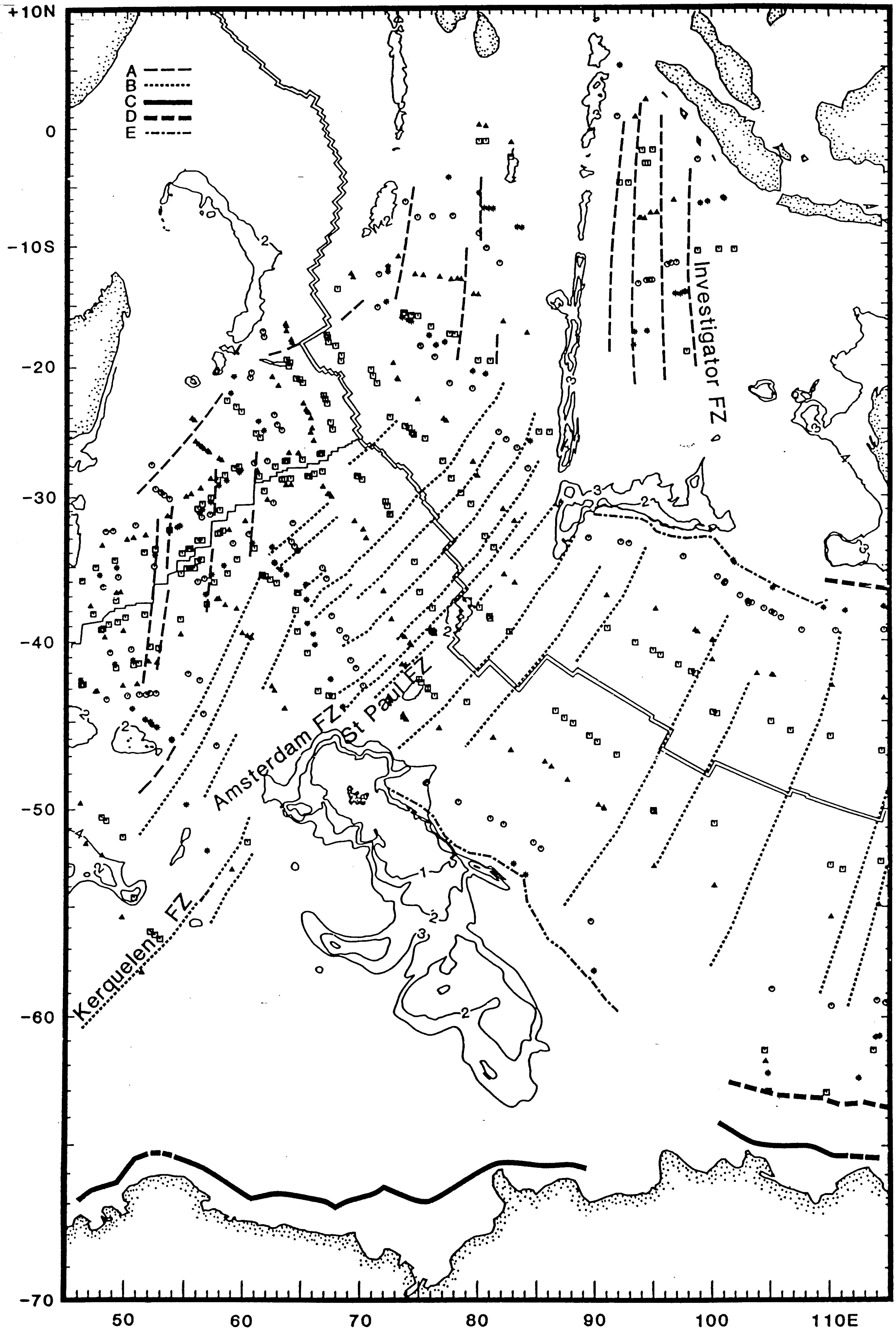


Figure 18



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

Figure 9A