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# Constraints on the proposed Marie Byrd Land–Bellingshausen plate boundary from seismic reflection data

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**Abstract.** Single-channel and multichannel marine seismic data off the coast of West Antarctica collected during two *Nathaniel B. Palmer* cruises (NP92-8 and NP96-2) in the vicinity of 65°S to 71°S, 220°E to 250°E, reveal a NNW trending graben. We interpret this graben to be part of the paleodivergent plate boundary between the Marie Byrd Land and Bellingshausen plates. This graben coincides with a -520 nT magnetic anomaly to the NNW and a -720 nT anomaly to the SSE, as well as a 20 mGal negative gravity anomaly. Seismic profiles subparallel to the graben (22 km/Ma half-spreading rate) reveal greater seafloor roughness to the NE, where seafloor spreading was slower, than to the SW (27 km/Ma half-spreading rate). These data allow the position of the Marie Byrd Land-Bellingshausen plate boundary to be constrained more precisely than has previously been possible, with a trend of N17°W from 68.52°S, 233.65°E to 68.41°S, 233.56°E. The sediment-filled graben has normal separation of sedimentary layers varying from 740 ±30 m to 580 ±20 m imaged in seafloor of age A33y (74 Ma).

## 1. Introduction

The lack of a detailed knowledge of plate tectonic boundaries in the southwest Pacific has been problematic for the reconstruction of the Australia, Antarctic, and Pacific (PAC) plates. In particular, this region contains the only boundary linking the plates of the rest of the world back to the Pacific plate: the spreading center between the Pacific plate and West Antarctica. Considering the Antarctic side to be a single plate results in extensive problems in the plate reconstructions. Accounting for the Bellingshausen plate and understanding its boundaries help make these reconstructions more precise.

The Pacific-Antarctic ridge has been understood to record motions of a three-plate system during Late Cretaceous and early Tertiary time since *Stock and Molnar* [1987] noted a variation in the direction and rate of spreading at the boundary on either side of the Antipodes fracture zone (AFZ) [*Stock et al.*, 1996] (formerly FZ 8.5 [*Cande et al.*, 1998]) from A31 time (approximately 68 Ma as determined using the revised time scale of *Cande and Kent* [1995]) to A18 time (40 Ma). The misfit of non-Pacific paleomagnetic poles when rotated back to the Pacific plate [*Gordon and Cox*, 1980; *Acton and Gordon*, 1994] also indicated that there could have been one or more unrecognized plate boundaries between the North Pacific and Antarctica. This boundary has been determined to be on the Antarctic side, so that Antarctica was formerly two separate plates [*Stock and Molnar*, 1987]. New data gathered by cruises NBP9208 and NBP9602 better define this boundary.



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The configuration of the Marie Byrd Land (MBL), Bellingshausen (BEL), and Pacific plates (Figure 1) developed from interactions of the Phoenix, Pacific, and Antarctic plates at the former subduction margin of West Gondwanaland in Late Cretaceous time. After part of the Pacific-Phoenix spreading ridge died, one segment of the Phoenix plate was captured by the Pacific plate and began moving northward with it (between 110 and 105 Ma) [*Luyendyk*, 1995; *Lonsdale*, 1997]. Farther east, however, another segment of the Phoenix plate (the Aluk plate) was still moving independently.

The Bellingshausen plate may have been yet another fragment of the Phoenix plate. Post A34 time, the Bellingshausen and Aluk plates were moving separately from the Pacific plate, with the Bellingshausen plate on the south side of the spreading center, opposite the Chatham Rise (J. M. Stock et al., Updated history of the Bellingshausen plate, submitted to Geology, 1997) (hereinafter referred to as Stock et al. (submitted manuscript, 1997)). The age of the Bellingshausen plate has been estimated as 79-61 Ma (Stock et al., submitted manuscript, 1997) (79 Ma is a minimum age estimate; the Bellingshausen plate could have been an independent plate before this time as well). It was likely subducting beneath MBL (West Antarctica) during this time (Stock et al., submitted manuscript, 1997). Since approximately A27 time (61 Ma), the Bellingshausen and MBL plates have been joined as part of the Antarctic plate, with the Pacific plate moving away from it, northward. At this time of plate reconfiguration, the fracture zones south of the Campbell Plateau switched from the previous left-stepping fracture zones to a right-stepping configuration [*Cande et al.*, 1995].

Stock et al. (submitted manuscript, 1997) have derived best fit finite reconstructions for the Late Cretaceous and early

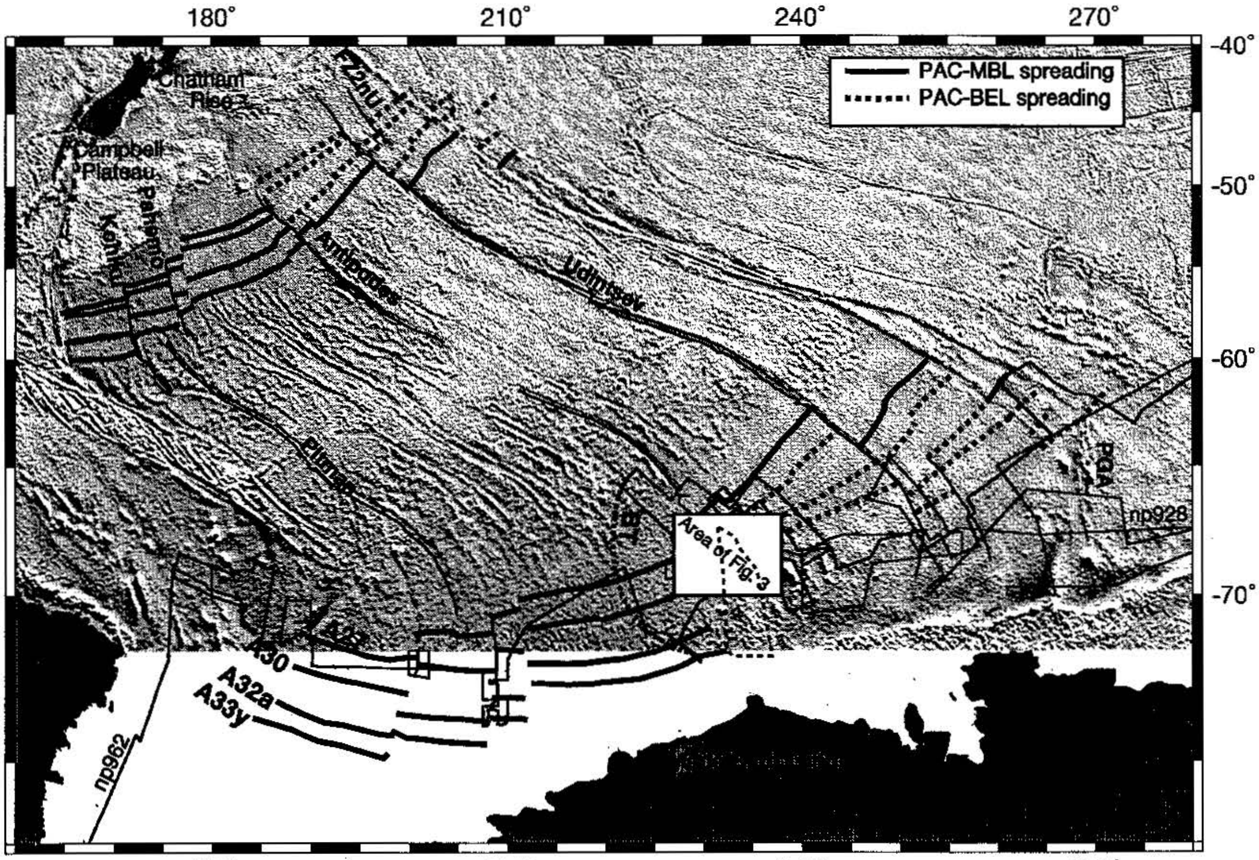



**Figure 1.** Map of study region and surrounding features in the SW Pacific, including chrons 27-32a, the NP92-8 and NP96-2 ship tracks, and the *Sandwell and Smith* [1997] gravity field. The thin, gray line indicates the NP92-8 ship track, and the thin, black line indicates the NP96-2 ship track. The different isochrons are labeled. Dashed isochrons were formed by Bellingshausen-Pacific spreading. The black, dashed, outlined polygon defines the region expected to be crust formed during Bellingshausen-Marie Byrd Land spreading. The thin, black, dashed curve, labeled BT, represents the Bellingshausen trough proposed by *McAdoo and Laxon* [1997]. PGA denotes the location of the Peter I gravity anomaly.

Tertiary magnetic anomalies formed at the Southwest Pacific Ridge. These reconstructions (Figure 2) show that the Antarctic side at this time consisted of two separate plates, Bellingshausen and MBL, whose mutual boundary lay near the Antipodes fracture zone (AFZ), as was earlier suggested by *Stock and Molnar* [1987] and *Mayes et al.* [1990]. The reconstruction changes the duration of existence of the Bellingshausen plate; it ceased to be independent at about A27 time (61 Ma). The magnetic anomalies are farther apart and parallel SW of the fracture zone, while they are closer together and opening eastward to the NE of the fracture zone (Figure 1). The matching conjugate offsets, along the fracture zones west of and including the AFZ, imply approximately 230 km of relative plate motion between the Bellingshausen and MBL plates [*Stock et al.*, 1996]. An alternative solution to the best fit finite rotations for magnetic anomalies is a two-plate system on the Pacific side rather than the Antarctic side of the PAC-MBL ridge. This has been discounted by Stock et al. (submitted manuscript, 1997), as it would require about 200 km of NNE directed convergence between the two-plate system between A32a (71 Ma) and A27 (61 Ma), placing a plate boundary SE of the mouth of the Bounty Trough (Figure 2), an area of presumed rifting during this time [*Davy*, 1993].

The Marie Byrd seamounts in the South Pacific mark an area of volcanism (Stock et al., submitted manuscript, 1997) which was the probable location for the MBL-Pacific-Bellingshausen triple junction during Late Cretaceous and early Tertiary time. The magnetic anomaly orientations in this area (Figure 3) suggest a two-plate system on the Antarctic side of the MBL-PAC ridge from at least 83 Ma to approximately 61 Ma (Stock et al., submitted manuscript, 1997). However, the location of the former boundary between these two plates is not well known because the basement topography is dominated by the Marie Byrd seamounts and more recent smaller-scale volcanism. An earlier study [*McAdoo and Laxon,* 1997] was not able to establish this location with sufficient precision to provide an independent constraint on relative plate motion across it. With the use of the Geosat and ERS-1 satellite marine gravity fields, *McAdoo and Laxon* [1997] placed this boundary in the Bellingshausen trough, slightly west of the AFZ (Figure 1). However, the magnetic anomaly data show continuous lineations crossing the Bellingshausen trough, and thus are more consistent with having the trace of the BEL-MBL boundary located farther east than proposed by *McAdoo and Laxon* [1997] (Figures 1 and 3). In this study, the seismic data from the NP96-2 and NP92-8 cruises reveal a more precise location for part of the fossil MBL-BEL boundary. We find that it lies close to, but not coincident with, the boundary determined by *McAdoo and Laxon* [1997].

Note that the eastern side of the Bellingshausen plate has also been studied. A strike-slip or transpressional BEL-Aluk boundary was imaged by satellite gravity and seismic data just

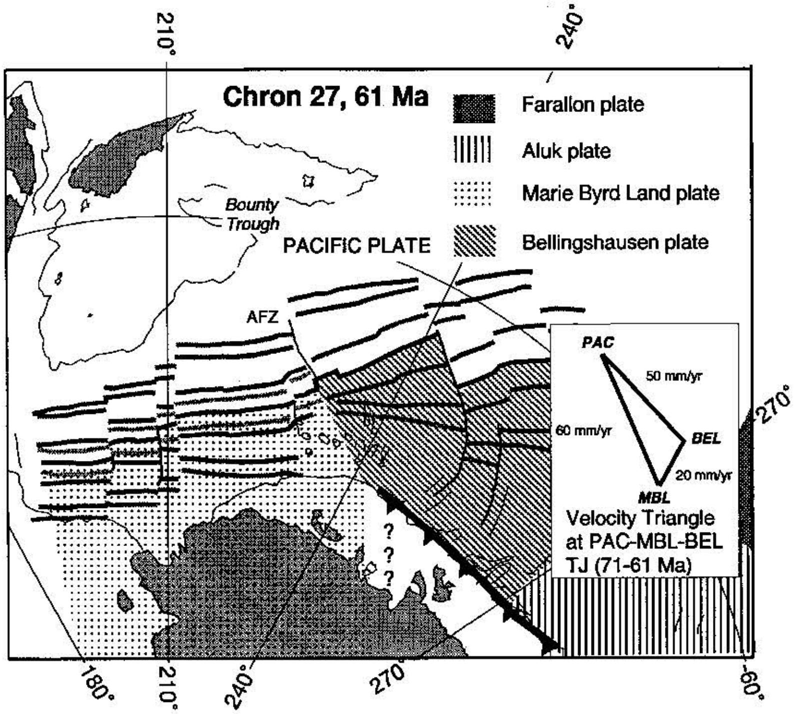



**Figure 2.** Tectonic reconstruction of plates in this region at the time of Anomaly 27 (61 Ma), showing the inferred extent of the Bellingshausen and Marie Byrd Land plates. Spacing and trends of isochrons differ on either side of the AFZ region, showing clearly that a paleoplate boundary must have been located here. Marie Byrd Land plate is held fixed. Rotations used for adjacent plates are PAC-MBL [*Cande et al.*, 1995], Lord Howe Rise-Australia [*Gaina et al.*, 1998], and Australia-East Antarctica [*Tikku and Cande*, 1997]. Velocity triangle shows inferred motions among MBL, BEL, and PAC at the region of their mutual triple junction averaged over the time interval from Chron 32a to Chron 27 (computed from rotations determined by *Stock et al.* [1996]). AFZ, Antipodes Fracture Zone. Question marks on West Antarctica indicate region of crust that may have belonged to either MBL or BEL depending on the orientation of the MBL-BEL boundary as it approached the continent.

west of Peter I Island (Figure 1), striking 45° oblique to the fracture zones in the area [*Gohl et al.*, 1997; *Cunningham et al.*, 1997].

The magnetic data from the NP92-8 and NP96-2 cruises suggest the location of the ancient BEL-MBL plate boundary, but its structure does not appear to be simple, due in part to the large flat-topped Marie Byrd seamounts. In light of the magnetic data, structural offsets in seafloor basement were investigated using single-channel and multichannel seismic reflection data and sonobuoy data from the NP92-8 and the NP96-2 cruises. These data, which image a graben coincident with an approximately 720 nT negative magnetic anomaly, support the location of a fossil N17°W trending divergent plate boundary between the ancient Bellingshausen plate and the Marie Byrd Land plate just east of the AFZ from 68.52°S, 233.65°E to 68.41°S, 233.56°E.

## 2. Data Analysis

Magnetic anomalies 32a - 27 (Figures 1 and 2) reveal a major discrepancy in spreading rates on either side of the AFZ (22 km/Ma half-spreading rate to the NE, increasing rapidly eastward, and 27 km/Ma half-spreading rate to the SW) (Figures 1 and 3). These spreading rates were determined for only the central region of Figure 3. In addition to these data, a suggested locality of the BEL-PAC-MBL triple junction trace southward from the projection of the AFZ (indicated by a gravity lineament from 50°S to 68°S (Stock et al., submitted manuscript, 1997)) influenced the focus of our study toward the seismic profiles in the proximity of the AFZ.

The seismic data analyzed in this study are a combination of single-channel, multichannel (48), and sonobuoy data (Table 1). These data have been submitted to the Antarctic Seismic Data Library System [*Childs et al.*, 1994; *Cooper*, 1995]. An array of 2 air guns was used for the source of the NP92-8, and an array of 2-5 generator-injector guns (420-1050 cubic inch displacement) was used for the NP96-2 seismic reflection data sets. The recording length was 8 s with a shot interval of 15 s. Multichannel data were collected on a 1.2 km long 48-channel streamer during the NP96-2 cruise. The data were despiked and filtered with a 10-60 Hz band-pass filter to remove significant low-frequency noise. There is, however, random burst noise of unknown origin that could not be removed by filtering. This noise is more prominent in the 1992 data set, because these are single-channel data which cannot be stacked. The 1996 data were able to be stacked. Thus Figure 4b is a stacked profile of the multichannel data.

In order to stack and migrate the data, a single, two-layer velocity model was used, with a velocity of 1.5 km/s above the seafloor and 3.0 km/s in the sediments below the seafloor. The velocity below the seafloor was established from a refracted arrival on a sonobuoy gather. Its value is not well constrained due to the deep water and limited offsets, and it should be treated as in the range of 2.9 - 3.1 km/s. The migrations shown in Figures 4a and 5 are done by a time domain Kirchoff method applied to the zero-offset data. It is unnecessary to remove the free-surface multiples because of the large water depth. We did not attempt to attenuate the interbed multiples because they do not appear to be an obvious problem with the data. Note that the hyperbolas formed during the migrations in Figures 4a and 5 are due to out-of-plane diffractions (example: Figure 4a, at 10893 km and 6.15 s, at the bottom of the most westerly, west dipping normal fault). These diffractions cannot be removed

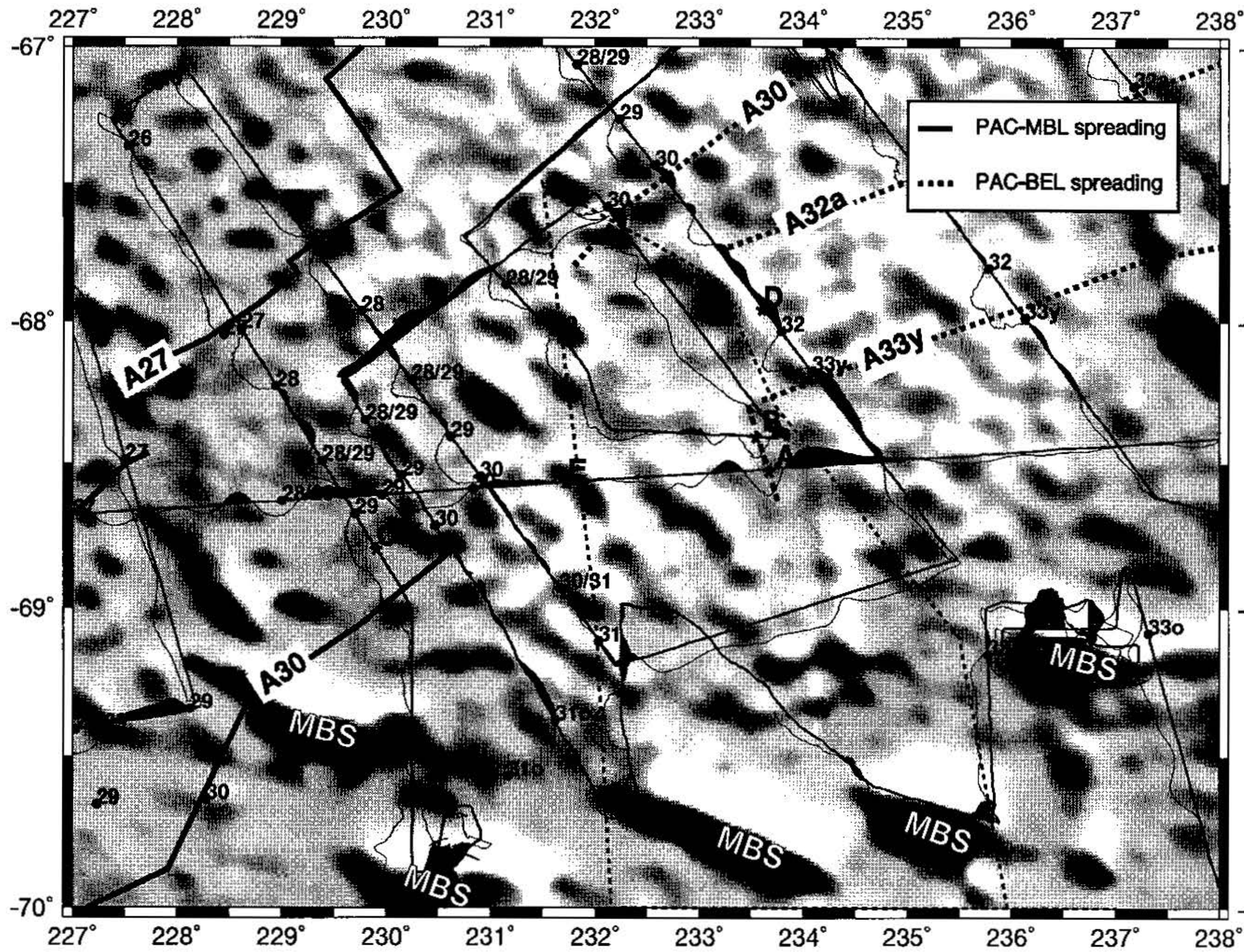


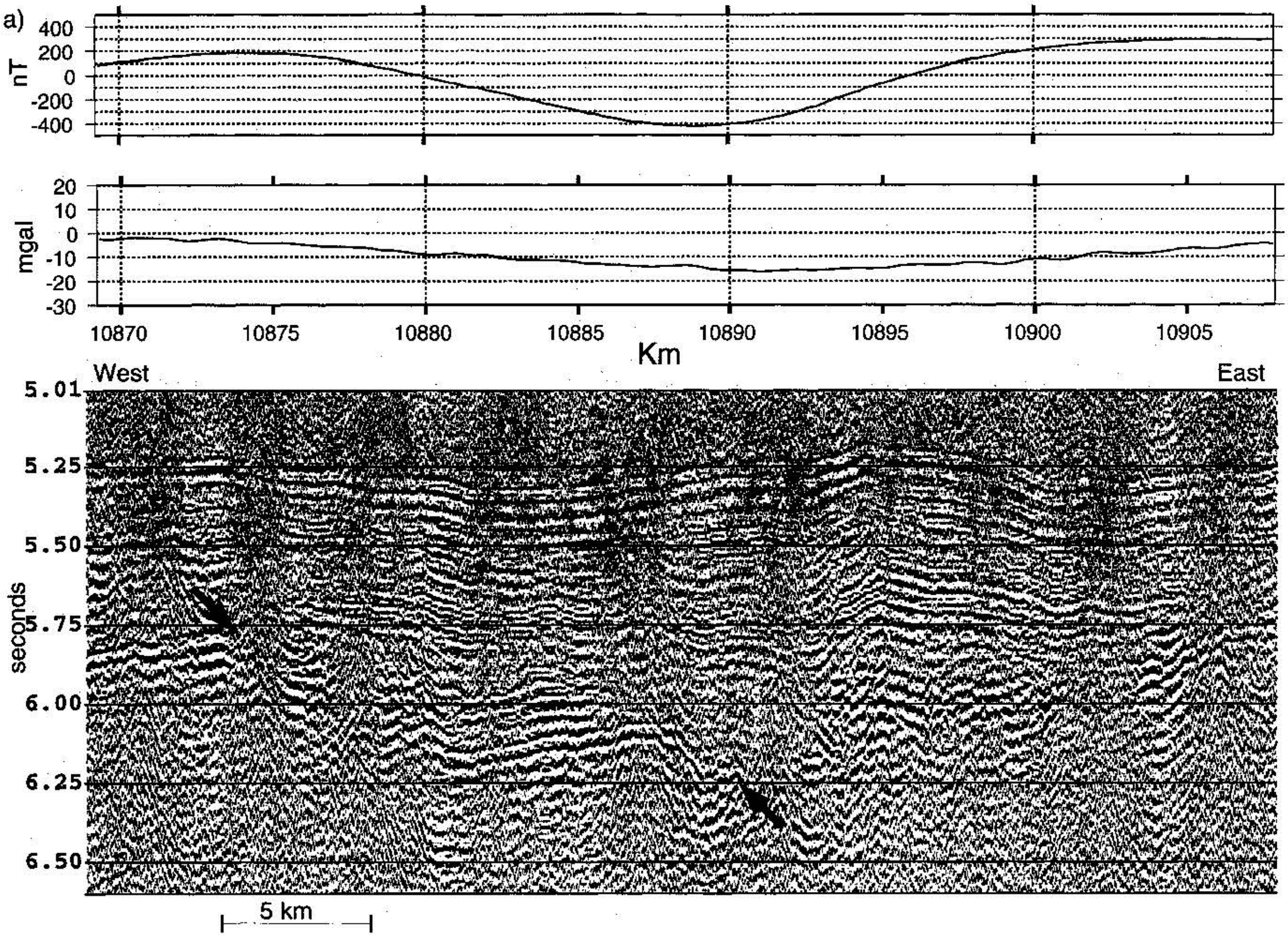

**Figure 3.** Enlarged figure of the study region (see Figure 1 for location). Magnetic anomalies are plotted perpendicular to the ship track with the positive anomalies filled in gray. Patterns of tracks are as in Figure 1. The magnetic anomaly picks are denoted by black circles labeled with their corresponding isochron number. The black, dashed, outlined polygon defines the approximate region of crust formed during Bellingshausen-Marie Byrd Land spreading. The dashed line through A and B denotes the approximate location of the graben. MBS, Marie Byrd seamounts. Letters denote important features on seismic lines as follows: A, graben imaged by NP92-8 data (Figure 4a); B, graben imaged by NP96-2 data (Figure 4b); C, profile which reveals smoother basement (fast spreading) (Figure 6a); D, profile which reveals rougher basement (slow spreading) (Figure 6b); E, seismic profile across inferred boundary between crust formed by MBL-PAC spreading and crust formed by MBL-Bellingshausen spreading, near the southern projection of the AFZ (Figure 5).

by processing; however, they do not obscure the fault offsets and sedimentary layers on which our interpretation of this image is based.

The seafloor spreading rates on either side of the AFZ (smoother fabric to the southwest, indicative of faster spreading (27 km/Ma half-spreading rate), and rougher fabric to the northeast, indicative of slower spreading (22 km/Ma half-spreading rate) *Hayes and Kane*, 1991; *Bird and Pockalny*, 1994]), are consistent with the observations seen in the multichannel data (Figures 6a and 6b). The relative roughness of the abyssal hill fabric, as interpreted from the seismic profiles, is consistent with slower spreading (PAC-BEL) to the northeast of the AFZ and faster spreading (PAC-MBL) to the southwest. A rigorous, quantitative analysis of the roughness data would not be valid because of the short profile length (elsewhere on the profile, frequent interruptions of younger volcanic intrusions

**Figure 4.** Two seismic profiles across the graben structure. The arrows indicate points from which the total vertical displacement was measured. The kilometers refer to the distance along the ship track (NP92-8 for Figure 4a and NP96-2 for Figure 4b). (a) Profile of single channel data from the NP92-8 cruise (location A in Figure 3), which has been despiked, filtered, and migrated using the two-layer velocity model. Above these data are plotted the free-air gravity and magnetic data. (b) Profile of 48-channel data from the NP96-2 cruise (location B in Figure 3), which has been despiked, filtered, and stacked using the two-layer velocity model. Above these data are plotted the free-air gravity and magnetic data. Note that Figure 4b, at the eastern end of the ship turned before the end of the graben was reached; however, adjacent lines show that the basement depth remains near 6 s (two-way time).

a)



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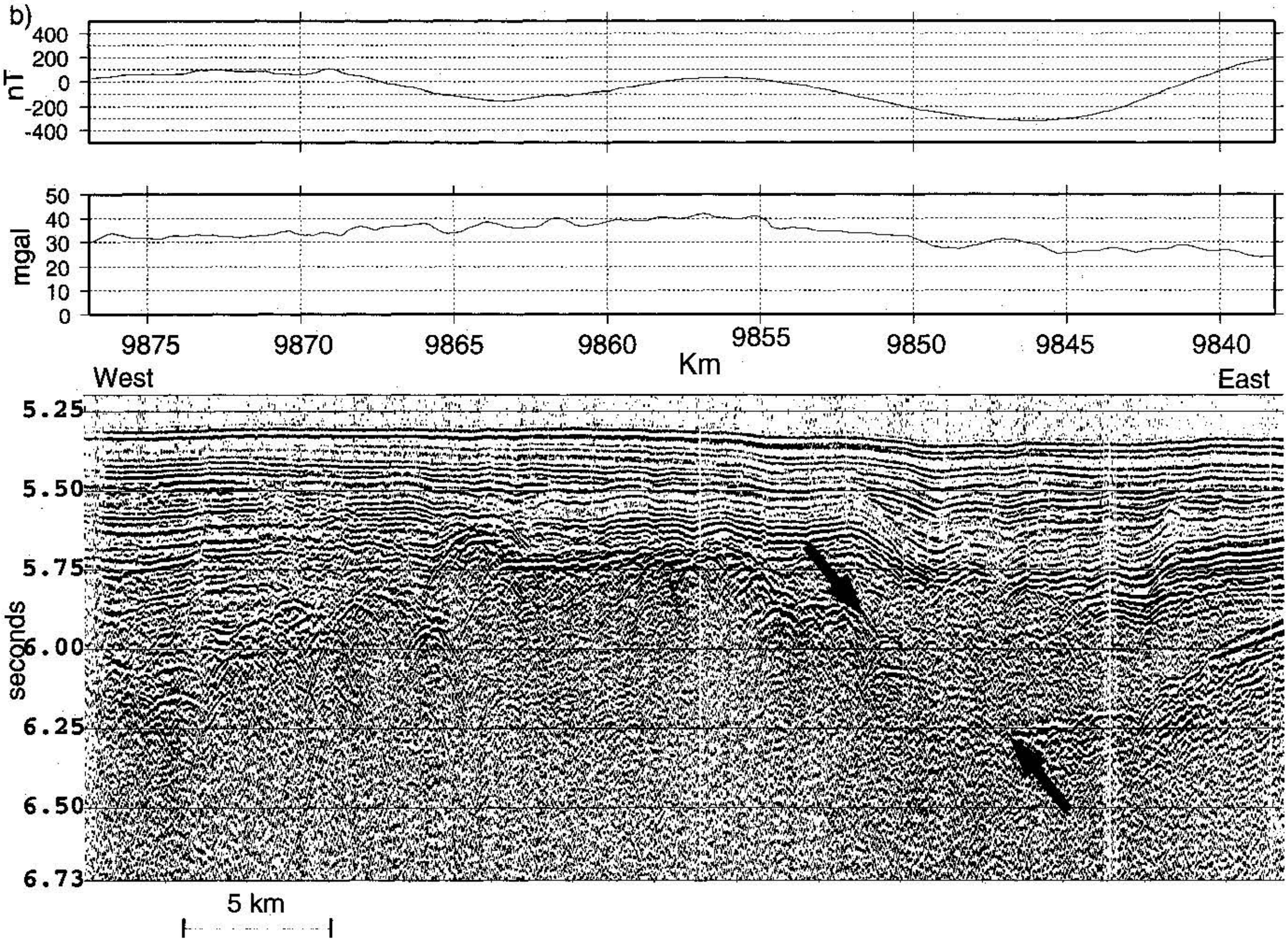

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seconds
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**Table 1.** Recording and Processing Parameters for Both the 1992 Single-Channel and the 1996 Multichannel Seismic Data

| | 1992 Single-Channel Data | 1996 Multichannel Data |
|---|---|---|
| Source | 2 air guns | 2-5 generator injectors |
| Recording length, s | 8 | 8 |
| Shot interval, s | 15 | 15 |
| Average trace interval, m | 25 | 25 |
| Streamer | 1 channel | 48 channel (1.2 km) |
| Filter, hertz bandpass | 10-60 | 10-60 |
| Deconvolved | yes | no |
| Stacked | no | yes |
| Despiked | yes | yes |
| Migrated | yes | no* |

* See text for explanation.

obliterate the original basement relief). Because both spreading rates fall into the category of a slow to intermediate spreading regime [*Bird and Pockalny*, 1994], the two profiles do not show extremely different roughness patterns, but the relative difference between them is apparent.

The free-air gravity data collected on these two cruises show a 20 mGal gravity low over both of the grabens imaged in the seismic data (Figures 4 and 5). Gravity ties were done in Punta Arenas, Chile, for the NP92-8 cruise and at McMurdo Base, Antarctica, and Punta Arenas for the NP96-2 cruise. These gravity anomalies are significantly low, as is expected over a slow spreading ridge [*Cochran*, 1979]. The magnetic data (calculated using IGRF90 for the 1992 cruise and IGRF95 for the 1996 cruise) indicate a -720 nT total field anomaly over the graben imaged in the NP92-8 data and a -520 nT anomaly over the graben imaged in the NP96-2 data. A comparison with magnetic anomalies measured elsewhere along these lines indicates that these anomalies are very significant. They are particularly noteworthy, because they are found on profiles parallel to the magnetic chrons formed by MBL-PAC spreading.

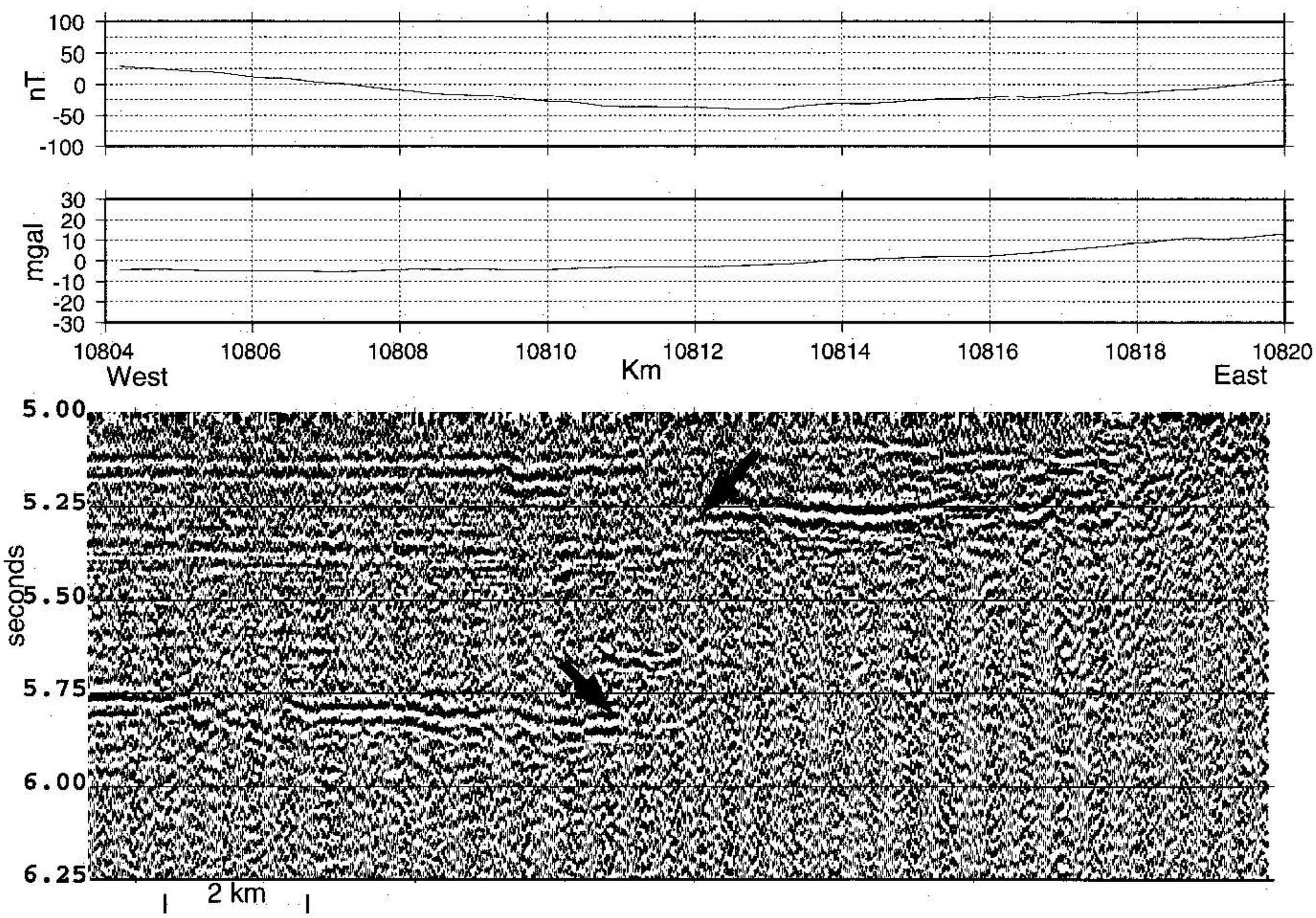


**Figure 5.** A processed profile of single-channel data crossing the western edge of crust formed by Bellingshausen-MBL spreading (location E in Figure 3) from cruise NP92-8. The arrows indicate points from which the total vertical displacement was measured. The kilometers refer to the distance along the ship track. The water bottom is at 5.12 s.

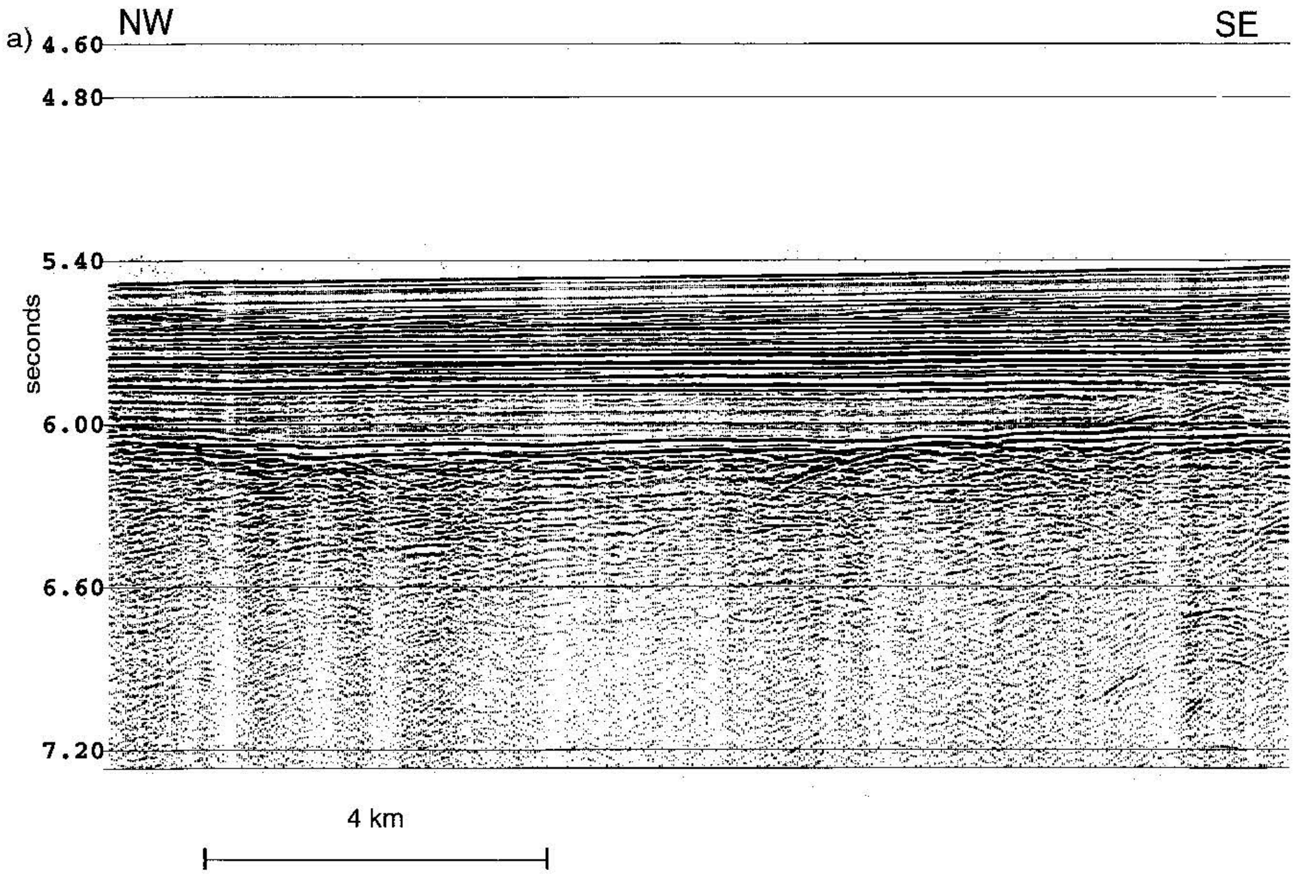


**Figure 6.** Two stacked seismic profiles in locations of different basement roughness. (a) Profile (location C in Figure 3) from the SW side of the AFZ where spreading rates were faster, and (b) profile (location D in Figure 3) from the NE side of the AFZ where spreading rates were slower. Both profiles were collected on the NP96-2 cruise.

Ship crossings parallel to MBL-PAC seafloor isochrons should record little or no magnetic anomalies, unless there were other plate motions oblique to the MBL-PAC ridge (i.e., BEL-MBL spreading), or there was a fracture zone in the vicinity. We have discounted the idea that these anomalies are due to a fracture zone because the anomaly is not very continuous, and it is higher amplitude than would be expected if caused by a fracture zone.

## 3. Results

The seismic profiles in the vicinity of the AFZ south of the southwest Pacific ridge (65°S-70°S, 135°W-120°W) reveal a basement with an average sediment thickness decreasing away from the Antarctic continent, from 1300 m to a thickness of 800 m. These sediment packages are highly disturbed by younger volcanism; however, some distinct structural features can still be discerned. Two cross sections show grabens, observed at 68.52°S, 233.65°E on NP92-8 and 68.41°S, 233.56°E on NP96-2 (Figures 4a and 4b) coincident with approximately -720 nT and -520 nT magnetic anomalies, respectively. In each case the graben crossing also corresponds to an approximately 20 mGal negative gravity anomaly. The lack of other similar structures on any adjacent lines suggests that these structures are related, and their similar offsets in apparently contemporary sedimentary layers indicate they were concurrently active. In addition, the shapes and amplitudes of the magnetic signatures associated with the two graben crossings are not seen elsewhere on lines of this orientation. Thus we infer these to be two crossings of the same graben, which trends N17°W and may have been formed by relative motion of the Bellingshausen and MBL plates.

The basement offsets on the bounding faults of the graben range from approximately 580±20 m to 740±30 m (Figures 4a, 4b, and 7). These offsets, which terminate at the younger layers, argue for faulting which is no longer active, but which did occur over an extended period of time. The most evident faulting is at the interface between the basement and sedimentary layer C. Some faulting can be seen in layer B, but the vertical separation in this layer and layer A appear to be mostly due to slump faulting as the sediment accumulated in the preexisting topography of the graben (Figures 4a, 4b, and 7). This structure is most likely a fossil spreading center, possibly formed from MBL-BEL spreading. The ENE direction of MBL-BEL spreading, suggested by Stock et al. (submitted manuscript, 1997), supports the hypothesis that this NNW trending graben may be one segment of the MBL-BEL fossil plate boundary. Projections of this graben to the northwest and southeast do not show the same magnetic signature on other ship crossings, nor is a graben seen in the seismic profiles. Thus this graben most likely represents a short segment of a spreading center which was bounded by transform faults.

A prominent feature in the seismic data is a vertical offset near the inferred western edge of newly formed crust (formed by BEL-MBL spreading); there is approximately 940±30 m of west-side-down structural offset of the top of the basement in the seismic profile at 68.57°S, 231.78°E (Figures 5 and 7). We

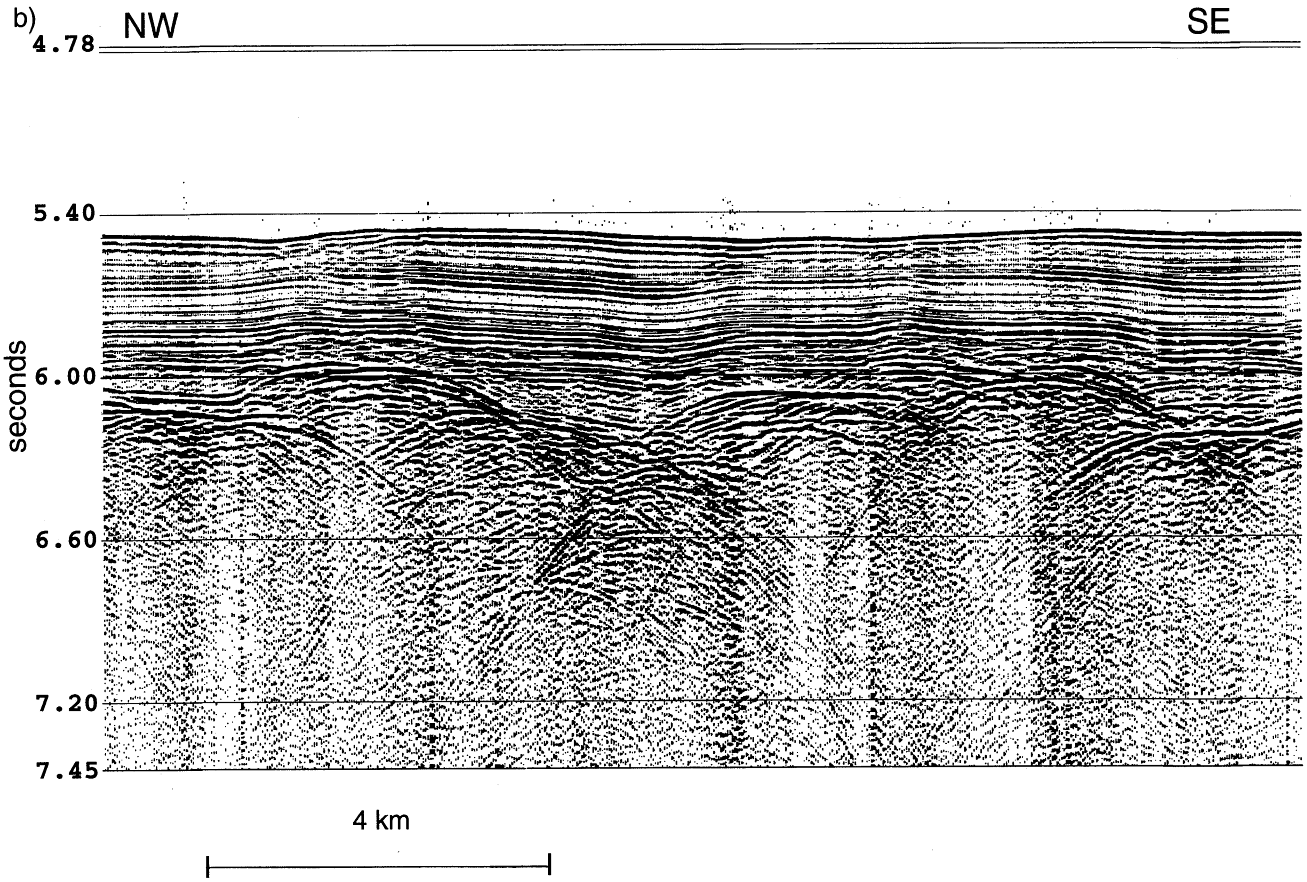


**Figure 6. (continued)**

have interpreted the same three sedimentary layers A, B, C on this profile; layers B and C are locally absent or very attenuated on the higher basement immediately to the east of this location. This feature may be related to the AFZ. However, the continuity of anomalies 28 and 29 suggests that if this structure is a segment of the AFZ, it cannot continue on a straight line to the south, but rather must curve around these anomalies to the east (Figure 3). This feature lies 81 km west of the graben imaged by the seismic data. The gravity data above this offset (Figure 5) do not indicate a large anomaly, and the magnetic data indicate only a small 65 nT anomaly. The gravity signals from this feature and the graben are not visible in the satellite gravity grid (Figures 1 and 3) due to the overwhelming gravity signal of the Marie Byrd seamounts. If there were a single, simple, NNW trending fracture zone in this location, its inferred age offset would be about 7 Ma, since the isochron for magnetic anomaly 30, 66.7 Ma, on the west side of the AFZ, abuts seafloor east of the AFZ along the projection of chron 33y, 74.3 Ma (Figure 3). This age difference might be expected to produce slightly deeper basement on the eastern side of the profile, opposite to the offset observed in the seismic data (Figures 5 and 7).

## 4. Conclusions

A remnant of the fossil boundary accommodating motion between the Bellingshausen and Marie Byrd Land plates is imaged in the seismic data of the NP96-2 and NP92-8 cruises as a NNW trending graben. This feature (crossed in two locations) coincides with a 520-720 nT negative magnetic anomaly and a 20 mGal negative gravity anomaly. This NNW trending fossil boundary, when active, would have accommodated the north-eastward displacement predicted by Stock et al. (submitted manuscript, 1997) along this boundary. The location is consistent with the suggested BEL-PAC-MBL triple junction trace near the AFZ on the Pacific plate (Stock et al., submitted manuscript, 1997), and it separates on the Antarctic side the PAC-Antarctic spreading into two regions of varying spreading rates. This dichotomy of spreading rates is most likely due to the existence of a third active plate, the Bellingshausen plate.

An alternative explanation of the graben in Figures 4a and 4b is nonfaulted basement which is situated between two volcanic intrusions. We discount this explanation because it does not explain the symmetry nor the normal faults on either side of the graben. Furthermore, other nearby profiles with volcanic intrusions show a nearly completely obliterated basement-sediment contact, which is not the case in Figures 4a and 4b. Moreover, the average basement depth along profiles such as those of Figures 6a and 6b (without basement offsets) is at 6.0 s (two-way travel time). By contrast, in Figures 4a and 4b the basement depth is down-dropped to 6.25 s (two-way travel time).

The graben imaged in this paper may only be one segment of a geometrically complex plate boundary. It is possible that other segments of this boundary could lie elsewhere. The divergent relative motion of the MBL and Bellingshausen plates and the NNW strike of their plate boundary, indicated by both this study and previous studies [*Stock and Molnar*, 1987; *Mayes et al.*, 1990; Stock et al., submitted manuscript, 1997],

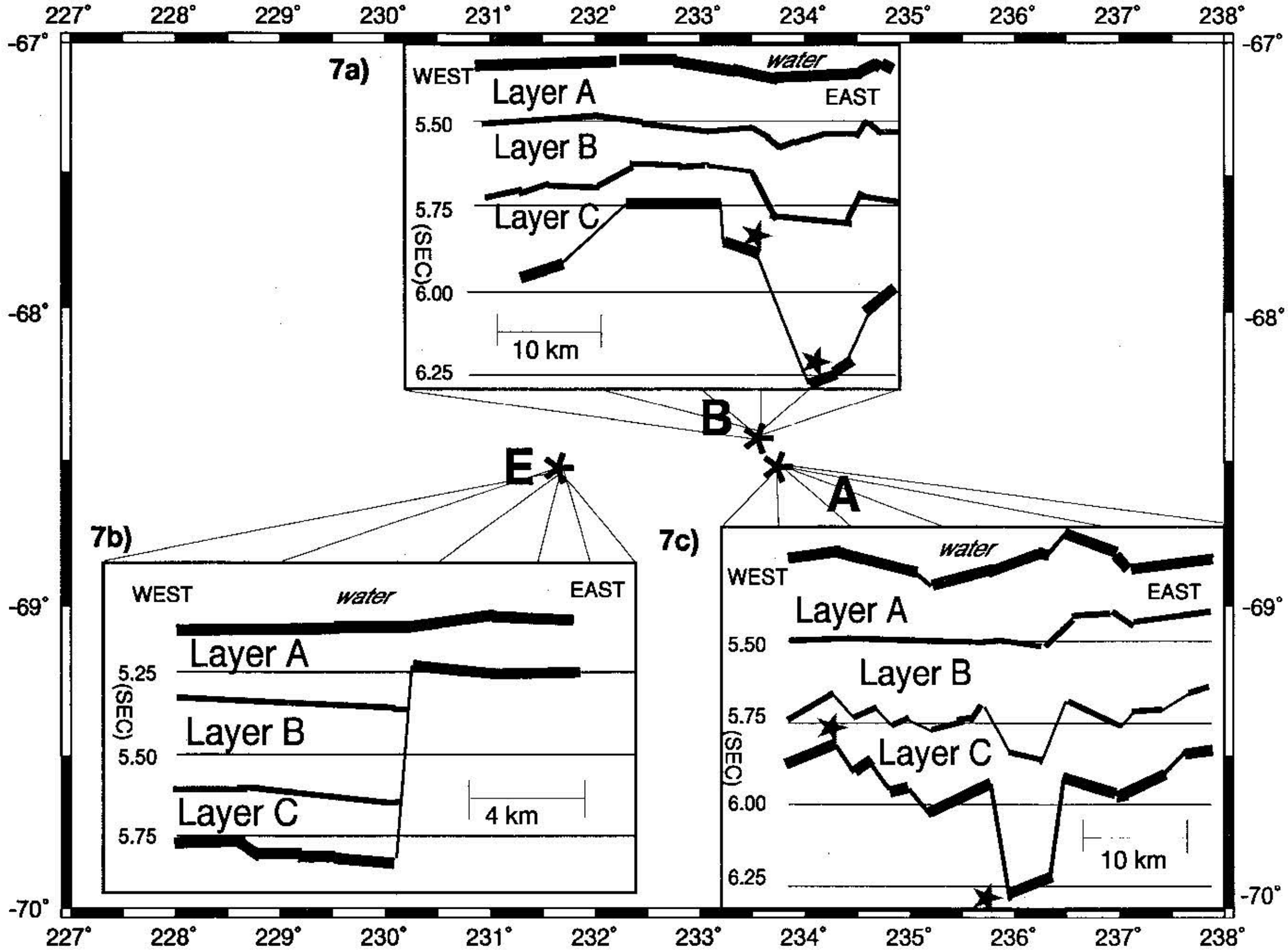


**Figure 7.** Shown are the line drawings for structures (a) B, (b) E, and (c) A in Figure 3. Locations shown are those in Figure 3. The vertical axis is two-way time. In Figure 7a, line drawing of the NW profile of the graben, showing sedimentary layers A, B, and C, as discussed in text. In Figure 7b, line drawing of the western edge of crust formed by Bellingshausen-MBL spreading, showing sedimentary layers A, B, and C. In Figure 7c, line drawing of the SE profile of the graben, showing sedimentary layers A, B, and C. Stars on Figures 7a and 7c indicate points from which vertical displacement was measured in Figures 4a and 4b.

imply that other segments are likely along this strike of N17°W; such segments could include NNW striking spreading centers and ENE striking transform faults.

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