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# Comparisons of Gravity Anomalies at Pseudofaults, Fracture Zones, and Nontransform Discontinuities from Fast to Slow Spreading Areas

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# Comparisons of gravity anomalies at pseudofaults, fracture zones, and nontransform discontinuities from fast to slow spreading areas

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**Abstract.** Published mechanisms for rift tip propagation at spreading centers include extensional deformation and an initial period of slow spreading. We investigate whether the gravity signal and inferred crustal structure at pseudofaults formed in medium to superfast spreading environments resemble the gravity signal at fracture zones or nontransform discontinuities formed in slow spreading environments. We find that altimetry-based gravity anomalies on the Mathematician, Bauer, Easter, Juan Fernandez, and northern Chile Ridge pseudofaults, located in 75–150 mm/yr (full rate) seafloor spreading environments, are similar in amplitude and form to Atlantic fracture zones with 20–30 mm/yr spreading rates. A 5–15 mGal positive mantle Bouguer anomaly is observed on the pseudofault bounding the eastern Juan Fernandez microplate, comparable to those at some similar age-offset nontransform discontinuities in slow spreading environments. Our results suggest that the deeps associated with active propagating rift tips result from both a dynamic mantle component and anomalous crust, the latter of which remains frozen at pseudofaults. We predict that any pseudofaults with age offsets more than ~1 m.y. and not coincident with hotspot volcanism will be associated with thin (and possibly unusually dense) crust, even in superfast seafloor spreading environments.

## 1. Introduction

A pseudofault represents the boundary between younger seafloor formed at a propagating ridge and the older seafloor into which the ridge propagated [Hey, 1977]. Following this definition, a fracture zone is essentially a pseudofault formed at a ridge with zero propagation rate. The ridge tip traces are also commonly referred to as nontransform discontinuities [e.g., Lonsdale, 1983; Macdonald et al., 1988]. In contrast to the less systematic patterns preserved off-axis from nontransform discontinuities [Spencer et al., 1997], the microplate-bounding pseudofaults examined here arise from generally unidirectional ridge propagation events [e.g., Searle et al., 1993; Mammerickx et al., 1988].

Models for the general kinematics of rift propagation assume that even in fast spreading environments, the spreading rate at the rift tip is zero, with full spreading rate attained ~50 km back from the tip [Hey et al., 1989; Kleinrock and Hey, 1989]. A record of the extensional deformation and crustal rifting at the propagating rift tip [Kleinrock and Hey,

1989] should be preserved along the pseudofault. Because this initial rifting operates at slow spreading rates, we expect the geophysical signal of pseudofaults to resemble that of slow spreading fracture zones or nontransform discontinuities.

The tips of active propagating rifts at the edge of Pacific microplates are pronounced local depressions (~4 km). These include Endeavor Deep at the Juan Fernandez microplate and Pito Deep at the Easter microplate [Anderson-Fontana et al., 1986; Yelles-Chaouche et al., 1987; Francheteau et al., 1987, 1988; Naar et al., 1991; Bird et al., 1998]. These deeps have been modeled as the dynamic product of along-axis mantle flow into the ridge tip [Phipps Morgan and Parmentier, 1986] and as the product of pure shear [Martinez et al., 1991] and simple shear [Hooft et al., 1995] extension. Pure or simple shear extension at an amagmatic rift tip should result in thin crust preserved in the pseudofault [Kleinrock and Hey, 1989]. In contrast, dynamic mechanisms for rift tip deep formation predict “normal” crustal thickness at the pseudofault outside the zone of dynamic activity. As pseudofaults outside the active rift tip are generally bathymetric lows but shallower than the active rift tip deeps, it appears that some combination of dynamic mantle processes and formation of thinner-than-normal crust operates at propagating ridge tips.

In this study we seek to address the following two questions: (1) Does crust produced near propagating rift tips

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resemble crust near slow spreading fracture zones, including propagating rift tips in fast spreading environments? We expect a closer resemblance to slow spreading fracture zones than fast spreading fracture zones because slow spreading occurs near the rift tip that forms pseudofaults [Hey *et al.*, 1989; Kleinrock and Hey, 1989; Naar *et al.*, 1991; Bird *et al.*, 1998]. (2) What is the relative significance of thin or dense crust versus dynamic mantle processes in the generation of deeps at propagating ridge tips? To address question (1), we compare the free air altimetry gravity signal across several pseudofaults with those across several fracture zones and nontransform discontinuities. To address question (2) we model the apparent local reduction in crustal thickness along a pseudofault associated with the Juan Fernandez microplate (within an area of superfast seafloor spreading), where sufficient data allow mantle Bouguer anomalies to be calculated.

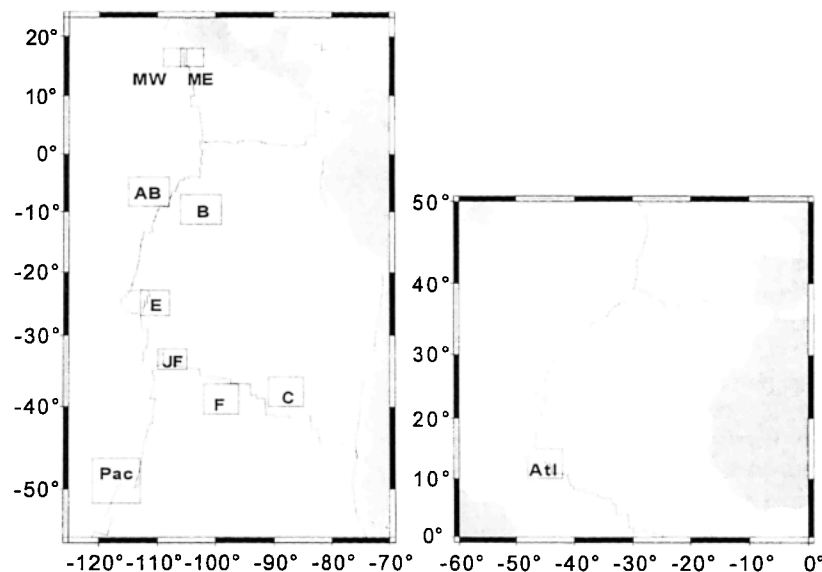
## 2. Background

A brief overview of gravity signals and seismic evidence for crustal thickness at fracture zones and nontransform discontinuities is a useful starting place for this study. The gravity signal characteristic of fracture zones formed in fast spreading environments is an asymmetric high-low pair, with a gravity high over upwarped youngerside seafloor adjacent to a generally higher-amplitude low over downwarped olderside seafloor. This signal is presumably the product of flexure in response to differential subsidence following "locking" of adjacent older and younger seafloor [Sandwell and Schubert, 1982] and of crustal thinning associated with reduced magma supply near the ends of ridge segments [Macdonald *et al.*, 1988]. Significant deviations from this characteristic signature arise primarily on fracture zone segments formed during times of changes in plate motion directions [McCarthy

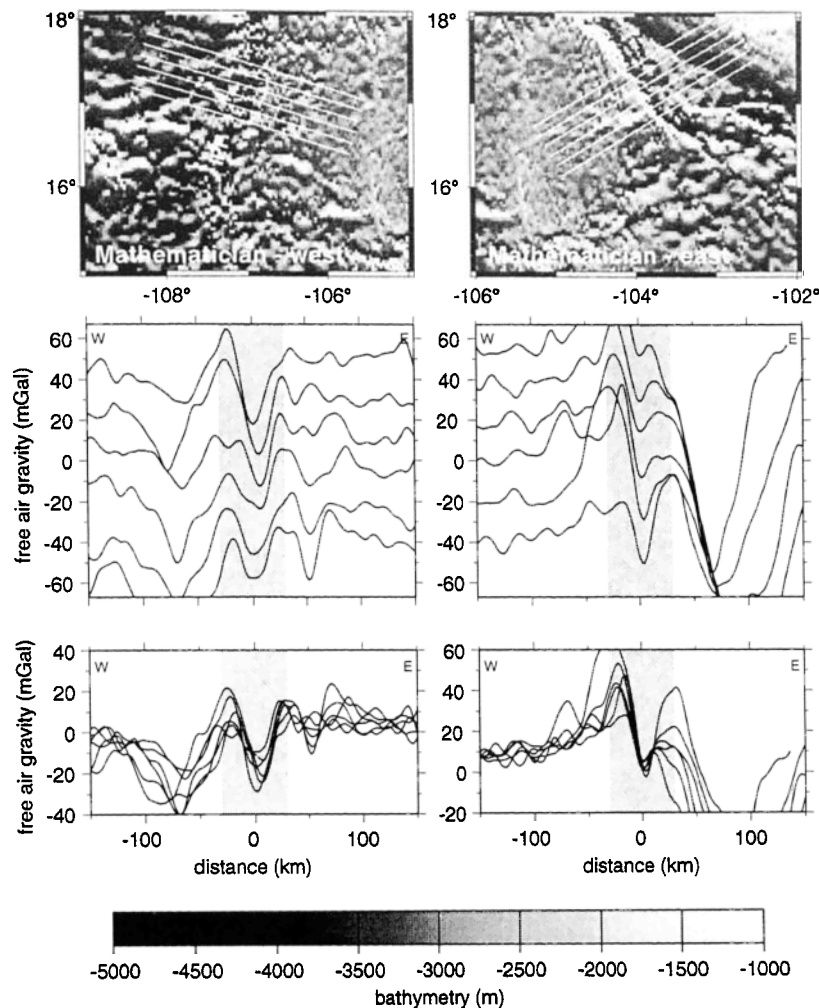
*et al.*, 1996]. Seismic studies of crustal structure at fast spreading transforms and fracture zones show no consistent trend: thinner, normal, and thicker crust are found [McClain and Lewis, 1980; Ouchi *et al.*, 1982; Trehu and Purdy, 1984; Barth, 1994; Van Avendonk *et al.*, 1998].

In contrast, at slow spreading ridges the free air gravity signal at fracture zones is dominated by a pronounced, fairly symmetric low. In general, the larger the transform offset or age offset, the larger the amplitude of the gravity low. Seismic and gravity data indicate abnormally thin crust along many parts of both larger offset fracture zones and smaller offset nontransform discontinuities [White and Mathews, 1980; Detrick and Purdy, 1980; Sinha and Loudon, 1983; Detrick *et al.*, 1982, 1993; Potts *et al.*, 1986; Minshull *et al.*, 1991; Zervas *et al.*, 1995; Tucholke *et al.*, 1997]. Crustal production near the ends of slow spreading ridge segments is believed to be limited predominantly by the focusing of magma accretion at the center of ridge segments, while thermal effects from adjacent older seafloor at the ridge-transform intersection are secondary [Lin *et al.*, 1990]. Crustal thinning at fracture zones also arises from large-scale detachment faulting that occurs preferentially near the boundaries of ridge segments, where the rate of extension is not accommodated by magmatic input [e.g., Detrick *et al.*, 1993; Tucholke *et al.*, 1997, 1998]. There is no simple relationship, however, between decreasing magma supply and increasing tectonic strain [Escartin *et al.*, 1999].

Free air gravity signals over the trace of nontransform discontinuities are more subdued and complex [e.g., Detrick *et al.*, 1993; Tucholke *et al.*, 1997; Maia and Gente, 1998]. Residual mantle Bouguer gravity anomalies, computed by assuming a uniform crustal thickness and subtracting the effects of lithospheric cooling, are found to be ~5-10 mGal along the discontinuities [Maia and Gente, 1998] and at some discontinuities are shifted toward inside corner (olderside)



**Figure 1.** Locations of pseudofaults and fracture zone segments shown in Figure 2-7. (left) Sites in Pacific Ocean. (right) Site in Atlantic Ocean. MW, Mathematician microplate, western boundary; ME, Mathematician microplate, eastern boundary; AB, anti-Bauer ridge; B, Bauer ridge; E, eastern portion of Easter microplate; JF, eastern portion of Juan Fernandez microplate; F, Friday trough; C, Crusoe trough; Pac, portions of Udintsev fracture zone; Atl, portions of two fracture zones just north of the Vema fracture zone.



**Figure 2.** The two pseudofaults associated with the formation of the Mathematician microplate as identified by *Mammerickx et al.* [1988]. Seafloor age offset across pseudofaults is  $\sim 5$ -6 m.y. (top) Two-min global topography grid [*Smith and Sandwell*, 1997]. White lines show locations of profiles. IPF, inner pseudofault; OPF, outer pseudofault. (middle) Profiles derived from 2-min global gravity grid [*Smith and Sandwell*, 1995]. (bottom) Profiles, overlain.

seafloor [*Tucholke et al.*, 1997]. On very slow spreading ridges, nontransform discontinuities may take the form of oblique spreading sections with thin crust [*Parson et al.*, 1997].

### 3. Altimetry Gravity Data

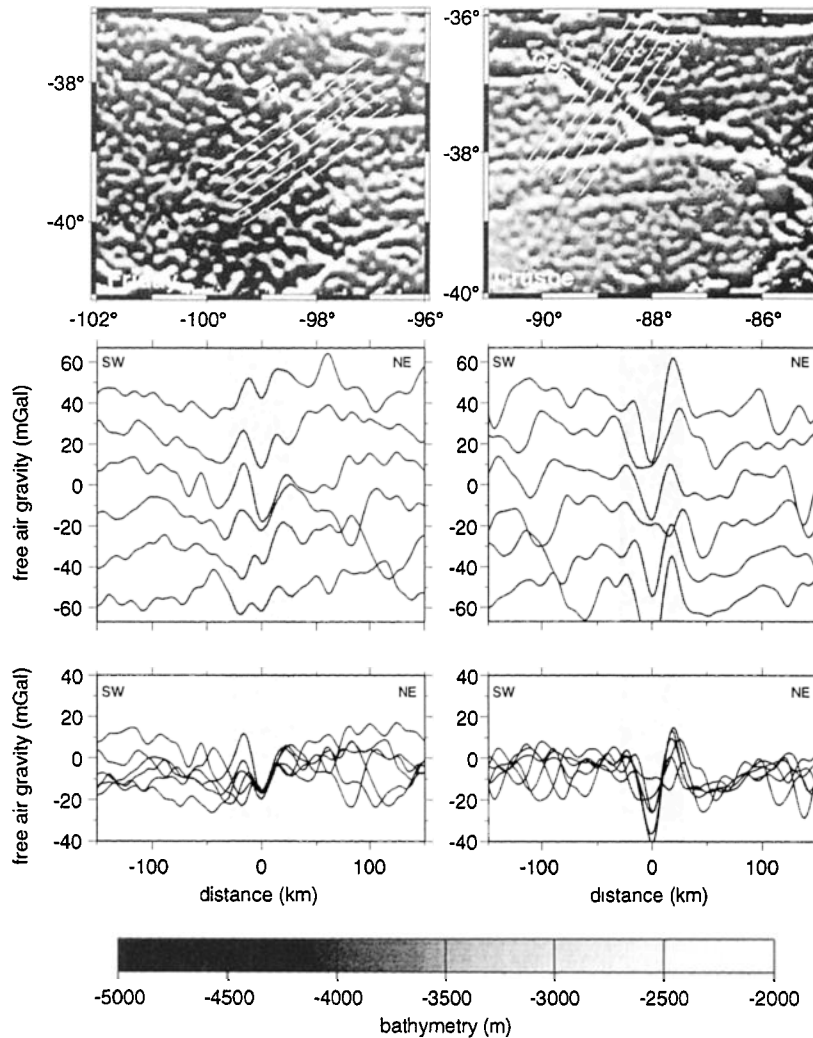
We compare the altimetry gravity signature of pseudofaults identified in Figure 1 with that of fracture zones and nontransform discontinuities. We examine eight major pseudofaults recognized to have formed in association with Pacific Ocean basin microplates. Four preserve the record of ridges propagating into seafloor  $\sim 5$ -6 m.y. old, two preserve the record of ridges propagating into  $\sim 1.5$  m.y. old seafloor, and for the other two the age offset across the pseudofault is unknown. Because the amplitude of free air gravity anomalies over fracture zones is generally correlated with the transform offset or seafloor age offset across the fracture zone, we attempt here to compare pseudofaults with fracture zones with comparable age offsets. Representative gravity profiles across pseudofaults, derived from the 2-min global

gravity grid [*Smith and Sandwell*, 1995], are shown in Figures 2-5.

#### 3.1. Pseudofaults

Two ridges propagated northward into seafloor with a  $\sim 5$ -6 m.y. age contrast as the Mathematician microplate formed on the East Pacific Rise (Figure 2) and as the Friday and Crusoe troughs formed on the flanks of the northern Chile Ridge (Figure 3). The altimetry gravity signal of these pseudofaults varies along strike but generally takes the form of a symmetric 30-50 mGal low,  $\sim 40$ -50 km wide, bounded by small-amplitude flanking highs (Figures 2 and 3).

A fairly symmetric but smaller amplitude gravity low ( $\sim 15$  mGal) occurs at the outer pseudofaults on the Juan Fernandez and Easter microplates, where ridges propagated northward into younger seafloor with an age contrast of 1.5 m.y. (Figure 4). On northward-propagating pseudofaults with unknown age offset on the Bauer microplate (Figure 5) the gravity signal is similarly a fairly symmetric trough of  $\sim 50$  km width, with amplitude intermediate (30 mGal) between those of the 1.5 m.y. and 5-6 m.y. age offsets.



**Figure 3.** The two pseudofaults associated with the formation of the Friday microplate as identified by *Tebbens et al.* [1997] and *Tebbens and Cande* [1997]. Seafloor age offset across pseudofaults is  $\sim 5$ -6 m.y. (top) Two-min global topography grid [*Smith and Sandwell*, 1997]. White lines show locations of profiles. IPF, inner pseudofault; OPF, outer pseudofault. (middle) Profiles derived from 2-min global gravity grid [*Smith and Sandwell*, 1995]. (bottom) Profiles, overlain.

### 3.2. Fracture Zones/Nontransform Discontinuities

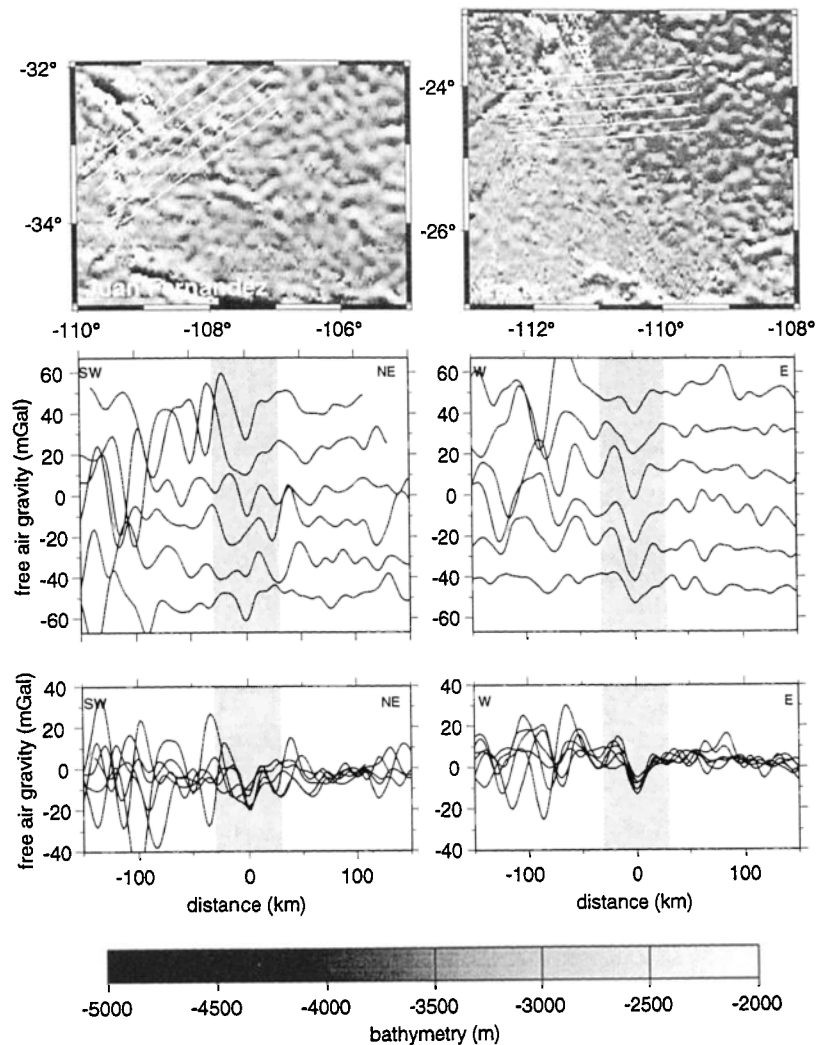
Figure 6 shows representative altimetry gravity anomalies over fracture zones formed at  $\sim 6$  m.y. age offset transforms in both slow (25-30 mm/yr full spreading rate) and fast spreading (80-85 mm/yr) regions. (See, for example, *Shaw* [1988], *Detrick et al.* [1993], and *Kruse et al.* [1996] for more detailed examination of trends and variability in fracture zone gravity signals.) On relatively simple fracture zone segments (i.e., no dramatic change in plate motions, no obvious interaction with hotspot magmatism), gravity anomalies from slow spreading environments are fairly symmetric  $\sim 40$ -50 mGal troughs; in fast spreading environments they are more asymmetric with a  $\sim 30$ -40 mGal anomaly; in both cases the gravity signatures are 50-60 km in width.

### 3.3. Discussion

In both form (symmetric low) and amplitude (40-50 mGal) the larger offset ( $\sim 5$ -6 m.y. age difference) pseudofaults more closely resemble comparable age-offset fracture zones formed on slow spreading ridges than those on fast spreading ridges.

Thus lithosphere preserved from the local environment of the propagating ridge tip, even in fast-spreading regions, resembles, to first order, the lithosphere preserved on long-lived slow spreading fracture zones. This basic observation supports the notion that the causes of thin crust in slow spreading fracture zones, including magma accretion focused away from the ends of ridge segments, amagmatic extension, and low-angle faulting, may also play a role near propagating ridge tips. From this limited data set we could not discern a relationship between gravity signature and the ratio of the propagation rate to spreading rate (angle of the "V" between propagating rift and pseudofault).

The smaller age-offset pseudofaults examined here (Figure 4) appear as semicontinuous  $\sim 15$  mGal lows; thus the small sample set examined indicates pseudofaults follow the overall trends observed on both fast and slow spreading fracture zones of increasing amplitude gravity signal with increasing offset. We can use this observation to predict rough bounds on the age offset across pseudofaults in magnetic quiet zones or where magnetic data are not available. For example, on the anti-Bauer and Bauer pseudofaults [*Goff and Cochran*, 1996]



**Figure 4.** The outer pseudofault associated with the formation of the Easter microplate as identified by *Naar and Hey* [1991] and *Bird et al.* [1998]. Seafloor age offset across pseudofaults is  $\sim 1.5$  m.y. (top) Two-min global topography grid [*Smith and Sandwell*, 1997]. White lines show locations of profiles. OPF, outer pseudofault. (middle) Profiles derived from 2-min global gravity grid [*Smith and Sandwell*, 1995]. (bottom) Profiles, overlain.

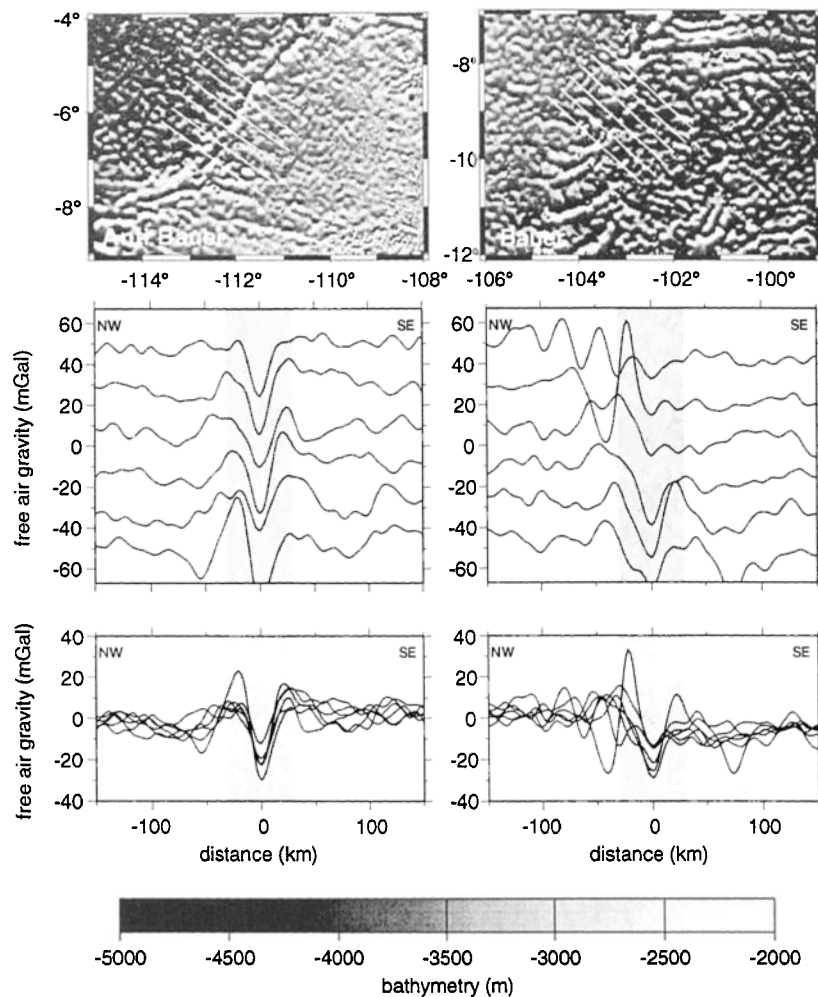
(Figure 5) the altimetry gravity anomalies are comparable in form and intermediate in amplitude between those seen at the  $\sim 1.5$  m.y. age offset and  $\sim 6$  m.y. age offset pseudofaults. Thus we predict that these pseudofaults separate seafloor with an age contrast between 1.5 and 6 m.y. This can be tested by dating sediment cores on either side of the pseudofaults in this area near the magnetic equator.

#### 4. Mantle Bouguer Anomalies

Direct comparison of altimetry gravity anomalies on small age-offset pseudofaults with comparable offset nontransform discontinuities is difficult because on slow spreading ridges these small age difference offsets are generally not stable with time and their topography and free air gravity anomalies may be quite complex [e.g. *Tucholke et al.*, 1997; *Maia and Gente*, 1998]. Fortunately, high-quality shipboard bathymetry and gravity data are available over the  $\sim 1.5$  m.y. age offset, northward-propagating outer pseudofault on the eastern margin of the Juan Fernandez microplate [*Hooff et al.*, 1995;

*Bird et al.*, 1998] (Figure 7). In this region we can subtract out the gravity effects of bathymetry variations and compute mantle Bouguer anomalies.

To compute mantle Bouguer anomalies, we assume a uniform crustal thickness (6 km) and uniform crustal and mantle densities ( $2700 \text{ kg/m}^3$  and  $3200 \text{ kg/m}^3$ , respectively). The contributions to the gravity signal from bathymetry and from undulations in the Moho (assuming constant crustal thickness) were computed via the method of *Parker* [1973] and subtracted from the shipboard gravity profiles, yielding mantle Bouguer anomalies along six east-west crossings of the pseudofault (Figures 8a-8f). We used the bathymetry grid of *Bird et al.* [1998], with nearly complete coverage based on contouring between Hydrosweep multibeam swaths using side-scan data as a guide [*Larson et al.*, 1992; *Kleinrock and Bird*, 1994; *Bird et al.*, 1998]. On all six mantle Bouguer anomaly profiles a small but discernible 5-15 mGal positive anomaly coincides with the pseudofault, with a width approximately comparable to that of the pseudofault (Figure 8). These pseudofault mantle Bouguer anomalies are



**Figure 5.** The two pseudofaults associated with the formation of the Bauer microplate as identified by *Goff and Cochran* [1996]. Seafloor age offset across pseudofaults is unknown. (top) Two-min global topography grid [Smith and Sandwell, 1997]. White lines show locations of profiles. (middle) Profiles derived from 2-min global gravity grid [Smith and Sandwell, 1995]. (bottom) Profiles, overlain.

comparable in magnitude and form to the 5-10 mGal positive mantle Bouguer anomalies found associated with the traces of Mid-Atlantic Ridge nontransform discontinuities with  $\sim 1$  m.y. age offsets [Tucholke *et al.*, 1997; Maia and Gente, 1998].

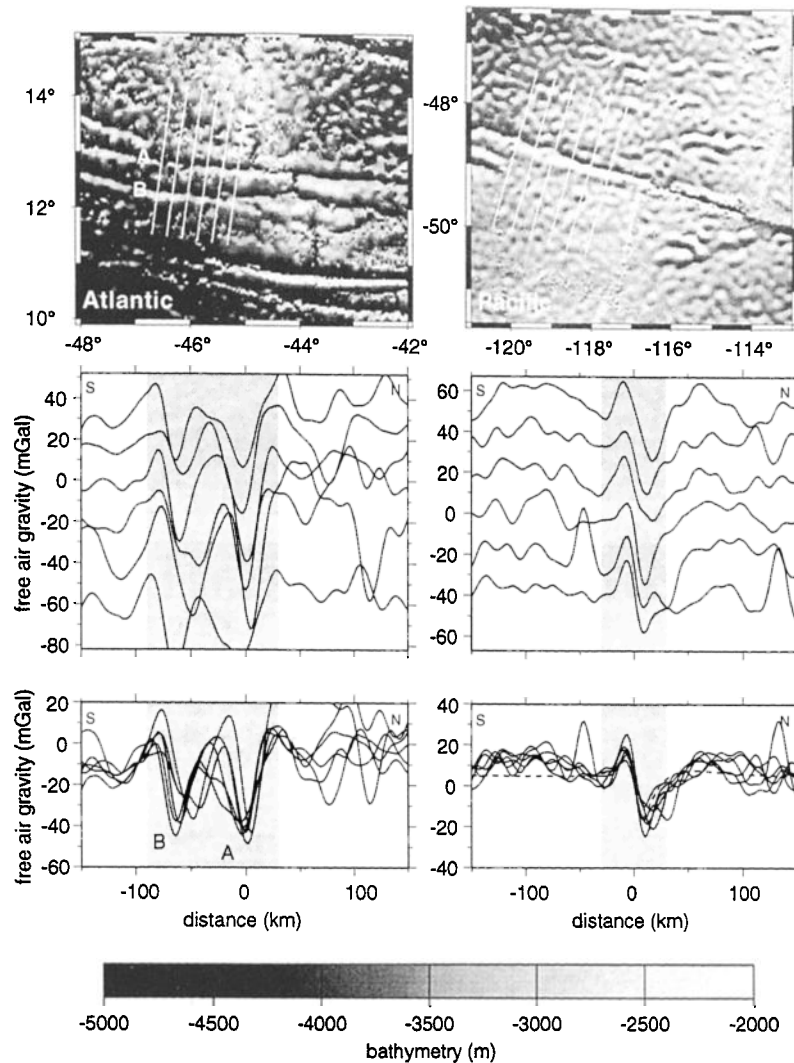
The mantle Bouguer profiles in Figure 8 are  $>50$  km distant from the active ridge tip, and so the local positive mantle Bouguer anomalies over the pseudofault probably reflect thin and/or dense crust rather than dynamic processes or mantle thermal anomalies. We note that we find no systematic temporal variation in the Juan Fernandez mantle Bouguer signature nor any consistent relationship between rift propagation rate and mantle Bouguer gravity.

If the 5-15 mGal mantle Bouguer anomalies reflect thin crust of “normal” density, they correspond to thinning of  $\sim 0.3$ -1 km at the pseudofault. We note that we cannot separate the effects of variations in crustal thickness from variations in crustal density. The diverse and highly differentiated (FeTi) basalts dredged along propagating rifts within  $\sim 50$  km [e.g., Christie and Sinton, 1981; Sinton *et al.*, 1983] of the rift tip may raise the average density of pseudofault crust. Some density variations may also arise from anomalous crustal structure associated with crustal thinning [e.g., Maia and Gente, 1998]. In the absence of

crustal thinning, an average crustal density excess of  $\sim 30$ -100  $\text{kg/m}^3$  ( $\sim 1$ -4%) across the pseudofault would be required to explain the mantle Bouguer anomalies.

The presence of thinner and/or denser crust at the pseudofault has implications for formation of the extreme deeps at the microplate-bounding propagating ridge tips. Mechanisms for the formation of the deeps include pure shear [Martinez *et al.*, 1991] and simple shear extension [Hooft *et al.*, 1995], initially thin crust associated with limited axial magma supply, the dynamic effects of along-axis mantle flow into the ridge tip [Phipps Morgan and Parmentier, 1986], hydraulic head loss [Sleep and Biehler, 1970], and flow in a colder than normal temperature regime beneath thin crust. The anomalous crust preserved at the Juan Fernandez pseudofault formed at the propagating ridge tip. Thus dynamic effects alone do not explain the Juan Fernandez observations. It appears that some combination of tectonic (amagmatic) extension and perhaps high-density crust exists at the rift tip, as GLORIA side-scan sonar data show no evidence for lava flow infilling for  $>50$  km southward from the ridge tip [Bird *et al.*, 1998] (in agreement with Hooft *et al.* [1995]).

If thin/dense crust alone, however, were the predominant



**Figure 6.** Representative gravity signals over “simple” parts of fracture zones. White lines show locations of profiles. (left) A and B, which indicate two fracture zones just north of the Vema fracture zone. The age offset on A is  $\sim 6$  m.y.; the age offset on B is  $\sim 3$  m.y. These formed at 25–30 mm/yr full spreading rate. (right) Udintsev fracture zone. Age offset is  $\sim 6$  m.y., formed at 80–85 mm/yr full spreading rate. Dashed line shows gravity signal expected from flexure associated with differential subsidence and thermal stresses, computed following method of *Christeson and McNutt* [1992]. (top) Two-min global topography grid [*Smith and Sandwell*, 1997]. White lines show locations of profiles. (middle) Profiles derived from 2-min global gravity grid [*Smith and Sandwell*, 1995]. (bottom) Profiles, overlain.

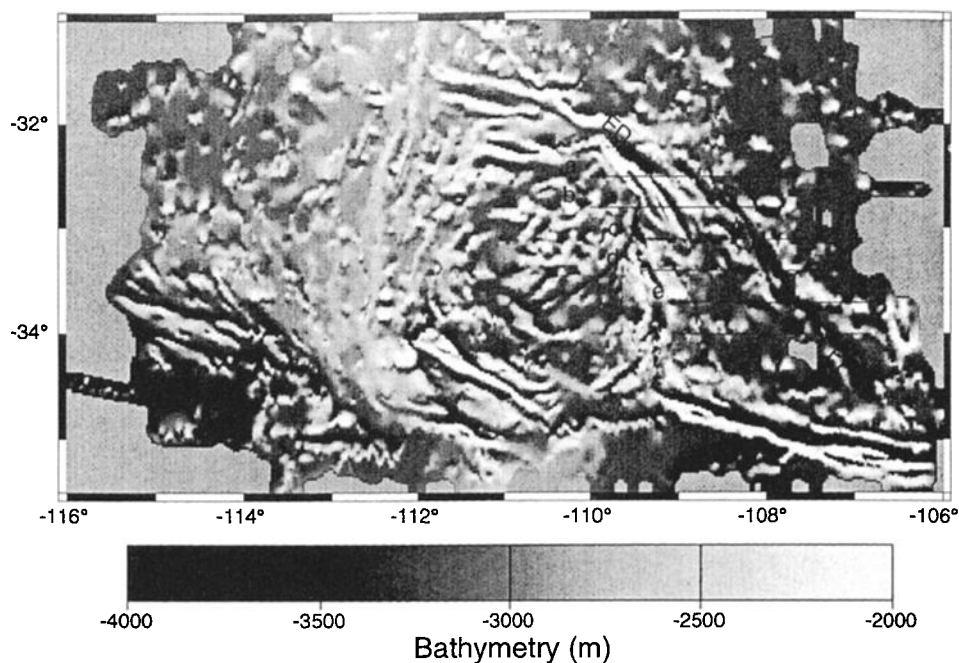
cause of the bathymetry low and mantle Bouguer gravity high at the ridge tip, as modeled by *Hooft et al.* [1995], the local ridge tip bathymetry and gravity signals should be similar to those at the pseudofault. This is not the case, as the active rift tips bounding microplates are 2–3 km deeper than their pseudofault traces [*Martinez et al.*, 1991; *Naar et al.*, 1991; *Bird et al.*, 1998]. Thus the Juan Fernandez gravity data indicate propagating rift tip deeps are generated by a combination of both anomalous crust and dynamic processes.

## 5. Discussion and Summary

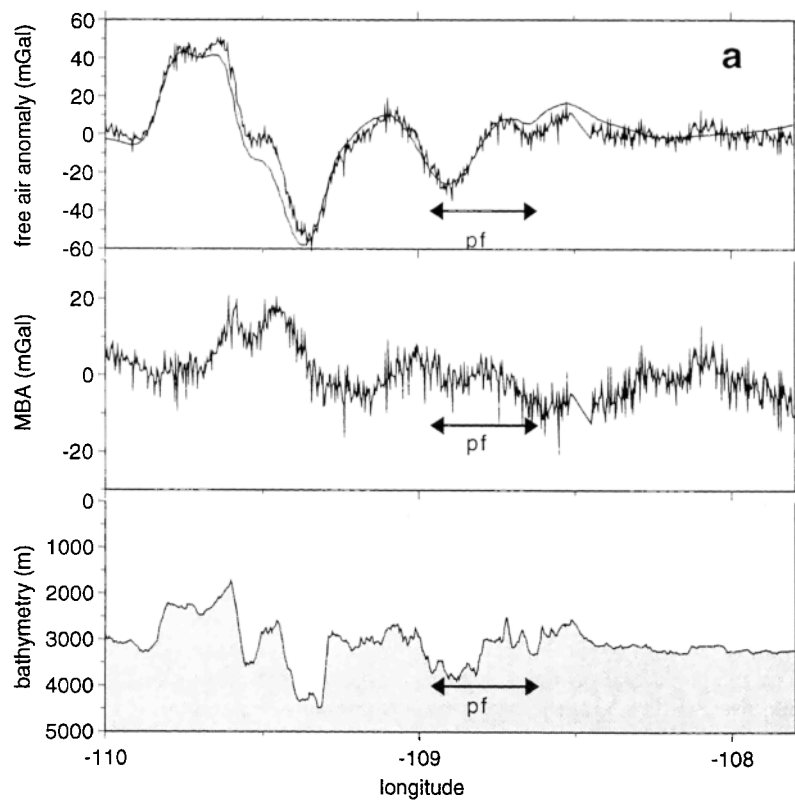
We realize that comparing pseudofaults (and nontransform discontinuity traces) with fracture zones requires some caution. For any propagating rift, there are two pseudofaults that form, an inner and an outer pseudofault [*Hey et al.*,

1989]. They undergo different kinds of deformation histories, such that the inner pseudofault undergoes some kind of pervasive simple shear, whereas the outer one does not, although the older side of the outer pseudofault may record episodes of tectonic rifting associated with the propagation of the rift tip into older lithosphere [*Kleinrock and Hey*, 1989]. There will be no transform shear or motion recorded on the outer pseudofault, whereas on a fracture zone the older side will record any deformation associated with the passage of the inside corner along the entire length of the transform fault. For example, *Tucholke et al.* [1997] found the mantle Bouguer highs on the older side of the nontransform discontinuity traces, suggesting an asymmetry in crustal thinning (thinner on the older side of the traces) in their mid-Atlantic study area. In our study areas in the Pacific basin (Figures 2–5), anomalous crust appears to be more symmetric





**Figure 7.** Shaded relief bathymetric map of the East Ridge axis, Endeavor Deep, and eastern outer pseudofault region of the Juan Fernandez microplate [Bird *et al.*, 1998]. Azimuth of illumination is from the northeast ( $45^\circ$ ); a-f indicate location of profiles shown in Figures 8a-8f, respectively. ED, Endeavor Deep. The pseudofault indicated in Figure 8 extends from ED to PF.



**Figure 8.** Profiles a-f crossing the outer pseudofault to the east of the Juan Fernandez microplate. All profiles use same distance scale on the x axis. Here pf indicates pseudofault. Pseudofault locations were identified from multibeam bathymetry, GLORIA side-scan data, and magnetic anomaly data [Bird *et al.*, 1998]. (top) Jagged line indicates shipboard free air gravity, and smooth line shows theoretical gravity assuming uniform crustal thickness (6 km), crustal density ( $2700 \text{ kg/m}^3$ ) and mantle density ( $3200 \text{ kg/m}^3$ ). (middle) Mantle Bouguer anomalies computed by subtracting uniform crustal thickness model from shipboard gravity. (bottom) Bathymetry.

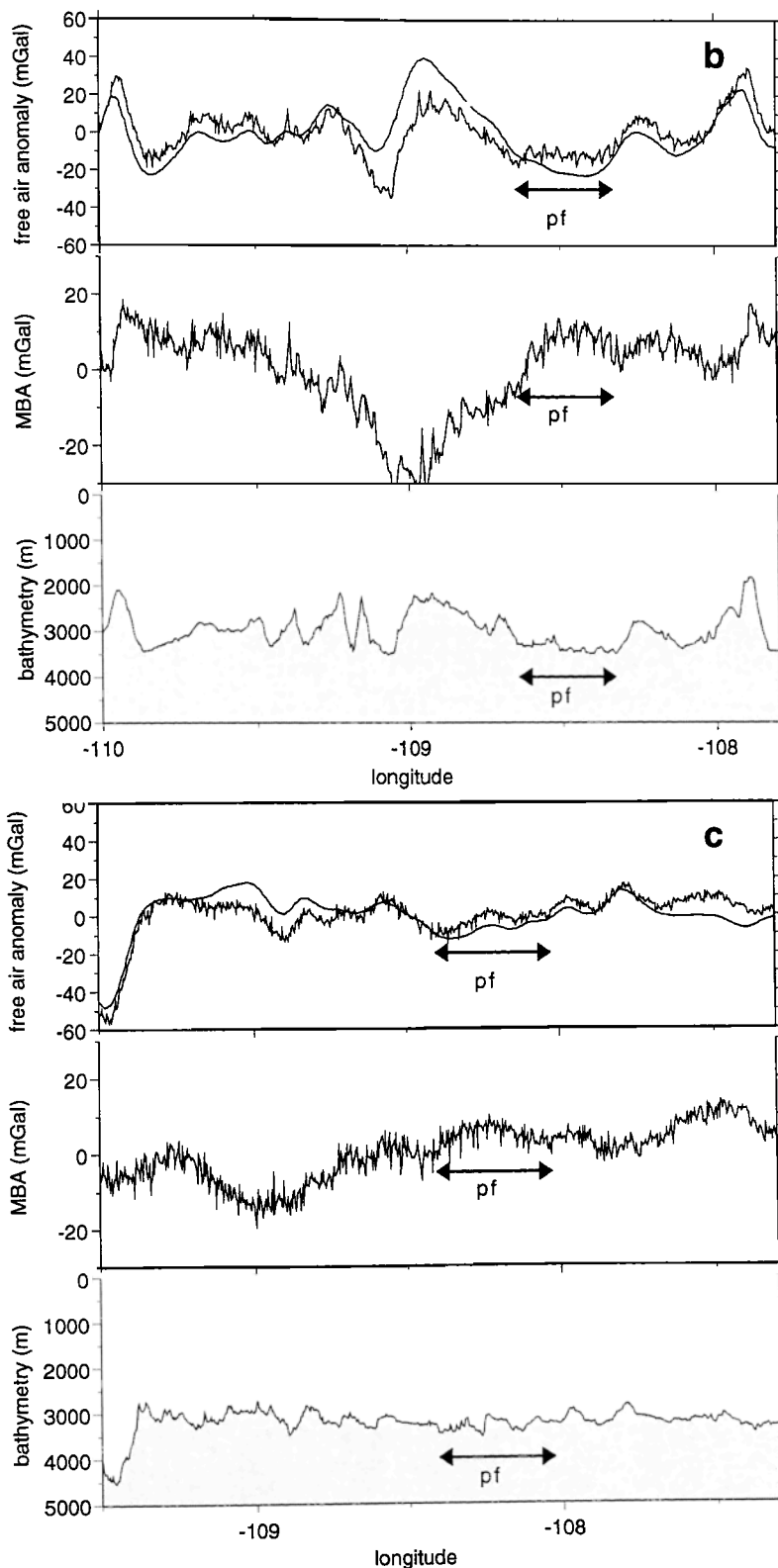


Figure 8. (continued)

with respect to the location of the pseudofaults (both outer and inner). However, the data we use in our study are of lower resolution than those of *Tucholke et al.* [1997], and thus we cannot rule out asymmetric patterns of thin and/or dense crust along the pseudofaults we have investigated here.

1. The amplitude and the shape of the altimetry gravity

signal over pseudofaults bounding Pacific microplates in fast spreading environments more closely resemble those over slow spreading fracture zones than those over fast spreading fracture zones. For pseudofaults with ~5-6 m.y. age offsets the gravity signals are fairly symmetric ~30-40 mGal lows and, in some places, have flanking highs (Figures 2 and 3).

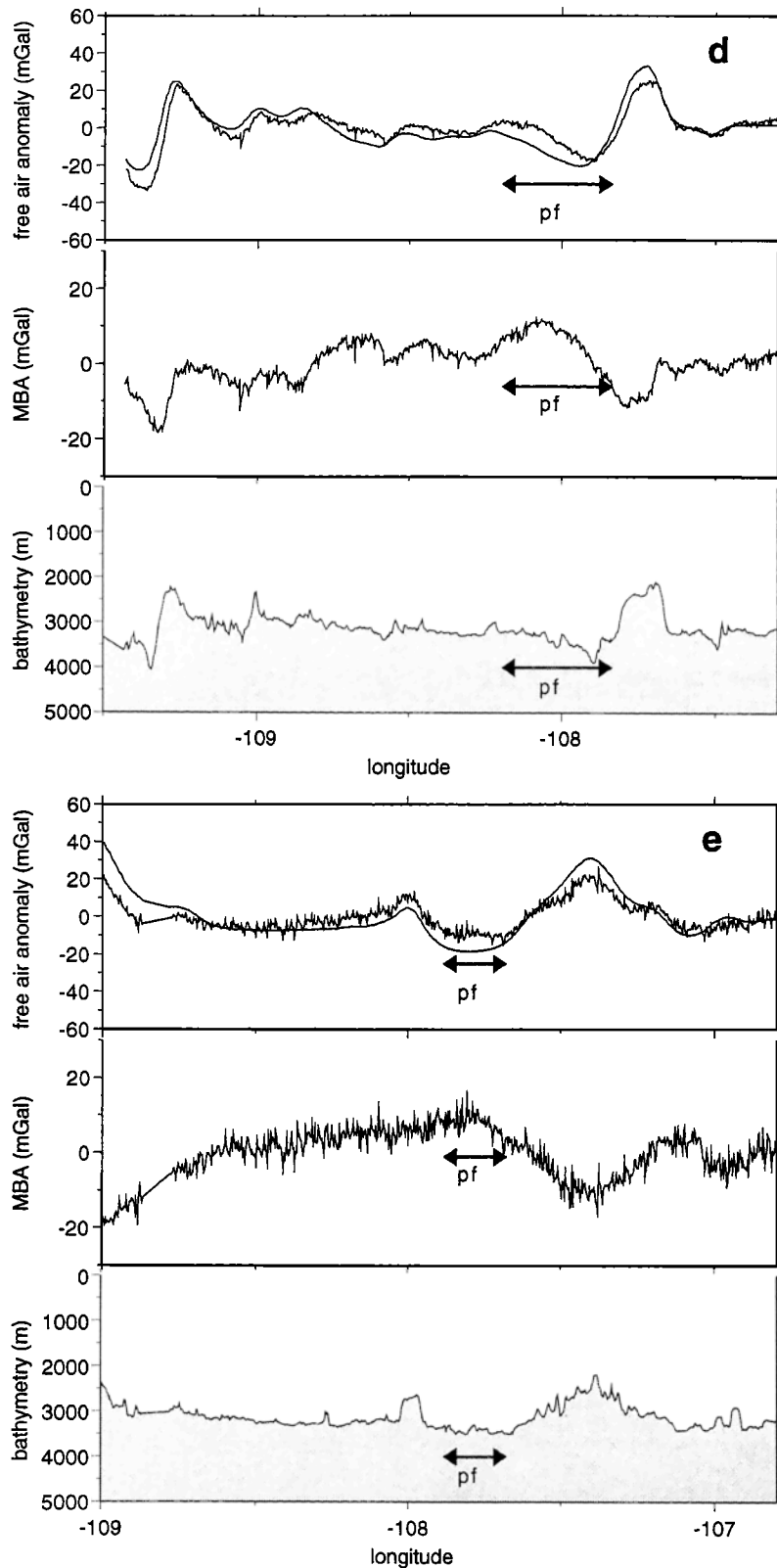


Figure 8. (continued)

Slow spreading fracture zones with this age offset have 30-50 mGal lows of similar form and width.

2. Mantle Bouguer anomalies on the outer pseudofault of the Juan Fernandez microplate are 5-15 mGal highs (Figure 8). The most plausible explanation for this positive anomaly is thin and possibly unusually dense crust near the

pseudofault. The mantle Bouguer anomalies at the pseudofault are similar to those observed on comparable age offset nontransform discontinuities on the mid-Atlantic ridge. Thus accretion processes at rift tips at both pseudofaults and nontransform discontinuities may be fundamentally similar.

3. On the microplate pseudofaults examined here the

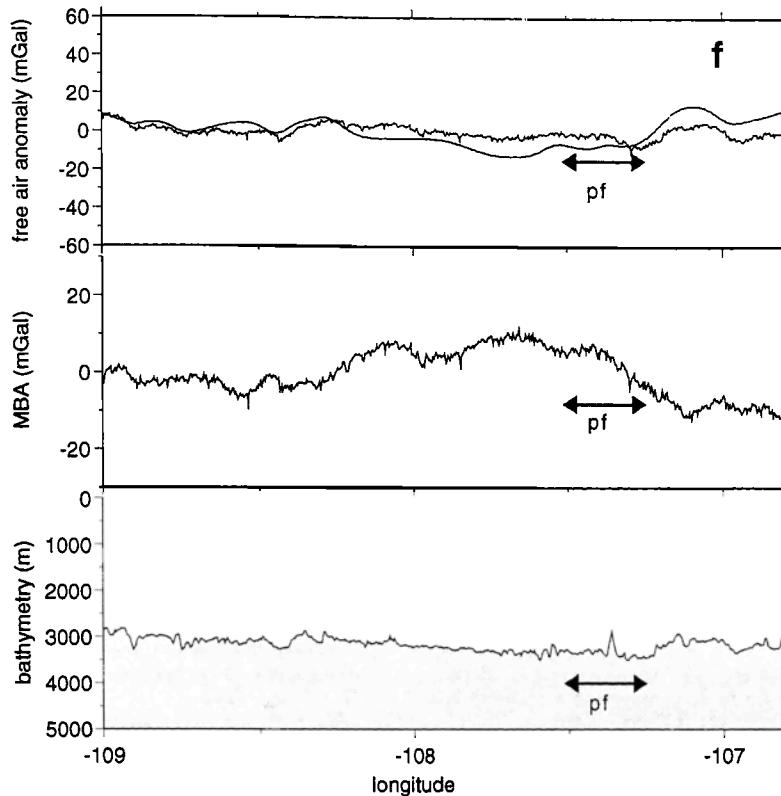


Figure 8. (continued)

amplitude of the pseudofault gravity low is greater for larger age offsets (Figures 2-4). Thus it appears that the amplitude of the pseudofault gravity signal could potentially serve as a rough gauge of age offset in magnetically quiet zones. This potential age-offset estimating technique could be readily tested by dating cores on both sides of a pseudofault.

4. Positive mantle Bouguer anomalies over the Juan Fernandez pseudofault are interpreted as a signature of thin and possibly denser than average crust. These mantle Bouguer anomalies and GLORIA imagery that shows no strong evidence for lava flow infilling of the active deep at the Endeavor Deep [Bird *et al.*, 1996] suggest that anomalous crust forms at the active deep and is preserved at the pseudofault rather than subsequently filled over by lava flows. This, in turn, suggests that the Pito and Endeavor Deeps are probably a result of both thin (and perhaps dense) crust [Martinez *et al.*, 1991; Hooft *et al.*, 1995] and dynamic effects [Phipps Morgan and Parmentier, 1986] as neither model by itself can explain the gravity, bathymetry, and GLORIA side-scan patterns at both the active deep and along the older portions of the pseudofaults.

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