

Constraints on hydrothermal heat flux through the oceanic lithosphere from global heat flow

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A significant discrepancy exists between the heat flow measured at the seafloor and the higher values predicted by thermal models of the cooling lithosphere. This discrepancy is generally interpreted as indicating that the upper oceanic crust is cooled significantly by hydrothermal circulation. The magnitude of this heat flow discrepancy is the primary datum used to estimate the volume of hydrothermal flow, and the variation in the discrepancy with lithospheric age is the primary constraint on how the hydrothermal flux is divided between near-ridge and off-ridge environments. The resulting estimates are important for investigation of both the thermal structure of the lithosphere and the chemistry of the oceans. We reevaluate the magnitude and age variation of the discrepancy using a global heat flow data set substantially larger than in earlier studies, and the GDH1 (Global Depth and Heat flow) model that better predicts the heat flow. We estimate that of the predicted global oceanic heat flux of 32×10^{12} W, 34% (11×10^{12} W) occurs by hydrothermal flow. Approximately 30% of the hydrothermal heat flux occurs in crust younger than 1 Ma, so the majority of this flux is off-ridge. These hydrothermal heat flux estimates are upper bounds, because heat flow measurements require sediment at the site and so are made preferentially at topographic lows, where heat flow may be depressed. Because the water temperature for the near-ridge flow exceeds that for the off-ridge flow, the near-ridge water flow will be even a smaller fraction of the total water flow. As a result, in estimating fluxes from geochemical data, use of the high water temperatures appropriate for the ridge axis may significantly overestimate the heat flux for an assumed water flux or underestimate the water flux for an assumed heat flux. Our data also permit improved estimates of the "sealing" age, defined as the age where the observed heat flow approximately equals that predicted, suggesting that hydrothermal heat transfer has largely ceased. Although earlier studies suggested major differences in sealing ages for different ocean basins, we find that the sealing ages for the Atlantic, Pacific, and Indian oceans are similar and consistent with the sealing age for the entire data set, 65 ± 10 Ma. The previous inference of a young (~20 Ma) sealing age for the Pacific appears to have biased downward several previous estimates of the global hydrothermal flux. The heat flow data also provide indirect evidence for the mechanism by which the hydrothermal heat flux becomes small, which has often been ascribed to isolation of the igneous crust from seawater due to the hydraulic conductivity of the intervening sediment. We find, however, that even the least sedimented sites show the systematic increase of the ratio of observed to predicted heat flow with age, although the more sedimented sites have a younger sealing age. Moreover, the heat flow discrepancy persists at heavily sedimented sites until ~50 Ma. It thus appears that ~100-200 m of sediment is neither necessary nor sufficient to stop hydrothermal heat transfer. We therefore conclude that the age of the crust is the primary control on the fraction of heat transported by hydrothermal flow and that sediment thickness has a lesser effect. This inference is consistent with models in which hydrothermal flow decreases with age due to reduced crustal porosity and hence permeability.

INTRODUCTION

The thermal evolution of the oceanic lithosphere governs its properties as a function of age and hence the style and nature of plate tectonics. Following the realization that seafloor heat flow is highest at mid-ocean ridges and decreases with distance [Von Herzen and Uyeda, 1963; Langseth *et al.*, 1966], the systematic variation of ocean depth and heat flow with age became the primary constraint on models of the thermal evolution of the lithosphere. The two sets of data jointly reflect the evolution with

age of the geotherm in the lithosphere, since the bathymetry depends on the temperature integrated over depth and the heat flow depends on the temperature gradient at the seafloor. The key features of the data, the decrease in heat flow and increase in seafloor depth with age, are described by models in which lithosphere formed at high temperature cools conductively as it spreads away from the ridge [McKenzie, 1967; Davis and Lister, 1974; Parsons and Sclater, 1977].

A principal failing of such conductive models is that the observed heat flow for ages 0-70 Ma is significantly less than predicted. This heat flow discrepancy is thought to reflect the transport of significant amounts of heat at the seafloor by water circulation [Lister, 1972; Williams *et al.*, 1974; Anderson and Hobart, 1976], rather than the conductive cooling assumed in the models. The circulation is thought to be divided into two

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major stages [Lister, 1982; Fehn and Cathles, 1986]. Near the ridge axis, "active" circulation occurs, during which water cools and cracks the rock, and heat is extracted rapidly by high-temperature water flow [Patterson and Lowell, 1982; Fehn et al., 1983]. Once cracking ceases, "passive" circulation transports lower-temperature water on the ridge flanks.

The discrepancy between the observed and predicted heat flow is the primary constraint on the volume and age distribution of the heat transferred by water flux [Wolery and Sleep, 1976; Sleep and Wolery, 1978; Anderson and Skilbeck, 1981]. Wolery and Sleep [1976] considered other thermal effects, such as chemical reactions between the water and crust, and concluded that they were small enough that the heat flow discrepancy could be treated as essentially all due to water circulation. As a result, the heat flow discrepancy is used to estimate the water flux. This discrepancy (Figure 1) can be shown as either a difference or the heat flow fraction, the ratio of the observed to predicted heat flow. The observation that the heat flow discrepancy is largest at the ridges and decreases with age is interpreted as indicating that the hydrothermal water flux decreases with age until a "sealing" age, defined by the observed and predicted heat flow being comparable, by which hydrothermal heat transfer has largely ceased.

These data are used to address two issues: how large are the hydrothermal heat and water fluxes as functions of age, and what causes these fluxes to decrease with lithospheric age? The volume of hydrothermal circulation has profound implications for the chemistry of the oceans, because seawater reacts with the crust, giving rise to hydrothermal fluid of significantly different composition [Wolery and Sleep, 1976, 1988; Rona et al., 1983]. The primary geochemical effects are thought to result from the high-temperature water flow observed at ridge axes [e.g., Corliss et al., 1979; Macdonald et al., 1980; Von Damm et al., 1985; Rona et al., 1986]. Nonetheless, the persistence of the heat flow discrepancy to ages of about 70 Ma indicates that much of the hydrothermal heat flux occurs away from the ridge axis (ages greater than ~100,000-1,000,000 years) by passive low-temperature circulation in older lithosphere [Wolery and Sleep, 1976, 1988; Morton and Sleep, 1985]. The effects of this off-axis flow have been observed [Langseth and Herman, 1981; Abbott et al., 1984; Williams et al., 1986; Fisher et al., 1990], and it is thought to have a much smaller geochemical effect than the near-axis flow, based on the major element chemistry of the fluid [Baker et al., 1991].

Estimates of the hydrothermal water flux derived from heat flow data are used for comparison of the water fluxes inferred with other techniques. These other techniques include direct measurements of near-ridge hydrothermal systems [e.g., Green et al., 1981; Baker and Hammond, 1992], inference of water fluxes from ocean chemistry [e.g., Wolery and Sleep, 1976, 1988; Edmond et al., 1979; Craig and Lupton, 1981], and modeling of geophysical observables such as the depth to magma chambers or seismicity which reflect the cooling of the ridge axis by hydrothermal flow [Morton and Sleep, 1985; Lin and Parmentier, 1989; Purdy et al., 1992].

The heat flow data are also crucial to investigating the processes which cause hydrothermal heat flux and thus presumably water flow to decrease with age. The "sealing" age estimated from the heat flow data shows when hydrothermal heat transfer at the seafloor has become minor but offers only indirect information about how this occurs. With hindsight, the term "sealing" age is not ideal for several reasons. First, this age is estimated from heat flow data, given the difficulty in

HEAT FLOW ANOMALY DUE TO HYDROTHERMAL FLUX

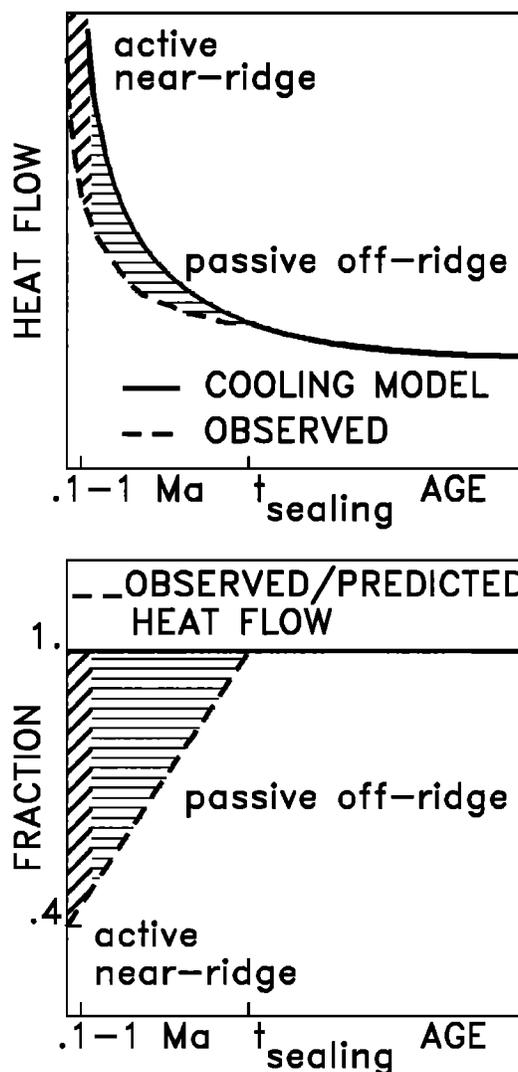


Fig. 1. Schematic illustration of estimation of hydrothermal flux from the heat flow anomaly. The anomaly, or difference between the heat flow predicted by a lithospheric cooling model and that observed (shaded), is presumably transported by water flux. The flux is thought to be divided into a near-ridge, high temperature, "active" flow and an off-ridge, low-temperature, "passive" flow. At a sealing age, the observed and predicted heat flow approximately coincide. The data can be presented either (top) in raw form or (bottom) as the fraction of the predicted heat flow that is observed.

determining water flow directly. Second, the reduction in hydrothermal heat transfer could occur in several ways. The porosity and permeability of the igneous crustal rocks may become too small, due to hydrothermal deposition of minerals, such that the rocks themselves "seal". "Sealing" could also reflect the igneous crust's being capped by thick hydraulically nonconductive sediments which isolate it from the seawater, such that convection could continue at depth but heat transfer at the seafloor would be conductive. Because the sealing age is an average value estimated from heat flow data, some water circulation may persist beyond it, but it does not, in general, transport significant amounts of heat.

Analysis of these issues to date has reflected the limitations of both the global heat flow data available and the conductive

model against which the measurements were compared to estimate the hydrothermal heat flux. In particular, assessment of the consistency or inconsistency of various estimates of near-ridge and off-ridge hydrothermal heat and water flux is difficult. Similarly, although it has been proposed that the sealing age for hydrothermal circulation varies between ocean basins and primarily reflects the effect of isolation of the crust from seawater by thick sediment, these propositions remain largely untested. Our goal here is to address these issues with the large heat flow data set now available and a model which better predicts the conductive heat flow.

In doing so, it is useful to bear in mind the strengths and limitations of approaches like ours, which use heat flow data averaged over lithosphere of a given age range. Such studies give global average estimates of the hydrothermal flux, which occurs by flow whose details presumably depend on local conditions. This approach has the advantage that the estimates of heat and water fluxes should average the local flow effects at the sites sampled [e.g., *Langseth and Herman, 1981*]. (They are, however, vulnerable to biases introduced by where sampling is possible, as discussed later.) The corresponding limitation of using averaged heat flow data is that the results say little about the flow at specific sites and the physical conditions giving rise to it. For example, knowledge of the aggregate off-axial flux gives no insight into how the flux is localized (many small sources or a few large ones) and the relevant water temperatures. Similarly, although we can identify the sealing age beyond which little heat is transported by hydrothermal flow, we can make at best indirect inferences about the processes causing this effect.

HEAT FLOW DATA and MODEL

We use a global heat flow data set (Figure 2) [*Stein and Stein, 1992*] significantly larger than that available to the earlier studies. We include only good quality experimental data and exclude data from marginal basins, whose thermal evolution may differ from that of larger oceanic plates [*Uyeda, 1977*]. Several of the individual values were obtained by averaging the results of detailed surveys on crust younger than 6 Ma to avoid biasing the data toward these sites' values. This averaging reduces the 5539 data to 4458.

The data were compared to a new model for the thermal evolution of the lithosphere, GDH1 (Global Depth and Heat flow) [*Stein and Stein, 1992*]. GDH1 (Figure 3), derived by joint inversion of depth and heat flow data, fits the variations of depth and heat flow with age significantly better than either a half-space model or a plate model with the parameters used by *Parsons and Sclater [1977]* (PSM). In particular, GDH1 reduces the systematic misfit to the depth and heat flow in older (>70 Ma) lithosphere, where PSM predicts depths deeper and heat flow lower than generally observed. An *F* ratio test indicates that the improved fit to the data, an 80% misfit reduction, is significant at the 99.9% level. The improvement in fit going from PSM to GDH1 is comparable to that obtained using PSM relative to a half-space model.

This improvement in fit results from the fact that relative to PSM, GDH1 has a thinner (95 ± 15 versus 125 ± 10 km) thermal lithosphere with a higher basal temperature (1450 ± 250 versus $1350 \pm 275^\circ\text{C}$). The thinner lithosphere gives a steeper

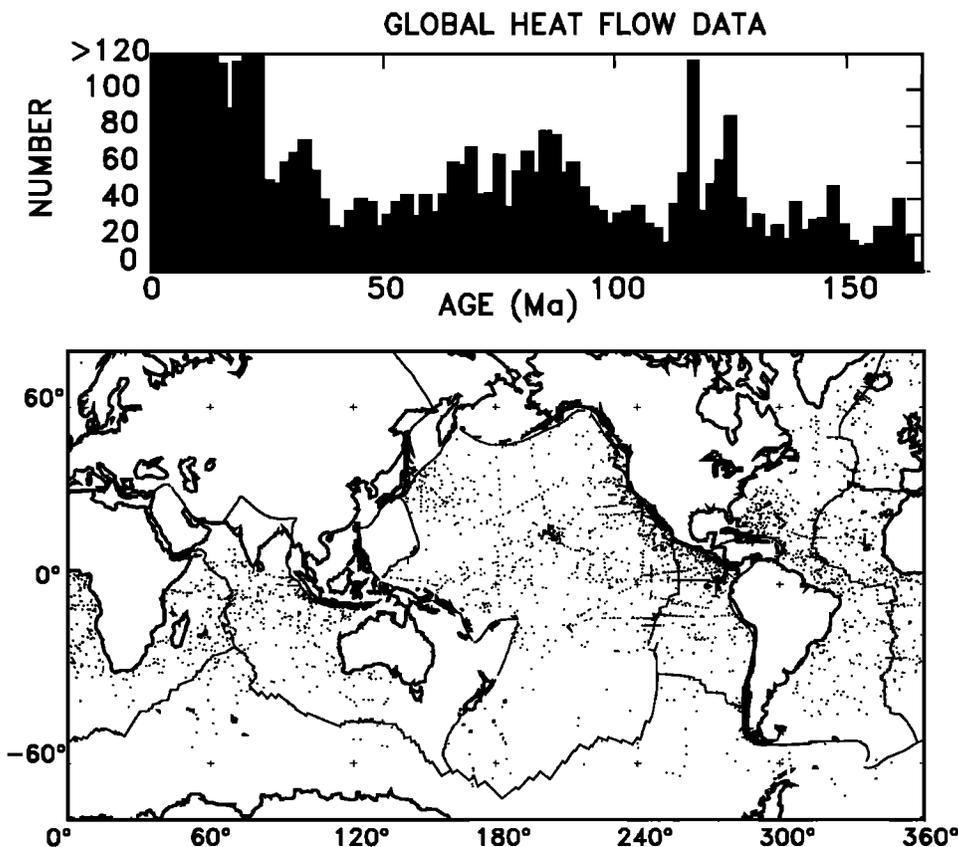


Fig. 2. Locations of the heat flow data used and their distribution as a function of age.

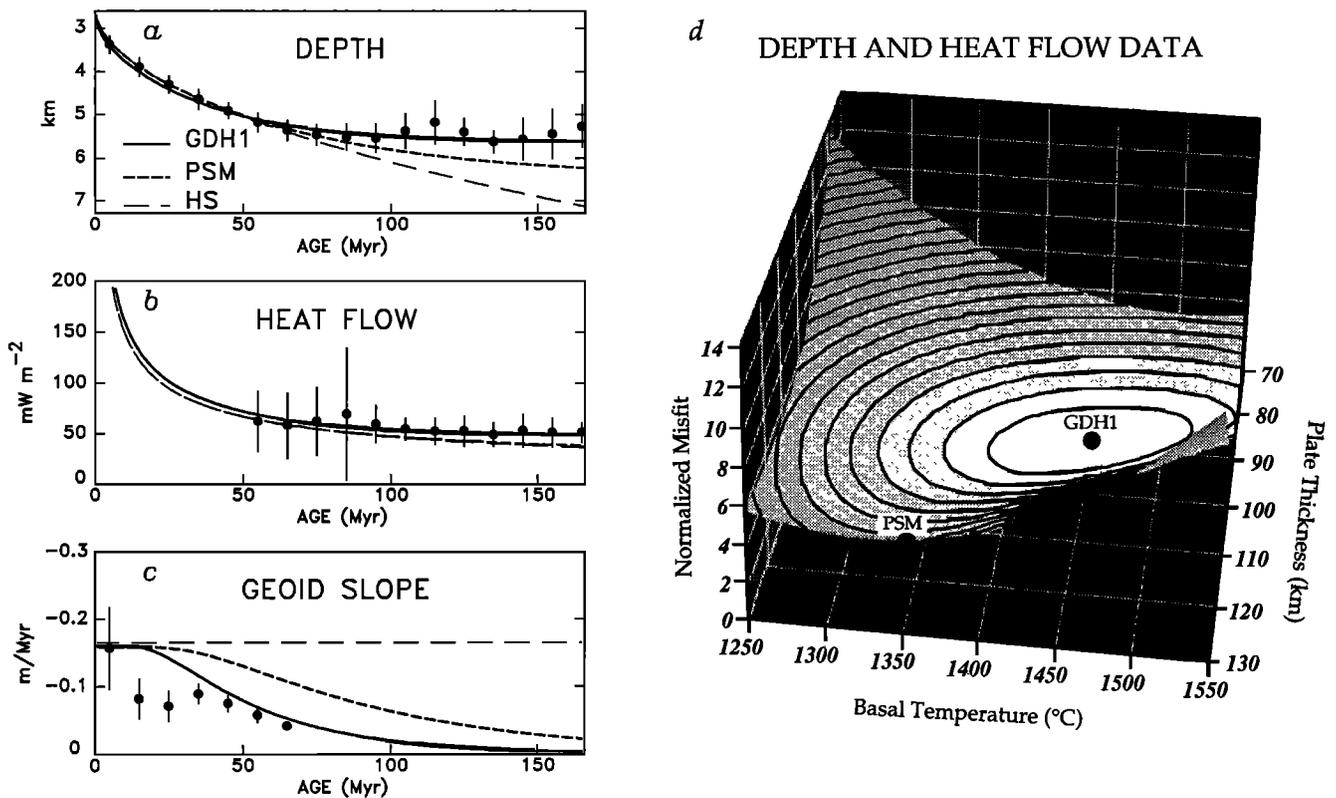


Fig. 3. (a) Depth and (b) heat flow data inverted to derive the GDH1 model, plotted in 10-m.y. bins, compared with the predictions of the GDH1, PSM, and half-space (HS) models. All the depths and the heat flow for ages older than 50 were used. In Figure 3b the HS and PSM curves overlap for ages younger than ~ 120 Ma. (c) Geoid slope data across fracture zones [Cazenave, 1984] which were not used in deriving GDH1, averaged in 10-m.y. bins, compared with the predictions of the three models, showing the positions of the GDH1 and PSM models. Values are normalized to the GDH1 misfit, and the contour interval is 0.5. The misfit for PSM is 5 times that for GDH1. The surface is plotted for the GDH1 coefficient of thermal expansion, $3.1 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$, so PSM which has a different value ($3.28 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$) plots slightly above the surface. The fitting function is discussed by Stein and Stein [1992].

geotherm, higher temperatures at depth, and higher heat flow. The asymptotic heat flow for old lithosphere for GDH1 is 48 mW m^{-2} , approximately 40% higher than the 34 mW m^{-2} value for PSM. Similarly, the thinner lithosphere results in less subsidence and hence shallower depths. The improved fits reflect the predicted higher temperatures that result largely from the thinner plate and would occur even if the basal temperature were not somewhat higher than in PSM.

Several points about the GDH1 model are worth noting for our application here. It is a plate model, in which the "flattening" (varying more slowly with age than for a half-space) of the depth and heat flow for older lithosphere are ascribed to the addition of heat from below. Because heat flow data for young lithosphere are thought to be biased by hydrothermal circulation, the primary constraints on such thermal models are the depth and heat flow for old lithosphere. As a result, whether to exclude a priori the depths of shallow areas such as swells and hotspot tracks is crucial. The choice is not clear-cut; exclusion of shallow areas inserts an a priori bias about what is "anomalous" and forces the model toward deeper values, whereas inclusion of these areas forces the model toward shallow depths. By not excluding such shallow areas in developing GDH1, we have a reference model for average thermal structure and the average addition of heat from below, relative to which hotspot tracks are perturbations. The heat flow perturbation due

to hotspots appears generally small, less than 10 mW m^{-2} [Stein and Stein, 1993].

The depth data used in deriving GDH1 were taken from studies based on the NOAA DBDB5 digital bathymetric data set. Although this data set, which is typically used for depth-age studies, has biases due to inadequate sampling, these biases do not appear excessive for depth-age studies in the Pacific [Phipps Morgan and Smith, 1992; Stein and Stein, 1993].

Because the goal of thermal models is to constrain thermal structure using properties observable at the surface, a useful way to compare models is to examine their predictions for data sets not used to derive the models. GDH1, though derived using data from the North Pacific and northwest Atlantic, fits heat flow and sediment-corrected depth data for the Indian Ocean basin better than PSM whether or not swells and hotspot tracks are excluded [Shoberg *et al.*, 1993]. Similarly, it better fits basement depths for Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) drill sites [Johnson and Carlson, 1992; Stein and Stein, 1993]. An additional independent constraint on the thermal structure comes from geoid slope data across fracture zones (Figure 3c). As for the depth and heat flow, the geoid slope's deviation from the predictions of a halfspace model provides an estimate of the thermal thickness of the lithosphere [Cazenave, 1984]. Although the data for ages

less than about 30 Ma appear to be biased by local effects of the fracture zones, the remaining data are better fit by GDH1 than by PSM. Hence although there is no unique or best solution to the inverse problem of inferring thermal structure and different data sets, uncertainty assignments, and fitting functions yield different results, a wide variety of data favor a thin lithosphere model like GDH1.

The new data and model provide a better basis for estimation of the heat flow anomaly due to hydrothermal circulation. Previous estimates faced the difficulty that the PSM (or the other) thermal models used underpredicted the heat flow data for old ages. The new data have greater areal coverage. Comparison of the data to the GDH1 predictions (Figure 4) suggests that the heat flow fraction is approximately 0.5 in young (0-5 Ma) lithosphere and increases with age to ~1 by 65 ± 10 Ma, by which essentially all heat transfer is conductive. The sealing age t_s is estimated by fitting a least squares line to the heat flow fractions for ages less than 50 Ma (Figure 4, bottom). This approach has the advantage that it is not biased by the heat flow discrepancy in young lithosphere, because heat flow data for ages < 50 Ma were not used in deriving GDH1. Moreover, the GDH1 model is also constrained by the depth data, which even without the heat flow data yield the same thermal structure [Stein and Stein, 1992]. Thus the agreement of the heat flow data with the model predictions at old ages and the discrepancy at young ages are not artifacts of the data used to derive the model.

HYDROTHERMAL HEAT FLUX

We use the heat flow data and model to reassess the hydrothermal heat flux, using an approach similar to those of Wolery

GLOBAL HEAT FLOW DATA

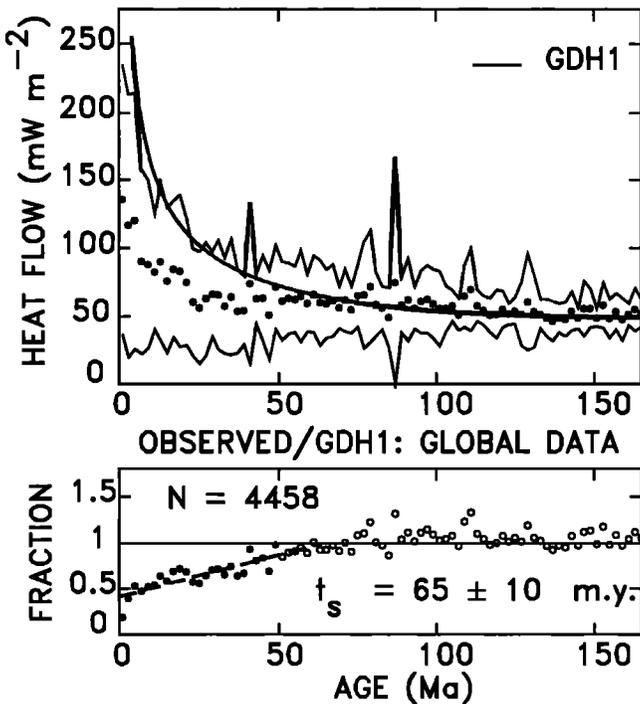


Fig. 4. Observed heat flow versus age for the global data set (Fig. 2) and predictions of the GDH1 model, shown in (top) raw form and (bottom) fraction. Data are averaged in 2-m.y. bins. The discrepancy for ages < 50-70 Ma presumably indicates the fraction of the heat transported by hydrothermal flow. The fractions for ages < 50 Ma (solid circles), which were not used in deriving GDH1, are fit by a least squares line. The sealing age, where the line reaches one, is 65 ± 10 Ma.

and Sleep [1976] and Sclater et al. [1980]. We divide the ocean basins into age intervals, with the i th age interval extending from t_{i-1} to t_i , where t_0 is zero. We then find the mean observed global heat flow data for each age interval, q_i , and its standard deviation, σ_{q_i} .

The average predicted heat flow for this interval is

$$q'_i = \left[\int_{t_{i-1}}^{t_i} q'(t) dt \right] / (t_i - t_{i-1})$$

where $q'(t)$ is the predicted heat flow for age t . For the GDH1 model,

$$q'(t) = 510 t^{-1/2} \quad t \leq 55 \text{ Ma}$$

$$= 48 + 96 \exp(-ct) \quad t > 55 \text{ Ma}$$

where $c=0.0278 \text{ Ma}^{-1}$, age is in Ma, and the heat flow is in mW m^{-2} . These expressions are easily integrated, giving

$$\int_{t_{i-1}}^{t_i} q'(t) dt = 1020 (t_i^{1/2} - t_{i-1}^{1/2}) \quad t_i \leq 55 \text{ Ma}$$

$$\int_{t_{i-1}}^{t_i} q'(t) dt = 1020 ((55)^{1/2} - t_{i-1}^{1/2}) + 48 (t_i - 55) - 3543 [\exp(-ct_i) - \exp(-c(55))] \quad t_{i-1} \leq 55 \text{ Ma}; t_i > 55 \text{ Ma}$$

$$\int_{t_{i-1}}^{t_i} q'(t) dt = 48 (t_i - t_{i-1}) - 3543 [\exp(-ct_i) - \exp(-ct_{i-1})] \quad t_{i-1} > 55 \text{ Ma}$$

where the integral is in $\text{mW m}^{-2} \text{ Ma}$. Although the predicted heat flow at the axis ($t=0$) is infinite, integration removes the singularity. Thus we obtain a finite value for the average heat flow in young lithosphere quite simply. The result is almost identical (within 0.4%) to that obtained using the series solution for the GDH1 plate model with a modified boundary condition at the ridge that conserves energy [Sclater et al., 1980].

If the area of crust with ages between t_{i-1} and t_i is A_i , the cumulative predicted and observed heat fluxes for ages less than t_n are

$$Q'_n = \sum_{i=1}^n A_i q'_i \quad Q_n = \sum_{i=1}^n A_i q_i$$

Thus the cumulative heat flux due to hydrothermal flow is the difference

$$Q_n^h = Q'_n - Q_n = \sum_{i=1}^n A_i (q'_i - q_i)$$

The uncertainty in the cumulative observed heat flux can be found using linear propagation of errors

$$\sigma_{Q_n}^2 = \sum_{i=1}^n A_i^2 \sigma_{q_i}^2$$

assuming the errors in the different age bins are independent. We also treat this quantity as the uncertainty in the cumulative

hydrothermal heat flux. This assumes that the uncertainty in the hydrothermal heat flux estimate is due to the uncertainty in the observed flux and neglects both uncertainties in the area-age relation and thermal model, and a possible sampling bias. Thus, as discussed shortly, the uncertainty we estimate for the cumulative hydrothermal heat flux is a lower bound.

For calculations, we use the area-age values from *Sclater et al.* [1980]. Because their youngest bin is 0-4 Ma, we add 0-1 and 0-2 Ma bins, assuming that their area is a quarter and a half, respectively, of that of the 0-4 Ma bin. Table 1 and Figure 5 show the results. For each age range, the difference between the average predicted and observed heat flow gives the estimated average hydrothermal heat flux. The resulting cumulative hydrothermal heat flux increases steadily until about 50 Ma and then levels off as the observed heat flow becomes approximately that predicted. The slight variation with age about the asymptotic value of $11 \pm 4 \times 10^{12}$ W is an artifact caused by the fact that the observed heat flow slightly exceeds the predicted value for some of the older age bins.

The two primary quantities of interest from such calculations are the estimates of total hydrothermal heat flux and the near-axial heat flux. We thus discuss each of these quantities.

Net Hydrothermal Heat Flux

We find that of the predicted global oceanic heat flux of 32×10^{12} W, $11 \pm 4 \times 10^{12}$ W or $34 \pm 12\%$ occurs by hydrothermal flow. This estimate is in good agreement with the value of 10×10^{12} W determined by *Sclater et al.* [1980]. Our estimate is 10% higher, because our predicted heat flow is for the GDH1 thermal model, whereas theirs was for the *Parsons and Sclater*

TABLE 1. Heat Flow Data and Model Results Assuming Only Uncertainties Due to Observations

Age, Ma	Area, 10^6 km ²	Average Heat Flow, mW m ⁻²	
		Predicted	Observed
0-1	3.5	1020	131 ± 93
0-2	7.1	721	136 ± 99
0-4	14.2	510	128 ± 98
4-9	19.7	204	103 ± 80
9-20	31.8	136	82 ± 52
20-35	42.6	98	64 ± 40
35-52	37.0	77	60 ± 34
52-65	29.7	66	62 ± 26
65-80	37.3	60	61 ± 27
80-95	27.9	56	59 ± 43
95-110	24.8	53	57 ± 20
110-125	15.2	51	53 ± 13
125-140	16.7	50	52 ± 20
140-160	8.3	49	51 ± 14
160-180	3.4	48	52 ± 10

Age, Ma	Cumulative Heat Flux, 10^{12} W		
	Predicted	Observed	Hydrothermal
1	3.6	0.4 ± 0.3	3.2 ± 0.3
2	5.1	1.0 ± 0.7	4.1 ± 0.7
4	7.2	1.8 ± 1.4	5.4 ± 1.4
9	11.3	3.8 ± 2.1	7.4 ± 2.1
20	15.6	6.5 ± 2.7	9.1 ± 2.7
35	19.8	9.2 ± 3.2	10.5 ± 3.2
52	22.7	11.5 ± 3.4	11.2 ± 3.4
65	24.6	13.3 ± 3.5	11.3 ± 3.5
80	26.9	15.6 ± 3.7	11.3 ± 3.7
95	28.5	17.3 ± 3.9	11.2 ± 3.9
110	29.8	18.7 ± 3.9	11.1 ± 3.9
125	30.6	19.5 ± 3.9	11.1 ± 3.9
140	31.5	20.4 ± 3.9	11.1 ± 3.9
160	31.9	20.8 ± 3.9	11.1 ± 3.9
180	32.0	21.0 ± 3.9	11.0 ± 3.9

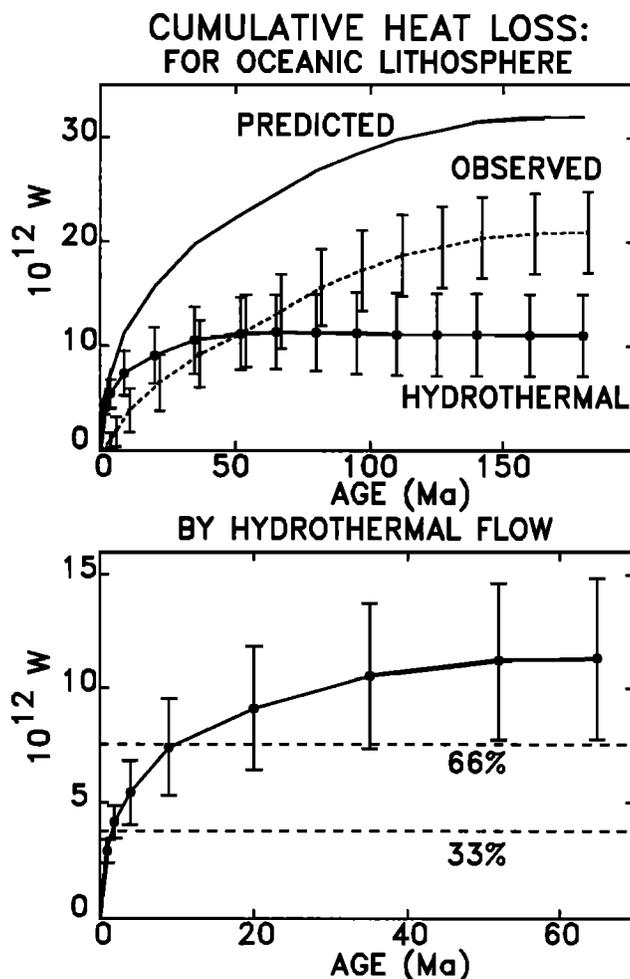


Fig. 5. (top) Cumulative predicted, observed, and inferred hydrothermal heat fluxes as a function of age. Data are listed in Table 1. The lines connect the points whose values were computed. For clarity, the 1 Ma point is not plotted, and the observed values are offset. Error bars are one standard deviation of the data. (bottom) Cumulative inferred hydrothermal heat flux for 0-65 Ma. Data are from Table 1, except for the 1 Ma point ($2.9 \pm 0.5 \times 10^{12}$ W) which is from Table 2. This estimate reflects the greater uncertainty in the near-axial value resulting from incorporating uncertainties in the thermal model and crustal area.

[1977] (PSM) model. Because GDH1 predicts heat flow about 10% higher than PSM, the hydrothermal discrepancy predicted for the same observed heat flow is about 10% higher.

Our hydrothermal heat flux estimates are, however, significantly greater than the values of $5-7 \times 10^{12}$ W obtained by *Wolery and Sleep* [1976] and *Sleep and Wolery* [1978]. Their estimates are lower in part due to the limited heat flow data then available. At the time, it was assumed that the sealing age for hydrothermal flow was ~20 Ma, whereas our larger data set indicates that hydrothermal heat flux continues to about 65 ± 10 Ma. Assuming a lower sealing age omits a significant amount of hydrothermal heat flux. For example, on a global basis, ~33% of the hydrothermal heat flux occurs for ages greater than 9 Ma (Table 1). *Wolery and Sleep's* [1976] estimate was also lower because they used a cooler temperature model, a 100-km-thick plate with a 1200°C basal temperature, which predicts asymptotic heat flow for old lithosphere of 30 mW m⁻², 38% less than for GDH1. The thermal model and the sealing age are not independent, in that the cooler model implies a younger sealing age. As discussed shortly, the choice of a model for young

lithosphere is not straightforward, and we use GDH1 because of its good fit to the depths and heat flow for old lithosphere.

Near-Axial Hydrothermal Heat Flux

The magnitude of the hydrothermal heat flux near the axis is of special interest because the geochemical effects of hydrothermal flow are thought to be greatest near the ridge, where water temperatures are highest [Staudigel *et al.*, 1981; Alt and Honnorez, 1984; Wolery and Sleep, 1988]. The relative fraction of near-axial versus off-axial heat flux is thus an important constraint on models.

We compute (Table 1) the cumulative hydrothermal heat flux for ages of 1, 2, and 4 Ma, and find values of 3.2 ± 0.3 , 4.2 ± 1.0 , and $5.4 \pm 1.4 \times 10^{12}$ W, respectively. These values correspond to 29%, 38%, and 49% of the net hydrothermal heat flux. They thus support the observation that most of the hydrothermal heat flux occurs in crust older than 1 Ma. The 0-4 Ma estimate is consistent with Sclater *et al.*'s [1980] estimate that 45% of the hydrothermal heat flux occurs in this age range.

Because such estimates of near-axial flux are often compared to those inferred from geochemical arguments, it seems useful to try to assess the uncertainty in our estimates further. The uncertainties quoted so far come from the standard deviation of the heat flow measurements in the relevant age range. Additional uncertainties result from the uncertainty in the area of crust of the relevant age and from uncertainty in the heat flow predicted by the thermal model.

The 0-4 Ma area from Sclater *et al.* [1980] is within 3% of one from a recent area-age compilation [Stoddard, 1989], which yields 13.8×10^6 km². The implied 0-1 Ma age area, 3.55×10^6 km², however, differs from the 2.94×10^6 km² estimated from global spreading rates [Chase, 1972]. Spreading rates from the recent global plate motion model NUVEL-1 yield essentially the same value as Chase's. Some of the 17% difference between these 0-1 Ma area estimates may be due to marginal basin spreading [Parsons, 1981].

To assess the uncertainty in the predicted heat flow, we consider alternative thermal models. It is unclear what model is most appropriate for predicting the thermal structure of young lithosphere if no hydrothermal cooling was present. The primary constraints on thermal models are the depth and heat flow in old lithosphere, which reflect both the basal temperature and plate thickness. For young lithosphere, the depth data are adequately fit by a cooling half-space model (Figure 3) and so are insensitive to plate thickness. Moreover, because in young lithosphere the hydrothermal circulation prevents the heat flow data from being used to constrain the model, the depths alone constrain only the product of the coefficient of thermal expansion and the melting or basal temperature. As a consequence, models are generally derived to fit old lithosphere and applied for young lithosphere, implicitly assuming that the basal temperatures for old and young lithosphere are the same. Though this approximation has limitations [Stein and Stein, 1992], it has the advantage of simplicity. Following this approach, we use GDH1 because it provides a good fit to heat flow and depths in old lithosphere.

We compare the 0-1 Ma hydrothermal heat flux predicted from GDH1 (Table 1) to those for several other models (Table 2). The Parsons and Sclater [1977] model, which is similar to GDH1 but somewhat cooler (Figure 3), predicts an average 0-1 Ma heat flow of 945 mW m^{-2} , compared to 1020 mW m^{-2} for GDH1. The Sleep [1975] model, which includes a ridge boundary condition which takes explicit account of the latent heat released during magma ascent and crust formation, has a 100-

TABLE 2a. Near-Ridge 0-1 Ma Hydrothermal Heat Flux Estimates, 10^{12} W, for Various Crustal Areas and Thermal Models

Area, 10^6 km^2	Model (Predicted Average Heat Flow, mW m^{-2})			
	GDH (1020)	PSM (945)	Sleep (810)	SGDH1* (1052)
3.55	3.2 ± 0.3	2.9 ± 0.3	2.4 ± 0.3	3.3 ± 0.3
2.94	2.6 ± 0.3	2.4 ± 0.3	2.0 ± 0.3	2.7 ± 0.3

*Sleep model with GDH1 plate thickness and basal temperature.

TABLE 2b. Near-Ridge 0-1 Ma Hydrothermal Heat Flux Estimates Including Assumed Uncertainties Due to Area, Melting Temperature, and Observations

Age, Ma	Area, 10^6 km^2	Melting Temperature, °C	Cumulative Hydrothermal Heat Flux, 10^{12} W
0-1	3.25 ± 0.3	1450 ± 200	2.9 ± 0.5
0-4	14.0 ± 0.3	1450 ± 200	5.3 ± 1.6

km-thick plate with a 1290°C basal temperature. We evaluate the heat flow for this model by differentiating the series solution for temperature with respect to depth and find average heat flow by integrating the resultant series over an age range. The model is even cooler than PSM and predicts an average 0-1 Ma heat flow of 810 mW m^{-2} . This model predicts an asymptotic heat flow of 32 mW m^{-2} and is thus too cold for old lithosphere, but we use it to represent an extreme case for young lithosphere. We also use a version of the Sleep model with a 95-km-thick plate and a 1450°C basal temperature, which combines the latent heat boundary condition and the GDH1 plate thickness and basal temperature. This model, SGHD1, has a 0-1 Ma heat flow of 1052 mW m^{-2} , slightly higher than for GDH1.

Table 2a shows the 0-1 Ma hydrothermal heat flux for these different models and area values. The individual estimates include only the uncertainty due to the heat flow observations, and the range of the estimates illustrates the effect of different areas and models. As noted by Sleep and Wolery [1978], the estimated hydrothermal heat flux is not very sensitive to the thermal model, owing to the large differences between the predicted and observed heat flow. We thus consider the basic result, that most of the hydrothermal heat flux occurs at ages greater than 1 Ma, quite robust.

We also approach this issue in another way, by explicitly considering the uncertainty in the hydrothermal heat flux due to the three factors. We assume that the predicted heat flow for young lithosphere as a function of age t is given by the half-space expression [Davis and Lister, 1974]

$$q'(t) = kT_m(\pi\kappa t)^{-1/2}$$

where k is thermal conductivity, T_m is melting temperature, and κ is thermal diffusivity. The predicted average heat flow between the ridge axis and age t is then

$$\bar{q}(t) = \frac{1}{t} kT_m(\pi\kappa)^{-1/2} \int_0^t (t')^{-1/2} dt' = cT_m^{-1/2}$$

where $c = 2k(\pi\kappa)^{-1/2}$. The corresponding hydrothermal heat flux is then

$$Q^h = A(\bar{q}(t) - q)$$

where A is the crustal area and q is the average observed heat flow. If we treat the area, the melting temperature, and the observations as variables and assume linear propagation of errors, the uncertainty in the hydrothermal heat flux is

$$\sigma_{Q_h}^2 = (\bar{q}(t) - q)^2 \sigma_A^2 + A^2 \sigma_q^2 + (Act^{-1/2})^2 \sigma_{T_m}^2 .$$

Using this expression, we estimate the near-ridge hydrothermal heat flux and associated uncertainty, assuming uncertainties in the area of crust, the thermal model (indicated by melting temperature) and the observations. We use an area estimate midway between the values mentioned previously, the GDH1 melting temperature, and assume uncertainties of $0.3 \times 10^6 \text{ km}^2$ in the area and 200°C in melting temperature. These area and melting temperature ranges, and thus the resulting values and uncertainties in hydrothermal heat flux, span the range of values considered earlier (Table 2a). These values, which include thermal model and area uncertainties, are quite similar to those which incorporated only the uncertainty due to the observations. We thus consider the values in Table 2b our best estimates of the near-axial hydrothermal heat flux. For these estimates, $2.9 \pm 0.5 \times 10^{12} \text{ W}$ or $26 \pm 4\%$ of the hydrothermal heat flux occurs within 1 m.y. of the axis, again showing that most of the hydrothermal heat flux is off-axial.

All of our estimates, however, do not include a possible systematic data sampling bias, which is difficult to assess but may be significant. Because heat flow measurements require about 10 m of sediment for the probe to be emplaced, measurements in young lithosphere are made in sediment ponds. Such measurements [Langseth *et al.*, 1992] suggest that water is flowing downward in the sediments, in accord with modeling [Lowell, 1980] indicating that in thinly sedimented regions, water should descend at low points and upwell at high ones. As a result, isotherms would be depressed at low points, giving lower conductive heat flow and raised at higher elevations, giving higher conductive heat flow [Lister, 1972]. The observations are thus biased to lower conductive heat flow, and hence tend to overestimate the discrepancy between the predicted and observed heat flux. As a result, our estimates of the uncertainties are lower bounds, and our estimates of the hydrothermal heat flux are upper bounds.

Comparison With Other Axial Estimates

Comparison of these estimates of hydrothermal heat flux with estimates from other techniques is not straightforward. The primary issue in comparing estimates is the age range over which they treat the heat flux. In particular, much attention has been directed to estimates of axial or near-axial hydrothermal heat loss, both in terms of its effects on the tectonics of the ridge axis and in terms of its geochemical effects.

The literature on this issue is complicated by the fact that terms such as "axial," "near-axial," and "off-axial" are often not defined. This ambiguity may be in part unavoidable in geochemical discussion, because it may be unclear over what age range various rock-water interactions extend. Our study has the advantage that for any age, the predicted and observed heat flow, and hence the hydrothermal heat flux, age can be easily estimated. We thus use "axial" for the interval 0-0.1 Ma, "near-axial" for 0-1 Ma, and "off-axial" for ages greater than 1 Ma. These divisions are, of course, somewhat arbitrary.

One commonly cited estimate [Morton and Sleep, 1985] is that 10-20% of the total hydrothermal heat loss occurs in the axial region. This value is based on modeling the hydrothermal cooling within 50,000-100,000 years of the ridge axis sufficient to yield a magma chamber at the depths where one is suggested by seismic data. This estimate is consistent with ours. Given the uncertainties in determining the ages of heat flow sites and the position of the ridge axis, it is difficult to reliably estimate the

observed heat flow within 0.1 m.y. of the axis. If we assume the same average observed heat flow as for 0-1 Ma (131 mW m^{-2}), and use the predicted average heat flow (3326 mW m^{-2}) for 0-0.1 Ma, the average axial hydrothermal heat flux would be 3095 mW m^{-2} , or about 3 W m^{-2} . Hence assuming an area of $0.3 \pm 0.03 \times 10^6 \text{ km}^2$, and a melting temperature of $1450 \pm 200^\circ\text{C}$ yields $0.9 \pm 0.1 \times 10^{12} \text{ W}$ or $8 \pm 1\%$ of the total hydrothermal heat flux within 0.1 Ma of the axis.

For comparison with estimates derived from measurements in the water column, it is useful to consider the hydrothermal heat flux per unit ridge length. For a typical ridge with a full spreading rate of 60 mm yr^{-1} , we predict an axial (0-0.1 Ma) hydrothermal heat flux of 18 MW km^{-1} . Although our calculations do not include a dependence of thermal structure (and hence heat flow) on spreading rate, an effect which is greatest close to the axis, the spreading rate here simply scales the age range into a distance. This estimate of about 10 MW km^{-1} for average spreading rates is consistent with those from other thermal models [Morton and Sleep, 1985]. Comparison with estimates from other techniques, however, is more difficult [Dymond *et al.*, 1988]. Estimates for the Juan de Fuca Ridge derived by sampling vents at the seafloor are about an order of magnitude lower, about 1 MW km^{-2} [Bemis *et al.*, 1993]. This discrepancy may reflect underestimation of the heat loss, because both some vents and the possibly-common low temperature flow are missed. Studies of hydrothermal plumes estimate their heat content at $\sim 1000 \text{ MW}$ [Baker and Massoth, 1987]. Assuming the plumes represent about 10 km of ridge length, the estimated flux per unit ridge length is about 100 MW km^{-2} , an order of magnitude higher than our estimate. Thus plumes appear to be transporting more heat than the total steady state surface flux for the cooling lithosphere. The discrepancy appears not to be an artifact of the age interval sampled, as the plume studies extend to distances of a few km off-axis, comparable to the age interval we assume. Hence if both the thermal and plume calculations are appropriate, the plumes observed may be intermittent, in accord with the observation that only a fraction of the ridge ($\sim 20\%$ for the Juan de Fuca) presently discharges plumes [Baker and Hammond, 1992].

We thus believe, because of this comparison and the comparison of our estimates with those of Sclater *et al.* [1980], that our estimates of the total, near-axial, and axial hydrothermal heat fluxes are reasonably robust. Uncertainties in these quantities remain, however, due to the uncertainties in both the data (including the sampling bias toward sedimented sites) and the thermal model.

Water Flux Estimates

Comparison with heat and water fluxes inferred from geochemical data is significantly more complicated. Geochemical estimates [e.g., Edmond *et al.*, 1979; Mottl, 1983] infer hydrothermal heat flux rates via calculations assuming a mass of fluid and its temperature. Because the inferred water flux rate $F = H/Tc_p$ is related to the hydrothermal heat flux H via the water temperature T and the specific heat of water c_p , the water temperature and specific heat assumed are significant. The specific heat depends on both temperature and composition. Sleep and Wolery [1978] show that the inferred water flux varies by a factor of almost 7 between inferred water temperatures of $100\text{-}400^\circ\text{C}$.

Although little is known about the temperatures of off-axis upwelling water, these temperatures are probably much lower than the high temperatures ($\sim 350^\circ\text{C}$) of the axial flow. Fehn and

Cathles' [1986] modeling predicts that within 25 km (~1 m.y.) of the axis, high-temperature flow will give way to low-temperature flow with temperatures less than ~100°C. As a result, the water flux should be even more dominantly off-axial than the heat flux, because a larger volume of low temperature water is needed to transport the same heat. Consider a simple case where the 0-1 Ma hydrothermal heat flux of 3×10^{12} W has an average water temperature of 250°C, and the remaining off-axial heat flux of 8×10^{12} W has an average water temperature of 50°C. Using for simplicity specific heats for pure water of 4.5 and 4.1×10^3 J kg⁻¹ s⁻¹ [*Helgeson and Kirkham*, 1974] gives a near-axial water flux of 8.5×10^{13} kg yr⁻¹ and an off-axial flux of 1.2×10^{15} kg yr⁻¹. Thus the near-axial flux transports 27% of the heat, but only 7% of the total (1.3×10^{15} kg yr⁻¹) water. For comparison, assuming average water temperatures of 300°C and 75°C yields near-axial and off-axial water fluxes of 6.6×10^{13} kg yr⁻¹ and 8.2×10^{14} kg yr⁻¹, with essentially the same fraction (8%) of the total (9×10^{14} kg yr⁻¹) water flux being near-axial.

Thus because most of the hydrothermal heat flux occurs at ages greater than 1 Ma, it is probably not appropriate to use the high (~350°C) water temperatures observed near the axis for describing processes that extend beyond very young ages. Calculations using these temperatures will underestimate the water flux for a given heat flux or overestimate the heat flux for a given water flux. For example, assuming that all the hydrothermal heat flux occurred via 300°C water would predict a much lower water flux, 2.4×10^{14} kg yr⁻¹.

These examples illustrate the difficulty in developing coupled estimates of hydrothermal heat and water fluxes. First, both heat flux and geochemical estimates are limited by our knowledge of the primary quantity for the calculation, hydrothermal heat flux, or water mass. For example, due to the low hydrothermal heat flux assumed from the then available data, *Wolery and Sleep*'s [1976] estimate of the total hydrothermal water flux, 2×10^{14} kg yr⁻¹, and *Mottl*'s [1983] estimate of near-axial water flux, 2×10^{13} kg yr⁻¹, are lower than ours. Other geochemically based water flux estimates are biased downward by the assumption that all water flow occurs at high axial temperatures, as noted by *Mottl* [1983].

Resolution of these difficulties may be some time in coming. Formulation of an appropriate model to relate water flux and heat flux is challenging given that the off-axial flow is rarely sampled and poorly understood. Ideally, one would like a model with appropriate temperatures for the relative amounts of near-axial and off-axial flow, covering the age range where the relevant reactions are thought to occur. Such a model would permit comparison of the geochemically inferred hydrothermal heat flux rates to those inferred from heat flow and use of the relative amounts to infer the age range for the geochemical interactions. Until the temperature data are available to constrain such a model, estimates involving water fluxes have considerable uncertainties because different temperatures give quite different fluxes. In addition, the variation in specific heat with fluid temperature and composition, and thus its variation as the flow changes with age, provides additional uncertainty. Given this challenge, we happily restrict our scope here to heat flow-based estimates.

SEALING AGE FOR HYDROTHERMAL FLOW

The age at which hydrothermal flow ceases to be significant is important for the thermal evolution of the oceanic crust. In addition, it may be important for the physical evolution of the

crust, because the cessation of hydrothermal flow may reflect, at least in part, decreased porosity of the basaltic crust due to hydrothermal deposition of minerals [*Jacobson*, 1992]. Because direct measurements of off-axial water flow are rare compared to heat flow measurements, most water flow is generally assumed to cease at approximately the sealing age, where the observed and predicted heat flow are approximately equal [*Wolery and Sleep*, 1976; *Anderson and Hobart*, 1976; *Anderson et al.*, 1977; *Sleep and Wolery*, 1978]. Beyond this age, heat transfer through the sediments immediately below the sea floor is thought to be primarily conductive, although some water circulation may continue in the basement rock underlying the sediment [*Anderson and Skilbeck*, 1981].

Estimation of the sealing age from the heat flow discrepancy depends on both the data available and the thermal model against which they are compared. Using the data set here and the GDH1 model, we find important differences from some of the sealing ages inferred previously. It has been assumed that significant differences exist between the sealing ages for different ocean basins. Figure 6 compares our data to the widely cited results of *Anderson and Skilbeck* [1981]. For the Pacific, *Anderson and Skilbeck* show the flux anomaly ending at ~20 Ma, whereas our data show it persisting to ~70 Ma. For the Atlantic, their data showed lower heat flow than we observe for the ~10-60 Ma range, presumably because of the limited data then available. The Indian Ocean data show a sealing age similar to their estimate. These data also reflect the anomalously high heat flow for Cretaceous age lithosphere in the Central Indian Ocean [*Stein and Weissel*, 1990], possibly associated with the diffuse plate boundary between the Indian and Australian plates [*Wiens et al.*, 1985; *Stein et al.*, 1990].

We estimate the sealing ages and test for differences between oceans by fitting a least squares line to the heat flow fraction in 2-m.y. bins for ages less than 50 Ma (Figures 4 and 7). The sealing age t_s is the age at which the line reaches one. The data are somewhat scattered but are adequate to define lines. By this measure, the sealing ages for the different oceans are comparable, with at most a suggestion that the Atlantic seals at a slightly younger age. We thus regard all three ocean basins as sealing at an age consistent with that of the entire data set (Figure 4), 65 ± 10 Ma.

This exercise illustrates the utility and limitations of the sealing age concept. Clearly, there is an age range for which the heat flow fraction increases toward one and beyond which the heat flow fraction is approximately one. The precise transition between these two ranges is not well defined, because the data are scattered and relatively sparse. As a result, the linear fit yields an estimate of the sealing age with considerable uncertainty. Presumably, this uncertainty reflects both the uncertainty in the heat flow measurements and the variation in heat flow for a given age range. One can thus think of the sealing age as an age range beyond which most heat transfer at the seafloor occurs by conduction.

Because the heat flow fraction measures only heat transfer at the seafloor, the observation that it is close to one indicates that the expected heat loss is occurring by conduction at the seafloor. This does not preclude water circulation at depth. In some areas, water flow may maintain the basement rock at a constant temperature, such that conduction through the sediment gives surface heat flow measurements correlated to basement topography [*Davis et al.*, 1989, 1992]. The global data set we use does not address such fine-scale variations, in that the sites are either isolated or areal averages.

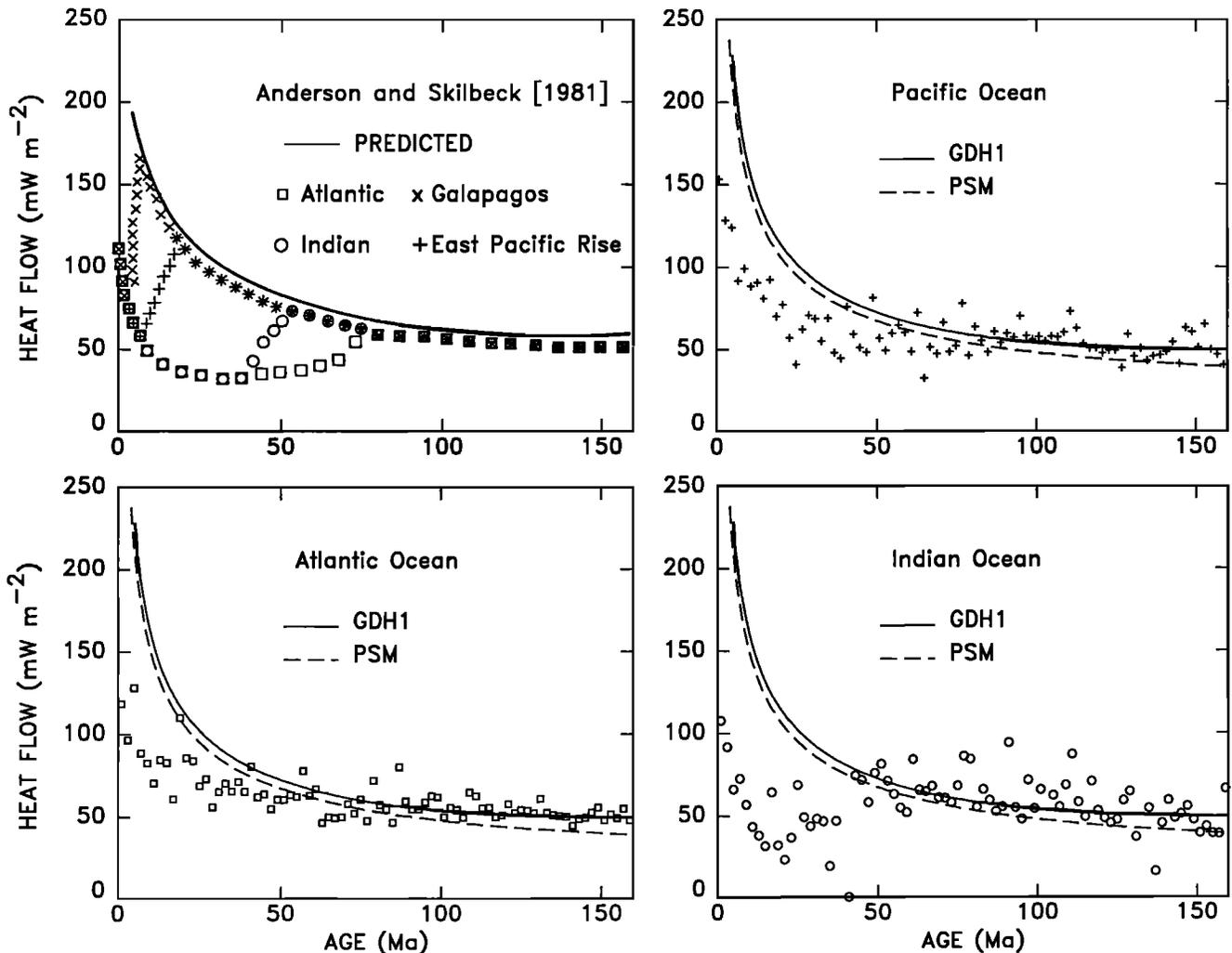


Fig. 6. Observed and predicted heat flow versus age for the ocean basins. (top left) Summary of results from earlier study [Anderson and Skilbeck, 1981]. In their figure, the predicted curve is schematic. Other panels show results for our larger data set, compared to predictions of reference models GDH1 and PSM [Parsons and Sclater, 1977]. We find that the sealing age for the Pacific is comparable to that for the other ocean basins, in contrast to the earlier result showing a much younger sealing age.

The linear fitting approach characterizes simply the presumably complex age and site dependence of the heat flow fraction. The scattered data appear inadequate to characterize the age dependence beyond a linear trend. The heat flow fraction might be expected to increase most rapidly for the younger (0-4 Ma) ages and more slowly near the sealing age, as perhaps suggested by the data.

Our Pacific sealing age differs from that of Anderson and Skilbeck [1981] because their data were compared to the predictions of a thermal model with an 80-km-thick lithosphere, a 1200°C basal temperature, and a thermal conductivity of $6.15 \times 10^{-3} \text{ cal } ^\circ\text{C}^{-1} \text{ cm}^{-1} \text{ s}^{-1}$. This model predicts too low heat flow in older lithosphere, which was not apparent because they had only data for 0-50 Ma lithosphere [Anderson and Hobart, 1976], whereas our data extend to older ages. As a result, their model at 20 Ma predicts heat flow $\sim 29 \text{ mW m}^{-2}$ lower than GDH1 and hence implies a younger sealing age. Thus global hydrothermal heat flux estimates using this young sealing age [Wolery and Sleep, 1976, 1988; Anderson et al., 1977; Sleep and Wolery, 1978] are significantly lower than ours.

It is not clear how much significance to ascribe to the scatter in the heat flow fraction for ages exceeding the nominal sealing

age. Some of the scatter presumably reflects the noise in the data, both from measurement uncertainties and topographic effects [e.g., Lachenbruch, 1968; Noel, 1984]. There also appear to be sites in relatively old lithosphere where heat flow studies indicate the water circulation occurs, such as the 80 Ma site discussed by Embley et al. [1983]. The limited number of sufficiently dense heat flow surveys on old lithosphere suggest that such water flow is not common. Considerably more such surveys would be required for any meaningful generalization about water flow. The heat flow data presently available indicate only that any water flow in older lithosphere is not transporting significant amounts of heat through the seafloor.

MECHANISM OF SEALING

The mechanisms which cause the heat flow discrepancy, and hence presumably hydrothermal circulation, to decrease with lithospheric age have long been of interest. Two primary effects, both of which may be present, are thought to contribute. Anderson and Hobart [1976] proposed that the heat flow fraction was low for young, unsedimented, crust and rose to about one once the basement rock was covered by 150-200 m of sediment. In

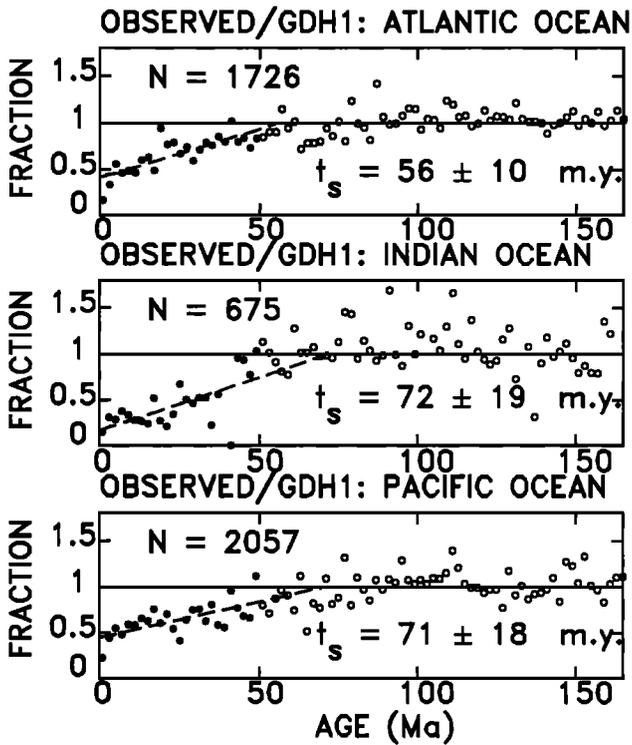


Fig. 7. Heat flow fractions versus age for the three ocean basins. Data are shown in 2-m.y. bins. The fractions for ages < 50 Ma (solid circles), which were not used in deriving GDH1, are fit by a least squares line. The sealing ages, where the line reaches one, are similar for the three oceans and consistent with the global average of 65 ± 10 Ma.

this model, the sediment isolates the crustal convective system, which no longer exchanges water with the ocean. A second possibility, suggested by the thinning of, and seismic velocity increase in, the uppermost layer 2A of the crust [Houtz and Ewing, 1976], is that the vigor of hydrothermal circulation is reduced with age by decreased porosity and hence permeability of the crust due to hydrothermal deposition of minerals [Anderson et al., 1977]. For this mechanism, the reduction in hydrothermal heat flow should correlate with variations in crustal seismic velocity, as both reflect the physical evolution of the crust. Often it is assumed that both increased sediment cover and reduced crustal permeability contribute to decreasing the hydrothermal flow and hence heat transfer (Figure 8) [Anderson and Skilbeck, 1981; Jacobson, 1992]. In such models, it is assumed that for ages older than the sealing age inferred from the heat flow, some passive hydrothermal circulation may still occur within the crust but is largely isolated from the seafloor by the integrated permeability of the sediment column.

The question is whether the increase in heat flow fraction to a sealing age is due primarily to the overlying sediment or age-dependent properties of the crust. The two possible effects appear similar in the data, because sediment thickness generally increases with age. In the hope of discriminating between these effects, we examine the heat flow fraction as a function of age, for sites with different sediment thicknesses. Of the 5539 sites, sediment thickness has been determined at 1494 from seismic reflection profiles. Sediment thicknesses are given in seconds of two-way travel time in 0.05-s increments. Assuming an average seismic velocity in sediment of 2 km/s, 1 s corresponds to 1 km of sediment.

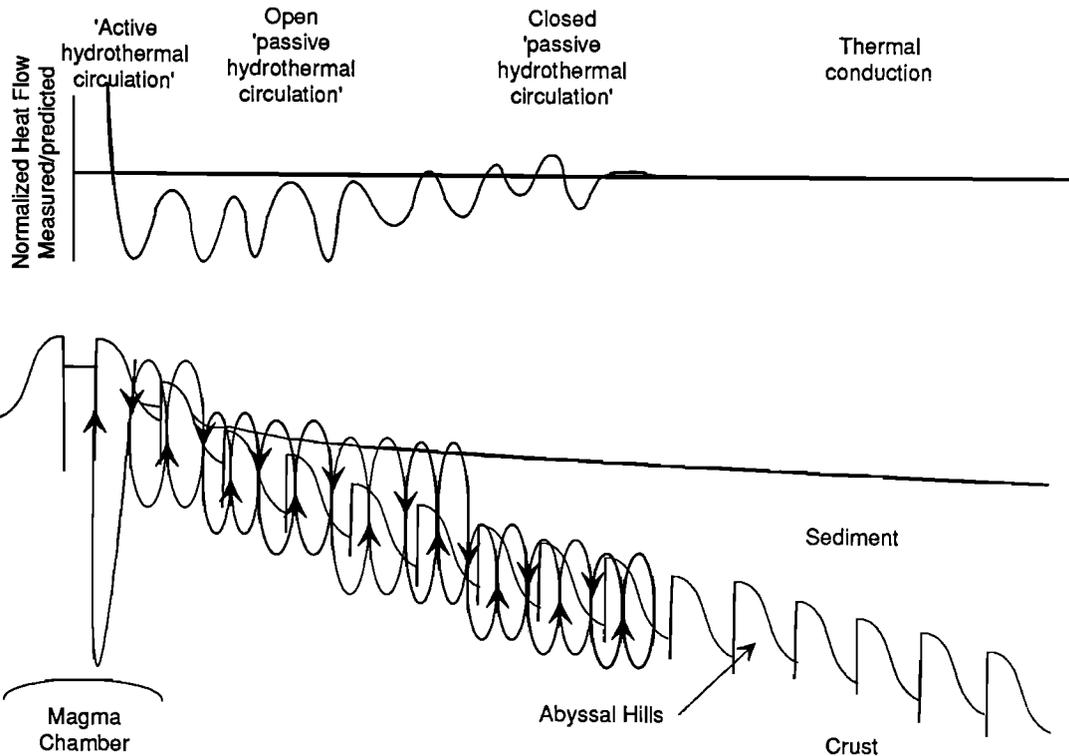


Fig. 8. Schematic model for the evolution of the hydrothermal system in the oceanic crust [Jacobson, 1992]. In this model, the heat flow fraction reaches one once sediment is thick enough to seal off the crust from the ocean. This age is considered to be the transition from "open passive hydrothermal circulation" to "closed passive hydrothermal circulation." Beyond this age, hydrothermal flow may continue in the crust, but it is isolated from the seafloor and hence produces no heat flow anomaly. Our results are consistent with the general features of this model, with the exception that the sealing appears to reflect crustal age primarily, and sediment thickness only secondarily.

Figure 9 shows the heat flow fraction as a function of age, for groups of sites with different sediment thicknesses. The data, though scattered, permit sealing age estimates. The sealing age decreases with increasing sediment thickness, being 98 ± 79 Ma for sites with less than 0.05 s (~50 m), 83 ± 32 Ma for sites with 0.05-0.2 s (~50-200 m) sediment, and 51 ± 17 Ma for sites with 0.2 s (~200 m) or more sediment. The sealing ages are sufficiently poorly determined that differences between them are not formally significant. The data suggest, however, the expected pattern of the more sedimented sites "sealing" at a younger age. It is striking, however, that even those sites with less than ~50 m sediment show the increase of heat flow fraction with age. It thus appears that 100-200 m of sediment is not required for the measured heat flow to approach that predicted. Moreover, the fact that sites with more than ~200 m sediment show the increase in heat flow fraction with age indicates that this amount of sediment is not in itself enough to cause the heat flow fraction to rise to one.

An alternative way to examine the effects of sediment on the heat flow is to use the sedimentary environment classification of *Sclater et al.* [1976]. The best sedimented sites, classified "A", have flat or rolling hills with more than 150-200 m of continuous sediment cover within 18 km. "B" sites have flat or rolling hills with generally continuous sediment cover, with either an outcropping basement high or thin sedimentary cover. Poorly

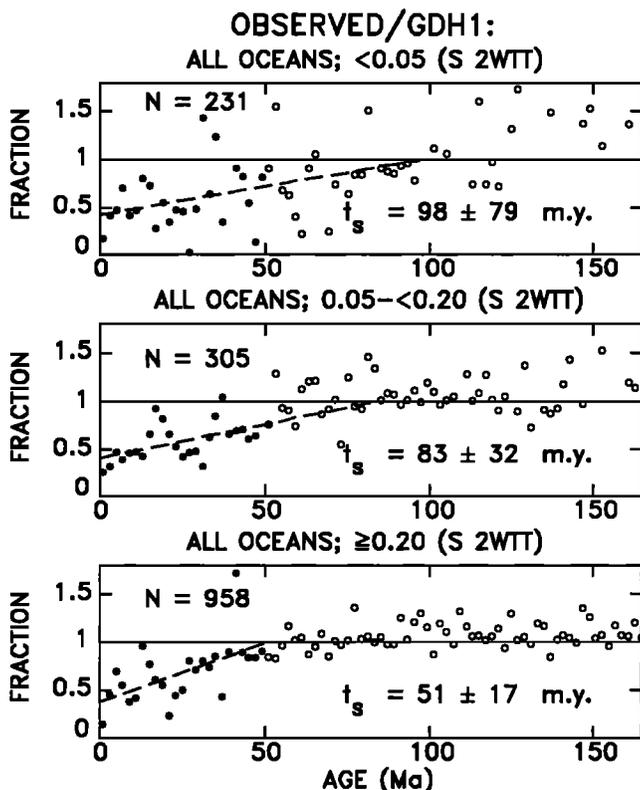


Fig. 9. Heat flow fractions versus age for groups of sites with different sediment thicknesses. Data are shown in 2-m.y. bins. The least squares line fit to the fractions for ages < 50 Ma (solid circles) gives the sealing age. All three groups show the increase in heat flow fraction with age, indicating that ~200 m of sediment is neither necessary nor sufficient to seal the crust. (top) Data for sites with less than 0.05 s (~50 m) sediment. (middle) Data for sites with 0.05-0.2 s (~50-200 m) sediment. (bottom) Data for sites with more than 0.2 s (~200 m) sediment. Some of the scatter results from the limited number of sites for lithosphere older than 50 Ma (top) and 100 Ma (middle).

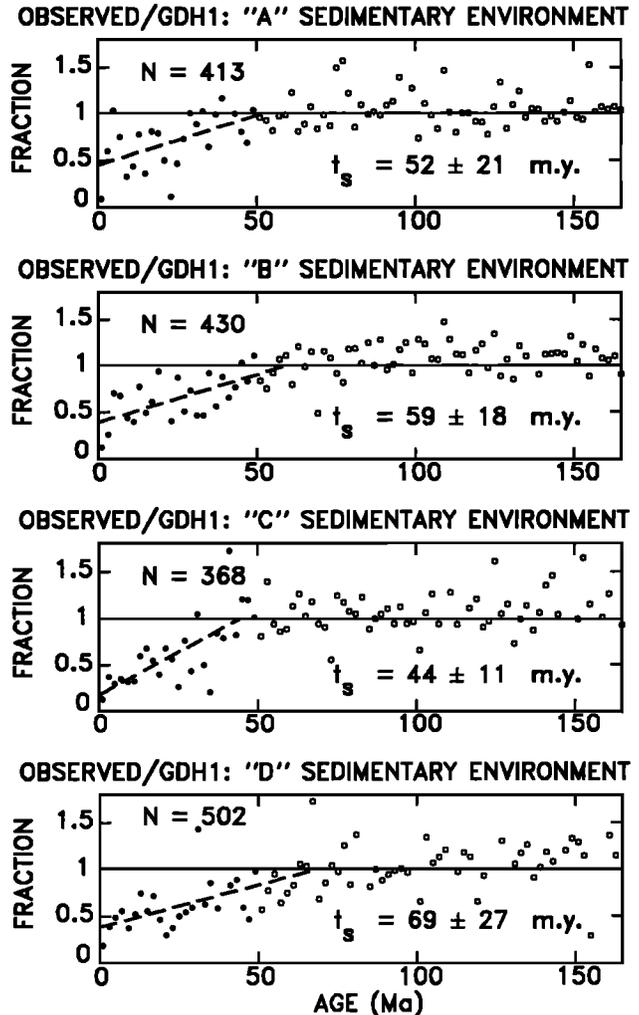


Fig. 10. Heat flow fractions versus age for different sedimentary environments, ranging from the best "A" to worst "D" (sediment ponds) sedimented. There is little difference between the behavior with age of the different environment types, indicating that the increase of heat flow fraction with age to a sealing age does not require significant sedimentary cover.

sedimented sites are classified as "C," rolling hills or rough topography with a thin or variable sediment cover, or "D," sediment ponds next to outcropping basement highs. It has been assumed that heat flow at A sites will be the least affected by hydrothermal circulation, whereas measurements at C or D sites may be significantly affected.

We thus examine (Figure 10) the heat flow fraction as a function of age for the sites with different sedimentary environments, and find little difference. There is a slight suggestion of older sealing ages for the assumed-poorer environments. These plots further suggest that the phenomenon of heat flow fraction increasing with age to one does not require significant sedimentary cover.

Additional insight can be obtained by considering the variation of sediment thickness with age at the heat flow sites. Figure 11 shows the median sediment thickness in 2-m.y. bins for the global data. As expected, sediment thickness increases with age. The scatter for a given age is large, because sites in very different settings are averaged. We characterize the average sediment thickness at sites with ages less than the sealing age by fitting a least squares line to the data for 0-50 Ma. The line

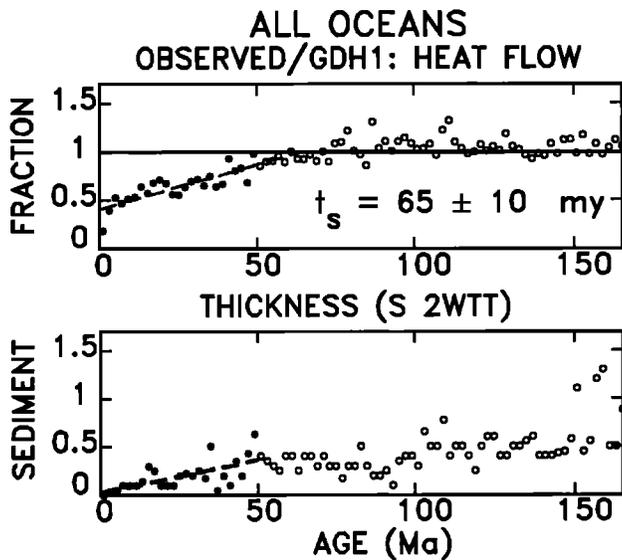


Fig. 11. Comparison of (top) the heat flow fraction versus age for the global data set to (bottom) the median sediment thickness at the sites versus age. The increase in heat flow fraction with age continues for (> 30 Ma) ages where sediment thickness exceeds ~ 200 m.

indicates that on average, a sediment thickness of $0.1 s$ (~ 100 m) occurs by 10 Ma and $0.2 s$ (~ 200 m) occurs by 33 Ma. Figure 9 shows that the heat flow fraction increases with age even for ages with sediment thicker than ~ 200 m.

Figures 9-11 together suggest that the primary control on the heat flow fraction, and thus the amount of hydrothermal heat flux, is the age of the crust. Even sites with less than ~ 50 m of sediment, and those with the poorest (D) sedimentary environment, show the heat flow fraction increasing with age. These data, together with the increase of heat flow fraction with age for the heavily sedimented and A environment sites, indicate that 100-200 m sediment is neither necessary nor sufficient for the heat flow to reach that predicted.

The effect of overlying sediment appears instead to be secondary, as suggested by the younger sealing ages for the heavily sedimented sites. Other evidence in favor of sedimentary cover having an effect comes from detailed surveys indicating a correlation between sediment thickness and heat flow [e.g., *Anderson and Hobart, 1976; Davis and Lister, 1977*] and regional average studies suggesting that sites with lower relief seal at younger ages [*Abbott et al., 1992*]. These results are consistent with ours in that for regional studies, where the crustal age varies only slightly, the heat flow variations may reflect sediment thickness.

The heat flow fraction is only an indirect indicator of the presence or absence of water circulation. Such circulation is best detected by the rare heat flow surveys with sites close enough to detect heat flow variations and correlate them with water velocities inferred from the temperature gradients and variations in the chemistry of the water in the sediment. *Anderson and Skilbeck [1981]* noted that both the standard deviation of heat flow measurements and the ratio of the standard deviation to the mean value were higher for age ranges less than the sealing age and decreased toward the sealing age. They interpreted this change as reflecting the slowing of convection. Our data (Figure 12) show this decrease, which continues beyond the sealing age. Thus although the decrease is consistent with convection largely stopping at the sealing age, the continued decrease in the measurement scatter may reflect the presence of some flow and con-

tinued evolution of crustal properties. It is also intriguing that the ratio of the standard deviation to the predicted heat flow is roughly constant with age. This constancy reflects the ratio of two quantities that both decrease with age, perhaps because the predicted heat flow (the near-surface gradient in the absence of water flow) indicates approximately the temperature difference available to drive water convection and the standard deviation in part reflects this convection.

The latter issues bear out the challenge in relating heat flow as a function of age to the mechanisms controlling water circulation. Most statements about water flow which are based on heat flow data are at most plausible inferences rather than demonstrated facts. It is thus useful to distinguish generalizations about the heat flow data from inferences about hydrothermal circulation. Our results show that the heat flow fraction depends primarily on crustal age and only secondarily on sediment distribution. These results are consistent with the idea that

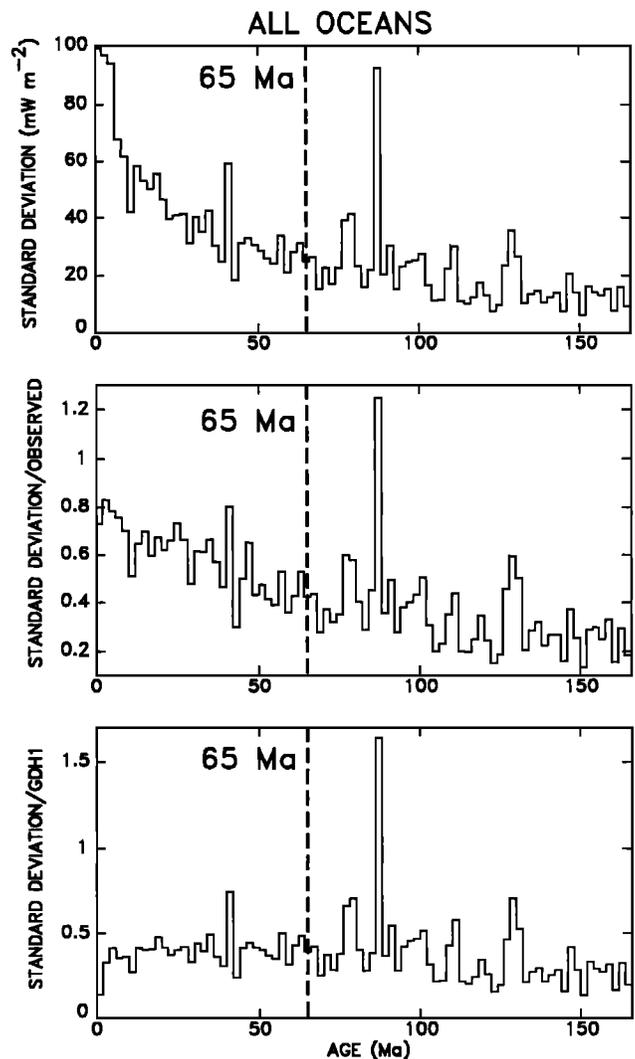


Fig. 12. (top) Standard deviation of the heat flow measurements in 2-m.y. bins versus age. (middle) Standard deviation normalized by the mean in each bin versus age. (bottom) Standard deviation normalized by the predicted heat flow for each bin versus age. The standard deviation and the standard deviation normalized by the mean decrease with age. This decrease has been interpreted as reflecting the slowing of convection. Note that both quantities continue to decrease beyond the average sealing age of 65 Ma. The standard deviation normalized by the predicted heat flow is roughly constant with age.

the heat flow fraction increases with age because of reduced flow in the crust due to decreased crustal porosity and hence permeability. Our results do not, however, show evidence for the idea that thick sediment is the primary control on the heat flow fraction approaching one and by implication the cessation of water flow. Instead, our results suggest that the overlying sediment may reduce, but not eliminate, the effects of water flow. Analysis of samples from drill sites, however, does not show the expected decrease in porosity with age [Johnson and Semyan, this issue], perhaps because the porosity measured in drill cores does not sample the appropriate spatial scales [Becker et al., 1982; Pezard, 1990].

Much clearly remains to be done before a clear understanding of the hydrothermal flow process is obtained. Such an understanding should ideally reconcile models based on large-scale average crustal properties, such as heat flow or seismic velocity, with site measurements of water flow and crustal physical properties.

CONCLUSIONS

We examine a large heat flow data set to reassess the basic ideas about the magnitude and distribution of hydrothermal heat flux that have been derived from smaller and more spatially limited data sets. Our primary results are as follows:

1. More than two thirds of the hydrothermal heat flux occurs at ages greater than 1 Ma. Given that the off-axial flux occurs via water flow at lower temperatures than the axial flux, even a larger fraction of the water flux will be off-axial. As a result, in estimating fluxes from geochemical data, use of the high water temperatures appropriate for the ridge axis may significantly overestimate the heat flux for an assumed water flux or underestimate the water flux for an assumed heat flux.

2. Our data show no significant difference in the sealing age for hydrothermal flow between the major ocean basins, in contrast to earlier studies. In particular, we find that hydrothermal heat flow in the Pacific extends to comparable ages as for the other ocean basins and suggest that earlier studies which found hydrothermal heat fluxes significantly lower than those we find were biased by an assumed-younger sealing age.

3. Our data do not support the traditional view that the cessation of hydrothermal flow, as inferred from the equality of observed and predicted heat flow, reflects the isolation of the basaltic crust from the ocean by ~200 m of sediment. Comparison of data from sites with different sediment thicknesses indicate that ~200 m of sediment is neither necessary nor sufficient to cause the observed heat flow to equal that predicted. It appears, instead, that the fraction of heat transported by hydrothermal flow depends primarily on crustal age and that sediment thickness has a lesser effect. These results are consistent with models in which water flow decreases with age primarily because of reduced crustal porosity and hence permeability.

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