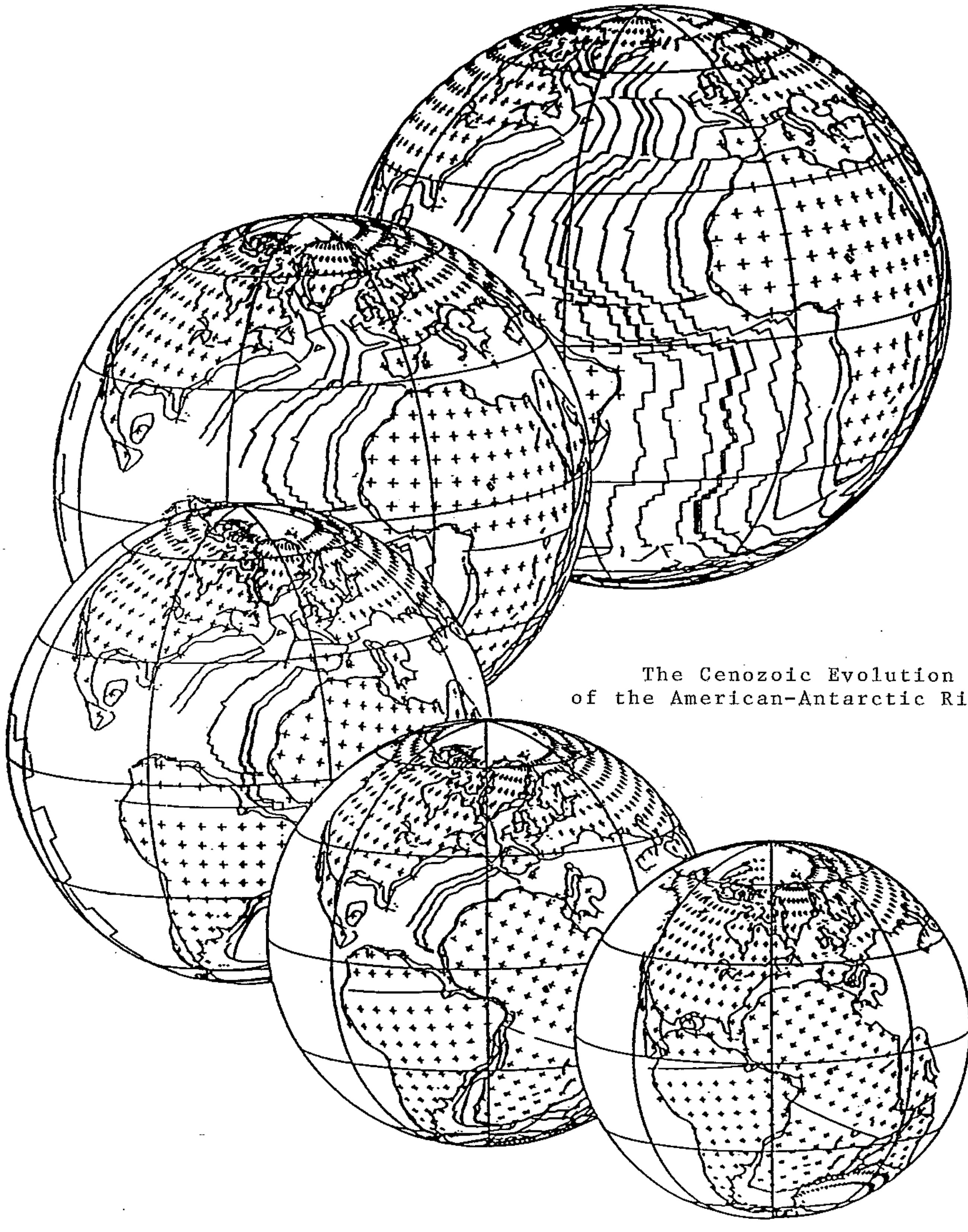
PALEOCEANOGRAPHIC MAPPING PROJECT
PROGRESS REPORT NO. 09-0286



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University of Texas Institute for Geophysics Technical Report No. 56

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ABSTRACT

New bathymetric and magnetic anomaly data for the American-Antarctic Ridge region of the South Atlantic are compiled and presented. The magnetic anomaly data are used to produce poles of rotation and angles of opening for six stages for the Cenozoic between anomaly 5 time (9.7 Ma) and anomaly 21 time (50.3 Ma). Synthetic spreading centers and fracture zones are generated, some of which give very close agreement with noted SEASAT derived gravity anomalies. Two large symmetrical regions of the American-Antarctic Ridge area could not have been formed at the present-day active American-Antarctic Ridge spreading centers. We conclude that the 560 kilometer long Bullard Fracture Zone was created just prior to anomaly 6 (20.4 Ma) time eliminating two or more spreading segments of the American-Antarctic Ridge. The change in spreading and direction which precipitated the realignment of transform faults was caused by the subduction of about 25% of the American-Antarctic Ridge at anomaly 6A or 6B time (21.0-23.0 Ma) at Jane Bank. An additional section of the ridge was subducted near Discovery Bank at about 7-10 Ma and about half of the remaining American-Antarctic Ridge will be subducted between 17 and 20 million years from now if present-day rates persist.

INTRODUCTION

The present-day boundary between the South American and Antarctic plates takes two different forms. As can be seen in figure 1, the western boundary between the Antarctic and South American plates consists of subduction and possible transform motion along the southern extension of the Peru-Chile Trench. The area this paper discusses concerns the American-Antarctic ridge, an extensional and transform plate boundary found east of the Scotia Arc. The American-Antarctic Ridge defines the South American-Antarctic plate boundary in the South Atlantic between the Bouvet triple junction at 55°S 0°E and the South Sandwich Trench at 61°S 27°W. The present day plate boundary is predominantly strike-slip with a few short spreading centers offset by long active transform faults that vary in length from less than 50 kilometers to greater than 560 kilometers. The southernmost transform fault, the South Sandwich Fracture Zone connects the last spreading center on the American-Antarctic Ridge with the South Sandwich Trench. Prior to the opening of the central and eastern Scotia Sea (about 22Ma) the South American plate continued at least as far south as 63°S and as far west as 38°W (Barker et al., 1984). The southern part of the ridge was subducted at Jane Bank and spreading ceased south of 62°S at about 20-22 million years ago. A second spreading center was probably subducted off Discovery Bank at some time later, possibly with the opening of the eastern Scotia Sea (about 7 Ma).

Before the major reorganization of the South Atlantic in the late Mesozoic-Early Tertiary, spreading along the South America-Antarctica plate boundary was mostly North-South changing gradually over time to Northwest-Southeast. After the major westward jump of the Mid-Atlantic Ridge south of the Falkland-Agulhas Fracture Zone (Barker, 1979) at about 65 Ma (anomaly 28 time), spreading along the American-Antarctic Ridge [AAR] seems to have shifted to being mostly east-west with some slight temporal variation. The latitude of the pole of opening during the Tertiary seems to have remained very high ($76^{o} \pm 7^{o}$) while the longitude seems to have shifted by almost 70^{o} (from $+45^{o}$ to -25^{o}). After the change in direction of spreading at 65 million years ago, a primary force on the direction of opening seems to have been first, the amount of eastward subduction along the western margin of South America and the Antarctic Peninsula and later, the amount of pull on the South American side of the AAR caused by subduction along the South Sandwich Trench and its precursor. Since the East Scotia Sea has opened only in the last eight million years at a rate of 50 mm/yr (which accelerated to 70 mm/yr about 1.5 Ma ago (Barker and Hill, 1981)) and because the spreading rate on the AAR is slow (about 20 mm/yr, Lawver and Dick, 1983), the South American Plate is being rapidly consumed as the trench advances eastward at 17 mm/yr absolute rate (Hartnady, personal communication). With the capture of the southern part of the American-Antarctic Ridge at about 22 Ma (Barker et al., 1984) some pieces of the South American plate may have been shifted to the Antarctic Plate as the East Scotia Sea began to open. As time went on, the South Scotia Ridge as the plate boundary between the Antarctic and Scotia plates became quite complex and may be acting today as a leaky transform fault (Barker et al, in prep.).

DATA

Underway bathymetry and magnetics data collected by U.S., British, South African, Argentinian and Japanese research ships have been compiled for the Southwest Atlantic along the AAR. Until recently (Lawver and Dick, 1983), some of the spreading centers and transform faults along the American-Antarctic Ridge were unknown so many of the ship tracks in this area had been run without regard to the probable tectonic fabric. We have merged the extensive British data set with all available NGDC (National Geophysical Data Center) data. The British data primarily cover the area to the South of and to the West of the Bullard Fracture Zone. The area to the north of the Bullard Fracture Zone is covered primarily by U.S. academic oceanographic data. Of major importance to the understanding of the AAR are the long profiles done by the various British ships orthogonal to the present day spreading centers between 58.5°S and 61°S. From these profiles, identifiable magnetic anomalies have been found. In turn, these have been used to determine Cenozoic poles of rotation and angles of opening between the South American and Antarctic plates.

BATHYMETRY

The submarine morphology of the Southwest Atlantic, the area between the Bouvet triple junction at 55°S 0°E and the Antarctic Peninsula, is easily divided into three regions. The southern part is the flat-lying Weddell Sea region with a water depth of greater than 5000 meters in the east gradually sloping upwards to about 4500 meters deep in the western part of the Weddell Sea. The northwestern part of the region is the elevated Scotia Arc and its associated back-arc basin, the Scotia Sea. The northeastern area consists of the American-Antarctic Ridge and the oceanic crust created by seafloor spreading along it during the Tertiary. The spreading on the AAR is slow (20mm/yr over the past 50 million years) and this region is characterized by very rough bathymetry with rift valleys offset by long transform faults.

The bathymetry of the region between the Bouvet triple junction and the South Sandwich Fracture Zone and its intersection with the South Sandwich Trench is dominated by three large transform faults shown in figure 1 and also seen in figure 2. The major northern transform fault is the Conrad Fracture Zone which offsets active spreading centers about 200 kilometers. The Bullard Fracture Zone at about 58°S offsets the active spreading centers 560 kilometers (Lawver and Dick, 1983) and divides the American-Antarctic Ridge into a northern half and a southern half. The existence of the Bullard Fracture Zone was first suggested by fault plane solutions done by Forsyth (1975), but it was not confirmed until 1980. The South Sandwich Fracture Zone connects the southern most active spreading center with the South Sandwich Trench over a distance of 330 kilometers. The trend of the long transform faults is roughly east-west (085°) with approximately north-south oriented spreading centers.

The northern half of the American-Antarctic Ridge consists of three spreading centers between the Conrad Fracture Zone and the Bullard Fracture Zone (Lawver and Dick, 1983). The three spreading centers are offset by two transform faults, the northern one with 92 km of offset and the southern one with 71 km of offset. The two northern spreading centers just south of the Conrad Fracture Zone are teleseismically quiet and so were not recognized until they were surveyed in 1980.

The southern spreading centers between the Bullard Fracture Zone and the South Sandwich Fracture Zone were reasonably well known and appear on the GEBCO chart of this region (LaBrecque et al., 1981). There seem to be at least four distinct spreading centers in the southern group of spreading centers with short to moderate offsets between the four. While it is possible that all of the spreading centers along the American-Antarctic Ridge are non-orthogonal to the transform faults, the one that lies immediately to the south of the Bullard Fracture Zone is distinctly non-orthogonal (see figure 3). Adaptation to changes in the spreading direction may be the cause of the observed non-orthogonality. Whether this particular non-orthogonality was caused by recent changes in spreading direction or is caused by difficult or impossible adaptation to present plate geometry by such a long offset transform fault is not known.

The spreading on the American-Antarctic Ridge is slow (approx. 20 mm/yr over the past 50 million years) so it is not surprising that this region is characterized by very rough bathymetry. In the areas within a hundred kilometers of the spreading centers along the AAR, the bathymetry is very rough (figure 5). Slow spreading ridges seem to have much more rugged topography than fast-spreading ridges (Menard, 1967; Shih, 1980), particularly if fine-scale topography is ignored. Shih suggests that this may be caused by increased lithospheric strength closer to slow spreading ridges dominated by large offset transform faults.

In the areas within two hundred kilometers of the spreading centers along the AAR the bathymetry is very rough. Unfortunately, there are very little data in areas that are known to be older than 20 million years that are not also complicated by crossings of fracture zone traces. The data that we do have such as the long east-west tracks run by R/V Islas Orcadas and R/V Melville at 56°S show very rugged and anomalously shallow topography within the first 10 million years of the spreading center at 45°W (see figure 4). Beyond 12 million years the bathymetry conincides at times with the age versus depth curve of Parsons and Sclater (1977), but does not give an exact match. Further south, there are bathymetric data within 10 million years of almost all the spreading centers along the AAR but the water depth is frequently less than 2500 meters and occasionally is as shallow as 2000 meters. Additional survey data will undoubtedly show even more extensive anomalously shallow bathymetry on oceanic crust younger than 5 million years old.

By anomaly 21 time according to the age versus depth curve of Parsons and Sclater, depth to basement should be 5000 meters. The region west of 16°W and north of 58°S is assumed to be older than 50 million years, although most of the seafloor in that region is shallower than 4500 meters (figure 2). It is possible that the seafloor is being pervasively uplifted prior to being subducted at the trench. Pre-trench uplift has been documented off the Aleutian and Kurile Trenches (Chapple and Forsyth, 1979) and in other areas. Other than pre-trench uplift, there is no reasonable tectonic explanation for such older crust being so shallow since the sediment thickness in this region is generally less than a few hundred meters (unpublished results from R/V Melville cruise).

Some fracture zones can be recognized in the available bathymetric data. There is a distinct curvature of the eastern half of the South Sandwich Fracture Zone at about 14-15°E where its general east-west trend changes to a southeasterly trend. This mirrors the noticeable northwest trend in the South Sandwich Fracture Zone as it approaches the South Sandwich Trench. While there is not have detailed coverage of the South Sandwich Fracture Zone to the east of 15°E, there are several profiles that indicate another probable fracture zone just to the north. The crossings of that fracture zone are remarkably similar (figure 5) as it curves to the southeast.

In contrast, the very striking Bullard Fracture Zone with its 560 kilometer of offset and depths greater than 6400 meters, does not show any evidence of the pronounced northward curvature found at the western end of the South Sandwich Fracture Zone nor does it show the southward curvature suggested by the southern fracture zones to the east of the American-Antarctic Ridge. Because of its great offset the Bullard Fracture Zone does appear to have a slight curvature but this is a factor of the mercator projection. While the northern transform faults can be detected in lines east of 9°W (the north-south trending dotted tracklines on figure 2), the curvature seen on the southern transform faults can not be detected on the northern ones because of insufficient bathymetric coverage to the west of 9°W. The northern fracture zones should show the same curvature as seen on the southern fracture zones for crust older than anomaly 6 (20 million years ago [Ma]) time.

SEISMIC DATA

Earthquake epicenter locations (epicenter source: National Earthquake Information Service (NEIS) 1985) are shown in figure 3. West of 24°W the recorded seismicity increases dramatically near the South Sandwich Trench and not all epicenters can be distinguished. As mentioned previously the northern two spreading centers are teleseismically quiet. Only the short spreading center at 59.5°S is noticeably active. The earthquake epicenters clearly delineate the Bullard transform fault as well as the active part of the South Sandwich Fracture Zone. The center two of the southern transform faults are teleseismically apparent while the northern most is quiet and the southern most if it exists is also quiet. The Conrad Fracture Zone to the north is not as teleseismically apparent as either the Bullard or South Sandwich Fracture Zones are.

The intraplate earthquakes at 59.5°S and 22°W have been the matter of some speculation. Right-lateral strike-slip fault plane solutions have been reported for these earthquakes (Farmer et al., 1982). Such a solution is in an opposite sense to that found on the transform faults along the South America-Antarctica plate boundary (Forsyth, 1975). It is probable since these intra-plate earthquakes do not seem to lie on the extensions of any known transform faults along the American-Antarctic Ridge that plastic deformation of the young southern end of the South American plate is occurring similar to the postulated deformation found on the Gorda Plate (reference ?). To the north of 58.5°S along the trench is older crust (50 to 70 million years old) while to the south of 58.5°S but north of the South Sandwich fracture zone the crust varies between very young at the ridge to at most 27 or so million years old at the trench. We assume that the younger more bouyant crust is not so easily subducted as the older crust to the north and hence the differential motion may produce the intra-plate right-lateral strike-slip seismicity.

SEASAT DATA

The American-Antarctic Ridge is on the edge of the region of good coverage by SEASAT data (Sandwell, 1984). Because SEASAT only collected satellite altimetry data when the Antarctic ice coverage was at its greatest, the data for the AAR regions is very noisy. The SEASAT-derived deflection of the vertical data (figure 6) is taken from Haxby (1985) with certain features highlighted. Figure 6 shows the curvature of the South Sandwich Fracture Zone discussed earlier as well as the very prominent anomaly caused by the Bullard Fracture Zone. It also shows a number of curved features north of the Bullard Fracture Zone which are inferred to be caused by fracture zones either current or abandoned.

MAGNETICS DATA

Previous work on the American-Antarctic Ridge (Sclater et al., 1976; Lawver and Dick, 1983) indicated that the central magnetic anomaly was easily identifiable not only by its shape and magnitude but also because it invariably occurred over a major bathymetric low characteristic of slow spreading ridges. Anomaly 5 (10 Ma) was also reasonably easy to pick out because of its distinctive shape, see figure 7. Beyond anomaly 5, anomaly 6 (20 Ma) could be identified by its large broad domal shape. Anomalies 7 and 8 (25-28 Ma) in the southern section of the AAR are identifiable as a pair of well separated discrete anomalies.

Previously published spreading rates for the AAR only reported data out to anomaly 5 time (Lawver and Dick, 1983) or Anomaly 3' (Sclater et al., 1976). While the published spreading rates were similar and gave total rates of opening for the AAR for the last 10 million years as roughly 19.5 mm/yr, calculated spreading rates using South America-Africa (SOAM-AFRC) and Africa-Antarctica (AFRC-ANTA) poles and angles of rotation back to early tertiary indicated a reasonably constant spreading. The match to the synthetic magnetic anomaly profiles (figure 8) give spreading rates of 19.6 mm/yr out to slightly younger than Anomaly 5, an increase to 22.4 mm/yr for the period Anomaly 5 to Anomaly 6 (10-20 million years ago) and a rate of 20.8 mm/yr for 20 million years ago to 50 million years ago.

On this general framework, other magnetic anomalies can be identified if a reasonably constant spreading rate and symmetrical spreading is assumed. Once the anomalies were identified as best as possible, their positions were digitized as well as the magnetic anomaly picks made along the Mid-Atlantic Ridge by Ladd (1974), Barker (1979) and data for the east-west line at 55.5°S (figure 7). Magnetic anomalies along the Southwest Indian Ridge from LaBrecque and Hayes (1979), Fisher and Sclater (1983), Patriat (unpublished) and Bergh (unpublished) were repicked if necessary, digitized and input into a interactive dimensionally-correct graphics display (Scotesean reference). By producing closure of assumed symmetrical anomalies along the Mid-Atlantic Ridge, the Southwest Indian Ridge and the American-Antarctic Ridge, poles of rotation and angles of opening for anomalies 5 and 6 were determined.

For anomalies 8, 11, 13, 18 and 21 there are insufficient matching pairs of magnetic anomalies on the American-Antarctic Ridge to constrain the pole and angle of opening for the ANTA-SOAM plate rotations. Consequently the best poles were determined for half-angle rotations for the SOAM-AFRC and AFRC-ANTA motions. The half-angle rotations were then improved by superimposing identified anomalies with the corresponding present day spreading centers on the American-Antarctic Ridge. From this exercise the poles and angles of rotation for ANTA-SOAM were derived that are shown in Table 1. While the later poles of opening for the Mid-Atlantic Ridge are Ladd's poles (1974), the poles for anomalies 18 and 21 reflect the inclusion of the Barker (1979) data and the picks from figure 6 with greatest emphasis on the re-picked Barker data. It is important in this exercise to make sure that the same part of each anomaly is picked on all three plates. While the anomaly 13 pole for SOAM-AFRC is straight from Ladd (1974) his anomaly 5 pole has been modified slightly although the modification does not have a large affect on the ANTA-SOAM pole. By anomaly 5 (9 Ma) time there are sufficient matched pairs of anomaly 5 on the American-Antarctic Ridge that closure around the Bouvet triple junction is used primarily to confirm our direct determination.

The half-angle rotations for anomalies 18 and 21 are shown in figure 9. When the pole of opening for anomaly 21 was determined, the northern anomaly 21 was not utilized initially because it was thought to have been formed on the Mid-Atlantic Ridge. The assumed spreading rate for its creation, if it had been produced at the American-Antarctic Ridge spreading center directly to the east, did not agree in position with the anomaly 21 formed on the Antarctic plate nor with a constant spreading rate. It was only after the hard-copy results of the interactive graphics terminal work were analyzed was it noticed that the northern anomaly 21 actually coincided with the southern spreading segment of the northern spreading centers. It was then realized that the curvature of the fracture zones that is noted to the southeast of the AAR would also appear to the northwest of the AAR if sufficient bathymetric data were available on the South American plate to the north of the Bullard Fracture Zone. The curvature does appear in the SEASAT data shown in figure 6. Since both the southern and northern observed anomaly 21 can be matched to the spreading centers (figure 9b) that created them and particularly since they are on different plates implying that a change of the pole of rotation would improve one match at the expense of the other, it is felt that the anomaly 21 pole of rotation is a good first approximation. Analysis of the anomaly 18 hard-copy of the half-angle rotation indicated that it had been formed at the central of the northern spreading centers (figure 9a). Again because the observed anomaly 18's were on different plates, it is felt that the pole of rotation for anomaly 18 is a good first approximation. By anomaly 13 time, the northern pick had been formed at the northern spreading center and agrees with a nearly constant spreading rate. Because of the oblique angle of the tracklines with the proposed synthetic fracture zones, it is difficult to determine where the fracture zones cross these lines although the one between the northern anomaly 18 and the northern anomaly 21 is fairly definite because it shows in the observed bathymetry.

APPLICATION OF DATA

The calculated ANTA-SOAM poles from Table 1 can be used to construct a 'synthetic' paleo-spreading center chart (figure 10). Figure 10 actually illustrates the projected average locations for magnetic anomalies that might be found if a complete survey of this region existed and that the present spreading ridge geometry has persisted in tact with time. The locations for anomalies 28 and 34 were calculated using SOAM-AFRC and AFRC-ANTA poles (Lawver et al., 1985) to produce the ANTA-SOAM rotations. The two older magnetic anomalies are used primarily to illustrate that an obvious change in spreading direction must have occurred between anomaly 28 and anomaly 21 times.

Since figure 10 shows where the magnetic anomalies formed at spreading centers that have the same shape and relative spacings as the present-day spreading centers would be found, a rather astounding outcome is that two large swaths of oceanic crust clearly could not have been formed by any of the presently existing spreading centers. Since these two large swaths are symmetrical, it can be assumed that a single or closely spaced set of spreading centers were responsible for both swaths. It must also be assumed that the spreading centers that formed these swaths were in some way eliminated at some point in the past. Since anomaly 6 west, formed at the southern most of the northern spreading centers, defines about half of the north side of the eastern Bullard Fracture Zone and anomaly 6 east, formed at the northern most of the southern spreading centers, defines about half of the south side of the western Bullard Fracture Zone, we assume that the Bullard Fracture Zone has existed at least since anomaly 6 time. At some time, possibly just prior to anomaly 6 time, the Bullard Fracture Zone appears to have broken through and connected the two present-day spreading centers while eliminating as many as three spreading centers and two fracture zones. One of the postulated abandoned fracture zones may be seen as the SEASAT-derived anomaly shown as a dashed line in the center of the northwest shaded area in figure 10.

If the Bullard Fracture Zone is assumed to be only slightly older than 22 million years old, then the pronounced curvature found on the other fracture zones produced prior to 22 Ma would not be seen along the Bullard Fracture Zone. The curvature of some of the other fracture zones can also be seen on the SEASAT-derived gravity map (figure 6). When these are superimposed on the synthetic paleo-spreading center figure, two of the prominent lineations from figure 6 superimpose on the synthetic fracture zones, see dotted lines on figure 10. In particular a SEASAT-derived gravity lineation falls on the northern fracture zone just north of the Bullard Fracture Zone. The South Sandwich Fracture Zone and its eastern extension as well as the Bullard Fracture Zone show up clearly on the SEASAT derived geoid map.

The poles of rotation used to produce the synthetic spreading center chart produce the curvature in the synthetic fracture zones between anomaly 8 and 13. This would be expected since the input data (the actual observed magnetic anomalies, figure 7) in fact showed curvature. The agreement with the SEASAT data (Haxby 1985; Sandwell, 1984) lends support to the idea that these fracture zones are indeed curved. A change in direction of motion is assumed to be responsible for both the curvature of the older fracture zones as well as for the creation of the 560 kilometer long Bullard Fracture Zone at about 22 million years ago. Given the poles and angles of rotation in Table 1, the only plausible explanation for the two shaded swaths shown in figure 10 is that the active spreading centers that created the two swaths were eliminated at about anomaly 6 time with the creation of the Bullard Fracture Zone and this was caused by a change in spreading direction.

A reconstruction of the paleo-spreading centers at anomaly 6 time (figure 11) shows that the two swaths of unknown crust were contiguous at 20 million years ago. Evidence for reorganization of other major fracture zones was recently presented for the Prince Edward Fracture Zone (Patriat et al., 1985). Patriat (1983) also noted a change in apparent spreading direction on the Southwest Indian Ridge at a little before anomaly 6 time.

It is not known if that change is related to the change found on the American-Antarctic Ridge.

CONCLUSIONS

Spreading on the American-Antarctic Ridge during the last 50 million years has been slow but reasonably constant (approx. 20 mm/year) with only a minor increase at about 22 million years ago (to 22.4 mm/year) and a subsequent decrease at about 7 million years ago to 19.6 mm/year. If the Kent and Gradstein (1985) timescale is used instead of the LaBrecque et al (1977) timescale then some of the variation in spreading rate disappears. At about anomaly 6 time a major event occured along the American-Antarctic Ridge. Accompanying the change in spreading direction and rate, the Bullard Fracture Zone formed, eliminating two or possibly three spreading centers. At that time the eastern Scotia Sea did not exist nor did most of the Central Scotia Sea exist (Barker and Hill, 1981).

At about anomaly 6A time [22.4 Ma] (Barker et al., 1984) , a major section (perhaps a quarter of its total length) of the American-Antarctic Ridge was subducted at Jane Bank (figure 12). It is surmised that the elimination of that section of pull on the South American plate, while very minor for the whole plate, had a significant impact for the isolated southernmost section of the plate and may have been a major factor with regard to the spreading rate and direction for this part of the plate. Prior to subduction of the ridge at Jane Bank, the direction of pull on the plate caused by the subduction was approximately WNW (Barker et al, 1984; figure 7). After the ridge segment was subducted, the pull changed to more E-W with perhaps a slight component of WSW pull.

If the Bullard Fracture Zone is indeed less than 25 million years old then that may have major significance for other areas of the world and for the way that some plate motions are calculated. Phillipe Patriat (Patriat et al., 1985) has felt for some time that the Prince Edward Fracture Zone on the Southwest Indian Ridge may be an example of a recent fracture zone that postdates much of the opening between Africa and Antarctica. Since the Prince Edward Fracture Zone was used by Fisher and Sclater (1983) to calculate some of their early Cenozoic poles of opening for the Southwest Indian Ridge, those poles should be re-examined.

The Bullard Fracture Zone may be considered a valid indicator of major plate motion between South America and Antarctica but only since anomaly 6 time (21 Ma). Prior to that time, even though the 560 km length of the Bullard Fracture Zone might imply 50 million years of offset between the two presently active spreading centers, it must be assumed that the Bullard Fracture Zone did not exist. Consequently paleo-plate motions can only be computed by matching identified magnetic anomalies known to have been produced at the same spreading centers. Since there are insufficient matched pairs of anomalies along the American-Antarctic Ridge to produce unambiguous poles of rotation for the major plates, half-angle rotations for the other two plate boundaries around the Bouvet triple junction were used to constrain the match of observed magnetic anomalies with the present-day spreading centers. Since in all the cases considered (anomalies 8, 13, 18 and 21), anomalies from both the Antarctic and South American plates were available, the resultant poles can be considered reasonably accurate.

The cause of the change in direction of opening, rate of opening and the formation of the Bullard Fracture Zone is believed to be the subduction of approximately 25% of the extensional plate boundary, 21 to 23 million years ago at Jane Bank (Barker et al., 1984). The forces acting on this isolated piece of the South American plate were sufficiently altered to produce the changes mentioned above. At sometime later, perhaps between 8 and 10 million years ago, another section of the American-Antarctic Ridge was subducted at Discovery Bank which may have resulted in the slight slowing in the rate of opening from 22.4 mm/year to 19.6 mm/year on the American-Antarctic Ridge observed at about 8 million years ago. Since the South Sandwich Trench is moving eastward at 17 mm/year absolute rate (Hartnady, personal communication), then it is estimated that much of the southern part of the American-Antarctic Ridge will be subducted between 17 and 20 million years from now.

Since the American-Antarctic Ridge region has not been explored with the knowledge of its Cenozoic tectonic framework, there are many areas that have little or no bathymetric or magnetic coverage. If all the fracture zones were better mapped, then the unusual nature of the Bullard Fracture Zone would have been noted earlier.

It is probable that other very large offset fracture zones, such as the Prince Edward Fracture Zone, are also younger than their length may imply. Since slight changes in spreading directions would cause the greatest problems at very large offset fracture zones, it is conceivable that such features may be transient and as difficulties arise maintaining the very large offset in the face of changes in plate motion, such very large offset fracture zones may be realigned as an en echelon suite of smaller offset fracture zones. The pronounced fracture zone ridge, in places shallower than 3000 meters, along most of the southside of the Bullard Fracture Zone is indicative of plate motion incompatibility. Possibly a new spreading center may develop along this transform fault or when the southern section of the present American-Antarctic Ridge is subducted the Bullard Fracture Zone may be realigned with respect to the trench possibly shifting some sliver of the South American plate to the Antarctic plate or vice-versa.

SUMMARY OF ROTATION POLES USED AND CALCULATED

Plate ID's		Magnetic Anomaly (Age in million yrs.)	Latitude (+North)	Longitude (+East)	Angle of Rotation	Source
1	2	5_o (9.7)	10.0	-40.0	1.42	Recalc. from various sources
1	2	6_o (20.4)	10.00	-36.9	2.5	Recalc. from various sources
1	2	8_o (27.5)	15.00	-44.62	3.98	Recalc. from various sources
1	2	13_y (35.2)	12.5	-45.0	5.26	Recalc. from various sources
1	2	18_o (42.7)	15.29	-50.39	6.92	Recalc. from various sources
1	2	21_o (50.3)	8.00	-40.00	8.87	Recalc. from various sources
2	3	5_o (9.7)	59.00	-35.0	-3.3	Recalc. from Ladd (1974)
2	3	6_o (20.4)	58.00	-35.0	-7.28	Interpolated from Ladd (1974
2	3	8_o (27.5)	58.01	-35.00	-10.21	Interpolated from Ladd (1974
2	3	13_y (35.2)	58.01	-35.00	-13.45	Ladd (1974)
2	3	18_o (42.7)	55.07	-32.71	-16.28	Recalc. from Ladd (1974)
2	3	21_o (50.3)	55.88	-30.72	-19.48	Recalc. from Ladd (1974)
1	3	5_o (9.7)	82.38	- 8.78	- 2.60	New data this paper
1	3	6_o (20.4)	76.11	-26.91	- 5.91	New data this paper
1	3	8_o (27.5)	76.01	- 7.34	- 7.82	
1	3	13_y (35.2)	76.01	- 3.74	-10.51	New data plus matching around triple junction
1	3	18_o (42.7)	69.92	6.19	-12.06	
1	3	21_o (50.3)	76.45	14.15	-15.11	

Table 1. Cenozoic rotation poles and angles of opening for ANTA(1)-AFRC(2), AFRC(2)-SOAM(3) and ANTA(1)-SOAM(3).

Plate identifications: 1, Antarctica; 2, Africa; 3, South America. Magnetic anomaly designations are subscripted: o, for old side of anomaly; y, for young side. Anomaly ages are taken from Palmer, 1983. Rotation angles are positive for a counterclockwis rotation when viewed from above the pole. Sources for ANTA-AFRC poles include published magnetic anomaly picks (LaBrecque and Hayes, 1979; Fisher and Sclater, 198 Sclater et al., 1981; Patriat et al., 1985; Patriat, 1983; Bergh and Norton, 1976; Goslin et al., 1981; Goslin and Patriat, 1984; Schlich, 1982) and Patriat (personal communication). Sources for AFRC-SOAM include Ladd (1974), Barker (1979) and some unpublished NGDC data (1985). Sources for ANTA-SOAM data are this paper.

NOTE: Poles + angles of rotation SUBJECT TO REVISION

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Figure 1. Generalized tectonic diagram showing the location of the American-Antarctic Ridge, Southwest Indian Ridge, Mid-Atlantic Ridge, Scotia Sea and Weddell Sea. Spreading centers are indicated by double line segments, active faults shown by single lines and trenches or presumed zones of underthrusting shown by toothed line. The 200-meter and 3000-meter contours are shown in light weight lines. CFZ: Conrad Fracture Zone, BFZ: Bullard Fracture Zone, SSFZ: South Sandwich Fracture Zone, BTJ: Bouvet Triple Junction; BI: Bouvet Islands. Boxed area is location of figure 2.

Figure 2. Bathymetric chart of American-Antarctic Ridge rgion. 500-meter contour interval. Dotted lines show points along ship tracks with bathymetry used to produce this chart.

Figure 3. Earthquake epicenter map of region. Pre-1963 earthquakes are shown as small black dots. Large symbols indicate greater than magnitude 5.0 while small symbols are 5.0 and less. Triangles represent epicenters shallower than 33 km. Squares are at 33 km. Circles are between 33 km and 100 km while hexagons represent epicenters deeper than 100 km. The deepest epicenters under the Scotia Arc lie between 140 and 190 kilometers.

Figure 4. Bathymetric profiles showing shallower than normal crust close to spreading centers. Dashed line is age versus depth profile calculated from Parsons and Sclater (1977).

Figure 5. Bathymetric profiles showing probable fracture zone crossings. Crust west of presumed fracture zone averages nearly 400 meters shallower than to the east.

Figure 6. SEASAT derived Geoid data courtesy of B. Haxby (personal communication). Heavy lines are deflection of the vertical derived gravity anomalies taken from Sandwell (1983) and Driscoll and Parsons (personal communication). The heavy lines seem to coincide with tectonic features shown in figure 10.

Figure 7. Magnetic anomaly chart of the American-Antarctic Ridge region. Well identified anomalies are shown stippled along with anomaly number. Speculative anomaly identifications are shown with anomaly number only. Magnetic anomalies are high-amplitude but short period over the Scotia Island arc at 26°W.

Figure 8. Magnetic anomaly profiles - need better figure.

Figure 9. Repreduction of hard-copy output of graphics terminal display. The identified magnetic anomalies of the Antarctic plate from figure 6 are shown dashed. They have been rotated by the half-angle with respect to the African plate. While the solid anomalies on the South American plate have been rotated by the half-angle with respect to Africa.

a) Shows the superposition of the Antarctic anomaly 21 on the southern spreading center and the South American anomaly 21 on the southernmost of the northern spreading centers (see circles).

b) Shows the superposition of anomaly 18 except South American anomaly 18 superposes on middle northern spreading center.

Figure 10. Plot of synthetic spreading centers derived from tables of poles and angles of rotation for SOAM-ANTA boundary. The present day spreading centers are rotated back to where they were created at various times in the past. In an ideal world these would coincide with the present day observed magnetic anomalies since that is the bases for calculating the rotation parameters. Hypothetical fracture zones were then sketched in connecting the synthetic paleo-spreading centers. The stippled areas are regions that could not have been produced at the observed present day spreading centers leading to the conclusion that the Bullard fracture zone is young and eliminated the spreading centers that might have produced the stippled regions.

Figure 11. Reconstruction of synthetic spreading centers at anomaly 6 time.

Figure 12. Anomaly 6 reconstruction of American Antarctic Ridge region and Scotia Sea. The southern section of the AAR has just been subducted at Jane Bank. The present position of the South Sandwich trench is drawn faintly to illustrate back-arc extensional development.

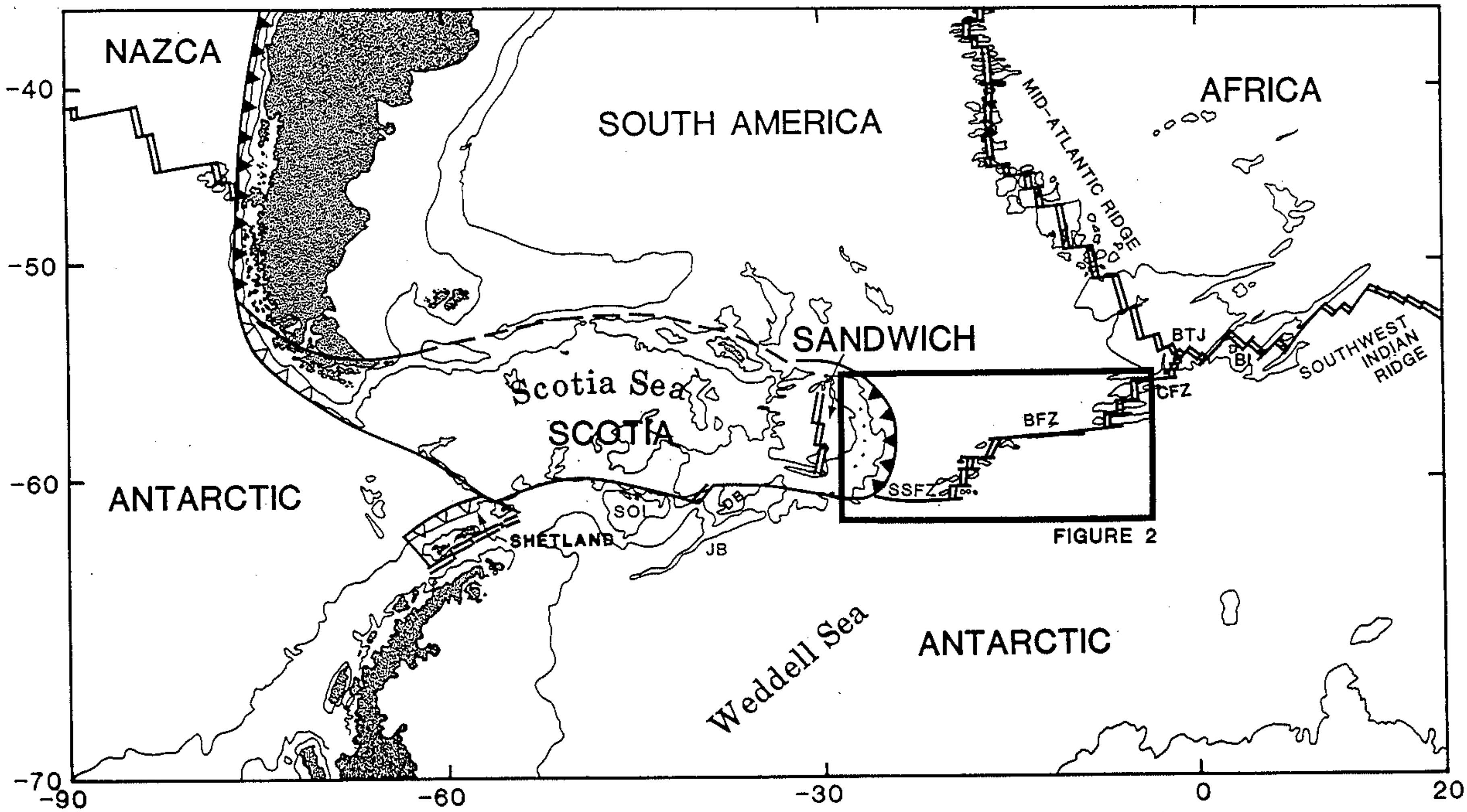

NAZCA
SOUTH AMERICA
AFRICA
MID-ATLANTIC RIDGE
SOUTHWEST INDIAN RIDGE
BTJ
BI
CFZ
BFZ
SSFZ
SANDWICH
Scotia Sea
SCOTIA
ANTARCTIC
SOI
DB
JB
SHETLAND
FIGURE 2
Weddell Sea
ANTARCTIC
-40
-50
-60
-70
-90
-60
-30
0
20

Figure 1

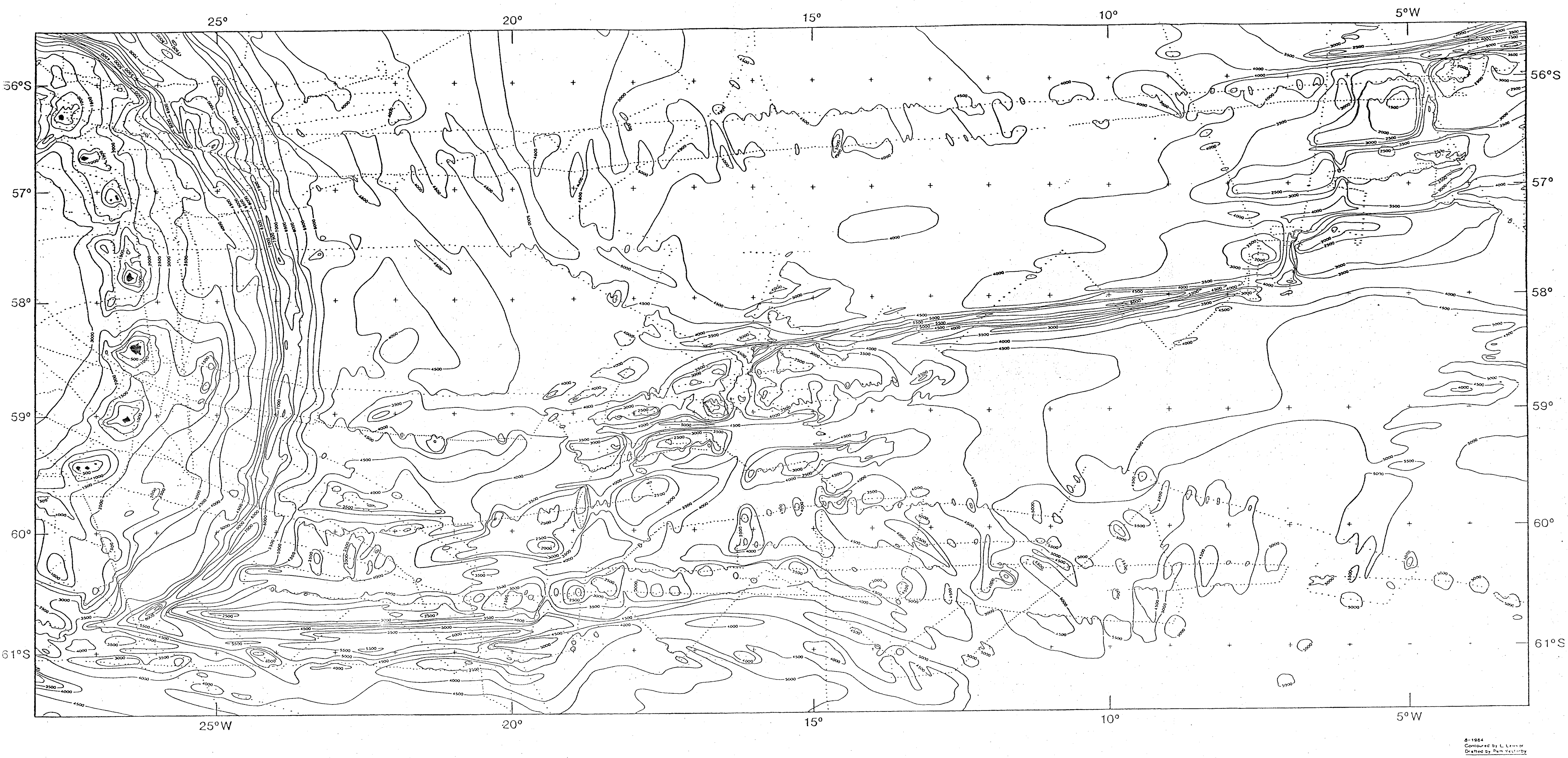


Figure 2

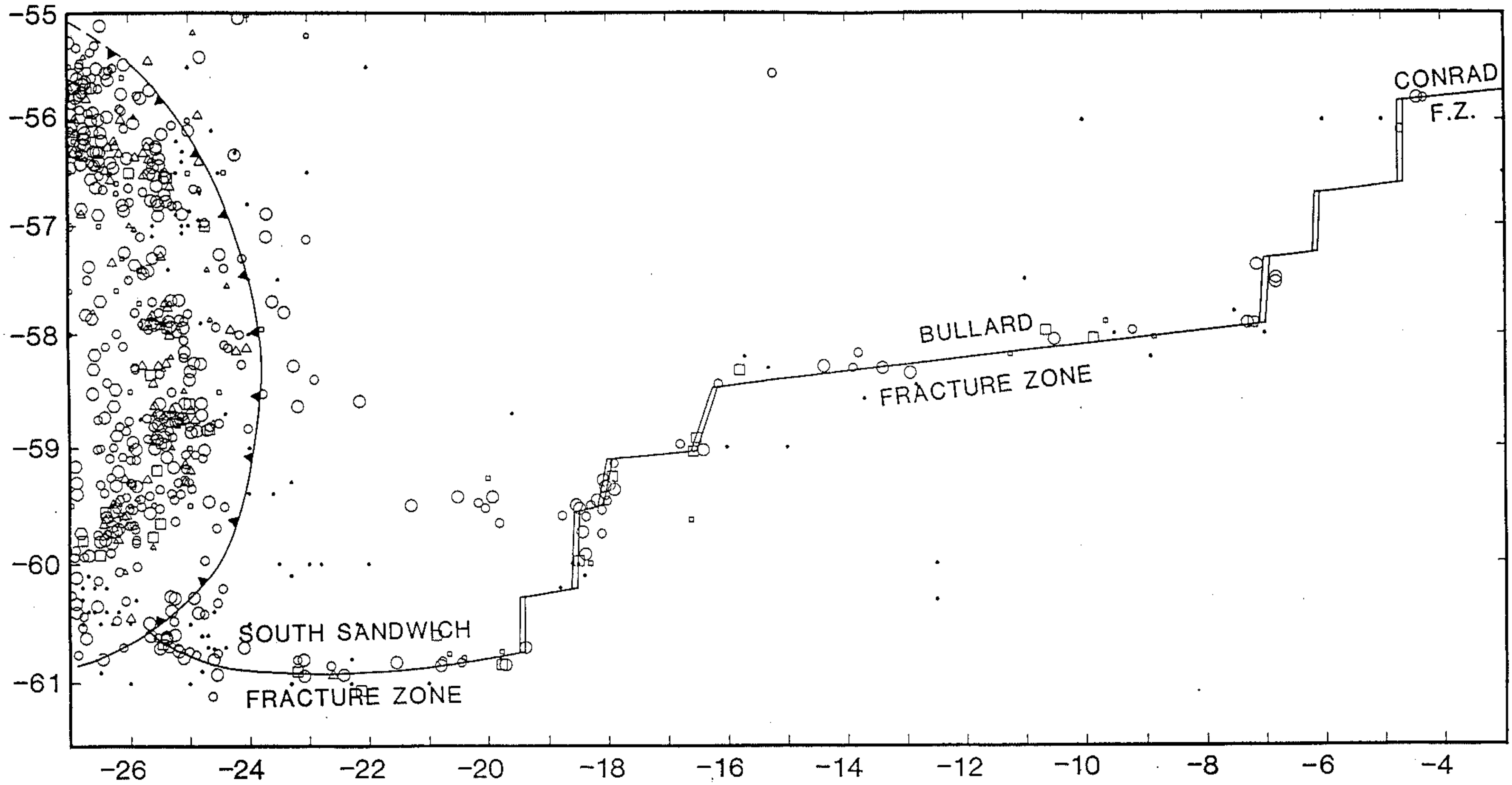

-55
-56
-57
-58
-59
-60
-61
-26
-24
-22
-20
-18
-16
-14
-12
-10
-8
-6
-4
CONRAD
F.Z.
BULLARD
FRACTURE ZONE
SOUTH SANDWICH
FRACTURE ZONE

Figure 3

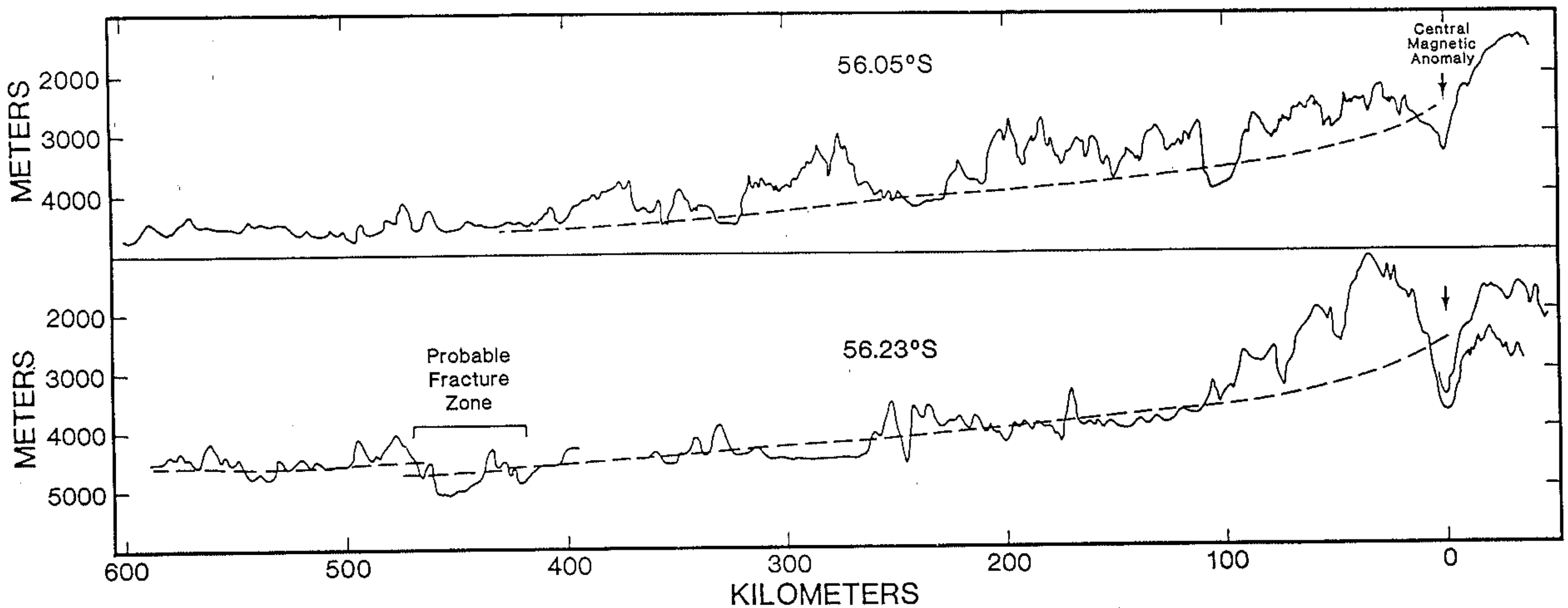
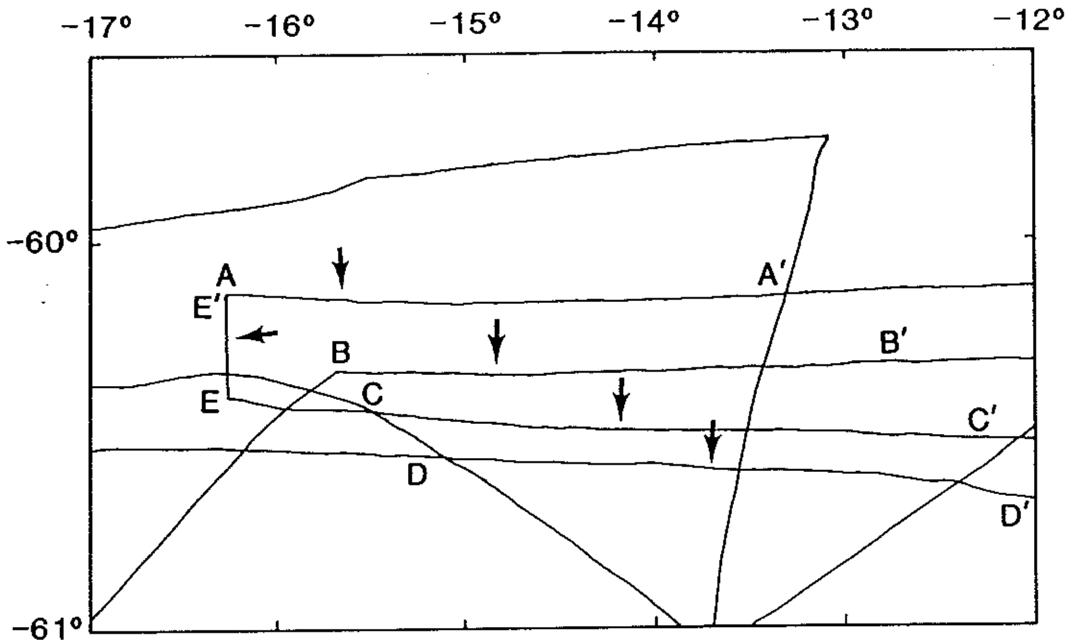
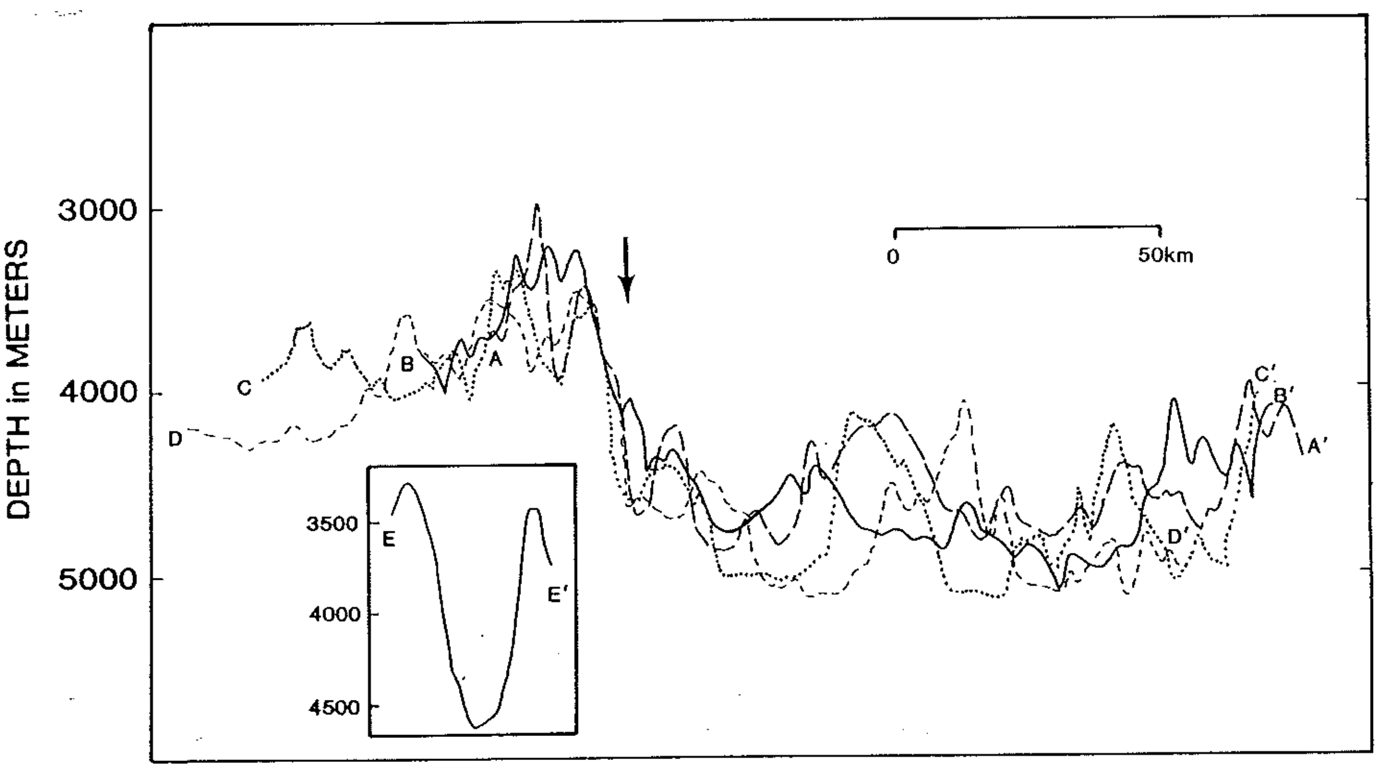

METERS
2000
3000
4000
56.05°S
Central
Magnetic
Anomaly
METERS
2000
3000
4000
5000
Probable
Fracture
Zone
56.23°S
600
500
400
300
200
100
0
KILOMETERS

Figure 4



−17°
−16°
−15°
−14°
−13°
−12°
−60°
−61°
A
E′
E
B
C
D
A′
B′
C′
D′



DEPTH in METERS
3000
4000
5000
0
50km
C
B
A
D
C′
B′
A′
D′
3500
4000
4500
E
E′

Figure 5

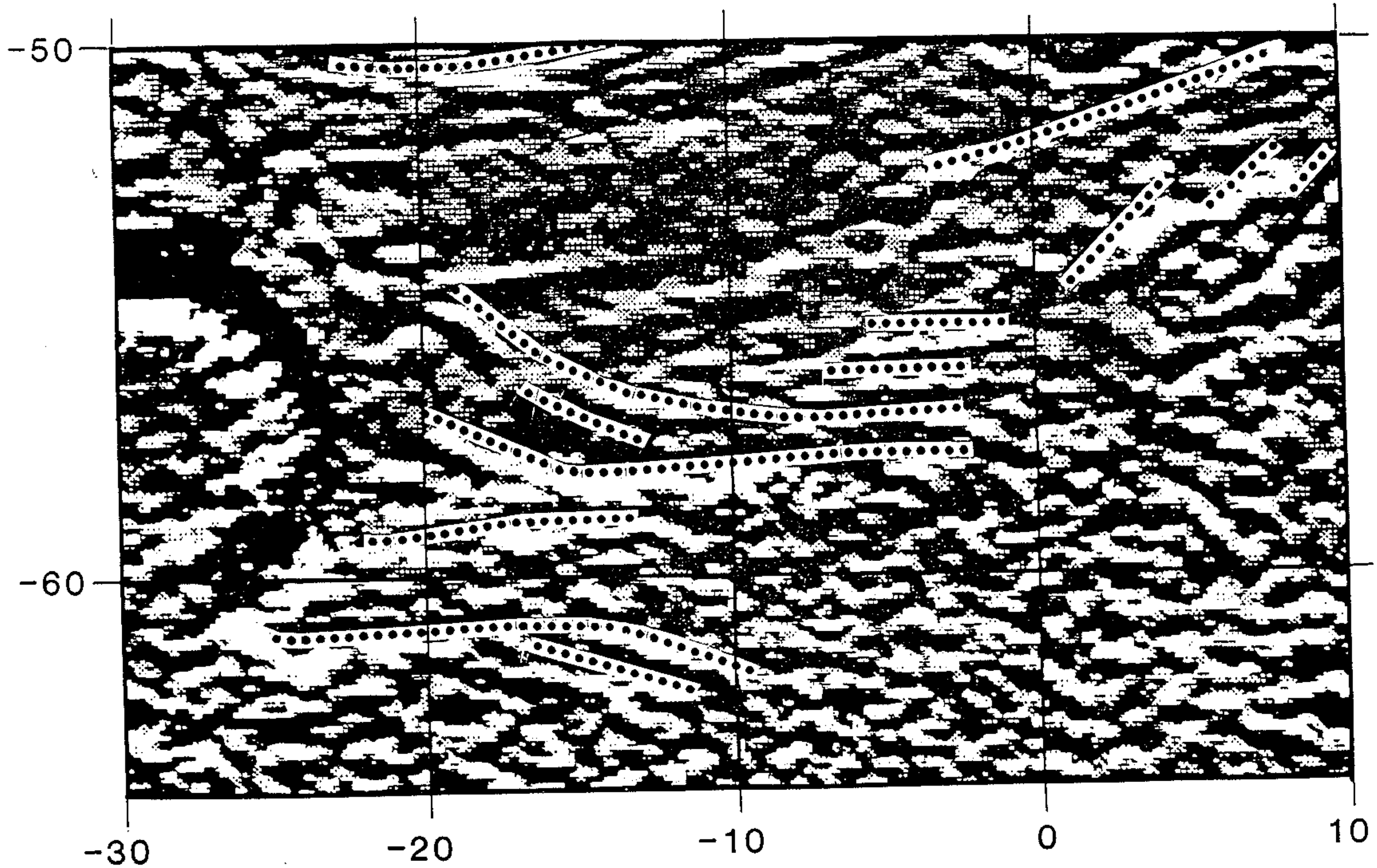
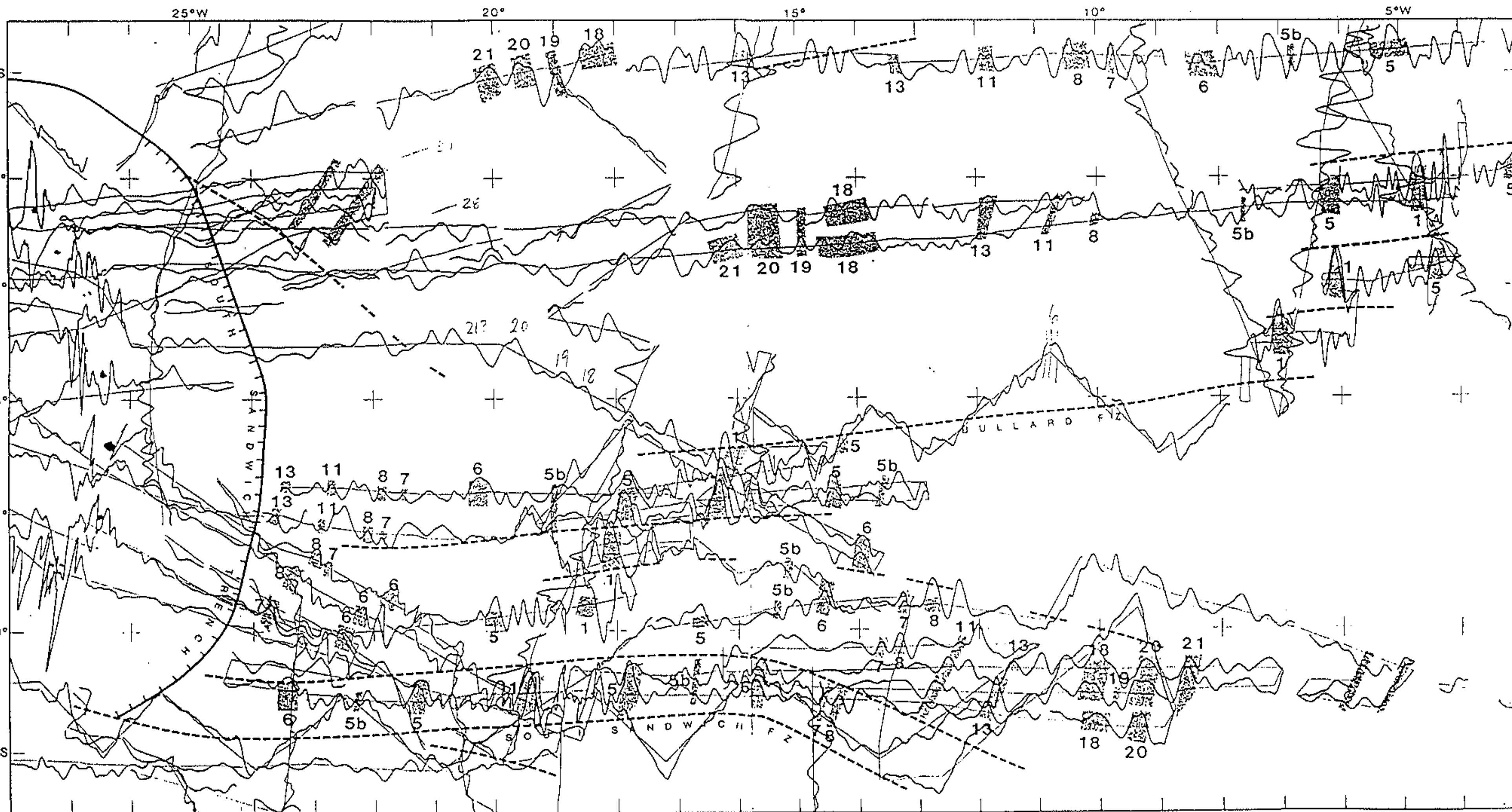


Figure 6



25°W
20°
15°
10°
5°W
55°S
56°
57°
58°
59°
60°
61°S
SOUTH SANDWICH TRENCH
BULLARD FZ
SOUTH SANDWICH FZ

Figure 7

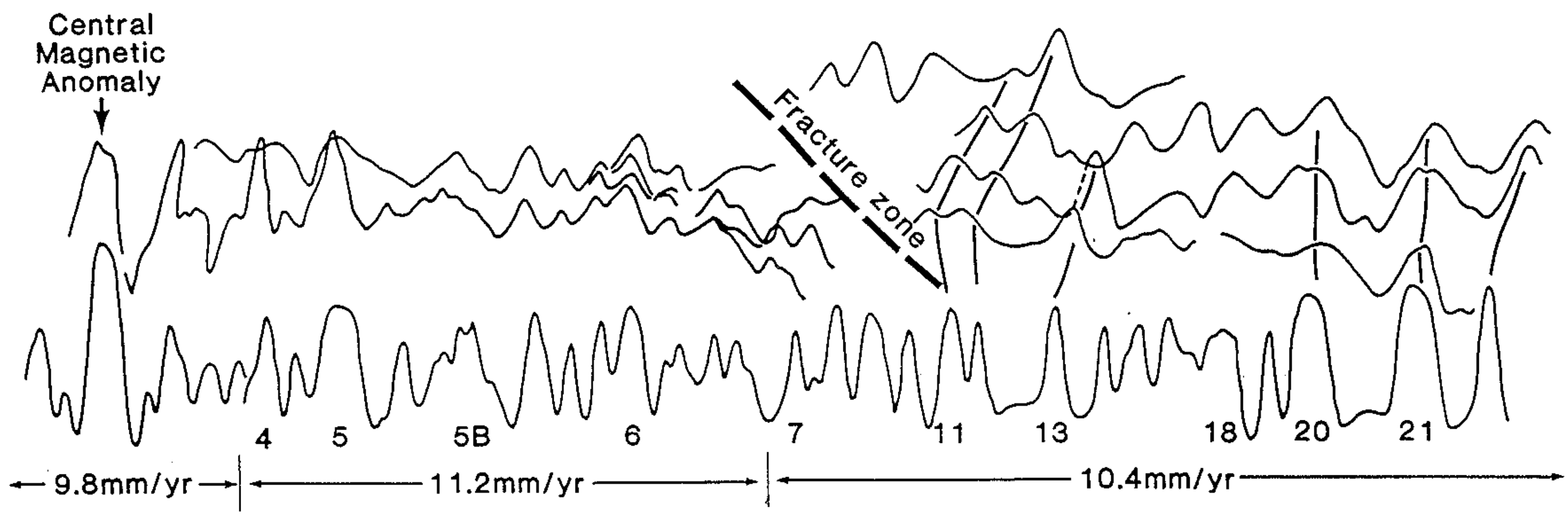

Central
Magnetic
Anomaly
Fracture zone
4
5
5B
6
7
11
13
18
20
21
9.8mm/yr
11.2mm/yr
10.4mm/yr

Figure 8

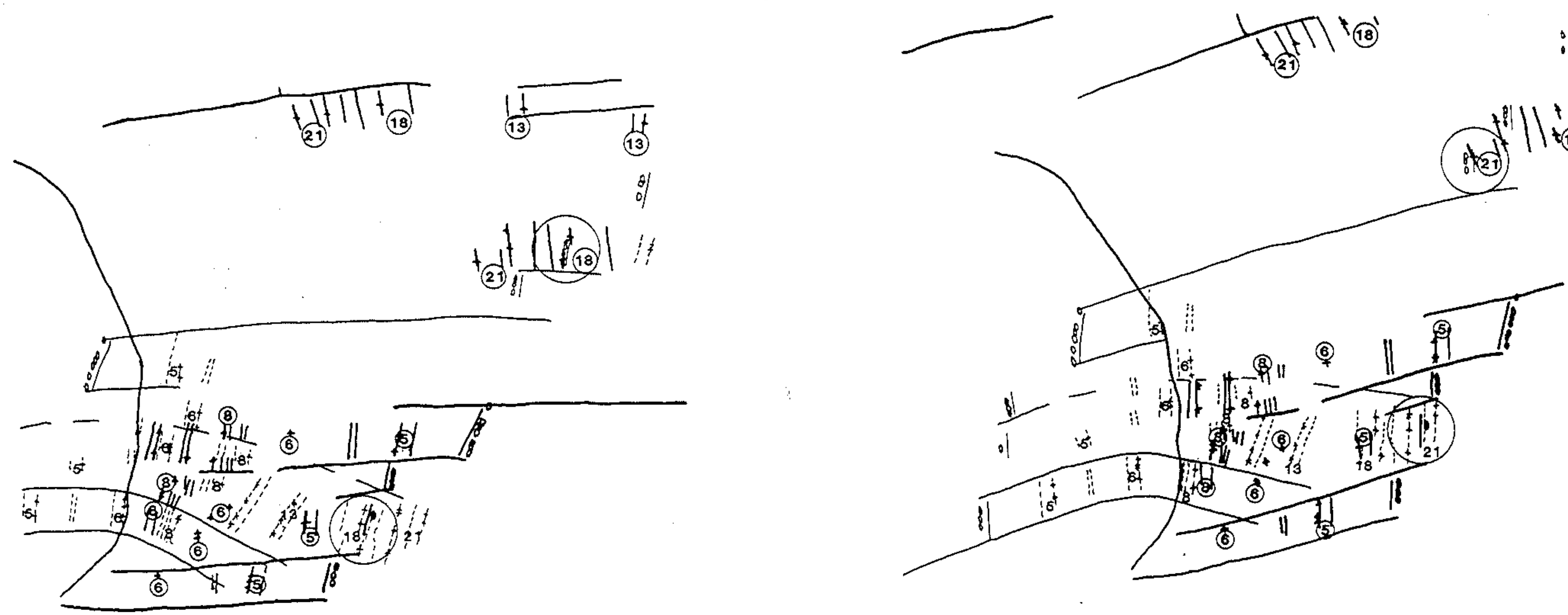


Figure 9

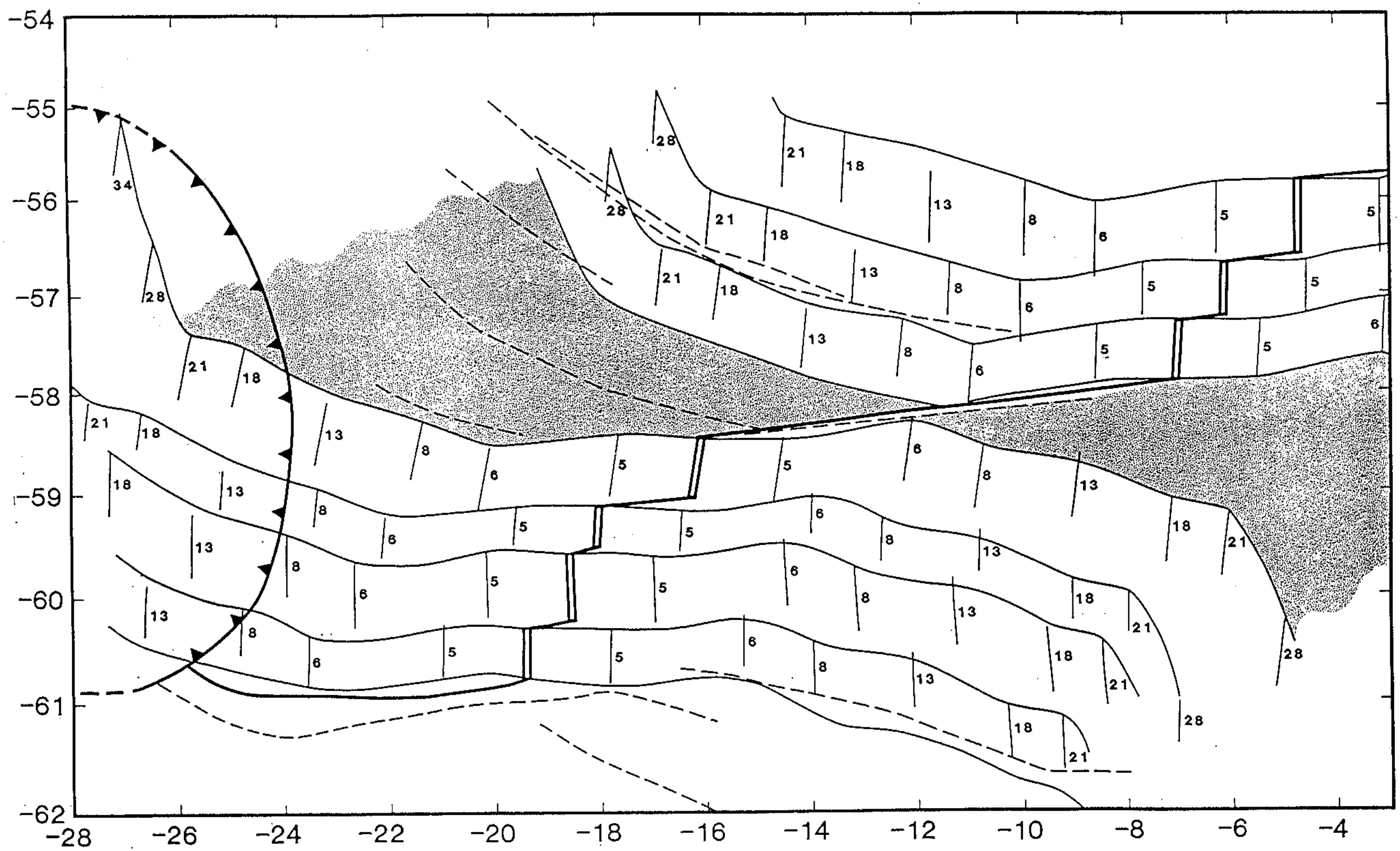


Figure 10

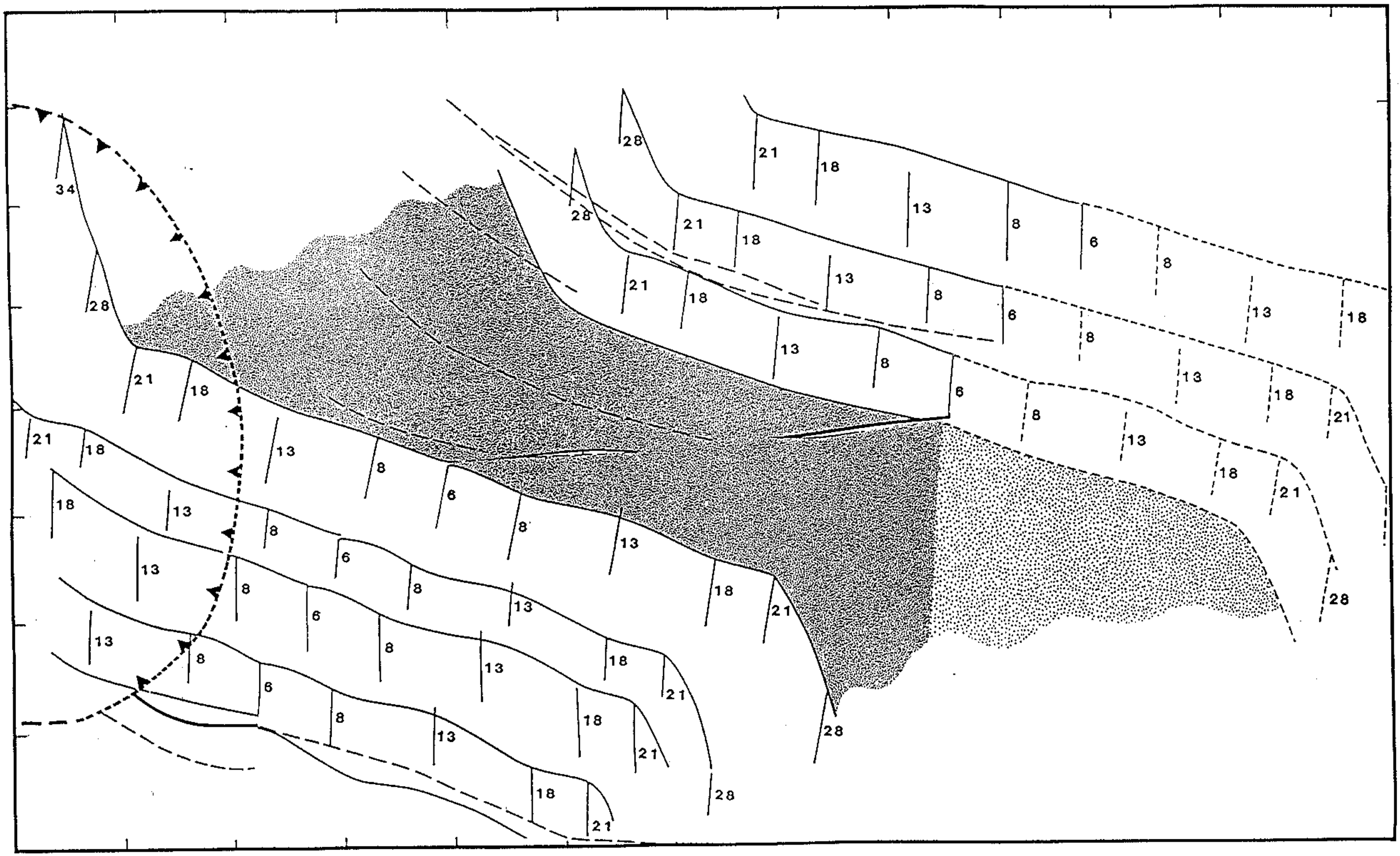


Figure 11

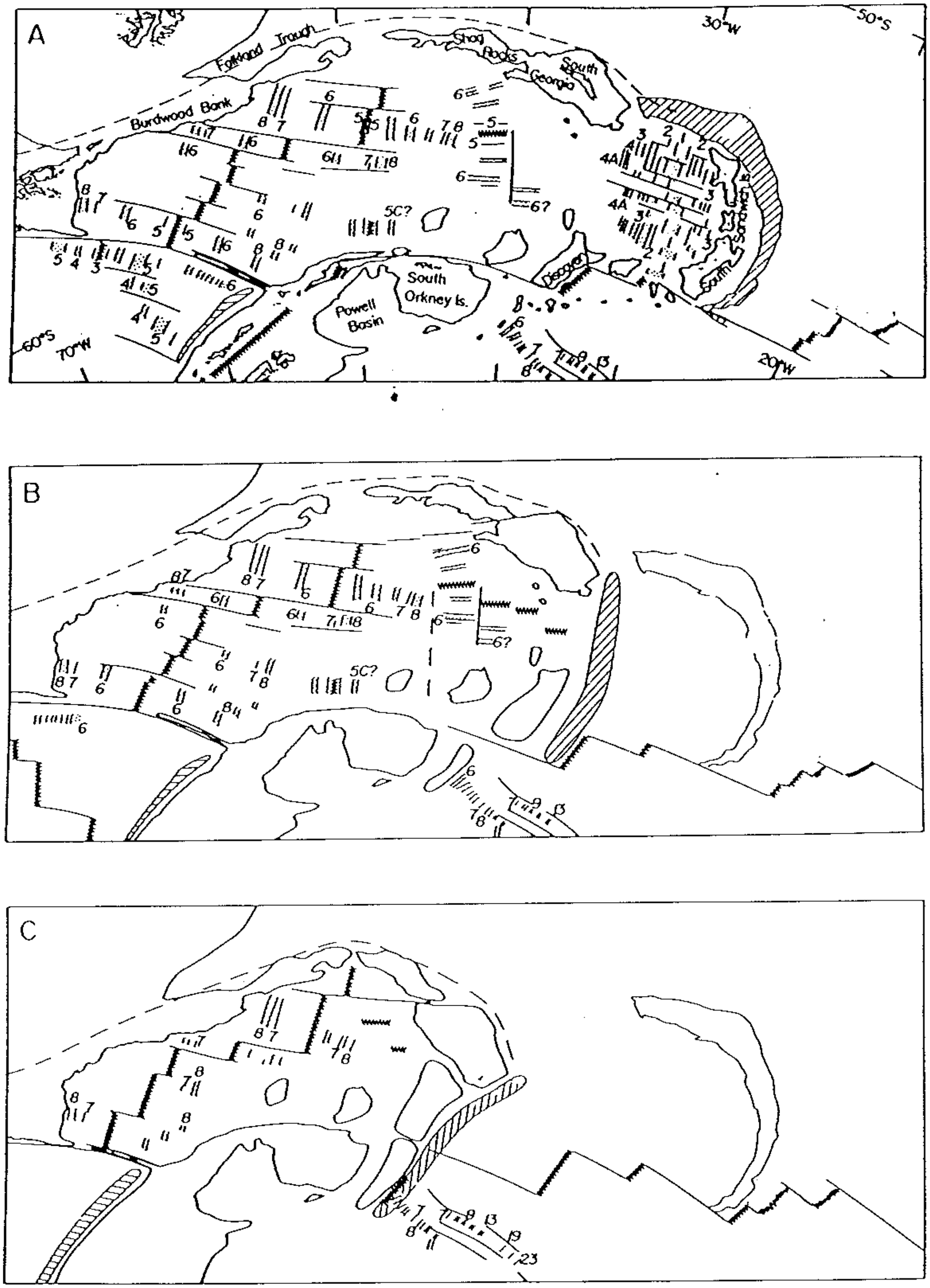


Fig. 7. Scotia Sea evolution. A. Magnetic anomaly identifications in the Scotia Sea (Barker and Hill, 1981) and northern Weddell Sea (this paper). Shallow (continental and island arc) areas defined by 2000 m isobath. B. 10 Ma reconstruction (anomaly 5). C. 20 Ma reconstruction (anomaly 6). In B and C, the present position of South Sandwich trench is drawn faintly to illustrate back-arc extensional development. Note that many aspects of the 20 Ma reconstruction are speculative.

(taken from Barker et al., 1984)

Figure 12