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Comparison of plate and asthenospheric flow models for the thermal evolution of oceanic lithosphere

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Abstract. Although seafloor depth and heat flow for young oceanic lithosphere can be described by modeling the lithosphere as the boundary layer of a cooling halfspace, a long standing question has been why data at older ages deviate from those expected for a halfspace. Two classes of models have been proposed for these deviations. In one, heat added from below "flattens" depth and heat flow In the other, asthenospheric flow beneath the lithosphere perturbs the depths. We compare recent versions of the model classes: the GDH1 thin-lithosphere plate model [Stein and Stein, 1992] and an asthenospheric flow model [Phipps Morgan and Smith, 1992]. The plate model fits heat flow data better than the flow model for all cases considered, and topographic data in all but one case. The flow model significantly overpredicts depths for the North Atlantic, because the assumed asthenospheric flow in the plate motion direction would yield deepening for old ages rather than the observed flattening. Overall, the GDH1 global average model does better than this flow model, whose parameters were fit to specific plates. Moreover, plate models fit to specific plates do better than the flow model. Plate models thus appear more useful than this flow model, suggesting that deviations from a cooling halfspace are largely thermal in origin.

Introduction

Because the thermal evolution of oceanic lithosphere is the primary mode of heat transfer from the earth's interior and the primary process controlling plate motions, considerable attention has been directed at using seafloor depth and heat flow to constrain thermal evolution models. The observation that depth and heat flow vary approximately with the square root of lithospheric age led to the generally accepted view that the lithosphere acts largely as the cold upper boundary layer of a cooling halfspace [Turcotte and Oxburgh, 1967]. However, for lithosphere older than ~70 Ma depth and heat flow "flatten", varying more slowly with age than for a halfspace. There has thus been much interest in investigating possible processes that may perturb the halfspace cooling, causing depths and heat flow to deviate from the expected square root of age variation.

Two primary perturbing processes have been proposed. In the first class, halfspace cooling is perturbed by the addition of heat from below. The commonly used such model is the plate model, in which an isothermal base of the lithosphere models the additional heat, which prevents continued halfspace cooling for older ages, and thus causes flattening [McKenzie, 1967]. Alternatively, heat might be added by discrete mantle plumes rather than everywhere [Heestand and Crough, 1981] such that the depths would be scattered but always shallower than for a halfspace. In the other class, depths are perturbed by pressure differences driving asthenospheric flow beneath plates [Schubert and Turcotte, 1972]. Such perturbations are commonly termed "dynamic," in contrast to "thermal" perturbations to lithospheric temperatures, although the latter derive from plate motion and are thus ultimately dynamic in origin.

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Models

We compare recent versions of the thermal and dynamic perturbation models to examine how well they fit the data, and draw inferences about the relative advantages of these specific models and of the model classes each represents. The models predict essentially the same depth and heat flow in young lithosphere, because in both halfspace cooling is the primary process. The predicted subsidence rate, or slope of the depth versus the square root of age, is linear: $s = 2(\kappa/\pi)^{1/2}\alpha T_m \rho_m/(\rho_m-\rho_w)$, where $\kappa = k/(\rho_m C_p)$ is thermal diffusivity, k is thermal conductivity, C_p is specific heat, α is volume coefficient of thermal expansion, T_m is basal temperature and ρ_m and ρ_w are mantle and water densities [Turcotte and Schubert, 1982].

The two models have different predictions at old ages. For the plate models, the depth and heat flow approach asymptotic values depending on the thermal plate thickness a. The asymptotic depth is $d_r + \alpha T_m a \rho_m/(2(\rho_m-\rho_w))$ where d_r is the depth of the ridge axis, and the asymptotic heat flow is kT_m/a. For a halfspace model, which corresponds to an infinitely thick plate ($a \rightarrow \infty$), depth increases continuously and heat flow decreases.

We examine the GDH1 plate model, characterized by a 95 km thick plate [Stein and Stein, 1992]. GDH1 was derived because the traditionally used 125-km thick plate model [Parsons and Sclater, 1977] systematically overpredicts depths and underpredicts heat flow for lithosphere older than 70-100 Ma. GDH1 significantly reduces this misfit to these data, which provide the key discriminant between models.

The Phipps Morgan and Smith [1992] (PMS) asthenospheric flow model differs somewhat from earlier flow models [Schubert and Turcotte, 1972; Schubert et al., 1978; Turcotte and Schubert, 1982] in which oceanic plates are assumed underlain by pressure-driven return flow in the direction opposite the absolute plate motion. Thus higher pressure occurs beneath old lithosphere, and depth flattens relative to that expected from halfspace cooling. PMS differs from the earlier models in that those oceanic plates bounded by continents are assumed underlain by pressure-driven flow in the absolute plate motion direction, so the depths of old lithosphere for these plates should be deeper than for halfspace cooling. In PMS, plates are characterized by four parameters differing between plates: the asthenospheric viscosity, the young-lithosphere subsidence rate, the flow geometry, and the ridge crest depth. The flow geometry depends on the absolute plate velocity, spreading rate, asthenospheric thickness, and whether the plate is continent or subduction zone bounded. The dynamic effect on topography is proportional to the assumed viscosity and absolute plate motion.

Comparisons

Figure 1 (top) compares the predictions of GDH1 and PMS to the North Pacific data. We used depths corrected for sediment loads [Renkin and Sclater, 1988], rather than uncorrected DBDB5 digital bathymetry, because without this correction basement depths appear too shallow. Heat flow were taken from the data set discussed by Stein and Stein [1992]. Although PMS was derived without using heat flow as a constraint, it is thermally the same as a cooling halfspace underlain by an isothermal asthenosphere. Heat flow as a function of age t for any plate can thus be predicted from the assumed subsidence rate s for the plate, using $q(t) = kT_m(\pi\kappa t)^{-1/2} = Bs\ t^{-1/2}$, where the heat flow to depth scaling factor is $B\ = k(\rho_m - \rho_w)/(2\kappa\alpha\rho_m) = C_p(\rho_m - \rho_w)/(2\alpha)$. The predicted heat flow shown is for the GDH1 parameters ($B =$ 1.4 mW m^{-3} Myr) and would be slightly (6%) less for the Parsons and Sclater [1977] ones.

GDH1 fits the depth data somewhat better than PMS, and the heat flow significantly better. Because GDH1 was developed to fit a combination of North Atlantic and North Pacific data, the good fit is not surprising. The PMS model is plate-specific, in that three primary parameters (viscosity, subsidence rate, and ridge depth) per plate are chosen to fit depths. Hence to compare plate-specific models, we derived a best-fitting plate model for the North Pacific, following the procedure used to derive GDH1 [Stein and Stein, 1992]. Parameters other than a, T_m, and d_r were set to the GDH1 values, such that the plate-specific plate model* has as many adjustable parameters as the flow model, and all three models have consistent scaling between subsidence and heat flow. The resulting plate model (NPC3), a 90 km thick plate with basal temperature 1400°C and a 2700 m ridge depth, fits the data better than PMS.

Figures 1 (bottom) and 2 (top) compare the predictions for the African and South American plates. The sediment-corrected depth data are from Hayes [1988]. The predicted depths for PMS are computed with their formulation, and match those in their figures [Phipps Morgan and Smith, 1992]. It appears, however, that some parameters actually used to compute their figures differ from those quoted. Because there was no dynamic perturbation to topography for African plate, the absolute velocity was zero, rather than the 10 mm/yr given. The magnitude of the perturbation for South America indicates that the asthenospheric viscosity used was ~42×10^{18} Pa s rather than the 7×10^{18} Pa s listed. The subsidence rate and ridge crest depth used, which were not listed, appear to be about 280 m My$^{-1/2}$ and 2200 m. GDH1, which was not derived using these data, fits the South American depths slightly better, and PMS does better for the African depths. GDH1 better fits heat flow.

The primary feature differentiating PMS from earlier flow models, the postulated dynamic subsidence of continent-

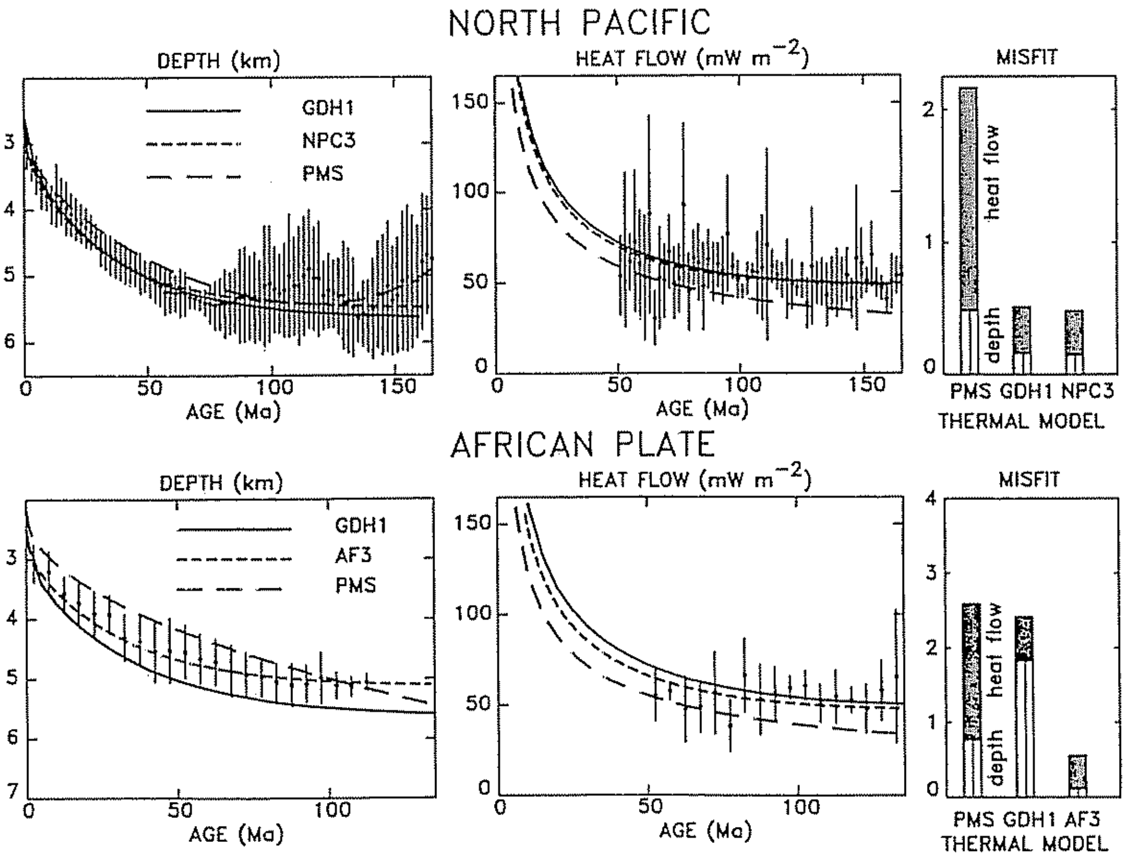

Figure 1. Comparison of depth and heat flow data for the North Pacific and African plates to GDH1, PMS, and plate-specific plate models. Both GDH1 and the plate-specific model (NPC3) fit the Pacific depth data better than PMS. PMS does better than GDH1 for the African depths, but the plate-specific plate model (AF3) does even better. PMS gives the poorest fit to the heat flow.

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*We know of no way to avoid the usage of "plate" (i.e. vs. halfspace) models for individual "plates" (e.g. Africa).

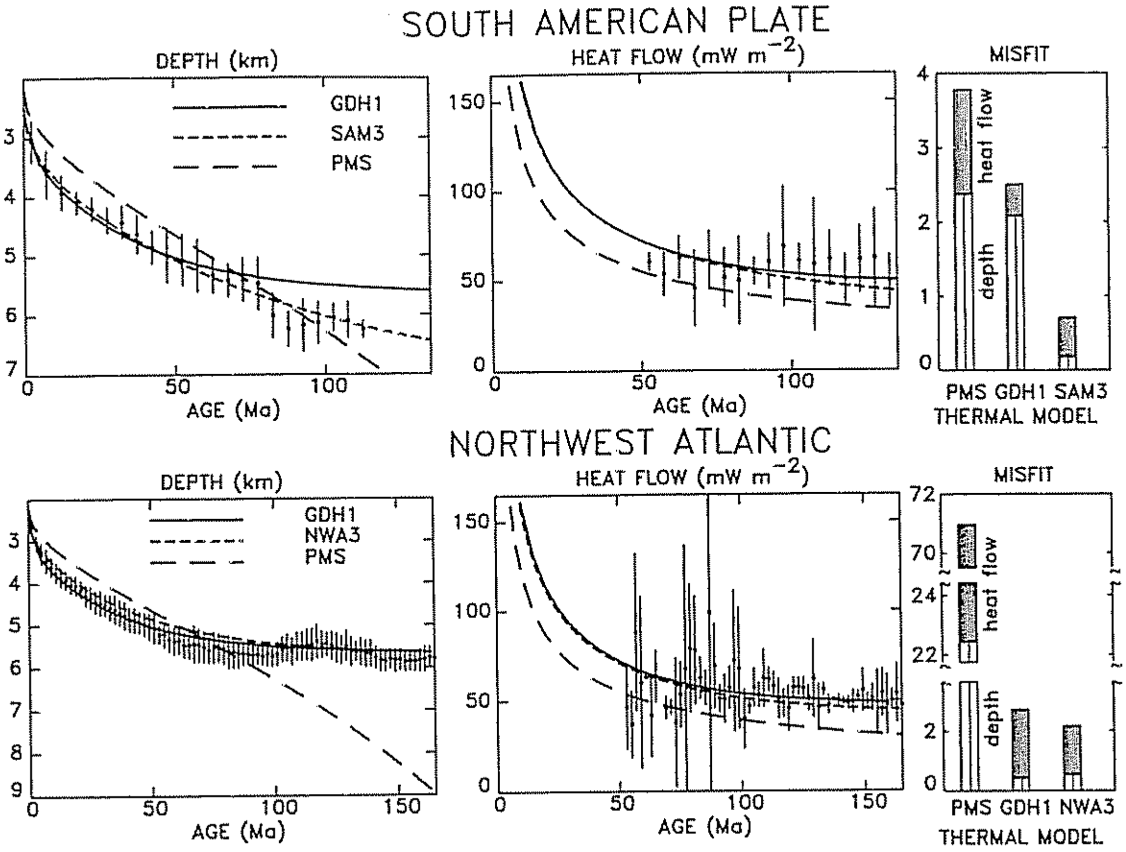

Figure 2. Comparison of depth and heat flow data for the South and North American plates to GDH1, PMS, and plate-specific plate models. GDH1 does slightly better than PMS for South American depths, and the plate-specific plate model (SAM3) does even better. PMS overpredicts the North Atlantic depths because of the presumed dynamic subsidence of continent-bounded plates. GDH1 and the plate-specific plate model (NWA3) fit the depth much better. PMS gives the poorest fit to the heat flow.

bounded oceanic plates, was included to model the unusually deep South American depths for old ages. Nonetheless, plate models with as many adjustable parameters do better, as shown by models AF3 and SAM3 (90 km and 150 km thick plates with basal temperatures 1325°C and 1450°C, respectively, and a 2500 m ridge depth).

The most interesting test of a model is a pure prediction of data not used in its derivation. This is not straightforward for the PMS model, because the procedure used to derive the viscosity and subsidence rate for each plate was not specified. Fortunately, this can be done by comparing data from the Northwest Atlantic (Figure 2, bottom) to the PMS prediction for the South American plate, because the North and South American plates are both continent-bounded and their absolute plate motion and spreading rates are similar [Gripp and Gordon, 1990]. PMS predicts depths much deeper than observed, up to 9 km, due to the postulated dynamic subsidence. Both GDH1 and plate-specific plate model NWA3 (a 105 km thick plate with basal temperature 1425°C and a 2400 m ridge depth) fit the sediment-corrected depth [Sclater and Wixon, 1986] and heat flow data much better. Given that these data were used in developing the two plate models, the good fit is not surprising, but the poor fit of PMS is striking.

Discussion

These comparisons bring out several points. GDH1, intended as an average model for oceanic lithosphere, generally fits the depth data as well or better than the PMS flow model, which has parameters adjusted to specific plates. We do not ascribe great significance to GDH1's slightly better fits for the Pacific or South America. Fits change somewhat depending on the dataset used [Stein and Stein, 1993] and on minor changes in model parameters, such as the ridge depth.

The dramatic misfit to Northwest Atlantic depths, however, is a serious failing of the PMS model, which predicts subsidence relative to a halfspace rather than the observed flattening. It thus appears that the postulated dynamic subsidence of continent-bounded plates is not a general phenomenon. Although one might argue that North America is somehow a special case, it seems inappropriate to assume so for this plate but not others, given that PMS was proposed as an alternative to both plate models and hotspot reheating.

It is interesting that plate models developed for individual plates fit noticeably better than PMS for these plates, given that both have the same number of adjustable parameters. Both plate and flow models are similar in that the depth data provide two constraints. The subsidence rate for young ages constrains the ridge temperature, and the depth at old ages constrains the magnitude of the postulated perturbation to halfspace cooling, and thus the plate thickness, asthenospheric viscosity, or channel thickness. Moreover, at a fundamental level, the plate-specific parameters assumed for both models have much in common, because the plate-specific parameters in the PMS flow model are implicitly thermal. The postulated 7% difference in subsidence rates for the Pacific and South American plates (300 vs.

280 m $\mathrm{Myr}^{-1/2}$) corresponds to ~80°C hotter ridge temperature for the Pacific. Similarly, the factor of 21 lower viscosity assumed (2×10^{18} vs. 42×10^{18} Pa s) implies an asthenosphere beneath the Pacific ~175°C hotter, for a dry olivine rheology with an activation energy of 0.52 MJ/mol [Brace and Kohlstedt, 1980]. Variations in mantle temperature and viscosity, perhaps due to mantle plumes, seem possible. At present, however, it is unclear whether the inferred variations in model parameters are justified for either plate or flow models, due to the difficulty in deriving other constraints on these parameters.

Our overall sense is thus that the PMS model has few advantages, and serious disadvantages, relative to plate models. Plate models can predict depth, heat flow, and geoid slope variations with age [Stein and Stein, 1994] reasonably well with a single, internally consistent, model. Hence a plate model is at least a good average description of perturbations from halfspace cooling. The challenge for alternative models is thus to fit the data as well or better. The PMS model's limitations do not, in our opinion, exclude other flow models. The most serious limitation we found, the predicted subsidence for the North Atlantic, results from the assumption of asthenospheric flow in the absolute motion direction for continent-bounded plates. Global flow models [e.g. Harper 1978] do not show this flow direction [Chase, 1979; Hager and O'Connell, 1979; Parmentier and Oliver, 1979]. Hence models (e.g. Schubert et al. [1978]) in which depth and heat flow perturbations are due to return flow, generally but not always opposite the plate motion direction, remain viable. It may be that the primary deviations from halfspace cooling are thermal, and hence described on average by a plate model, whereas the next level of regional deviations reflect temperature and pressure variations due to asthenospheric flow.

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References

Brace, W. F., and D. L. Kohlstedt, Limits on lithospheric stress imposed by laboratory experiments, *J. Geophys. Res.*, *85*, 6248–6252, 1980.

Chase, C. G., Asthenospheric counterflow: A kinematic model, *Geophys. J. R. astron. Soc.*, *56*, 1–18, 1979.

Gripp, A. E., and R. G. Gordon, Current plate velocities relative to the hotspots incorporating the NUVEL-1 global plate motion model, *Geophys. Res. Lett.*, *17*, 1109–1112, 1990.

Hager, B. H., and R. J. O'Connell, Kinematic models of large-scale flow in the Earth's mantle, *J. Geophys. Res.*, *84*, 1031–1048, 1979.

Harper, J. F., Asthenosphere flow and plate motions, *Geophys. J. R. astron. Soc.*, *55*, 87–110, 1978.

Hayes, D. E., Age-depth relationships and depth anomalies in the southeast Indian Ocean and south Atlantic Ocean, *J. Geophys. Res.*, *93*, 2937–2954, 1988.

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

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

Parmentier, E. M., and J. E. Oliver, A study of shallow global mantle flow due to the accretion and subduction of lithospheric plates, *Geophys. J. R. astron. Soc.*, *57*, 1–21, 1979.

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.

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.

Renkin, M. L., and J. G. Sclater, Depth and age in the North Pacific, *J. Geophys. Res.*, *93*, 2919–2935, 1988.

Sclater, J. G., and L. Wixon, The relation between depth and age and heat flow and age in the western North Atlantic, in *The Geology of North America: The Western North Atlantic Region, M*, edited by P. R. Vogt and B. E. Tucholke, pp. 257–270, The Geological Society of America, 1986.

Schubert, G., and D. L. Turcotte, One-dimensional model of shallow-mantle convection, *J. Geophys. Res.*, *77*, 945–951, 1972.

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

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, in *The Mesozoic Pacific, Geophys. Monogr. Ser. vol. 77*, edited by M. Pringle, W. W. Sager, W. Sliter and S. Stein, pp. 53–76, AGU, Washington, D. C., 1993.

Stein, C. A., and S. Stein, Constraints on hydrothermal heat flux through the oceanic lithosphere from global heat flow, *J. Geophys. Res.*, *99*, 3081-3095, 1994.

Turcotte, D. L., and E. R. Oxburgh, Finite amplitude convective cells and continental drift, *J. Fluid Mech.*, *28*, 29–42, 1967.

Turcotte, D. L., and G. Schubert, *Geodynamics: applications of continuum physics to geological problems*, John Wiley, New York, 1982.

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