UNCERTAINTIES IN THE RELATIVE POSITIONS

OF THE AUSTRALIA, ANTARCTICA, LORD HOWE AND

PACIFIC PLATES DURING THE TERTIARY

by

JOANN MIRIAM STOCK

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Signature of Author____

Department of Earth and Planetary Sciences
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Certified by____

Peter H. Molnar
Thesis Supervisor

Accepted by____

Chairman, Department Committee

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Abstract

Parameters describing finite rotations and estimates of the uncertainty regions for relative plate motion at the Pacific-Antarctica, Australia-Antarctica, and Lord Howe Rise-Australia spreading centers have been combined to yield a range of possible finite rotations describing the relative positions of the Pacific, Australia, Antarctica, and Lord Howe plates since the late Cretaceous. If the Pacific-Australia plate boundary has had its present trend since anomaly 18 time, reconstructions show 420 ± 110 km of motion of the Pacific plate relative to the Lord Howe Rise since anomaly 6 time (~19.5 my), 770 ± 330 km since anomaly 13 time (~35.6 my), and 820 ± 260 km since anomaly 18 time (~43.0 my). If the Antarctica, Pacific, Australia, and Lord Howe plates are all assumed to have been rigid, uncertainties in the reconstructions for times prior to anomaly 18 require 600 ± 300 km of convergence between the Pacific and Lord Howe Rise between anomaly 31 time (68 my) and anomaly 22 time (53 my).

If the Lord Howe Rise had been fixed to the Pacific plate until the Eocene, as suggested by geologic studies in New Zealand, and if a plate boundary existed through what is now the Antarctica plate, marine magnetic reconstructions require convergence between East and West Antarctica between anomaly 22 time (~53 my) and the initiation of Pacific-Australia motion. Four situations were examined: separation of Australia from Antarctica at ~53 my or at ~95 my, with initiation of the Pacific-Australia plate boundary either at ~43 my or at ~35.6 my. With these possibilities, the least deformation is required in Antarctica if Australia separated from Antarctica at ~95 my and if the Pacific-Australia plate boundary developed at ~43 my. This situation also brings 70-80 my paleomagnetic poles from the Pacific and East

Antarctica plates into closest agreement. However, large uncertainties in the reconstructions and lack of geologic constraints on the tectonic history of Antarctica do not allow any of the alternative plate histories to be eliminated conclusively.

Finally, a comparison of Lord Howe Rise-Australia and Pacific-West Antarctica stage poles for the interval 68 my to 59 my (anomalies 31 to 25) shows that at least three plate boundaries existed in the region during this interval: the Pacific-Antarctic ridge, the Tasman Sea spreading center, and at least one other (between Australia and Antarctica, within Antarctica, or through New Zealand).

Thesis supervisor: Peter H. Molnar
Title: Associate Professor of Geophysics

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Introduction

Reconstructions of the past relative positions of lithospheric plates, derived from matching magnetic anomaly and fracture zone data across spreading centers, provide important constraints on the amount of deformation between rigid plates connected by convergent or transform boundaries. In the South Pacific and southeast Indian Ocean, reconstructions of Pacific-Antarctica and Antarctica-Australia relative positions can be used to study the evolution of the Pacific-Australia plate boundary through New Zealand since the late Cretaceous. Most reconstructions have been made without detailed analysis of their uncertainties, so the range of possible relative positions between these plates at a given time has not been discussed (see Walcott [1978] for an exception). Here we examine the uncertainties in these marine magnetic reconstructions and combine them to study two problems: the range of possible motion along the Pacific-Australia boundary during the latter half of the Cenozoic, and the possible existence of other plate boundaries in this system since late Cretaceous time.

A reconstruction of the relative positions of two converging plates cannot be directly obtained; instead, it is found by matching magnetic anomalies and fracture zones across other spreading centers that separate the two converging plates from other plates. To determine the uncertainties in such a reconstruction, one must obtain the range of possible poles and angles for each pair of plates and then combine them to estimate the resultant range of possible poles and angles for the two converging plates. We recomputed finite rotations for the Pacific-Antarctica and Antarctica-Australia spreading centers, incorporating estimates of uncertainties in the locations of the data points to determine the range of possible poles and angles which yield acceptable fits for a given reconstruction. These possible reconstructions were then combined to obtain a range of possible plate reconstructions in the South Pacific-southeast Indian Ocean-Tasman Sea area for late Cretaceous and Cenozoic time. This study is part of a larger project in which we will combine these results with poles and uncertainty regions from other oceans to obtain uncertainties in the past relative positions of Pacific-North America, Farallon-North America and Nazca-South America plates.

Method for Determining Poles and Angles

All of the data used here were re-evaluated from published magnetic and bathymetric profiles or from ship crossings of fracture zones on published maps. We re-examined the positions of magnetic anomaly points to eliminate dubious identifications and to insure that the locations for each anomaly correspond to the same age of the reversal history. We also re-evaluated all of the fracture zone positions, and kept only those data points which are on ship tracks and have either definite bathymetric expressions or for which an offset can be reasonably inferred from missing or repeated magnetic anomalies. Based on the accuracy of navigation and the quality of magnetic and bathymetric data, we assigned an estimate of uncertainty (in km) to the position of each data point (Table 1). The numbers and ages of the magnetic anomalies used in these reconstructions are based on the timescale of LaBrecque et al. [1977]: anomaly 5 (9.8 my); anomaly 6 (19.5 my); anomaly 13 (25.6 my); anomaly 18 (43.0 my); anomaly 25 (59.0 my); anomaly 28 (64.0 my); anomaly 31 (67.8 my); and anomaly 32 (71.9 my).

Each new pole and angle was computed using Hellinger's [1979] method. This method consists of two steps: a search to find the angle of rotation about a given pole that gives the best fit to the data, and an iterative search within a specific region to find the location of the pole that gives the best fit. The data were divided into separate groups for each continuous magnetic anomaly or fracture zone segment; points on one plate were rotated to the other plate about a pole, and a separate great circle was fit to the data for each segment. The distance of each data point from its great circle was then computed, and divided by the uncertainty in position assigned to that point, to provide a weighted distance for the point. The sum of the squares of all the weighted distances (known as the measure of fit) was minimized to obtain the best fit angle of rotation for the particular pole position. A search was then conducted to find the pole position with the smallest measure of fit.

The method described above gave an estimate of the pole and angle that yielded the best-fitting rotation for the two plates. We were also interested in determining the uncertainty in each best fit pole and angle. This uncertainty is represented by a region in latitude-longitude space containing poles with different angles that yield possible fits to the data used, given the uncertainties in the data. This uncertainty region was obtained by mapping the measure of fit as a function of the pole position on a grid of latitude and longitude lines in the region surrounding the best pole. For a pole at each latitude-longitude point on the grid, the best angle and the corresponding measure of fit were calculated. Pole positions with equal measures of fit were then contoured to give an estimate of the shape of the uncertainty region in latitude and longitude. To find the extent of the uncertainty region, reconstructions were made using poles and angles along the axes of the measure-of-fit contour regions. We examined each of these reconstructions carefully to determine whether it provided an acceptable fit to the data, within the previously estimated uncertainties in the data points. This uncertainty region is therefore subjective in that its boundary represents poles that, in our opinion, constitute marginal or unacceptable matches of the data. Often this boundary region follows a constant measure-of-fit contour, but this is not always so. We define this region by the position of the best fitting pole and the corresponding angle, with four other pole positions and corresponding angles for those poles that mark the ends and sides of the elliptical confidence region surrounding the best fitting pole (Table 2).

Discussion of Reconstructions - Southeast Indian Ocean

Fracture zone control in the southeast Indian Ocean is poor. The complicated topography associated with most of the southeast Indian Ocean, especially in the Australia-Antarctica discordant zone and in the vicinity of the ridge axis, makes it difficult to identify clear fracture zones, although general trends have been inferred by previous workers [Weissel and Hayes, 1972; Weissel et al., 1977].

We re-evaluated all of the magnetic and bathymetric data available for Eltanin fracture zone crossings in this region (Table 1). Although there are many places where the Eltanin tracks cross fracture zones, these fracture zone points are uniformly distributed throughout the region. They do not show a pattern of widely-spaced individual fracture zones with substantial offset, as in the South Pacific; rather, they indicate many closely-spaced fracture zones with small offset of the magnetic lineations on either side. Because of the wide spacing of the Eltanin tracks compared to the inferred spacing of the fracture zones, individual fracture zones cannot be correlated to the north or south. In addition, the many small offsets of the current ridge axis make it difficult to correlate fracture zones across the Australia/Antarctica plate boundary.

Rather than base our reconstructions on inferred fracture zone trends, we have used the only fracture zones that we can confidently identify as continuous features: the Tasman and Balleny fracture zones on the Antarctica plate, north and west of the Balleny Islands [Hayes et al., 1974].

The spacing between the Tasman and Balleny fracture zones is approximately equal to the width of the southwestern margin of the South Tasman Rise, and the offset of isobaths on the Balleny fracture zone is about equal to the offset of the two halves of the southern margin of the South Tasman Rise. Therefore, we correlated the Tasman fracture zone on the Antarctica plate with the western edge of the South Tasman Rise on the Australia plate. Although we use only this one fracture zone, which can be correlated across the current spreading center, it is sufficient to obtain a good fit, because the magnetic anomaly points used in the reconstructions come from a ridge 7000 km long and give very strong constraints on the location of the finite poles.

Magnetic anomaly lineations due to Australia-Antarctica spreading exist on the Antarctica plate from 65°E to 175°E longitude and on the Australia plate from 84°E to 160°E longitude. We divided them into three sections: those west of Kerguelen or Broken Ridge (western section); those from east of Kerguelen or Broken Ridge to south of Tasmania (central section); and those in the south Tasman Sea on the Indian plate, or east of Balleny Island on the Antarctica plate (eastern section). Best fit reconstructions for anomalies 6 and 13 (Figures 1a, 2a) show an adequate match of all three sections by rotation of the points on the Australia plate about an appropriate finite pole. However, for anomaly 18 (Figure 3) the three sections of data cannot be fit to a single plate boundary. Either the western and central sections, or the eastern and central sections, can be well fit to a single plate boundary, with the remaining section falling short by about 100 km; or the eastern and western sections can be fit to one another, resulting in an overlap of 50-100 km in the central section. This misfit implies some deformation of either the India-Australia plate or the Antarctica plate between anomaly 18 time and anomaly 13 time. If such deformation did continue since anomaly 13 time, it was on a small enough scale that its effect is not detectable within the uncertainties in the data for anomalies 13 and 6. Therefore, we have only worried about this deformation for the anomaly 18 reconstruction.

There are several possible places where this deformation might have occurred. A small amount of compressional motion between the eastern and western portions of the India-Australia plate has been postulated to be presently occurring [Minster and Jordan, 1978; Stein and Okal, 1978]; if such motion took place between anomaly 18 and 13 time, then the far western points should be ignored and the best fit for anomaly 18 should be based only on the eastern and central sections. If the India-Australia plate has behaved rigidly, but complicated ridge jumping has occurred in the region of the Pacific-Antarctica-Australia triple junction, then the easternmost data points should be ignored and the fit should be based on the central and western sections. If the Antarctica plate deformed between the times of anomalies 13 and 18, then only those points on the East Antarctica half of the Antarctica plate should be used in the reconstruction.

Since not enough data exist to eliminate any of these possibilities, poles corresponding to fits based on each of these possibilities are included in the uncertainty region of the anomaly 18 pole (Figure 3). Because of this additional ambiguity, the uncertainty region for anomaly 18 in the south-east Indian Ocean is larger than the uncertainty regions for anomalies 13 or 6. The best pole for anomaly 18 time (Figure 3a) gives the best fit of points from all three sections, with underlap of the eastern and western points, and overlap of points from the central section.

We did not recalculate a best fit pole for anomaly 5 in the southeast Indian Ocean. Instead, we used Minster and Jordan's [1978] instantaneous best fitting angular velocity vector along the Australia-Antarctica plate boundary (11.85°N, 34.74°E, 0.672°/my) to derive a pole for Australia-Antarctica relative position. The angle was obtained by multiplying this instantaneous rate by 9.8 million years. Estimates of the instantaneous poles of Australia-Antarctica motion vary considerably [Minster and Jordan, 1978; Tapscott, 1979], so the uncertainties in the anomaly 5 pole should be greater than the 95% confidence regions associated with any of these instantaneous poles. The uncertainty region that we used for this anomaly 5 pole was obtained by using the same axial lengths and orientations as those for the anomaly 6 reconstruction.

The large amount of overlap in the uncertainty regions for the poles for the times of anomalies 6, 13, and 18 (Figure 14) suggests that the spreading history between Australia and Antarctica may have been relatively simple since at least the time of anomaly 18. The pole describing the fit of Australia to Antarctica [Weissel et al., 1977] also falls within the uncertainty regions of these poles, so that the finite pole of Australia-Antarctica motion may have been fairly constant since these two plates rifted apart prior to at least anomaly 22 time. We did not attempt to calculate uncertainties in the pole describing the Australia-Antarctica fit, because it is based on geologic correlations between the two continents and on continental shelf morphology. However, comparison of the Weissel et al. [1977] pole with other proposed poles for this fit [Griffiths, 1974; Laird et al., 1977; Norton and Molnar, 1977] suggests that the uncertainty in the fit is larger than the uncertainties in any of the later magnetic anomaly reconstructions of Australia-Antarctica relative positions.

<u>Discussion of Reconstructions - South Pacific</u>

Poles and uncertainty regions for Pacific-Antarctica spreading were calculated using fracture zone and magnetic anomaly locations from Molnar et al. [1975] (Table 1). Reconstructions were made for the times of anomalies 5, 6, 13, 18, 25, and 31 (Figures 5-10).

With the exception of the pole for anomaly 5, all of the recalculated poles were close to those obtained by Molnar et al. [1975]. Molnar et al. used the instantaneous Pacific-Antarctica pole of Minster et al. [1974] for anomaly 5 time. This pole, and the instantaneous poles of Minster and Jordan [1978] (RM2 geohedron and best-fitting angular velocity), however, all lie outside of the recalculated uncertainty region for anomaly 5, indicating a change in the Pacific-Antarctica pole between the times of anomalies 5 and 2! or 3.

The uncertainties in the revised reconstructions are at least twice as large as the uncertainties estimated by Molnar et al. [1975], as Hellinger [1979] found for anomalies 13 and 18. Despite these larger uncertainty regions, the general trend suggests that the pole of Pacific-Antarctica motion has been changing steadily through time. Its projection in the southern hemisphere moved south between anomaly 31 (68 my) and anomaly 13 (35.6 my), and then northwest between anomaly 13 and the present (Figure 11).

Discussion of Reconstructions - Tasman Sea

Magnetic anomaly locations in the Tasman Sea were re-evaluated from magnetic profiles plotted perpendicular to ship track [Weissel et al., 1977; Weissel and Hayes, 1977] and from the preliminary reports of the Eltanin cruises [Hayes et al., 1975, 1976, 1977, 1978]. Fracture zone locations were re-evaluated from these data sources and from the maps of the

Antarctic Research Series [Hayes et al., 1974]. Although many fracture zones can be inferred to exist from magnetic anomaly offsets, there are only three which have enough ship crossings to be used in the reconstruction calculations. Of these, the northernmost one cannot be shown to involve crust older than anomaly 29, so it was not used in the anomaly 32 reconstruction (Table 1).

Northwest-southeast spreading in the Tasman Sea began prior to anomaly 33 time, with the separation of the Lord Howe Rise from eastern Australia. Spreading ceased at anomaly 24 time, so that anomaly 24 forms the central northwest-southeast trending anomaly in the Tasman Sea, with older anomalies flanking it on each side. Anomalies 25 through 33 can be clearly identified on east-west magnetic profiles, but there are more data points for anomalies 28 and 32 than the others. Therefore, we have made reconstructions for those two times. Poles and angles for the times of anomalies 25 and 31 (Table 3) were obtained by interpolation using best fits for anomaly 28 and anomaly 32 (Figures 12 and 13).

Combined Reconstructions for Anomalies 5, 6, 13, 18 - Pacific-Australia

The past positions of the Pacific plate relative to West Antarctica, and of the India-Australia plate relative to East Antarctica, were easily derived from marine magnetic data which show simple spreading histories along the Pacific-Antarctic Ridge and the Southeast Indian Ridge since at least anomaly 18 time (43 my). The past positions of the Pacific and India-Australia plates are harder to calculate directly, since the Pacific-Australian boundary has been primarily convergent and transform; this motion can only be obtained by combining results from Pacific-Antarctica and Antarctica-Australia spreading, constrained by geologic and geophysical data from the current Pacific-Australia boundary through the Macquarie Ridge, New Zealand, and the Hikurangi-Kermadec trench system.

Molnar et al. [1975] calculated past positions of the Pacific plate relative to the India-Australia plate and inferred an Eocene to Recent tectonic history of the Pacific-Australia boundary, which Carter and Norris [1976] showed to be in general accord with the geologic history of the South Island for this time period. Ballance [1976] used the geology of the North Island to further constrain the location of the Pacific-Australia plate boundary, still in agreement with the results from the marine magnetic reconstructions. In this paper we combined our best fit poles and uncertainty regions for Pacific-Antarctica and Antarctica-Australia relative positions to derive resultant poles and uncertainty regions for Pacific plate-Australia plate relative positions at the times of anomalies 5, 6, 13, and 18 (Figure 14). These differ from previous results [Packham and Terrill, 1975; Walcott, 1978] because they are based on revised, different poles and uncertainty regions for Pacific-Antarctica and Antarctica-Australia spreading.

Our results suggest that the Pacific-Australia finite pole may not have changed very much from about anomaly 18 time (43 my) to anomaly 6 time (19.5 my). The uncertainty regions are large, on the order of 500 km along the long axis and 300 km along the short axis, but for the times of anomalies 6, 13, and 18 they all overlap significantly, so that within the uncertainties it is possible that the pole has stayed in the same place.

The revised poles and angles also indicate that the Pacific-Australia finite pole changed some time between the times of anomalies 6 (19.5 my) and 5 (9.8 my). Because our reconstructions only examine the configuration of the system at specific times in the past, this change in the position of the finite pole cannot be dated more precisely. The difference between the revised anomaly 5 pole and the location of the current best-fitting angular velocity vector for the Pacific and India-Australia plates [Minster and Jordan, 1978] suggests that the Pacific-Australia finite pole continued to change over the past 9.8 million years. However, the location of the instantaneous pole of Pacific-Australia motion is poorly known, so the change of the finite pole since anomaly 5 time is correspondingly uncertain.

Because marine magnetic reconstructions are based on the assumption of rigid lithospheric plates, they should be cautiously applied to the study of deformation within New Zealand itself. The present Australia-Pacific plate boundary through New Zealand is a 200 km wide zone of distributed dextral shear, faulting, and compression [e.g. Walcott, 1978] which passes northward into subduction of the Pacific plate beneath the North Island at the Hikurangi Trench and southward into subduction of the Australia plate beneath the Fiordland margin of the South Island [Christoffel and van der Linden, 1972]. It is not clear to what extent bending and shear may be responsible for the current shapes of the Lord Howe Rise and the Campbell Plateau. In the figures in this paper, New Zealand is divided into two rigid blocks along the Alpine Fault; this is an approximation only, since this is not a rigid boundary and its position and orientation may have changed with time.

A knowledge of the location and orientation of a plate boundary with respect to the instantaneous pole of motion between the two plates allows one to calculate the relative motion along the boundary. This cannot be done very accurately for the past Pacific-Australia plate boundary through New Zealand due to large uncertainties in the reconstructions. Positions of past instantaneous poles from anomaly 18 to anomaly 6 time are very uncertain, because the large uncertainty regions of the finite poles overlap. The past position and orientation of the Pacific-Australia boundary is also uncertain, because the history of shear and bending in New Zealand is not well known. Therefore, a better way to examine the motion between the two plates is to examine the uncertainty in the position of a point on one plate relative to the other plate at specific times in the past. The possible paths traveled by this point through time indicate the expected motion across a plate boundary in that location, whatever the orientation of the plate boundary.

The poles and uncertainty regions calculated for Pacific-Antarctica and Antarctica-Australia positions were used to derive the uncertainties in the past positions of two South Island (Pacific plate) points relative to the Lord Howe Rise (Australia plate), at the times of anomalies 18, 13, and 6. A combination of these results to find the path traveled by these points with respect to a fixed Lord Howe Rise (Figure 15) shows that from anomaly 13 time to the present, the best fit paths of these points closely follow the trend of the current zone of shear deformation, with ~350 km of displacement from anomaly 13 time to anomaly 6 time and ~420 km of displacement from anomaly 6 time to the present. The uncertainties in the locations of these points at anomaly 6 and anomaly 13 time do not overlap, so that even in the most extreme case, some motion of the Pacific plate with respect to the Australia plate is required. However, a comparison of the anomaly 13 and anomaly 18 positions shows 100% overlap, suggesting that the Pacific and Australia plates could have been fixed with respect to one another during this time. The best fit paths show a small amount of counterclockwise rotation of the Pacific plate with respect to the Australia plate during this interval; such motion is insignificant when compared with later displacements between the two plates and might be difficult to trace in the geologic record.

The limits on total displacement across the plate boundary, derived from the uncertainties in point positions (Figure 15) are: 820 ± 260 km since anomaly 18 time (43.0 my);

770 ± 330 km since anomaly 13 time (35.6 my); and 420 ± 110 km since anomaly 6 time (19.5 my). The total displacement across the Alpine and Wairau faults in the South Island is estimated to be 570 km, based on the offset plus the observed horizontal shear of the Permian ultramafic belt and the schist-greywacke boundary [Walcott, 1978]. If all of this deformation is of Cenozoic age, the uncertainties in the plate tectonic reconstructions require that strike-slip deformation along the Alpine-Wairau system began prior to anomaly 6 time (19.5 my). If the shear and strike-slip motion associated with the Alpine-Wairau system represents the total deformation along the Australia-Pacific plate boundary, then this plate boundary was initiated in New Zealand no earlier than the time of anomaly 18 and probably between the times of anomalies 13 (35.6 my) and 6 (19.5 my).

Within the uncertainties, any type of motion might have taken place between the Pacific and Australia plates from anomaly 13 time to anomaly 18 time. Geologic evidence from New Zealand shows no major displacement during this interval, although a zone of subsidence, block faulting, and flysch basin formation began suddenly at about the Eo-Oligocene boundary and continued until late Oligocene time [Norris et al., 1978]. This zone of subsidence, the Moonlight Trough, currently trends north-northeast and is offset along the Alpine fault; its original trend may have been modified by subsequent dextral shear, so that its orientation cannot be used to constrain the uncertainties in Pacific-Australia motion. However, the amount of relative motion observed in the geologic record is small enough that the possibility of substantial motion during this interval can probably be eliminated.

Arc volcanics first appeared on the North Island at 24-20 my and extended southward with time, suggesting that the Hikurangi subduction margin east of the North Island formed by southward propagation from the Kermadec Trench [Ballance, 1976]. Our results show 400 ± 370 km of convergence between the Pacific and Australian plates in the interval between anomalies 18 (~43 my) and 6 (~19.5 my). This is consistent with slow subduction taking place for some time before arc vulcanism began. Within the uncertainty limits of plate tectonic reconstructions, it is possible that the entire Pacific-Australia boundary through New Zealand (consisting of subduction of the Pacific plate under the North Island and right lateral shear across the South Island) developed slowly as a continuous zone of deformation between the times of anomalies 18 and 6.

Combined Reconstructions for Anomalies 18, 22, 25, 31

It is difficult to constrain the uncertainties in the Pacific Australia finite rotations for times prior to anomaly 18, because we have no quantitative estimate of the uncertainty in the closure of Australia to Antarctica. The finite rotation used here for the Australia-Antarctica fit is 30° of rotation about 10.3°N, 32.7°E [Weissel et al., 1977]. This rotation is derived from matching geologic and morphological features across the continental edges, so that the uncertainties in the pole and angle of rotation are difficult to assess and cannot be studied with the techniques used for the reconstructions of magnetic anomalies and fracture zones. Uncertainties in the pole and angle of this rotation are not incorporated into any of the following reconstructions.

The time of rifting of Australia away from Antarctica is also uncertain. Magnetic anomalies between anomaly 18 and the older magnetic quiet zones adjacent to the Australia and Antarctica continents were previously identified as anomalies 19 through 22 [Weissel and Hayes, 1972; Weissel et al., 1977], so that Australia was assumed to have separated from Antarctica shortly before the time of anomaly 22 (53 my). For such a date of rifting, the southeast Indian Ocean would have formed at a nearly constant rate since rifting. Recently, Cande et al. [1981] reinterpreted these anomalies as anomalies 20 through 34, formed at a very slow spreading rate after initial rifting of Australia from Antarctica approximately 85-100 million years ago [S. Cande, personal communication, 1981]. We explored the consequences of these two possibilities on the plate configurations in this region by making two alternative assumptions about the age of the break-up between Australia and Antarctica: first, that the fit described the relative configuration of these plates throughout the interval 68 my (anomaly 31) to 53 my (anomaly 22); and, second, that the fit describes the relative configuration of Australia and Antarctica only for times previous to 95 my.

Poles and angles based on the second assumption were obtained by direct interpolation between the Australia-Antactic closure rotation (10.3 N, 32.7 E, - 30.0°) assumed to be appropriate at 95 my and the best fit rotation describing the relative position of Australia with respect to Antarctica at the time of anomaly 18, 43 my (11.47°N, 31.03°E, - 23.58°) by assuming a constant spreading rate. Because the time of rifting and subsequent spreading rates between Australia and Antarctica are not well known, no uncertainties are estimated for these rotations; these rotations are only used to provide a reasonable indication of how usch early rifting might have affected the positions of Australia and Antarctica at the times of anomalies 22, 25, and 31. The uncertainties given for point positions at these times represent minimum uncertainty regions based only on uncertainties in the reconstructions of the other oceans and would certainly be larger if the uncertainties in the Australia-Antarctica poles could be included.

Additional uncertainties arise in the location of plate boundaries in this system for times prior to anomaly 18. Molnar et al. [1975] suggested that deformation occurred between East and West Antarctica before Pacific-Australia relative motion began in the mid-Tertiary. Weissel et al. [1977] assumed that Antarctica has been a rigid plate since late Cretaceous time but that a plate boundary existed in New Zealand since the late Cretaceous. If such a plate boundary existed, the motion on it must have been small, since geologic evidence for it is lacking; the late Cretaceous through late Eocene time was a period of shallow marine sedimentation in New Zealand, with no apparent tectonic influence to suggest the existence of a nearby plate boundary [Carter and Norris, 1976]. Although paleomagnetic evidence indicates that Antarctica was at least two plates prior to the Cretaceous [Scharnberger and Scharon, 1970], no conclusive geologic evidence from Antarctica exists to resolve the possibility of late Cretaceous to Eocene deformation there. In order to study this problem, we used two alternative assumptions: first, that Antarctica has remained a rigid plate but that deformation occurred along a plate boundary through New Zealand since late Cretaceous time; and second, that the Lord Howe Rise was part of the Pacific plate until the mid-Tertiary but that motion took place between East and West Antarctica prior to the initiation of Pacific-Australia motion.

If the development of the Pacific-Australia plate boundary in New Zealand is correlated with the late Eocene-Early Oligocene age of the beginning of extension in the South Island, it occurred no earlier than anomaly 18 time and possibly as late as anomaly 13 time. Therefore, in reconstructions which allow for deformation in Antarctica, either the anomaly 18 or the anomaly 13 relative positions of the Lord Howe and Pacific plates can be used as their original relative positions. This causes only a small change in the plate configuration of the Pacific-India boundary, but it makes a large difference in the amount of deformation required in Antarctica. To demonstrate the effects of some of the different possible assumptions, we show the past relative positions of the Australia, Antarctica, Pacific, and Lord Howe plates for the case in which Australia and Antarctica were closed at 53 my and for which a plate boundary through New Zealand existed at least since anomaly 18 time. These are divided into two groups: first, assuming no Antarctic deformation (Figures 19-21); and, second, assuming deformation in Antarctica but no plate boundary through New Zealand prior to anomaly 18 time (Figures 22-24).

Constraints on Deformation in New Zealand

Analysis of the first set of reconstructions, which assume that Antarctica does not deform but that a plate boundary traversed the New Zealand region since anomaly 31 time, shows 300 km of overlap between the Campbell Plateau and the Lord Howe Rise for the time of anomaly 22 (Figure 19) and 200 km of overlap at the time of anomaly 25 (Figure 20). The uncertainty in this overlap can be determined by keeping the Lord Howe Rise fixed and calculating the uncertainties in the relative positions of two points on the Pacific plate at this time (Figure 25). Since the long axis of the uncertainty region is nearly parallel to the plate boundary, the uncertainty in the overlap at both of those times is ±25 km. It should be emphasized that a different finite rotation matching Australia back to Antarctica at the time of anomaly 22 would displace all of these uncertainty regions by some amount that might increase or reduce the observed overlap (see below).

The best fit paths of points on the Pacific plate relative to a fixed Lord Howe Rise indicate 600 ± 300 km of westward motion of the Pacific plate with respect to the Lord Howe Rise from the time of anomaly 31 to the time of anomaly 22, with 250 ± 100 km of eastward motion from anomaly 22 time to anomaly 18 time. The uncertainty regions do not overlap for the times of anomalies 31, 25, and 22, so some motion of the Pacific plate relative to Australia is required during this interval, regardless of the rotation used to close Australia back to Antarctica.

A regional plate tectonic history based on the assumptions made here of four rigid plates (Pacific, Australia, Lord Howe, and Antarctica) and of Australia-Antarctica rifting at anomaly 22 time therefore indicates east-west convergence between the Pacific plate and the Lord Howe plate from anomaly 31 time to anomaly 22 time; east-west extension between the Pacific and Lord Howe plates between anomaly 22 time and anomaly 18 time; and some compression accompanied by strike-slip motion from anomaly 18 time to the present. The nature of the exact motion would depend on the orientation of the plate boundary.

If separation of Australia from Antarctica began at about 95 my instead of at about 53 my, the history of motion of points along the Lord Howe-Pacific plate boundary is considerably different. Assuming that the Lord Howe, Australia, Antactica, and Pacific plates have been rigid, there is no overlap of the Campbell plateau and the Lord Howe Rise for times previous to anomaly 18. Instead, the best fit paths of points on the Pacific plate relative to a fixed Lord Howe Rise show 550 km of westward motion between the times of anomalies 31 and 25, 75 km of roughly westward motion between the times of anomalies 25 and 22, and 300-350 km of northward motion between the times of anomalies 22 and 18 (Figure 26). The minimum uncertainty regions given for the positions of these points are large, up to 300 km along the semimajor axis. For the times of anomalies 22 and 25 they overlap slightly, but for the times of anomalies 31 and 18 they do not overlap at all, indicating that 700 ± 300 km of northwest-southeast convergence should have taken place in the New Zealand region between anomalies 31 and 18 (68 to 43 my).

Both of these cases, which assume that a plate boundary has existed in New Zealand since late Cretaceous time, require substantial motion across this plate boundary during late Cretaceous through Eocene time. If the past orientation of the Pacific-Lord Howe plate boundary through New Zealand were similar to its orientation today, then this motion would have been a minimum of 300 km of convergence. This amount of motion exceeds what might be expected based on geologic data from the New Zealand region. It appears, therefore, that the assumptions used here of rigid plates and no Antarctic deformation are incorrect, since they give results that are inconsistent with the geologic history of New Zealand.

Constraints on Deformation in Antarctica

If the Lord Howe Rise were part of the Pacific plate until some time in the Eocene, with no relative motion between the Australia and Pacific plates, then to satisfy plate tectonic constraints, another plate boundary must be postulated somewhere in the system, such as between East and West Antarctica. The amount of deformation across this plate boundary would depend on the time Australia separated from Antarctica, the time when deformation in Antarctica ceased, and the time of initiation of the Australia-Pacific plate boundary. To explore the nature and magnitude of deformation across a plate boundary in Antarctica, we made the simplifying assumption that deformation in Antarctica ceased instantaneously when Pacific-Australia motion commenced. We then considered four simple cases by varying two assumptions: the time of separation of Australia from Antarctica (95 my vs 53 my) and the time of initiation of the Pacific-Australia plate boundary in New Zealand (anomaly 18 time, 43 my, vs anomaly 13 time, 35.6 my). The past positions of two points on West Antarctica relative to fixed East Antarctica are used to show the type of motion expressed across a plate boundary in this region.

If rifting of Australia from Antarctica is assumed to take place at the time of anomaly 22 (53 my), substantial motion across a plate boundary within Antarctica is required (Figure 27). If the Lord Howe Rise is assumed to have been part of the Pacific plate prior to anomaly 18 time (43 my), the past positions of points on West Antarctica show convergence from anomaly 31 time to anomaly 18 time, when Antarctic deformation is assumed to end (Figure 27a). The uncertainty regions given are only minimum uncertainty regions, but they overlap at the times of anomalies 31, 25, and 22, so that it is possible that no relative motion of East and West Antarctica occurred during this interval. Convergence of 900 ± 400 km in the Ross Sea region, increasing to 2000 ± 600 km near the Weddell Sea, would have occurred in the interval between anomalies 22 and 18 (53-43 my), however.

An alternative is that the Pacific-Australia plate boundary through New Zealand began at about anomaly 13 time (35.6 my), and Australia-Antarctica separation began at anomaly 22 time (Figure 27b). In this case, the best fit paths for past positions of plates on West Antarctica relative to East Antarctica indicate clockwise separation of West Antarctica from East Antarctica in the interval between anomalies 31 and 22, followed by convergence of 1900 ± 300 km in the Ross Sea region and 3000 ± 1000 km near the Weddell Sea until anomaly 13 time. The best fit positions of these points require more relative motion between anomaly 31 time and anomaly 22 time for this case (Figure 27b) than for the previous case (Figure 27a).

If separation of Australia and Antarctica began at ~95 my and constant slow spreading took place until ~43 my, much less Antarctic deformation is necessary (Figure 28). Assuming that the motion between the Pacific and Australia plates began at anomaly 18 time, the motion of West Antarctica with respect to East Antarctica would still be counterclockwise rotation between the times of anomalies 31 and 22, followed by convergence between the times of anomalies 22 and 18. The best fit paths show less motion in Antarctica for this earlier age of

Australia separation (Figure 28a) than for the ~ 53 my age of Australia separation (Figure 27a). All of the minimum uncertainty regions overlap, so that it is possible that little deformation occurred in Antarctica between anomaly 31 time (68 my) and anomaly 18 time (43 my).

Slightly more deformation would have occurred in Antarctica if the Pacific-Australia plate boundary through New Zealand did not develop until about anomaly 13 time (35.6 my) instead of anomaly 18 time. Best fit paths for the motion of West Antarctica, with East Antarctica held fixed (Figure 28b), again show counterclockwise rotation between the times of anomalies 31 and 22, followed by convergence until the time of anomaly 13. Total convergence is larger for this age of initiation of the Pacific-Australia plate boundary (35.6 my; Figure 28b) than for an earlier age of initiation (43 my; Figure 28a). The minimum uncertainty regions for past positions of these points suggest that some convergence is required during the interval between anomalies 31 and 13.

In all of these situations, convergence of East and West Antarctica is required between anomaly 22 time (53 my) and the time of development of the Pacific-Australia plate boundary through New Zealand.

Paleomagnetic Constraints

To further resolve the plate history of this region prior to anomaly 18 time, we tested various situations for compatibility with the apparent polar wander curves of the Pacific and East

Antarctica plates. For East Antarctica we used Suarez and Molnar's [1980] pole positions at 70 and 80 my. Paleomagnetic measurements from Upper Cretaceous (70-80 my) volcanic rocks from the Chatham Islands give a south pole at 70.45°S, 177.77°W, with an associated circle of confidence of 6.2° [Grindley et al., 1977]. Since the Chatham Islands are east of New Zealand, near the outer edge of the Chatham Rise, their position and orientation with respect to a rigid Pacific plate probably were not affected by Cenozoic shear deformation and bending along the Pacific-Australia plate margin. Therefore, rotation of the Pacific plate back to East Antarctica should bring the Chatham Islands pole into coincidence with the apparent polar wander path of East Antarctica at 70-80 my.

We rotated the Chatham Islands pole back to East Antarctica at the times of anomaly 31 (68 my) and anomaly 34 (80 my) using five previously discussed alternative models of the regional plate history: no deformation in Antarctica (a); separation of Australia from Antarctica at anomaly 22 time, and the development of the Pacific-Australian boundary through New Zealand at anomaly 13 time (b) or anomaly 18 time (c); separation of Australia from Antarctica at 95 my, and the development of the Pacific-Australian plate boundary through New Zealand at anomaly 13 time (d) or anomaly 18 time (e) (Figure 29). Poles and angles used for the 80 my rotations were obtained by direct extrapolation from younger rotations in the South Pacific Ocean and the Tasman Sea, and by interpolation between the rotations for anomaly 18 and closure in the southeast Indian Ocean (Table 3).

None of these five situations give best fit results which are close to the East Antarctica polar wander path at 70 my. For 80 my, however, the Chatham Islands paleomagnetic pole falls fairly close to the East Antarctica apparent polar wander path in all five situations. For both the 70 my and 80 my rotations, situation (e) puts Grindley et al.'s pole for the Chatham Islands closest to the East Antarctica pole. However, the uncertainties in the paleomagnetic poles, and in the rotations used to compare them, combine to give such large uncertainty regions that any of situations (a) through (e) are equally acceptable.

Further Tests

We tested a final set of assumptions about the plate configurations in this region: that there was not a plate boundary through either Antarctica or the Lord Howe Rise/ Campbell Plateau prior to anomaly 25 time. If this were the case, and if Australia and Antarctica did not separate until the time of anomaly 22, then the Lord Howe Rise-Pacific block would have formed one plate separating from another plate, East Gondwana (containing pre-rift Australia and Antarctica). The instantaneous pole of motion of the Lord Howe Rise relative to East Gondwana should therefore have been the same during the time interval when they formed one plate. To test this, we computed the stage poles for Lord Howe Rise-

Australia motion between anomaly 32 time and anomaly 28 time, rotated them back to East Antarctica using the Australia-Antarctica fit rotation, and compared them with the positions of possible Pacific-West Antarctica stage poles for anomaly 31 to anomaly 25 time (Figure 30).

The uncertainty regions of these stage poles do not overlap, suggesting that the Tasman Sea spreading center and the Pacific-Antarctic Rise were not part of a single boundary separating the same two plates in this time interval. Another plate boundary, presumably either between the Lord Howe plate and the Pacific plate, or between East and West Antarctica, apparently is required; more than one plate boundary could have existed.

The difference in these stage poles could also be due to deformation in Antarctica since the time of anomaly 25. If the Lord Howe Rise and the Campbell Plateau had rifted away from East Gondwana as one piece, but Antarctica had subsequently deformed, these stage poles would not be in the same place. The rotation required to match the Pacific-West Antarctica stage poles back to the Lord Howe Rise-East Antarctica stage poles should then also rotate West Antarctica back to its original position in Gondwana with respect to East Antarctica.

There is a large range of possible rotations which can bring part of the uncertainty regions of these two stage poles into coincidence. A representative rotation chosen to produce maximum overlap of the uncertainty regions for the two stage poles (26° about 26°S, 54°E) gives original positions of West Antarctica and the Campbell Plateau that overlap East Antarctica, reconstructed Australia, and the Lord Howe Rise, and puts the Pacific-West Antarctica spreading center in the same location as the Lord Howe Rise-Australia spreading center. Since these two spreading centers were active simultaneously, they cannot have lain in the same place, so this particular rotation is clearly erroneous.

If separation of Australia from Antarctica began at about 95 my, then at least three plate boundaries - Pacific Antarctica, Lord Howe Rise-Australia, and Australia-Antarctica - would have been active during the late Cretaceous. The possible existence of another plate boundary in the region cannot be conclusively established until uncertainties in the Australia-Antarctica fit are available, but it seems likely under all of the sets of assumptions that we have discussed.

Some problems in these reconstructions may be due to the assumption that the Lord Howe Rise-North Island block was rigid throughout the time of these reconstructions. Seismic activity suggests that a zone 200-300 km wide is currently deforming parallel to the plate boundary through this region [Scholz et al., 1973]. Ductile deformation and bending of up to 400 km is observed in New Zealand itself [Walcott, 1978]. It is not known to what extent dextral shear may have caused the present configurations of the Lord Howe Rise, Chatham Rise, and Campbell Plateau, but if it is of the same order as the deformation observed in New Zealand, then significant deformation should probably be removed before the plate reconstructions can be quantitatively evaluated. Some extension within the Lord Howe plate could also have occurred; the Norfolk Basin, which contains low amplitude magnetic anomalies [Hochstein and Reilly, 1976] may have resulted from extension some time in the early Cenozoic. For lack of sufficient knowledge we have treated the Lord Howe Rise as a rigid plate; this is an approximation that may change as more is learned about the history of the ocean floor northwest of New Zealand.

Because reconstructions are done for finite times, it is hard to incorporate the process of initiation and propagation of plate boundaries through time. In one of the sets of reconstructions, we assumed instantaneous initiation of separation between Australia and Antarctica at anomaly 22 time, instantaneous propagation of a plate boundary through New Zealand at anomaly 18 time, and instantaneous cessation of spreading in the Tasman Sea at anomaly 24 time. Due to these assumptions, for the interval between anomalies 22 and 24 only one spreading center (Pacific-Antarctic) was active, and another one must be postulated somewhere - either in Antarctica or New Zealand - to satisfy the constraints of plate tectonics. It is possible that spreading in the Tasman Sea could have been slowing down as rifting began between Australia and Antarctica, so that in the dynamic system there may be no need to invoke the existence of another plate boundary between anomaly 24 and anomaly 22 times.

Conclusions

Within the limits of their uncertainties, reconstructions of the past relative positions of the Pacific and Australia plates agree well with the amount and timing of deformation observed since the Eocene along the Pacific-Australia plate boundary in New Zealand. In particular, the reconstructions give a history of displacement across this plate boundary of 820 ± 260 km since about 43 my ago (anomaly 18), 770 ± 330 km since about 35.6 my ago (anomaly 13), and 420 ± 110 km since about 19.5 my ago (anomaly 6). The best fit reconstructions show little or no motion between about 43 my and 35.6 my, followed by displacement parallel to the current zone of shear deformation between the Pacific and Australia plates.

If the deformation along the Alpine fault system is all due to relative motion of the Pacific and Australian plates in the Cenozoic, Walcott's [1978] estimate of 570 km of right lateral faulting and bending on the Alpine system implies that deformation on this fault system began prior to about 19.5 my and probably more recently than 35.6 my. These results are consistent with geologic evidence of block faulting, flysch basin formation, and rapid subsidence during the Oligocene, all of which may be due to the formation and development of the Australia-Pacific plate boundary. In the vicinity of the North Island, slow subduction may have taken place during the Oligocene, prior to the late Oligocene-early Miocene initiation of arc vulcanism in the North Island. Results suggest that the instantaneous pole for Pacific-Australia motion may have been fixed from about 43 my to about 19.5 my, so that deformation was of similar style throughout this interval. At some time after about 19.5 my this instantaneous pole began to change and has continued to change until the present time. The change of the pole position within the past 20 my may correlate with a change of deformational style along the Pacific-Australia boundary, from strike-slip faulting to bending and, most recently, to include some compression.

Reconstructions for late Cretaceous through Eocene time require substantial motion across an Australia-Pacific plate boundary if the only other boundaries in the system are the Pacific-Antarctica, Antarctica-Australia, and Australia-Lord Howe Rise spreading centers. The quiet sedimentation and lack of tectonic activity in the New Zealand region from the late Cretaceous through the late Eocene is inconsistent with this result, implying that the assumptions used in deriving the reconstructions are inappropriate.

The most likely way to alter these assumptions is to assume that no plate boundary existed between the Australia and Pacific plates prior to the Eocene, but that relative motion took place between East and West Antarctica. In this case, the amount of relative motion that would have occurred between East and West Antarctica depends on the time of separation of Australia from Antarctica, and the time of initiation of the Pacific-Australia plate boundary through New Zealand. Because of the uncertainties in Australia-Antarctica relative positions prior to about 43 my, and the lack of geologic constraints from Antarctica, there are many possibilities for the early Cenozoic history of the region. We considered four possibilities in order to examine a range of possible plate configurations: initiation of spreading between Australia and Antarctica about 53 or 95 my ago and formation of a plate boundary between the Pacific and the Lord Howe Rise about 35.6 or 43.0 my ago. Of these cases, the one in which Australia separated from Antarctica about 95 my ago and the Pacific-Australia plate boundary developed about 43 my ago seems most likely, since it requires the least deformation in Antarctica and brings paleomagnetic data for the Pacific and East Antarctica plates into best agreement. We cannot eliminate the other possibilities, however, and intermediate cases are, of course, possible.

Based on these assumptions, a reasonable early Cenozoic history of the region appears to be: (1) Australia separated from Antarctica in the middle to late Cretaceous; (2) throughout much of this time, the Lord Howe Rise and Campbell Plateau were parts of the same plate spreading apart from two other plates (West Antarctica and Australia); (3) apparently, some deformation took place in Antarctica between late Cretaceous and late Eocene time, but the exact timing and amount of this deformation is uncertain; (4) the Australia-Pacific plate boundary through New Zealand developed in late Eocene to early Oligocene time.

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PACIFIC PLATE

ANOMALY 31

-46 67	-150 00			2
-46 62	-152 90		CON 8-6	2
-44 82	-145 56		ELTANIN 20	2
-45.61	-147.67		CON 12-12	2
-44 71	-145 03		ELTANIN 24	2
-46 91	-153 25		ELTANIN 17	2
-48 46	-161 97	10	ELTANIN 33	2
-48 30	-162 05	10	CON 8-6	2
-35 08	-144 86		CON 9-5	2
-35 00	-144 84		DC6702	2
-55 90	177.12		ELTANIN 33	2
-55 19	177 67		ELTANIN 32	2
-55 00	178 59		ELTANIN 27	2
-54 00	-176 72		ELTANIN 43	2
-54.19	-177 46		MONSOON 6	2
-51.29	-172.37	15	VEMA 16-7	2
-50.29	-170 44	15	ELTANIN 25	2
-49 06	-168 05	15	ELTANIN 19	2
-47 89	-166 77	15	ELTANIN 23	2

FRACTURE ZONE POINTS

-44.45	-121.40	10	FZ III	2
-44.75	-120 25	20	FZ III	2
-47 33	-126 50	20	MENARD	2
-48 60	-119 97	20	MENARD	2
-53 64	-132 84	10		2
-53.83	-132 03	10		2
-54.42	-129 20	20		2
-54 72	-127 50	10		2
-55.18	-125 70	10		2
-51 72	-142 83	11	ELTANIN 17	2
-52 42	-140 17	8	ELTANIN 19	2
-52 55	-139 75	20		2
-53 78	-151 82	20	ELTANIN 33	2
-54 40	-143 80	20		2
-49 90	-113 95			2
-49.65	-114 87			2
-45.12	-134.32			2
-52 92	-119 32			2
-52.73	-120 05			2
-51.23	-127 40			2
-49 95	-131 63			2
-47.67	-126 58			2
-54.00	-120 10			2
-52.45	-128 85			2
-50.95	-134 70	7	CON 12-12	2
-51 45	-140 10	13	ELTANIN 19	2
-50.44	-143 00	11	ELTANIN 17	2
-50.32	-143.30	10		2
-49.61	-144 85	10		2
-46 07	-150.60			2
-50 30	-146 85	11	ELTANIN 17	2
-48.42	-151 00	10	ELTANIN 17	2
-57 03	-140.28			2
-56 82	-141 20			2
-56 54	-142.50			2
-55 97	-143 82			2
-55 80	-144.53			2
-48 87	-162 65	30		2
-47.00	-154.40	30		2
-50.50	-159 80	20		2
-52 48	-137.00	13	ELTANIN 17	2
-50 90	-145 00	7	ELTANIN 20	2

WEST ANTARCTIC PLATE

ANOMALY 6

-61 05	-140 26	10	HUDSON	2
-60.15	-138 83	10	ELTANIN 20	2
-59 35	-137 42	20	VEMA 16-7	2
-57.60	-110 87		HUDSON	2
-55 41	-107 65		CON 12-12	2
-51.11	-103 79		ELTANIN 20	2
-44 74	-101 13	10	ELTANIN 20	2
-57 41	-110 34		ELTANIN 43	2
-49 75	-102 96		ELTANIN 25	2
-65 27	-154.41		ELTANIN 42	2
-63 46	-144 87		ELTANIN 25	2

ANOMALY 13

-60.18	-123 74	15	ELTANIN 20	2
-59.25	-130 00	50		2
-56.39	-100 97	15	HUDSON	2
-58 07	-104.28		ELTANIN 23	2
-58.84	-121 16	15	HUDSON	2
-50 48	-95 71		ELTANIN 25	2
-66 54	-147 96		ELTANIN 42	2
-57 61	-119 37	30	ELTANIN 23	2
-55 59	-100 39	20	CON 12-12	2
-59 05	-130 56	13	ELTANIN 20	2
-59 28	-121 98	18	VEMA 16-7	2

ANOMALY 18

-55 52	-90 60	20	CON 12-12	2
-56 14	-98 76			2
-58 55	-101 53		ELTANIN 23	2
-50 21	-92 47		ELTANIN 25	2
-66 04	-140 84	15	ELTANIN 42	2
-60 05	-126 82	15	ELTANIN 20	2
-59 28	-118.68	15	VEMA 16-7	2
-60 50	-120 90	15	ELTANIN 20	2

ANOMALY 25

-60 02	-112 67	15	VEMA 16-7	2
-61 66	-114.38	10	ELTANIN 21	2
-61.68	-114 72	20	ELTANIN 20	2
-65 38	-128 70	10	ELTANIN 42	2
-61 80	-114 40	15	ELTANIN 19	2

ANOMALY 31

-65 67	-119.75	20	ELTANIN 33	2
-64 81	-117 83	10	ELTANIN 42	2
-64 36	-108 60	10	ELTANIN 42	2
-62 23	-106.08	15	ELTANIN 21	2

WEST ANTARCTIC PLATE FRACTURE ZONES

-46 88	-108 08	20		2
-48 55	-97 85	20		2
-51 19	-103 45	20		2
-57 66	-111 25	20		2
-57 74	-110 08	20		2
-55 48	-127 55	20		2
-55 92	-126.45	20		2
-56 86	-120 10	30		2
-56 82	-141 20	10		2
-58 21	-135 22	20		2
-58.29	-134 90	20		2
-52.89	-95 25			2
-57 71	-115 66	8	ELTANIN 23	2
-51 89	-98 67			2
-58 00	-99 00			2

WEST ANTARCTIC PLATE

-57 92	-99 57			2
-56.97	-101 60	15	ELTANIN 20	2
-56 18	-109 90			2
-55 34	-114 55			2
-61 43	-96 50	15		2
-59 95	-101 75	8	ELTANIN 23	2
-59.08	-104 88	9	ELTANIN 20	2
-58 49	-107 23	11	ELTANIN 23	2
-57 89	-109 35	9	ELTANIN 43	2
-56 46	-119 72			2
-56 42	-120 12			2
-61 98	-101 05	15		2
-61 83	-101 41	15		2
-59 94	-107 95	10	ELTANIN 23	2
-59 01	-110 17	13	ELTANIN 19	2
-57 58	-116 00			2
-55 07	-129 10			2
-54 72	-131 50			2
-54 58	-132 15			2
-54 46	-132 87			2
-64 50	-113 13	20		2
-60 24	-125 60	4	ELTANIN 20	2
-59 76	-127 50	4	ELTANIN 25	2

EAST ANTARCTIC PLATE

ANOMALY 6

-55 80	135 00	15	ELTANIN 34	1
-55 81	129 57	15	ELTANIN 35	1
-55 50	128 80		ELTANIN 35	1
-54 92	117 00		ELTANIN 35	1
-55 08	120 95		ELTANIN 35	1
-55 05	124 50		ELTANIN 37	1
-55 10	124 96		ELTANIN 37	1
-55 38	126 21		ELTANIN 39	1
-55 77	133.95		ELTANIN 39	1
-55 75	132.60	15	ELTANIN 41	1
-55 80	132 03	15	ELTANIN 41	1
-55 82	137 49		ELTANIN 41A	1
-55 78	137 41	15	ELTANIN 41A	1
-54 97	119 79		ELTANIN 44	1
-54 92	114 12		ELTANIN 45	1
-46 68	82 77		ELTANIN 47	1
-49 90	90 71		ELTANIN 47	1
-48 25	88 40	15	C8	5
-55 49	110.06		ELTANIN 49	1
-52 86	95 02		ELTANIN 49	1
-49.76	90 25		ELTANIN 49	1
-53 82	100 00		ELTANIN 49	1
-65.57	167 85		ELTANIN 50	1
-65.61	168 02	15	ELTANIN 50	1
-64.75	169.93	15	ELTANIN 50	1
-47.28	88.38	15	ELTANIN 54	1
-49 97	90 72	15	ELTANIN 54	1

ANOMALY 13

-59 36	134.95	15	ELTANIN 34	1
-59 31	128.31	15	ELTANIN 35	1
-59.30	127.88	15	ELTANIN 35	1
-59 38	125.96		ELTANIN 37	1
-59 34	132.47	15	ELTANIN 41	1
-59 37	132 07	15	ELTANIN 41	1
-59 25	121.92		ELTANIN 44	1
-59 16	120.00		ELTANIN 44	1
-50 80	82 15		CORE 8	5
-59 30	113 95		ELTANIN 45	1
-59 40	114 68		ELTANIN 45	1
-48 52	75.50		ELTANIN 47	1
-59 53	110.10	15	ELTANIN 49	1
-55 68	89 60		ELTANIN 49	1
-58 79	105 06	15	ELTANIN 50	1
-51 76	84 66		ELTANIN 53	1
-52 08	85 31		ELTANIN 54	1
-35 60	67 20		MD 1-3	6
-41 20	69 10	15	GA 4-7	6
-41 70	69 50	15		6
-68 71	173 37	15	ELTANIN 52	1
-66 60	176 10	25	GL 28	3
-66.50	176 25		ELTANIN 32	3
-67 00	175.50	25	ARIES 12	3
-67 25	175 10	25	ELTANIN 27	3
-68 65	173 50		GL 28	3
-68 80	173.15		ELTANIN 27	3

ANOMALY 18

-42 15	67.60	15	GA 4-5	6
-42 70	68 20	15		6
-36 95	65 70		MD 1-3	6
-67 25	178 85		ELTANIN 32	3
-67 27	178.60		GEOS	3
-67 35	178 40		ELTANIN 27	3
-68 85	176.30		ELTANIN 27	3
-60.03	126 08		ELTANIN 37	1
-60 75	132 01	15	ELTANIN 41	1
-60 66	132 03		ELTANIN 41	1
-60.74	120 11		ELTANIN 44	1
-60.67	120.12		ELTANIN 44	1
-60 79	114 17		ELTANIN 45	1
-60 83	113.84		ELTANIN 45	1
-57 98	89 86		ELTANIN 49	1
-53 41	83 99	15	ELTANIN 54	1
-52.85	82 99	15	ELTANIN 54	1

FRACTURE ZONE POINTS

-56 35	148 75	15	TASMAN FZ	4
-57 40	149.25	15	TASMAN FZ	4
-62 05	152.25	15	TASMAN FZ	4
-62.35	152 45	15	TASMAN FZ	4
-61 25	154.60		BALLENY FZ	4
-61.70	155.00		BALLENY FZ	4
-62.25	155.50		BALLENY FZ	4
-62.85	156.10		BALLENY FZ	4

Table 1. List of fracture zone and magnetic anomaly points used, uncertainty estimate (in km), ship track or name of fracture zone (if available) and source of data. Uncertainties are only given for points used in pole determination program. Source codes are: 1= Hayes et al. [1975-1978]; 2= Molnar et al [1975]; 3= Weissel et al. [1977]; 4= Hayes et al. [1974]; 5= Sclater et al. [1976]; 6= Schlich [1975].

POINTS ON THE AUSTRALIA PLATE

ANOMALY 6				
-44 32	135 00	15	ELTANIN 34	1
-54 81	149 96		ELTANIN 36	1
-57 05	154 91	15	ELTANIN 36	1
-56 69	157 22	15	ELTANIN 36	1
-44 43	132 94	15	ELTANIN 35	1
-43 32	127 97		ELTANIN 35	1
-44 33	131 55	15	ELTANIN 37	1
-43 33	126 24		ELTANIN 39	1
-44 39	132 04	15	ELTANIN 41	1
-44 34	132 02	15	ELTANIN 41	1
-44 30	131 49	15	ELTANIN 41A	1
-44.17	137 04	15	ELTANIN 41A	1
-48 16	142 17		ELTANIN 42	1
-42 46	105 25		ELTANIN 45	1
-43 83	114.38		ELTANIN 45	1
-40 06	99 93	15	ELTANIN 47	1
-39 40	98 39	15	ELTANIN 48	1
-35 50	82 31		ELTANIN 48	1
-35 99	90 26		ELTANIN 48	1
-42 88	110 17		ELTANIN 49	1
-28 45	79 90		CORE 2	5
-40 11	99 91		ELTANIN 49	1
-42 26	105 05		ELTANIN 50	1
-37 90	95 13	15	ELTANIN 54	1
-42 10	103 82		ELTANIN 54	1
-43 35	122 41		ELTANIN 54A	1
-44.44	133 02		ELTANIN 54A	1
ANOMALY 13				
-39 88	134 95		ELTANIN 34	1
-39 69	134 11	15	ELTANIN 35	1
-39 96	116 96	15	ELTANIN 35	1
-39.52	127 85		ELTANIN 35	1
-39 56	130.41	15	ELTANIN 35	1
-51 89	155 80		ELTANIN 36	1
-39 72	134 20		ELTANIN 39	1
-39 52	127 17		ELTANIN 39	1
-39 58	132.02	15	ELTANIN 41	1
-39 59	132 07		ELTANIN 41	1
-39 59	131.54	15	ELTANIN 41A	1
-39.75	133 78		ELTANIN 41A	1
-39 89	137 50	15	ELTANIN 42	1
-39 78	119 77		ELTANIN 44	1
-26 30	83 15	15	GC 25	5
-25 70	82 37	15	CORE 1,2	5
-33 00	89 40		V-16	5
-33 30	92 15		C-11	5
-38 50	105 85		C8	5
-37.00	102 35		527	5
-37.56	103 07		ELTANIN 45	1
-39.34	114 53	15	ELTANIN 45	1
-37 87	104 39		ELTANIN 47	1
-34.33	97.50		ELTANIN 48	1
-33.39	92.84		ELTANIN 48	1
-39 37	110 48		ELTANIN 49	1
-38 12	105 05		ELTANIN 50	1
-49 52	160 18		ELTANIN 53	1
-36 17	100 99		ELTANIN 54	1
-39.32	107 63		ELTANIN 54	1
-51 90	155 65	25	CO803	3
-49 60	160 15		ELTANIN 34	1
-51.80	156 10			3
-51.77	156 20	25		3
-27 73	84 50		526	1
-51 50	157 55	25		3
ANOMALY 18				
-50 40	155 80			3
-48 40	160 20		ELTANIN 34	1
-51 14	152 28		ELTANIN 42	1
-50 25	156 15		GL 26	3
-25.85	84 40	15	GL 26	5
-38 37	134 47	15	ELTANIN 34	1
-38 40	134 48		ELTANIN 35	1
-37 15	128 00		ELTANIN 35	1
-38 34	130 62		ELTANIN 35	1
-50 48	154 97		ELTANIN 36	1
-38 30	134.92	15	ELTANIN 39	1
-38 44	129.78	15	ELTANIN 39	1
-38 52	138 23	15	ELTANIN 40A	1
-38 46	132.12		ELTANIN 41	1
-38 42	132.06	15	ELTANIN 41	1
-38 37	131 48		ELTANIN 41A	1
-38.49	132.97		ELTANIN 41A	1
-38 71	118.75		ELTANIN 44	1
-34 76	101 84	15	ELTANIN 45	1
-37.80	114.50		ELTANIN 45	1
-38.06	111 26		ELTANIN 49	1
-34.81	101.74	15	ELTANIN 49	1
-38.51	105 13	15	ELTANIN 50	1
-48 31	160 67		ELTANIN 53	1
-37 86	109 46		ELTANIN 54	1
ANOMALY 25				
-39 95	156.05		ELTANIN 34	1
-39.48	155.75		ELTANIN 54B	1
-45 80	156.05		0906	3
-41.05	157.00		3215	3
-38.90	155 35		1812	3
-33 10	153 65		KH-68	3
-42 85	157 10		ELTANIN 53	1
-39 64	155.84		ELTANIN 39	1
-36 16	154.76		ELTANIN 48	1
-34 68	153 74		ELTANIN 47A	1
-36 62	155 01		ELTANIN 47A	1
-35 72	154 36		ELTANIN 47A	1
-38 06	155.00		ELTANIN 47A	1
ANOMALY 28				
-40.61	154 72		ELTANIN 34	1
-39 75	154 05		ELTANIN 54B	1
-47 35	155 00		ELTANIN 36	1
-43.70	155.80		GL 29	3
-45 20	153 85		0906	3
-40.90	155.00		3215	3
-45 08	153.93		ELTANIN 53	1
-43.50	155.61		ELTANIN 53	1
-43 18	155.30		ELTANIN 53	1
-40 69	154 76		ELTANIN 39	1
-36 79	153 37		ELTANIN 48	1
-34 69	152 60		ELTANIN 47A	1
-36.71	153.30		ELTANIN 47A	1
-35.67	152.56		ELTANIN 47A	1
ANOMALY 31				
-44 10	154 10		GL 29	3
-39.95	152.80		ELTANIN 54B	1
-41 21	153.42		ELTANIN 34	1
-40 75	153 18		3215	3
-44.06	154 08		ELTANIN 53	1
-37.11	152 27		ELTANIN 48	1
-41.79	153.61		ELTANIN 39	1
-37.55	152.42		ELTANIN 47A	1
-36.71	152.01		ELTANIN 47A	1

AUSTRALIA PLATE

ANOMALY 32				
-38.12	151 98	20	ELTANIN 47A	1
-41.59	152.57	20	ELTANIN 34	1
-40.10	151.65	20	ELTANIN 54B	1
-44.00	153.00		GL 29	3
-40 60	151 95	20	3215	3
-39 05	151 80	20	1812	3
-42.40	153 03	20	ELTANIN 39	1
-37.30	151 61	20	ELTANIN 48	1
-36 69	151 31	20	ELTANIN 47A	1
FRACTURE ZONE POINTS				
-44 70	152 75			3
-44 20	154 60			3
-40 98	154 17			3
-40 65	155 40			3
-35 00	152 15			3
-34.70	152 65			3
-41 51	152 74			3
-42 08	151 60			3
-45 60	144 40	15	TASMAN FZ	4
-46.75	144 75	15	TASMAN FZ	4
-47.80	145 20	15	TASMAN FZ	4

LORD HOWE PLATE

ANOMALY 25				
-39.31	157.31		ELTANIN 34	1
-39 10	157.15		1812	3
-45 20	157 75		0906	3
-40 65	158.50		3215	3
-38.69	158.93		ELTANIN 39	1
-35.79	155 78		ELTANIN 47A	1
-38.08	158.14		ELTANIN 47A	1
ANOMALY 28				
-44.99	160.01		ELTANIN 34	1
-43.00	158 30		GL 29	3
-44 05	159 00		0906	3
-40 10	160.00		3215	3
-33 03	155 70		KH-68	3
-43 80	158 79		ELTANIN 53	1
-43 09	158.37		ELTANIN 53	1
-43 42	158.58		ELTANIN 53	1
-46 98	161 13		ELTANIN 53	1
-37.85	157.71		ELTANIN 39	1
-45 07	159.94		ELTANIN 40A	1
-33 91	155 79		ELTANIN 47A	1
-34.70	156 38		ELTANIN 47A	1
-37.59	157 62		ELTANIN 47A	1
-38.15	157 96		ELTANIN 47A	1
ANOMALY 31				
-42.95	159 75		0906	3
-39 83	161.00		3215	3
-42 55	160.00		GL 29	3
-39.10	160.45		1812	3
-45 37	161 54		ELTANIN 53	1
-43.10	160.16		ELTANIN 53	1
-37.22	158.60		ELTANIN 39	1
-33.96	156 83		ELTANIN 47A	1
-38.21	159 24		ELTANIN 47A	1
-34 70	157.53		ELTANIN 47A	1
ANOMALY 32				
-45.22	164.18		ELTANIN 34	1
-42.30	161.45	20	GL 29	3
-41.85	161.00		0906	3
-39 58	161 75	20	3215	3
-39.15	161.45		1812	3
-37 09	158 89	20	ELTANIN 39	1
-34 00	157 75	20	ELTANIN 47A	1
-34 65	158.34	20	ELTANIN 47A	1
-36 72	158 74		ELTANIN 47A	1
-35.71	158 42	20	ELTANIN 47A	1
-37.61	159 32	20	ELTANIN 47A	1
-38.24	160 29	20	ELTANIN 47A	1

FRACTURE ZONE POINTS

-42 25	159 70			3
-43 05	157 60			3
-39 40	158 35			3
-38 60	160 00			3
-33 60	155 35			3
-33 10	155 40			3
-38 25	160 30			3
-41 85	161 10			3

PACIFIC PLATE

ANOMALY 6				
-40 90	-118 88	10	OC7008	2
-43 28	-120 42	10	ELTANIN 38	2
-44 31	-120.92	20	ELTANIN 20	2
-48.70	-126.78		ELTANIN 43	2
-49 01	-126 97		SOTUTHTOW	2
-50.03	-127 26		ELTANIN 28	2
-52 98	-145 22		ELTANIN 23	2
-55 28	-155 47	10	ELTANIN 19	2
-56 11	-156 62	10	ELTANIN 25	2
-56 45	-157 30	20	VEMA 16-7	2
-63 29	179 57		MONSOON 6	2
ANOMALY 13				
-51 67	-150 00		HUDSON	2
-52 57	-151 89		ELTANIN 33	2
-31.35	-136 67		CON 9-5	2
-47 60	-131 62		ELTANIN 19	2
-47.91	-131 87		SOUTHTOW	2
-51.19	-133 64	20	CON 12-12	2
-51 90	-150 59	15	ELTANIN 23	2
-53 23	-159 05	16	ELTANIN 19	2
-54 37	-160 64	13	ELTANIN 25	2
-39 82	-127 34		CON 8-6	2
ANOMALY 18				
-62 84	173 04		ELTANIN 32	2
-59 08	-175 01	20	ELTANIN 33	2
-58 84	-172 95	41	MONSOON 6	2
-51 58	-152 29	15	ELTANIN 33	2
-58 01	-168 34	15	ELTANIN 43	2
-46.52	-133.28	10	SOUTHTOW	2
-47 33	-133 92	15	ELTANIN 19	2
-51.52	-152 15	30	ELTANIN 23	2
-52 64	-160 28	22	ELTANIN 19	2
-53 90	-161.86	14	ELTANIN 25	2
-40.85	-130 54		CON 8-6	2
ANOMALY 25				
-58 65	177 65		ELTANIN 32	2
-53.70	-157.60	30		2
-60.85	171.14		ELTANIN 32	2
-60.96	170.34		MONSOON 6	2
-50.20	-157 24	10	ELTANIN 23	2
-50.02	-156.76	10	ELTANIN 33	2
-48 62	-141.17		CON 12-12	2
-42 43	-137 13		CON 8-6	2
-34 16	-142 47		CON 9-5	2
-35 08	-142 10		OC6702	2
-58 40	178 30		ELTANIN 27	2
-57 23	-179 68		ELTANIN 33	2
-56 73	-175 02		MONSOON 6	2
-56 25	-172 30		ELTANIN 43	2
-52 20	-165 79	10	ELTANIN 25	2
-51 10	-164 24	10	ELTANIN 19	2

Table 1 (continued)

Table 2: Best fit poles and angles, and poles and angles representing the outer limits of uncertainty regions for revised reconstructions

South Pacific Pacific-Antarctica	Best pole	4 end members			
A5	72.0 N -70.0 W 9.75°	69.0 N -80.0 W 9.10°	75.0 N -60.0 W 10.40°	73.0 N -76.0 W 9.75°	71.0 N -68.0 W 9.70°
A6	71.25 N -73.19°W 15.41°	73.0 N -68.0 W 15.95°	69.0 N -78.0 W 14.80°	71.0 N -76.0 W 15.25°	71.0 N -70.0 W 15.45°
A13	74.83 N -56.86 W 28.01°	74.20 N -57.0 W 27.85°	75.40 N -57.0 W 28.14°	77.30 N -34.0 W 32.62	70.60 N -73.0 W 24.71°
A18	75.08 N -51.25 W 32.56°	74.70 N -51.25 W 32.62°	75.40 N -51.25 W 32.48°	75.90 N -44.0 W 34.23°	74.30 N -57.0 W 31.17°
A25	71.61 N -57.47 W 40.11°	72.0 N -60.0 W 39.65°	71.0 N -56.0 W 40.40°	74.0 N -44.0 W 44.60°	70.0 N -62.0 W 38.35°
A31	71.65 N -49.0 W 53.75°	72.0 N -40.0 W 57.25°	70.0 N -56.0 W 50.45°	72.0 N -50.0 W 53.70°	71.0 N -48.0 W 53.60°
Southeast Indian Ocean Australia-Antarctica					
A6	8.95 N 32.07 E -11.90°	18.0 N 29.0 E -12.10°	5.0 N 34.0 E -11.80°	7.0 N 30.0 E -11.92°	11.0 N 34.0 E -11.86°
A13	11.68 N 31.81 E -20.46°	14.0 N 30.0 E -20.74°	8.0 N 35.0 E -20.08°	13.0 N 33.0 E -20.56°	10.0 N 31.0 E -20.42°
A18	11.47 N 31.03 E -23.58°	14.0 N 32.0 E -23.70°	7.0 N 33.0 E -22.86°	13.0 N 37.0 E -23.32°	9.0 N 28.0 E -23.44°
Tasman Sea Lord Howe-Australia					
A28	-4.49 S 139.36 E -5.66°	-12.0 S 140.0 E -6.72°	8.0 N 138.0 E -4.64°	-4.0 S 136.0 E -5.48°	-4.0 S 144.0 E -5.80°
A32	-10.63 S 139.33 E -12.30°	-18.0 S 144.0 E -16.48°	0.0 S 132.0 E -9.26°	-13.0 S 137.0 E -13.01°	-8.0 S 142.0 E -11.82°

Table 3: Other poles and angles used in reconstructions. Sources: 1 = interpolation between recalculated poles (Table 2); 2 = Weissel et al. [1977]; 3 = Minster and Jordan [1978]. a = assumes closure of Australia to Antarctica at ~53 my b = assumes closure of Australia to Antarctica at ~95 my

Anomaly	Source	Best Pole			End Members		
		λ	φ	θ	λ	φ	θ
Southeast Indian Ocean (Australia-E. Antarctica)							
5	1	11.85	34.74	-6.60	8.0	36.3	-6.54
					14.0	36.3	-6.58
					10.0	33.0	-6.61
					15.5	32.0	-6.71
22[a]	2	10.3	32.7	-30.0			
22[b]	1	-11.19	-148.57	24.85			
25[b]	1	-11.05	-148.37	25.56			
31[b]	1	-10.84	-148.07	26.66			
Pacific Ocean (Pacific-W. Antarctica)							
22	1	72.7	-55.81	37.43	71.09	-60.34	35.79
					72.09	-54.34	37.70
					73.09	-58.34	37.0
					74.09	42.34	41.62
Tasman Sea							
25	1	-4.49	139.36	-2.12			
31	1	9.48	-40.60	10.08			

Figure Captions

Figure 1 Reconstruction for anomaly 6, Southeast Indian Ocean: best fit rotation (a) and end member rotations (b) through (e), with map showing extent of uncertainty region (f). Triangles represent fracture zone points; circles represent magnetic anomaly locations. The Antarctica plate (open symbols) is held fixed and the Australia plate (filled symbols) is rotated about poles shown in (f) (Table 1).

Figure 2 Reconstruction for anomaly 13, Southeast Indian Ocean: best fit rotation (a) and end member rotations (b) through (e), with map showing extent of uncertainty region (f). Symbols are the same as in Figure 1.

Figure 3 Reconstruction for anomaly 18, Southeast Indian Ocean: best fit rotation (a) and end member rotation (b) through (e), with map showing extent of uncertainty region (f). Best fit rotations without anomalies from the far eastern section (h) and without anomalies from the far western section (g) are also shown. Symbols are the same as in Figure 1.

Figure 4 Mercator projection showing the location of best fit poles and their uncertainty regions for Australia-Antarctica relative positions for the times of anomalies 6, 13, and 18. Estimates of the Antarctica-India instantaneous pole from the best-fitting angular velocity vector between the two plates (square) and RM2 geohedron (triangle) [Minster and Jordan, 1978] are also shown.

Figure 5 Reconstructions for anomaly 5, South Pacific Ocean: best fit rotation (a) and end member rotations (b) through (e), with map showing extent of uncertainty region (f). Triangles represent fracture zone points: circles are magnetic anomaly locations. The Antarctica plate (filled symbols) is held fixed and the Pacific plate (open symbols) is rotated about the poles indicated in (f)(Table 1).

Figure 6 Reconstructions for anomaly 6, South Pacific Ocean: best fit rotation (a) and end member rotations (b) through (e), with map showing extent of uncertainty region (f). Symbols are the same as in Figure 5.

Figure 7 Reconstructions for anomaly 13, South Pacific Ocean: best fit rotation (a) and end member rotations (b) through (e), with map showing extent of uncertainty region (f). Symbols are the same as in Figure 5.

Figure 8 Reconstructions for anomaly 18, South Pacific Ocean: best fit rotation (a) and end member rotations (b) through (e), with map showing extent of uncertainty region (f). Symbols are the same as in Figure 5.

Figure 9 Reconstructions for anomaly 25, South Pacific Ocean: best fit rotation (a) and end member rotations (b) through (e), with map showing extent of uncertainty region (f). Symbols are the same as in Figure 5.

Figure 10 Reconstructions for anomaly 31, South Pacific Ocean: best fit rotation (a) and end member rotations (b) through (e), with map showing extent of uncertainty region (f). Symbols are the same as in Figure 5.

Figure 11 Orthographic projection showing the location of best fit poles and their uncertainty regions for Pacific-Antarctica relative positions for the times of anomalies 5, 6, 13, 18, 25 and 31. Square represents the instantaneous pole of Pacific-Antarctica motion from Minster and Jordan [1978].

Figure 12 Reconstructions for anomaly 28, Tasman Sea: best fit rotation (a) and end member rotations (b) through (e), with map showing extent of uncertainty region (f). Triangles represent fracture zone points; circles are magnetic anomaly locations. Australia plate (open symbols) is held fixed and the Lord Howe plate (closed symbols) is rotated about poles indicated in (f) (Table 1).

Figure 13 Reconstructions for anomaly 32, Tasman Sea: best fit rotations (a) and end member rotations (b) through (e), with map showing extent of uncertainty region (f). Symbols are the same as in Figure 12.

Figure 14 Orthographic projection of the New Zealand Region showing the location of the Pacific-Australia finite poles and the uncertainty regions for the times of anomalies 5, 6, 13 and 18. Also shown are estimates of the location of the present Pacific-Australia instantaneous pole, from the best-fitting angular velocity vector between the two plates (triangle) and RM2 geohedron (square) [Minster and Jordan, 1978].

Figure 15 Orthographic projection showing New Zealand, the positions of two points on the Pacific plate at the present, and best fit positions of these points at the times of anomalies 6, 13, and 18. Oval regions represent the uncertainties in the past positions of these points, derived from uncertainties in marine magnetic reconstructions. The 2 km bathymetric contour of the Lord Howe Rise and the Campbell Plateau is shown for reference.

Figure 16 Best fit configuration of the Australia, Antarctica, and Pacific plates for anomaly 6 time. Magnetic anomaly locations and fracture zone positions are shown with different symbols: star (anomaly 31),

Figure 16 (contd.) circle with fringe (anomaly 25), diamond (anomaly 18), circle (anomaly 13), square (anomaly 6), triangles (fracture zones). Filled symbols are on the Australia and Pacific plates, open symbols on the Antarctica and Lord Howe plates. In this and in subsequent figures, Antarctica is kept fixed with respect to the center of the diagram.

Figure 17 Best fit configuration of the Australia, Antarctica, and Pacific plates for anomaly 13 time. Symbols and conventions are the same as in Figure 16.

Figure 18 Best fit configuration of the Australia, Antarctica, and Pacific plates for anomaly 18 time. Symbols and conventions are the same as in Figure 16.

Figure 19 Best fit configuration of the Australia, Antarctica, Lord Howe, and Pacific plates for anomaly 22 time, assuming that Australia-Antarctica separation began at anomaly 22 time and that a plate boundary has traversed the New Zealand region since the late Cretaceous. Symbols and conventions are the same as in Figure 16.

Figure 20 Best fit configuration of the Australia, Antarctica, Lord Howe, and Pacific plates for anomaly 25 time, assuming that Australia-Antarctica separation began at anomaly 25 time and that a plate boundary has traversed the New Zealand region since the late Cretaceous. Symbols and conventions are the same as in Figure 16.

Figure 21 Best fit configuration of the Australia, Antarctica, Lord Howe, and Pacific plates for anomaly 31 time, assuming that Australia-Antarctica separation began at anomaly 31 time and that a plate boundary has traversed the New Zealand region since the late Cretaceous. Symbols and conventions are the same as in Figure 16.

Figure 22 Best fit configuration of the Australia, Antarctica, Lord Howe, and Pacific plates for anomaly 22 time, assuming that the Lord Howe Rise was fixed to the Pacific plate until ~43 my but that Antarctica was two plates prior to this time. Symbols and conventions are the same as in Figure 16.

Figure 23 Best fit configuration of the Australia, Antarctica, Lord Howe, and Pacific plates for anomaly 25 time, assuming that the Lord Howe Rise was fixed to the Pacific plate until ~43 my but that Antarctica was two plates prior to this time. Symbols and conventions are the same as in Figure 16.

Figure 24 Best fit configuration of the Australia, Antarctica, Lord Howe, and Pacific plates for anomaly 31 time, assuming that the Lord Howe Rise was fixed to the Pacific plate until ~43 my but that Antarctica was two plates prior to this time. Symbols and conventions are the same as in Figure 16.

Figure 25 Orthographic projection showing the positions of two points on the Pacific plate at the times of anomalies 18, 22, 25, and 31, relative to fixed Lord Howe Rise. The best fit position of the Campbell Plateau with respect to fixed Lord Howe Rise at the time of anomaly 22 is also shown. This figure assumes that Australia-Antarctica separation began at ~43 my.

Figure 26 Orthographic projection showing the positions of two points on the Pacific plate at the times of anomalies 18, 22, 25, and 31, relative to fixed Lord Howe Rise. The best fit position of the Campbell Plateau with respect to fixed Lord Howe Rise at the time of anomaly 22 is also shown. This figure assumes that Australia-Antarctica separation began at ~95 my.

Figure 27 Uncertainties in the positions of two points on West Antarctica relative to fixed East Antarctica at the times of anomalies 13, 18, 33, 25, 31, assuming that Australia-Antarctica separation began at ~53 my. The Lord Howe Rise is assumed fixed to the Pacific plate until ~43 my (a) or ~35.6 my (b). Sea level and the 2 km bathymetric contour are shown.

Figure 28 Uncertainties in the positions of two points on West Antarctica relative to fixed East Antarctica at the times of anomalies 13, 18, 22, 25, 31, assuming that Australia-Antarctica separation began at ~95 my. The Lord Howe Rise is assumed fixed to the Pacific plate until ~43 my (a) or ~35.6 my (b).

Figure 29 Position of the Chatham Islands 70-80 my paleomagnetic pole of Grindley et al. [1977] when rotated back to East Antarctica at 68 my (triangles) or 80 my (squares). Alternative assumptions used are: no deformation in Antarctica since mid-Cretaceous time (a); post middle Cretaceous deformation in Antarctica. with Australia-Antarctica separation beginning at ~53 my and the Lord Howe Rise fixed to the Pacific plate prior to anomaly 13 time (b) or anomaly 18 time (c); post middle Cretaceous deformation in Antarctica, with Australia-Antarctica separation beginning at ~95 my and the Lord Howe Rise fixed to the Pacific plate prior to anomaly 13 time (d) or anomaly 18 time (e). The East Antarctica paleomagnetic poles and uncertainty regions from Suarez and Molnar [1979] for 70 and 80 my are shown for comparison.

Uncertainties in all of the rotated positions of poles (b) through (e) are comparable to the one shown for rotated Chatham Islands 70 my pole b. Uncertainties in the position of poles a would be smaller.

Figure 30 Positions of possible instantaneous poles of Lord Howe-East Antarctica motion between anomalies 32 to 28 time (circles), and possible instantaneous poles of Pacific-West Antarctica motion between anomalies 31 and 25 time (triangles). Lord Howe instantaneous poles have been rotated back to East Antarctica assuming that separation of Australia from Antarctica began at ~53 my. Circled points are best fit stage poles.

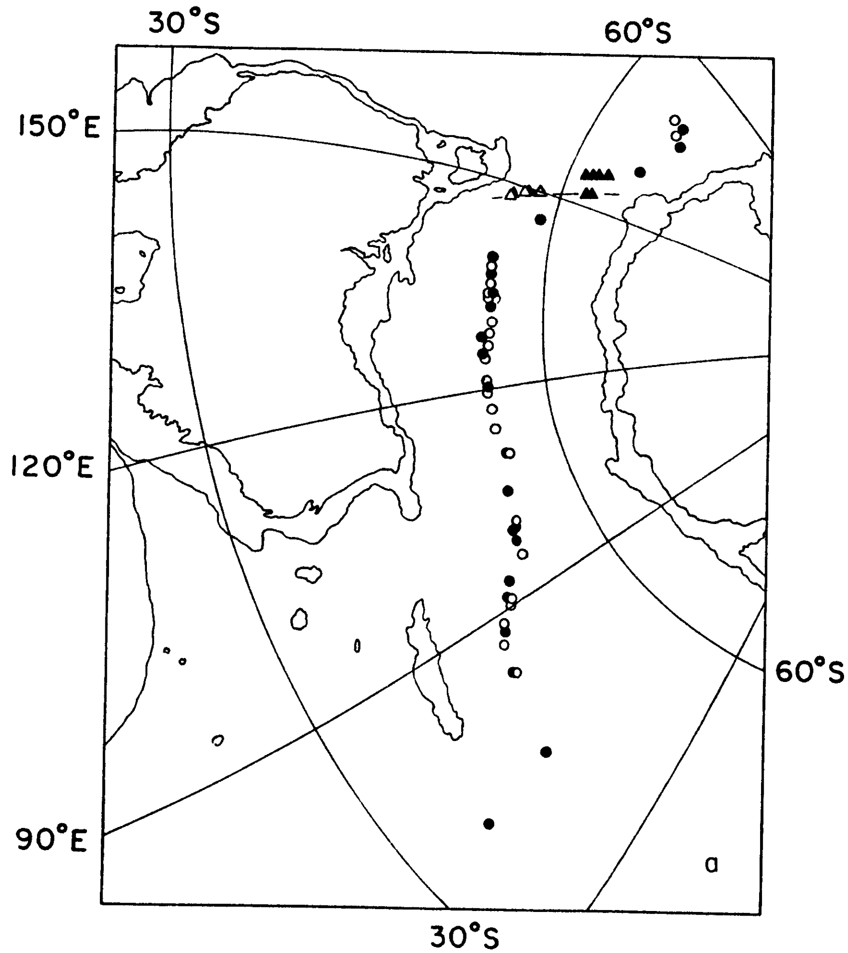


Figure 1a

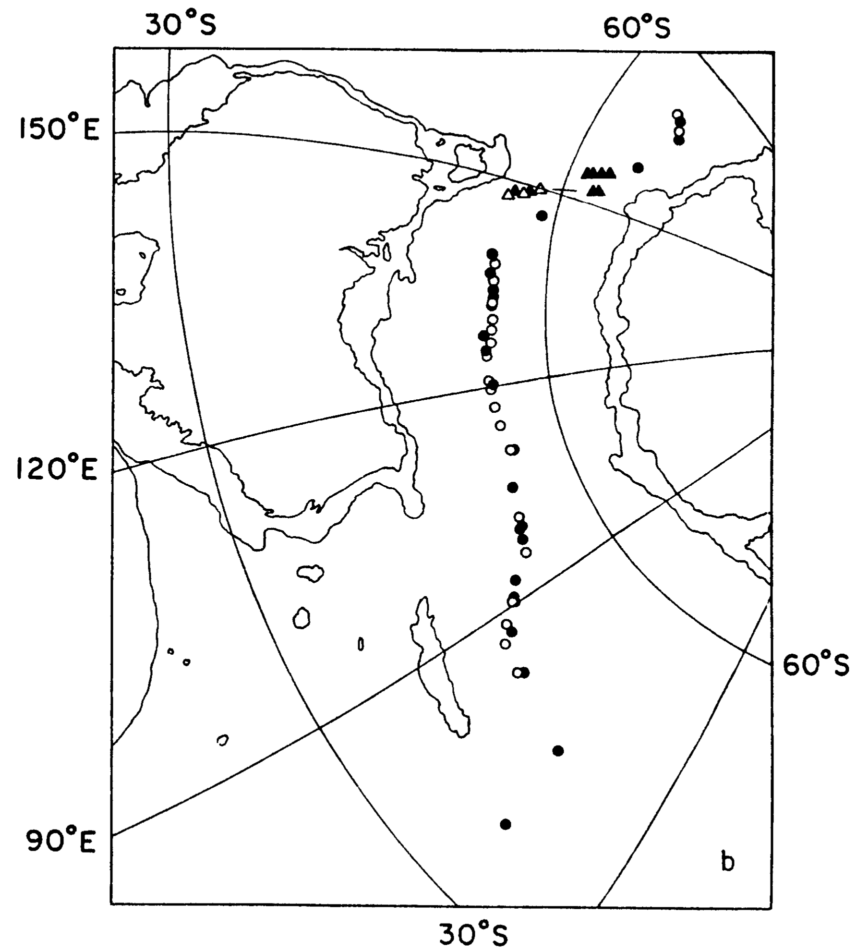


Figure 1b

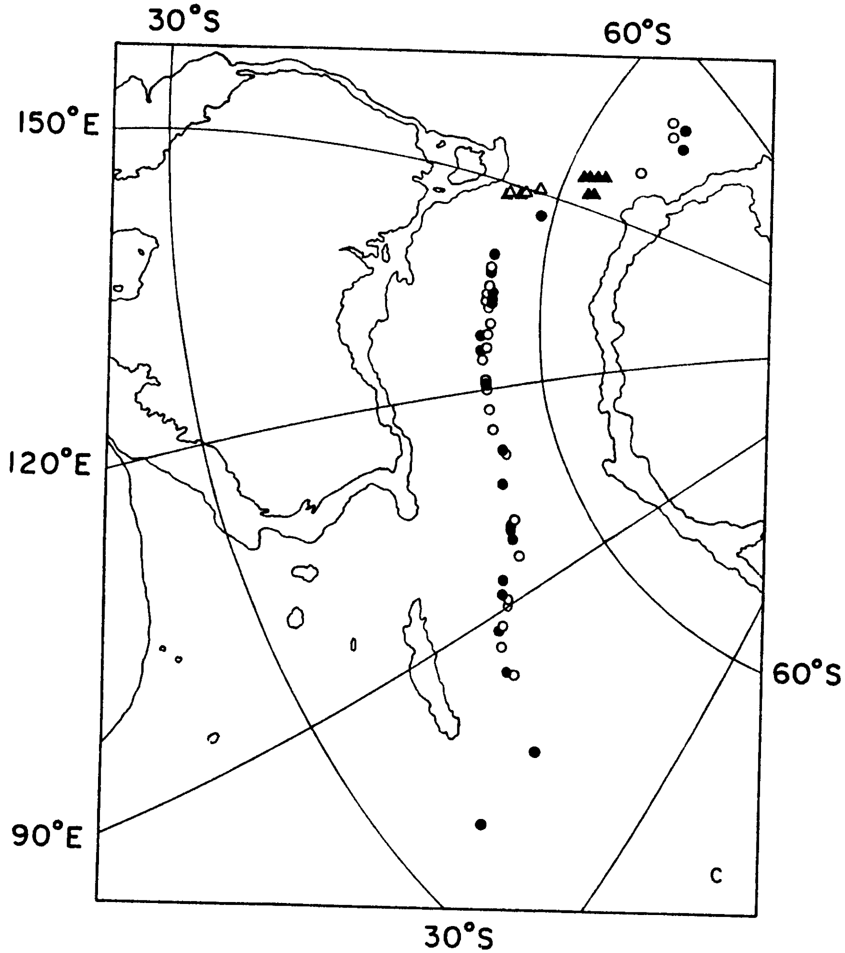


Figure 1c

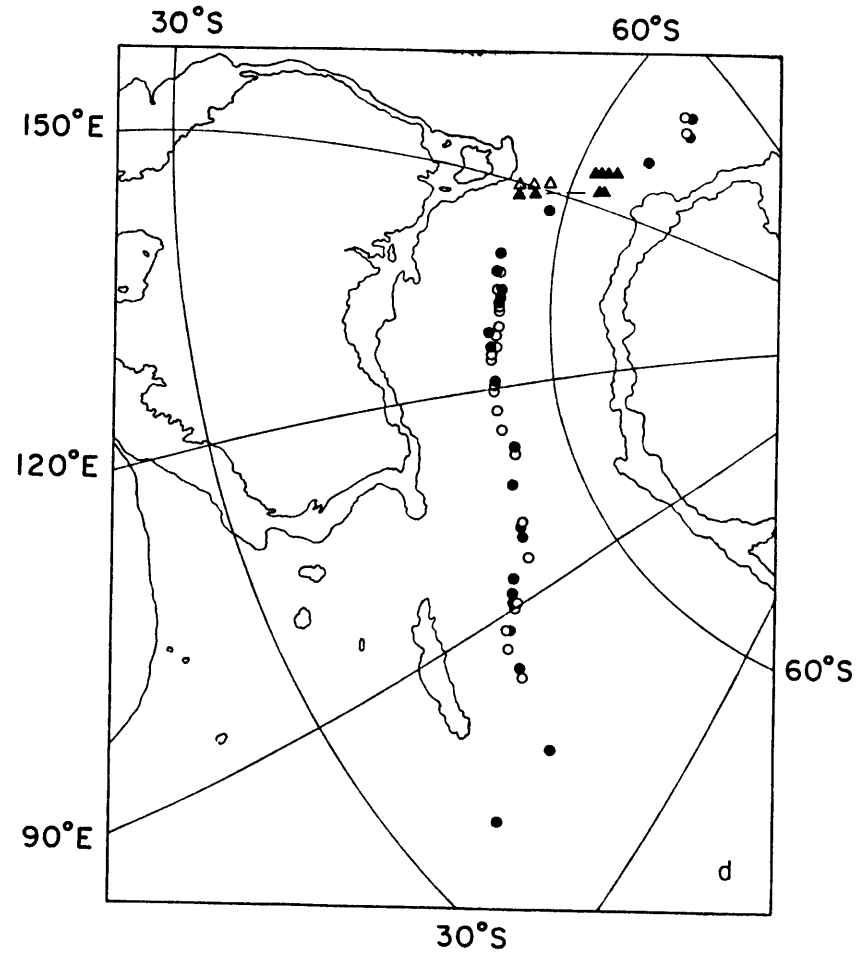


Figure 1d

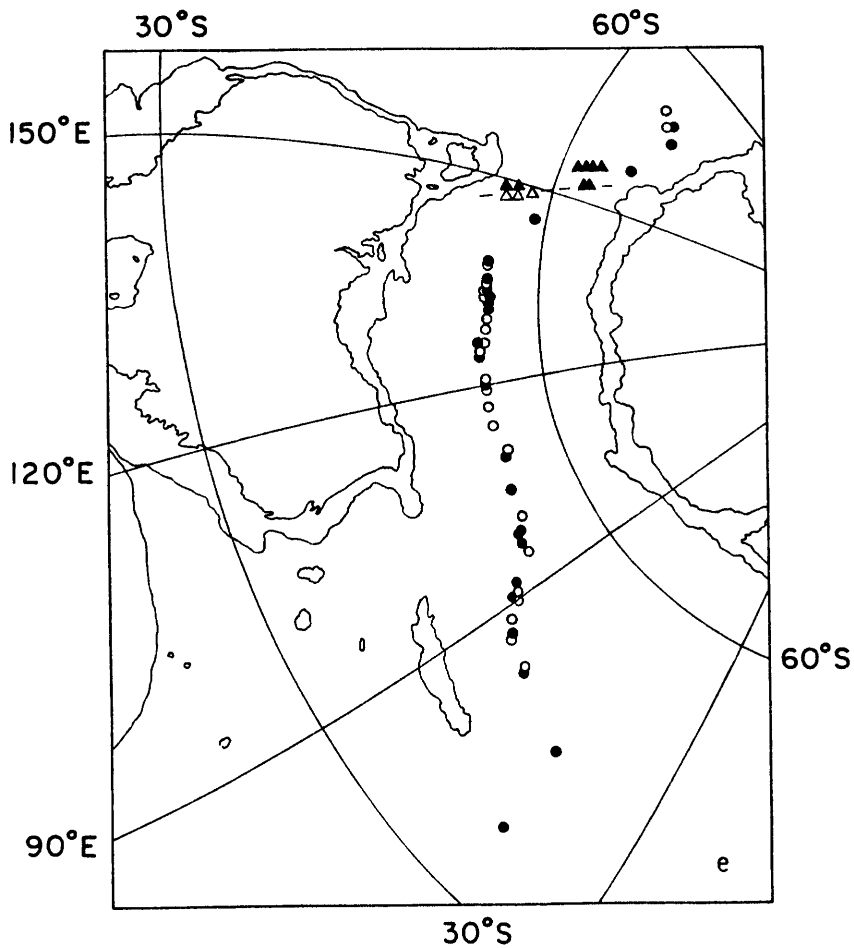
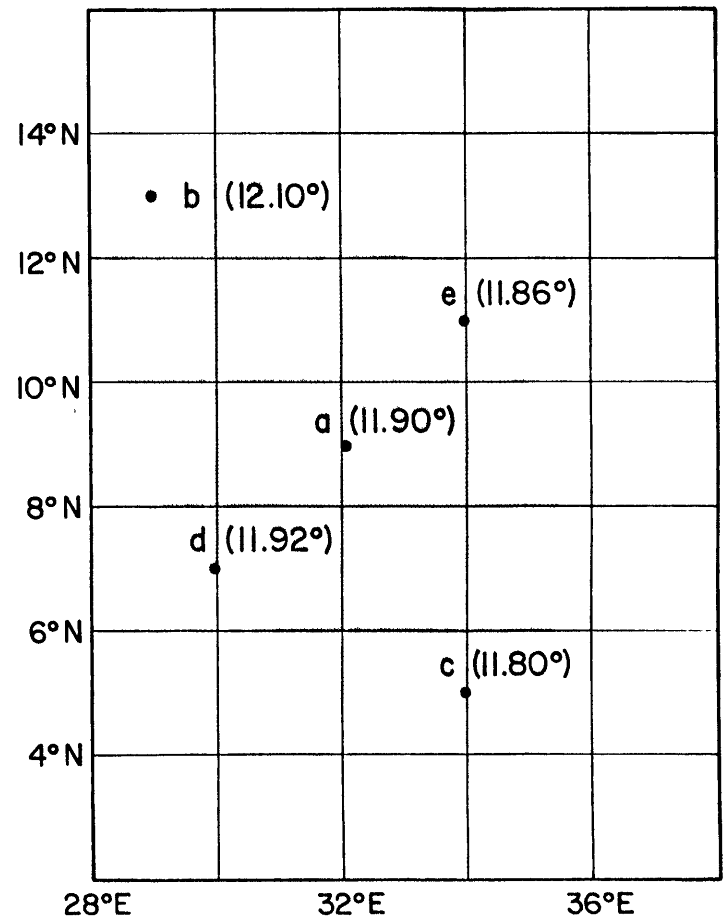


Figure 1e



Anomaly 6
Southeast Indian Ridge
best pole and uncertainty region

Figure 1f

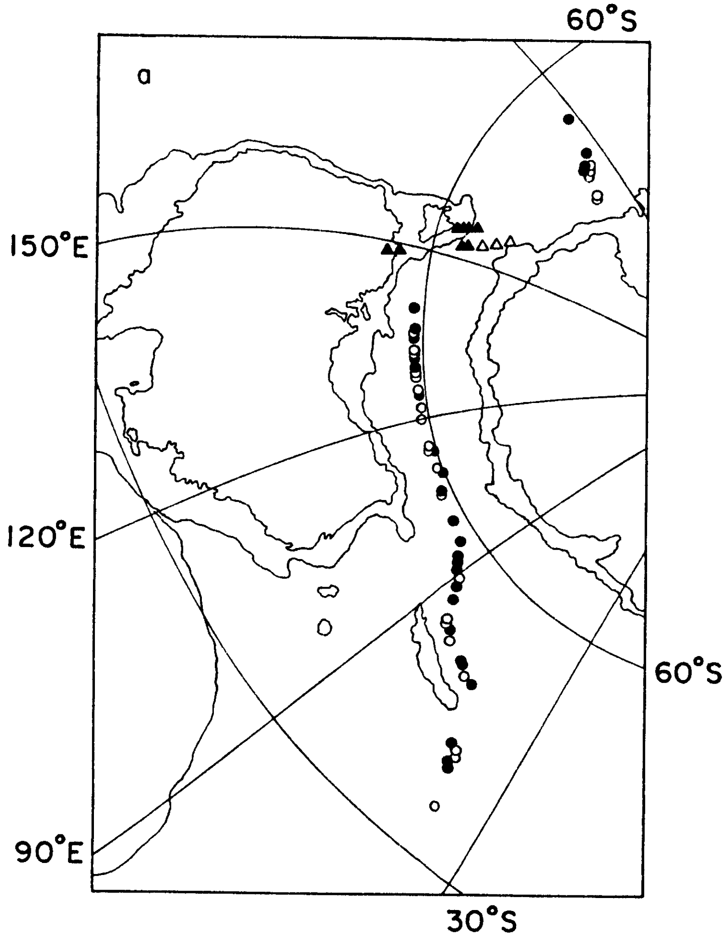


Figure 2a

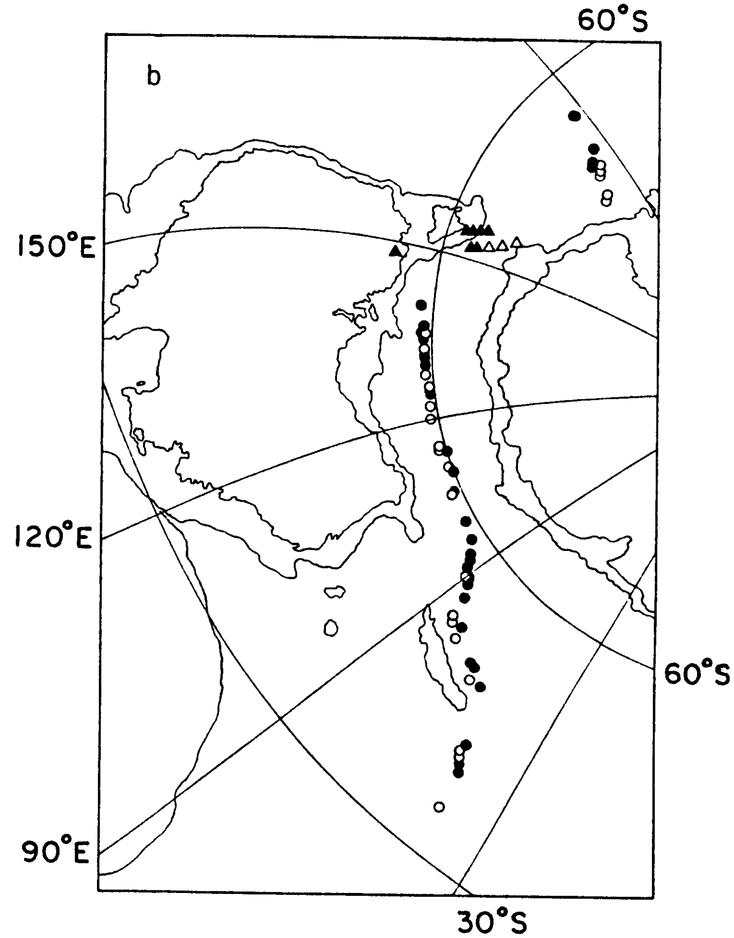


Figure 2b

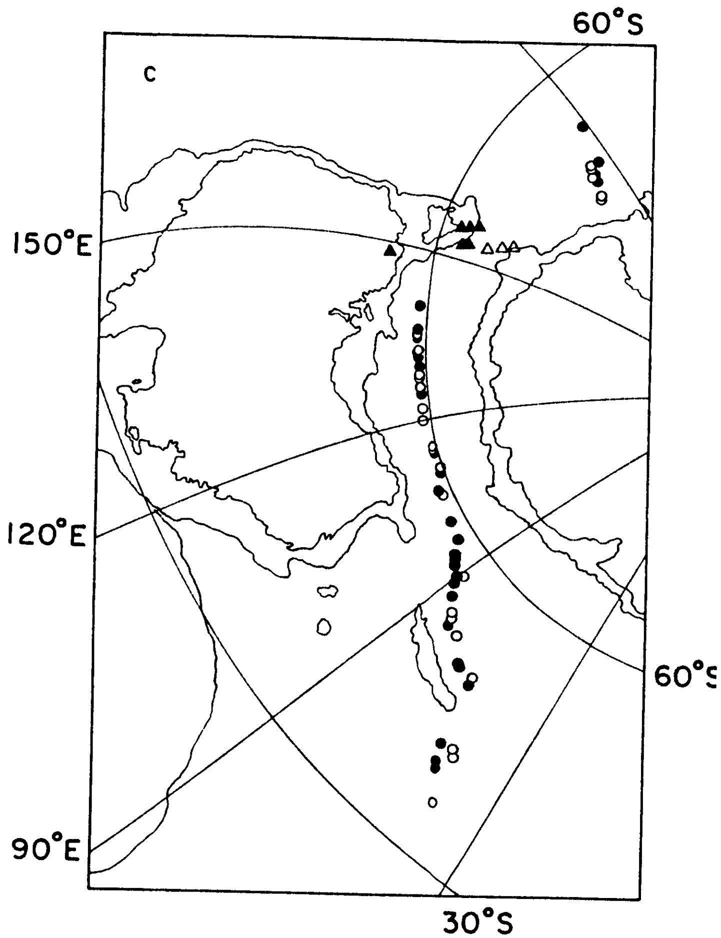


Figure 2c

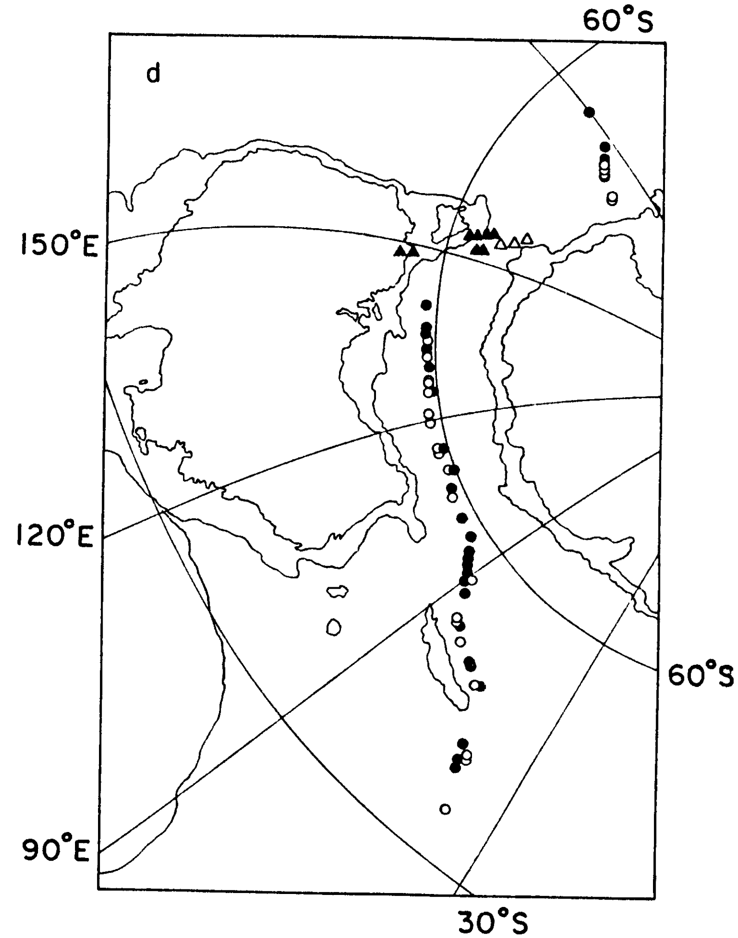


Figure 2d

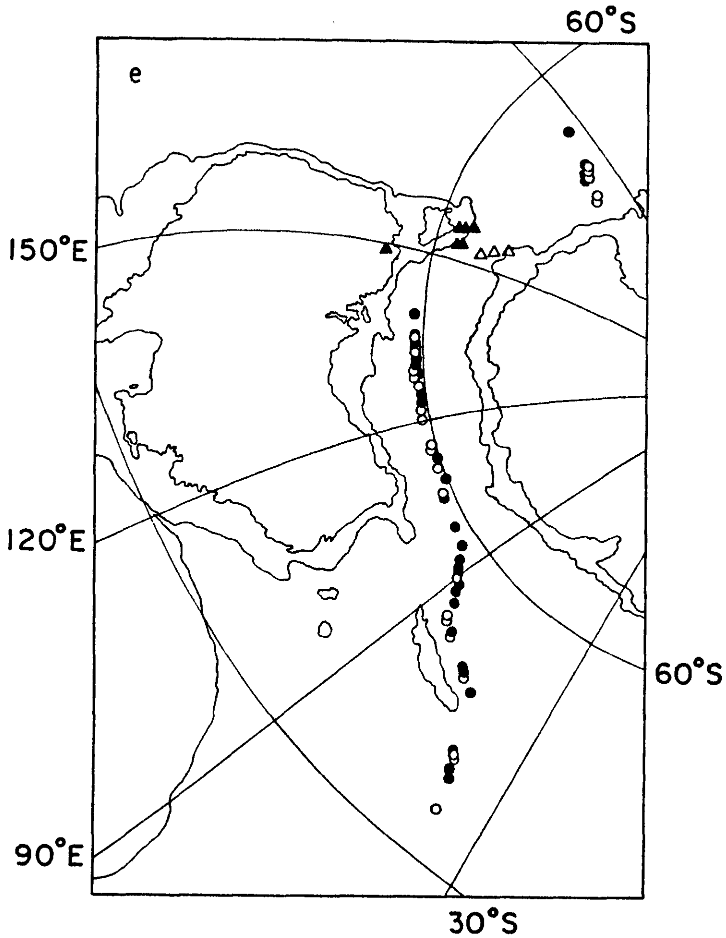
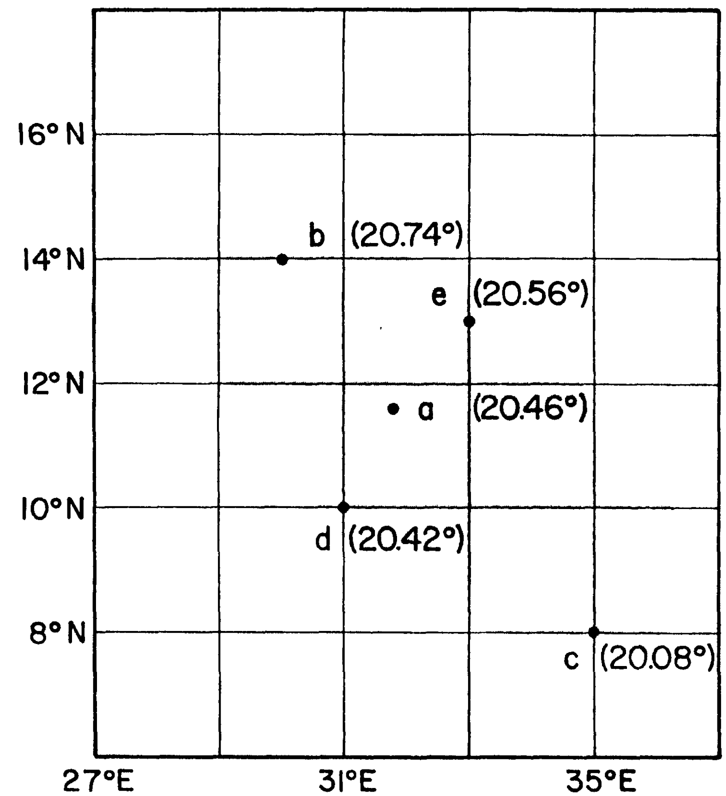


Figure 2e



Anomaly 13
Southeast Indian Ridge
best pole and uncertainty region

Figure 2f

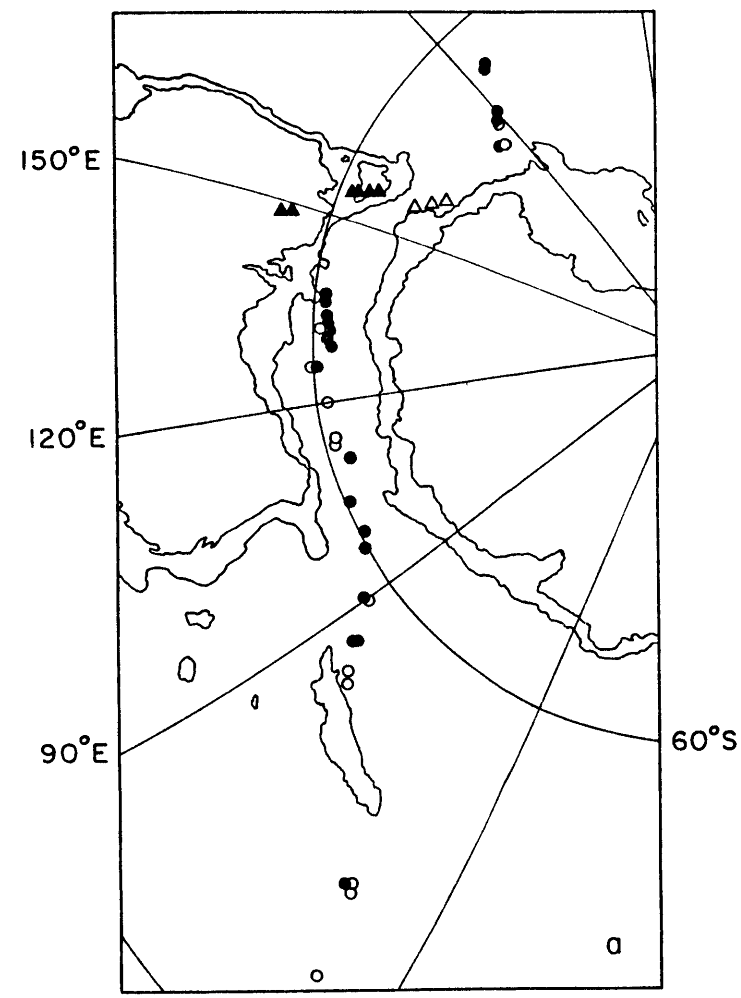


Figure 3a

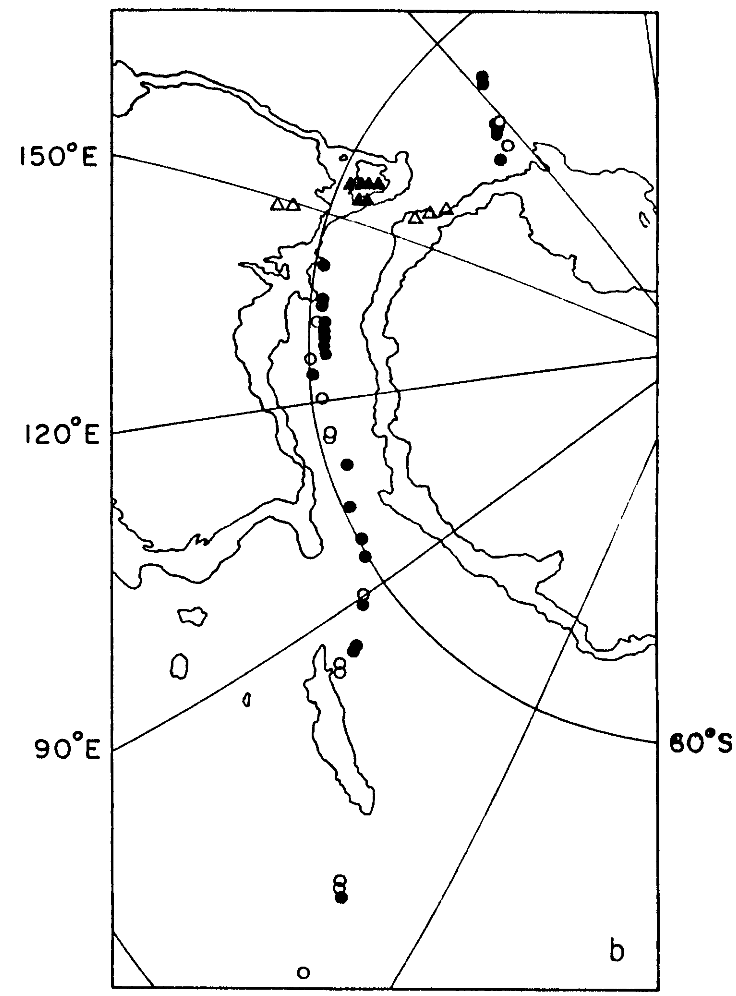


Figure 3b

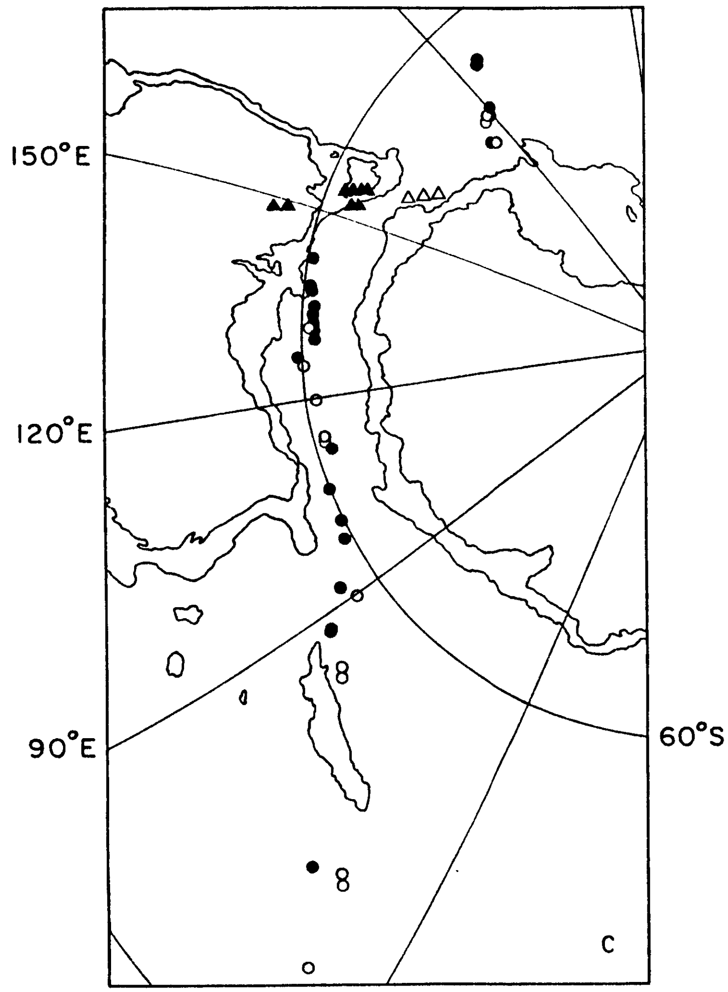


Figure 3c

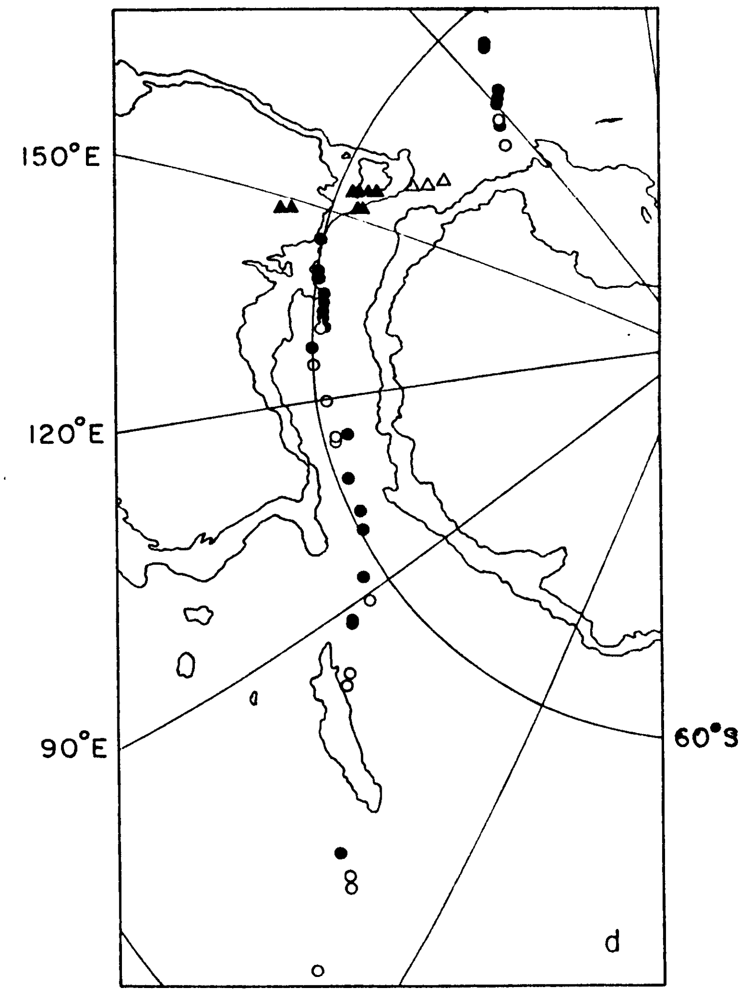


Figure 3d

Figure 3e

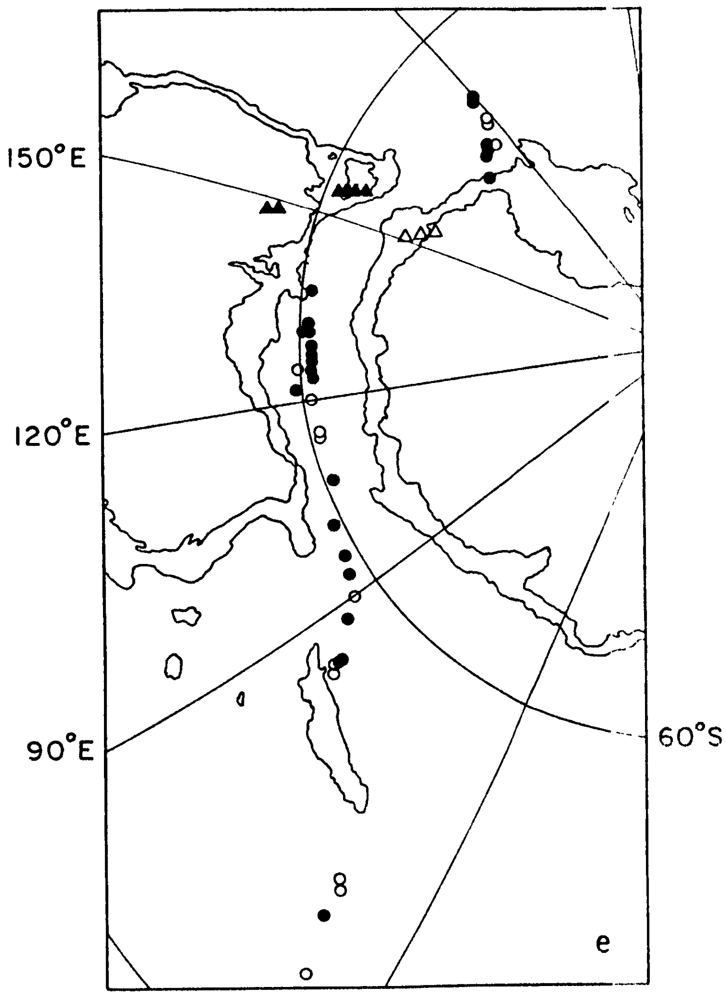
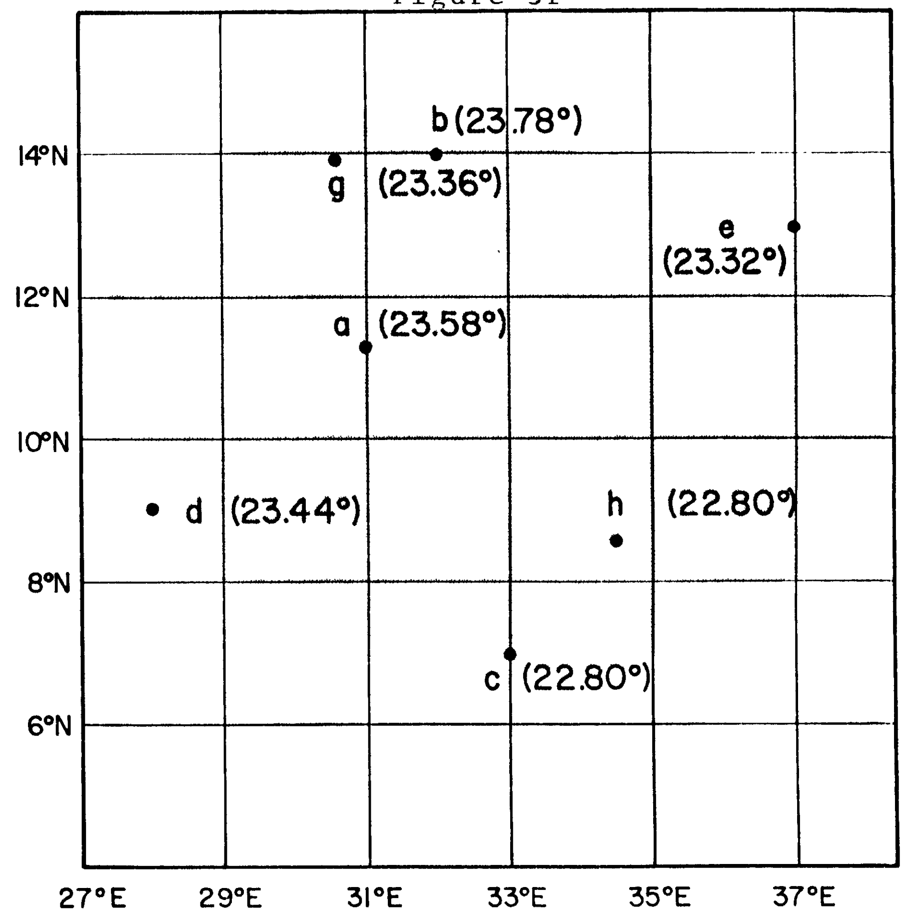


Figure 3f



Anomaly 18
Southeast Indian Ridge
best pole and uncertainty region

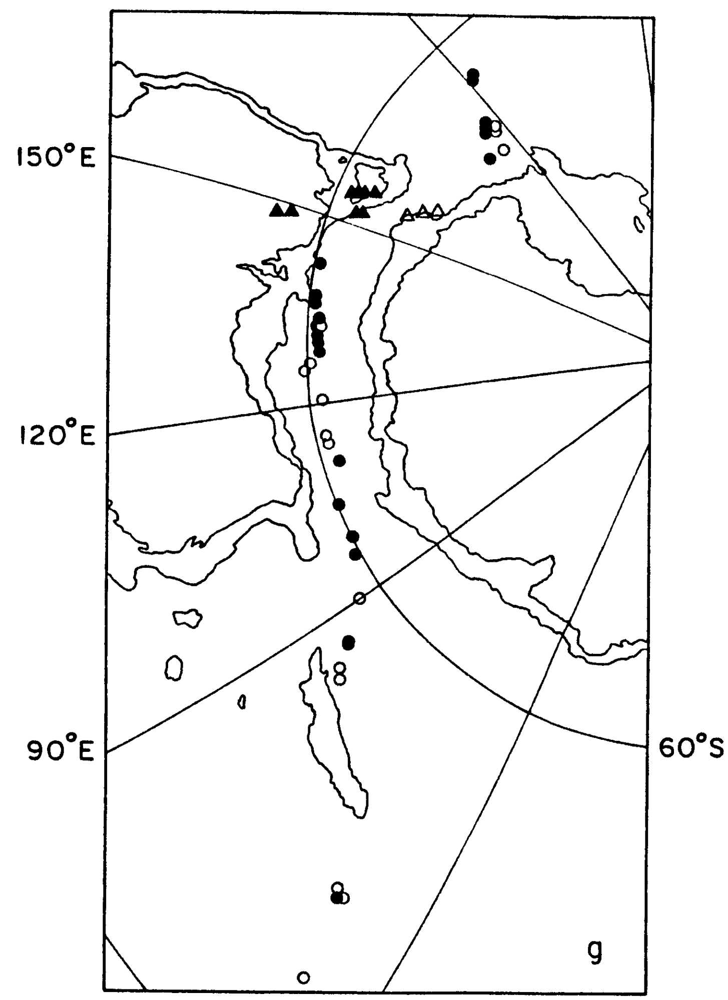


Figure 3g

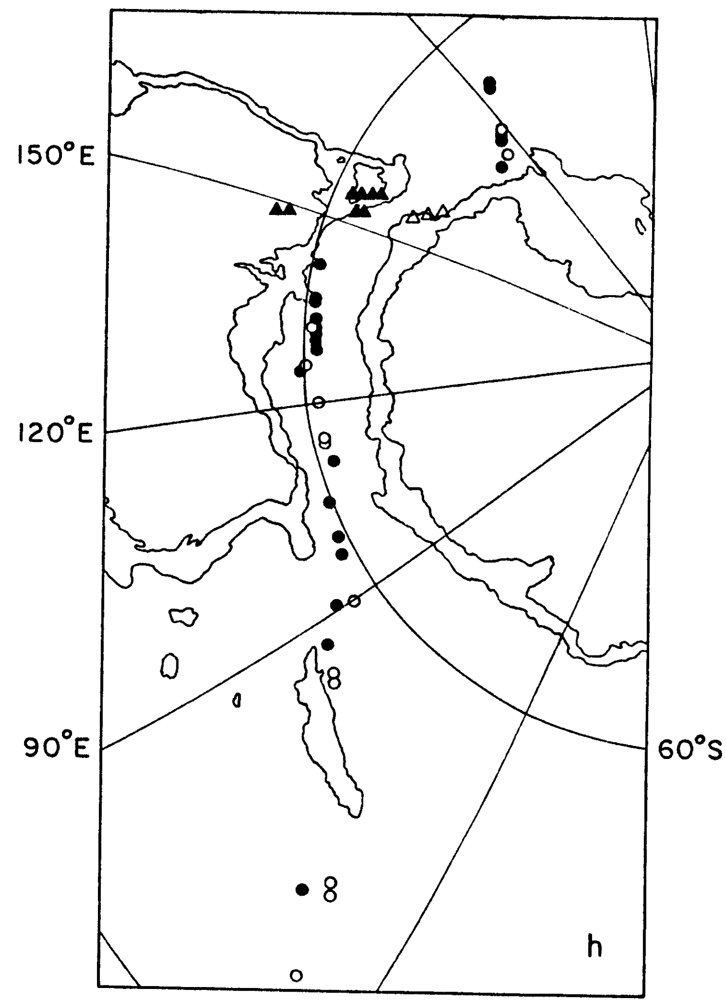


Figure 3h

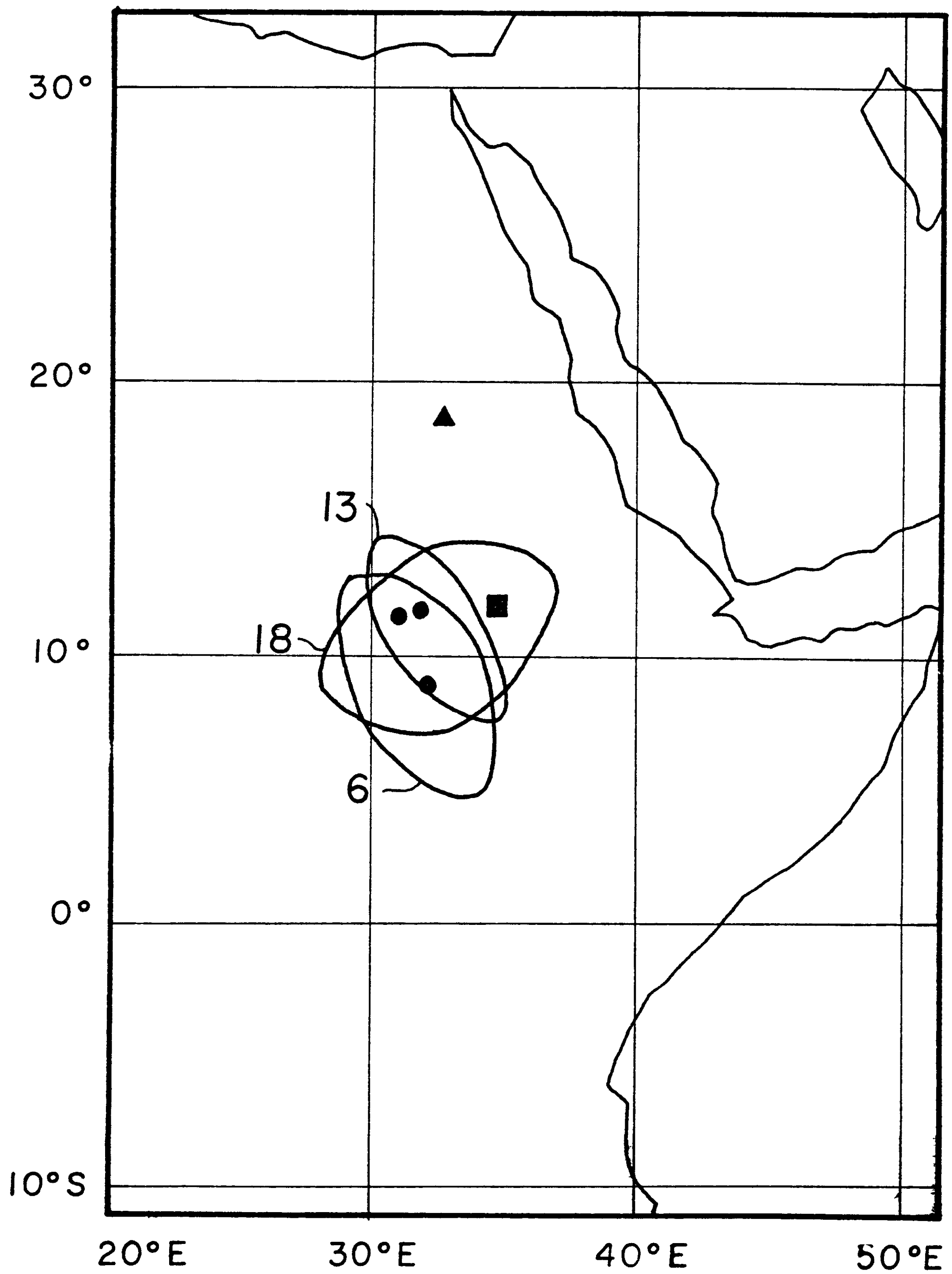


Figure 4

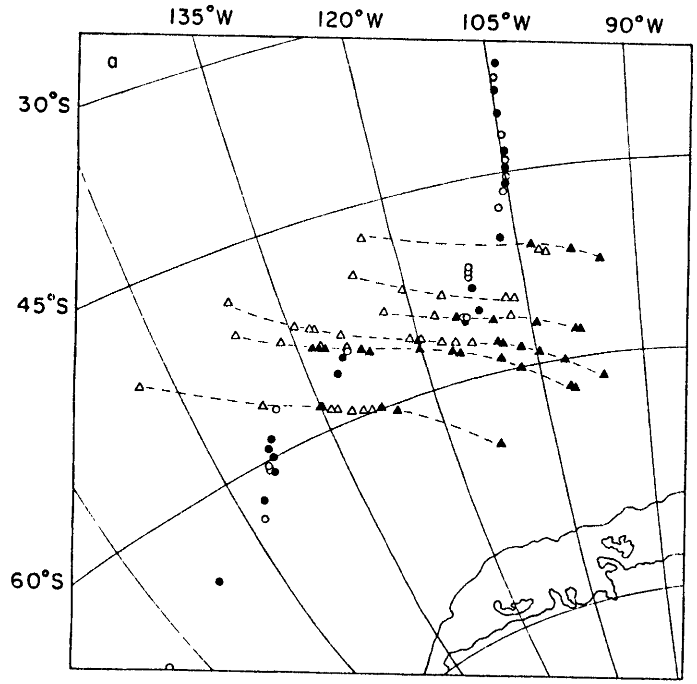


Figure 5a

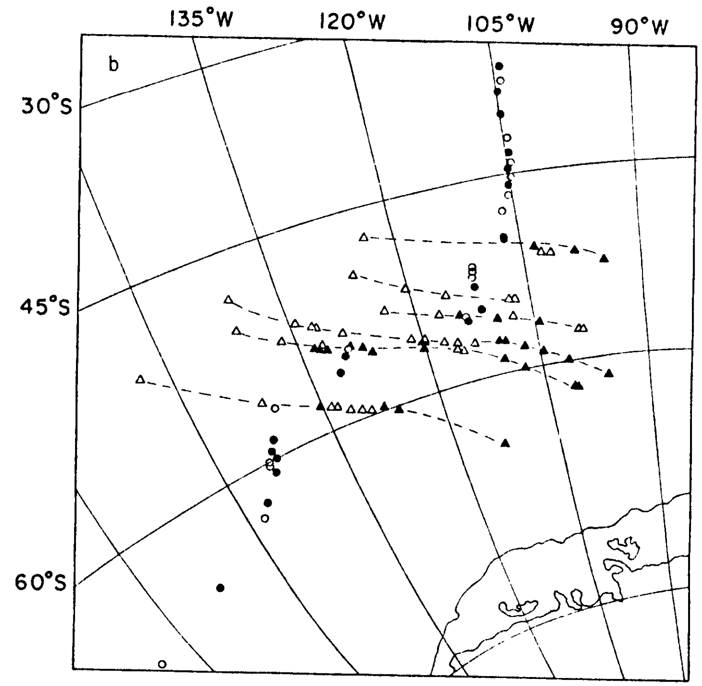


Figure 5b

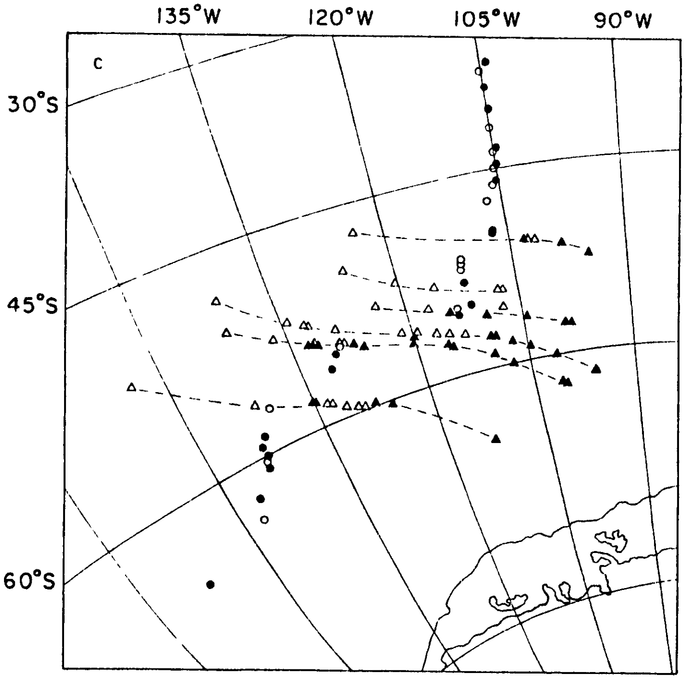


Figure 5c

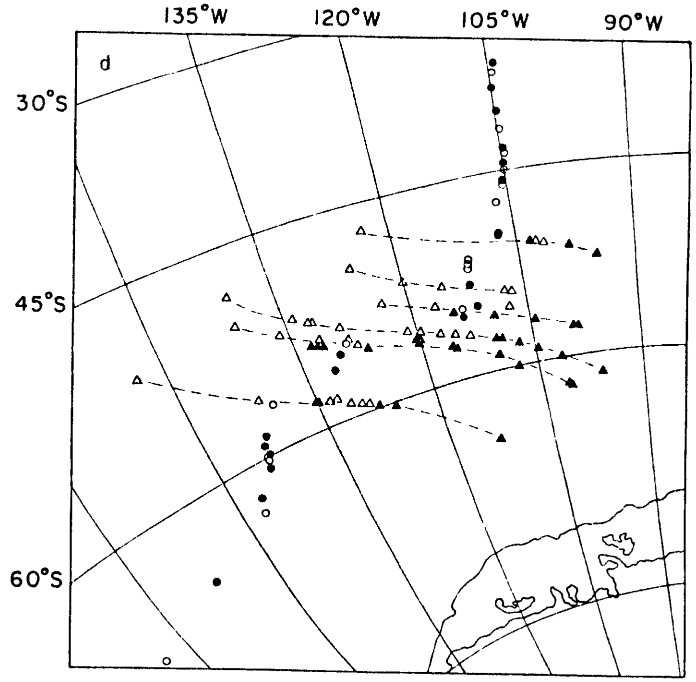


Figure 5d

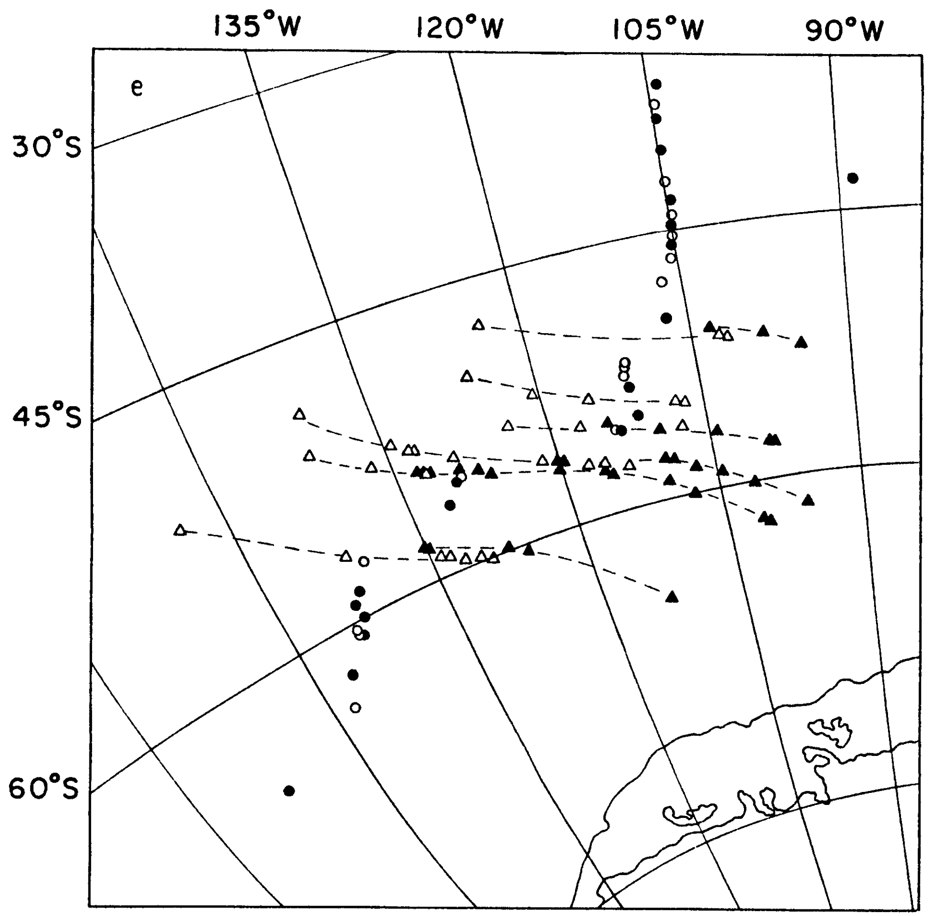


Figure 5e

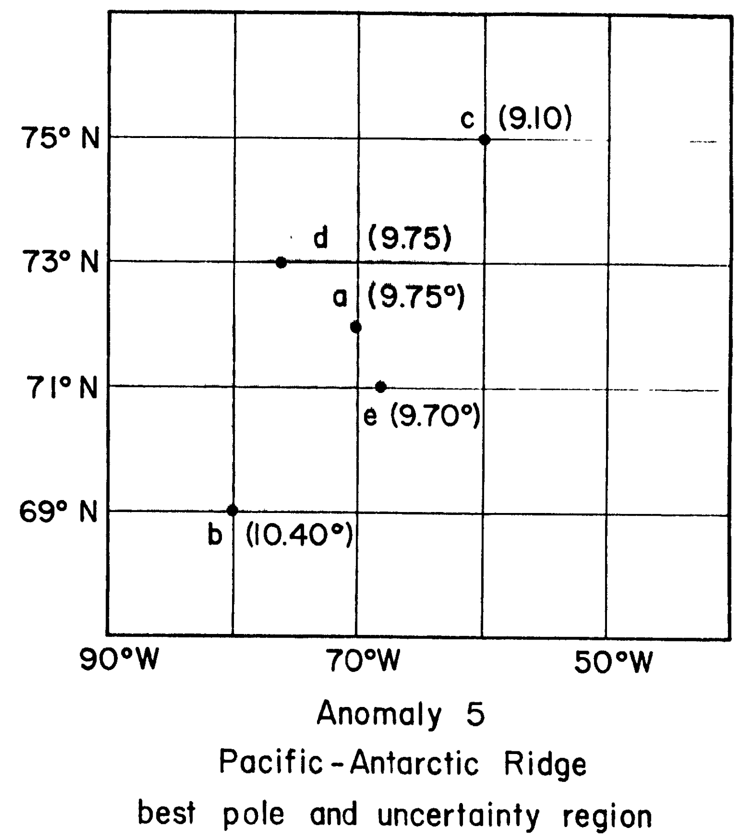


Figure 5f

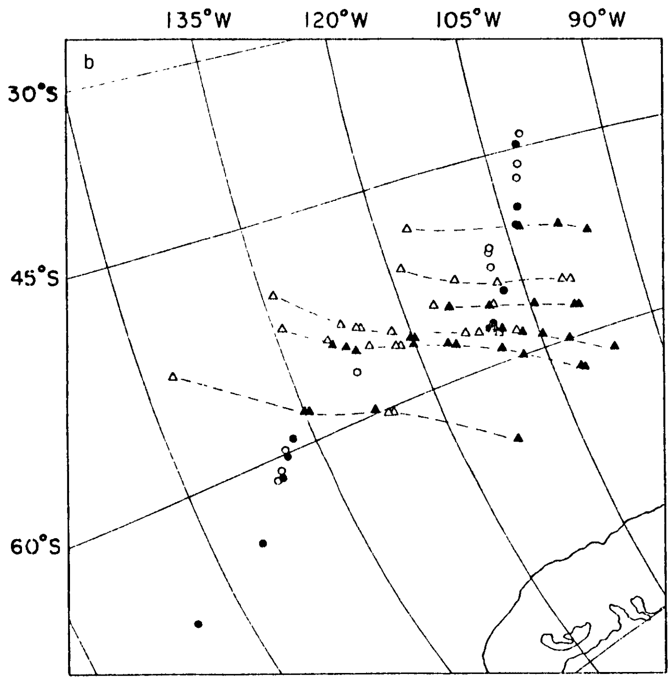


Figure 6b

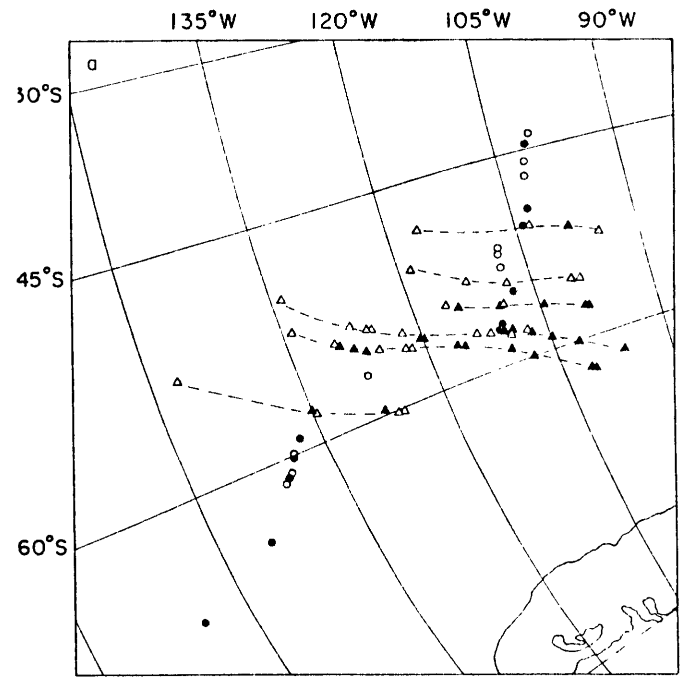


Figure 6a

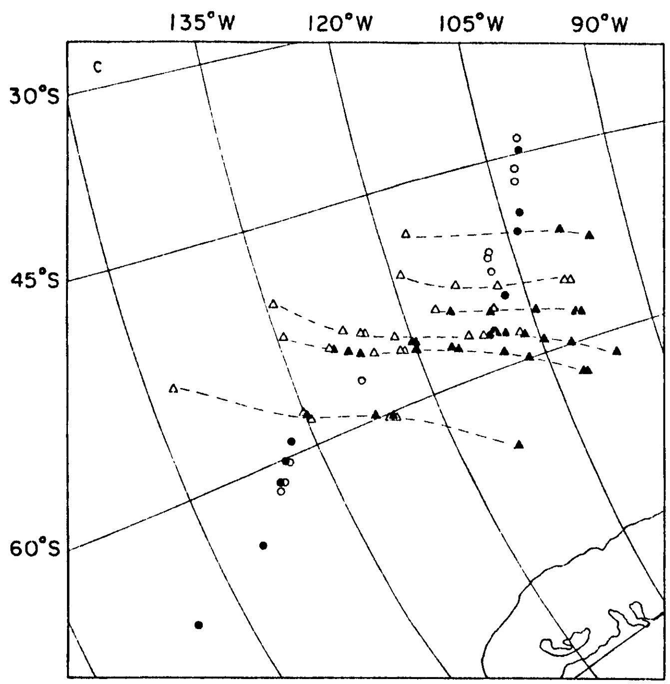


Figure 6c

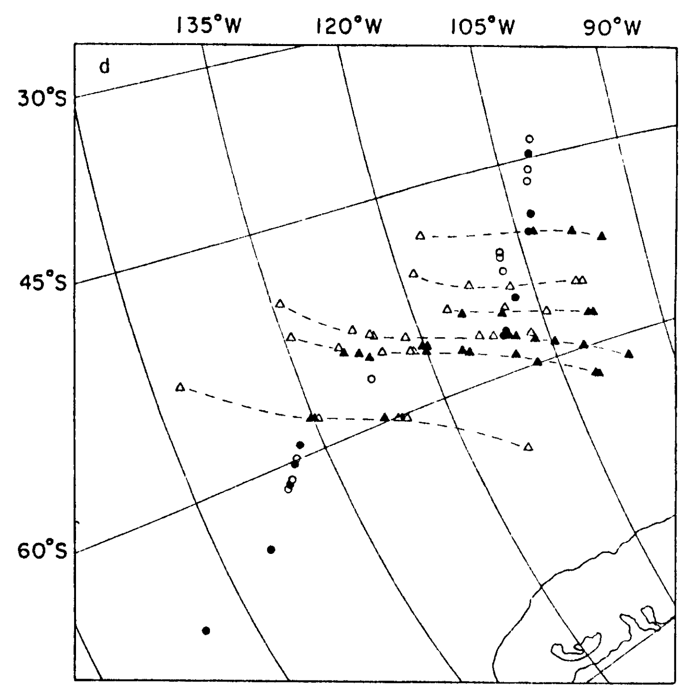


Figure 6d

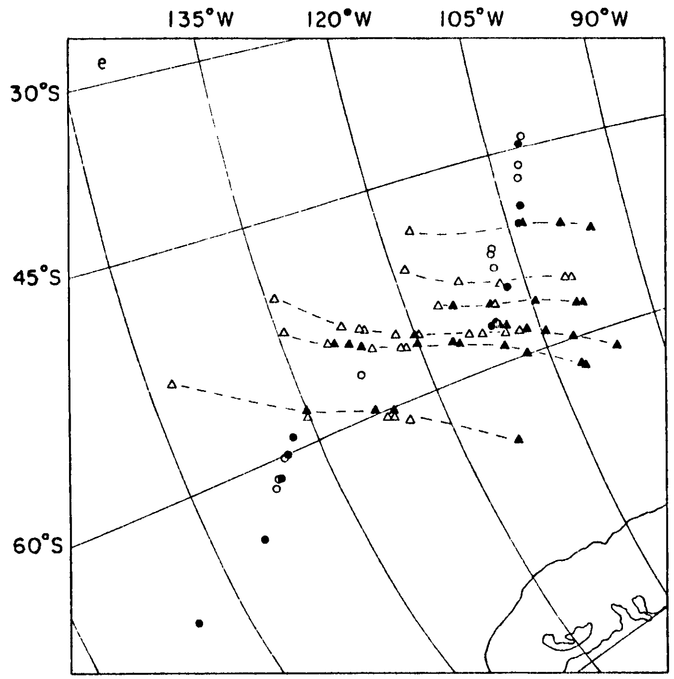
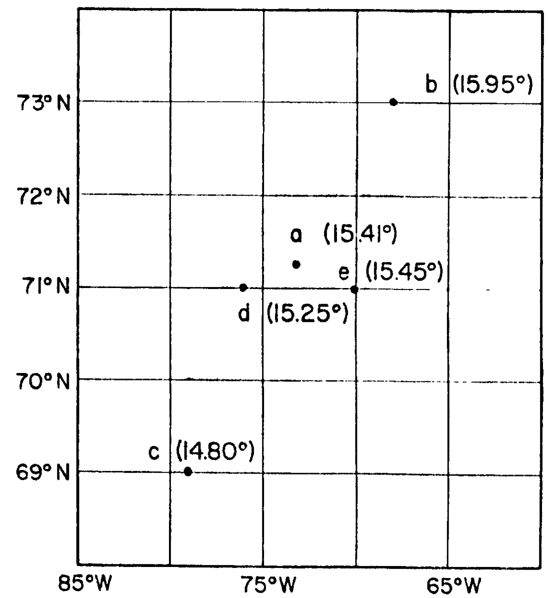


Figure 6e



Anomaly 6
Pacific-Antarctic Ridge
best pole and uncertainty region

Figure 6f

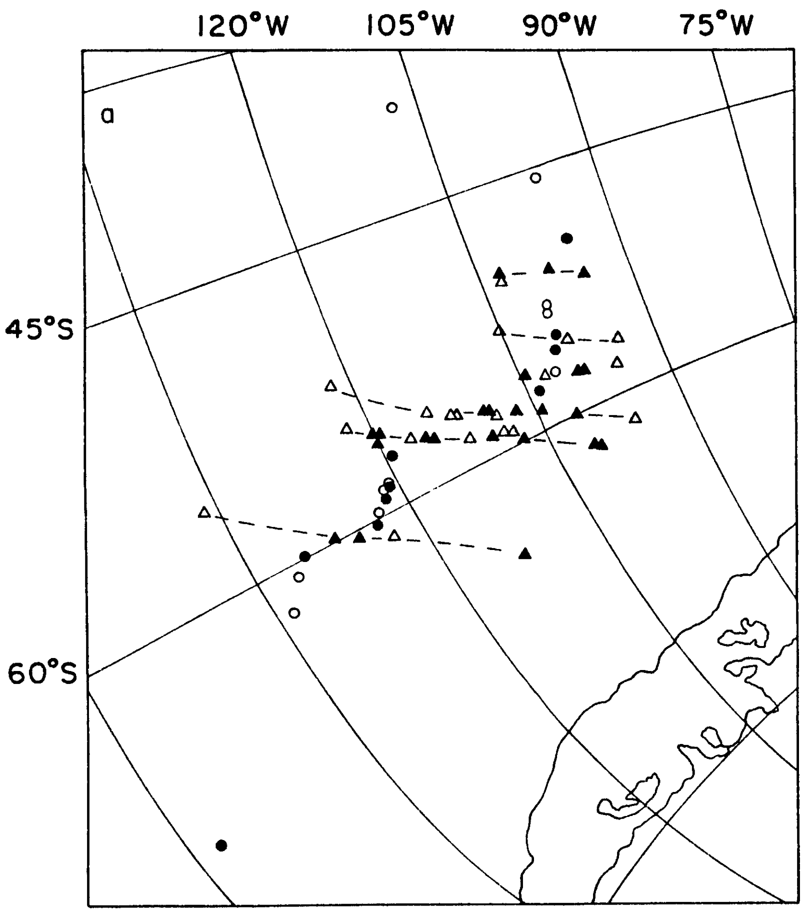


Figure 7a

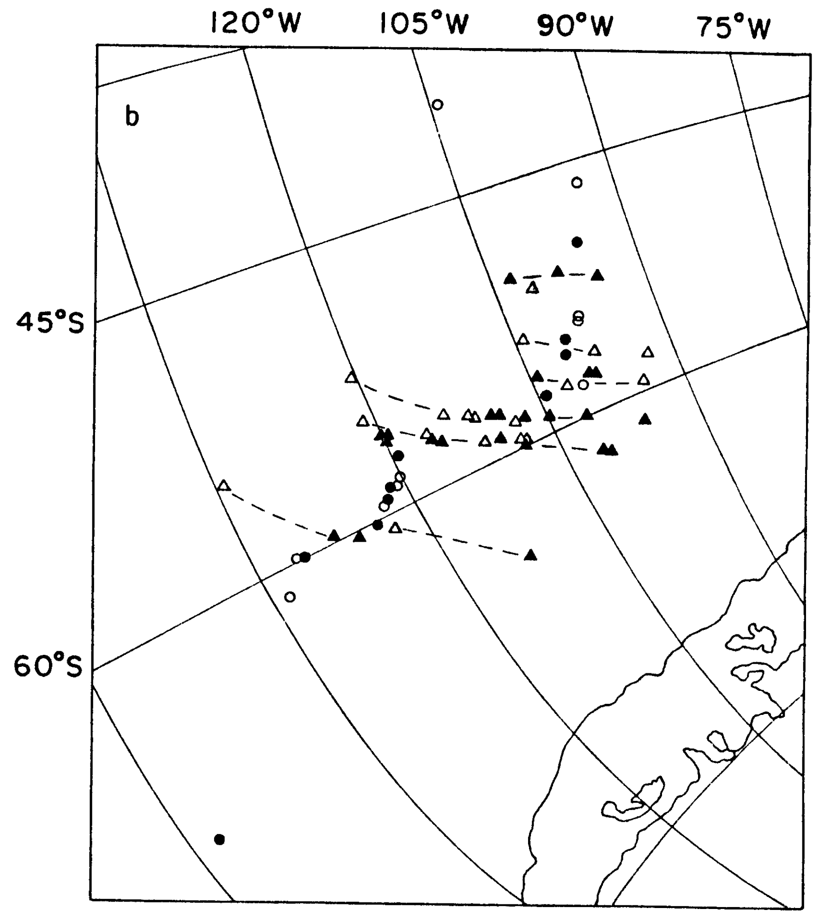


Figure 7b

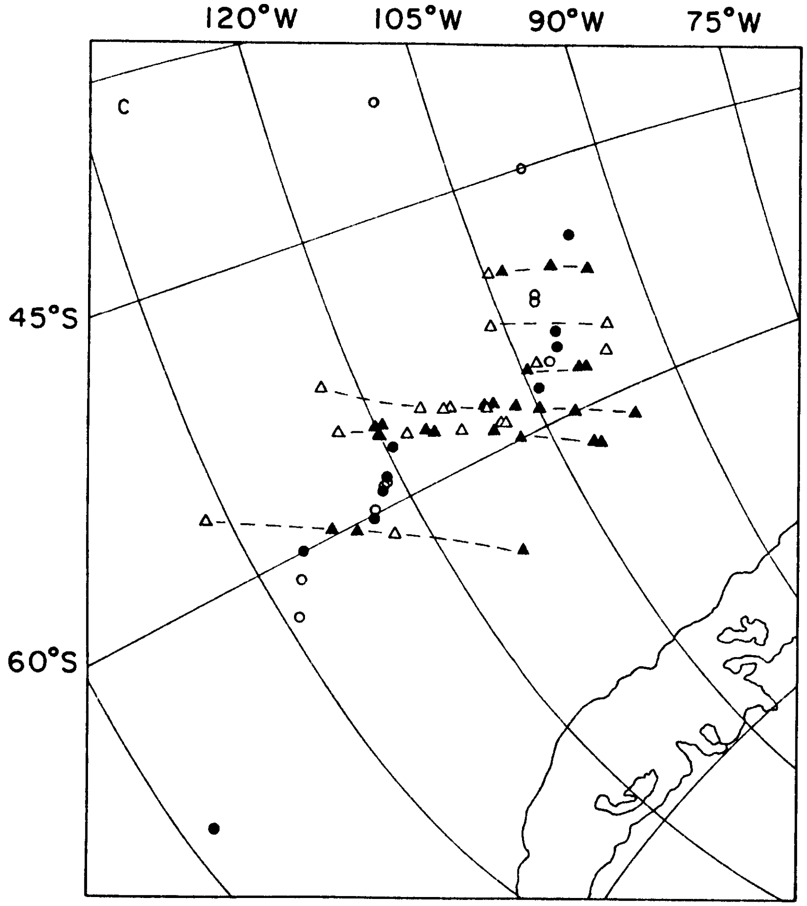


Figure 7c

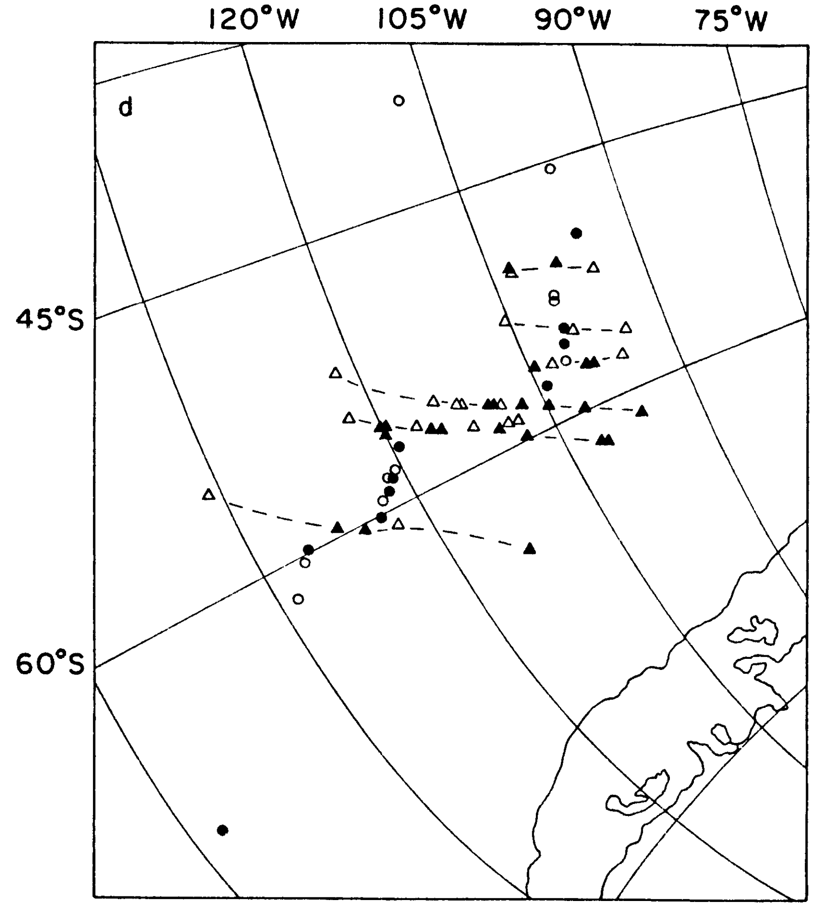


Figure 7d

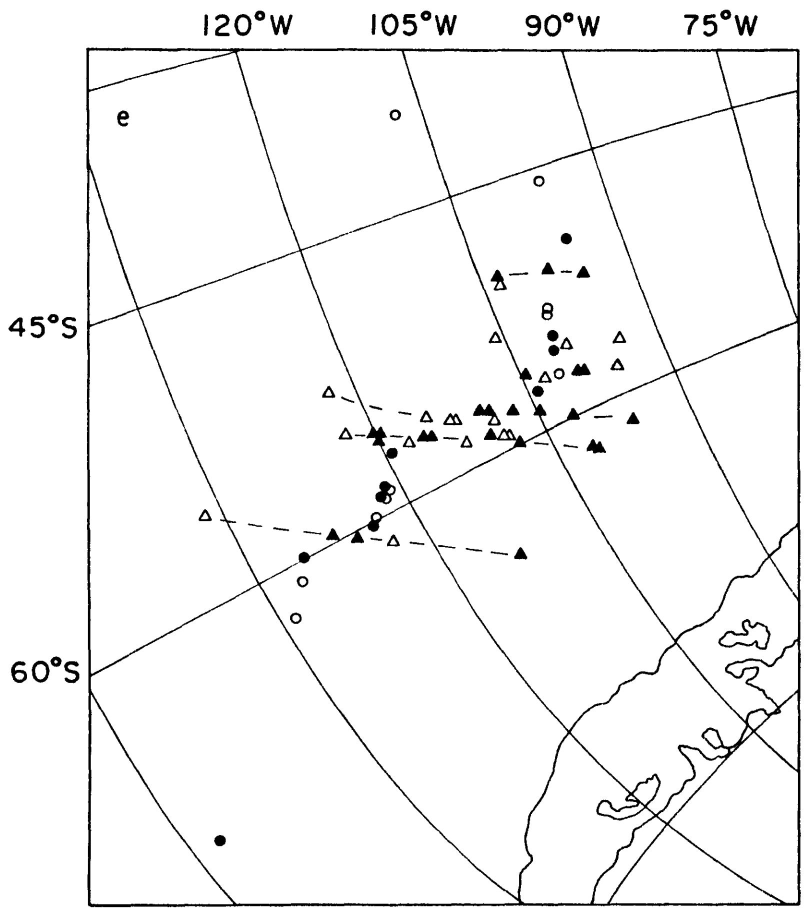
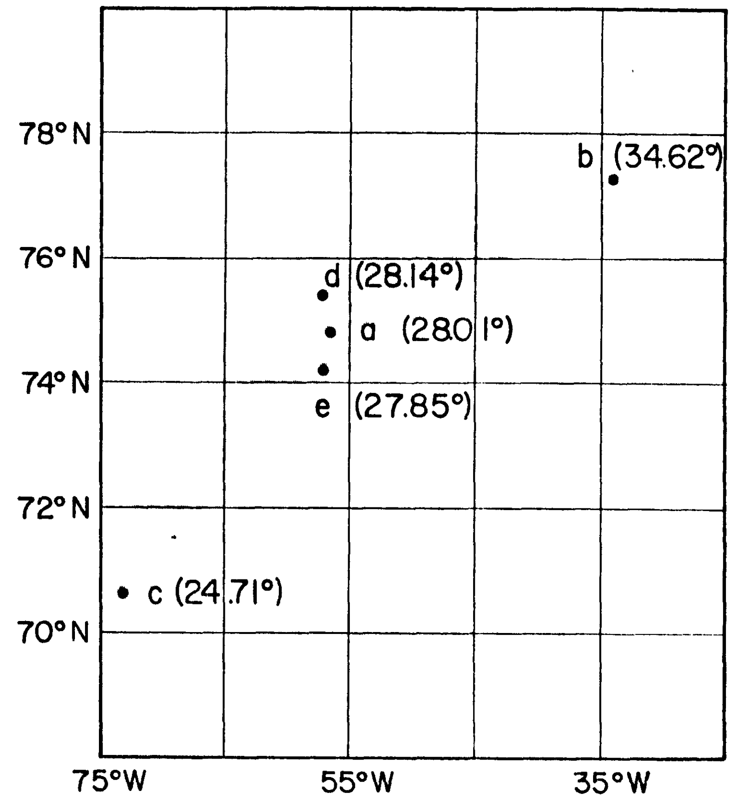


Figure 7e



Anomaly 13
Pacific-Antarctic Ridge
best pole and uncertainty region

Figure 7f

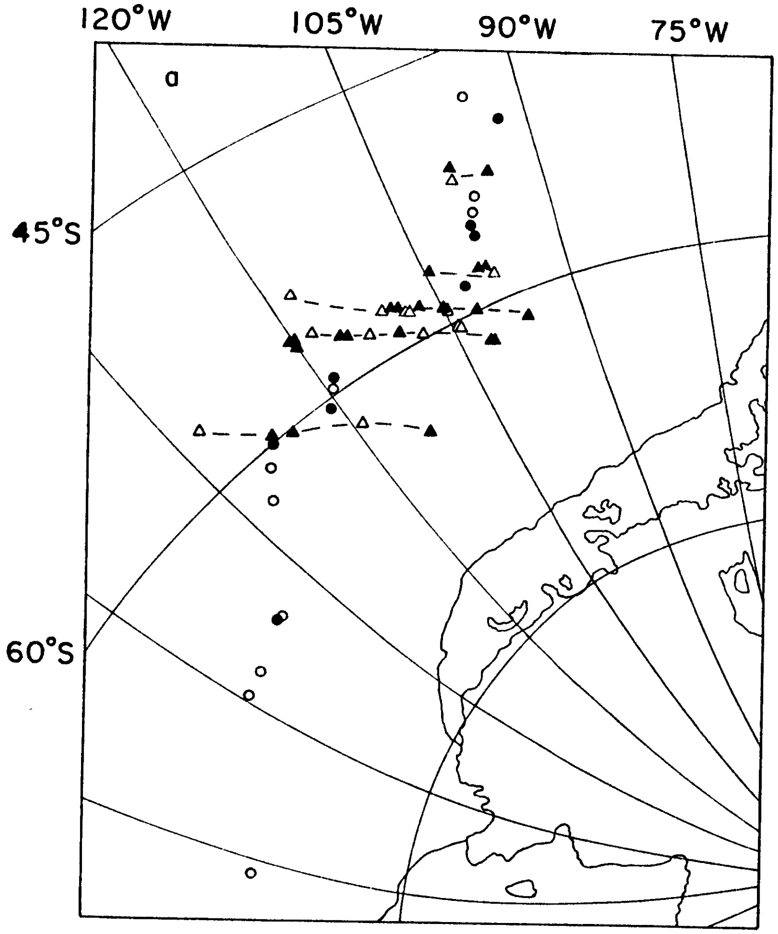


Figure 8a

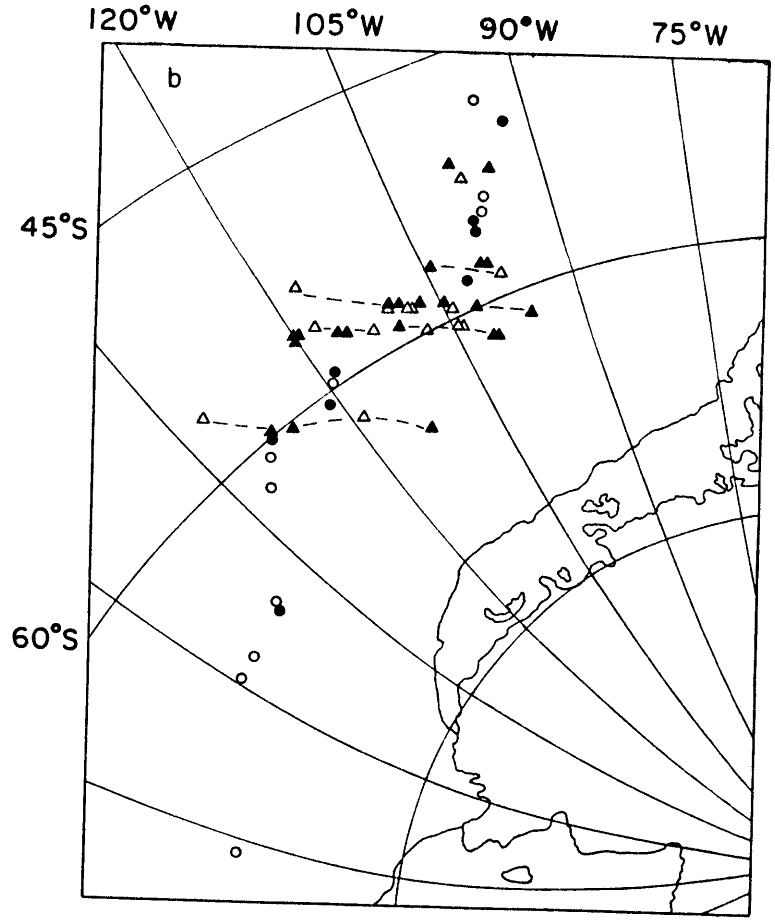


Figure 8b

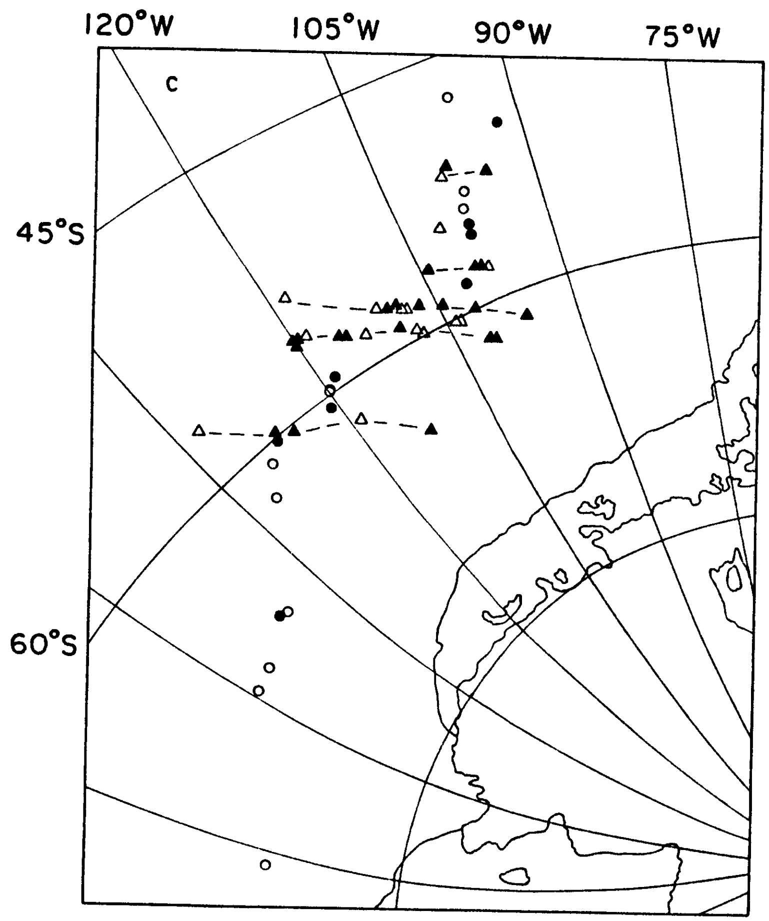


Figure 8c

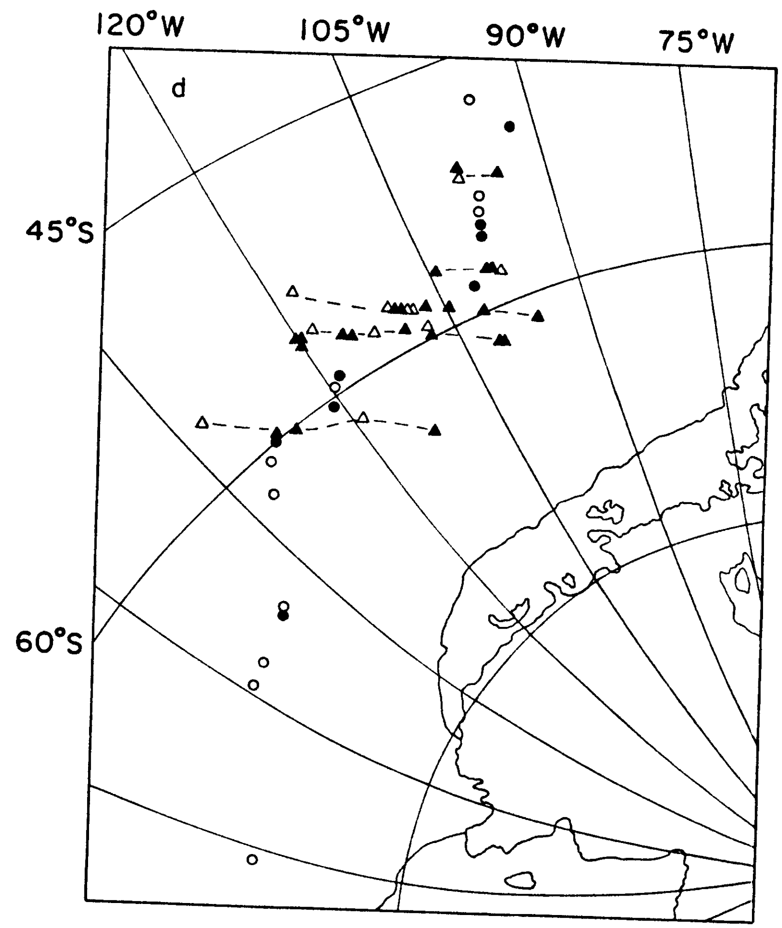


Figure 8d

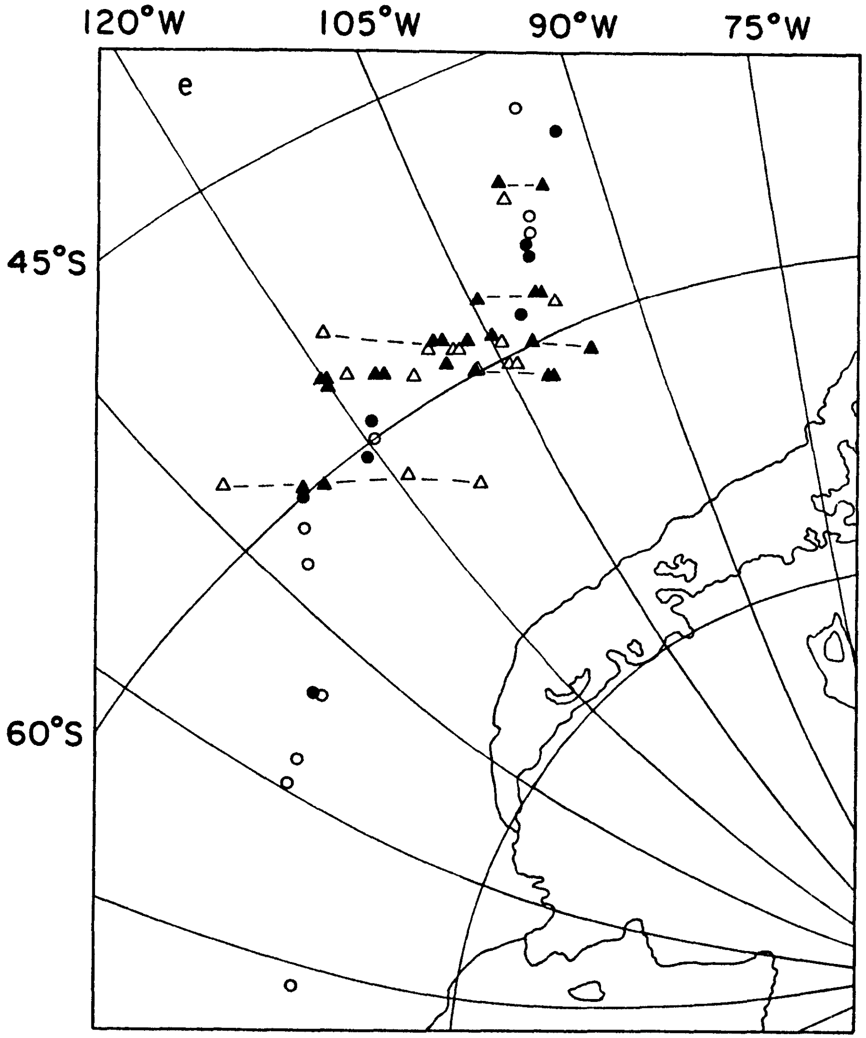


Figure 8e

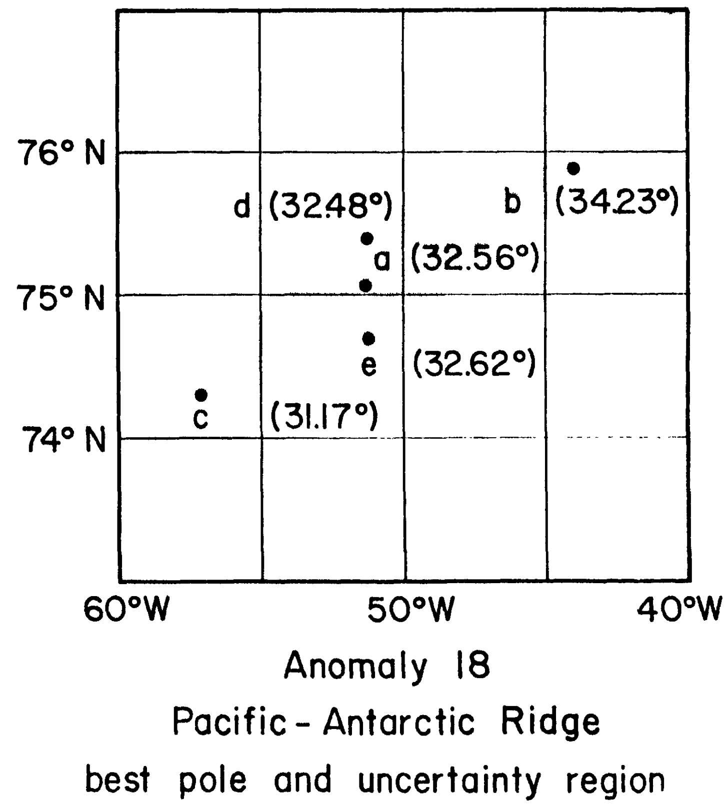


Figure 8f

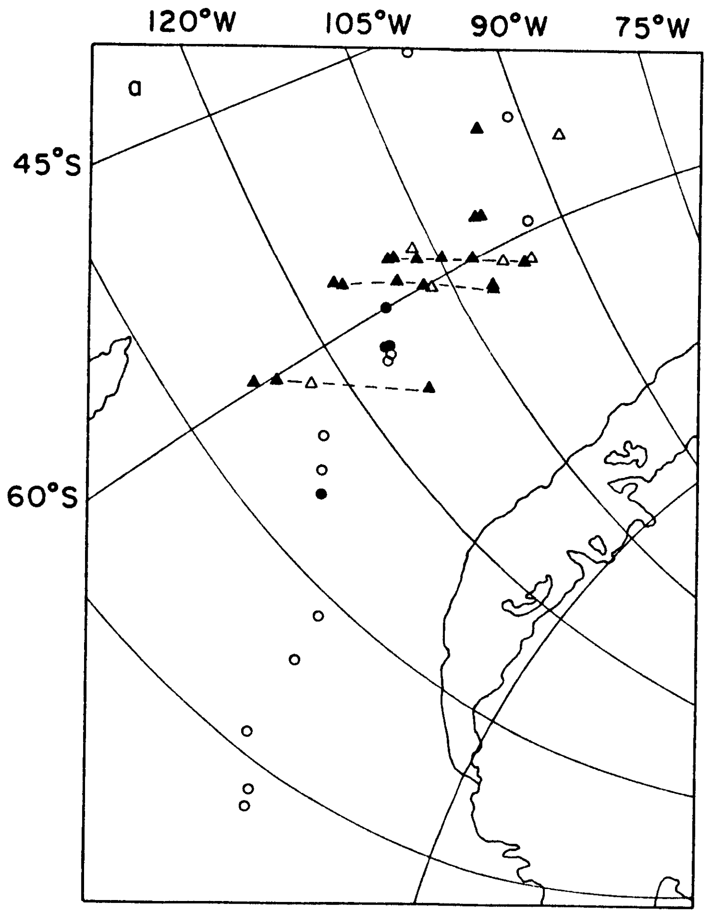


Figure 9a

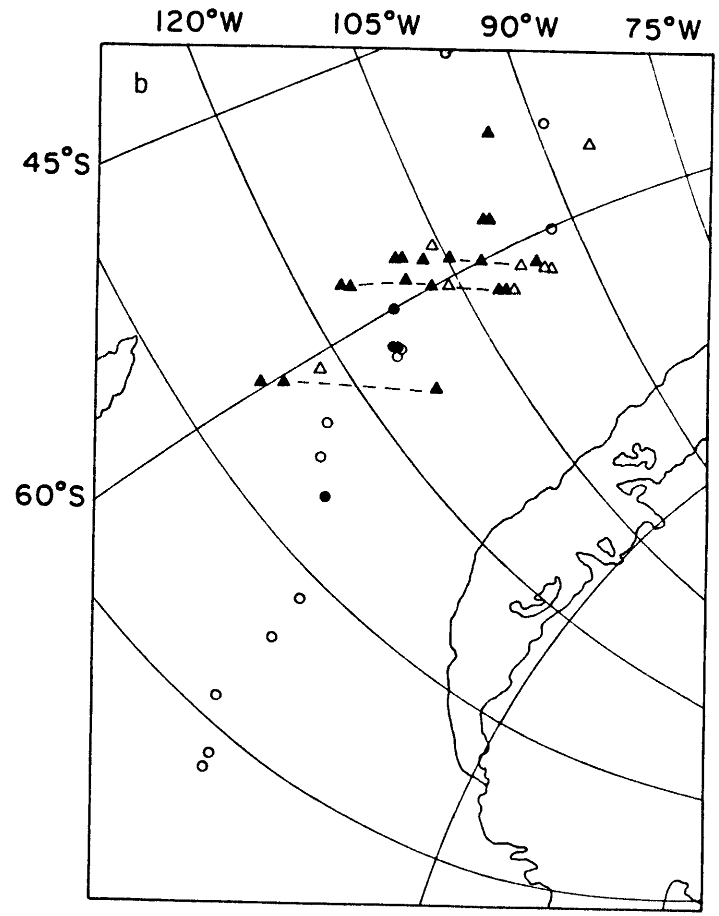


Figure 9b

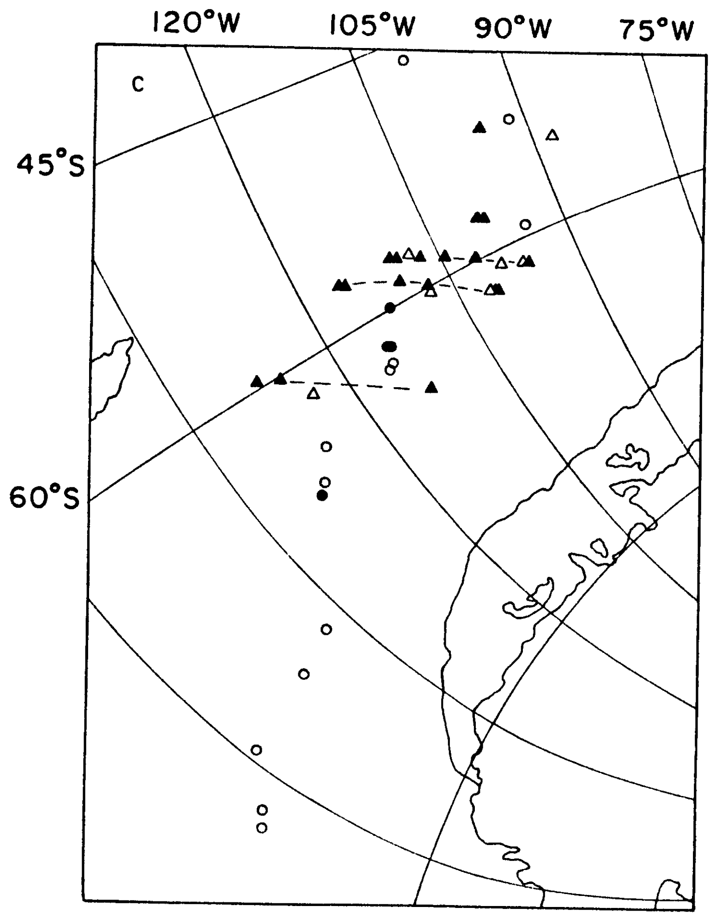


Figure 9c

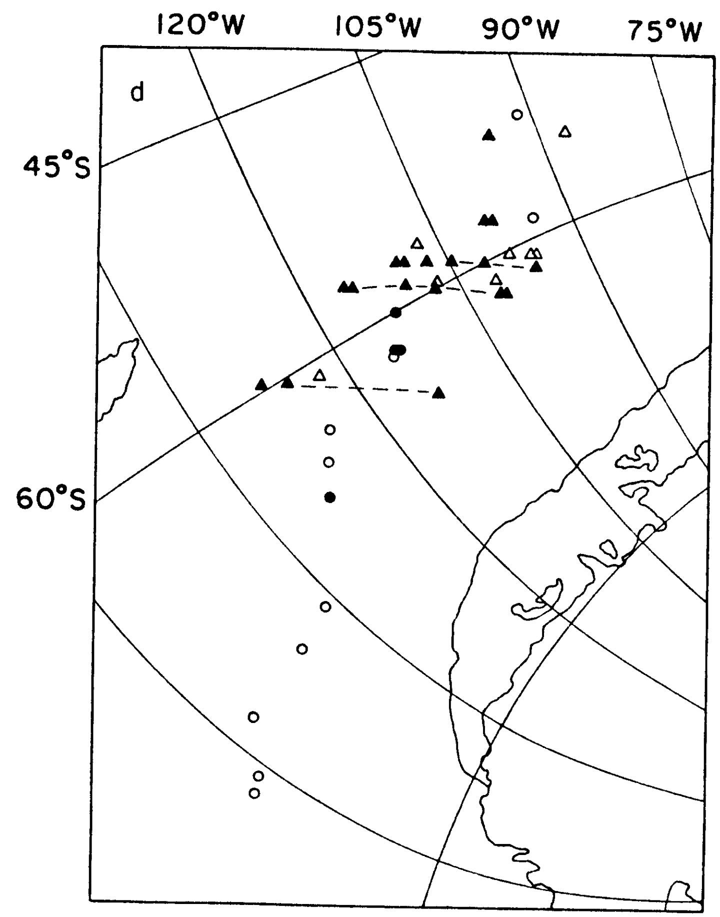


Figure 9d

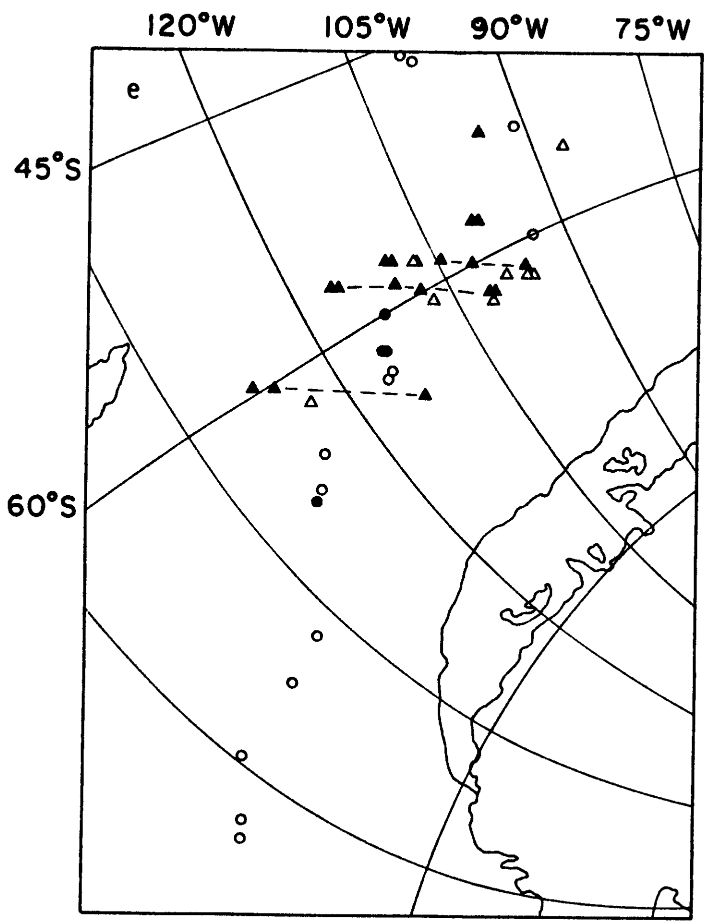
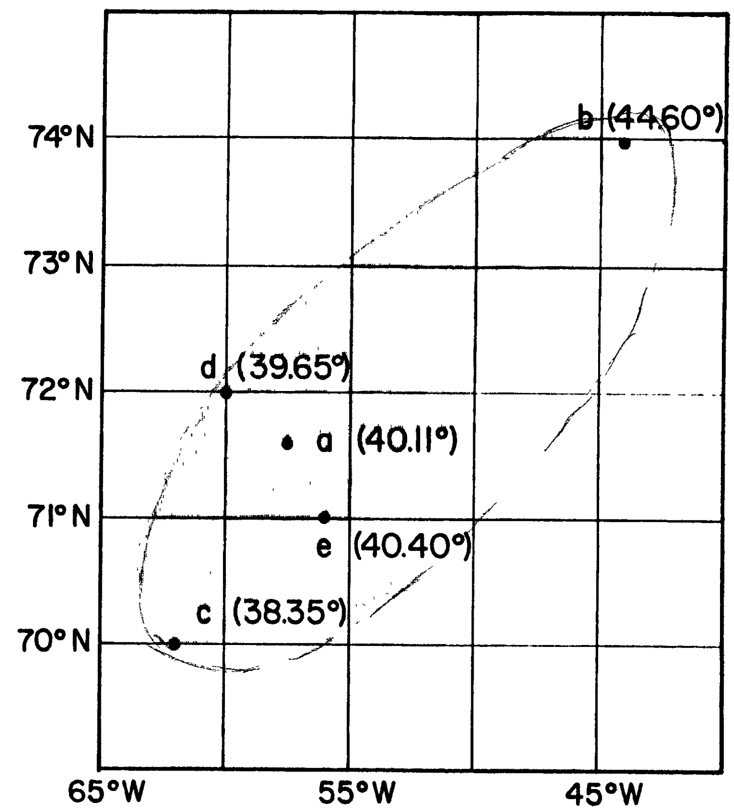


Figure 9e



Anomaly 25
Pacific - Antarctic Ridge
best pole and uncertainty region

Figure 9f

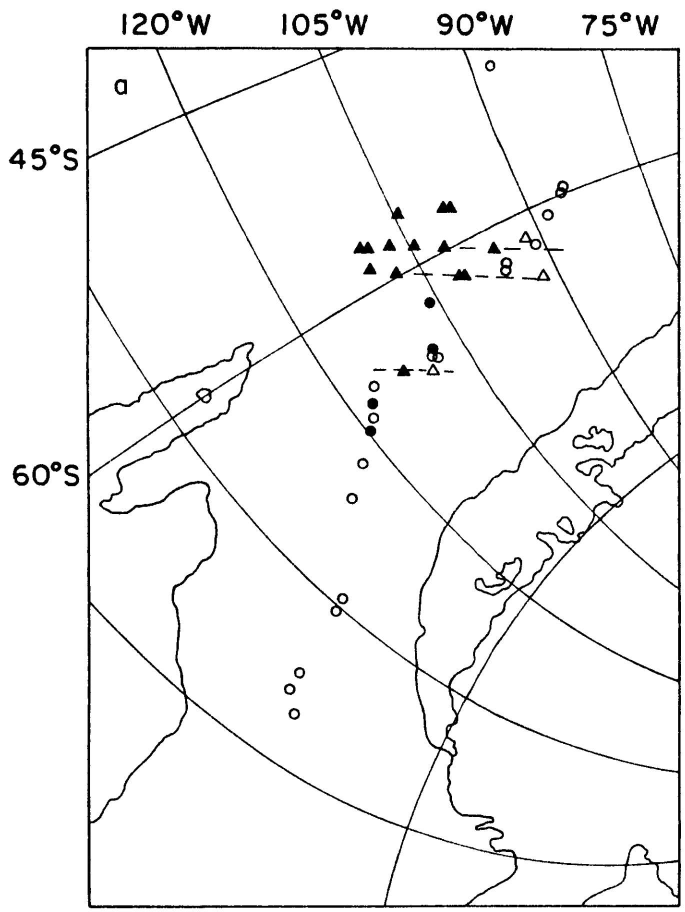


Figure 10a

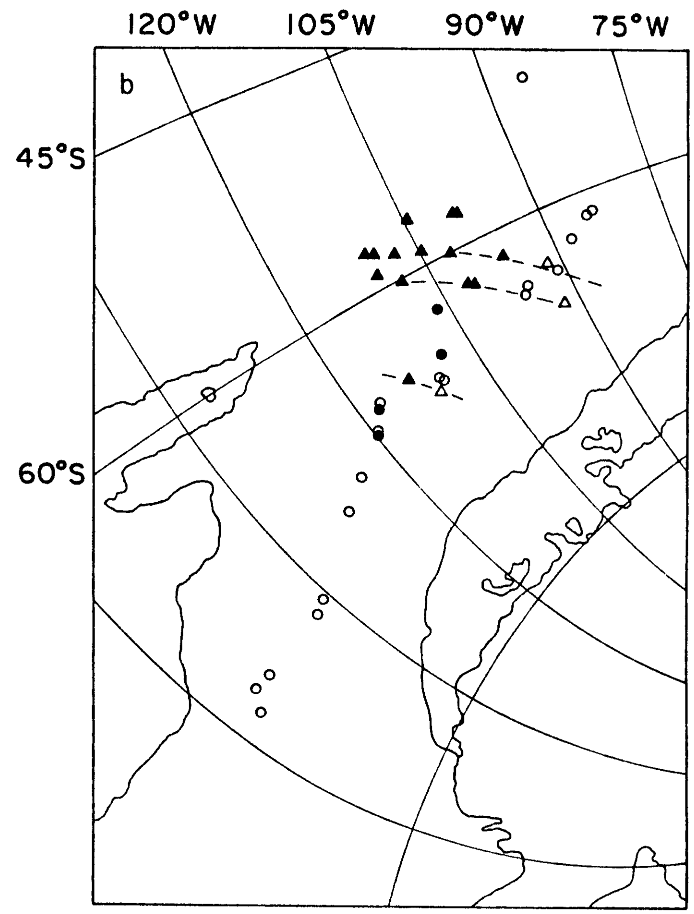


Figure 10b

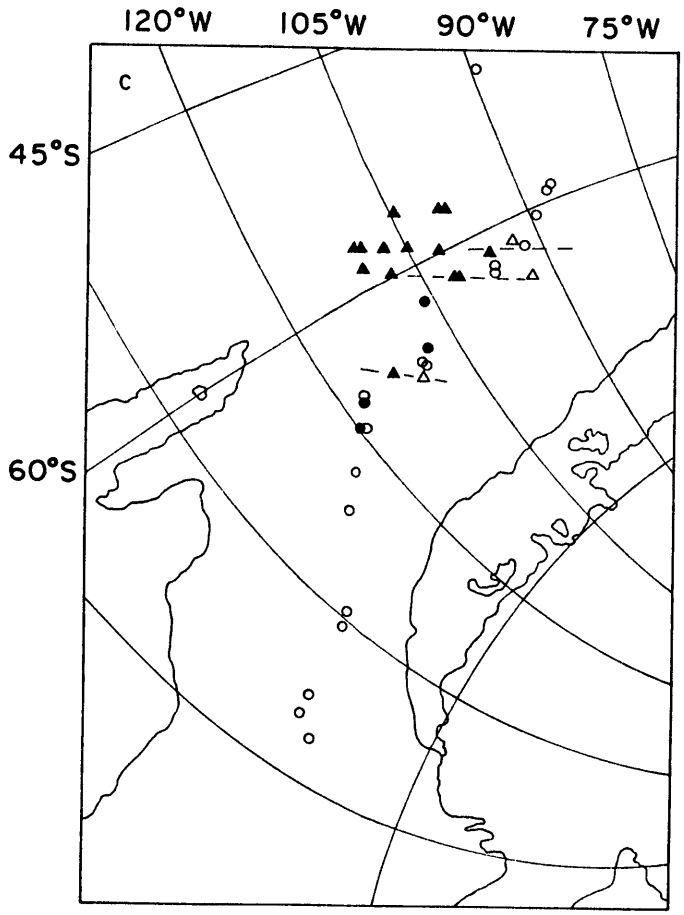


Figure 10c

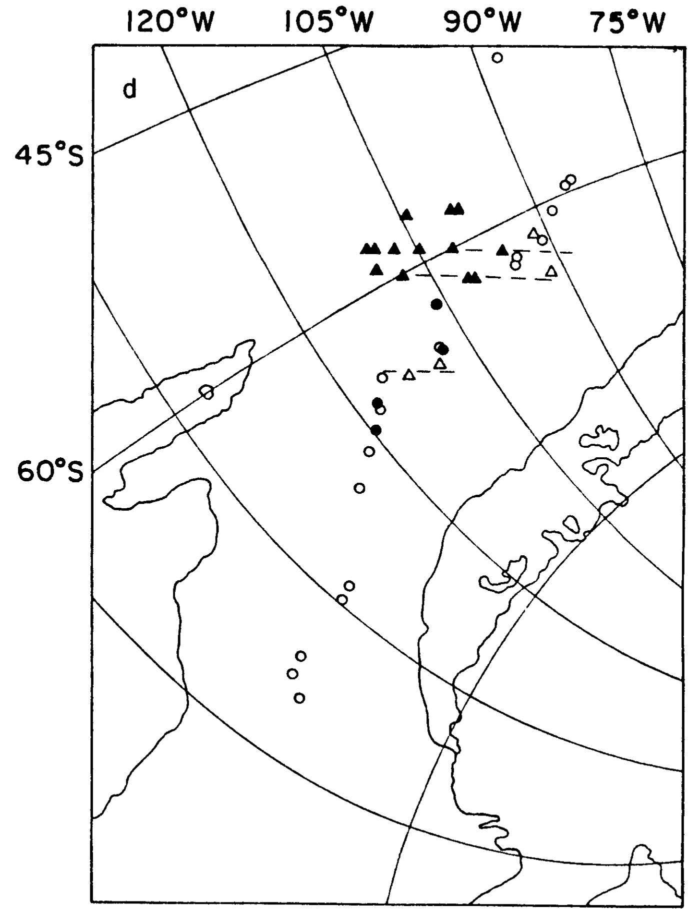


Figure 10d

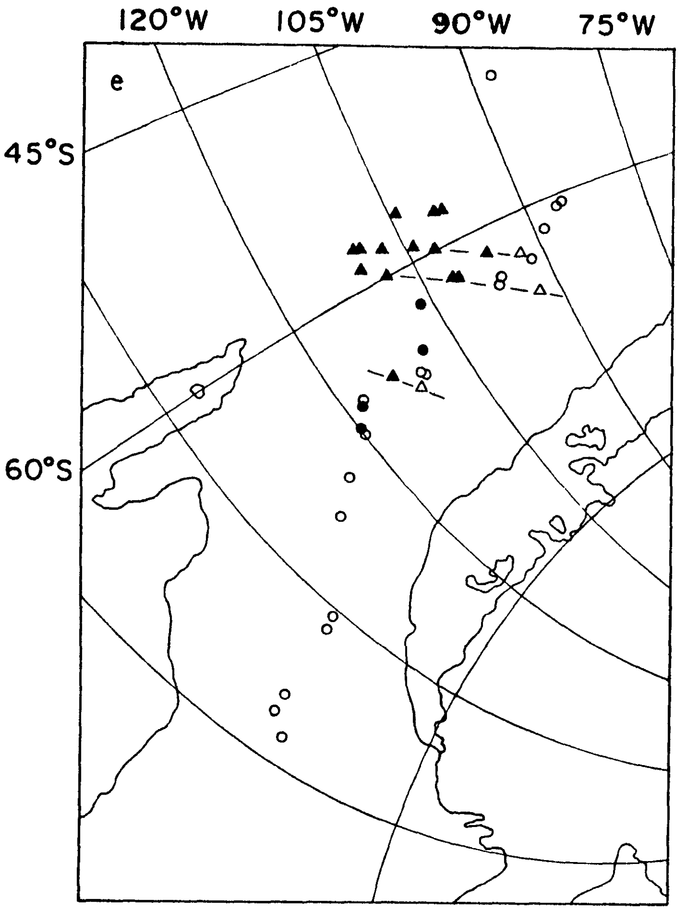
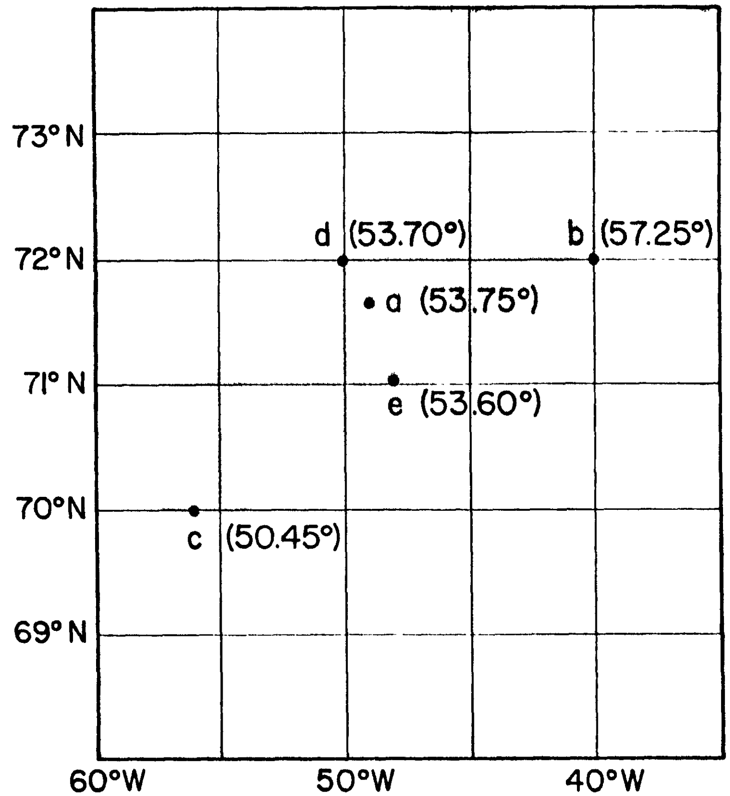


Figure 10e



Anomaly 31
Pacific - Antarctic Ridge
best pole and uncertainty region

Figure 10f

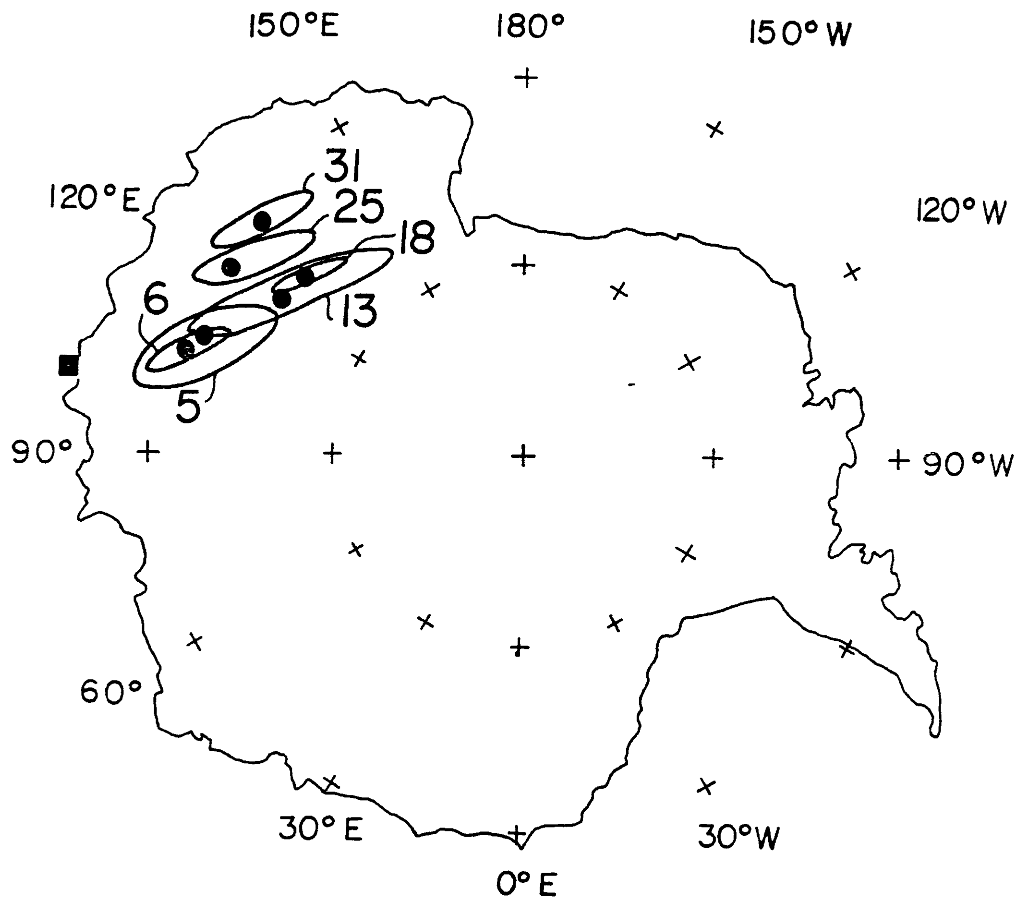


Figure 11

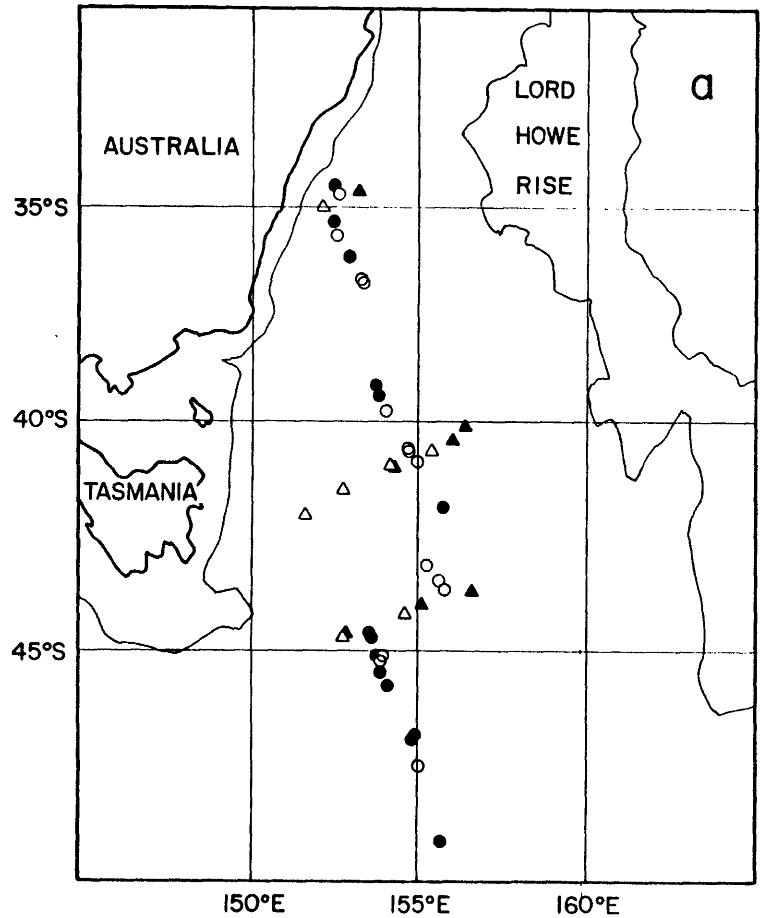


Figure 12a

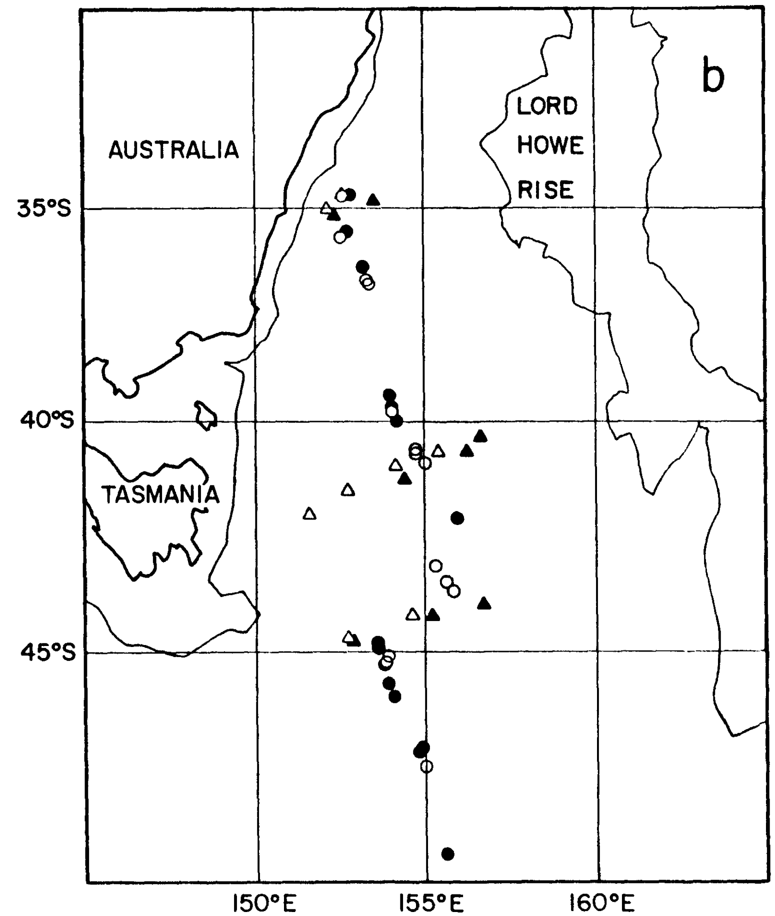


Figure 12b

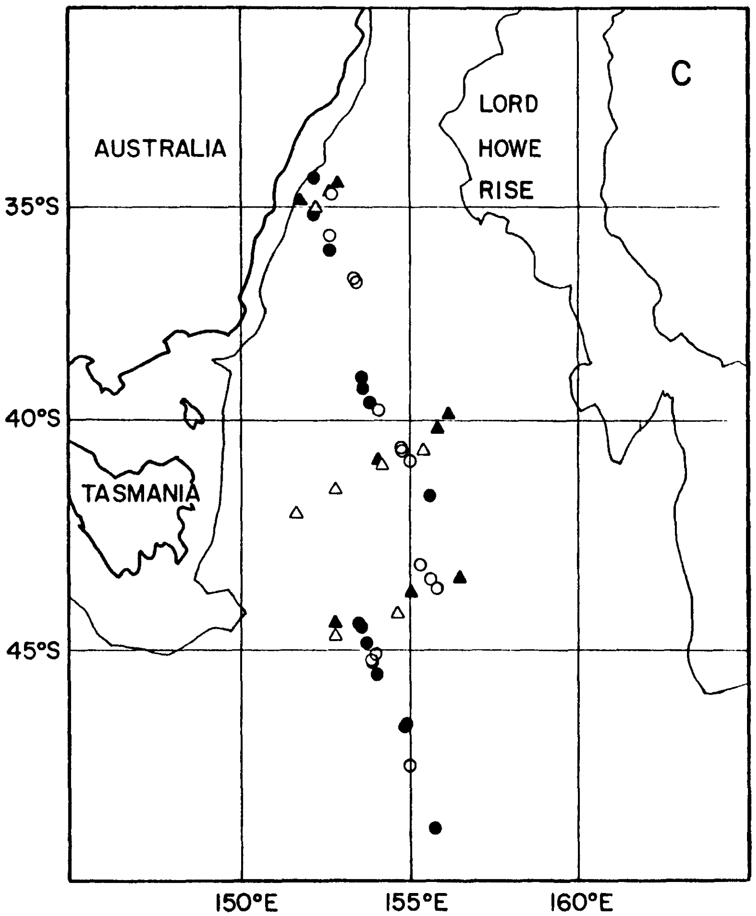


Figure 12c

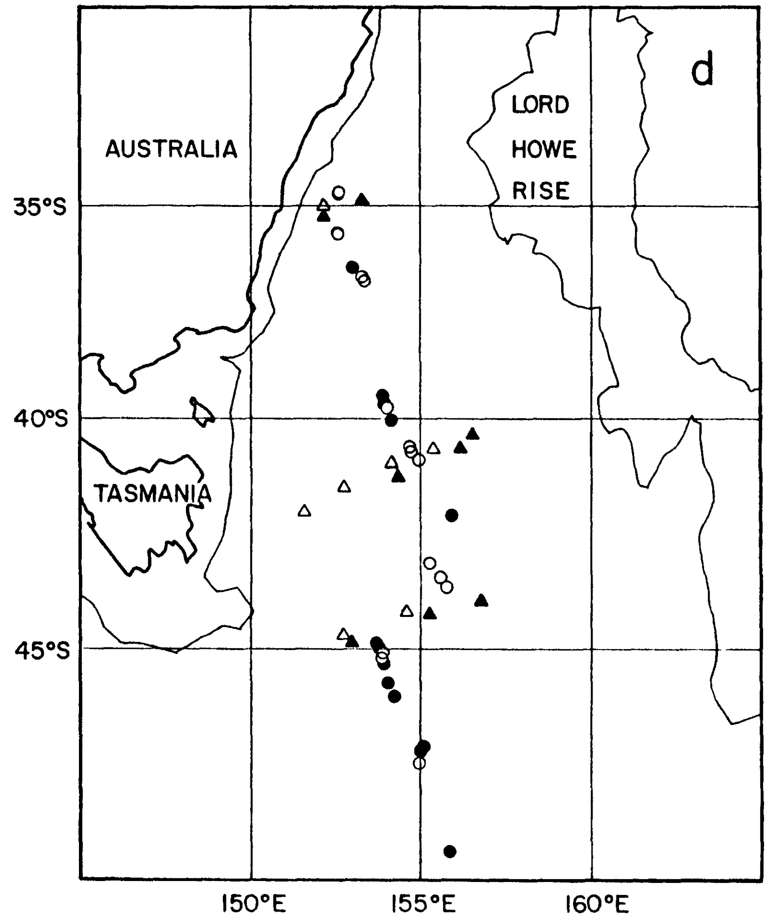


Figure 12d

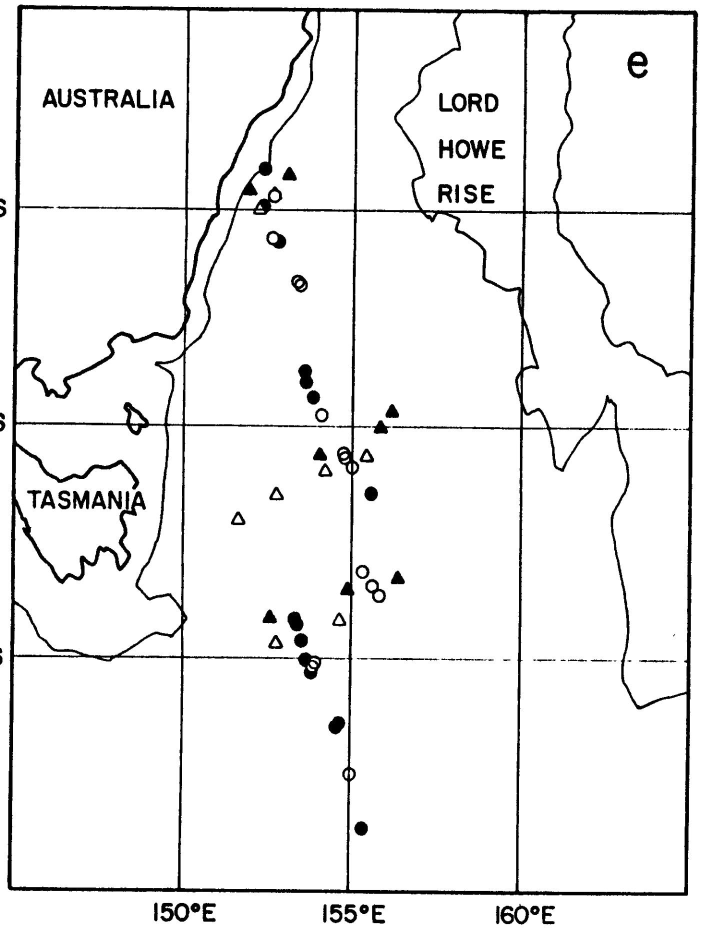
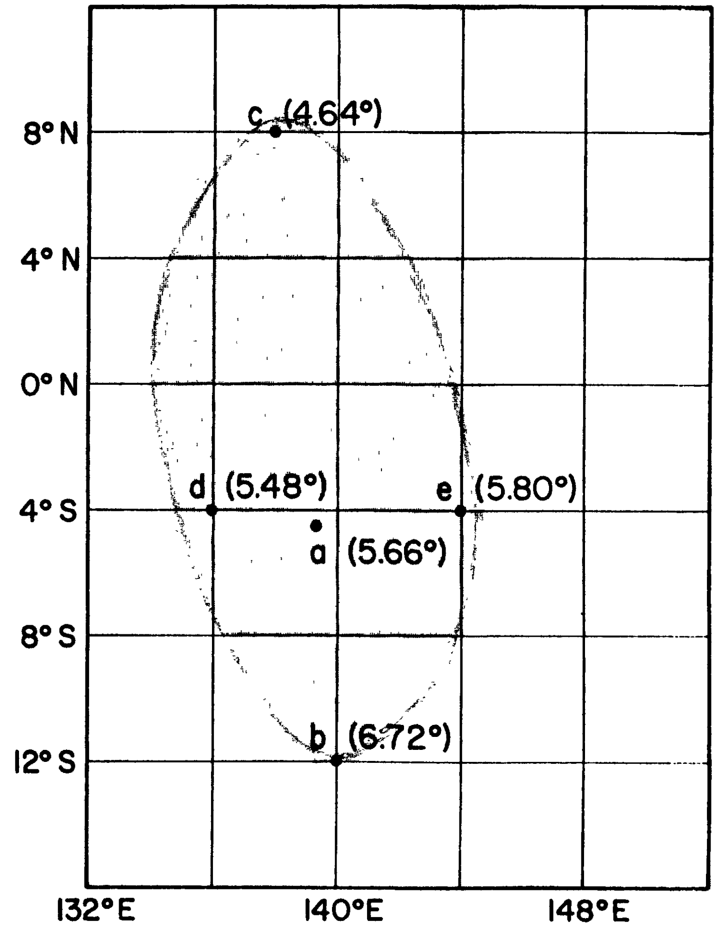


Figure 12e



Anomaly 28 - Tasman Sea
best pole and uncertainty region

Figure 12f

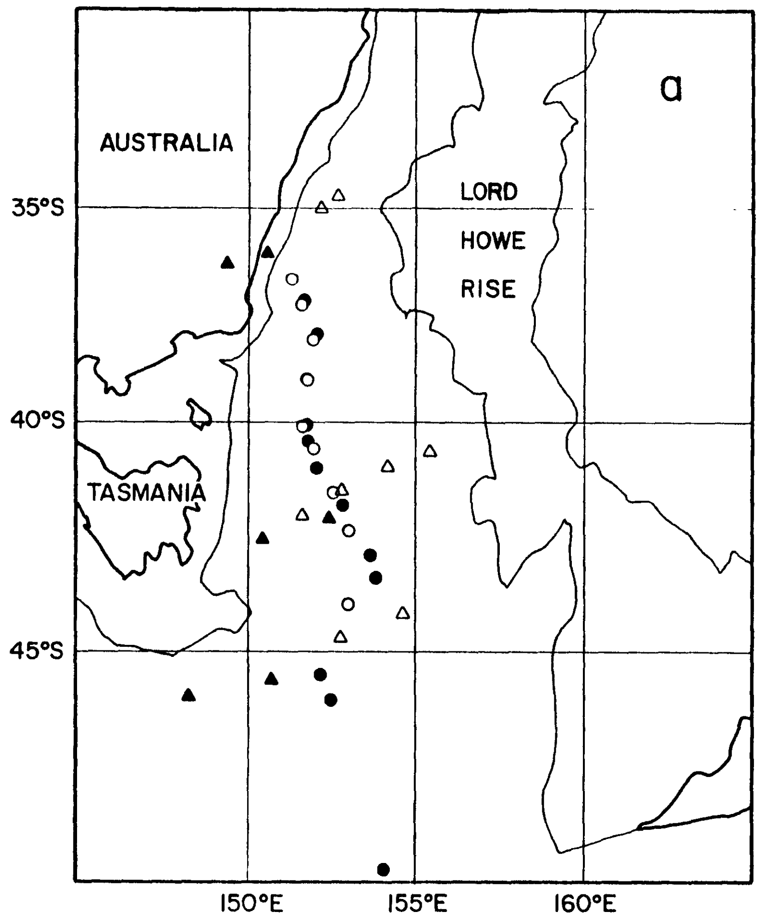


Figure 13a

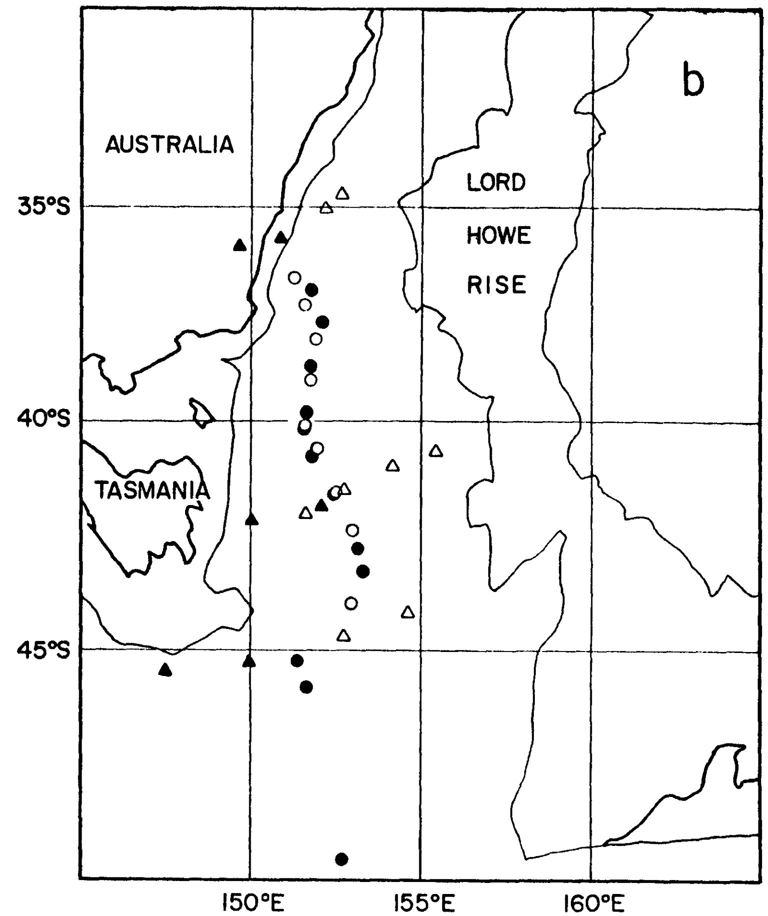


Figure 13b

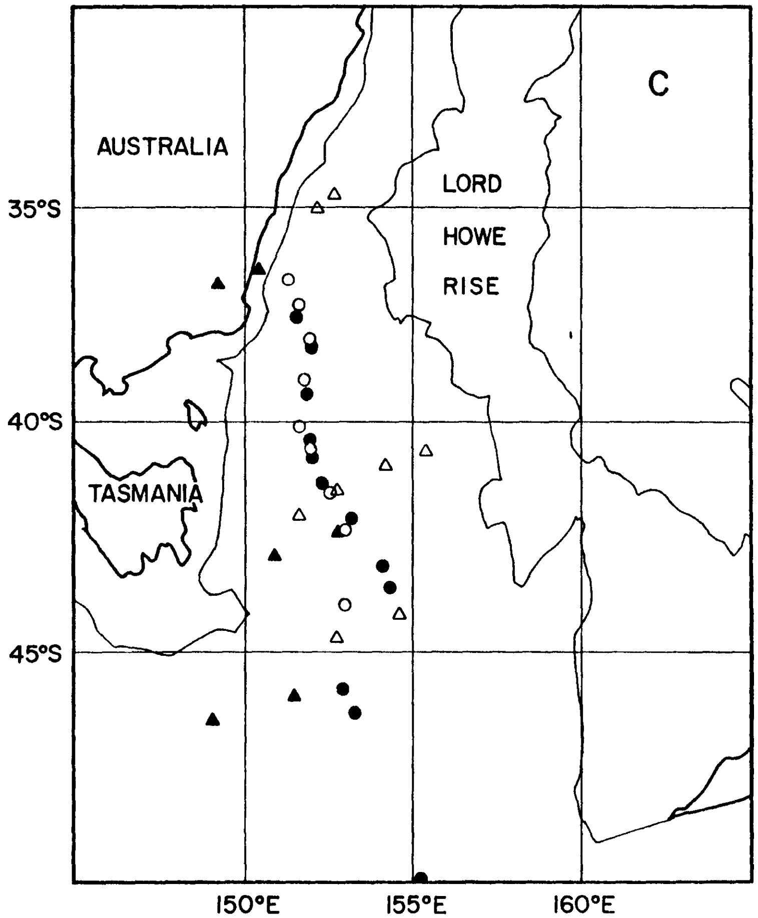


Figure 13c

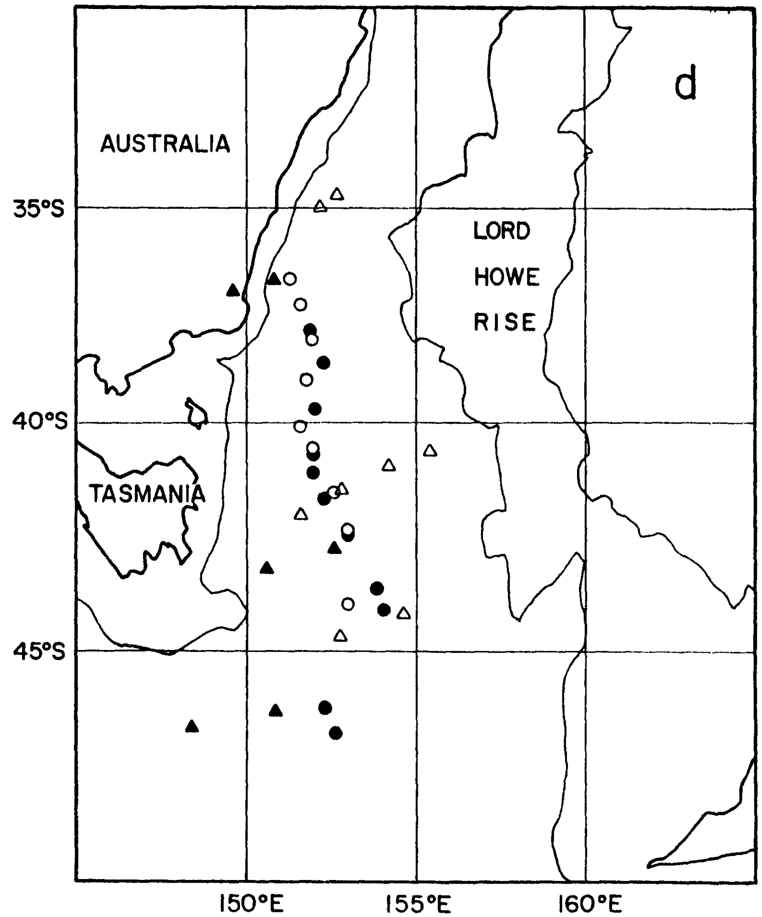


Figure 13d

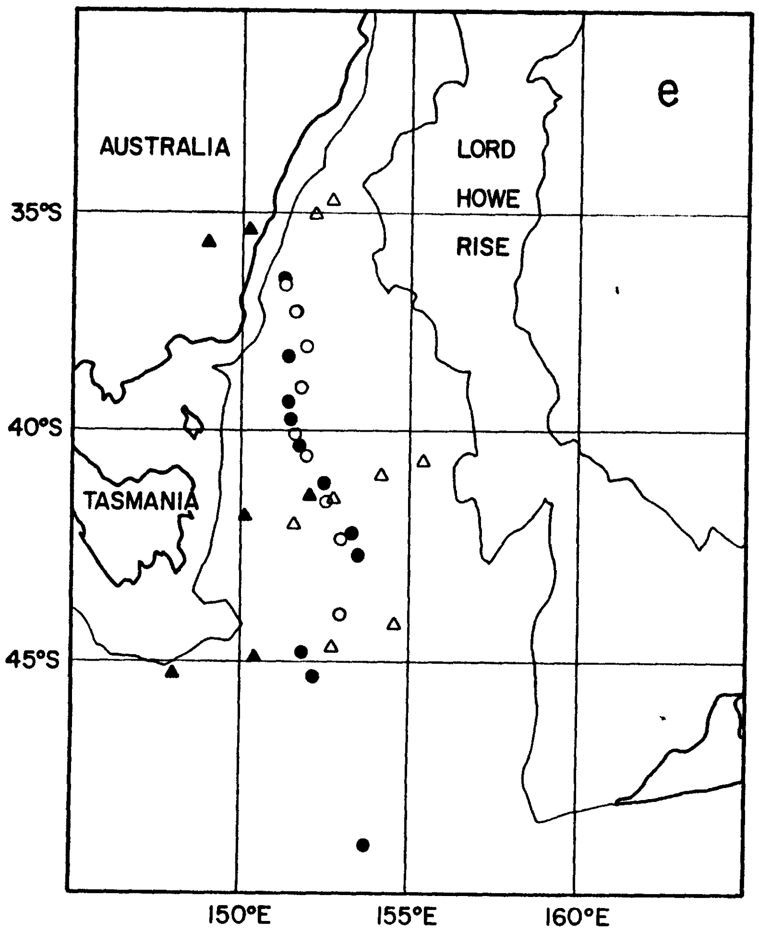
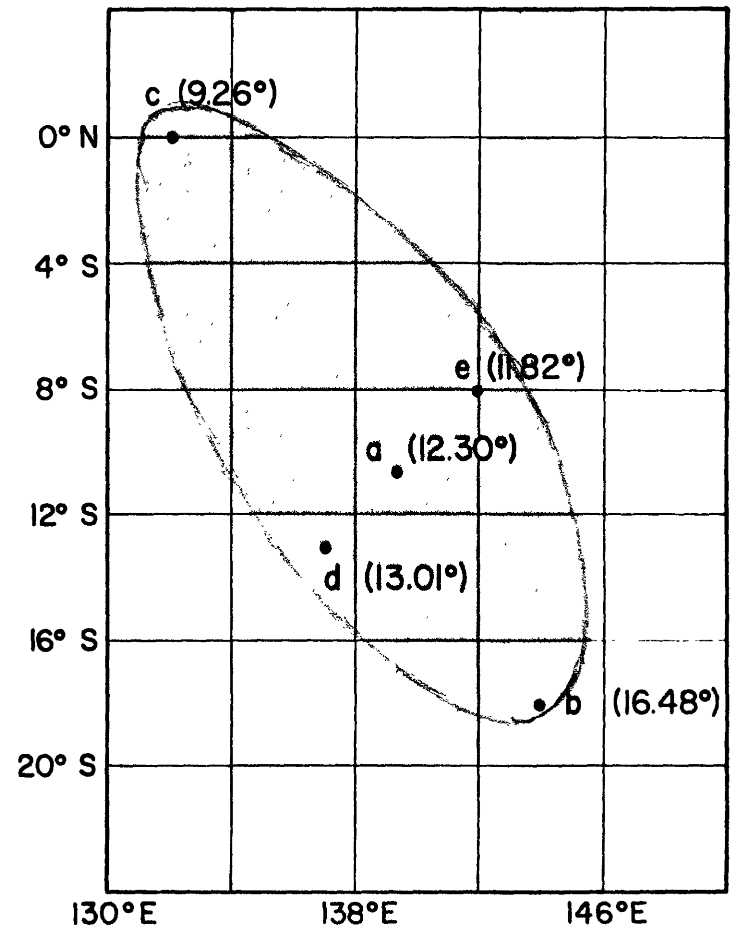


Figure 13e



Anomaly 32 - Tasman Sea
best pole and uncertainty region

Figure 13f

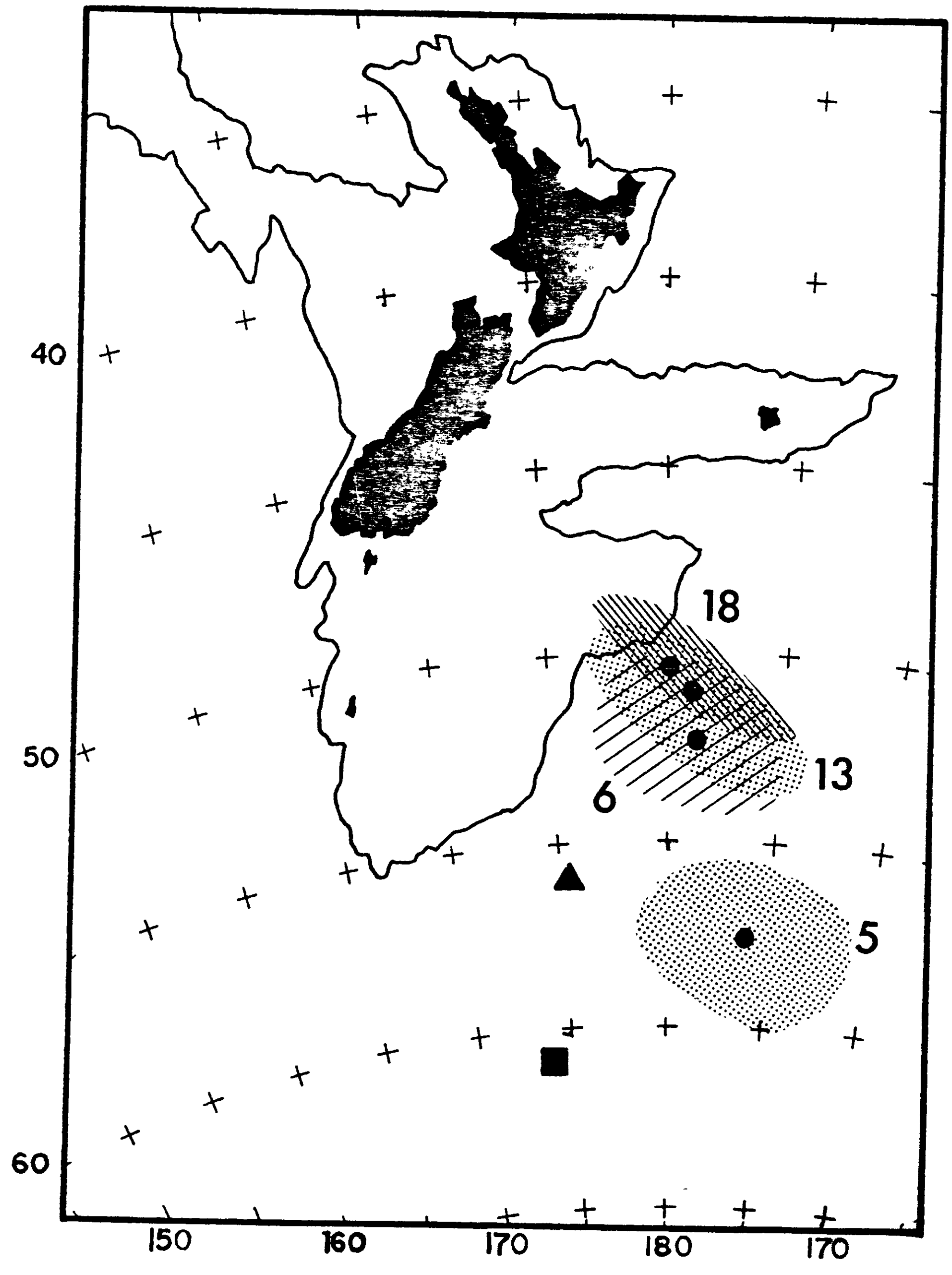


Figure 14

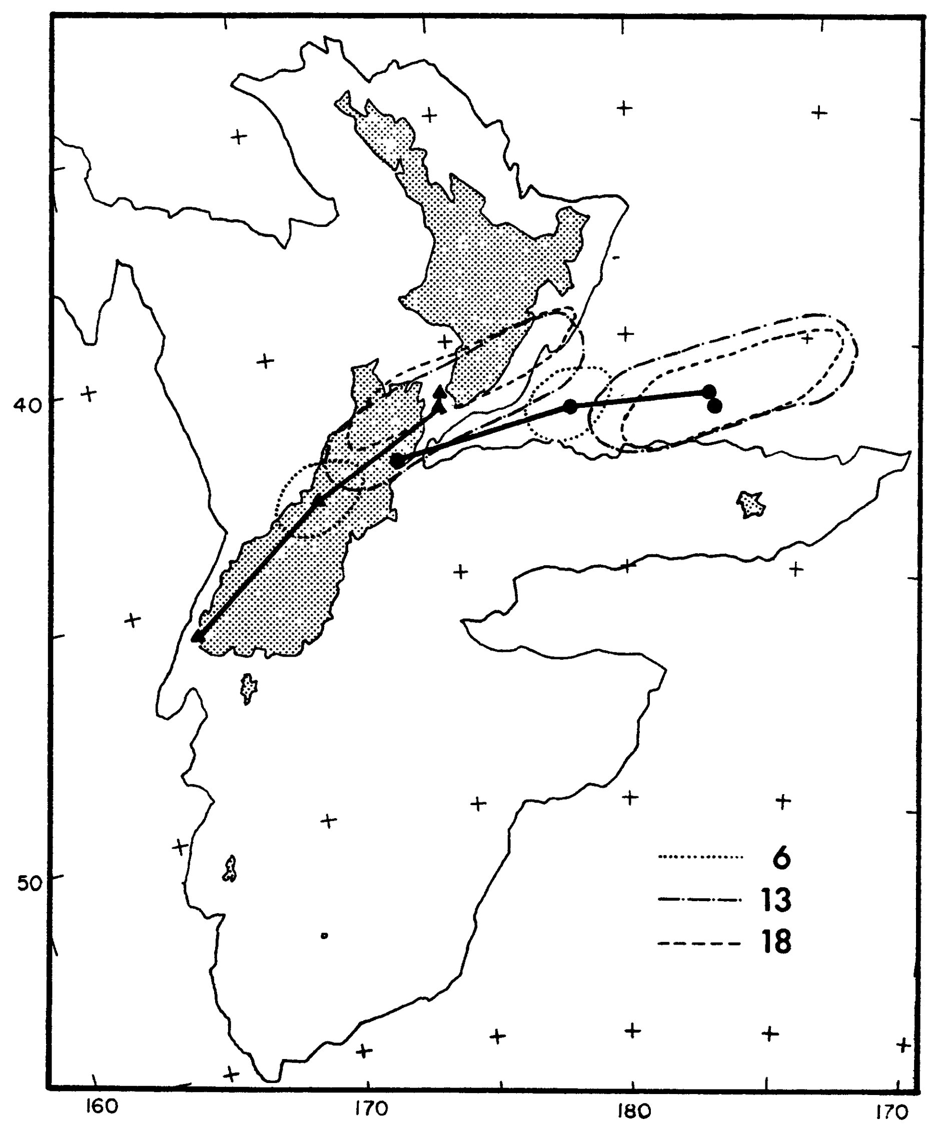


Figure 15

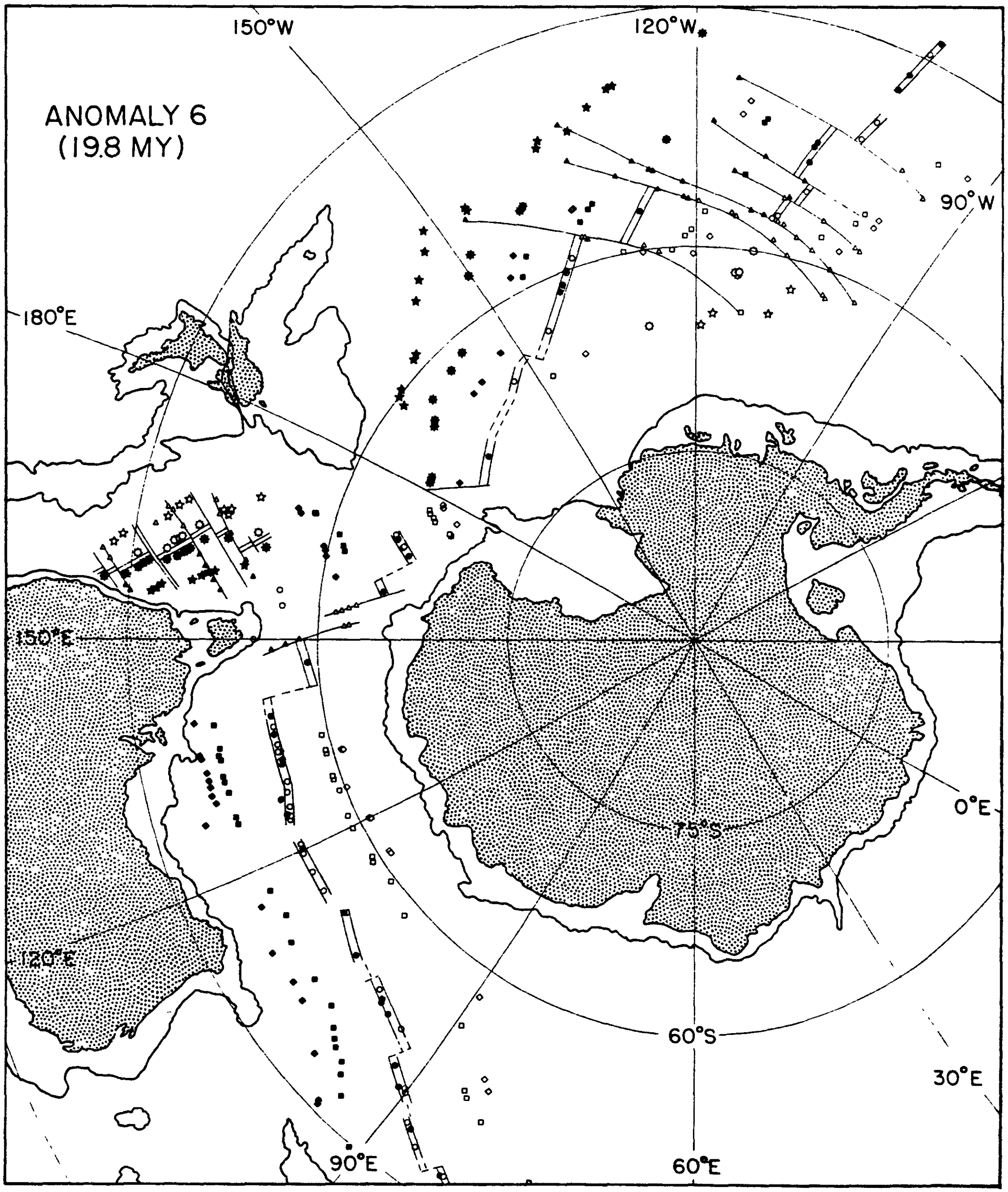

ANOMALY 6
(19.8 MY)
150°W
120°W
90°W
180°E
150°E
120°E
90°E
60°E
30°E
0°E
60°S
75°S

Figure 16

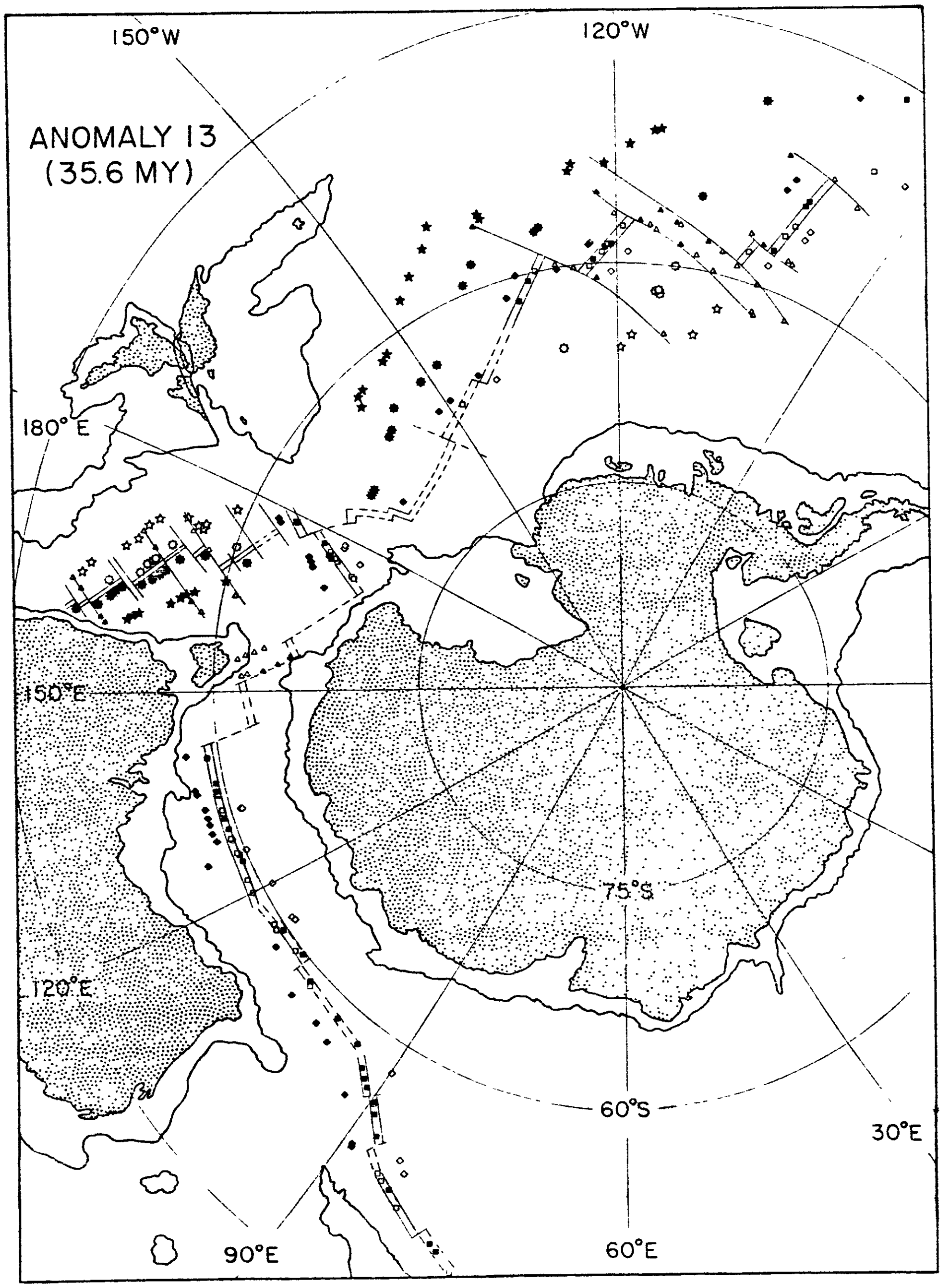


Figure 17

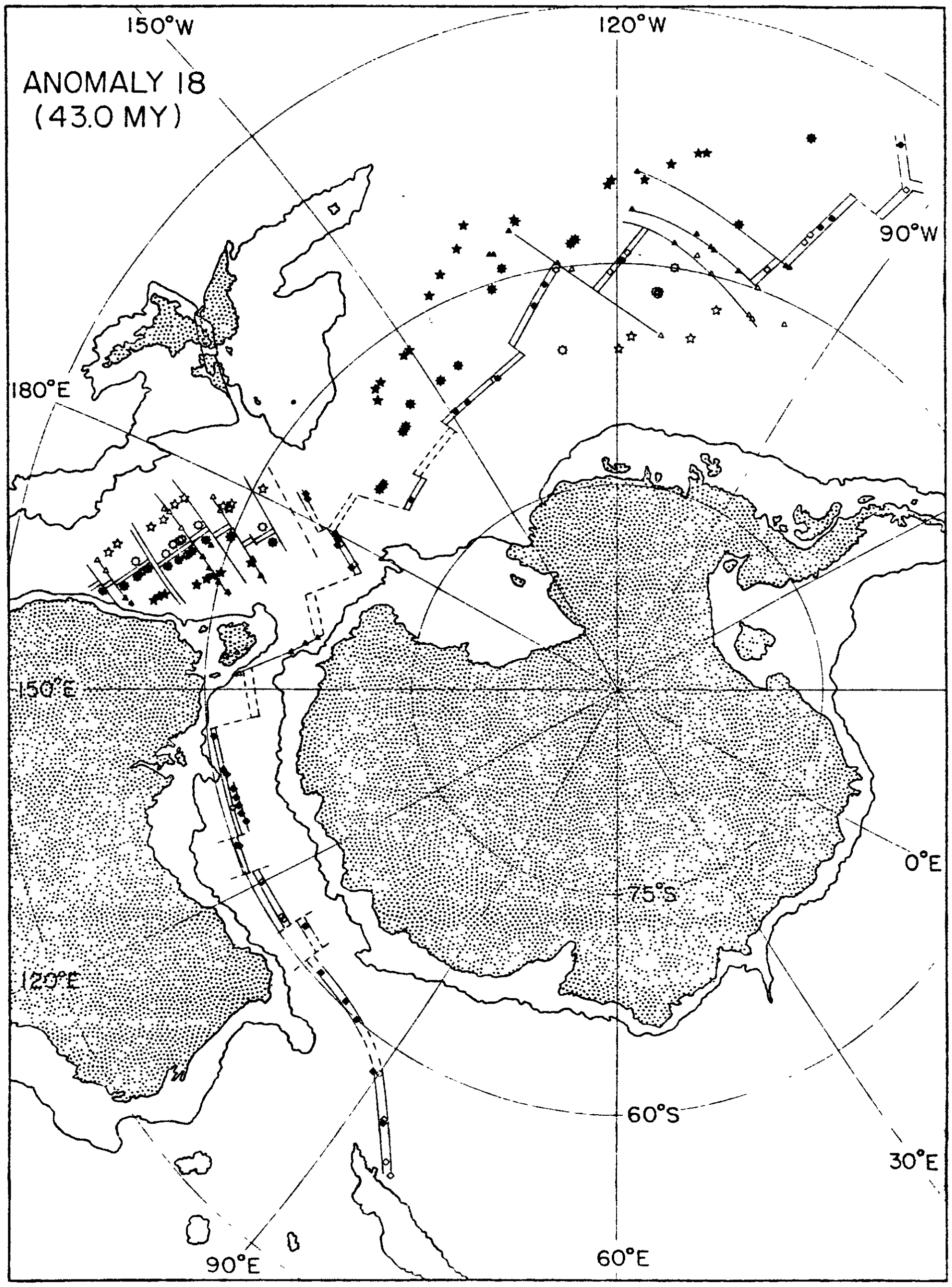

ANOMALY 18
(43.0 MY)
150°W
120°W
90°W
180°E
150°E
120°E
90°E
60°E
30°E
0°E
75°S
60°S

Figure 18

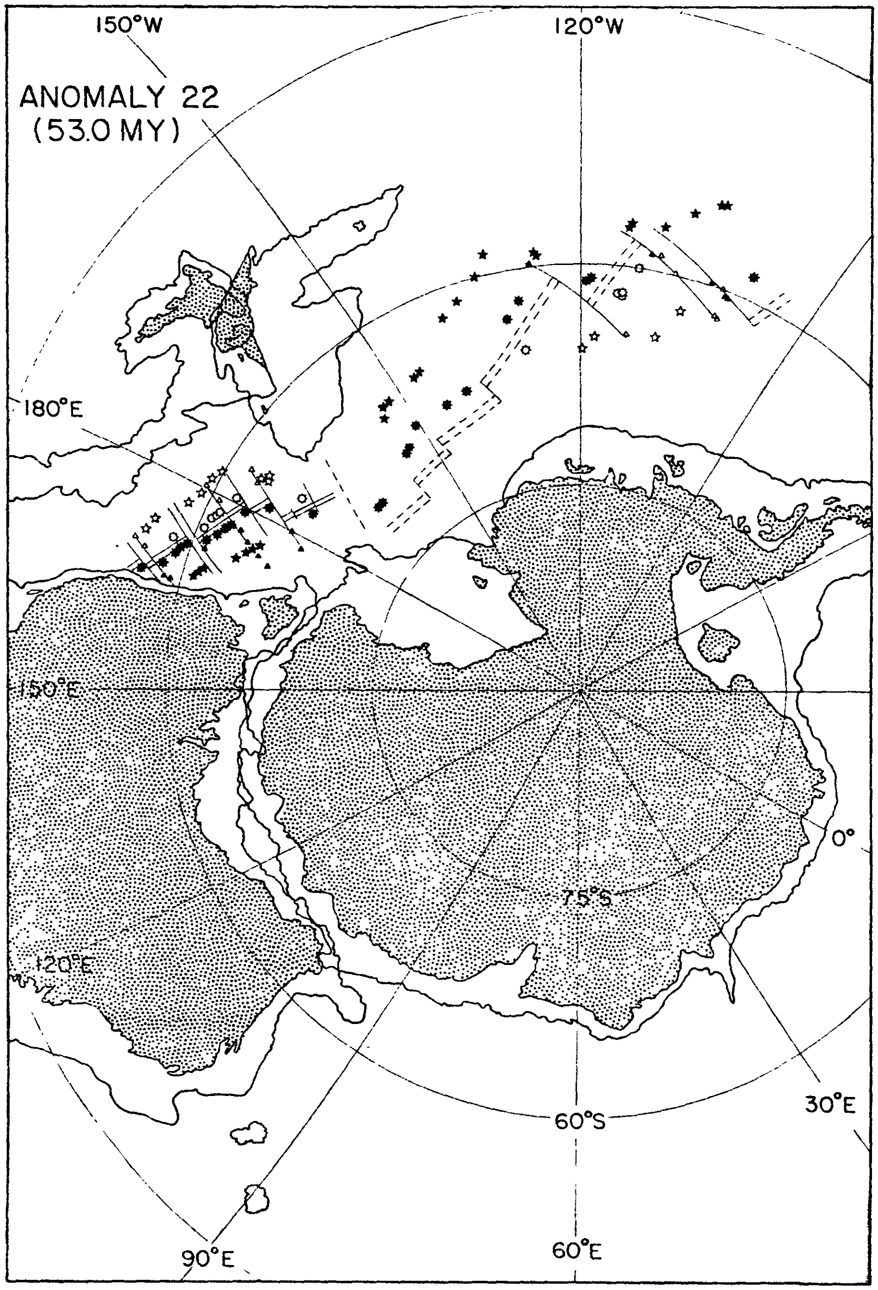

150°W
120°W
ANOMALY 22
(53.0 MY)
180°E
150°E
120°E
90°E
60°E
60°S
75°S
30°E
0°

Figure 19

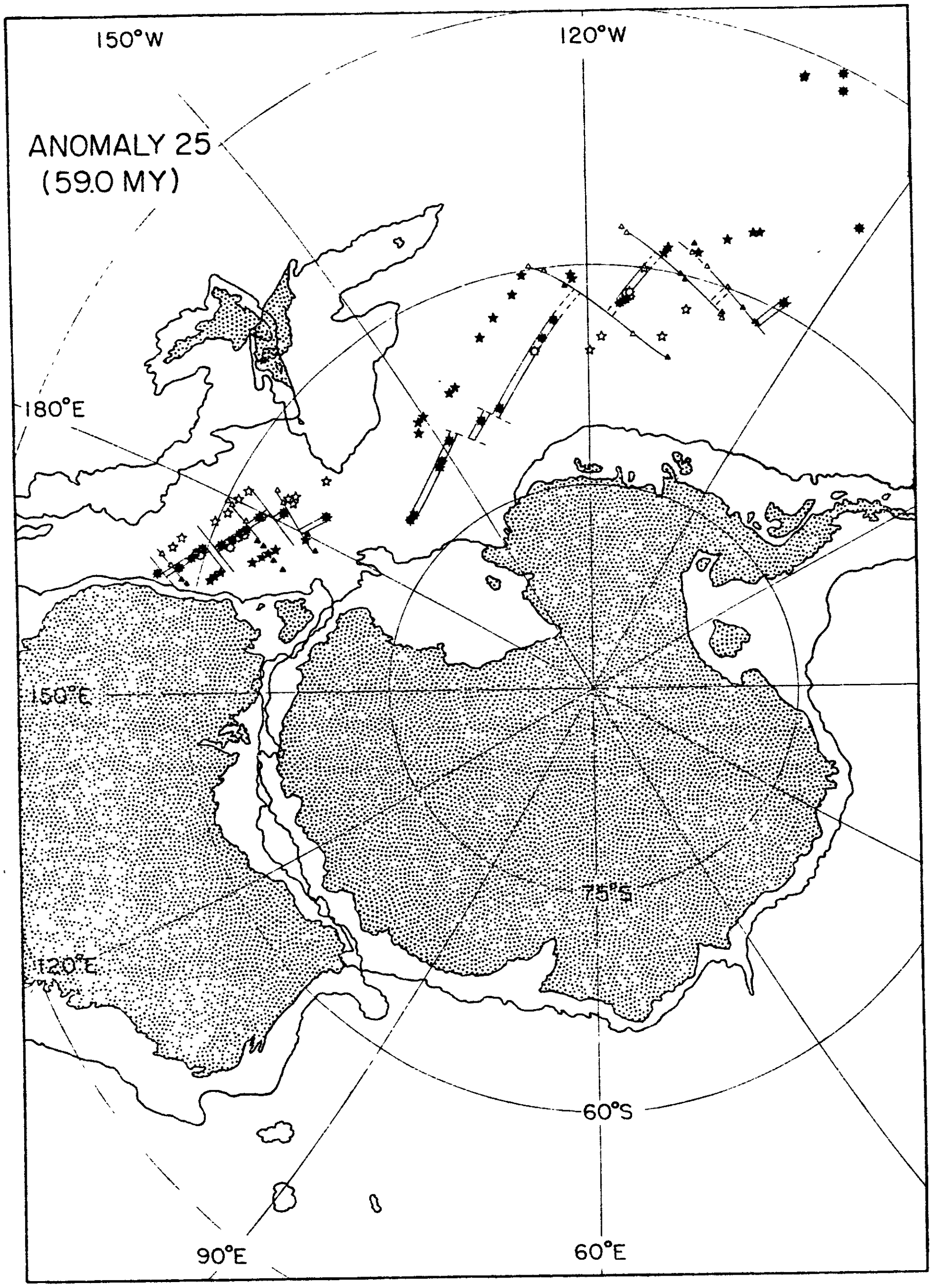
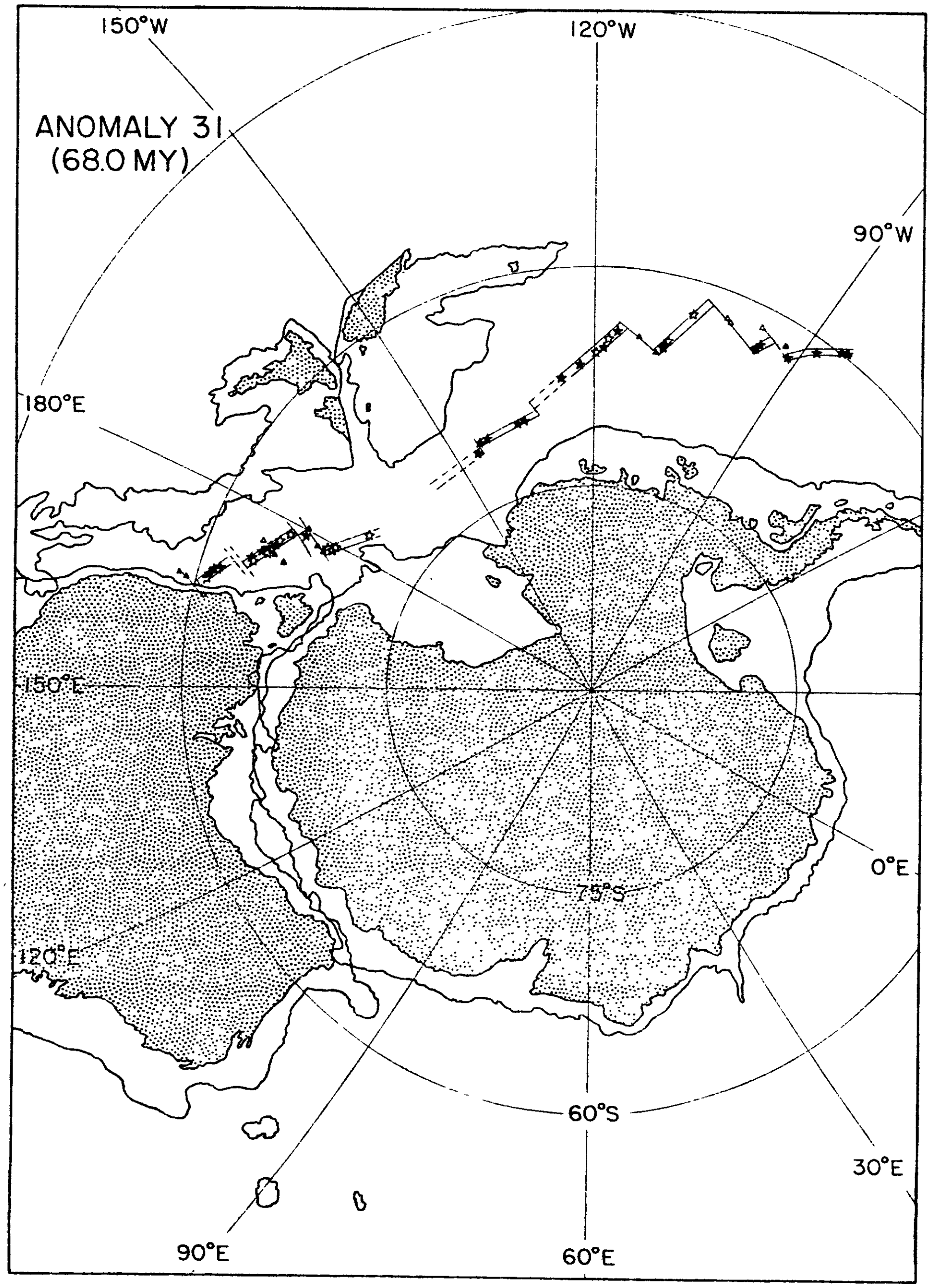


Figure 20



ANOMALY 31
(68.0 MY)
150°W
120°W
90°W
180°E
150°E
120°E
90°E
60°E
30°E
0°E
60°S
75°S

Figure 21

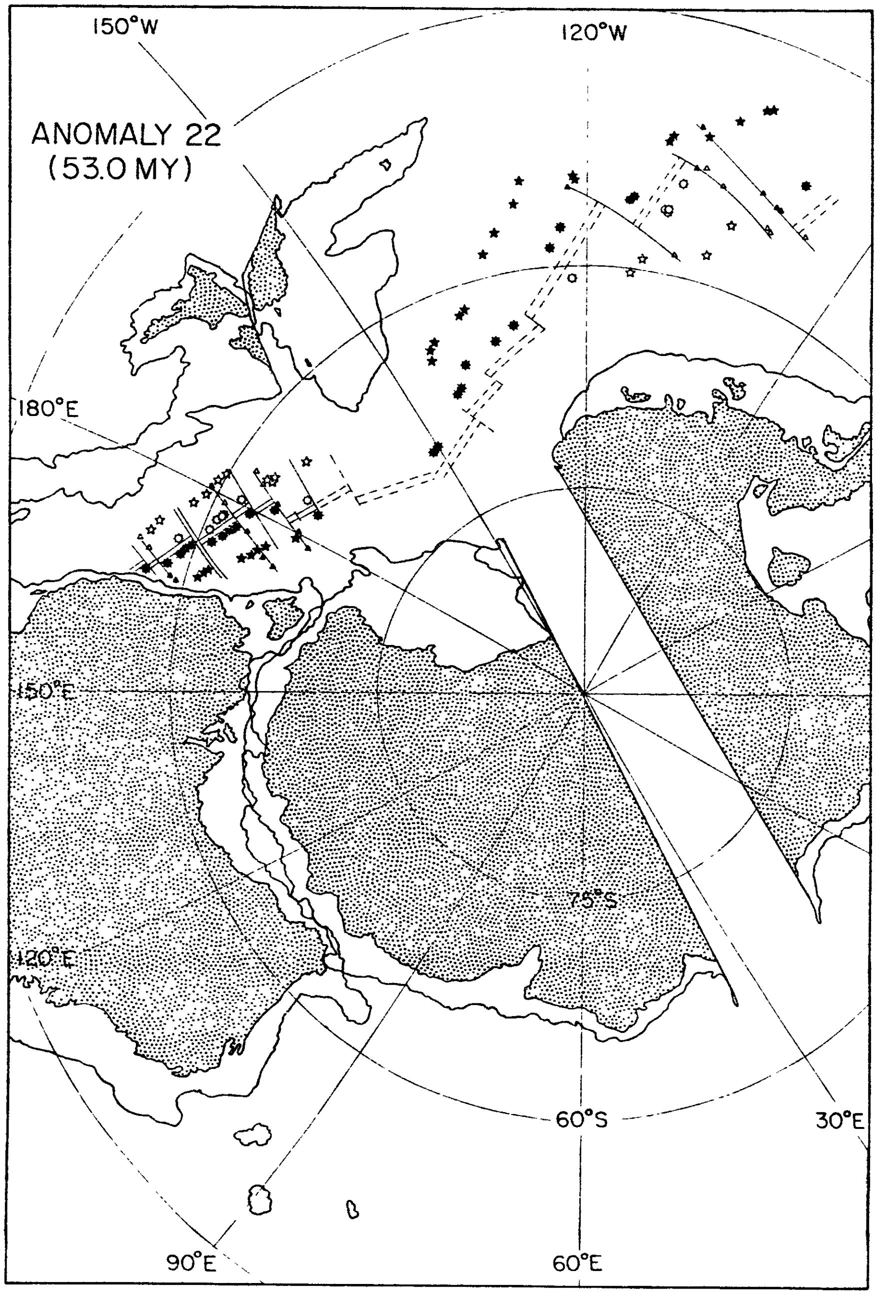


Figure 22

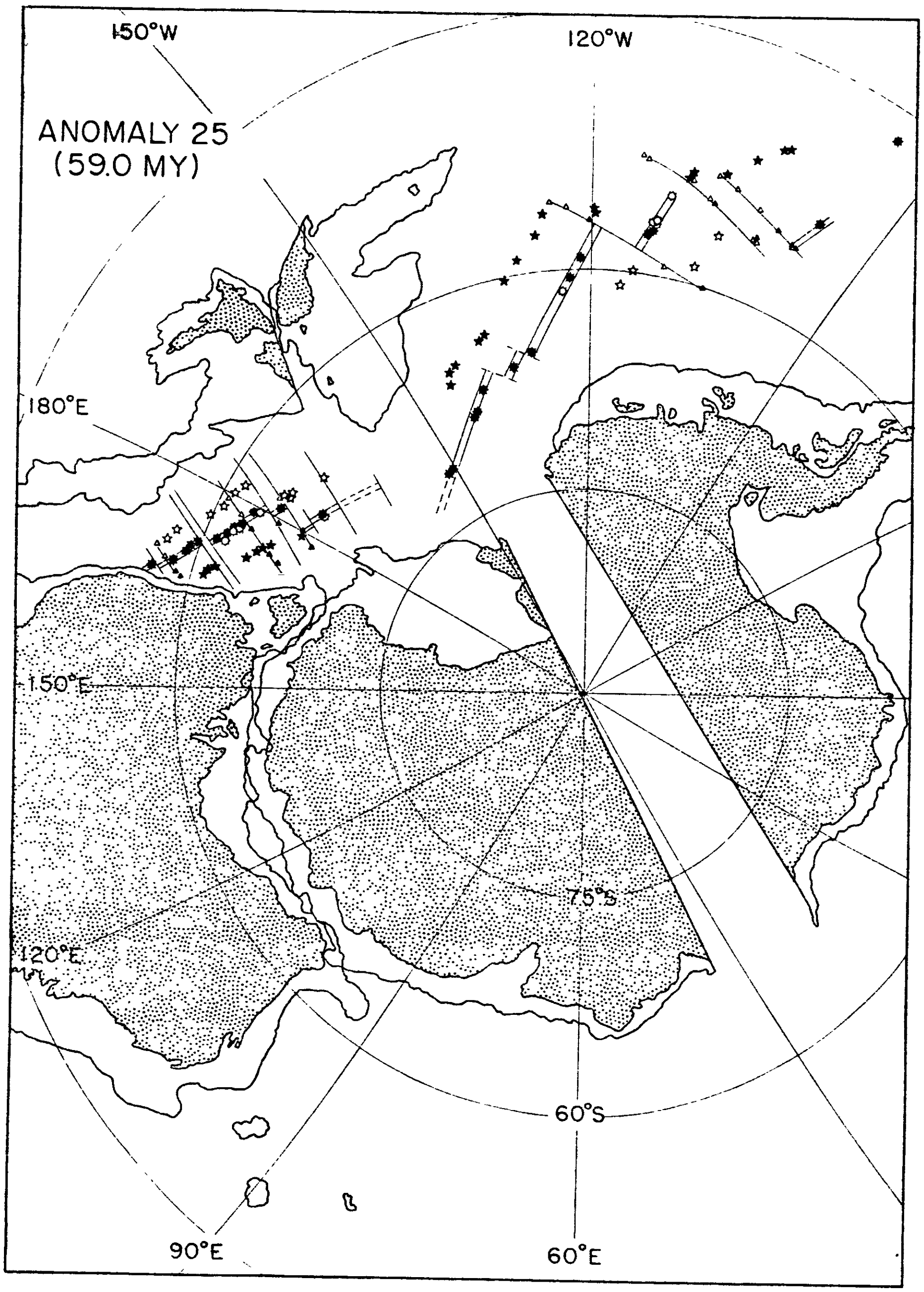


Figure 23

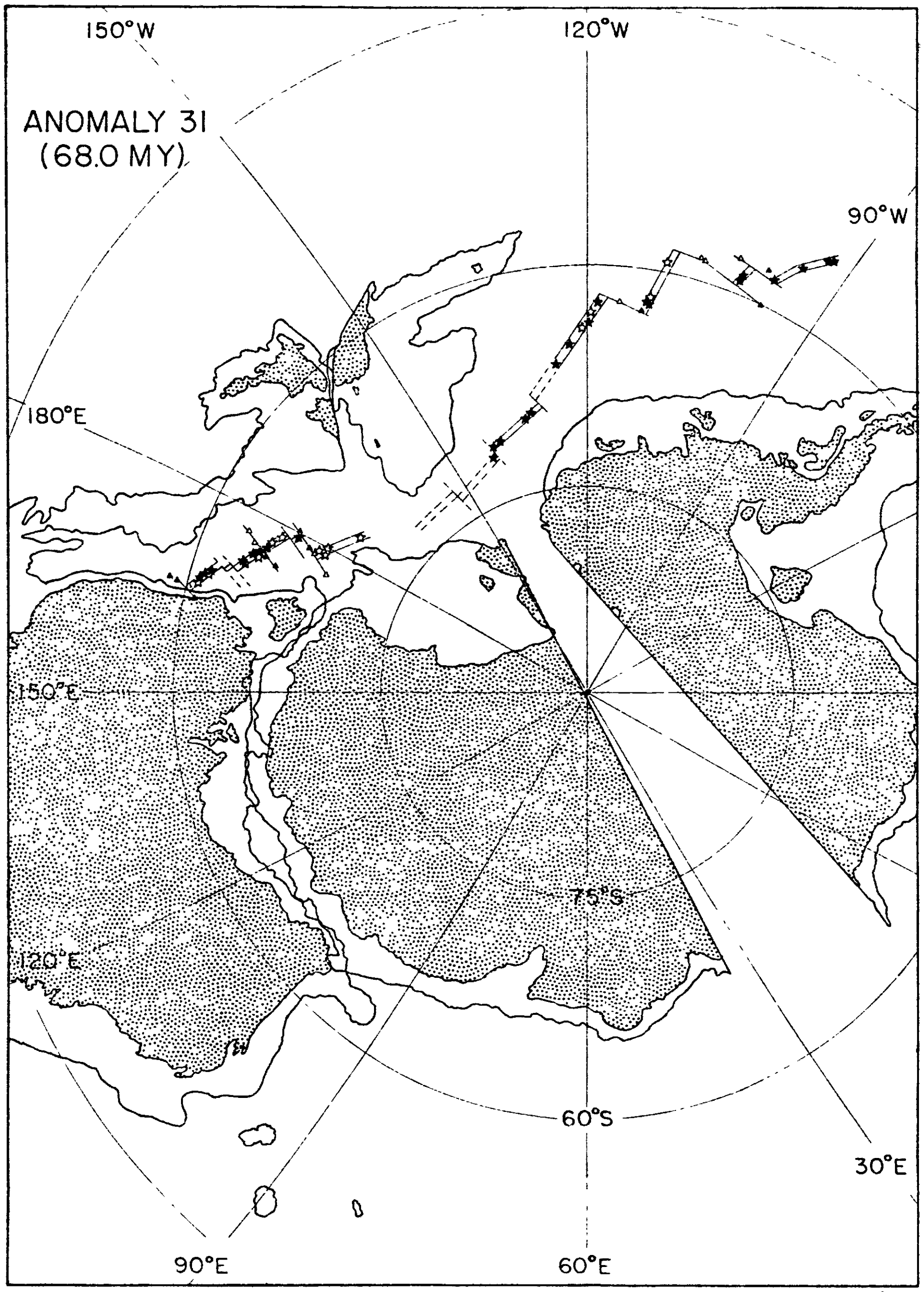

150°W
120°W
ANOMALY 31
(68.0 MY)
90°W
180°E
150°E
75°S
120°E
60°S
30°E
90°E
60°E

Figure 24

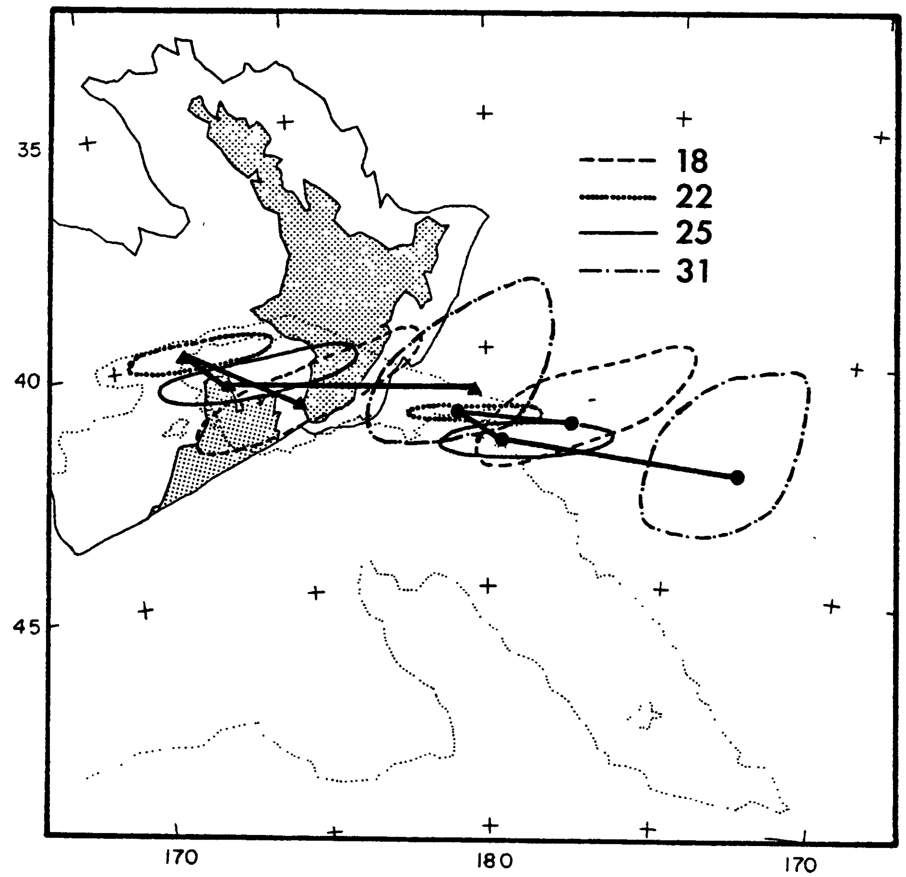


Figure 25

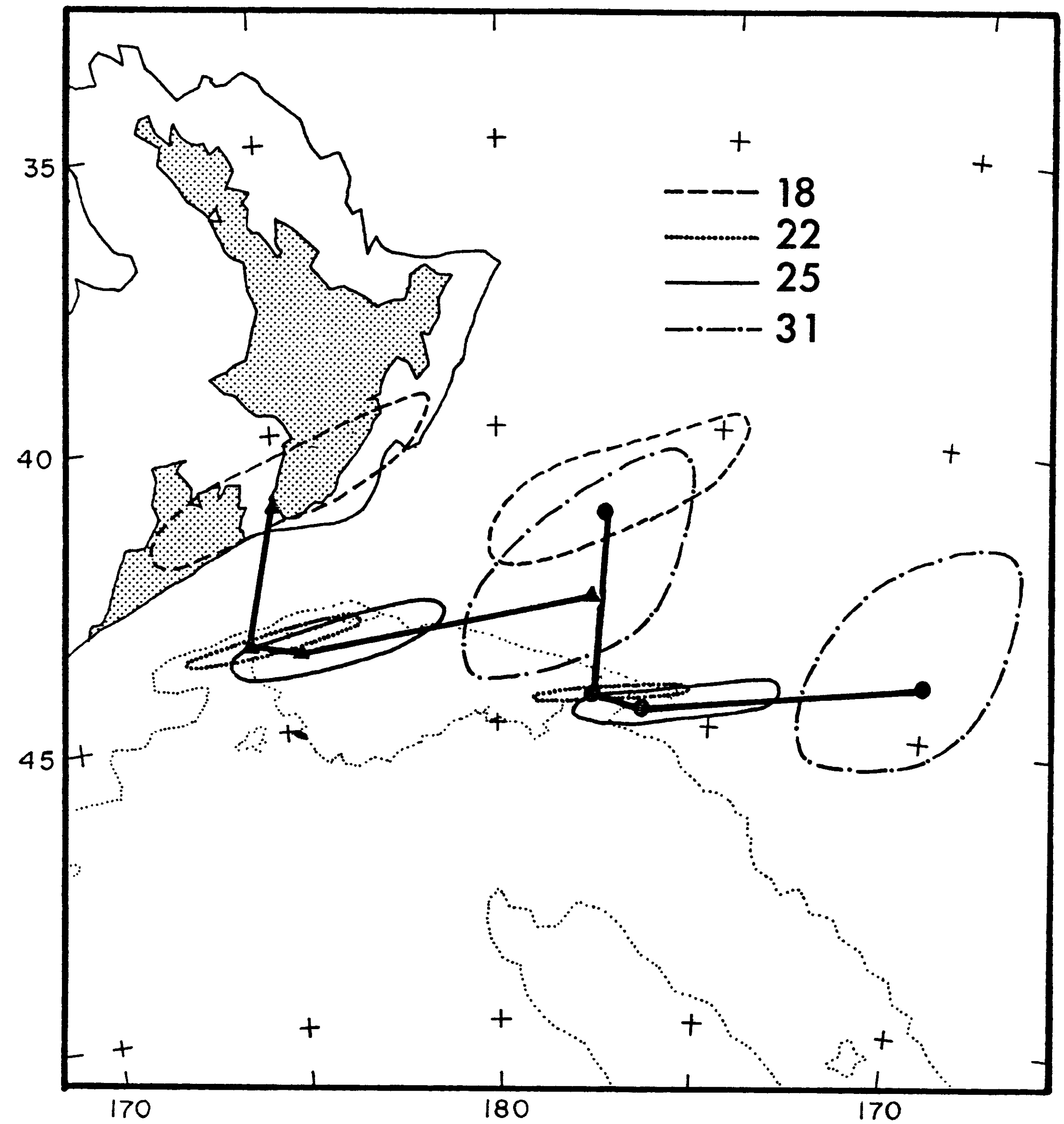


Figure 26

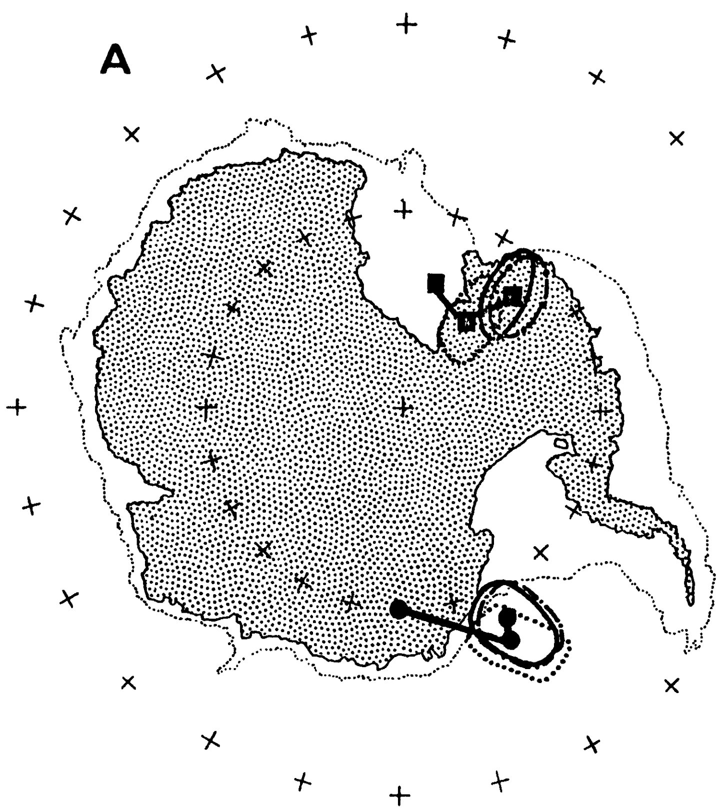


Figure 27a

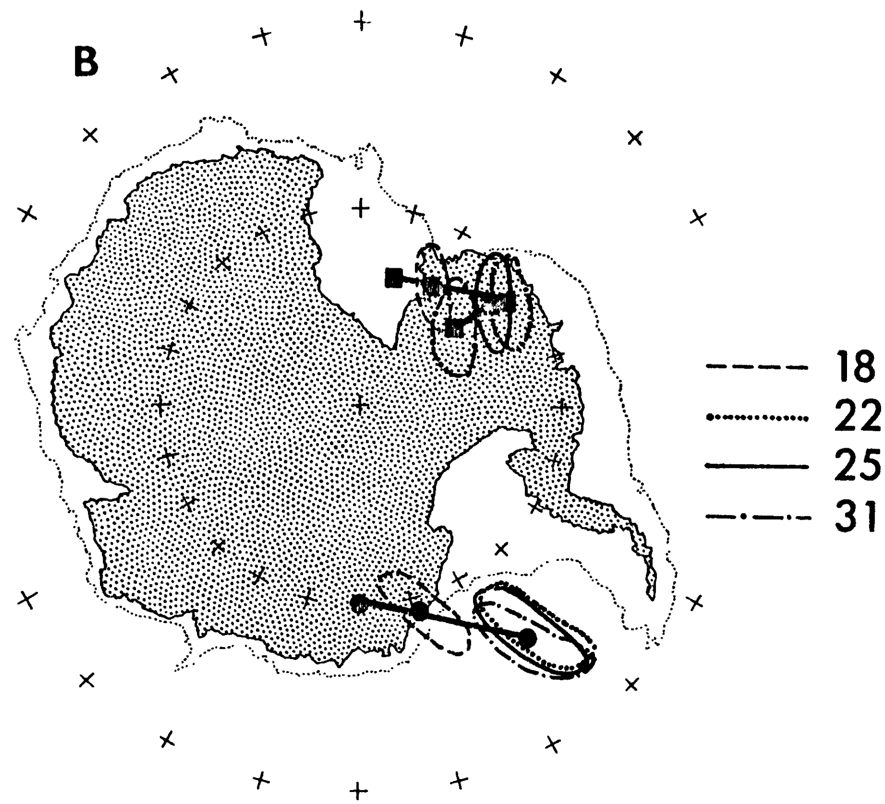


Figure 27b

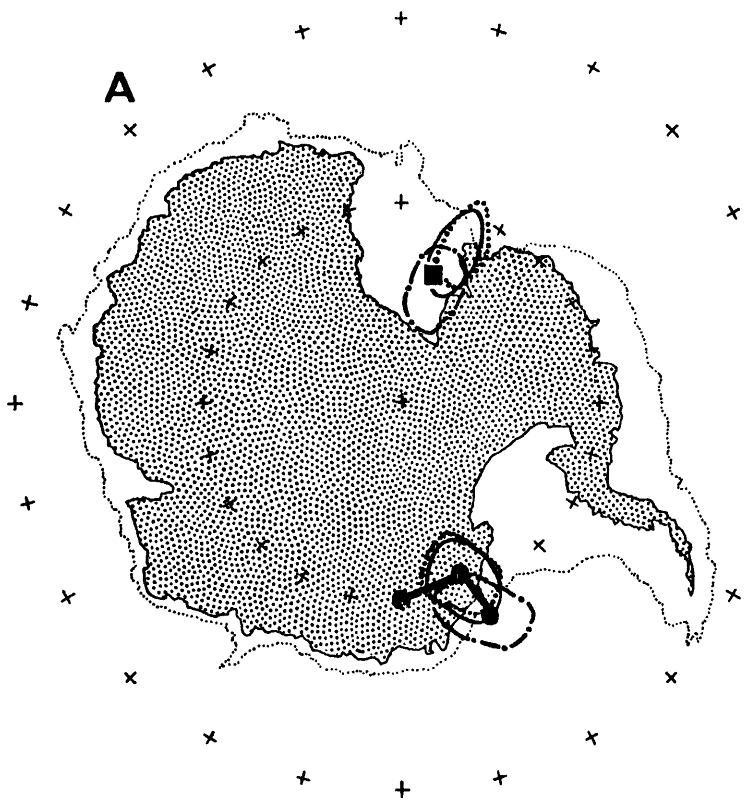


Figure 28a

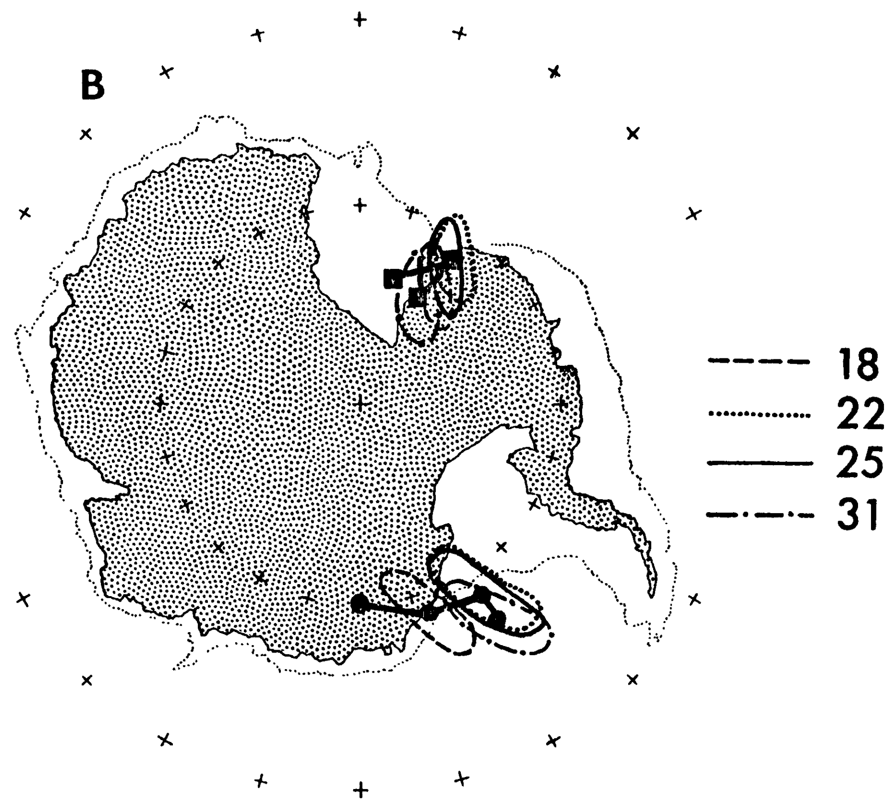


Figure 28b

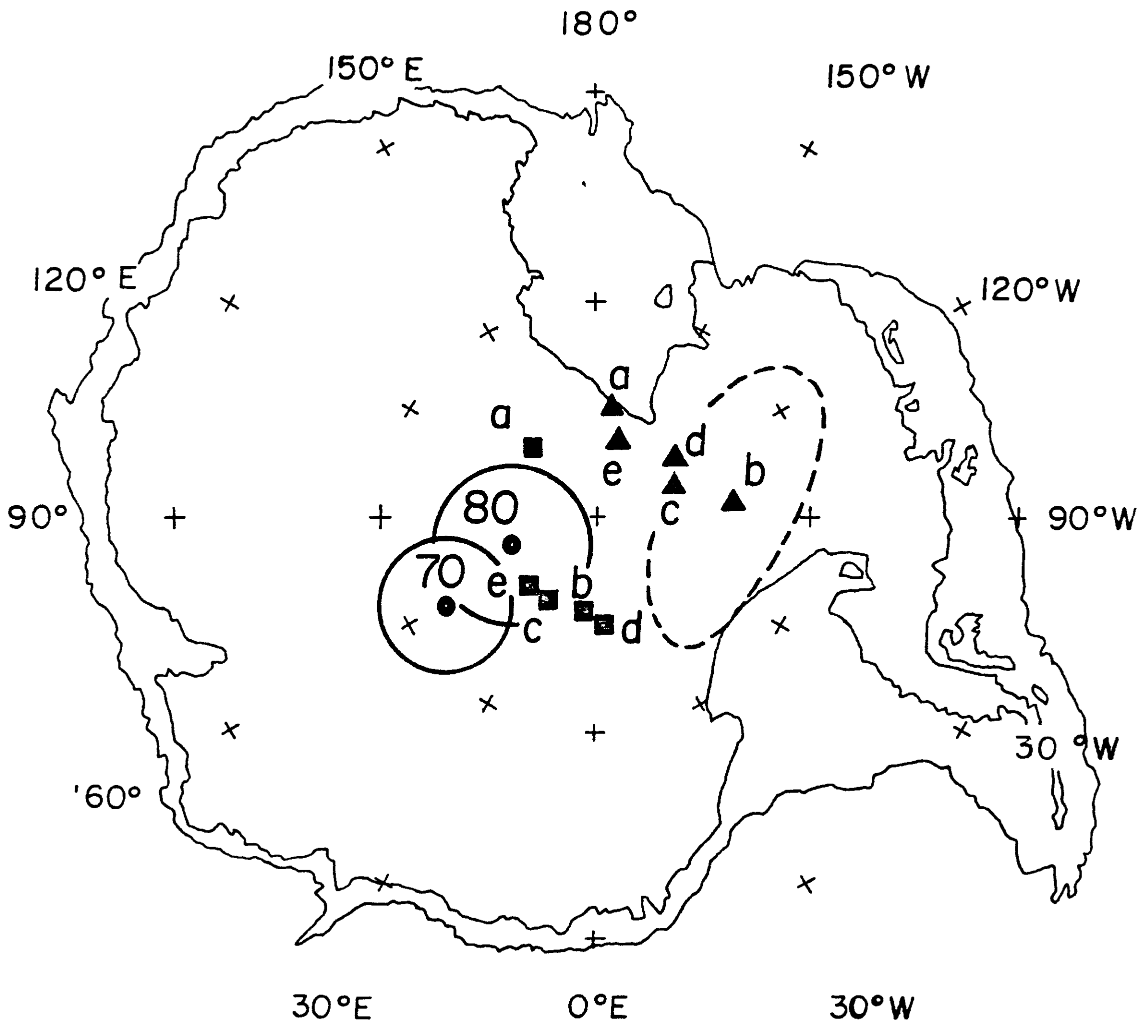
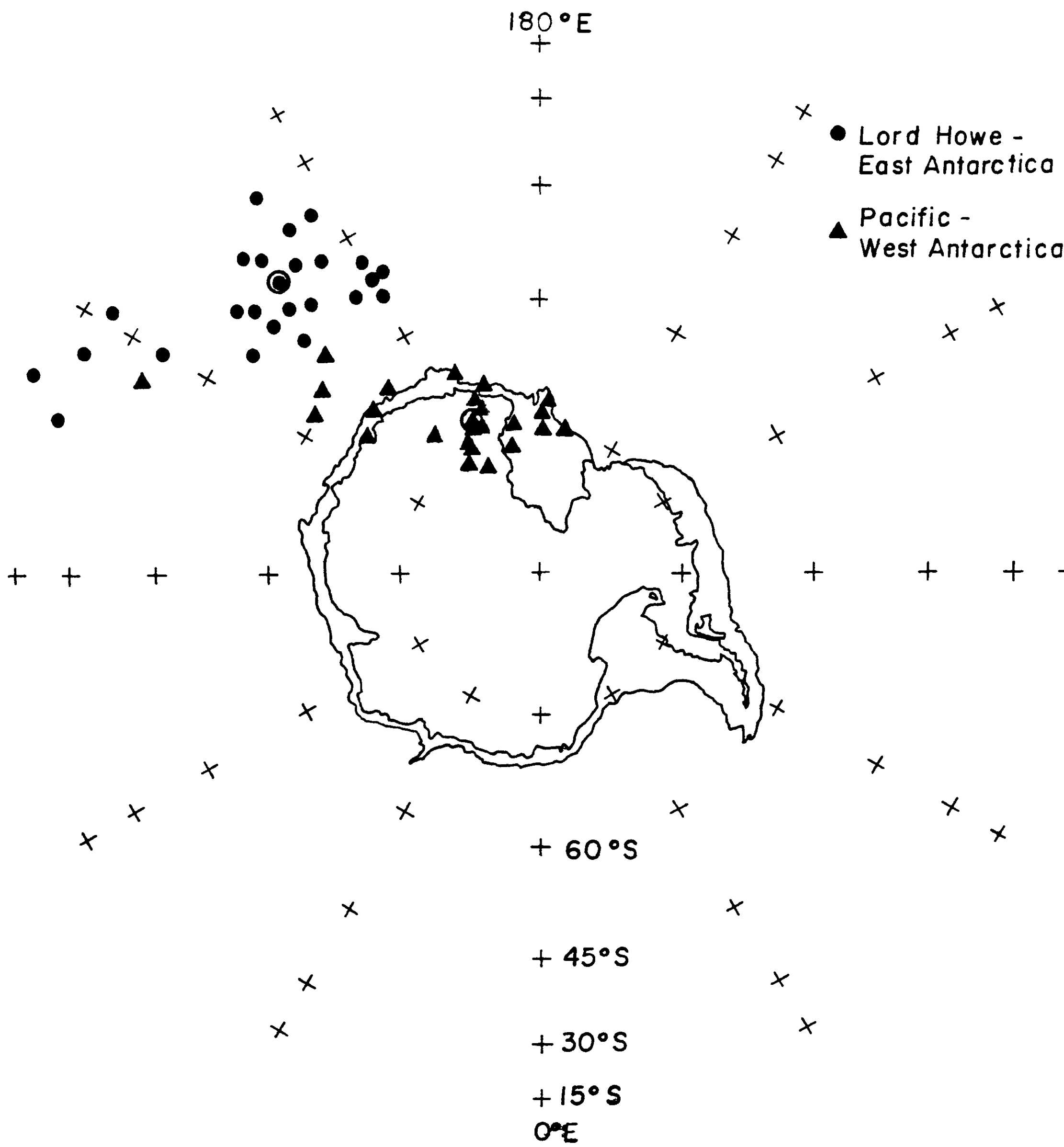

180°
150° E
150° W
120° E
120°W
90°
90°W
'60°
30 °W
30°E
0°E
30°W
80
70
a
b
c
d
e
a
b
c
d
e

Figure 29



180°E
Lord Howe -
East Antarctica
Pacific -
West Antarctica
60°S
45°S
30°S
15°S
0°E

Figure 30

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