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VARIATION OF SEA FLOOR DEPTH WITH AGE: A TEST OF MODELS BASED ON DRILLING RESULTS

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Abstract. Previous analyses of the variation of depth with age in oceanic basins have demonstrated a systematic square root of age dependence in crust younger than 80 Ma. These studies used depths determined from marine seismic data, which have uncertainties due to the assumed sediment velocity. As an alternative, we compiled the basement depths from all DSDP and ODP drill sites that sampled 'normal' ocean crust in the Atlantic, Pacific and Indian Oceans, up to recent drilling (Leg 136). We applied further criteria to the data, rejecting any site not formed at a mid ocean ridge, or that did not penetrate extrusive basalts of MORB composition. The remaining high quality data set is small (77 sites), but adequate to test models of the thermal structure of the upper mantle. Our new results also show that the square root of age ($t^{1/2}$) variation incorrectly estimates the observed depth for crustal ages older than 90 Ma. However, our data suggest a plate thickness of 104 ± 9 km and a basal temperature of 1400 ± 140 °C, and agree, at all ages, with the recent inversion by Stein and Stein, 1992.

Introduction

Many phenomena associated with plate tectonics are surficial expressions of large-scale convection in the mantle, and therefore represent the thermal boundary layer of a convection 'cell'. The systematic increase in seafloor depth and the decrease in heat flow with increasing sea floor age are readily observable, and these are primary constraints on the effective thermal structure of the boundary layer.

A. Models of Mantle Thermal Structure. The evolution of seafloor younger than 80 Ma can be adequately modeled by the cooling of a simple half-space, and basement depth and heat flow are predicted (and observed) to vary as the square root of age ((Davis and Lister, 1974; Parsons and Sclater, 1977; Renkin and Sclater, 1988). A cooling half-space (HS) model, however, systematically overestimates depths and underestimates heat flow for crustal ages greater than 90 Ma. Alternatively, the 'cooling plate' model (Langseth et al., 1966; McKenzie, 1967) assumes that thermal evolution is constrained by an isothermal boundary at a fixed depth, so that depth and heat flow asymptotically approach constant values at in both the HS and plate models for young ages, the inclusion of the isothermal lower boundary predicts the observed flattening of depth and heat flow trends at ages greater than 90 Ma (Parsons and Sclater, 1977). Consequently, the average thermal structure of the oceanic upper mantle can be determined by using global heat flow, basement depth and age data to estimate the parameters of the plate model.

B. Plate Model Parameters. Although McKenzie (1967) formulated the model boundary layer as a rigid plate, the effective elastic thickness of the lithosphere (Bodine et al, 1991) and the maximum depths of earthquakes (Wiens and Stein, 1983) suggest that the region above the isothermal layer cannot directly correspond to the lithosphere. Because the upper mantle rocks become ductile at temperatures lower than the inferred basal temperature, the plate model implies only that the thickness of the thermal boundary layer approaches an asymptotic limit, corresponding to a depth near 100 km, with a temperature near 1400°C. Parsons and Sclater (1977) made the first evaluation of thickness and temperature using a heat flow and basement depths. They did not perform a rigorous inversion, but estimated model parameters from the slopes and asymptotic values of curves relating heat flow and depth to the age of the seafloor. In the Parsons and Sclater Model (hereafter, PSM), the basal temperature is 1350 ± 275° C, and the thickness is 125 ± 10 km.

While a closer fit to old crustal ages than the HS model, PSM still underestimates heatflow and overestimates depth for crustal ages beyond 90 Ma. In a recent rigorous evaluation of the plate model, Stein and Stein (1992) performed a simultaneous inversion of depth and heatflow measurements, using a more extensive data set than PSM. In their Global Depth and Heatflow model (hereafter GDH1; Stein and Stein, 1992), the best-fitting basal temperature is 1450 ± 100°C, with a plate thickness of 95 ±10 km

C. Reliability of Data to Test Age/Depth Models. Both the PSM and GDH1 determinations of plate parameters rely on seismic reflection data to estimate basement depth and sediment thickness. While these data have wide geographical coverage, the most accurate crustal depths are those acquired directly by drilling. The original PSM analysis included the available drilling data, to Leg 41. Subsequent efforts have included much larger data sets, but relied heavily on global bathymetric and sediment thickness compilations (Cochran, 1986; Renkin and Sclater, 1988; Robinson and Parsons, 1988; Hayes, 1988). Since the PSM analysis, DSDP/ODP penetrated basement at numerous additional sites, and although this data set is not large, it is sufficient to estimate the model parameters based on drilling results alone.

Method/Technique

We used all data available from DSDP and ODP legs that recovered oceanic basement rocks, up to Leg 136. We then applied formal criteria to select only those sites which qualify as 'normal ocean crust'. The major source of our data was the DSDP CD-ROM disk, containing the full digital database compiled from the DSDP, supplemented by the volumes of the Initial Reports of the Deep Sea Drilling Project and the Ocean Drilling Program. The techniques used are described in Johnson and Pariso (1992).

A. Site Selection. Criteria for inclusion of a drill site (Figure 1) were that the basement rocks have (a) extrusive basalt morphology, (b) a mid-ocean ridge basalt (MORB) composition, and (c) an origin at a mid-ocean ridge spreading center. The MORB geochemical filter that was applied (SiO_2 contents between 45% and 55%: MgO contents between 2% and 15%: and TiO_2 values greater or equal to 0.5%) eliminated all rock types except tholeiitic basalts (L. Autio, pers. comm.). We also applied a geographical filter to the data, including Atlantic, Pacific and Indian Ocean sites, and excluding back arc basins, continental margins, fracture zones, seamounts and regions obviously affected by hotspots. Because of the drill site selection process, there is an bias in the data toward western Atlantic, northern Pacific and Indian Ocean sites. We also applied a 'depth filter' that excluded sites (all younger than 90 Ma) more than ± 1000 meters from the expected $t^{1/2}$

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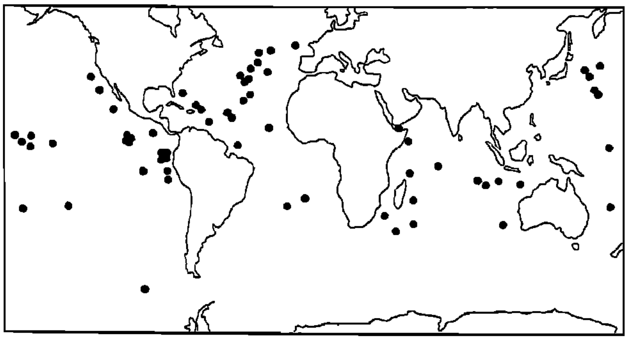

Figure 1 - Location diagram of the Deep Sea Drilling Project and Ocean Drilling Project sites used in this study.

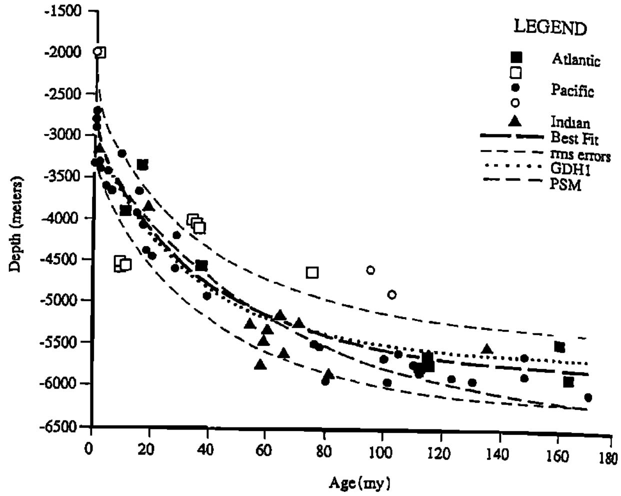

Figure 2 - Basement depths for the drill sites, as a function of age and plotted on a linear scale. Also shown are the PSM (long dashes) and GDH1 (dotted line) models. The heavy dashed line is the best fit of the drilling data (equation 7a), with the rms errors shown as short-dashed lines. Sites are identified by symbol, with unfilled symbols representing the 'outlier' data discussed in the text.

age variation, although we are aware of the logical circularity of this criterion. The uncertainties of the uncorrected crustal depths and sediment thickness are those associated with the drill pipe length and vertical orientation, less than 10 meters.

B. Age Dating of the Drill Sites. We gave first priority to the ages determined from magnetic anomalies, since we are primarily interested in crustal age. Where the magnetic anomaly data were ambiguous, we used the paleontological age of the basal sediments directly overlying basement rocks. We used a radiometric date in only one case (Site 595; R. Duncan, pers.comm., 1987).

C. Sediment Correction. Oceanic basement subsides under the load of overlying sediments, and therefore a subsidence correction related to sediment thickness must be applied to the data. The correction can be applied to either the observed seafloor depth (d_w) or to the basement depth (d_b). Assuming that Airy compensation is achieved by displacing mantle material of density ρ_m, the corrected depth of the unsedimented basement surface (d_c) is given by

$$d_c = d_w + [(\rho_m - \rho_s)/(\rho_m - \rho_w)]h \qquad (1a)$$

$$= d_b + [1 - [(\rho_m - \rho_s)/(\rho_m - \rho_w)]h \qquad (1b)$$

where ρ_s is average sediment density of the sediments, ρ_w is seawater density and h is sediment thickness. Parsons and Sclater (1977) assumed an average sediment density ρ_s = 1700kg m^{-3}, with ρ_m = 3330 kg m^{-3}, and ρ_w = 1000 kg m^{-3}, and used $d_c = d_w + 0.7h$ to estimate corrected basement depth. Colin and Fleitout (1990) assumed a linear increase of density with depth in the sediment layer. The corrected depth of the unsedimented basement is

$$d_c = d_w + Ah - Bh^2 \qquad (2a)$$

$$= d_b + (A-1)h - Bh^2 \qquad (2b)$$

where $A = (\rho_m - \rho_o)/(\rho_m - \rho_w)$ and $B = (d\rho/dz)/2(\rho_m - \rho_w)$. We also used a linear dependence of sediment density with thickness, based on the downhole logs of ODP Site 807, largely because logging data was available (Kroenke et al, 1991). We have taken ρ_o = 1530 kg m^{-3} and $d\rho/dh$ = 6.4x10^{-3} kg m^{-4} and the corrected depth is given by

$$d_c = d_b - 0.22h - (1.4\times10^{-4})h^2 \qquad (3)$$

We applied all three correction methods (PSM; Colin and Fleitout, 1990; and equation 3) to the drilling data and note that the inversion is not very sensitive to method.

Results and Analysis

A. General Results. Figure 2 shows our data compilation, and the PSM and GDH1 models. The data demonstrate that the PSM model systematically overpredicts the drill site depths older than 90 Ma. The Cover of this issue shows the same data set as Figure 2, but plotted in the form of depth versus (age)$^{1/2}$. As shown by other data sets (Stein and Stein, 1992), the actual sea floor depths depart systematically from the $t^{1/2}$ fit beyond 90 Ma. Our data do not show any further change with increasing age older than 90 Ma, consistent with an approach to thermal equilibrium.

B. Statistical Model. A recent version of the plate model (Stein and Stein, 1992) describes the depth to the unsedimented basement surface as a function of age by

$$d(t) = d_r + d_s\,[1 - (8/\pi^2)\exp(ct)] \qquad (4)$$

where d_r is the depth to the ridge crest, d_s is the asymptotic subsidence, $c = -K(\pi^2)/(a^2)$, a is the asymptotic thermal plate thickness and t is the age of the seafloor. The oceanic basement surface includes roughness arising from local features (Goff, 1992) and adding the roughness of the basement surface, the statistical model becomes

$$d_i = d_r + d_s\,[1 - (8/\pi^2)\exp(ct_i)] + r_i + e_i \qquad (5)$$

where i denotes the *ith* observed depth, r_i is the rms roughness, and e_i is the true error. In our analysis, we assume an initial axial depth of d_r = 2600 meters (Stein and Stein, 1992), and minimize the expression

$$r^2 + e^2 = (1/N)\Sigma_i\{(d_i - d(t_i))^2\} \qquad (6)$$

to estimate the best fitting parameters, d_s and c by nonlinear least squares. Note that the cross term [2re] does not appear in equation (6) because the expectation value <re> = 0, and

Table 1 - Summary of Constants Used in Plate Model

thermal expansion coefficient	α	3.1 x 10^{-5} °C
specific heat	Cp	1.171 kJ kG^{-1} °C^{-1}
thermal conductivity	k	3.138 W m^{-1} °C^{-1}
thermal diffusivity	K	8.04 x 10^{-7} m^{-2} s^{-1}
mantle density	ρ_m	3330 kg m^{-3}
water density	ρ_w	1000 kg m^{-3}
axial depth	d_r	2600 m

that the residual error cannot be less than the inherent surface roughness r. This condition also applies to both the PSM and GDH1 models. We also made a fit of the data to a simple $t^{1/2}$ model, for ages less than 90 Ma (Figures 2 and Cover).

The results of our inversions of the drilling data are summarized in Table 2, with the appropriate coefficients of the PSM and GDH1 models. The best-fitting plate model for the drilling data is given by

$$d(t) = 5825 - 2615 \exp(-0.023\, t) \tag{7a}$$

with an rms error of 427 meters, and an adjusted coefficient of determination (R^2) of 0.85. The fit is significant at the 99% confidence level. Our inversion, based solely on the drilling data, allows us to calculate new estimates of plate thickness and basal temperature (Table 2) as 104 ± 9 km and 1400 ± 140 °C. The best fitting 'root-t' model for seafloor less than 90 Ma in age is given by

$$d(t) = 2600 + 340\, t^{1/2} \tag{7b}$$

with an rms error of 419 m and $R^2 = 0.81$.

C. Sources Responsible for Scatter in the Data. Although our drilling data set is small, and there are uncertainties associated with the ages and sediment loading, the compilation represents an unusually accurate measurement of basement depths. Because different techniques were used to determine crustal ages for the DSDP/ODP data set, the associated errors are difficult to determine. We estimate that the post-Cretaceous magnetic chronology to be known accurately to 3% (Harland et al, 1982) and therefore the error in age is larger at older sites. Our inversion fortunately, is not very sensitive to age in the older drill sites.

Our data set shows an rms error of 427 meters; possible sources of this variation include (a) inherent basement roughness (Goff, 1992; Colin and Fleitout, 1990), (b) variation in initial axial depths, (c) influence of regional or local tectonics, (d) post-formation uplift due to hot spots (Heestand and Crough, 1981: Crough, 1978) and/or small-scale mantle circulation (Hayes, 1988), (e) variations in crustal thickness, and (f) systematic regional subsidence differences (Cochran, 1986). It is beyond the scope of this study to carry out a comprehensive analysis of these factors, but some simple estimates can be useful.

Colin and Flietout (1990) fit a variety of models to their bathymetry data, filtering the residuals at different levels. With no applied cutoff (all bathymetric features included), they found an rms roughness near 870 m. With a cutoff of 750 m (near our cutoff value at 1000 m), their residual value is 375 m, and with a cutoff at 300 m, their residual is 250 m. Similarly, in their analysis of individual profiles from the Atlantic, Hayes and Kane (1991) estimated the unfiltered rms roughness to be near 250 m. Our rms value of 427 m is comparable to the 375 m value from Colin and Fleitout (1990). Furthermore, if we exclude the 13 apparent outliers (the open symbols, Figure 2 and Cover), the re-computed rms deviation from (7a) is 240 m, similar to Hayes and Kane (1991). These considerations suggest that much of the scatter in our data represents the roughness of the abyssal hills. The observation that our residual value compares favorably to those previously published enhances our confidence that the small drilling data set is representative of the wider ocean basins.

Discussion and Conclusions

Table 2 and Figure 2 (and Cover) show that equation (7a) a good fit to the drilling data. Given the statistical limitations of the three models (PSM, GDH1, and this study), we cannot make a statistically rigorous test between them. Even assuming the errors in the model coefficients are valid and have Gaussian distributions, neither PSM nor GDH1 is statistically distinguishable from the drilling model. Our estimated basal temperature, 1400 ± 140 °C, lies between the temperatures inferred from PSM and GDH1. However, two qualitative observations suggest that the present inversion is more consistent with GDH1 model. First, both our inversion and the GDH1 fit the drilling data well at all ages, whereas PSM shows a large systematic misfit for ages greater than 90 Ma. Secondly, the plate thickness estimated from the drilling results (104 ± 9 km) is closer to the GDH1 value (95 km) than to the PSM value (125 km). Although not conclusive, the drilling data seem to support the GDH1 model.

Table 2 - Summary of Model Parameters

	DSDP/ODP		PSM		GDH1
parameters	Plate	HS	Plate	HS	Plate
d_s [1] (meters)	3225±150	-	3900±400	-	3050±550
c [2] (eqns 4 & 5)	0.023±.004	-	0.016±.003	-	0.028±.004
b [3] ($m^2\ my^{-1}$)	350±35	340±10	355±35	350±45	365±85
a (km)	104±9	-	125±9	-	95±10
T_m (°C)	1400±140	350±45	1350±275	1390±180	1450±100

Note: [1] is defined in equation 4, [2] refers to equations 4 and 5, and [3] is the slope of the $t^{1/2}$ relationship. PSM parameters and errors as given by Parsons and Sclater (1977) or estimated from the averages of Atlantic and Pacific values from their Table 2. GDH1 errors estimated from errors in thickness and basal temperature.

In summary, our depth vs age data compilation, which requires no assumptions about the seismic velocities of sediments, is free of influence from major hotspots and local crustal tectonics, shows agreement with the previously determined $(age)^{1/2}$ relationship, at least to crustal ages of approximately 90 Ma. Beyond 90 Ma, the observed basement slopes flatten, both absolutely and in comparison with the $(age)^{1/2}$ variation, consistent with previous observations, and with the approach of the older sites to thermal equilibrium. Our data do not exhibit the anomalously 'elevated' $t^{1/2}$ relationship associated with either the African and South East Indian Ocean plates (Hayes, 1988), or south Pacific data (Cochran, 1986), because the older drilling sites are located largely in the north Pacific and western Atlantic. Examination of the sources of variability in the data indicates that the inherent basement roughness (i.e., abyssal hills) accounts for much of the scatter. Finally, the new GDH1 model, which uses a simultaneous inversion of heat flow and basement depths to constrain the cooling plate model, appears to be an excellent fit to the drilling data. Applying our new compilation to the Stein and Stein (1992) model predicts a plate thickness of 105 km and basal temperature of 1400 °C, only slightly different from their estimated values.

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