GEOPHYSICAL HEAT FLOW

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Introduction

Heat flow is a directly measurable parameter at Earth's surface that provides important constraints on the thermal state of its interior. When combined with other data, it has proved useful for models of Earth's origin, structure, composition, and convective motion of at least the upper mantle. Because oceanic crust is mostly thin (about 5–8 km) and deficient in heat-producing radioactive elements compared to continental crust, marine heat flow measurements are particularly illuminating for the cooling and dynamics of the oceanic lithosphere. Indeed, they have provided an important constraint in the development and refinement of the plate tectonics paradigm over the past three decades.

Initially influenced by concepts of Sir Edward Bullard, the first successful marine heat flow measurements obtained shortly after the end of World War II were among the first applications of remote electronics in the deep sea. Other than a general understanding of seafloor topography, little information on the nature of the Earth beneath the oceans was then available, so theories to explain the measurements were largely unconstrained. Probably the most important initial finding was that the mean oceanic heat flux was not much different from the mean of the available continental values, contrary to conventional expectations of that era. However, the entire field of marine geophysics (especially seismic reflection and refraction, and geomagnetism) was also being transformed by instrumentation development, and the availability of ships as seagoing platforms gave rise to a 'golden age' of ocean exploration between about 1950 and 1970. The large-scale (> 1000 km) variations of marine heat flux were shown to be consistent with the plate tectonic paradigm that explained the mean depth and age of much of the ocean floor. Heat flow is now useful for studies of seafloor tectonics and other marine geophysical problems.

Marine heat flow measurements now number more than 15 000, and with the exception of high latitude regions, are distributed over most of Earth's main ocean basins (**Figure 1**). Values range over about two orders of magnitude (about 10–1000 $\mathrm{mW\,m^{-2}}$), with a general systematic spatial distribution at large (> 1000 km) scales but also a large variability at small (< 50 km) scales caused by pervasive hydrothermal circulation in mostly young (< 50–70 million years (My)) ocean crust. The spatial distribution and magnitudes of marine heat flow values may be used to deduce the geometry and intensity of such circulation.

Measurements and Techniques

Instrumentation and Development

Techniques for marine measurements were developed with the realization that the temperature of the deep (>2 km) ocean is mostly horizontally stratified, and relatively constant over long time scales (>100 years). In this situation, the heat flux from the Earth's interior is reflected in a relatively uniform temperature gradient with depth beneath a flat seafloor. Heat flow is the product of the magnitude of this temperature gradient and the thermal conductivity of the material over which it is measured. Gradients are commonly measured using a vertically oriented probe with temperature sensors surmounted by a weight that is lowered from a ship to penetrate the relatively soft sediments that cover most of the seafloor. Thermal conductivity is either measured with *in situ* sensors during the seafloor penetration by transient heating experiments or aboard ship on sediment cores.

For instrumental simplicity, the initial heat flow equipment used only two thermal sensors at either end of a 3–4 m long probe with *in situ* analog recording techniques on paper or film. Subsequently the number of sensors has been increased, due to a desire to measure nonlinear temperature gradients and thermal conductivity that may vary with depth. The wide range of measured thermal gradients and the developments in solid-state electronics have made digital recording the present standard. 'Pogo' measurements, i.e., multiple penetrations on the same station, combined with nearly real-time acoustic telemetry of raw data have proven useful for investigation of small-scale (< 10–20 km) marine heat flow variability, the origins of which are still not fully understood.

It was necessary for the 'Bullard' probe to remain undisturbed in the seafloor for most of one hour to

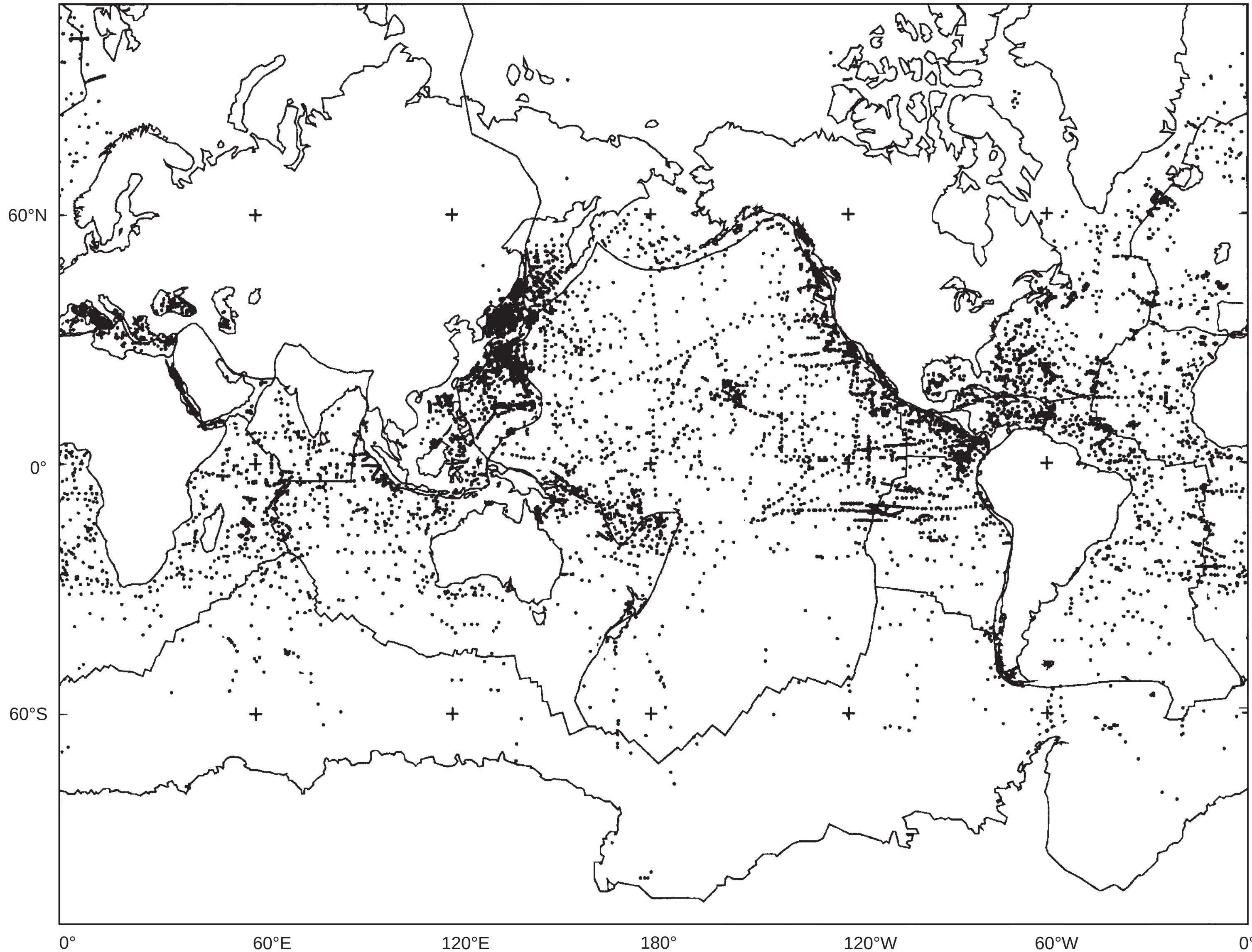

Figure 1 Locations of marine heat flow measurements (dots). Thin lines show the location of the major plate boundaries.

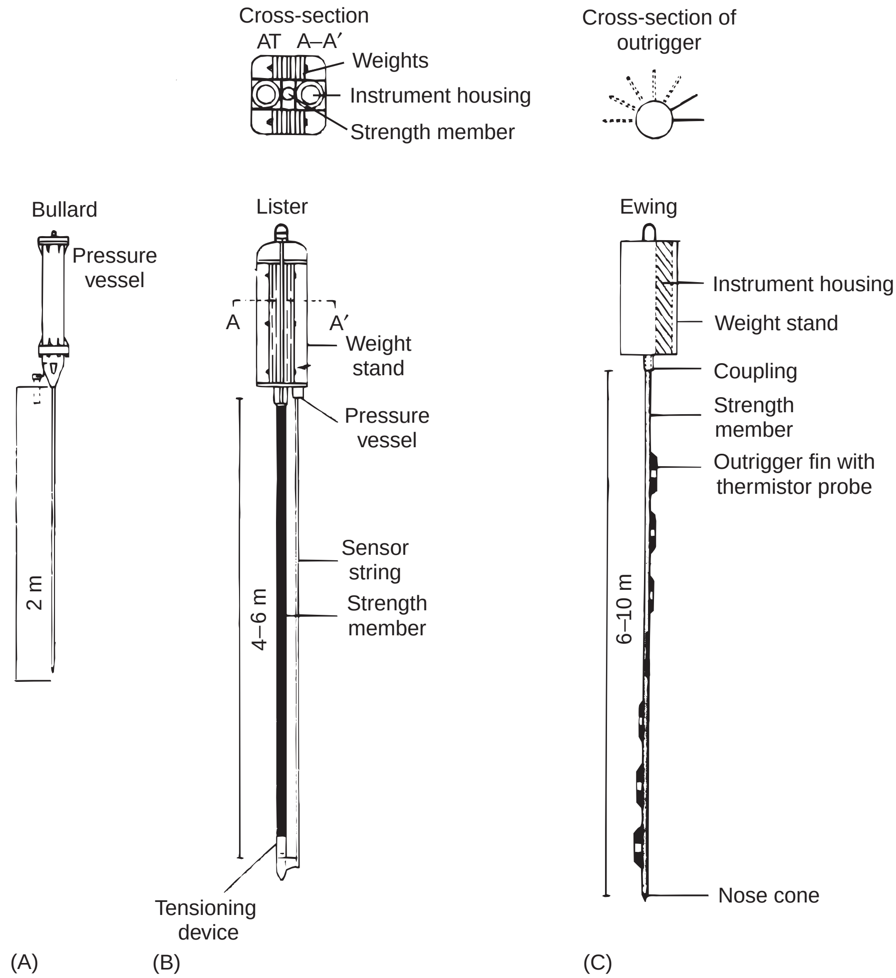

Figure 2 Diagrams of the three most commonly used marine heat flow probes. (Reproduced with permission from Louden KE and Wright JA (1989) Marine heat flow data: a new compilation of observations and brief review of its analysis. In: Wright JA and Londen KE (eds) *Handbook of Seafloor Heat Flow*, pp. 2–67, Boca Raton: CRC Press.

approach thermal equilibrium with the sediments because of its relatively large diameter (about 2–3 cm). This probe has been largely supplanted by either much smaller (about 3 mm diameter) individual probes mounted in outrigged fashion on a larger ('Ewing') probe to attain deep (5–6 m) penetration, or a 'violin-bow (Lister)' probe consisting of a small (about 1 cm) sensor string mounted parallel to, but separate from, the main strength member (**Figure 2**). Both are capable of *in situ* thermal conductivity measurements, utilizing either a constant heat source or a calibrated pulse (approximating a delta function) after the gradient measurement. The measurement time in the seafloor is 15–20 min. Depending mostly on the desired spacing during pogo operations, the mean time between measurement is 1–2 h. Even with acoustic data telemetering, battery life can be 2–3 days, thereby allowing many measurements during a single lowering. Real-time ship location accuracy now approaches a few meters with differential Global Positioning System navigation, although the uncertainty of the probe location during pogo operations in normal ocean depths (4–5 km) is typically 200 m or more. Hence 1–2 km is a useful minimum spacing between pogo penetrations unless seafloor acoustic transponder navigation is employed for higher accuracy (about 10 m) navigation. Instrumentation is also available to determine temperatures to depths up to about 600 m below the seafloor during deep-sea drilling to establish the uniformity of heat flow to greater depths, and may be the only method for reliable measurements in shallow seafloor (<1 km) regions where ocean temperatures are more variable. Geothermal probes have also been developed for use with manned submersibles, allowing visual control of measurements in regions with large lateral gradients of heat flux or over specific geological features. A development is underway to install geothermal instrumentation on an autonomous underwater vehicle (ABE) for measurements in regions that are remote or difficult for normal ship operations.

Environmental Corrections

Although most measurements on the deep seafloor with the usual instrumentation do not require corrections, they may be needed for some regions with unusual environmental parameters. As mentioned above, shallow water measurements may be subject to temporal bottom water temperature (BWT) variability, causing nonlinear gradients in the seafloor. Using heat conduction theory, corrections may be applied if BWT variability is monitored for a sufficient period (months to years if possible) before the geothermal measurements. Conversely, nonlinear temperature–depth profiles can be inverted to yield BWT history assuming that the initial gradient was linear. This inverse procedure is non-unique, although closely spaced measured temperatures to a sufficient depth below the seafloor and well-determined thermal conductivity can reduce uncertainties. Continental margins and some deep-sea trenches are examples of regions where non-linear gradients have been measured, usually correlated with strong and variable deep currents that are probably focused by the seafloor topography. Topography causes lateral heat flow variability even with uniform and constant BWT, because the seafloor topography distorts isotherms that would otherwise be horizontal below a flat surface. Seafloor sedimentation reduces the heat flow measured because recently deposited sediments modify the seafloor boundary condition to which the equilibrium gradient must adjust. Corrections usually become significant when sedimentation rates exceed a few tens of meters per million years and/or the total sediment thickness exceeds 1 km.

Vertical pore water flow in sediments may either enhance (for upward flow) or reduce (for downward flow) temperature gradients because the water advects some of the heat otherwise conducted upwards. The effects become significant for flow rates greater than a few centimeters per year, and nonlinear gradients may be expected if upward flow rates exceed about $10\,\mathrm{cm\,year^{-1}}$. It is unusual for rates on normal deep seafloor to exceed the latter value because the fluid permeability of pelagic sediments is too low, but coarser and sometimes rapidly deposited sediments of continental margins may support relatively rapid flows.

Range of Measured Parameters

As discussed later, the plate tectonic paradigm predicts that the highest thermal gradients and heat fluxes should be found in the youngest seafloor, and the lowest values in the oldest. Although this is generally true when measurements are averaged over regions of various seafloor ages, considerable variability occurs over the youngest seafloor as a result of vigorous hydrothermal circulation. The cooling of hot and permeable upper ocean crust supports seawater convection in the crust over lateral circulation scales of at least several to a few tens of kilometers; vertical scales probably do not exceed a few kilometers. The highest gradients and heat fluxes (up to $100^{\circ}\mathrm{C\,m^{-1}}$ and $100\,\mathrm{W\,m^{-2}}$, respectively) are measured in sediments near seafloor vents where fluids upwell, and the lowest ($< 0.005^{\circ}\mathrm{C\,m^{-1}}$ and $0.005\,\mathrm{W\,m^{-2}}$, respectively) where fluids downwell. Mean upper basement fluid velocities may be several meters per year, and much greater in conduits that support vigorous seafloor venting. The detailed pore water flow and permeability structure for any system of seafloor hydrothermal circulation have not yet been investigated in detail and are probably very complex.

After the seafloor ages to 50–70 My, hydrothermal circulation appears to decrease to a level where modulation of the surface heat flux is small to negligible (**Figure 3**), probably dependent on the thickness and uniformity of sediment cover. For the oldest seafloor (100–180 My), heat flux is relatively uniform at about $50\,\mathrm{mW\,m^{-2}} \pm 10\%$. This value probably reflects the secular cooling of the upper oceanic mantle.

Thermal conductivity of marine sediments generally varies less than a factor of two, from about 0.7 to $< 1.4\,\mathrm{W\,m^{-1}\,K^{-1}}$. The lowest values are associated with red clays or siliceous oozes, which have up to 70% or more of water by weight and the highest with carbonate oozes or coarse sediments near continental margins with a high proportion of quartz. Since water has a low thermal conductivity ($0.6\,\mathrm{W\,m^{-1}\,K^{-1}}$), sediments with a large percentage of water have low thermal conductivity. Since calcium carbonate and quartz have high thermal conductivity (about $3\,\mathrm{W\,m^{-1}\,K^{-1}}$ and $4\,\mathrm{W\,m^{-1}\,K^{-1}}$, respectively), sediments with a large percentage of either of these minerals have high thermal conductivity. Conductivity variations with depth may be caused by: (1) turbidity flows that sort grain sizes into layers with different proportions of pore water; (2) ice rafting in higher latitudes that may intersperse higher conductivity sediments derived from the continents and lower conductivity marine pelagic sediments; and (3) variability in the proportion of calcium carbonate in sediments near the equator deposited over climate (e.g., glacial) cycles.

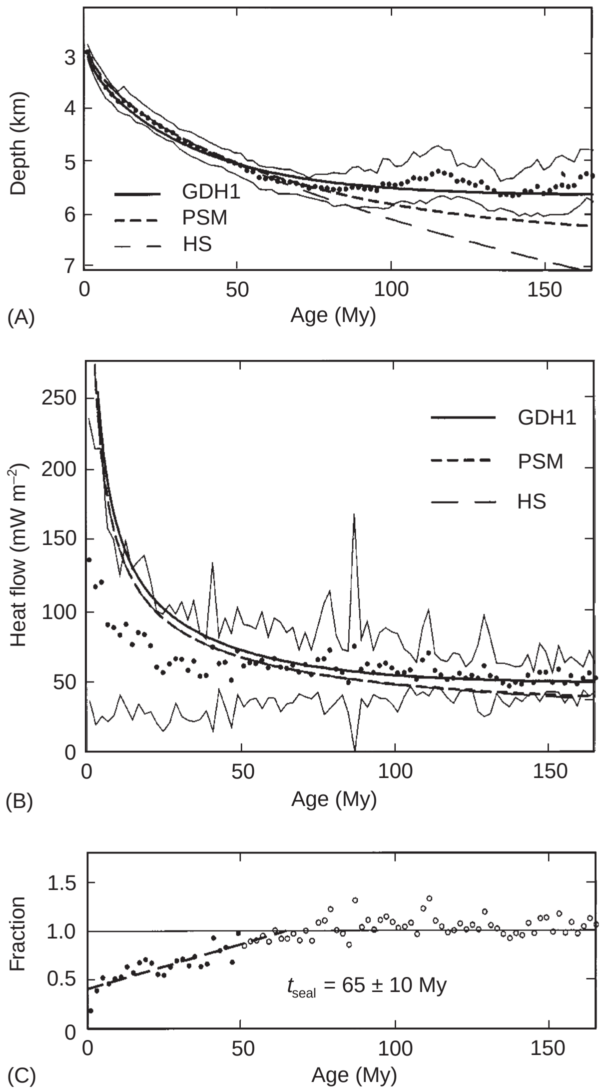

Figure 3 Data and models for ocean depth (A) and heat flow (B) as a function of age. (Reproduced with permission from Stein and Stein, 1992.) The data are averaged in 2 My bins, and one standard deviation about the mean value for each is shown by the envelope. Shown are the plate model of Parsons and Sclater (1977) (PSM), a cooling halfspace model with the same thermal parameters (HS), and the GDH1 plate model from Stein and Stein (1992). (C) Heat flow fraction (observed heat flow/GDH1 prediction) with age averaged in 2 My bins. The discrepancy for ages $<$ 50–70 My presumably indicates the fraction of the heat transported by hydrothermal flow. The fractions for ages $<$ 50 My (closed circles), which were not used in deriving GDH1, are fit by a least squares line. The sealing age, where the line reaches the fractional value of one, is 65 $\pm$ 10 My.

When thermal conductivity varies rapidly with depth the temperature–depth profile may not be linear. If thermal conductivity has been measured at closely spaced depth intervals, then the heat flow can be calculated using a method introduced by Bullard. This approach assumes the absence of significant heat sources or sinks and one-dimensional, steady-state, conductive heat flow. Thus there is a linear relationship between temperature and the thermal resistance of the sediments (the sum from the surface to the depth of the temperature measurement of the inverse of thermal conductivity times the sediment thickness for that given thermal conductivity). The slope determined from a least-squares fit of this 'Bullard plot' gives the appropriate conductive heat flux.

Thermal Models

Data for Thermal Modeling

Oceanic lithosphere forms at midocean ridges, where hot magma upwells, and then cools to form plates as the material moves away from the spreading center. As the plate cools, heat flow decreases and the seafloor deepens (**Figure 3**). However, only shallow (less than 1 km) measurements of lithospheric temperatures are possible. Hence, the two primary data sets used to constrain models for the variation in lithospheric temperature with age are seafloor depths and heat flow. The depth, corrected for sediment load, depends on the temperature integrated over the lithospheric thickness. The heat flow is proportional to the temperature gradient. Initially seafloor depths rapidly increase, with the average increase relative to the ridge crest proportional to the square root of the crustal age. However, for ages greater than about 50–70 My, the average increase in depth is slower and the curve is said to 'flatten.' Mean heat flow also decreases rapidly away from the ridge crest, with values approximately proportional to the inverse of the square-root of the age, but after about 50 My this curve also 'flattens.'

Halfspace and Plate Models

Two different mathematical models are often used to describe the thermal evolution of the oceanic lithosphere, the halfspace (or boundary layer) and plate models. For the halfspace model, the predicted lithospheric thickness increases proportionally with the square root of age. Hence depth and heat flow vary as the square root of age and the reciprocal of the square root of age, respectively. However, the halfspace model cannot explain the 'flattening' of the curves. Alternatively, the plate model represents the lithosphere as a layer with a fixed constant temperature at its base. Initially, the cooling for the plate model is the same as the halfspace model, but for older ages the influence of the lower boundary results in slower cooling, approximately predicting the observed flattening of the depths and heat flow at older ages. The plate base is assumed to represent a depth at which additional heat is supplied from the mantle below to prevent the halfspace cooling at older ages. However, the model does not directly describe how this heat is added.

Reference Models

Thermal models are solutions to the inverse problem of finding the temperature as a function of age that best fits the depth and heat flow. The data are used to estimate the primary model parameters (typically plate thickness, basal temperature, and thermal expansion coefficient), subject to other parameters generally specified *a priori*. The global average depth/heat flow variation with age, calculated for a specific model, data, and parameters is used as a reference model to represent 'normal' oceanic lithosphere. 'Anomalies', deviations from the reference model, are then investigated to see if they reflect a significant difference in thermal (or other) processes from the global average. It is important to realize that anomalies (defined as those observed minus the model-predicted values) for various reference models may differ significantly, and hence lead to different tectonic inferences.

Until recently, a 125 km-thick plate model by Parsons and Sclater (denoted here PSM) was commonly used. Subsequently, as more data became available, it was noted that PSM systematically overpredicts depths and underpredicts heat flow for lithosphere older than 70–100 My, causing widespread 'anomalies.' A later joint inversion of the depth and heat flow data by Stein and Stein found that these 'anomalies' are reduced significantly by a plate model termed GDH1. GDH1 has a thinner lithosphere (95 ± 10 km), and a basal temperature of 1450 ± 100°C, consistent with the PSM estimate (1350 ± 275°C). GDH1 predicts heat flow in $\mathrm{mW\,m^{-2}}$ as a function of age, t, in millions of years equal to $510\,t^{-1/2}$ for ages less than about 55 My, and $48 + 96\exp(-0.0278\,t)$ for older ages. Inversion of the same data, while prescribing a basal temperature of 1350°C (a typically assumed temperature for upwelling magma at the ridge based on results from experimental petrology), also yields a thin (100 km) plate, with a somewhat higher value of lithospheric conductivity and hence makes very similar predictions. As the quality of the observed data and our understanding of the physics of processes affecting lithospheric thermal evolution improve, new and better reference models will be developed.

Application to Lithospheric Processes

Using a reference model for the expected heat flow, regions can be examined to observe if the measured heat flow differs from that predicted and, if so, to study the causes of the discrepancy. Two primary discrepancies are assumed to reflect hydrothermal circulation and midplate swells.

Hydrothermal Circulation

Heat flow measurements for crust of ages 0–65 My are generally lower than the predictions of all commonly used reference models (**Figure 3**). Because the heat flow measurements primarily reflect conductive heat flow, this difference has been attributed to hydrothermal water flow in the crust and sediments transporting some of the heat assumed in thermal models to be transferred by conduction. The missing heat transported by convection must appear somewhere, either as high conductive heat flow or as advective discharge to the sea. It is estimated that of the predicted global oceanic heat flux of 32×10^{12} W, approximately one third occurs by hydrothermal flow.

Characteristic heat flow patterns in young crust appear associated with water flow. Surveys at sites like the Galapagos Spreading Center show high heat

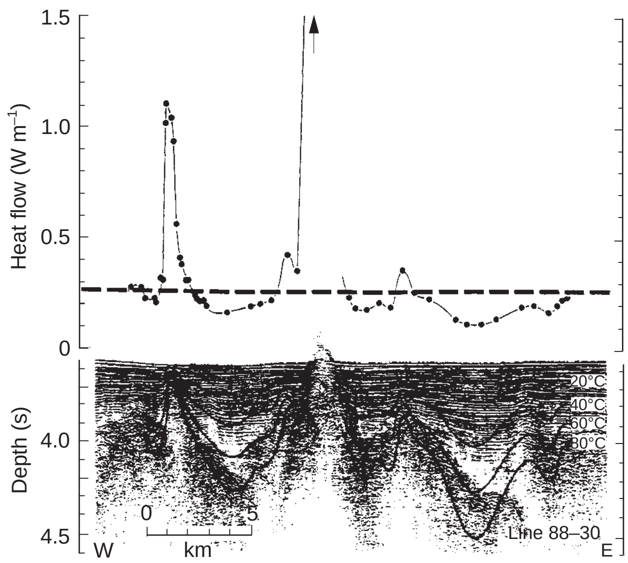

Figure 4 Portion of the heat flow data from the FlankFlux survey on the Juan de Fuca Ridge sites where bare rock penetrates the sediment column have dramatically higher heat flow than the surrounding areas. Away from these outcrops, heat flow varies inversely with depth to basement rock. Expected heat flow for its age is shown with the dashed line. (Reproduced with permission from Davis EE, Chapman DS, Mottl MJ *et al.* (1992) FlankFlux: an experiment to study the nature of hydrothermal circulation in young oceanic crust. *Canadian Journal of Earth Sciences* 29: 925–952.)

flow associated with presumed upwelling zones at basement highs or fault scarps, and low heat flow associated with presumably down-flowing water at basement lows. Heat flow over the highs may be two to ten (or more) times greater than at nearby sites where water may be recharging the system (**Figure 4**). Closely spaced surveys in young crust show high scatter, presumably in part due to the local variations in sediment distribution, basement relief, and crustal permeability.

The most spectacular evidence for hydrothermal circulation are vents near the ridge crest where hydrothermally altered water at temperatures up to 400°C exits the seafloor. Hot rock or magma at shallow depths provides a large heat source for the flow. The high sulfide content of the hot fluids supports unusual local biota from bacteria to tube worms. Vent areas show complex flow patterns with very high heat flow close to low heat flow. Although most vigorous vents are near spreading centers, on older crust isolated crystalline crust outcrops surrounded by a well-sedimented area can also vent measurable amounts of hydrothermal fluid (e.g., the FlankFlux survey area on the Juan de Fuca plate).

The persistence of the heat flow discrepancy well away from ridges indicates that hydrothermal heat loss occurs in older crust. The 'sealing age,' defined as that beyond which measured heat flow approximately equals that predicted, is presumed to indicate the near cessation of heat transfer by hydrothermal circulation. The sealing age for the entire global data set is about 65 ± 10 My. Hence, although there are presumably local variations, water flow in older crust seems not, in general, to transport significant amounts of heat. However, some heat flow surveys (e.g., in the north-west Atlantic Ocean on 80 My crust and the Maderia Abyssal Plain on 90 My crust) indicate that hydrothermal circulation may continue, even if relatively little heat is lost by convection into the sea water. The reasons for the 'sealing' are not well understood. An earlier view was that 100–200 m of sediment would be sufficiently impermeable to 'seal' off the crust from the sea, so that heat flow at these sites would yield a 'reliable' value, i.e., that predicted by conduction-only thermal models. However, many such sites have lower than expected values. A simple way to reconcile these observations with the present understanding of seafloor hydrology to assume that if water cannot flow vertically through thick sediments at a particular site, it may flow laterally to a fault or basement outcrop, and then be manifested as either high conductive heat flow or hot water exiting to the sea, such as observed for the FlankFlux area. It has been suggested that the porosity and permeability of the crust decrease with increasing age, thus significantly reducing the water flow. However, recent studies of permeability and seismic velocity suggest that most of the rapid change occurs within the first 5–15 My and that older crust may still retain some relatively permeable pathways.

Hydrothermal circulation has profound implications for the chemistry of the oceanic crust and sea water, because sea water reacts with the crust, giving rise to hydrothermal fluid of significantly different composition. The primary geochemical effects are thought to result from the high-temperature water flow observed at ridge axes. Circulation of sea water through hot rock removes magnesium and sulfate from sea water and enriches calcium, potassium, silica, iron, manganese, and other elements within the hydrothermal solution. Estimating the volume of water flowing through the crust depends on the heat capacity of the water, the heat lost by convection, and the assumed temperature of the water, the latter having the largest uncertainties. Although the heat flow anomaly is greatest in young lithosphere, only about 30% of the hydrothermal heat loss and 7% of the water flow occurs in crust younger than 1 My. This effect should be significant for ocean chemistry because a water volume equivalent to that of the total ocean is estimated to circulate through the oceanic crust about once every 0.5–5 My.

Hot Spots

Oceanic midplate swells are identified by seafloor depths shallower than expected for their lithospheric age. Thus, models of the processes giving rise to these regions rely on assessments of how their heat flow and other properties differ from unperturbed lithosphere. The origin of these swells is generally thought to be related to upwelling mantle plumes (hot spots) that result in uplift and volcanism. Two basic types of models have been proposed for their origin. In one, the swell is a thermal effect due to the hot spot thinning and heating the lithosphere at depth. In the second, the uplift is primarily due to the dynamic effects of the upwelling plume, which may largely reflect thermal buoyancy forces within the upwelling mantle. The thermal models predict significantly larger heat flow anomalies than do the dynamic models. Detailed heat flow measurements have been made for Hawaii, Cape Verde, Reunion, Bermuda, and Crozet swells. Relative to the PSM reference curve, large heat flow anomalies are suggested. However, relative to both measured heat flow from off-swell lithosphere and the GDH1 reference curve, smaller heat flow anomalies (less

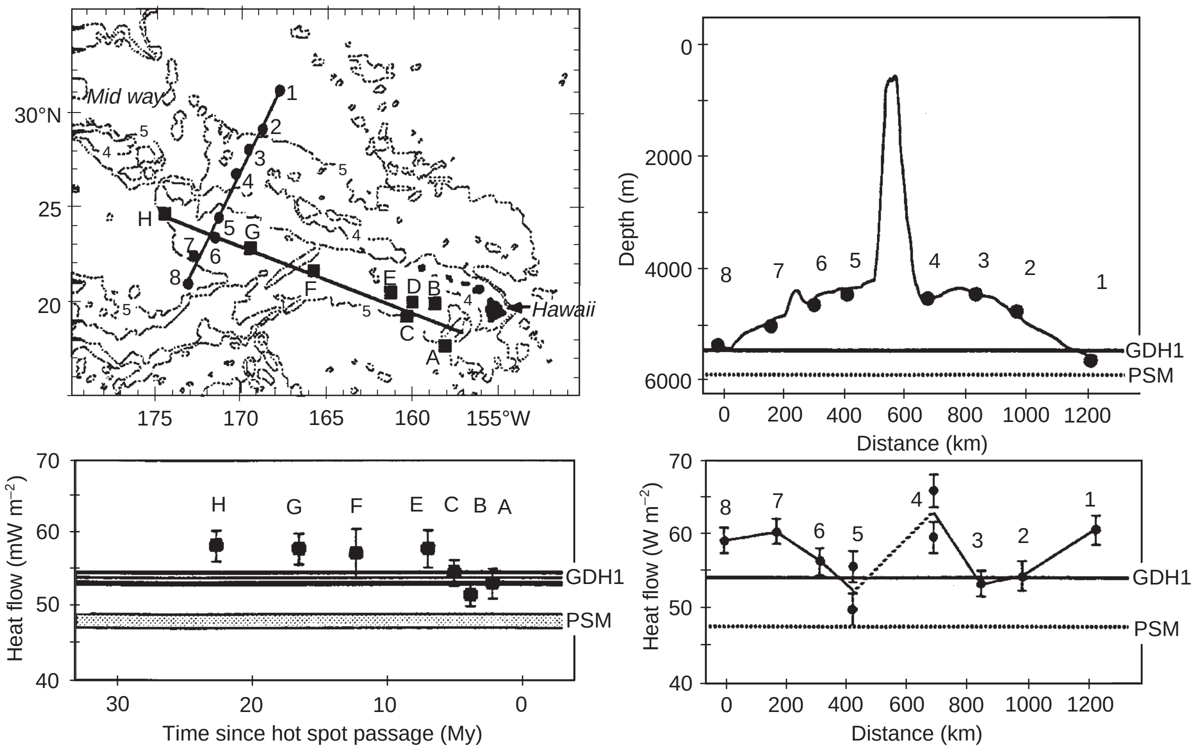

Figure 5 Heat flow data for transects along (lower left) and across (lower right) the Hawaiian Swell at the locations shown (upper left). The heat flow, though anomalously high with respect to the Parsons and Sclater (PSM) model, is at most slightly above that expected for GDH1. The predicted heat flow values are for 100 My (lower right) and 95–110 My (lower left). Figure modified from Von Herzen *et al.* (1982, 1989). (Reproduced with permission from Stein CA and Stein S (1993) Constraints of Pacific midplate swells from global depth-age and heat flow-age models. *The Mesozoic Pacific, American Geophysical Union Monograph* 77: 53–76.)

than 5–8 mW m^{-2}) are deduced, supporting the idea of a primary dynamic mechanism for hotspots (**Figure 5**).

Application to Marine Margin Studies

Subduction Zones

Many extensive marine heat flow surveys have been done near the Japanese subduction zones. On average, observed heat flow from the trench axis to the forearc area is lower than that characteristic of the crust seaward of the trench. However, heat flow is higher and more variable over the volcanic arc and back arc region compared to the area seaward of the trench. Recent surveys for subduction zones, including Barbados, Nankai, and Cascadia, show that heat flow is highly variable. Within accretionary prisms, high values are often associated with upward advection of pore fluids, typically found along faults and the bottom decollement. Although they have not been investigated extensively, the active nonaccretionary forearcs seem to have the lowest mean heat fluxes (20–30 mW m^{-2}). Relatively low heat flow values over the subducting lithosphere are the thermal consequence of the subduction of one plate beneath another. Overall, heat flow depends on the age, rate, geometry, and thermal structure of the subducting plate and the sediment thickness and deformation history of the region. Heat flow in marginal basins behind the volcanic arcs is often high. Many back arc basins with high heat flow appear to have formed by back-arc spreading processes similar to those at midocean ridges, within the last 50 My.

Passive Continental Margins

Passive continental margins form after continental crust is rifted and seafloor spreading occurs. Because rifting heats the lithosphere, heat flow data can be used to constrain models of rifting. Subsequent to rifting, margins slowly subside as cooling occurs. Simple models for this process suggest that subsequent to rifting the additional heat will almost completely dissipate within 100 My. Although the amount of radioactive heating from continental crust may introduce some variability, older passive margins typically have heat flows similar to old oceanic crust, whereas young margins, such as in the Red Sea, have high heat flow.

Gas Hydrates

Gas hydrates, solid composites of biogenically derived gasses (mainly methane) combined with water ice, may be present in marine sediments, especially at continental margins, under the correct pressure and temperature conditions. Gas hydrates are detected by direct sampling, and inferred from seismic reflection data when a strong bottom-simulating reflector (BSR) is produced by the seismic velocity contrast between the gas hydrate and the sediment below. Given a depth (and thus pressure) of a bottom-simulating reflector, its temperature can be predicted from known relationships and a heat flow calculated. Alternatively, heat flow data can be used to estimate the bottom-simulating reflector temperature. The volume of hydrocarbons contained in marine gas hydrates is large. Changes in eustatic sea level (hence pressure) or bottom seawater temperatures could result in their release and thus increase greenhouse gasses and affect global climate.

Further Reading

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GLACIAL CRUSTAL REBOUND, SEA LEVELS AND SHORELINES

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Introduction

Geological, geomorphological, and instrumental records point to a complex and changing relation between land and sea surfaces. Elevated coral reefs or wave-cut rock platforms indicate that in some localities sea levels have been higher in the past, while observations elsewhere of submerged forests or flooded sites of human occupation attest to levels having been lower. Such observations are indicators of the relative change in the land and sea levels: raised shorelines are indicative of land having been uplifted or of the ocean volume having decreased, while submerged shorelines are a consequence of land subsidence or of an increase in ocean volume. A major scientific goal of sea-level studies is to separate out these two effects.

A number of factors contribute to the instability of the land surfaces, including the tectonic upheavals of the crust emanating from the Earth's interior and the planet's inability to support large surface loads of ice or sediments without undergoing deformation. Factors contributing to the ocean volume changes include the removal or addition of water to the oceans as ice sheets wax and wane, as well as addition of water into the oceans from the Earth's interior through volcanic activity. These various processes operate over a range of timescales and sea level fluctuations can be expected to fluctuate over geological time and are recorded as doing so.

The study of such fluctuations is more than a scientific curiosity because its outcome impacts on a number of areas of research. Modern sea level