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# A Tectonic Chart for the Southern Ocean Derived from Geosat Altimetry Data

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## ABSTRACT

We present a new tectonic fabric map of the Southern Ocean south of 45°S derived from Geosat altimeter profiles and published bathymetric charts and magnetic anomaly picks. The interpretation of the Geosat data is based on an analysis of the first derivative of the geoid profiles (i.e., vertical deflection profiles). To improve the accuracy and resolution of the vertical deflection profiles, 22 repeat cycles from the first year of the Geosat/Exact Repeat Mission (Geosat/ERM) were averaged. At wavelengths less than about 200 km, the vertical deflection is highly correlated with sea-floor topography and thus reveals major features in areas that were previously unsurveyed. The density of the Geosat data is greatest in the high latitudes where lineated bathymetric features such as fracture zones, spreading ridges, trenches, and rifted margins stand out. To construct the tectonic fabric chart, the Geosat data are analyzed in combination with available shipboard bathymetric data and magnetic anomaly identifications.

## INTRODUCTION

Over the past decade, satellite altimetry has become an important technique for studying the tectonics of remote ocean areas (Haxby et al., 1983; Sandwell, 1984). Spacecraft such as Seasat and Geosat use pulse limited radars, along with very accurate orbits, to measure the topography of the ocean surface (see, Johns Hopkins Applied Physics Laboratory Technical Digest, 1987). Since the sea surface is nearly an equipotential surface of the Earth's gravity field (marine geoid), variations in sea surface topography reveal variations in gravitational potential. At short wavelengths (< 200 km), the topography of the sea surface mimics the sea-floor topography. The accuracy and resolution of these satellite-derived gravity measurements are now comparable to state-of-the-art shipboard gravity measurements. Thus satellite altimeters provide important reconnaissance information over vast areas of uncharted sea floor such as the Southern Ocean and Antarctic continental margins.

The close correlation between the short wavelengths of the geoid (20-200 km) and the sea-floor topography allows altimetry data to be used to chart tectonic features of the ocean floor such as fracture zones, seamounts, and spreading ridges. This information is critical in the Southern Ocean where there are large regions containing few if any shipboard data. Here we present a new tectonic map of the oceans south of 45°S derived from a combination of Geosat altimeter profiles and published bathymetric charts, and magnetic anomaly picks. The map provides new detailed information on the dispersal of the Gondwana fragments from Antarctica and on the tectonic evolution of the South Pacific Ocean basin.

Recent interpretation of vertical deflection profiles (i.e., the along-track derivative of the geoid profiles) (Gahagan et al., 1988) from Seasat data have permitted the construction of a preliminary tectonic chart of the world's ocean floor. The next step in the analysis of the altimeter data is to compare the lineations, identified in the vertical deflection data, with the available bathymetric data and marine magnetic anomalies to derive a tectonic fabric map of the ocean floor. Such an approach has already been applied in the South Pacific (Mayes et al., 1990) and in the Indian Ocean (Royer et al., *1989*). In this chapter, we complement the latter analyses by including the tectonic fabric of the far South Atlantic. The combined maps form a new general tectonic chart for the Southern Ocean. This article is a companion paper to that of Sandwell and McAdoo (1988), which presented the Geosat altimeter data collected around Antarctica and to the paper by Lawver et al. (in press) which describes the evolution of the Antarctic continental margins.

Virtually every type of plate boundary, continental margin, oceanic island, and deep-sea basin are found in the Southern Ocean south of 45°S (Figure 1, oversize enclosure). The Antarctic plate covers about 75% of this area; the remaining 25% is shared by the South American, African, Australian, Pacific, and Scotia plates. The present-day plate boundaries include the following sea-floor spreading ridges: the South Atlantic Ridge, the South American-Antarctic Ridge, the Southwest Indian Ridge, the Southeast Indian Ridge, the Pacific-Antarctic Ridge, the Chile Rise, and the South Sandwich backarc spreading center. They include the following transform boundaries: the Shackleton Fracture Zone and the north and south Scotia Ridges which are the transform fault system that bounds the Scotia Sea; and the following trenches: the Hjort Trench south of New Zealand, the Chile Trench, and the South Sandwich Trench. The deep-sea basins in the Southern Ocean are the Weddell Abyssal Plain, the African-Antarctic Basin, the Enderby Basin, the Australian-Antarctic Basin, the Amundsen and Bellingshausen Abyssal Plains off West Antarctica, the Mornington Abyssal Plain west of South America, and the Scotia Sea. In addition, the Southern Ocean is the site of many submarine platforms of various origin among which the largest are the Falkland Plateau, the Conrad Rise, the Kerguelen Plateau, the Chatham Rise, and the Campbell Plateau.

### Summary of the Tectonic History of the Southern Ocean

Except for the Southeast Pacific, the opening of the Southern Ocean resulted in the dispersal of the Gondwana fragments. This presentation of the major events in the formation of the Southern Ocean goes clockwise from the Weddell Sea as the ocean floor surrounding the Antarctic margins becomes younger.

Many models have been proposed for the early opening of the Weddell Sea and the motion of the Antarctic Peninsula relative to South America and East Antarctica (see discussion in Lawver et al., in press), and the early history is still controversial. LaBrecque and Barker (1981) and LaBrecque and Cande (1986) have identified Late Jurassic magnetic anomalies in the Weddell Sea (M25 to M29; 157 to 160 Ma). In order to reconcile the direction of motion inferred by these magnetic lineations with the clockwise motion of the Antarctic Peninsula suggested by paleomagnetic results (Grunow et al., 1987), the age of these magnetic lineations would have to be younger, i.e., Early Cretaceous. A younger age and the orientation of these lineations would be compatible with regard to the development of a triple junction with initiation of sea-floor spreading between South America and Africa. Since most of the conjugate half of the Weddell Sea Basin anomalies have been subducted beneath the Scotia Sea, the age discrepancy is difficult to resolve. In contrast, the evolution of the South American-Antarctic Ridge since the Late Cretaceous (Chron 34, 84 Ma) is better understood (Barker and Jahn, 1980; Bergh and Barrett, 1980; LaBrecque and Barker, 1981; LaBrecque and Keller, 1982; Lawver and Dick, 1983; Barker and Lawver, 1988). Two major changes in spreading direction have been recognized: one gradual change starting at Chron 31 (68 Ma, Paleocene) and one abrupt change at Chron 6 (20 Ma, early Miocene).

The South Atlantic began to open in the Early Cretaceous and shows symmetric Mesozoic magnetic anomalies (M4 to M0; 124 to 118 Ma) in the Argentina and Cape Basins, and in the Georgia Basin and the Natal Valley (Rabinowitz and LaBrecque, 1979; Goodlad et al., 1982; Martin et al., 1982). Except for several ridge jumps south of the Falkland-Agulhas Fracture Zone which have progressively eliminated most of the initial 1400 km offset across this fracture zone, the geometry of the South Atlantic spreading has remained very stable with only a few small changes in the direction of spreading (Cande et al., 1988). The largest ridge jump occurred at Chrons 31/28 (68/64 Ma) when the ridge jumped from the Agulhas Basin westward to Meteor Rise (Barker, 1979; LaBrecque and Hayes, 1979). This reorganization at Chrons 31/28 occurred contemporaneously with a slowing down of the spreading rate in the South Atlantic and with drastic changes in rates or directions of spreading in the Indian Ocean.

The early separation of Africa and Antarctica is well documented by symmetric Mesozoic magnetic anomalies (M16 to M0, 142 to 118 Ma) identified off Dronning Maud Land (Antarctica) (Bergh, 1977, 1987) and in the Mozambique Channel (Ségoufin, 1978; Simpson et al., 1979). Since then, sea-floor spreading along the Southwest Indian Ridge has been continuous with medium to slow spreading along a general north-south direction (Bergh and Norton, 1976; LaBrecque and Hayes, 1979; Patriat, 1979, 1987; Bergh and Barrett, 1980; Sclater et al., 1981; Fisher and Sclater, 1983; Bergh, 1986; LaBrecque and Cande, 1986). Two major changes in the direction of motion occurred between Chrons 32 (74 Ma) and 24 (56 Ma) (Patriat et al., 1985; Royer et al., 1988).

The age of the rifting of India and Sri Lanka from Antarctica is not well known but probably began between Chrons M10 and M0 (130 and 118 Ma). No magnetic anomalies have yet been identified off eastern India or in the Enderby Basin off Antarctica. The magnetic anomaly pattern off western Australia dates the separation of Greater India as Chron M9/M10 (129/130 Ma) (Markl, 1974, 1978; Veevers et al., 1985). The cessation of sea-floor spreading in the Somali Basin between Africa and the Madagascar-India block just subsequent to Chron M0 (118 Ma) (Ségoufin and Patriat, 1980) gives a lower limit for the initiation of motion between India and Antarctica. Paleogeographic reconstructions of the Mesozoic basins in the Indian Ocean (Lawver et al., 1985) provide further indication that India cannot have been separated from Antarctica earlier than Chron M10 and that their separation probably occurred before Chron M0 (Lawver et al., 1985; and in press). The next event in the development of the southern Indian Ocean corresponds with a major reorganization of the spreading centers during the mid-Cretaceous (~96 Ma). At that time, India separated from Madagascar and began its northward drift toward Asia that is later documented by the Paleogene sequence of magnetic anomalies in the Mascarene, Madagascar, and Crozet Basins (McKenzie and Sclater, 1971; Schlich, 1975, 1982; Norton and Sclater, 1979; Patriat, 1987). The breakup between Australia and Antarctica is also dated at 95 Ma (Cande and Mutter, 1982; Veevers, 1986). Sea-floor spreading in the Australian-Antarctic Basin is characterized by very slow spreading rates from Chron 34 (84 Ma) to Chron 20 (45 Ma) (Cande and Mutter, 1982). The most recent major tectonic event to affect the Indian Ocean basins occurred in the middle Eocene when India collided with Eurasia. Directions of motion changed dramatically in the central Indian Ocean (Schlich, 1975, 1982; Patriat, 1987). Sea-floor spreading initiated between the Kerguelen Plateau and Broken Ridge (Mutter and Cande, 1983; Royer and Sandwell, 1989) as the spreading rates increased between Australia and Antarctica (Weissel and Hayes, 1972; Cande and Mutter, 1982; Vogt et al., 1983). This is also the time when sea-floor spreading began south of the Tasman Sea (Weissel et al., 1977).

Prior to 100 Ma, a subduction zone extended from north of New Zealand, which was attached to Marie Byrd Land, to the tip of the Antarctic Peninsula (Barker, 1982). In the southwest Pacific, the breakup between South New Zealand and Marie Byrd Land occurred in two steps during the Late Cretaceous. Chatham Rise split from the Campbell Plateau and Marie Byrd Land prior to Chron 34 (84 Ma), opening up the Bounty Trough (Davey, 1977). Chatham Rise and the Campbell Plateau then rifted away from Marie Byrd Land at approximately Chron 34 (84 Ma) (Mayes et al., 1990). The sea-floor magnetic anomaly pattern in the South Pacific records two major plate boundary reorganizations that occurred after the Late Cretaceous (Christoffel and Falconer, 1972; Herron, 1972; Molnar et al., 1975; Herron and Tucholke, 1976; Weissel et al., 1977; Barker, 1982; Cande et al., 1982; Cande and Leslie, 1986; Stock and Molnar, 1987). From Chron 32 (74 Ma) to Chron 25 (59 Ma), at least four different spreading centers were active (Figure 2A): one between the Pacific plate and the Marie Byrd Land part of West Antarctica, one between the Pacific and Bellingshausen-West Antarctic plates, one between the Pacific and Farallon plates and one between the Bellingshausen and Aluk plates. A fifth plate boundary between the Bellingshausen plate and Marie Byrd Land has not been documented. Between Chron 25 and Chron 21 (50 Ma), the Bellingshausen plate and a part of the Pacific plate transferred onto the Marie Byrd Land or Antarctic plate (Figure 2B), leading to a Pacific-Antarctic-Farallon-Aluk plate system. The next major reorganization took place in the late Oligocene between Chron 7 (26 Ma) and Chron 6 (21 Ma). The Farallon plate split into the Nazca and Cocos plate while the southern tip of the Chile Rise (Antarctic/Nazca) started subducting under South America. The collision of the Antarctic/Aluk spreading center with the Antarctic Peninsula resulted in the stabilization of the Antarctic continental margin. As a result of these collisions, changes in the spreading direction are observed simultaneously along the East Pacific Rise (Pacific/Nazca), the Chile Rise, and the Pacific-Antarctic Rise.

The development of the Scotia Sea and dispersal of the continental fragments of the Scotia Arc are extremely complex (e.g., review by Barker and Dalziel, 1983). At least four different spreading systems have been identified in the Scotia Sea (Barker, 1972; Barker and Burrell, 1977; Hill and Barker, 1980; British Antarctic Survey, 1985). The oldest magnetic anomaly identified in the Scotia Sea is Chron 10 (30 Ma) (LaBrecque and Rabinowitz, 1977). The most recent reorganization of the spreading system occurred at Chron 4a (8 Ma) when the spreading ridge west of the South Sandwich Arc became active.

## Tectonic Fabric of the Southern Ocean

Figure 3 (oversize enclosure) presents the lineated structures of the Southern Ocean interpreted from the vertical deflection profiles (Geosat). The procedure to produce such a map is fully described in Mayes et al. (1990) and Royer et al. (1989). The vertical deflection profiles are presented in Sandwell and McAdoo (1988). Since the Geosat coverage in the southern polar region, where seasonal sea ice can corrupt the radar altimeter data, is more complete than Seasat coverage (Geosat has operated for two austral summers while Seasat only operated during one austral winter), our interpretations are based solely on Geosat data. In order to reduce the noise level of the vertical deflection profiles from Geosat, 22 exact repeat profiles (1 year) have been averaged; this also improves coverage in areas of temporary sea ice. After averaging, a digital, band-pass filter was used to eliminate wavelengths greater than 4000 km and smaller than 20 km. The 164 km spacing of the Geosat profiles at the Equator decreases toward the high latitudes, being 82 km at 60°S. The uniform coverage and high density of the Geosat data are particularly suitable for tectonic fabric mapping.

Our interpretation, shown in Figure 3, is based on averaged and filtered vertical deflection profiles. The peaks (blue symbols) and troughs (red symbols) of the vertical deflection data correspond to maxima and minima in the gradient of the marine geoid, respectively. Peaks and troughs in vertical deflection are well correlated with the gradient in the bathymetry (Figure 4). After identifying the maxima and minima along the profiles, we interpret and connect peaks and troughs from profile to profile (Figure 5). These interpreted lineations (fabric) reflect lineated features of the sea floor such as trenches, fracture zones, and spreading ridges. Continental shelf breaks, which are often poorly

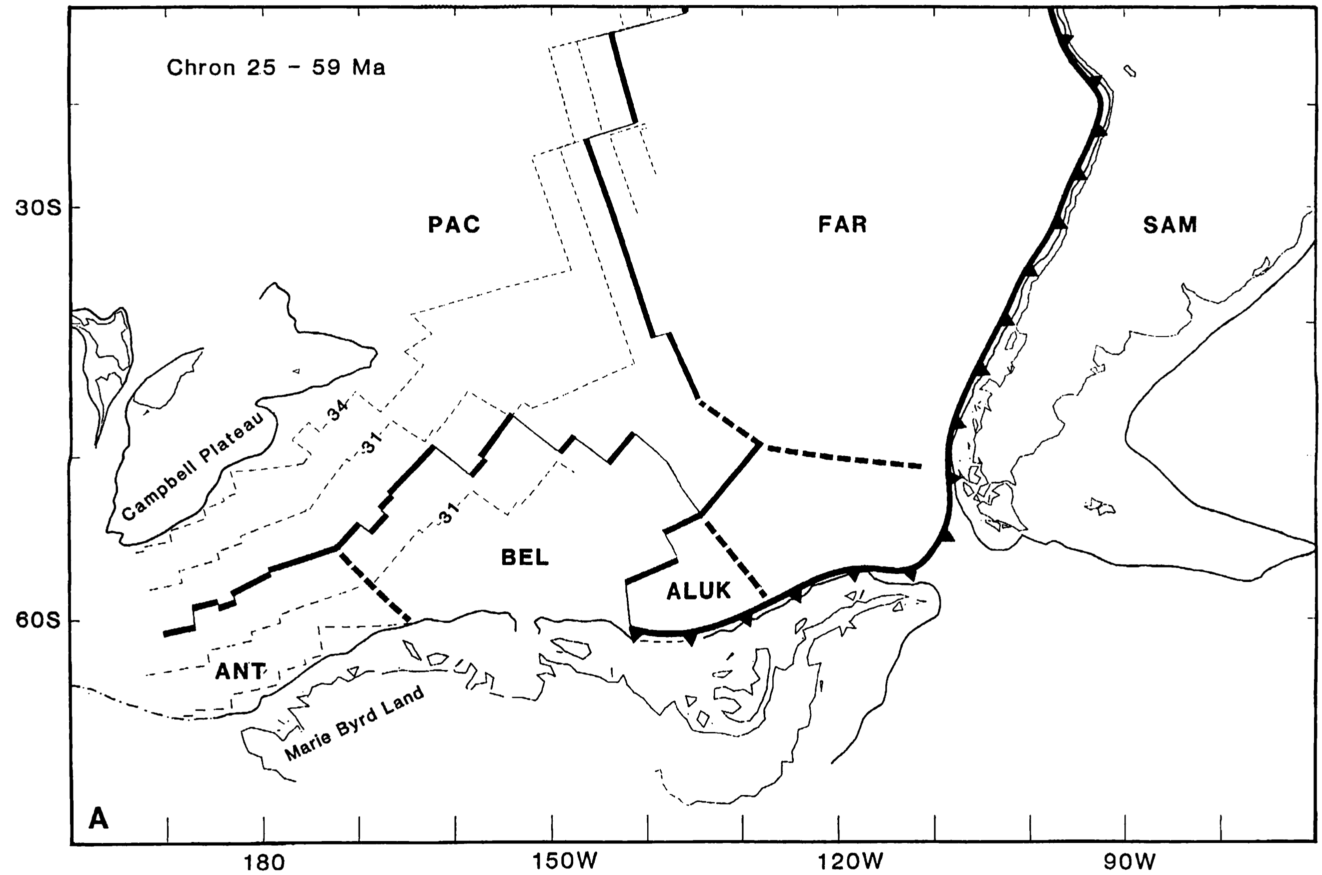


Figure 2—Reconstructions of the South Pacific at A) Chron 25 (59 Ma), B) Chron 21 (50 Ma), and C) present-day chart of the South Pacific that outlines the two main changes in the plate geometry since the Late Cretaceous: between Chrons 25 and 21, and between Chrons 7 and 5 (after Mayes et al., 1990). Thick line segments represent the spreading ridge segments. Undocumented but suspected plate boundaries are represented by a thick dashed line. Saw-toothed lines represent the trenches; thin lines with open saw-teeth show the extinct trenches. Thin dashed lines represent the isochrons still present in the Southern Pacific, and the numbers refer to the corresponding chrons (Chrons 34, 31, 25, 21, 7 and 5; respectively: 84, 68, 59, 50, 26 and 11 Ma). The stippled area shows the portion of the Pacific plate that transferred onto the Antarctic plate between Chrons 25 and 21. ANT = Antarctic plate, BEL = Bellingshausen plate, FAR = Farallon plate, PAC = Pacific plate, SAM = South American plate.

charted around Antarctica because of the lack of shipboard data, also appear as lineations in the data. Isolated features such as seamounts and submarine ridges produce strong signatures in the vertical deflection profiles. However, because many of these features are probably narrower than the spacing of Geosat profiles, they are not well resolved by this technique. For the sake of clarity, the major seamounts and submarine plateaus in Figure 3 are outlined by their bathymetric contours rather than by the scattered peaks and troughs observed in the vertical deflection.

## A New Tectonic Chart for the Southern Ocean

Figure 6 combines the structural information interpreted from the vertical deflection profiles with a compilation of magnetic picks and bathymetric contours. The sources for the magnetic anomaly data have been acknowledged in a previous section. The bathymetric contours have been digitized from the GEBCO chart series (Johnson et al., 1980; Falconer and Tharp, 1981; Hayes and Vogel, 1981; LaBrecque and Rabinowitz, 1981; Fisher et al., 1982; Mammerickx and Cande, 1982; Monahan et al., 1982). We have also incorporated recent detailed mapping of the Astrid Ridge (Bergh, 1987), the Conrad Rise (Driscoll et al., 1985, unpublished manuscript) and the Kerguelen Plateau (Schlich et al., 1987).

Fracture zones are the most numerous tectonic features of the Southern Ocean seen in the lineation map (Figures 3, 4). The most prominent fracture zones in the South Atlantic are the Falkland-Agulhas Fracture Zone and the Bullard Fracture Zone east of the South Sandwich Trench. The en échelon Du Toit, Bain, and Prince Edward Fracture Zones offset the Southwest Indian Ridge by more than 800 km. The Kerguelen Fracture Zone separates the Crozet and Enderby Basins. The George V, Tasman, and Balleny Fracture Zones connect the Antarctic and south Australian margins. The main fracture zones in the South Pacific are the large-offset Udintsev, Tharp, Heezen, and Tula Fracture Zones, and the Hero and Shackleton fracture zones in the Drake Passage. All of these major fracture zones produce one or more prominent lineations in the vertical deflection.

The main information contained in the interpretation of

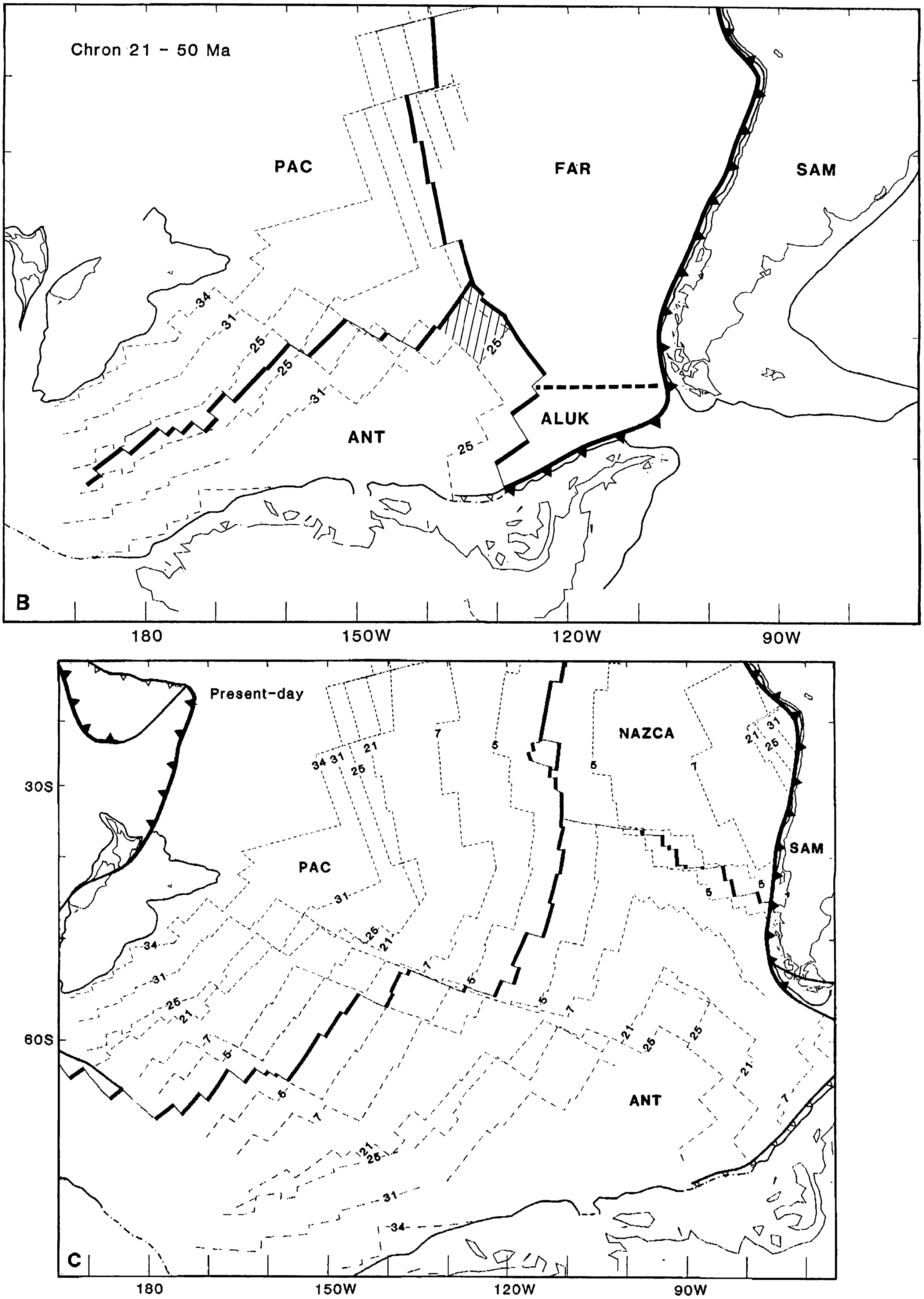


Figure 2. Continued.

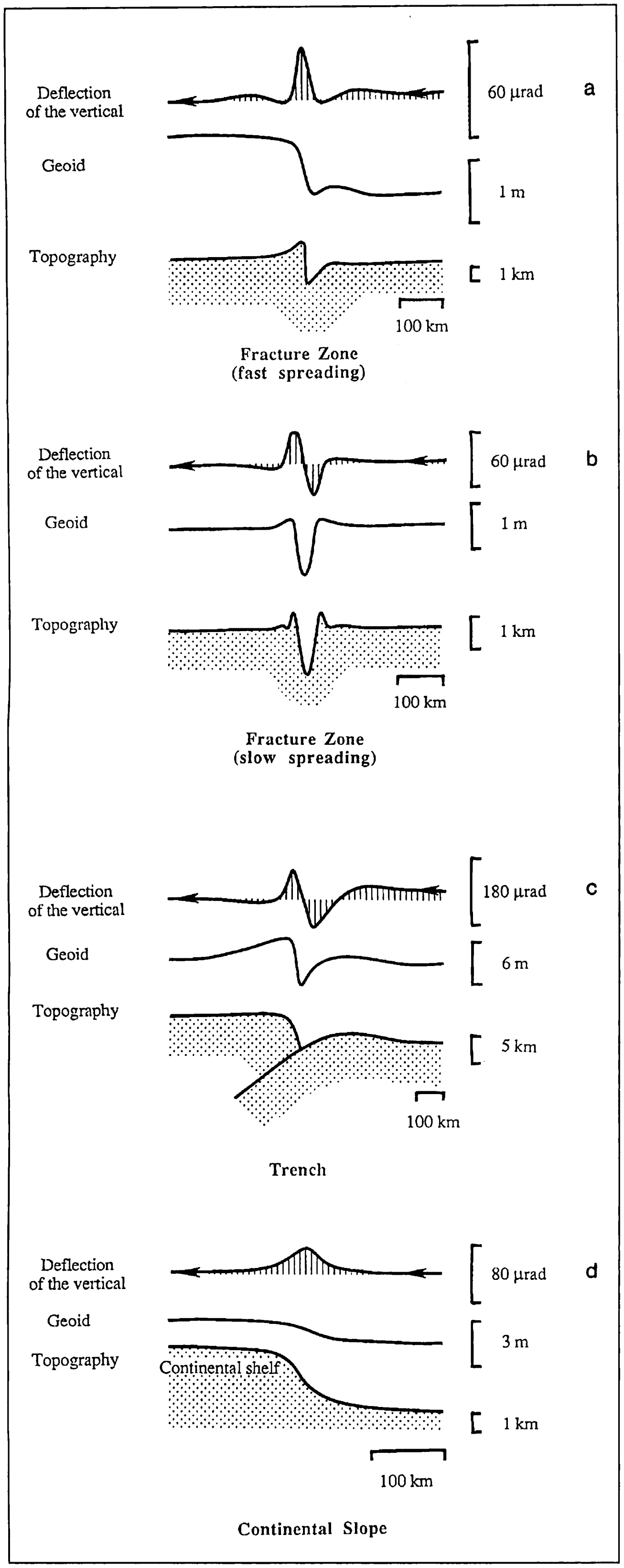


**Figure 4—Examples of signatures in the vertical deflection profiles associated to lineated fabric of the ocean floor: a) and b) fracture zones, c) a trench, and d) a continental margin.**

the vertical deflection profiles with respect to fracture zone lineations concerns the inferred spreading directions. Even when the sea-floor spreading history appears to be uniform such as in the South Atlantic, subtle changes in the Geosat lineations can be observed (Cande et al., 1988). In other instances, fracture zone lineations record continuous changes in spreading direction such as in the South Pacific. On the Antarctic plate in the Pacific (90°W to 180°, 50°S to 70°S), the orientations of the fracture zones shift progressively from southeast-northwest to almost east-west. As a result, the large offset Heezen and Tharp Fracture Zones converge toward each other as they approach the Pacific-Antarctic Ridge. The change of motion at Chron 6 along the South American-Antarctic Ridge (Barker and Lawver, 1988) is seen as a series of parallel, arcuate lineations in the Weddell Sea Basin. A more abrupt change of motion is indicated in the African-Antarctic Basin where the fracture zones north of the Astrid Fracture Zone display two sharp bends, first toward the west and then toward the east, corresponding to two changes of motion of opposite senses along the Southwest Indian Ridge. These changes occurred between Chrons 32 and 24 (Royer et al., 1988). The juxtaposition of fracture zone trends are evidence for reorganization in the plate boundaries. For instance, south of Conrad Rise in the Indian Ocean, two tectonic trends are observed. The north-northeast–south-southwest oriented lineations reflect the direction of motion between Antarctica and Africa from the Late Jurassic to Late Cretaceous while the southwest-northeast fracture zone in the Crozet Basin records the drift of India away from Antarctica in the Late Cretaceous and Paleogene. This change corresponds to the mid-Cretaceous reorganization of the plate boundaries in the Indian Ocean. In the South Atlantic, south of the Bouvet Triple Junction, the fracture zone lineations related to the Southwest Indian Ridge intersect the fracture zones from the South American-Antarctic Ridge (Sclater et al., 1976; Barker and Lawver, 1988); the cusps defined by the fracture zone lineations may be interpreted as the trace left by the Bouvet Triple Junction on the Antarctic plate.

In addition to spreading direction, the amplitudes and spacings of fracture zone lineations (Figure 3) depend somewhat on spreading rate. Fracture zones that formed at slow spreading ridges (< 35 mm/a half rate) are characterized by a deep topographic trough and correspondingly high amplitude vertical deflection signatures (Figure 4B). In contrast, fracture zones that formed at medium or fast spreading ridges (> 35 mm/a) have much lower-amplitude topographic and vertical deflection signatures; along these fracture zones the step caused by the age offset in the sea floor dominates (Figure 4A). The spacing of fracture zones also depends somewhat on spreading rate; fracture zones that formed at slow spreading ridges are more closely spaced than fracture zones that formed at fast spreading ridges (Sandwell, 1986). The overall result of these two rate-dependent processes is that vertical deflection lineations are more abundant and prominent on sea floor that formed at low spreading rates (e.g., South Atlantic, Figure 5) than they are on sea floor that formed at higher spreading rates (e.g., South Pacific, Figure 5). Thus an examination of the vertical deflection profiles can reveal important changes in spreading rates (Small and Sandwell, 1989).

For example, in the South Atlantic, the vertical deflection data shows very few lineations over the sea floor generated during the Cretaceous Magnetic Quiet Period or during the Late Cretaceous (Argentina Basin). When the spreading rates dropped in the late Paleocene (Chron 31), new fracture zones appeared, although some of them do not extend beyond Chron 20 when the spreading rates increased slightly (Cande

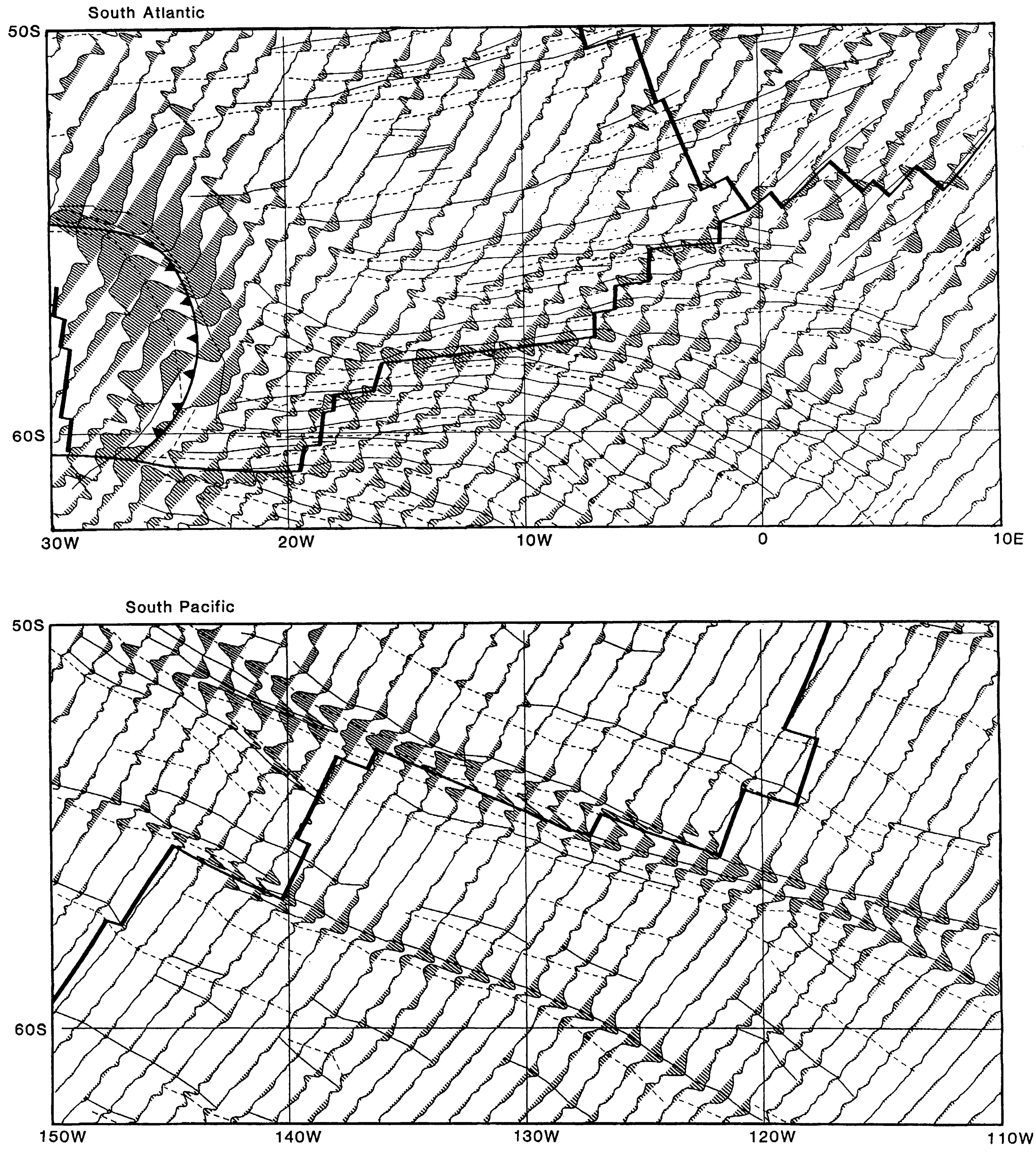


Figure 5—Interpreted vertical deflection profiles in the South Atlantic (top) and the South Pacific (bottom). Vertical deflection is plotted at right angle to the descending ground tracks (i.e., going northeast to southwest), every two data points (~ 7 km), positive to the north. Amplitude scale is 30 μrad (microradians) per degree of longitude. Plain and dashed lines show profile-to-profile correlations of the peaks and troughs in the vertical deflection data. Plates boundaries in the South Atlantic are the South Atlantic Ridge, the Southwest Indian Ridge, and the South American-Antarctic Ridge which connect at the Bouvet triple Junction (at 54°S, 0°E); to the west are the South Sandwich Trench and backarc spreading center. In the South Pacific, the Pacific-Antarctic Ridge is offset from north to south by the Heezen and Tharp Fracture Zones (Eltanin Fracture Zone System) and by the Udintsev Fracture Zone.

et al., 1988). Similar disruptions in the fracture zone pattern occur in the Southwest Pacific where they clearly outline the increase in the sea-floor spreading velocity at Chron 5 (Mayes et al., 1990). Although sea-floor spreading between Wilkes Land (Antarctica) and Australia was initiated in the Late Cretaceous at very slow spreading rates (Cande and Mutter, 1982), fracture zones can clearly be observed only at Chron 18 when the spreading rate drastically increased from 10 to 22 mm/a (half rate). The apparent absence of fracture zones during the slow spreading phase may be caused by the sediment coverage in the vicinity of the margins; however, the magnetic lineations in this area are continuous and are parallel to the coastlines. Another change in the spreading regime may have occurred in the Late Cretaceous in the Weddell Sea Basin (~ 70°S) where abrupt changes in the roughness of the vertical deflection profiles are observed (Haxby, 1988).

Other lineations observed in the Geosat altimeter data can be related to spreading ridges and topographic features produced on active and passive margins. Although spreading centers produce typical signatures in the deflection of the vertical profiles, the spacing of the profiles do not generally permit an accurate mapping of the spreading ridge segments. There are two exceptions south of 45°S where ridge segments can be sampled over several profiles: in the African-Antarctic (Southwest Indian Ridge) and the Australian-Antarctic (Southeast Indian Ridge) basins. Nevertheless, the vertical deflection data can be used to complement identifications of spreading axes that have previously been identified from bathymetric, magnetic, and earthquake epicenter data. The Southwest Indian Ridge is a very slow spreading ridge (< 10 mm/a) characterized by a deep inner valley (Bergh, 1986, unpublished manuscript; LaBrecque and Rabinowitz, 1981), whereas the Southeast Indian Ridge, spreading at medium rate (~30 mm/a), shows a central rise (e.g., Weissel and Hayes, 1972; Vogt et al., 1983). The faster Pacific-Antarctic ridge has smoother topography (e.g., Molnar et al., 1975) which produces only a small signal in the geoid (Sandwell and McAdoo, 1988). Because of the segmentation of the South Atlantic Ridge south of 45°S and its oblique orientation with respect to the Geosat profiles, the vertical deflection signature produced by the South Atlantic Ridge is difficult to distinguish from the fracture zone signal. A detailed analysis of vertical deflection signatures over spreading ridges is presented in Small and Sandwell (1989). Some previously identified extinct spreading centers in the Scotia Sea and the South Pacific can also be mapped from the Geosat profiles. They are seen as major lineations at a right angle to the fracture zone pattern. In the South Pacific, an extinct spreading center can be seen at about 60°S, 100°W on the Antarctic plate (Mayes et al., 1990); the new location of the spreading center is clearly visible on the Pacific plate at 48°S, 146°W. The abandonment of the spreading center corresponds to the plate boundary reorganization that took place between Chrons 25 and 21 in the South Pacific (Figures 2A, 2B).

Trenches are easily identified in the vertical deflection data by their large signatures (e.g., Figure 5). Even fossil trenches such as the one west of the Antarctic Peninsula (Figure 2C) produce a large signature. Troughs associated with presently active or old plate boundaries such as the Hudson Trough in the southeast Pacific, the Falkland Trough south of the Falkland Plateau, and the trough southeast of South Orkney Island in the Weddell Sea are visible in the Geosat data. Also conspicuous are the rifted margins of submarine plateaus: the Kerguelen Plateau which broke apart from Broken Ridge in the middle Eocene (Mutter and Cande, 1983; Coffin et al., 1986; Royer and Sandwell, 1989), and the Campbell Plateau which split off Marie Byrd Land in the Late Cretaceous (Christoffel and Falconer, 1972; Mayes et al., 1990). The continental shelf breaks of Antarctica are identifiable from the Astrid Ridge to George V Land south of Tasmania. Unfortunately, the Antarctic continental margins along the Ross Sea and Marie Byrd Land are south of the coverage of the Geosat orbits (72° of latitude). The new ERS1 satellite, whose orbits will reach 81° of latitude, will cover these remote places. South of Australia, correlations between the vertical deflection data with the continent ocean boundary deduced from magnetic (König, 1980, 1987) and seismic (Talwani et al., 1979; Veevers, 1986, 1987) evidence permit the definition of a criterion for recognition of the structural limit on the Geosat data (Royer and Sandwell, 1989). Such criterion has permitted the mapping of the conjugate continent-ocean boundary off Wilkes Land and is in agreement with interpretations of the few seismic lines available in this remote area (Eittreim and Smith, 1987).

Several intriguing features which are conspicuous in the Geosat data are not yet understood. West of the Kerguelen Plateau and a few degrees southeast of the Kerguelen Fracture Zone, there is a small visible ridge (~ 68°S, 62°E) striking southwest-northeast which may correspond to the Early Cretaceous spreading center between India and Antarctica. In the southernmost part of the Weddell Sea Basin, the vertical deflection data outline a series of small and parallel lineations which cannot be extended to the fracture zone lineations lying farther north. Haxby (1988) speculated that they define an early direction of motion between East Antarctica and South America.

## CONCLUSION

The high-density Geosat data set permits the interpretation of structural trends on the ocean floor. By combining this information with the sparse ship-track data set describing the ages of the sea floor, we have derived a tectonic fabric map of the ocean floor (Figure 6, oversize enclosure). The arrival of satellite altimeters, along with the accumulation of shipboard collected data during the last three decades, has allowed major improvements to be made in the mapping and understanding of the Southern Ocean. Some areas such as the southernmost part of the Weddell Sea, the basins off Marie Byrd Land and the Ross Sea, and the margins of West Antarctica still remain poorly charted. Based on this combined information, improved and detailed reconstructions have recently been proposed for the evolution since the Late Cretaceous of the South Atlantic (Cande et al., 1988; Shaw and Cande, 1990), the Indian Ocean (Royer et al., 1988; Royer and Sandwell, 1989), and the South Pacific (Mayes et al., 1990). Models for the early opening of the Southern Ocean after the breakup of Gondwana in the Late Jurassic need to be revised in the light of the new tectonic constraints in the Weddell Sea, the African-Antarctic Basin, and the Enderby Basin.

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