GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO 14, PAGES 1913-1916, JULY 15, 1995

Geoid data and thermal structure of the oceanic lithosphere

W. Philip Richardson and Seth Stein
Department of Geological Sciences, Northwestern University, Evanston,

Carol A. Stein
Department of Geological Sciences, University of Illinois at Chicago, Chicago,

Maria T. Zuber
Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore and Geodynamics
Branch, NASA Goddard Space Flight Center, Greenbelt,

Abstract. A long-standing question is whether old oceanic lithosphere continues cooling as the boundary layer of a halfspace or approaches thermal equilibrium, as modeled by a finite thickness plate. Although the latter is the most direct inference from seafloor depths and heat flow, other explanations have been proposed We investigate this issue using published results for the derivative of the oceanic geoid with age estimated from geoid offsets across fracture zones Such data have not been used extensively in analyses of the thermal evolution of the lithosphere, primarily because they are inconsistent with two commonly used thermal models: a halfspace or a 125-km-thick plate. Recent studies, however. find that depth and heat flow data are better fit by a thinner (95 km) plate model We thus compile published geoid slope results. and find that these data, though scattered. can discriminate between the models Geoid slope changes with age. rather than being constant as predicted for a cooling halfspace This variation is greater than predicted for a thick plate and is better fit by a thin plate. Geoid data should thus be useful for improving thermal models of the lithosphere

Introduction

Much effort has been directed toward describing the thermal evolution of oceanic lithosphere. Because temperatures at depth are not directly measurable, simple models have been proposed as general descriptions of average thermal structure as a function of age. Young lithosphere can be modeled as the upper boundary layer of a cooling halfspace. because seafloor depth and heat flow vary approximately with the square root of lithospheric age. However, for ages >~70 Myr depth and heat flow "flatten", varying more slowly with age than for a halfspace It is thus often assumed that halfspace cooling stops for older ages because heat added from below balances heat lost at the seafloor The plate model, a simple common description for this perturbation, uses an isothermal base of the lithosphere to model its thermal equilibration (Figure 1) [McKenzie, 1967]. The plate model fits the data reasonably well, but does not directly describe how heat is added [e.g. Parsons and McKenzie, 1978; Fleitout and Doin, 1994]. Although plate and halfspace models are the same for young ages, they differ for ages old enough that the basal condition has an effect.

Other explanations for the flattening have been offered In one, flattening is analogous to that associated with mantle plumes [e.g. Heestand and Crough, 1981] and reflects the dynamic pressure of the plumes, with some heating of the lithosphere. Another possibility is that volcanism masks subsidence due to halfspace cooling. A third possibility is that depths are perturbed by asthenospheric flow [Schubert et al, 1978]

Because depth and heat flow vary enough between locations that multiple mechanisms may operate, the issue is which effect is primary for old lithosphere. The need to address this question is illustrated by the fact that both halfspace models and a commonly used 125-km-thick plate model, denoted PSM [Parsons and Sclater, 1977], systematically overpredict depths and underpredict heat flow for old lithosphere, causing apparent "anomalies." Recent inversion of depth and heat flow data [Stein and Stein, 1992], however, found that these "anomalies" are reduced significantly by a plate model termed GDH1 with a thickness of 95 km, thinner than previously assumed (Figure 2). This result brings to mind analyses showing that the derivative with age of the geoid, an equipotential of the gravity field, was

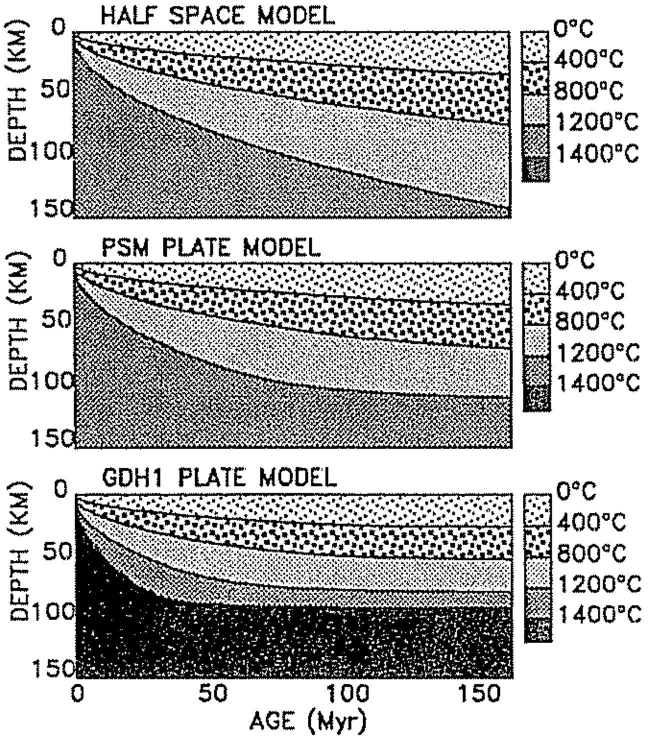

Figure 1. Isotherms for three thermal models. The lithosphere continues cooling for all ages in a halfspace model, equilibrates for ~125 Myr lithosphere in the PSM thick (125 km) plate model, and equilibrates for ~70 Ma lithosphere in the GDH1 thin (95 km) plate model.

Paper number 95GL01595
0094-8534/95/95GL-01595$03.00

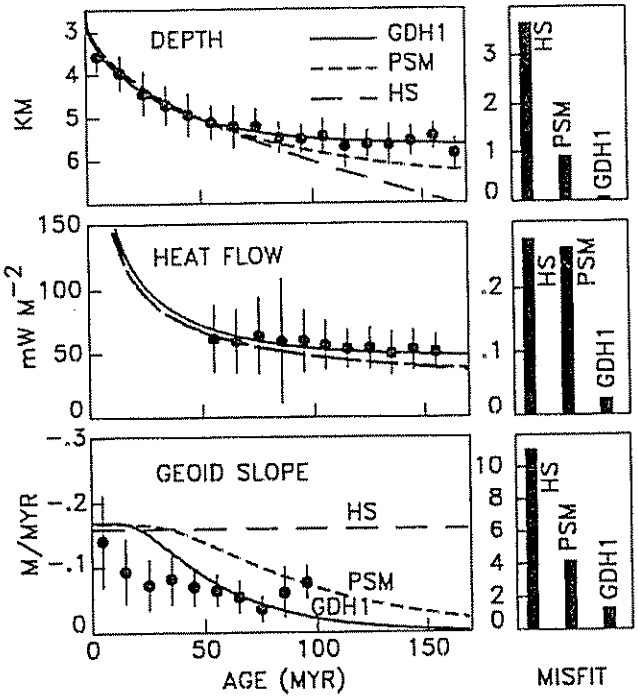

Figure 2. Comparison of thermal model predictions to data not used in deriving models. Global depths exclude hotspot swells [Kido and Seno, 1994]. Global heat flow are from Stein and Stein [1992], who used only North Pacific and Northwest Atlantic values to derive model GDH1. Heat flow data for ages less than 50 Myr are not used as they appear biased by hydrothermal circulation. Halfspace (HS) and PSM model predictions for heat flow are similar. Geoid slopes are from Figure 4b. The GDH1 thin-plate model fits better all three data types than either the halfspace or PSM thick-lithosphere models.

better fit by a thin (~100 km) lithosphere [Detrick, 1981; Cazenave, 1984]. These analyses drew little attention because they were inconsistent with the prevailing models, a halfspace or a thick plate. Given the recent depth and heat flow results, it seems natural to reexamine whether geoid data can help discriminate between the different thermal models.

Surface Observables and Thermal Models

The primary constraints on the temperature T as a function of age t and depth z in the lithosphere come from three surface observables: ocean depth, heat flow, and geoid slope. Thermal models are developed using depth and heat flow data, and then compared to both geoid data and other data (earthquake depths, seismic velocity and attenuation, flexural response) that reflect the geotherm more indirectly, via assumptions about rheology and other physical properties. The surface observables constrain combinations of the primary thermal model parameters: plate thickness a, basal temperature T_m, and coefficient of thermal expansion α (Table 1). Halfspace models can be treated as infinitely thick plates. Although at young ages depth and geoid slope do not depend on plate thickness and cannot distinguish between plate and halfspace models, data at older ages are sensitive to differences between models (Figures 1, 2).

In plate models the geotherm evolves to a steady-state linear gradient, so depth, heat flow, and geoid slope tend to asymptotic values. Depth (i.e. subsidence relative to the ridge) is proportional to the net thermal density anomaly and thus the integrated geotherm. Because this integral is proportional to heat lost as the plate cools, a thin-plate model predicts shallower depths for old lithosphere than thick-plate or halfspace models. Heat flow is proportional to the seafloor geotherm, so a thin-plate model predicts higher asymptotic heat flow than thick-plate or halfspace models. The geoid depends on the depth-weighted integral of the thermal density anomaly, and thus the weighted integral of the geotherm [Cazenave, 1984]. The derivative of the geoid with age is constant for a halfspace model. For a plate model, the predicted slope is the same as for a halfspace at young ages, but "rolls off" at older ages at a rate depending inversely on plate thickness. This deviation from halfspace behavior reflects the lithosphere approaching equilibrium thickness at older ages, and is analogous to "flattening" of depth and heat flow.

As plate and halfspace models differ in bottom boundary conditions, the predicted temperatures differ most at depth. Hence geoid slope, which is weighted by depth, is in principle the best of the observables for discriminating between models. Ocean depth is second, whereas heat flow is poorest because it reflects near-surface temperature. Figure 2 illustrates this effect: predicted geoid slopes for the models differ significantly at younger ages than do depths, whereas heat flow differs least.

The situation is complicated because the geoid is dominated by long-wavelength features thought to reflect deep mass variations due to mantle convection. Thus geoid slope is easily estimated near ridges but is harder to obtain consistent estimates for at older ages. As a result, geoid slope is generally estimated from the change in the geoid across fracture zones, which juxtapose lithosphere of two different ages.

Geoid Slope Data

We compiled published results for geoid slope estimated from the ratio of the geoid offset measured by satellite altimetry across a fracture zone to the age difference, as a function of the mean age of the two sides. Only studies reporting explicitly both geoid offset (or slope) and age were used. These studies use various processing techniques in an attempt to separate the geoid effect of the age contrast from long wavelength components, presumably reflecting sublithospheric mantle flow, and shorter wavelength components, which may reflect flexure, thermal stresses, lateral asthenospheric flow, and other processes near the fracture zone [Sandwell, 1984; Parmentier and Haxby, 1986; Robinson et al., 1988; Wessel and Haxby, 1990].

Due to processing differences, estimates for a given fracture zone vary, as illustrated by Figure 3 for the Mendocino Fracture Zone. The three studies use data from the Seasat altimeter and many of the same profiles, but different processing. Despite the scatter, an overall trend appears, especially because the two most discordant estimates at the oldest ages (107 Myr, 133

Table 1. Constraints on thermal models $T(z,t)$

OBSERVABLE	PROPORTIONAL TO	REFLECTS
Young Ocean Depth	$\int T(z,t)\,dz$	αT_m
Old Ocean Depth	$\int T(z,t)\,dz$	$\alpha T_m a$
Old Ocean Heat Flow	$\frac{\partial T(z,t)}{\partial z}\Big\|_{z=0}$	T_m / a
Geoid Slope	$\frac{\partial}{\partial t}\int zT(z,t)\,dz$	$\alpha T_m \exp(-t/a^2)$

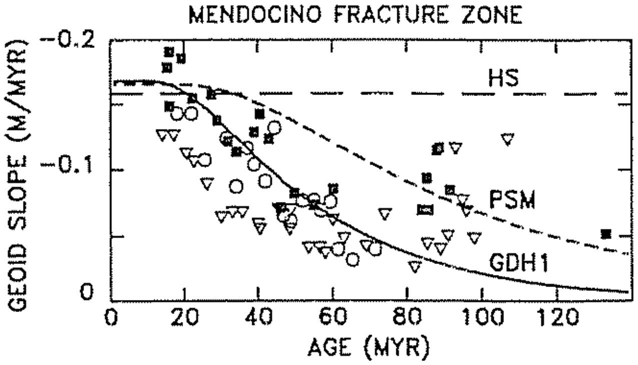

Figure 3. Geoid slope data across the Mendocino Fracture Zone compared to predictions of thermal models. Data from: Detrick [1981] (circles), Sandwell and Schubert [1982] (squares), and Marty et al. [1988] (triangles). Despite scatter, the data are better fit by the "roll-off" for a plate model than the constant slope for a halfspace. The GDH1 thin-plate model fits better than the PSM thick-plate model.

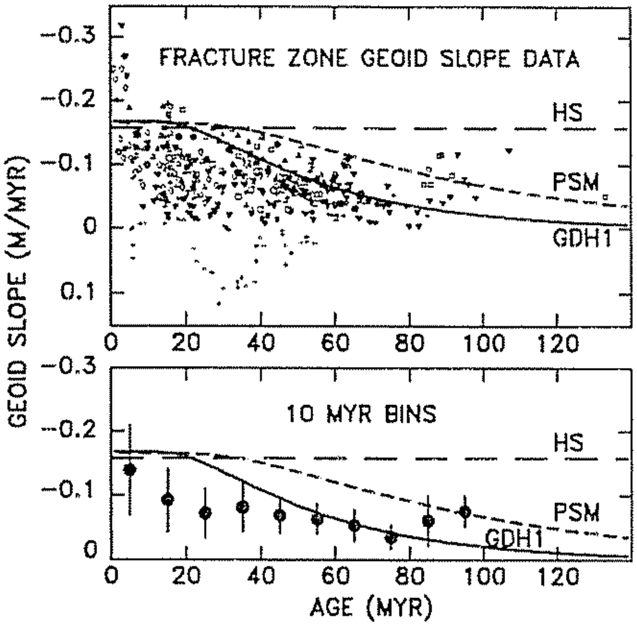

Figure 4. *Top*: Geoid slope data across various fracture zones and model predictions. Data from: Detrick [1981] (closed circles), Cazenave et al. [1982] (open circles) Sandwell and Schubert [1982] (squares), Cazenave et al. [1983] (stars), Cazenave [1984] (diamonds), Driscoll and Parsons [1988] (open triangles), Marty et al. [1988] (closed triangles), Freedman and Parsons [1990] (crosses). *Bottom*: Data in 10-Myr bins, excluding those with wrong (positive) sign and questionable two oldest points from the Mendocino. χ^2 misfits (Figure 2) show that GDH1 thin-plate model fits ~8 times better than the halfspace model, and ~3 times better than the thick-plate PSM model.

Myr) are questionable [Sandwell and Schubert, 1982; Marty and Cazenave, 1988]. Figure 4a shows the results for other fracture zones. Figure 4b shows these data in 10-Myr bins, excluding those with the wrong (positive) sign, following the authors' suggestion that these data were anomalous, and the two questionable oldest points from the Mendocino.

We compared these data to three thermal models: a halfspace (HS) with parameters from Carlson and Johnson [1994], the PSM thick-plate model, and the GDH1 thin-plate model. This comparison (Figures 2 and 4b) shows three points, despite the scatter in the data. First, geoid slope varies with age, rather than being constant as predicted by a halfspace model. Second, this variation is more rapid than predicted for the thick-plate PSM model, but is closer to that predicted for the GDH1 model with a thinner lithosphere. The χ^2 misfits (Figure 2) illustrate these points; compared to the GDH1 value (1.3), the halfspace value (11.1) is about eight times worse, and the PSM value (4.2) is about three times worse. Third, all three models misfit data, especially for ages younger than ~30 Myr.

Discussion

These results argue for using geoid data to investigate thermal evolution of oceanic lithosphere. Even this non-ideal data set, a composite of different studies, gives a picture consistent with that from depth and heat flow data. Most significantly, although no model fits geoid data very well, the GDH1 plate model does much better than a halfspace. This result is robust to the choice of halfspace model parameters, because slope at young ages is constrained at ~-0.15 m/Myr both by near-ridge (as opposed to fracture zone) observations and the requirement that model parameters match depth data for young ages. As a result, reasonable halfspace models make similar predictions and do not fit the data as well as a plate model.

Because depth, geoid, and heat flow are better fit by a plate model than a halfspace, they collectively favor old lithosphere approaching thermal equilibrium. Different data yield similar results, although the specific misfit values vary. For example, GDH1 does better than a halfspace for various depth data not used to derive the model [Johnson and Carlson, 1992; Stein and Stein, 1993; Shoberg et al., 1993; Kido and Seno, 1994], some of which attempt to exclude depths shallowed by hotspot tracks. Hence in our view old lithosphere approaches thermal equilibrium, of which a plate model like GDH1 is a reasonable (though simplified and non-unique) description.

It is, of course, possible to argue that a halfspace model is correct, but depth, heat flow, and geoid data are all non-thermally perturbed. Because the simple plate model does better for all three data types, this alternative seems contrived and contrary to Occam's principle[1]. Moreover, to date no such alternative model has been explicitly formulated or tested with all three data types. The one non-thermal perturbation model that has been explicitly tested with depth and heat flow data [Phipps Morgan and Smith, 1992, 1994] does worse than plate models [Stein and Stein, 1994].

Similarly, the fact that the thin-plate GDH1 model fits about three times better than the thick-plate PSM model is striking, because no geoid data were inverted to derive GDH1. Hence we regard it as a good average description of the thermal evolution of the oceanic lithosphere, although no such simple model can describe the full complexity of the process.

The fact that a thin-plate model developed by inverting depth and heat flow fits geoid data reasonably well also gives insight into the geoid data. Because geoid slopes were not fit well either by a halfspace or thick-plate model, it was natural to assume that these data were biased and of little value. However, in view of our result that data at older ages are reasonably consistent with depth and heat flow data, perturbing processes

---

[1] "Assumptions should not be multiplied unnecessarily", William of Occam, c. 1320 AD

need be postulated primarily for the younger offsets and the geoid data can be used to investigate them. This situation is analogous to that for heat flow data, which are consistent with depth data at older ages, so the misfit at young ages can be plausibly attributed to hydrothermal flow and used to study it.

The other reason for not using geoid to constrain lithospheric thermal models, scatter in the data, seems overemphasized. As for depth and heat flow, the mean values vary smoothly enough with age to be useful constraints on thermal models. The scatter has two causes: processing differences between studies and intrinsic geological variability. Although the intrinsic portion of the scatter cannot be eliminated by more consistent data, it does not preclude making useful thermal models from the mean values, while recognizing that the scatter reflects effects other than age-dependent thermal structure. To emphasize this, we use standard deviations of the data in each age range, rather than standard deviations of the mean. For example, because long fracture zones are few, all data older than 80 Myr are from the Mendocino and it is not clear that the unmodeled change in data trend is a global phenomenon. Nonetheless, even for this composite data set, the standard deviation divided by the mean of geoid data is no worse than for heat flow, though greater than for depths.

In summary, existing geoid data suggest the value of combining consistently-processed geoid data sets with depth and heat flow in studying thermal evolution of the lithosphere. Fortunately, new data is becoming available, and improved analysis techniques are being developed [e.g. Gibert and Courtillot, 1990]. In particular, Doin et al. [1992] find that ocean-wide geoid data indicate the lithosphere deviating from halfspace cooling, in accord with fracture zone results. Hence geoid data, together with depth and heat flow, favor old lithosphere approaching thermal equilibrium, as described approximately by the plate model. Improved geoid data and analysis can thus help improve our understanding of how heat is added from below, and the causes of variations about the mean thermal state.

Acknowledgements. Much of this research was conducted at the Laboratory for Terrestrial Physics, NASA Goddard Space Flight Center, by Richardson as a summer student and the Steins as visiting scientists. Additional support came from NASA grants NAG 5-1944 and NSF grant EAR-9022476. We thank R. Phillips and N. Sleep for helpful reviews.

References

Carlson, R., and H. Johnson, Thermal evolution of the oceanic upper mantle, *J. Geophys. Res.*, *99*, 3201–3214, 1994.

Cazenave, A., Thermal cooling of the lithosphere: constraints from geoid data, *Earth Planet. Sci. Lett.*, *70*, 395–406, 1984.

Cazenave, A., B. Lago, and K. Dominh, Geoid anomalies over the Northeast Pacific fracture zones from satellite altimeter data, *Geophys. J. R. astron. Soc.*, *69*, 15–31, 1982.

Cazenave, A., B. Lago, and K. Dominh, Thermal parameters of the oceanic lithosphere inferred from geoid height data, *J. Geophys. Res.*, *88*, 1105–1118, 1983.

Detrick, R., Geoid anomalies across the Mendocino Fracture Zone, *J. Geophys. Res.*, *86*, 11,751–11,762, 1981.

Doin, M., L. Fleitout, and P. Colin, Geoid anomalies and deep structure of continental and oceanic lithospheres (abstract), *Eos Trans. AGU, Fall supplement*, 578, 1992.

Driscoll, M., and B. Parsons. Cooling of the oceanic lithosphere - evidence from geoid anomalies across fracture zones, *Earth Planet. Sci. Lett.*, *88*, 289–307, 1988.

Fleitout, L., and M. Doin, Evolution of oceanic lithosphere (abstract), *Eos Trans. AGU, Fall supplement*, 648, 1994.

Freedman, A., and B. Parsons, Geoid anomalies over Atlantic fracture zones, *Earth Planet. Sci. Lett.*, *100*, 18–41, 1990.

Gibert, D., and V. Courtillot, Thermal isostasy in the South Atlantic, *Geophys. Res. Lett.*, *17*, 251–254, 1990.

Heestand, R., and S. Crough, Effect of hot spots on the oceanic age-depth relation, *J. Geophys. Res.*, *86*, 6107–6114, 1981.

Johnson, H., and R. Carlson, The variation of seafloor depth with age, *Geophys. Res. Lett.*, *19*, 1971–1974, 1992.

Kido, M., and T. Seno, Dynamic topography compared with residual depth anomalies in oceans and implications for age-depth curves, *Geophys. Res. Lett.*, *21*, 717–720, 1994.

Marty, J., and A. Cazenave, Thermal evolution of the lithosphere beneath fracture zones inferred from geoid anomalies, *Geophys. Res. Lett.*, *15*, 593–596, 1988.

Marty, J., A. Cazenave, and B. Lago, Geoid anomalies across Pacific fracture zones, *Geophys. J.*, *93*, 1–23, 1988.

McKenzie, D., Some remarks on heat flow and gravity anomalies, *J. Geophys. Res.*, *72*, 6261–6273, 1967.

Parmentier, E., and W. Haxby, Thermal stresses in the oceanic lithosphere: evidence from geoid anomalies at fracture zones, *J. Geophys. Res.*, *91*, 7193–7204, 1986.

Parsons, B., and D. McKenzie, Mantle convection and the thermal structure of the plates, *J. Geophys. Res.*, *83*, 4485–4496, 1978.

Parsons, B., and J. Sclater, An analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res.*, *82*, 803–827, 1977.

Phipps Morgan, J., and W. Smith, Flattening of the sea-floor depth age curve as a response to asthenospheric flow, *Nature*, *359*, 524–527, 1992.

Phipps Morgan, J., and W. H. F. Smith, Correction to "Flattening of the sea-floor depth-age curve as a response to asthenospheric flow", *Nature*, *371*, 83, 1994.

Robinson, E., B. Parsons, and M. Driscoll, Effect of a shallow low-viscosity zone on mantle flow, geoid anomalies and depth-age relationships at fracture zones, *Geophys. J. R. astron. Soc.*, *93*, 25–43, 1988.

Sandwell, D., Thermomechanical evolution of fracture zones, *J. Geophys. Res.*, *89*, 11,401–11,413, 1984.

Sandwell, D., and G. Schubert. Geoid height-age relation from SEASAT altimeter profiles across the Mendocino fracture zone, *J. Geophys. Res.*, *87*, 3949–3958, 1982.

Schubert, G., D. Yuen, C. Froidevaux, L. Fleitout, and M. Souriau, Mantle circulation with partial shallow return flow *J. Geophys. Res.*, *83*, 745–758, 1978.

Shoberg, T., C. Stein, and S. Stein, Constraints on lithospheric thermal structure for the Indian Ocean from depth and heat flow data. *Geophys. Res. Lett.*, *20*, 1095–1098, 1993.

Stein, C., and S. Stein, Global variation in oceanic depth and heat flow with lithospheric age, *Nature*, *359*, 123–129, 1992.

Stein, C., and S. Stein, Constraints on midplate swells from global depth-age and heat flow-age models, in *Geophys. Monogr. 76*, edited by M. Pringle, W. Sager, W. Sliter and S. Stein, pp. 53–76, AGU, Washington, D. C., 1993.

Stein, C., and S. Stein, Comparison of plate and asthenospheric flow models for the thermal evolution of oceanic lithosphere, *Geophys. Res. Lett.*, *21*, 709–712, 1994.

Wessel, P., and W. Haxby, Thermal stress, differential subsidence, and flexure at oceanic fracture zones, *J. Geophys. Res.*, *95*, 375–391, 1990.

W. Philip Richardson and Seth Stein, Department of Geological Sciences, Northwestern University, Evanston, IL 60208

Carol Stein, Geological Sciences (m/c 186), University of Illinois at Chicago, 845 W. Taylor St., Chicago, IL 60607-7059

Maria Zuber, Earth and Planetary Sciences, Johns Hopkins University, Baltimore MD 21218 and Geodynamics Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771

(Received Jan. 23, 1995; accepted Mar. 3, 1995.)