

CONSTRAINTS ON LITHOSPHERIC THERMAL STRUCTURE  
FOR THE INDIAN OCEAN FROM DEPTH AND HEAT FLOW DATA

Tom Shoberg<sup>1</sup>, Carol A. Stein<sup>2</sup> and Seth Stein<sup>1</sup>

**Abstract.** Models for the thermal evolution of oceanic lithosphere are primarily constrained by variations in seafloor depth and heat flow with age. These models have been largely based on data from the Pacific and Atlantic Ocean basins. We construct seafloor age relations for the Indian Ocean which we combine with bathymetric, sediment isopach and heat flow data to derive curves for depth and heat flow versus age. Comparison of these curves with predictions from three thermal models shows that they are better fit by the shallower depths and higher heat flow for the GDH1 model, which is characterized by a thinner and hotter lithosphere than previous models.

### Introduction

Variations in seafloor depth and heat flow with lithospheric age provide the primary constraints on models of thermal evolution of oceanic lithosphere, because these surface observables reflect the evolution of the geotherm as the lithosphere ages and cools. The subsidence and hence seafloor depth depend on the temperature integrated with depth in the lithosphere, whereas the heat flow depends on the near surface temperature gradient.

These variations are grossly described by a model in which the oceanic lithosphere behaves as the cold upper boundary layer of a cooling halfspace such that depth and heat flow vary as  $\text{age}^{1/2}$  and  $\text{age}^{-1/2}$ , respectively [Davis and Lister, 1974]. However, because for lithosphere older than 70 Ma the depth and heat flow data "flatten", varying more slowly with age, the lithosphere is typically modeled as a cooling plate [McKenzie, 1967]. Plate models are characterized by the plate thermal thickness  $a$  which the lithosphere approaches at old ages, and the temperature  $T_m$  at a depth equal to the plate thickness. The plate model behaves like a cooling halfspace for young ages, until an age old enough that the thermal effect of the lower boundary condition causes flattening. The isothermal lower boundary condition models the additional heat input from below, which inhibits the halfspace from cooling for older ages, and thus causes flattening.

The commonly used plate model is a  $125 \pm 10$  km thick plate with a  $1350 \pm 275^\circ\text{C}$  basal temperature [Parsons and Sclater, 1977]. Although this model (here denoted as PSM) fits the data better than a halfspace model, it generally

overpredicts depths and underpredicts heat flow for lithosphere older than 70-100 Ma [e.g. Von Herzen et al., 1989; Stein and Stein, 1992; Johnson and Carlson, 1992]. As a result, areas with depth or heat flow that are anomalous with respect to the PSM model often are similar to the average lithosphere of that age.

A recent joint inversion of depth and heat flow data yielded a best-fitting plate model with a thickness of  $95 \pm 15$  km and a basal temperature of  $1450 \pm 250^\circ\text{C}$  [Stein and Stein, 1992]. The primary feature of this model, GDH1 (for Global Depth and Heat flow), is a thinner lithosphere than in PSM. Because the geotherm is proportional to  $T_m/a$ , the thinner lithosphere gives a steeper geotherm, higher temperatures at depth, and higher heat flow. Similarly, the thinner lithosphere predicts less subsidence, which is proportional to the heat lost in cooling, and hence the product  $T_m \cdot a$ . As a result, GDH1 significantly better fits the depth and heat flow data. The improved fits reflect the predicted higher temperature gradient that results largely from the thinner plate, and would occur even if the basal temperature were not somewhat higher than in PSM.

The GDH1 and PSM models were generated using only data from the North Atlantic and North Pacific. Data from the Indian Ocean would provide an independent test of the models, but a depth-age curve for the Indian Ocean has not been presented in the literature. We thus generate such a curve and compare depth and heat flow data with predictions of the "thin-hot" GDH1 model, the "thick-cold" PSM model, and the "thicker-colder" halfspace model.

### Analysis

Oceanic lithosphere in the Indian Ocean basin includes portions of the Indian, Australian, Africa, and Antarctic plates. A seafloor age map (Figure 1) was constructed using magnetic anomaly identifications from Cande et al. [1989] and Fullerton et al. [1989]. We estimated age boundaries for which no lineations were recorded by using plate rotation models [Patriat and Segoufin, 1988; Royer et al., 1988; Royer and Sandwell, 1989; Royer and Chang, 1991]. For further interpretation we followed Royer and

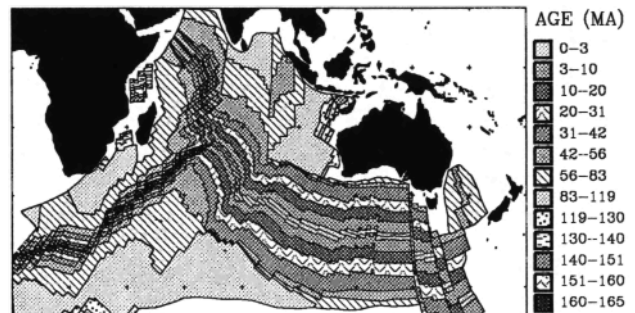


Fig. 1: Age provinces of the Indian Ocean lithosphere.

<sup>1</sup> Department of Geological Sciences, Northwestern University, Evanston, IL

<sup>2</sup> Department of Geological Sciences, University of Illinois at Chicago, Chicago, IL

Copyright 1993 by the American Geophysical Union.

Paper number 93GL00985

0094-8534/93/93GL-00985\$03.00

Schlich [1988], Powell et al. [1988], Fullerton et al. [1989] and Simpson et al. [1979]. The seafloor was divided into age bins based on anomaly numbers, and absolute ages were assigned using the timescale of Harland et al. [1990].

We used the NOAA DBDB5 data set, which contains depths at grid points every 5'. While this data set, which is typically used for depth-age studies, may have some biases due to inadequate sampling, these do not appear excessive for depth-age studies in the Pacific [Phipps Morgan and Smith, 1992; Stein and Stein, 1993].

Points with depths less than 1000 m were deleted, to eliminate continental shelves and islands. We did not use data near the Java Trench, in the Argo Abyssal plain (Figure 2), whose depths may be perturbed by near-trench flexure. We excluded the Tasman Sea, generally considered part of the Pacific. Points within 1° squares were averaged to produce the uncorrected depth data set. A few points are thus averaged across age boundaries, but this effect is second-order compared to the large age bins.

We digitized sediment thickness contours from the isopach maps of Rabinowitz et al. [1988] for the area west of 130°E and Ludwig and Houtz [1979] for the area between 130°E and 170°E. Locations with sediment cover thicker than 5 km, such in the western Somalia Basin, and in the Bay of Bengal, were excluded.

We estimated sediment cover by locating each depth point with respect to the appropriate isopach contour using an algorithm of Bevis and Chatelain [1989]. The basement depth was then found by applying a correction for isostatic unloading of sediment [Le Douaran and Parsons, 1982]. The heat flow data were taken from the data set discussed by Stein and Stein [1992] and separated into the same age bins as the depths.

## Results

Figure 3 shows the mean and median depths for 1° squares within each age bin. The two values are similar. The apparent difference in the uncertainties is largely because the means are shown with one standard deviation

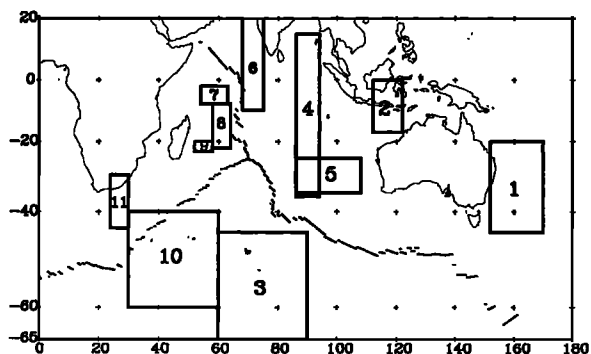


Fig. 2: Map of the Indian Ocean showing the location of areas that were excluded from the entire data set or were treated as perturbed by excess volcanism. Rectangular regions of exclusion were chosen for simplicity. In the primary data set, only the Tasman Sea (1) and Argo Abyssal Plain (2) were excluded. For the "No hot spot" data set, the Kerguelen (3), Ninetyeast Ridge (4), Broken Ridge (5), Chagos-Laccadive Ridge (6), Mascarene Plateau (7) and (8), Reunion (9), Crozet Plateau and Conrad Rise (10), and Agulhas Plateau (11) areas were also excluded.

(ideally 67% of the data), whereas the medians are shown with quartile ranges (50%). For comparison, basement depths from ODP/DSDP drill sites in the Indian Ocean are also shown. These depths, from legs 22, 24, 25, 26, 27 and 119, were corrected for sediments in the same manner.

We compared the depths and heat flow (Figure 3) with the predictions of three thermal models, GDH1, PSM, and a halfspace (HS) model with the PSM thermal parameters and ridge depth. The heat flow misfit is to data with ages older than 50 Ma in order to exclude the effect of hydrothermal circulation. The depth misfit is to data for all ages. The improved fit of GDH1 relative to PSM is comparable to that for PSM relative to the halfspace model.

We also considered the depths after removing anomalously shallow areas (Figure 2) that may reflect excess volcanism. The remaining depths (Figure 3) are somewhat deeper, but the depth-age curve is similar, and significantly better fit by GDH1.

For oceanic lithosphere older than 70 Ma both data sets are generally shallower than the GDH1 predictions. In fact, the full depth dataset and the heat flow for ages greater than 50 Ma are best fit by an 80 km thick plate with a 1450°C basal temperature and coefficient of thermal expansion  $3.0 \times 10^{-5} \text{ } ^\circ\text{C}^{-1}$ . This result is interesting as GDH1 was constructed using depth data that included swells and regions of possible excess volcanism, because their suppression would bias the model to greater depths. As a result, GDH1 could be considered biased somewhat toward shallow depths [Stein and Stein, 1993].

## Discussion

The fact that GDH1 best fits the Indian Ocean depth and heat flow data argues for such a model, in which the lithosphere is thinner and hotter at depth than traditionally thought. This is an independent test of the PSM and GDH1 models, which were derived without Indian Ocean data. We also consider it significant that although no geoid data were used to derive GDH1, it better fits fracture zone geoid data, which reflect a depth-weighted integral of the geotherm [Stein and Stein, 1993].

We thus expect the GDH1 thermal structure to be a better approximation of that within oceanic lithosphere. Both because the data are satisfied by a range of similar plate models [Stein and Stein, 1992; 1993], and the plate model is the simplest model that can fit both heat flow and depth data, we do not ascribe great significance to the details of the predicted temperature structure beyond the general property that it is somewhat hotter at depth than earlier models. We anticipate that a thinner and hotter lithosphere will be a general feature of models found from analysis of depth, heat flow, or geoid data with age.

It is, of course, impossible either to construct a single best model or for a single model to fit the data perfectly. In constructing a model, we chose the form of the model and the data it should fit. GDH1 was constructed using the plate formulation, such that depth and heat flow are fit jointly. Even within this formulation, the best fitting models will differ depending on the data selection and processing (e.g. sediment correction and spatial averaging), the modeling assumptions, and the fitting procedure.

Whether to exclude shallow areas such as swells and hot spot tracks is crucial. The choice is not clear-cut; exclusion of shallow areas inserts a bias about what is "anomalous,"

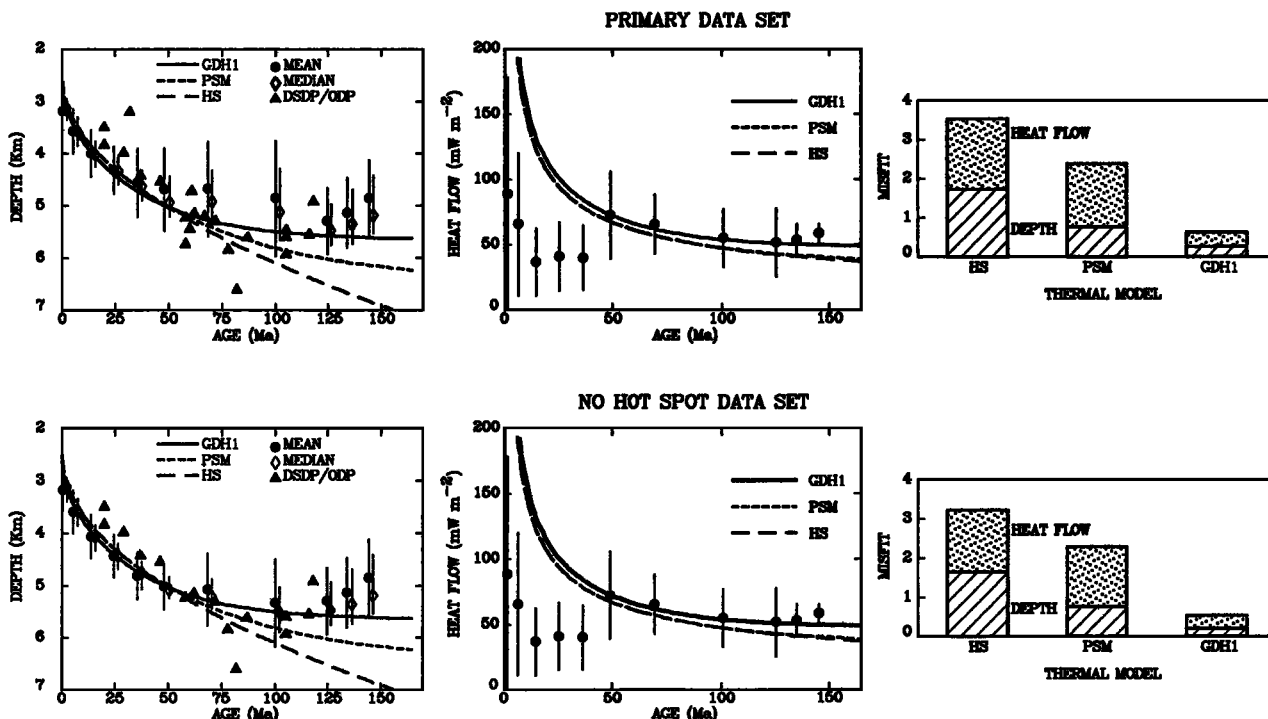


Fig. 3: (top) Depth-age curves, heat flow-age curves, and Reduced- $\chi^2$  misfits for the primary Indian Ocean data set compared with predictions of the GDH1 and PSM plate models, and a halfspace (HS) model. (bottom) Same comparisons using a data set with regions of excess volcanism (Figure 2) removed.

and forces the model toward deeper values, whereas inclusion of these areas forces it toward shallow depths. Moreover, because older lithosphere has had more opportunity to be perturbed, a significant portion of it may be perturbed. Such shallow areas were not excluded in developing GDH1, because the goal was to develop a model for average thermal structure to be used for identifying perturbations. The alternatives are to develop models using the deepest depths [Parsons and Sclater, 1977], or to use a halfspace model which treats all shallower depths as perturbations [Davies and Pribac, 1993].

The Indian Ocean illustrates these difficulties. Even after excluding the excess volcanism, the Indian Ocean is shallower than GDH1 predicts. One could argue that most of the remaining old lithosphere, such as the Exmouth Plateau, is anomalously shallow and should be excluded. This exclusion would leave little old lithosphere, and thus make it difficult to resolve any thermal structure beyond that expected for halfspace cooling. We thus face the philosophical choice of accepting a halfspace as the reference, or using a reference like GDH1 which attempts to describe the average topography for older lithosphere.

Given that GDH1 provides a better average fit to the Indian Ocean lithosphere, it is interesting to consider the remaining misfit. Some may be due to anomalously shallow areas of old lithosphere beyond those excluded as due to excess volcanism. Much of the remaining misfit reflects the differences in subsidence rates between and within plates. Such variations occur for the Indian Ocean Basin, as shown by comparison of depths on opposite flanks of the different ridges (Figure 4). Some of these differences appear significant even given the scatter ( $\pm \sim 500$  m) of depths for a given age range on any ridge flank.

We view these differences as perturbations on an average thermal structure which GDH1 or similar models seek to characterize. Depth variations along ridges or on opposing ridge flanks have been attributed to variations in mantle temperature [Cochran, 1986; Marty and Cazenave, 1989] or to asthenospheric flow [Phipps Morgan and Smith, 1992]. These alternatives parallel the two primary proposed mechanisms for flattening the depth-age curve, heat addition from below or asthenospheric flow [Schubert et al., 1978]. Our sense is that both mechanisms may contribute to perturbing the depth-age variation. The overall depth-age flattening seems to us, however, difficult to interpret as due to asthenospheric flow alone, as proposed by Phipps Mor-

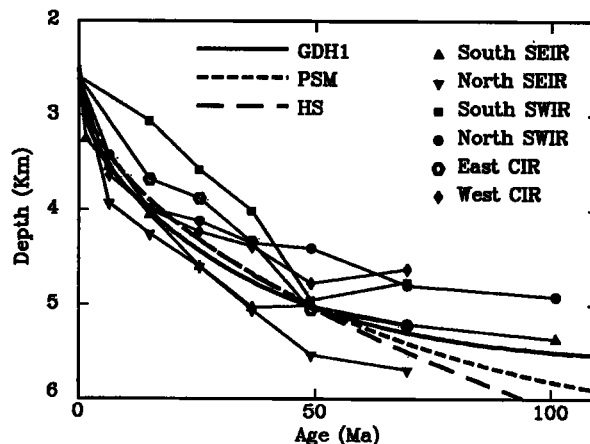


Fig. 4: Depth-age curves from the "No hot spot" data set on opposite flanks of the Indian Ocean ridges.

gan and Smith [1992]. The facts that both the depth and geoid for old lithosphere flatten in a consistent fashion [Colin and Fleitout, 1990] and that the depth, heat flow, and geoid data are reasonably well fit by a single thermal model like GDH1 [Stein and Stein, 1993] favor the flattening being primarily a thermal effect. Obviously much remains to be done before either the flattening or the along-ridge and across-ridge depth variations are understood.

**Acknowledgements.** We thank Luce Fleitout for helpful discussions, and two anonymous reviewers for useful comments. This research was supported by NSF grants OCE-9019572 and EAR-9022476, and NASA grant NAG-5-1944.

#### References

- Bevis, M., and J.-L. Chatelain, Locating a point on a spherical surface relative to a spherical polygon of arbitrary shape, *Math. Geol.*, **21**, 811–828, 1989.
- Cande, S., J. LaBrecque, R. Larson, W. Pitman, III, X. Golovchenko, and W. Haxby, Magnetic Lineations of the World's Ocean Basins, *AAPG Map*, Tulsa, 1989.
- Cochran, J. R., Variations in subsidence rates along intermediate and fast spreading mid-ocean ridges, *Geophys. J. R. astron. Soc.*, **87**, 421–454, 1986.
- Colin, P., and L. Fleitout, Topography of the ocean floor: Thermal evolution of the lithosphere and interaction of deep mantle heterogeneities with the lithosphere, *Geophys. Res. Lett.*, **17**, 1961–1964, 1990.
- Davies, G. F., and F. Pribac, The Darwin Rise: Persistence to the present, mantle origin, and relation to Cretaceous volcanism, *The Mesozoic Pacific, American Geophysical Union Monograph*, in press, 1993.
- Davis, E., and C. Lister, Fundamentals of ridge crest topography, *Earth Planet. Sci. Lett.*, **21**, 405–413, 1974.
- Fullerton, L., W. Sager, and D. Handschumacher, Late Jurassic-early Cretaceous evolution of the eastern Indian Ocean adjacent to Northwest Australia, *J. Geophys. Res.*, **94**, 2937–2953, 1989.
- Harland, W. B., R. L. Armstrong, A. V. Cox, L. E. Craig, A. G. Smith, and D. G. Smith, *A geologic time scale 1989*, 263 pp., Cambridge Univ. Press, New York, 1990.
- Johnson, H., and R. Carlson, The variation of sea floor depth with age: a test of existing models based on drilling results, *Geophys. Res. Lett.*, **19**, 1971–1974, 1992.
- Le Douaran, S., and B. Parsons, A note on the correction of ocean floor depths for sediment loading, *J. Geophys. Res.*, **87**, 4715–4722, 1982.
- Ludwig, W. J., and R. E. Houtz, *Isopach map of sediments in the Pacific Ocean Basin and Marginal Sea Basins*, AAPG Map, 1979.
- Marty, J. C., and A. Cazenave, Regional variations in subsidence rate of oceanic plates: a global analysis, *Earth Planet. Sci. Lett.*, **94**, 301–315, 1989.
- McKenzie, D. P., Some remarks on heat flow and gravity anomalies, *J. Geophys. Res.*, **72**, 6261–6273, 1967.
- Parsons, B., and J. G. Sclater, An analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res.*, **82**, 803–827, 1977.
- Patriat, P., and J. Segoufin, Reconstruction of the Central Indian Ocean, *Tectonophysics*, **155**, 211–234, 1988.
- 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.
- Powell, C. McA., S. R. Roots, and J. J. Veevers, Pre-breakup continental extension in East Gondwanaland and the early opening of the eastern Indian Ocean, *Tectonophysics*, **155**, 261–283, 1988.
- Rabinowitz, P., N. Dipiazza, and P. Matthias, *Isopach map of sediments in the Indian Ocean*, AAPG Map, 1988.
- Royer, J.-Y., and T. Chang, Evidence for relative motions between the Indian and Australian plates during the last 20 Myr from plate tectonic reconstructions, *J. Geophys. Res.*, **96**, 11,779–11,802, 1991.
- Royer, J.-Y., and D. T. Sandwell, Evolution of the Eastern Indian Ocean since the Late Cretaceous: constraints from Geosat altimetry, *J. Geophys. Res.*, **94**, 13,755–13,782, 1989.
- Royer, J.-Y., and R. Schlich, Southeast Indian Ridge between the Rodriguez triple junction and the Amsterdam and Saint-Paul Islands: detailed kinematics for the past 20 m.y., *J. Geophys. Res.*, **93**, 13,524–13,550, 1988.
- Royer, J.-Y., P. Patriat, H. W. Bergh, and C. R. Scotese, Evolution of the Southwest Indian Ridge from the Late Cretaceous (anomaly 34) to the Middle Eocene (anomaly 20), *Tectonophysics*, **155**, 235–260, 1988.
- Schubert, G., D. A. Yuen, C. Froidevaux, L. Fleitout, and M. Souriau, Mantle circulation with partial shallow return flow: Effects on stresses in oceanic plates and topography of the sea floor, *J. Geophys. Res.*, **83**, 745–758, 1978.
- Simpson, E. S. W., J. G. Sclater, B. Parsons, I. O. Norton, and L. Meinke, Mesozoic magnetic lineations in the Mozambique basin, *Earth Planet. Sci. Lett.*, **43**, 260–264, 1979.
- Stein, C. A., and S. Stein, A model for the global variation in oceanic depth and heat flow with lithospheric age, *Nature*, **359**, 123–129, 1992.
- Stein, C. A., and S. Stein, Constraints on Pacific midplate swells from global depth-age and heat flow-age models, *The Mesozoic Pacific, American Geophysical Union Monograph*, in press, 1993.
- Von Herzen, R. P., M. J. Cordery, R. S. Detrick, and C. Fang, Heat flow and the thermal origin of hot spot swells: the Hawaiian swell revisited, *J. Geophys. Res.*, **94**, 13,783–13,799, 1989.

T. Shoberg and S. Stein, Department of Geological Sciences, Northwestern University, Evanston, IL 60208-2150.

C. A. Stein, Department of Geological Sciences, University of Illinois at Chicago, Chicago, IL 60680.

(Received March 5, 1993;  
accepted April 12, 1993)