Heat Flow and Hydrothermal Circulation

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INTRODUCTION

Hydrothermal circulation through young oceanic lithosphere is one of the primary modes of interaction between the solid earth and the ocean/atmosphere system (Figure 1). This circulation occurs because newly formed young oceanic lithosphere cools as it moves away from the ridges. Although most of the cooling occurs by upward heat conduction through the lithosphere, significant cooling also occurs via circulation of cold seawater through the rock. Thus hydrothermal circulation is a consequence of the plate tectonic cycle, as are several other of the primary processes (e.g. volcanism and the uplift/erosion cycle) by which the solid earth interacts with the ocean and atmosphere.

The papers in this volume illustrate the importance of hydrothermal circulation for a wide range of processes. The hydrothermal fluid differs significantly in composition from seawater [*Wolery and Sleep*, 1976; *Seyfried*, 1995; *Von Damm*, 1995], indicating that it altered the composition of the crust [*Humphris and Thompson*, 1978; *Staudigel et al.*, 1981; *Alt*, 1995], and gives rise to mineral deposits [*Rona*, 1988; *Hannington*, 1995; *Mills and Elderfield*, 1995]. The flux of hydrothermal fluid also has a major effect on the chemistry of the ocean and atmosphere [*Wolery and Sleep*, 1976, 1988; *Edmond et al.*, 1979; *Fyfe and Lonsdale*, 1981; *Hart and Staudigel*, 1982; *Rona et al.*, 1983; *Kadko et al.*, 1995]. Moreover, the heat removed from the crust raises the temperature of the deep ocean, with both near-ridge [*Lupton*, 1995] and oceanwide [*Helfrich and Speer*, 1995] consequences. In particular, the high-temperature hydrothermal vents provide a unique and important deep water biological environment [*Baross and Deming*, 1995; *Hessler*, 1995].

Important parameters for many of these processes are the volumes of heat and water transferred by hydrothermal circulation. Considerable attention has been devoted to estimating these fluxes, both in total and as a function of crustal age, and drawing inferences about what controls their variation with age. Despite its apparent simplicity, the problem is surprisingly challenging because the water flow varies dramatically in space, time, and temperature [*Little et al.*, 1987; *Schultz et al.*, 1992]. Hence although the dramatic high-temperature vents at ridges [*Corliss et al.*, 1979; *Macdonald et al.*, 1980; *Rona et al.*, 1986] and the corresponding plumes [*Baker and Massoth*, 1987; *Baker and Hammond*, 1992] can be directly sampled, the results are difficult to extend to the more diffuse low-temperature flow thought to extend to considerable

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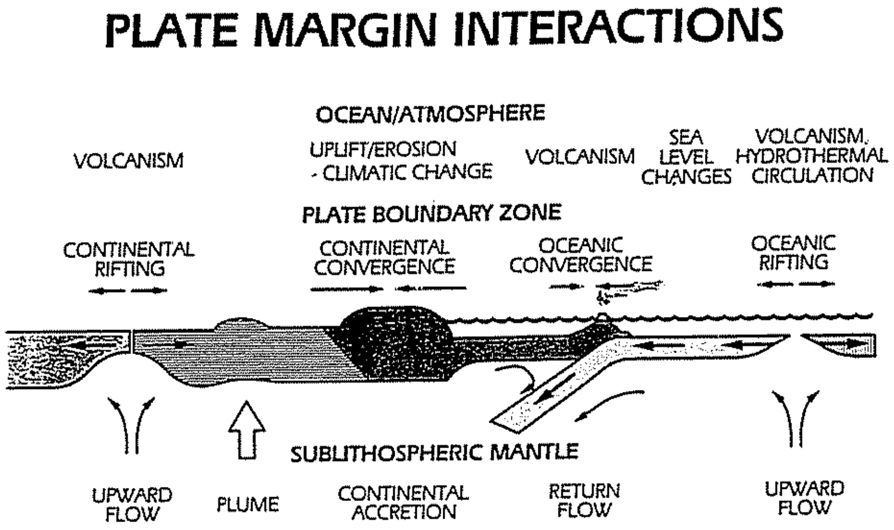

Fig. 1. Cartoon summarizing some of the primary modes of interaction between the solid earth and the ocean/atmosphere system. Hydrothermal circulation in young oceanic lithosphere is a consequence of plate tectonics.

distances from the ridges [*Anderson et al.*, 1977; *Langseth and Herman*, 1981; *Embley et al.*, 1983; *Abbott et al.*, 1984; *Williams et al.*, 1986; *Fisher et al.*, 1990, 1994; *Langseth et al.*, 1992].

As a result, the primary estimates of the hydrothermal heat and water flux are derived indirectly from inferences about how the circulation cools young oceanic lithosphere. By far the most important such inference comes from the fact that the heat flow measured at the sea floor for ages less than about 50-70 Myr is significantly less than predicted by thermal models of the cooling lithosphere in which all upward heat transfer takes place by conduction in the rock. This heat flow discrepancy is represented either as a difference or as the heat flow fraction, the ratio of the observed to predicted heat flow. Figure 2 shows the heat flow discrepancy for a large (approximately 5000 point) global heat flow data set [*Stein and Stein*, 1992; 1994]. In this data set, several detailed local surveys are consolidated into single points, to avoid the data being dominated by many points from a few small areas. The data are compared to lithospheric cooling model GDH1 (Global Depth and Heat flow) derived by joint inversion of the variations in seafloor depth and heat flow with age [*Stein and Stein*, 1992; 1993]. For our application here, the choice of cooling model generally has only minor effects, because for most models the predicted heat flow in young lithosphere is similar [*Stein and Stein*, 1994].

The discrepancy between the observed and predicted heat flow is thought to reflect the transport of significant amounts of heat at the sea floor by water circulation rather than the conductive cooling assumed in the models. *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 volume and age distribution of the heat transferred by water flux [*Wolery and Sleep*, 1976; *Anderson and Hobart*, 1976; *Sleep and Wolery*, 1978]. The circulation is sometimes thought of as divided into two stages [*Lister*, 1982; *Fehn and Cathles*, 1986; *Cathles*, 1990]. Near the ridge axis where the temperature gradients in the rock are high, "active" or "forced" circulation is thought to occur, 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]. In older crust where the temperature gradients are lower, vigorous rock cracking is presumed to have ceased, and "passive" or "free" circulation transports lower temperature water. The two-stage distinction is somewhat arbitrary in that diffuse low-temperature flow, as well as focused high-temperature flow, occurs even close to ridge axes [*Schultz et al.*, 1992; *Rona and Trivett*, 1992]. 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. For the data shown, a simple least-squares fit to the heat

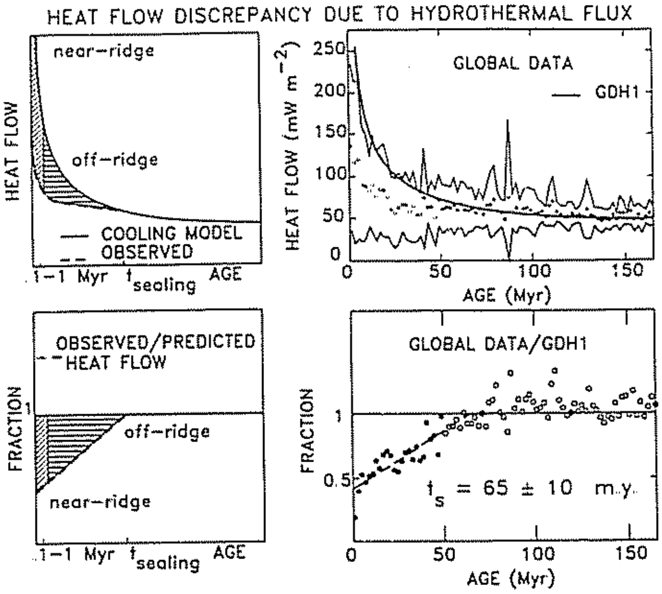

Fig. 2. Estimation of hydrothermal heat flux from heat flow data. Left: The heat flow discrepancy, the difference between the heat flow predicted by a lithospheric cooling model and the lower values observed (shaded), is assumed to indicate the heat transported by water flux. The data and model can be presented either in raw form *(top)* or as the fraction of the predicted heat flow that is observed *(bottom)*. The water flux is thought of as divided approximately into high-temperature near-ridge flow and low-temperature off-ridge flow. Beyond a "sealing age", defined as that where the observed and predicted heat flow approximately coincide, hydrothermal heat transfer is presumed to have largely ceased. Right: Observed heat flow versus age for the global data set and predictions of the GDH1 thermal model, shown in raw form *(top)* and fraction *(bottom)*. Data means and standard deviations are shown for 2-Myr bins. The sealing age estimated by a least squares fit to the heat flow fractions for ages < 50 Myr (closed circles) is 65 ± 10 Myr.

flow fractions for ages less than 50 Myr yields a sealing age of 65 ± 10 Myr, beyond which hydrothermal heat transfer has largely ceased. Because about 60% of the oceanic crust is younger than 65 Myr, off-axial flow should be a widespread phenomenon.

Our goal here is to summarize some inferences from heat flow-based studies which are of interest to those studying other (e.g. petrological, geochemical, oceanographic, or biological) manifestations of hydrothermal circulation. We focus primarily on application of global-scale data, with some discussion of smaller-scale studies. The results we summarize illustrate both that heat flow can tell a great deal, and that there are key issues which heat flow alone cannot resolve.

ESTIMATION OF HYDROTHERMAL HEAT AND WATER FLUX

The first issue we discuss is estimation of the hydrothermal heat and water fluxes from heat flow data. The basic result is that the overwhelming majority of the heat and water flux occurs away from the ridges, presumably by low-temperature flow. This point, which was recognized in early studies using heat flow data [*Wolery and Sleep*, 1976] and also emerges from thermal models of the near-ridge region [*Morton and Sleep*, 1985], has important implications for geochemical studies [e.g. *Sleep and Wolery*, 1978; *Mottl*, 1983]. Because much attention has been focussed on the spectacular high temperature flow at ridge crests, it is useful to review the evidence indicating the volumetric importance of lower-temperature flow away from the ridges.

The approach used to estimate the hydrothermal heat flux is straightforward. The difference between the predicted and observed heat flow (Figure 2), weighted by the area of crust of different ages, is integrated to estimate the cumulative hydrothermal heat flow as a function of age [*Wolery and Sleep*, 1976; *Anderson et al.*, 1977; *Sleep and Wolery*, 1978; *Sclater et al.*, 1980]. The analysis is posed in terms of the predicted and observed average heat flow as functions of age, $q(t)$ and $q_o(t)$. The cumulative predicted and observed heat losses as a function of age are

$$Q(t) = \int_0^t (dA/d\tau)\, q(\tau)\, d\tau$$

and

$$Q_o(t) = \int_0^t (dA/d\tau)\, q_o(\tau)\, d\tau ,$$

where the crustal area for a given age is dA/dt. The inferred cumulative heat loss due to hydrothermal flow is thus

$$Q^h(t) = Q(t) - Q_o(t) = \int_0^t (dA/d\tau)\, [\, q(\tau) - q_o(\tau)]\, d\tau .$$

Heat Flux

Figure 3 shows estimates of the cumulative predicted, observed, and hydrothermal heat losses derived from the data and model in Figure 2. The plot illustrates three basic points, discussed in detail by *Stein and Stein* [1994]. First, of the predicted global oceanic heat flux of about 32×10^{12} W, $\sim 11 \pm 4 \times 10^{12}$ W or $\sim 34 \pm 12\%$ occurs by

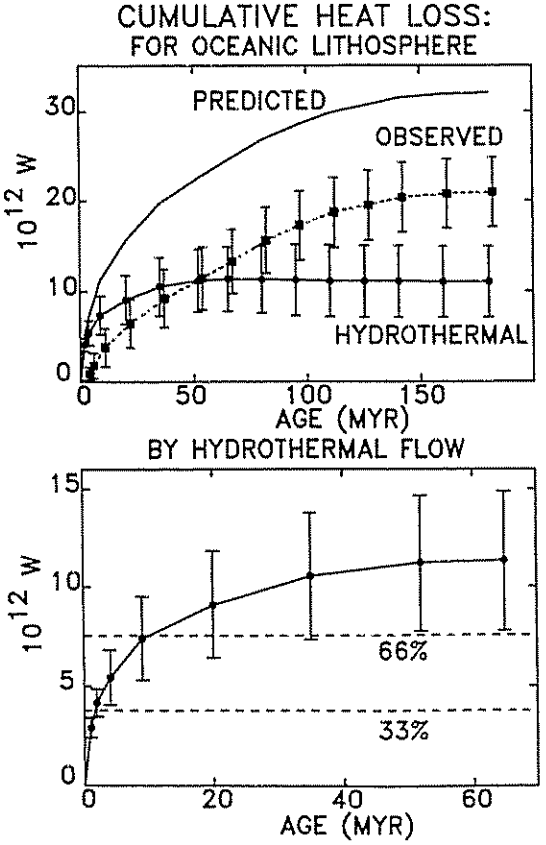

Fig. 3. *Top:* The cumulative hydrothermal heat flux as a function of age is inferred from the difference between that predicted by the GDH1 plate cooling model and that integrated from seafloor observations. The lines connect the points whose values were computed. For clarity, the 1 Myr point is not 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 Myr. Values are the same as in the top panel, except for the 1 Myr estimate, which here reflects the greater uncertainty in the near-axial value resulting from incorporating uncertainties in the thermal model and crustal area. Approximately one third of the inferred hydrothermal heat flux occurs in crust younger than 1 Myr, and another third occurs in crust older than 9 Myr. [*Stein and Stein*, 1994].

hydrothermal flow. Second, most of this hydrothermal heat loss occurs away from the ridges. The estimated hydrothermal heat flux within 1 Myr is $3.2 \pm 0.3 \times 10^{12}$ W, 29% of the net hydrothermal heat flux. If we adopt for simplicity a nomenclature of "axial" for the interval 0-0.1 Myr, "near-axial" for 0-1 Myr, and "off-axial" for ages greater than 1 Myr, approximately 70% of the hydrothermal heat flux is off-axial. Third, the cumulative hydrothermal heat flux increases steadily until ~50-70 Myr, and then levels off, because the observed heat flow becomes approximately that predicted.

Although these numerical results have uncertainties from the predicted heat flow, observed heat flow, and integration method, they are relatively robust and comparable to other estimates [*Stein and Stein*, 1994]. The uncertainty due to numerical evaluation of the integrals can be assessed from an alternative evaluation using analytic expressions for the heat flow and area. A linear fit to the mean observed heat flux (in mW m^{-2}) as a function of the age t (in Myr) gives approximately $q_o(t) = 130 - 3.4t$ for $t \le 20$ Myr and $q_o(t) = 62$ for $20 < t < 50$ Myr [*Pelayo et al.*, 1994]. The predicted heat flow for the GDH1 model, for ages t (in Myr) less than 50 Myr, is $q(t) = 510\, t^{-1/2}$, and the crustal area for a given age is given approximately by $dA/dt = C_0\,(1 - t/180)$ where C_0 is the creation rate, 3.45×10^6 km^2 yr^{-1} [*Parsons*, 1981]. Integration gives results similar to the earlier ones: a hydrothermal heat flux of about 10^{13} W by 50 Myr, with about 1/3 occurring within 1 Myr [*Pelayo et al.*, 1994].

The most interesting uncertainty is due to the scatter in the data as a function of age. Some of the scatter is observational, resulting from the process of measuring the seafloor temperature gradient and scaling it by a measured or inferred thermal conductivity to estimate the heat flow. Much of the scatter, however, probably indicates intrinsic variation in heat flow for sea floor of a given age. Because heat flow reflects the near-surface temperature gradient, it should be a relatively less stable measure of the geotherm than the seafloor depth or geoid slope, both of which reflect the integrated temperature. As a result, variations in near-surface properties can cause greater scatter in the heat flow. Some heat flow variability may also reflect regional variations in the geotherm, which seem likely given differences in seafloor subsidence rates [*Marty and Cazenave*, 1989]. The heat flow variability is highest for young sea floor (Figure 2), presumably largely due to the complexity of the hydrothermal circulation geometry. The data may also be affected by sampling biases discussed later. Estimation of the heat flow for a given age thus differs from the common statistical problem of using multiple measurements to estimate a single well defined entity, because the scatter for a given age is an intrinsic feature of the process. Because we focus on the overall hydrothermal heat loss versus age, we use the mean observed heat flow and characterize the scatter for each age range by the standard deviation of the data, rather than the smaller standard deviation of the mean.

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 [*Sleep and Wolery*, 1978; *Stein and Stein*, 1994]. The flux estimate also does not depend crucially on the boundary condition used to model the ridge [*Stein and Stein*, 1994; *Pelayo et al.*, 1994]. Because inclusion of these uncertainties gives a similar estimate of the 0-1 Myr hydrothermal flux ($2.9 \pm 0.5 \times 10^{12}$ W), the basic result that most hydrothermal heat flux is off-axial appears robust.

It is worth noting that this result assumes that the heat flow discrepancy is both reasonably accurately described and can be interpreted in terms of hydrothermal flow. Both assumptions are plausible but difficult to verify. The first assumption requires that the thermal model used to predict the heat flow without hydrothermal cooling be grossly appropriate. Because the heat flow data for young lithosphere are thought to be biased downward by hydrothermal circulation, the thermal models are constrained from heat flow in old lithosphere and seafloor depths for all ages [*Parsons and Sclater*, 1977; *Stein and Stein*, 1992]. Although a particularly crucial parameter, the thermal conductivity, is consistent with that inferred from laboratory studies [*Denlinger*, 1992], a dramatically different value could change the estimated hydrothermal heat flux significantly. Similarly, the assumption that the heat flow discrepancy reflects hydrothermal flow seems plausible [*Wolery and Sleep*, 1976] but is not easily tested, precisely because of the difficulty in directly estimating hydrothermal fluxes.

Water flux

Although the heat flux presumed to be associated with hydrothermal flow is the quantity directly estimatable from the heat flow data, the magnitude and distribution with age of the corresponding water flux is of greater interest, because it is the water flux that affects ocean chemistry. The water flux near the axis where water temperatures are highest is thought to have the major geochemical effects on the oceans [*Hart and Staudigel*, 1978; *Staudigel et al.*, 1981; *Alt and Honnorez*, 1984; *Bowers and Taylor*, 1985; *Wolery and Sleep*, 1988]. The role of the lower temperature off-axial water flux is less clear, because its volume and composition are poorly known. Although a given mass of off-axial fluid would have less geochemical effect than for axial fluid, because of its lower temperature and composition closer to that of sea water [*Baker et al.*, 1991], off-axial fluid may have significant net effects because of its presumed large volume [*Mottl and Wheat*, 1994].

Because water fluxes are difficult to estimate from direct measurements, geochemical studies often infer hydrothermal heat flux rates from heat flux via calculations assuming a mass of fluid and its temperature [e.g. *Edmond et al.*, 1979; *Mottl*, 1983]. A complexity arises because estimation of water flux from heat flux requires an assumption about the water temperature. The water flux $F = Q/Tc_p$ is related to the hydrothermal heat flux Q via the water temperature T and the specific heat of water c_p, which in turn depends on both temperature and composition. Hence for a given heat flux, the inferred water flux varies by a factor of almost seven assuming different water temperatures from 100-400°C [*Sleep and Wolery*, 1978]. Although little is known about the temperatures of off-axis upwelling water, these temperatures are probably much lower than the high temperatures (~350°C) of the axial flow. *Fehn and Cathles'* [1986] modeling predicts that within 25 km (~1 Myr) of the axis, high-temperature flow will give way to low-temperature flow with temperatures less than ~100°C. An even more dramatic decrease emerges from *Mottl and Wheat*'s [1994] estimate of the minimum effective temperature of upwelling water required to match the hydrothermal heat loss. In their calculation, the temperature of off-axial flow drops below 10°C by 5 Myr, and below 2° by 35 Myr.

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. This effect may be further enhanced because even at the ridges, much of the flow may be low-temperature rather than high-temperature [*Schultz et al.*, 1992; *Rona and Trivett*, 1992]. The relative magnitude of the low-temperature water flux can be illustrated using the simple assumption that the 0-1 Myr 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 25°C. Using for simplicity specific heats for pure water of 4.5 and 4.0×10^3 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 2.5×10^{15} kg yr^{-1}. Thus in this example the near-axial flux transports 27% of the heat, but only 3% of the total (2.6×10^{15} kg yr^{-1}) water. Hence 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.

These examples illustrate the limitations of estimates of hydrothermal heat and water fluxes due to poor knowledge of the distribution and temperature of off-axial flow, which is rarely sampled and poorly understood. Resolution of these difficulties will be challenging. One non-trivial difficulty is that in geochemical discussion, it may be unclear over what age range various rock-water interactions extend. Although for heat flow-based analyses the age range is easily defined, the appropriate comparison with reported geochemical "axial," "near-axial," and "off-axial" fluxes may be hard to make. Information relevant to the variation in geochemical flux as a function of age is being provided by studies of the alteration history of oceanic crust [e.g. *Staudigel et al.*, 1981; *Staudigel and Hart*, 1986] and studies integrating heat flow data with studies of the temperature and composition of hydrothermal fluid [e.g. *Mottl and Wheat*, 1994].

CESSATION OF HYDROTHERMAL FLOW

The second issue we address is what physical process causes the heat flow discrepancy, and thus presumably hydrothermal circulation, to decrease with age. As noted earlier (Figures 2, 3), by about 50-70 Myr the average observed heat flow approaches that predicted by the thermal model, suggesting that little heat transfer at the sea floor occurs by hydrothermal flow. A basic question is what causes this apparent decrease in hydrothermal heat transfer. Because the off-ridge water flux is difficult to sample, ideas about this issue come largely from comparison of observed and predicted heat flow.

The presumed near-cessation of hydrothermal circulation is simply and approximately characterized by a "sealing age", defined as that beyond which the measured heat flow approximately equals that predicted. Even given the scatter in the data (Figure 2), they are clearly divided into younger ages where the heat flow fraction is noticeably less than one and increases with age, and an older range where the heat flow fraction is close to one and no longer varies significantly. This transition occurs because, as discussed later, heat flow for ages older than about 20 Myr is essentially constant, whereas the predicted heat flow continues to decrease until about 70 Myr. The sealing age for the entire global heat flow data set is about 65 ± 10 Myr. Hence although there are presumably local variations, water flow in older crust does not in general transport significant amounts of heat.

The term "sealing" age is slightly misleading. Despite its connotation of fluid flow, this age is estimated from heat flow data and reflects a deficit in heat flow relative to a thermal model, which is interpreted as reflecting water flow. Heat flow at a site can be less than predicted from lithospheric cooling for various reasons, only some of which directly reflect fluid flow. The connection between a heat flow deficit and fluid flow is clear near the ridges, where the flow is observed. At older ages, although there is some evidence for fluid flow, the relation between the fluid flow and a heat flow deficit is less clear. In one end-member view, heat flow is low because water flow extending upward to depths just below the sea floor lowers the temperature gradient there. This situation is often visualized as cellular convection in the sediments and perhaps the upper crust. In another view, the temperature gradient is lower than expected because water flow at greater depth, perhaps near the top of the igneous crust, transfers heat laterally. Hence the presumed reduction in hydrothermal heat transfer beyond the sealing age could occur in several ways. "Sealing" could reflect the igneous crust's being isolated from the sea water by thick hydraulically non-conductive sediments, such that the heat flow fraction would to be low for young unsedimented crust and rise to about one once the basement rock is covered by 100-200 m of sediment [e.g. *Anderson and Hobart*, 1976]. Alternatively, the porosity and permeability of the igneous crustal rocks may become small enough, due to hydrothermal deposition of minerals, that the rocks themselves "seal" and lateral heat transfer ceases [e.g. *Anderson et al.*, 1977].

It has been generally assumed that of these two possible mechanisms that may cause circulation to cease with age, the primary effect is due to overlying sediment. In this interpretation thick sediment is presumed to seal off the igneous crust, such that areas with regionally thick sediment yield "reliable" heat flow values on average equal to those predicted by lithospheric cooling models [*Sclater et al.*, 1976]. As we shall see, the data indicate that this is not the case.

Variation of heat flow with sediment thickness and crustal age

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 can be investigated by considering the heat flow fraction at sites where sediment thickness has been determined from seismic reflection profiles. For the first mechanism, the heat flow fraction should approach one for thick sediments, regardless of age. For the second mechanism, the heat flow fraction should approach one for sufficiently old crust, regardless of sediment thickness. Although the two effects might be difficult to separate for a small data set, because sediment thickness generally increases with age, the global data are numerous enough to distinguish the two.

Plate 1 shows a smoothed surface plot of the heat flow

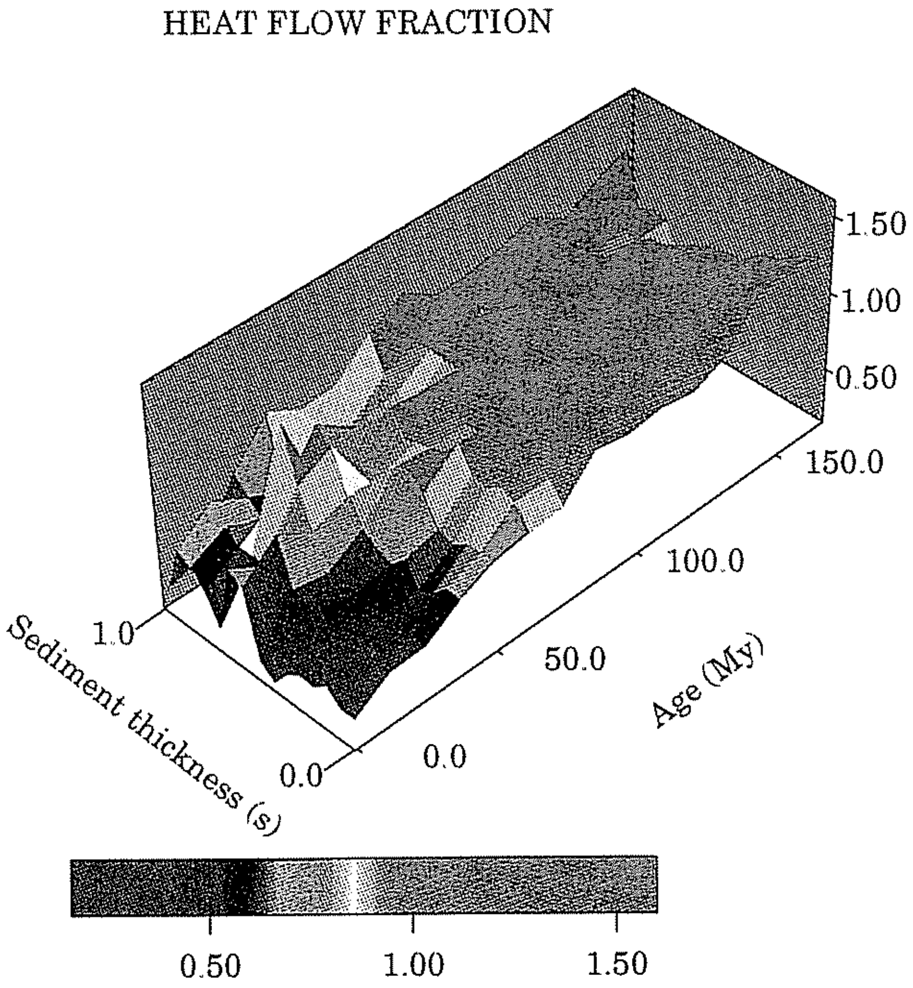

Plate 1. Smoothed surface plot of the heat flow fraction relative to GDH1, as a function of seafloor age and site sediment thickness (quoted in seconds of two-way travel time). The heat flow fraction increases smoothly with age from low values near the ridges to about one, regardless of the sediment thickness. Contrary to earlier suggestions, ~100-200 m (0.1-0.2 s) of sediment is in general neither necessary nor sufficient to bring heat flow to the value predicted by lithospheric cooling models. Hence crustal aging, rather than sediment thickness, appears to be the primary factor controlling the fraction of heat transferred by hydrothermal flow.

fraction relative to GDH1, as a function of seafloor age and the sediment thickness directly beneath the site. Sediment thickness are given in seconds of two-way seismic wave travel time. The 1337 data were winnowed for thicknesses between 0-1 seconds of two-way travel time, corresponding approximately to 0-1 km of sediment, and heat flow fractions less than two. The plot shows that the heat flow fraction increases smoothly with age from low values near the ridge to about one, regardless of the sediment thickness. Hence about 100-200 m (0.1-0.2 seconds) of sediment appears neither necessary nor sufficient to cause heat flow to approach that predicted by the cooling model. The data have some scatter, especially because few sites with young ages have thick sediments, but the pattern seems clear.

Although the heat flow fraction varies primarily with crustal age, the plot also suggests a secondary variation with sediment thickness. Our previous analysis of these data showed sealing ages of 98 ± 79 Myr for sites with less than 0.05 s (~50 m) sediment, 83 ± 32 Myr for sites with 0.05-0.2 s (~50-200 m) sediment, and 51 ± 17 Myr for sites with 0.2 s (~200 m) or more sediment [*Stein and Stein*, 1994]. Although the sealing ages are sufficiently poorly determined that these differences are not formally significant, they suggest a younger sealing age for the more sedimented sites.

The same conclusion, that sediment thickness has only a secondary effect, emerges from consideration of heat flow data grouped into the sedimentary environment classification of *Sclater et al.* [1976]. In this system, sites are classified "A" to "D" (Figure 4), with "A" sites having the best locally continuous sediment cover, and the worst ("D") sites being sediment ponds next to outcropping basement highs. Sclater et al. [1976] argued that "A" sites would yield "reliable" values unaffected by hydrothermal circulation and equal on average to the predictions of plate cooling models. However, examination of the heat flow fraction as a function of age for the sites with different sedimentary environments shows little difference [*Stein and Stein*, 1994]. In particular, because the heat flow fraction at "A" sites does not reach one until about 50 Myr, these sites are not "reliable" indicators of the heat flow expected from plate cooling.

The data thus show that for crustal ages less than about 50 Myr, even well sedimented sites rarely show conductive heat flow equal to that predicted by the cooling model. In other words, whether the measured heat flow will approach that for the cooling model is much better predicted by the crustal age than the sediment thickness. Although this effect may not be visible for a local survey where the variation in ages is small, it is a clear feature of the global data.

The simplest interpretation of these observations is that age-dependent processes are the primary control on hydrothermal circulation, which becomes less vigorous as the crust ages. The observations do not, of course, require any particular age-dependent mechanism. They are in general consistent with proposals that flow decreases due to reduction in porosity and hence permeability by hydrothermal deposition of minerals [e.g. *Anderson and Skilbeck*, 1981]. Such changes in physical properties have also been proposed based on variations in seismic velocities with age [*Houtz and Ewing*, 1976; *Anderson and Skilbeck*, 1981; *Jacobson*, 1992; *Shaw*, 1994]. As discussed later, we believe that a mechanism of this type is the most plausible explanation for the heat flow at older ages rising to that predicted by the cooling model.

This interpretation of the heat flow fraction data, which disagrees with what has been often suggested, is not unique for two reasons. First, it relies on interpreting the heat flow fraction as directly reflecting hydrothermal flow. Detailed local studies indicate a possible complication due to the fact that heat flow measurements probably are biased toward lower values, and thus overestimate hydrothermal flow. Second, the possible effect of sediment is characterized either by sediment thickness immediately below sites or sedimentary environment, a crude characterization of the local sediment-rock geometry usually derived only from data along one profile. Neither parameter fully represents the local sediment-rock geometry. As discussed in the next section, these two effects do not seem large enough to change our view that crustal aging is more significant than sediment thickness.

HEAT FLOW IN YOUNG LITHOSPHERE

The third issue we address is characterization of heat flow in young oceanic lithosphere, and use of these data to draw further inferences about hydrothermal flow. A prominent feature of the data is that the scatter as a function of age is greatest at young ages, presumably due to the complexities of the circulation pattern (Figure 2). As a result, some studies focus on this variability and use it to investigate local hydrologic processes, whereas others look at average properties with age to address processes on a larger scale. The two approaches yield complementary information.

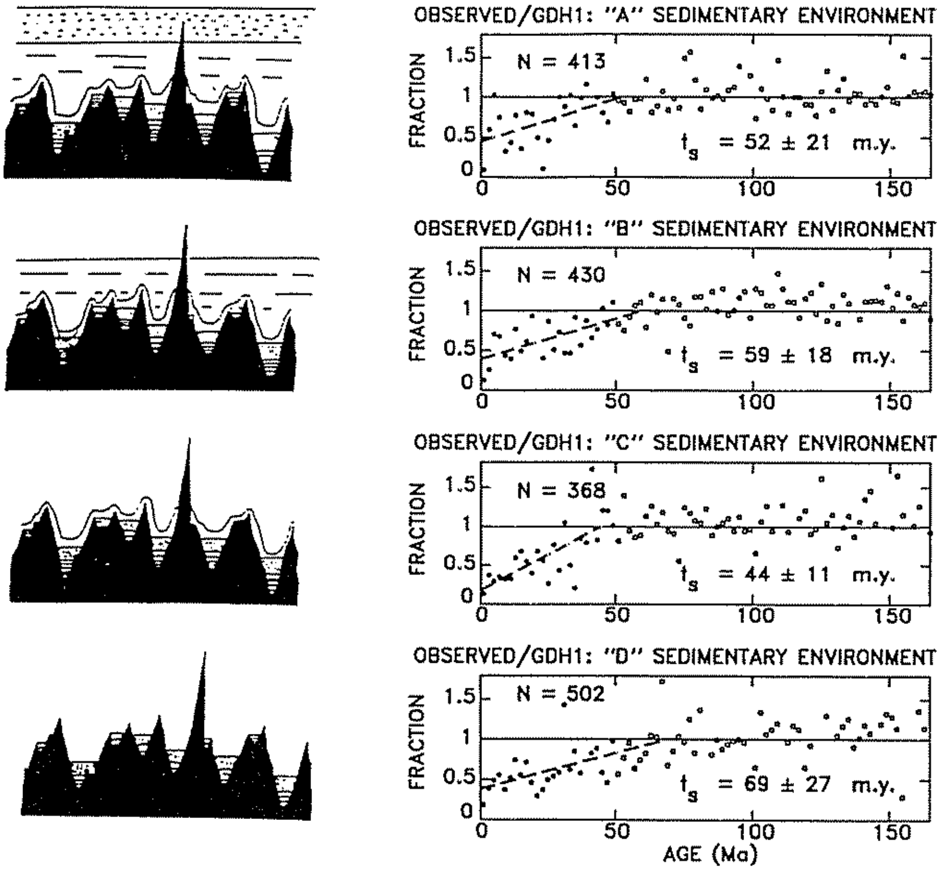

Fig. 4. Heat flow fractions versus age *(right)* for sites with different sedimentary environments [*Stein and Stein*, 1994]. Environments ranging from the best "A" to worst "D" (sediment ponds) sedimented are illustrated *(left)* by figure from *Anderson et al.* [1977]. Data for the different sedimentary environments increase in a similar way with age, as illustrated by the least-squares line fit to the data for ages less than 50 Myr. Hence crustal age appears much more important than sedimentary environment in determining whether the measured heat flow will approach that predicted by the cooling model. Contrary to earlier suggestions, even well sedimented ("A") sites younger than 50 Myr are not "reliable" indicators of the heat flow expected from plate cooling.

Results from densely sampled surveys

Our basic ideas about the mechanics of hydrothermal flow result from relatively densely sampled (kilometer spacing) heat flow surveys. The heat flow is highly variable, as illustrated by data from the FlankFlux survey on the Juan de Fuca plate (Figure 5) [*Davis et al.*, 1989]. A primary characteristic of these data is that heat flow varies with igneous basement relief, such that heat flow is highest over basement highs which are also the sites of relatively thinner sediment. This correlation is interpreted as reflecting hydrothermal flow, because conduction alone should give the opposite effect, lower heat flow over igh topography [*Lachenbruch*, 1968; *Fisher and Becker*, 1995]. To overcome this conductive refraction, lateral heat transfer must occur within the crust.

Several effects may contribute to the variations in heat flow. Hydrologic modeling [e.g. *Lowell*, 1980; *Fisher et al.*, 1990, 1994; *Fisher and Becker*, 1995] indicates that water should flow downward over basement lows, and upward over highs. Isotherms would thus be depressed at low points, giving lower conductive surface heat flow. In the common situation where bare rock outcrops near sediments, observations [e.g. *Langseth et al.*, 1992] suggest significant lateral water flow in the rock and associated downward flow in the sediments. As a result, sites where bare rock comes close to or outcrops at the sea floor can have dramatically higher heat flow than surrounding

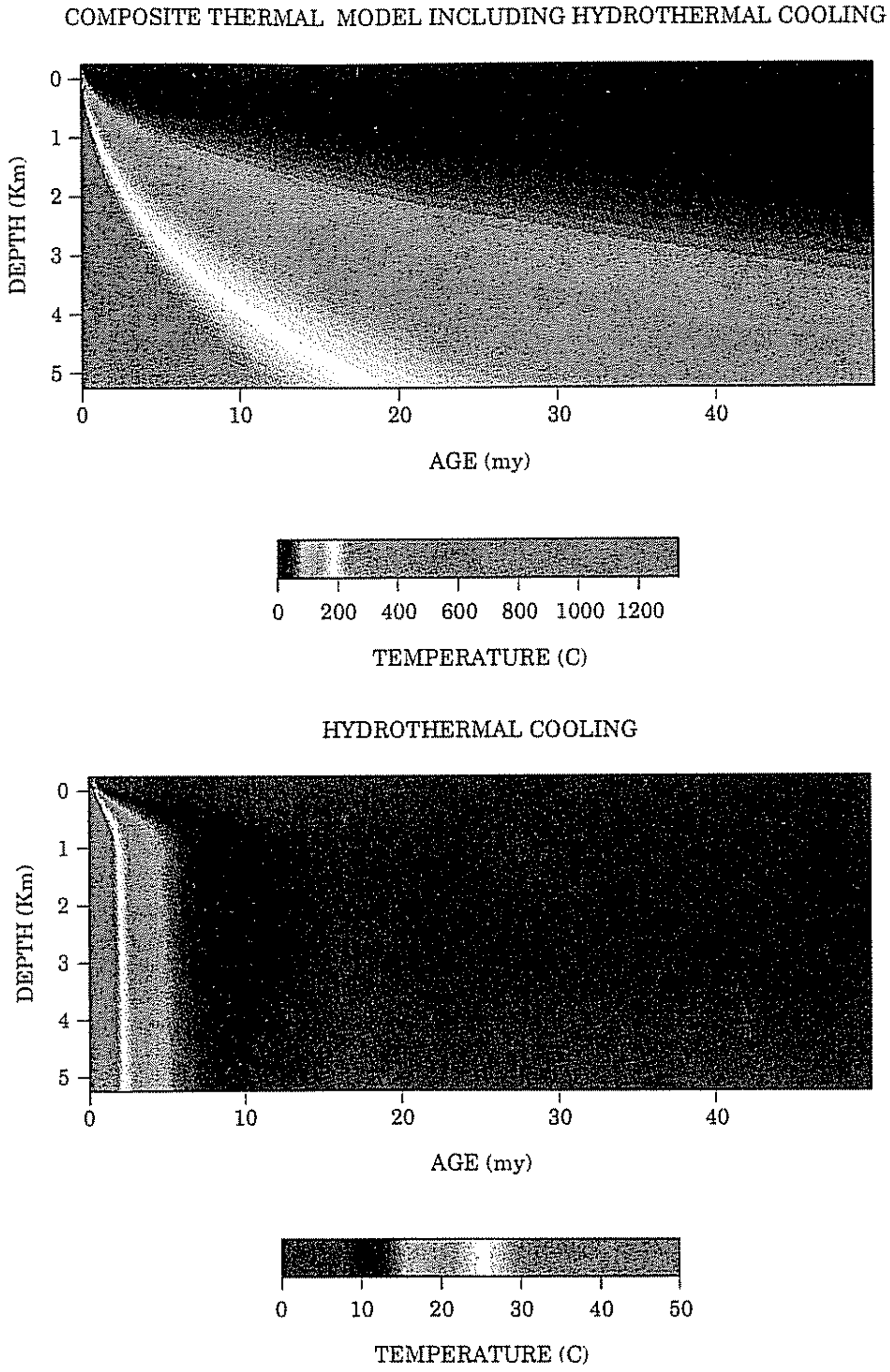

Plate 2. *Top:* Temperature field for the CYH1 model, which incorporates the effect of hydrothermal cooling. *Bottom:* Hydrothermal cooling for the CYH1 model, shown as the temperature difference between this model and the same model without hydrothermal cooling. For clarity the temperature scale is cut off at 50°C. Near the axis, the earthquakes and magma chamber depths require cooling of hundreds of degrees. Away from the axis, only minor cooling is required to match the heat flow data.

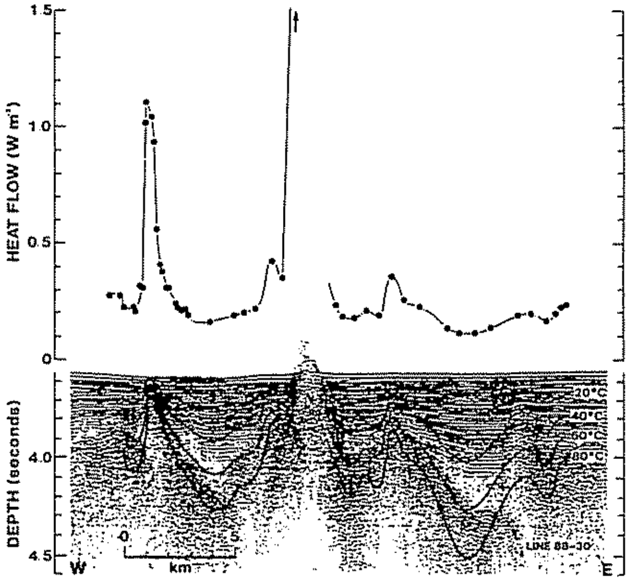

Fig. 5. Portion of the heat flow data from the FlankFlux survey on the Juan de Fuca plate. Sites where igneous basement rock is close to or outcrops at the sea floor have dramatically higher heat flow than the surrounding areas. Away from these outcrops, heat flow varies inversely with depth to basement. Figure from *Davis et al.* [1989].

areas. For the FlankFlux area, *Davis et al.* [1989] note that the heat flow varies inversely with depth to basement rock, or equivalently is inversely proportional to sediment thickness, suggesting that the igneous basement is maintained as an essentially isothermal surface by fluid flow near its top. Another possible contribution to variability is that faults may provide high-permeability paths for fluid flow [e.g. *Williams et al.*, 1974].

Where densely sampled data are available, the heat flow variations can be used to constrain site-specific flow models incorporating aspects of the local topography, sediment cover, and presumed permeability distribution [e.g. *Davis et al.*, 1989; *Fisher et al.*, 1990, 1994; *Fisher and Becker*, 1995]. The results are nonunique in that various assumptions about permeability structure and flow geometry can simulate features of the observed heat flow. Additional insight can be obtained from geochemical studies [e.g. *Wheat and Mottl*, 1994] and information from ocean drilling about properties of the ocean crust [e.g. *Anderson and Zoback*, 1982; *Becker et al.*, 1983; *Becker*, 1990]. Such modeling is giving useful insights into possible flow geometries. As these local studies become more common, the challenge is to incorporate their results into a general description useful at yet-unmodeled sites.

Implications for the cessation of hydrothermal flow

The results of the detailed surveys have implications for the global heat flow data set and the inferences drawn from it in the last section about the dependence of hydrothermal flow on crustal age and sediment thickness. As illustrated by Figure 5, randomly sampled data from areas with hydrothermal circulation may not have a Gaussian distribution about a mean, because there are likely to be more low than high measurements. Individual heat flow observations may thus be biased toward low values. This effect can be enhanced by the fact that when bare rock borders sediment-filled lows, instrumental considerations require that measurements be made in the sediments, where heat flow may be depressed by downward water flow. Thermal blanketing due to deposition of cold sediment [*Von Herzen and Uyeda*, 1963; *Hutchison*, 1985] can also reduce heat flow, but this effect should be small for areas with vigorous hydrothermal circulation and nearly constant temperature at the sediment/basement interface [*Wang and Davis*, 1992].

A natural question is how serious an effect this bias causes for the global data set, which is sparsely sampled, such that on average there is less than one point within an area comparable to that of the detailed surveys. Our view is that the sampling bias is real but is not large enough to explain the low heat flow for almost all crust younger than 50 Myr (Plate 1 and Figure 4). This assessment is based on examination of heat flow data from the FlankFlux area and three other densely sampled regions of very young lithosphere (Figure 6). These areas are generally, though not uniformly, well sedimented relative to most young lithosphere. The youngest survey area is Middle Valley, a sediment-covered portion of the Juan de Fuca Ridge [*Davis and Villinger*, 1992]. Slightly older crust is included in the survey of the Galapagos Spreading Center, a region including mounds where the highest heat flow is measured [*Green et al.*, 1981]. The oldest survey area, the Costa Rica Rift, includes data around DSDP/ODP site 504B [*Langseth et al.*, 1988].

As expected, the data have considerable scatter, presumably due to the hydrothermal circulation. As for FlankFlux, the highest values occur above basement highs. The fact that the heat flow above these highs exceeds the GDH1 predictions, and thus the conductive heat flow expected if there were no hydrothermal flow, implies considerable lateral heat transport [*Davis et al.*, 1989, 1992; *Wheat and Mottl*, 1994].

The measured heat flow in these surveys generally exceeds the average of the global data, which (as discussed shortly) varies slowly with age. Of these surveys,

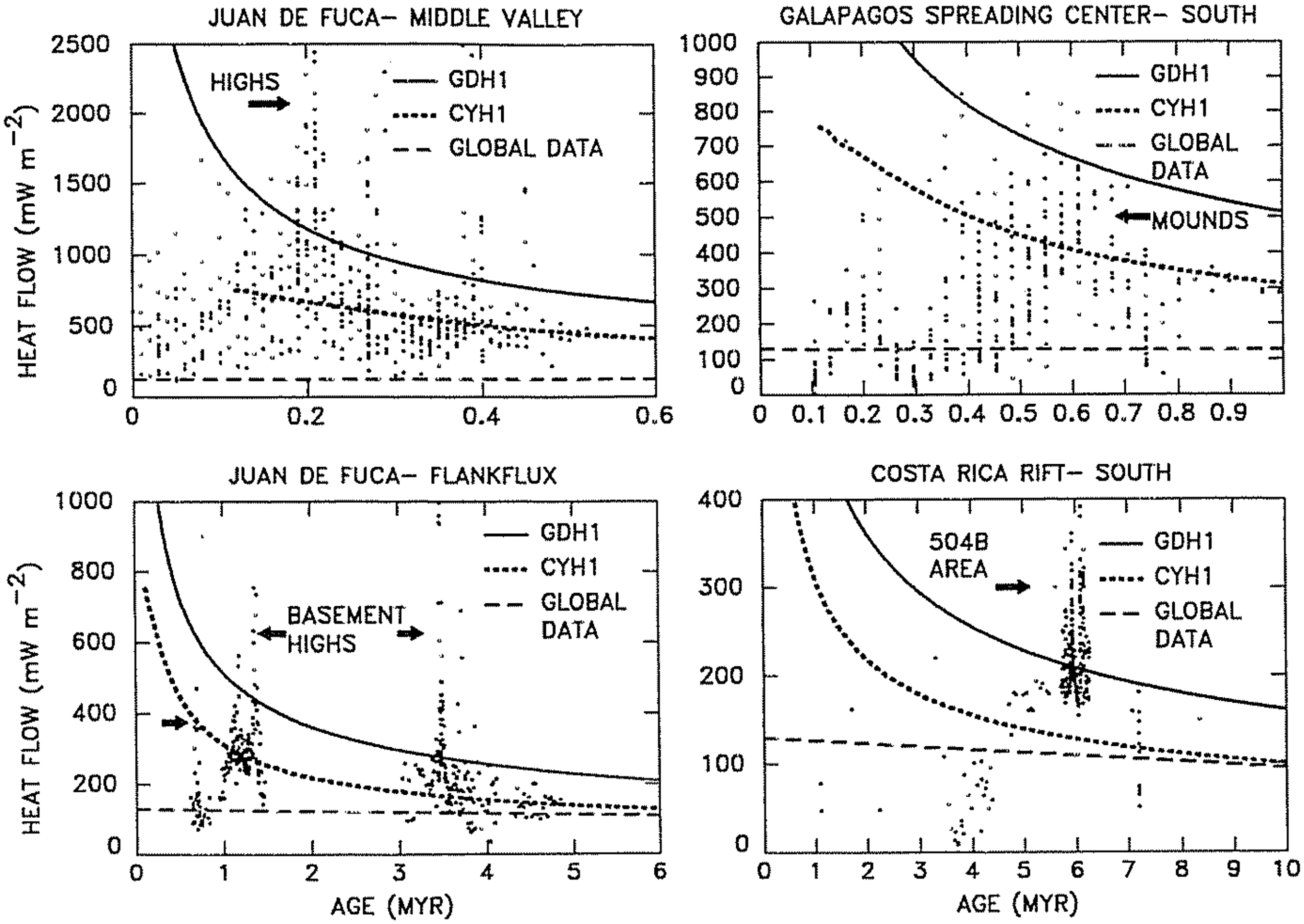

Fig. 6. Heat flow data from four densely sampled surveys of generally well sedimented young lithosphere. Two of the surveys are on the Juan de Fuca plate: Middle Valley [*Davis and Villinger*, 1992], and FlankFlux [*Davis et al.*, 1992], which includes the data shown in Figure 5. Also shown are surveys near the Galapagos Spreading Center [*Green et al.*, 1981] and the Costa Rica Rift, including DSDP/ODP site 504B [*Langseth et al.*, 1988]. For graphic purposes, a few of the highest values are not shown. Most heat flow values are higher than the global average, presumably due to the sampling bias. In general, the measured values are significantly lower than predicted by the GDH1 model, which includes no hydrothermal cooling, suggesting that hydrothermal heat transfer is pervasive. Most values exceeding those predicted occur over high features. Also shown are the predictions of the CYH1 model (discussed later) which predicts the average heat flow versus age for young lithosphere including the effects of hydrothermal cooling.

the FlankFlux and Middle Valley ones were not included in the global data set, and the Galapagos and Costa Rica ones were included only as single composite points, so that many points from a few small areas would not dominate the data set. We interpret the observation that the heat flow values from these surveys generally exceed the global average as reflecting the sampling bias, because these data are from regions more thickly sedimented than most sites of this age in the global data, and as such are less prone to be biased to low values. It is interesting that unusually high heat flow occurs near site 504B, suggesting that this extensively-studied area may not be representative of the thermal regime of young oceanic crust.

Because most of the values are lower than predicted by the GDH1 model, these data indicate that even for heavily sedimented areas, the measured conductive heat flow is generally less than predicted by plate cooling. This result would not change if the *Parsons and Sclater* [1977] model were used instead of GDH1. The two models' predictions are similar in this age range, with the Parsons and Sclater model predicting 7% lower heat flow (e.g. 473 rather than 510 mW m^{-2} at 1 Myr). Although one could adopt significantly colder thermal models, these would significantly underpredict the observed heat flow at older ages [*Stein and Stein*, 1994].

Although for sparse data, such as in the global data set, we can only compare a model to individual points or their mean in a given age range, the dense surveys offer the prospect of doing better. The real test for the magnitude of heat transfer by hydrothermal circulation is how the spatially averaged conductive heat flow in an area compares to the spatially averaged heat flow predicted by a cooling model. Ideally, this averaging would circumvent possible sampling biases, such as might result from a large number of high values measured on a small feature like a basement high. *Green et al.* [1981] estimated that the average conductive heat flux for the Galapagos survey area was ~37% of that predicted by plate cooling, indicating that about 2/3 of the heat is transferred by hydrothermal flow. Such comparisons will be needed for other survey areas to assess the significance of hydrothermal heat transfer.

In our view, the detailed survey results are consistent with those from the global data (Plate 1 and Figure 4), in that the heat flow discrepancy remains even for these well sedimented areas. The vast majority of the data for these areas have heat flow lower than predicted by plate cooling. Hence although the mechanics of the process remain unclear, and there is clearly much to be done before they are understood, our view remains that crustal aging is the primary factor causing the heat flow to approach that predicted by cooling models. What may be happening is that even in heavily sedimented areas (such as "A" environments), water can flow for sufficient distances laterally near the top of the igneous crust that it eventually reaches a basement outcrop or high, and then exits to the ocean. The average heat flow that would be measured would depend on whether these exit sites were sampled. In this scenario, the heat flow discrepancy can persist until the igneous crust becomes old enough that lateral water flow transfers little heat, because of a combination of reduced permeability, lower water flux, and smaller temperature contrast with the surrounding rock. Because the crust is laterally variable, the reduction of permeability need not occur everywhere, so long as it restricts lateral flow for significant distances. Thus even though some older crust may remain relatively permeable [e.g. *Larson et al.*, 1993], the reduction in lateral heat transfer would cause heat flow at older ages to approach the purely conductive value.

Characterization of average heat flow

Given the scatter of the measured heat flow in young lithosphere, is often implicitly assumed that the average there is too strongly controlled by local hydrology to be usefully characterized or modeled. In fact, inspection of the global heat flow for young lithosphere as a function of age (Figure 7) indicates that despite the scatter, the mean heat flow varies smoothly. As shown, the observed mean heat flow can be approximated by a simple two-stage linear fit: $q_o(t) = 130 - 3.4t$ for $t \leq 20$ Myr and $q_o(t) = 62$ for $20 < t < 50$ Myr [*Pelayo et al.*, 1994]. The fact that these data are easily characterized in this convenient way has several applications.

One use of such a characterization, discussed later, is in modeling the average hydrothermal flow as a function of age. The mean heat flow averages the local variations in heat flow that reflect the circulation details and appear as the "scatter" in the data. A second use of such a characterization is for analytical purposes, such as the integration for cumulative observed and hydrothermal heat loss. Using the linear fit to the data simplifies calculation, with little loss of accuracy compared to numerical integration. A third use is in comparing the intensity of hydrothermal circulation between different areas. For example, we used this two-stage fit in Figure 6 to represent the globally averaged data.

Thermal model for young lithosphere

Because lithospheric cooling models overpredict the observed heat flow in young lithosphere, it is natural to seek models including hydrothermal circulation that do better. One approach is to make site-specific models. These models have the advantage that they can ideally describe the complexities of the data, but have the limitation that they cannot predict heat flow at sites other than those they represent. An alternative approach is to develop models for the average heat flow as a function of age in young lithosphere. Such models do not attempt to describe local circulation patterns. Instead, they permit estimation of the hydrothermal cooling as a function of age, prediction of how this cooling may vary as a function of spreading rate or other parameters, and investigation of possible sampling bias in the heat flow data.

To explore the utility of such global models, we recently [*Pelayo et al.*, 1994] developed one such model using three basic constraints. First, the observed heat flow constrains how much the surface temperature gradient is reduced by hydrothermal cooling. Second, the cooling near the ridge axis can be estimated from the observations that both magma chambers inferred from seismic imaging and earthquakes occur deeper than expected for a thermal model of the ridge axis without hydrothermal cooling [*Sleep et al.*, 1983; *Morton and Sleep*, 1985; *Huang and Solomon*, 1988; *Lin and Parmentier*, 1989; *Sleep*, 1991; *Purdy et al.*, 1992; *Phipps Morgan and Chen*, 1993]. Third, the model is required to be consistent with depth data and heat flow data for older ages beyond which hydrothermal circulation has presumably ceased.

The model uses *Morton and Sleep*'s [1985] formulation, in which heat loss by hydrothermal cooling is represented by crustal heat sinks. We started with a model with the same primary parameters as GDH1, which assumes no hydrothermal cooling, and added sufficient hydrothermal cooling to match the data for young ages. Hence if no cooling were assumed, the model would be essentially the same as GDH1 except near the ridge, where the composite model has a boundary condition more suitable for near-ridge modeling. We fit heat flow data only for ages older than 10 Myr, to reduce the possible downward sampling bias in the heat flow measurements. The 10 Myr threshold was chosen in the hope of reducing the effect of the sampling bias, while leaving enough data in the age range where hydrothermal circulation occurs to constrain the model. We call this a composite model, because of the multiple constraints. The constraints are the depth and heat flow data for older ages (which constrain the overall thermal model), the earthquake and magma chamber depths (which constrain the near-axial geotherm), and the heat flow for 10-50 Myr (which constrain the surface temperature gradient for these ages).

These constraints do not uniquely determine the distribution of heat sinks. We thus required the distribution of heat sinks to decrease smoothly with distance away from the ridge, simulating the most intense cooling near the ridge, and sought simple sink distributions which could match general features of the data. Different heat sink distributions were needed for fast and slow spreading ridges (Figure 8). Model I, which better fits the earthquake and magma depths at slow (< ~20 mm/yr half rate) spreading ridges, has sinks extending to depths of 4 km at the axis and 2 km off axis. In model II, which better explains the magma chamber depths at faster spreading ridges, sinks extend to shallower depths of 2 km at the axis and 1 km off axis. The models differ because the shallow sink distribution in model I provides insufficient cooling at the magma chamber depths. On the other hand, model II can be precluded for ridges spreading more slowly than 15-20 mm/yr because the ridge axis would freeze, because the heat loss due to cooling exceeds the heat supplied. Hence near the ridge, the earthquake and magma chamber depths constrain the depth of cooling, whereas away from the ridge the heat flow data constrain the net hydrothermal heat loss but not its depth.

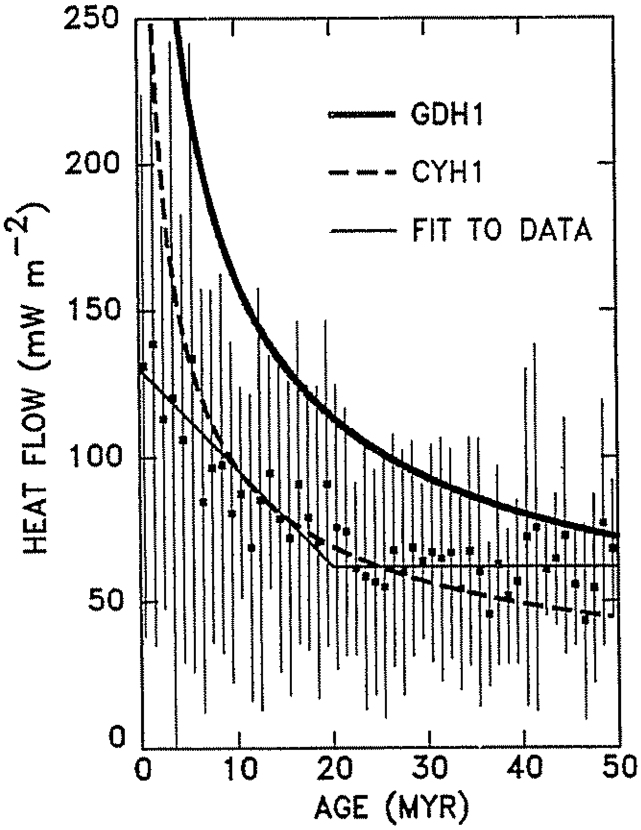

Fig. 7. Globally averaged heat flow data and models for young lithosphere. Data means and standard deviations are shown for 1-Myr age bins. The means are well approximated by a simple two-stage linear fit. Also shown are the predicted heat flow for the GDH1 model, which has no hydrothermal cooling, and the CYH1 model, which includes hydrothermal cooling. CYH1, which was fit to the heat flow for ages greater than 10 Myr, predicts values higher than observed for younger ages, in accord with the expected sampling bias [*Pelayo et al.*, 1994].

Because the effects of spreading rate are small except in the youngest lithosphere, the two models can be treated as a single spreading rate independent model for ages older than ~0.5 Myr and half spreading rates greater than 10 mm/yr. A useful approximation for these conditions is that the predicted model heat flow out to 50 Myr is $q_c(t) = 308\ t^{-1/2}$, where the heat flux is in mW m^{-2} and age t is in Myr. This representation of the predicted heat flow is labeled CYH1 (for Composite Young Hydrothermal) in Figures 6 and 7.

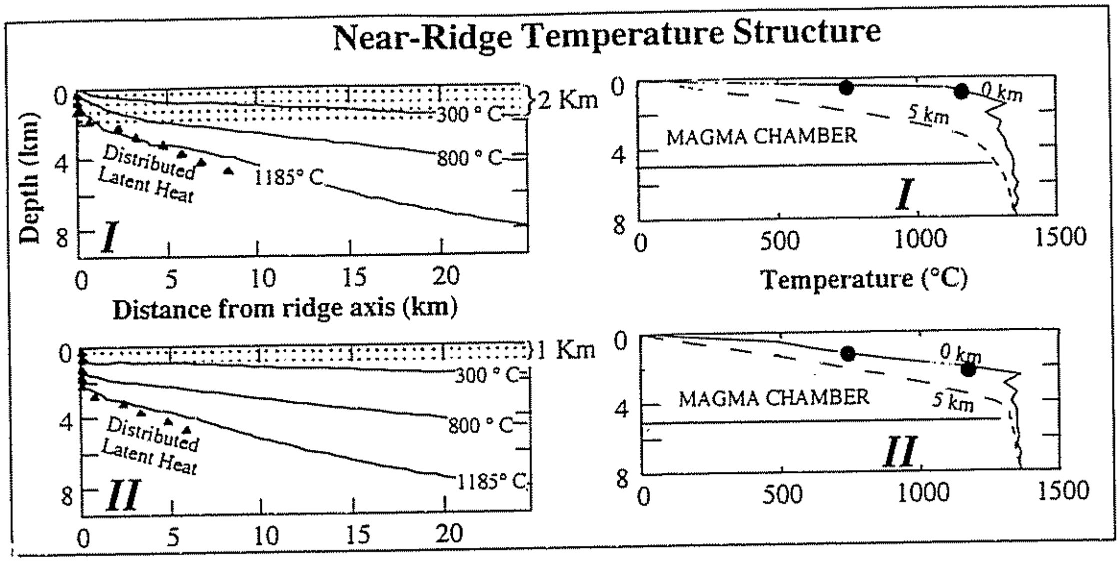

Fig. 8. Comparison of thermal models for two hydrothermal sink distributions at 40 mm/yr half-spreading rate. Models I and II have different sink distributions (stipple), both at and off the ridge axis (left), and hence different geotherms (right) beneath the axis (0 km) and 5 km away. Depths to the predicted 750°C and 1185°C isotherms (solid circles), corresponding to the predicted deepest seismicity and magma chamber tops, are shown for the ridge axis geotherms. Geotherm oscillations are artifacts of the 0.5-km computation grid. Model I better fits the data at slow (< ~20 mm/yr half rate) spreading ridges, whereas model II better fits data at faster spreading ridges. The two models can be treated as a single spreading rate independent model for most applications [*Pelayo et al.*, 1994].

Model predictions for heat flow

As shown in Figure 7, the heat flow for ages greater than 10 Myr is reasonably well fit by CYH1, because the model was constrained to do so. For ages younger than 10 Myr, where the model was not constrained by heat flow data, CYH1 predicts heat flow much higher than the mean observed, in accord with the expected downward sampling bias for heat flow observations.

One test of CYH1's utility is to see how well it predicts heat flow in well sedimented lithosphere younger than 10 Myr, which should be less affected by the sampling bias. We examined this issue using the dense surveys in young lithosphere shown in Figure 6. CYH1 offers a reasonable fit to the average values for three of the four dense surveys. For illustration, we plot the age$^{-1/2}$ approximate heat flow for CYH1 closer to the ridge (0.1 Myr) than is probably justifiable, given that very near the ridge the predicted heat flow is lower than the approximation and spreading rate dependent. The good fit is encouraging, in that CYH1 is making a pure prediction, because neither these data nor any other heat flow data for ages less than 10 Myr were used to derive it. As noted earlier, the data from the dense surveys should permit comparison of the predicted and observed spatially averaged heat flux. This comparison would be more meaningful than that for individual points, because models like CYH1 only attempt to predict spatially averaged heat flow. The general agreement of the model and data, however, suggests that this type of model can be useful and is worth further exploration.

As noted earlier, most sites in these surveys have heat flow significantly higher than the global average, which is essentially independent of these data. Presumably these higher values occur because these sites have thicker sediment than is typical of those of the same age in the global data, so they are less influenced by the downward sampling bias. Hence CYH1, which is ideally not unduly influenced by this bias, fits these observations better than the global data in this age range. The heat flow on the basement outcrops is so high that it exceeds the CYH1 prediction, and is even higher than predicted for GDH1, implying lateral heat transport.

Model predictions for hydrothermal heat flux

The composite model allows us to estimate the hydrothermal heat flux, hopefully with minimum effect from the sampling bias. The predicted cumulative hydrothermal heat flux is the difference $Q_c^h(t) = Q(t) - Q_c(t)$ between the cumulative heat flux for the GDH1 model $Q(t)$ and that for the composite model $Q_c(t)$. Because CYH1 predicts heat flow for ages less than 10 Myr higher than is observed in the apparently-biased global data, CYH1 predicts a higher cumulative heat flux and thus lower cumulative hydrothermal heat flux than are inferred directly from the data (Figure 9). Nonetheless, as for our earlier estimate (Figure 3), most of the heat loss occurs for ages older than 1 Myr and thus by off-axial and presumably low-temperature water flow. The sampling bias thus does not dramatically change estimates of the net hydrothermal heat flux or the implication that it occurs largely away from ridge axes.

We can also use the composite model to explore how hydrothermal heat flux may vary with spreading rate. Figure 10 (top) shows the average heat flow at the ridge axis (defined as crust less than 0.1 Myr old) assuming no hydrothermal circulation and for the two distributions of heat sinks. The predicted hydrothermal heat loss for each model is the difference between the no-sink case and the predicted heat flux. Model I, for the slower rates, predicts ~1 W m^{-2} of hydrothermal heat loss, whereas model II, for the faster spreading rates, predicts about twice as much. We focus on the average for model II and do not ascribe much significance to its minor variation with spreading rate.

For comparison with estimates from measurements in the water column, it is useful to consider the predicted hydrothermal heat loss per unit ridge length. At a slow ridge (10 mm/yr half-rate), the hydrothermal heat flux would be 1 W m^{-2} times the area on both sides of the axis within 0.1 Myr, or 2 MW per km ridge length. At 30 mm/yr half-rate (similar to the Juan de Fuca Ridge), hydrothermal heat flux within 0.1 Myr is 15 MW km^{-1}. This ~10 MW km^{-1} estimate for average spreading rates is similar to others [*Morton and Sleep*, 1985; *Stein and Stein*, 1994]. Comparison with field-based estimates is more difficult [*Dymond et al.*, 1988], because only a few areas have been studied, using various methods on different space and time scales. Estimates from seafloor sampling along the Juan de Fuca Ridge are an order of magnitude lower, ~1 MW km^{-1} [*Bemis et al.*, 1993], perhaps because of missed vents and/or low-temperature flow. Studies of hydrothermal plumes estimate their heat content at ~1000 MW [*Baker and Massoth*, 1987]. Assuming the plumes represent ~10 km ridge length, the estimated flux per unit ridge length is ~100 MW km^{-1}, an order of magnitude higher than our estimate. Thus plumes appear to remove more heat than the steady state surface flux for the cooling lithosphere. The discrepancy is not an artifact of the age interval sampled, as the plume studies extend a few km off-axis, comparable to the age interval we assume. Hence if both estimates are appropriate, observed plumes may be intermittent, in accord with the observation that only a fraction of the ridge (~20%) presently discharges plumes [*Baker and Hammond*, 1992]. Plumes also may sample water from further off-axis than 0.1 Myr. More data, sampling larger areas of the ridge system over longer time periods, will be needed to resolve these issues.

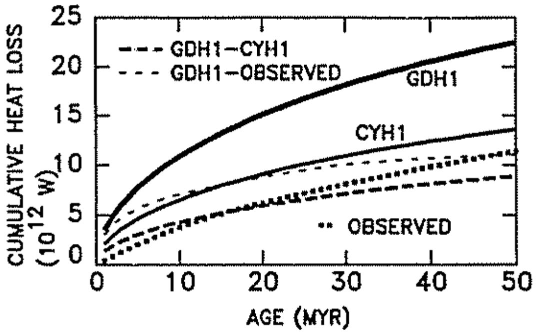

Fig. 9. Comparison of the cumulative hydrothermal heat losses inferred directly from the global data and from the CYH1 model. The difference between the cumulative heat losses predicted by the GDH1 model and estimated from the data (labeled "observed") gives an estimate of the hydrothermal heat flux (upper dashed line). The difference between the cumulative heat losses predicted by GDH1 and the CYH1 model gives a lower estimate (lower dashed line) of the hydrothermal heat flux. Because CYH1 predicts heat flow for ages less than 10 Myr higher than is observed in the apparently-biased global data, CYH1 predicts a higher cumulative heat flux and lower cumulative hydrothermal heat flux than are inferred directly from the data [*Pelayo et al.*, 1994].

For greater distances from the axis, the model predictions depend less on spreading rate. The two models predict similar hydrothermal heat loss averaged over 0-1 Myr (Figure 10, bottom), ~0.5 W m^{-2}. This is about half that inferred from the data, again presumably due to the sampling bias.

Several of the model predictions accord with previous ideas. The fact that Model I, with the deeper sinks, fits better for slow ridges is consistent with *Purdy et al.*'s [1992] suggestion that water penetrates deeper for slow spreading because faults extend deeper. The idea of more hydrothermal heat loss for rapid spreading seems plausible [*Baker and Hammond*, 1992], although direct data to confirm it is not available. The requirement from the earthquake depths for more hydrothermal cooling near the ridge than is required by the heat flow away from the

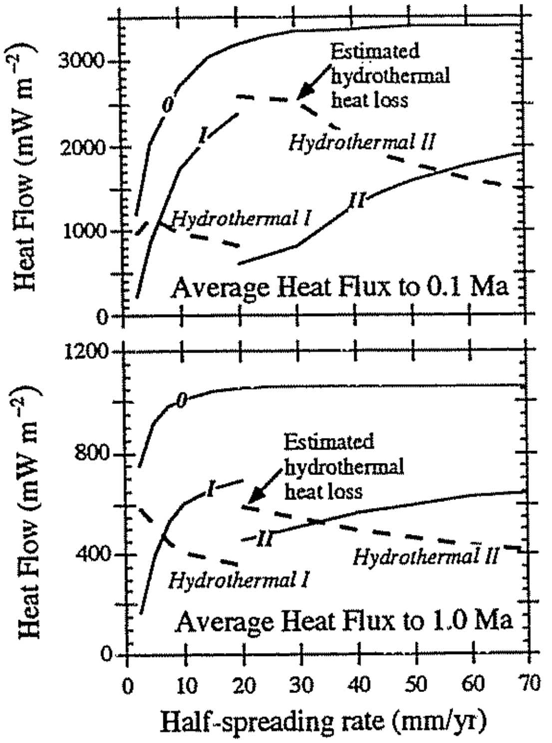

Fig. 10. *Top:* Average axial heat flux (to age of 0.1 Myr) for the composite model, assuming no hydrothermal circulation ("0") and for the two distributions of heat sinks ("I" and "II") which model the effects of hydrothermal circulation in young and old lithosphere. Dashed lines show the predicted hydrothermal heat flux, the difference between "0" and the two models. The predicted hydrothermal heat loss is greater for faster spreading. *Bottom:* Average near-axial heat fluxes (to age of 1.0 Myr). The predicted hydrothermal heat loss does not vary significantly with spreading rate. [*Pelayo et al.*, 1994].

ridge is consistent with *Lin and Parmentier*'s [1989] modeling.

Model implications for crustal cooling

For various purposes, it would be interesting to know how much and to what depth the crust is cooled by hydrothermal flow. Unfortunately, these features of the thermal model are not well constrained by the data. Away from the ridge, the requirement that the model match the heat flow data constrains only the surface temperature gradient. The same reduction in heat flow can result from different distributions of heat sinks with depth, and thus different temperature distributions. We postulated a concentration of shallow heat sinks sufficient to reduce the heat flow to that observed. Hence the temperatures (Plate 2, top) away from the ridge are only slightly cooler than were no hydrothermal cooling present (Plate 2, bottom). Although the ridge earthquake and magma chamber depths require in excess of 200°C cooling within 0.1 Myr of the axis, the heat flow data at ages older than a few Myr require surprisingly little cooling. For example, at 10 Myr, the observed heat flow of ~96 mW m^{-2}, compared to the predicted 161 mW m^{-2}, requires only that the temperature gradient be reduced from 51° km^{-1} to 30° km^{-1}, or ~20° cooling at 1 km depth. This small amount of off-ridge cooling is consistent with *Mottl and Wheat*'s [1994] estimate of low water temperatures for off-ridge flow, because their approach is conceptually similar.

In contrast, *Lin and Parmentier*'s [1989] formulation, in which hydrothermal circulation is modeled by an enhanced thermal conductivity to a depth of 6 km, predicts greater cooling away from the axis. Because the heat flow data provide no depth resolution, we consider the issue unresolved. It will be challenging to resolve, in that although isotopic data from ophiolites suggests that the high-temperature near-axial circulation extends to about 5 km [*Gregory and Taylor*, 1981], the depth of off-axial flow is unclear. Our assumption of shallow off-axial flow is generally consistent with recent hydrologic models [e.g. *Fisher et al.*, 1994; *Fisher and Becker*, 1995], which assume even shallower flow, in part because of drilling results indicating that high permeability is restricted to the upper few hundred meters.

Naturally, we do not ascribe great credence to this or other specific features of this composite model. Models of this type with different parametrizations, or models in which the cooling is described otherwise, will differ in their predictions. Even given our formulation, the heat sink distribution could be made more complicated to better fit the data older than about 35 Myr. We have not fine-tuned the model, because the simple representation seemed adequate to explore the model's utility. Based on the results shown, we believe that CYH1 or similar models can have several useful applications. First, they can predict heat flow and hydrothermal cooling as a function of age in young lithosphere, and thus permit comparisons to data from different regions. Second, they provide a crude way of predicting hydrothermal flux for comparison with estimates from other techniques, such as water sampling and geochemistry. Third, they permit some, hopefully meaningful, exploration of how hydrothermal flux may vary as a function of spreading rate and other parameters.

AFTERWORD

Although heat flow is an indirect way of studying hydrothermal circulation, heat flow data can tell us a surprising amount about the circulation given two basic assumptions. These assumptions are that the discrepancy between the observed and predicted heat flow reflects hydrothermal heat transport, and that the thermal models are not grossly inappropriate. Given these assumptions, it is almost inescapable that most of the hydrothermal flux occurs away from ridge axes. Moreover, given these assumptions, the most straightforward interpretation of the global heat flow data is that the processes causing hydrothermal heat transfer to decease with age depend primarily on crustal age, and at most secondarily on sediment thickness. Finally, the data show that the average heat flow in young lithosphere can be usefully characterized and modeled to estimate the average hydrothermal cooling.

We see two major challenges for future heat-flow based studies of hydrothermal circulation. One challenge is to use local studies to improve our overall understanding of the hydrothermal process by identification of properties common to different areas. Ideally, useful generalizations about how the distances, rates, and geometry of the flow vary with the local properties can be reached, such that it will be possible to go beyond site-specific models. A test might be whether such generalizations improve our understanding of off-axial flow to the point that they permit better a priori prediction of heat flow in young lithosphere than the global average data or an average hydrothermal model like CYH1.

A second challenge is to overcome the limitations of heat-flow based studies by integrating other data types. The CYH1 model shown here, which is based on heat flow, earthquake depths, and magma chamber depths, is a simple example. Another approach which shows great promise are local studies integrating heat flow, water flux, ocean crustal properties, and other geophysical and geochemical data. Hopefully such approaches will improve our understanding of the complex process of hydrothermal circulation on its various spatial and temporal scales. For example, a better understanding of long-distance water flow will hopefully be able to reconcile the different ideas that emerge from global and local studies about the relative roles of crustal aging and sediment in stopping hydrothermal flow.

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