S

SEAFLOOR HEAT FLOW: METHODS AND OBSERVATIONS

Earl E. Davis[1] and Andrew T. Fisher[2]
[1]Geological Survey of Canada, Sidney, BC, Canada
[2]University of California at Santa Cruz, Santa Cruz, CA, USA

Definitions

Heat flow. The rate of thermal energy transfer in a medium driven either conductively along a thermal gradient or advectively via mass transport. The standard unit is watts, W. The term is also used to describe a subdiscipline of geophysics, as in the title of this entry.

Conductive heat flux. The heat flow per unit area diffusing by conduction along a thermal gradient, determined as the product of the thermal gradient and thermal conductivity. The standard unit is W m^{-2}. The term *heat flow density* has been used correctly as a synonym; the term *heat flow*, traditionally but inexactly used as a synonym for heat flux, more strictly applies to the integrated heat flux over a specified area or region (watts).

Advective heat flux. The rate of heat transfer per unit area carried by a moving medium, proportional to the velocity and the heat capacity of the medium. The standard unit is W m^{-2}.

Thermal conductivity. The quantity that defines the ability of a medium to transfer heat by steady-state diffusion. The standard unit is W m^{-1} K^{-1}.

Hydrothermal circulation. Large-scale pore-fluid convection driven by thermal buoyancy, in which fluid flux and advective heat flux are strongly influenced by the permeability structure of the host formation.

History of observations

Pioneering measurements of temperature below the seafloor (e.g., Petterson, 1949; Revelle and Maxwell, 1952; Bullard, 1954) were made to compare the thermal state of the ocean crust with that of continents and thus to improve the knowledge of the present-day heat loss from the Earth. The early data demonstrated that gravity-driven probes and corers that penetrated a few meters into seafloor sediments could provide meaningful geothermal gradients, and they provided a foundation for the marine heat flow discipline. Methods for measuring the seafloor thermal gradient and thermal conductivity (the product of which is conductive heat flux) improved in subsequent years, the number and geographic distribution of determinations increased, and patterns of seafloor heat flux were gradually revealed. Initially, the average seafloor heat flux appeared to be similar to that through continents, despite the contribution from crustal radiogenic heat production, which is significant in the continental crust but not in the oceanic crust. Heat-flux values over midocean ridges were found to be significantly higher on average than in the flanking basins, but locally, values were often inexplicably scattered (Von Herzen and Uyeda, 1963; Lee and Uyeda, 1965). Higher heat flux at midocean ridges was consistent with emerging ideas about seafloor spreading, although the values measured were lower than expected from early theoretical models for the formation of ocean lithosphere. For nearly 2 decades, regionally low and scattered seafloor heat-flux values remained unexplained.

By the 1970s, studies began to be done with improved navigation, and with more closely spaced measurements made in the context of local sediment and igneous crustal structure. Results provided a sound basis for the hypothesis that hydrothermal circulation in the igneous crust and advective loss through unsedimented igneous outcrops caused both the scatter and the lower-than-expected values in young areas (Lister, 1972). Further

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improvements to instrumentation and observational strategies, in particular the development of probes that could be used with great efficiency for multiple measurements during a single instrument lowering, and the practice of making measurements in the context of geologic structure, led to the use of heat flux in the study of the process of hydrothermal circulation itself (Williams et al., 1974). With this new knowledge, it was possible to decipher the variability in measurements in a way that could lead to a better quantification of deep-seated heat flux, the goal of the original marine heat flow studies, and to understand the hydrologic processes behind the perturbations. Thus began a diverse range of applications of marine heat flow over a broad range of scales. A summary of the suite of tools currently in use for these studies is provided in the next section, along with a brief description of how heat-flux determinations are made. This is followed by a few examples of data from specific studies that illustrate how data are used, and a summary of some of the major conclusions that have been made through such studies.

Methods

Shallow measurements in marine sediments

Heat flux through the seafloor is often determined using temperatures measured with a series of sensors mounted on the outside of gravity-driven corers (Figure 1a), and thermal conductivities measured on the recovered sediment cores. Depths of penetration in excess of 10 m can be achieved in soft sediment, providing a valuable check on potential perturbations from bottom-water temperature variations, although accuracy is often limited by physical disturbances caused by the coring process, by changes in the physical properties of the recovered material, by incomplete recovery, and by the imperfect depth registration between the cores and the intervals between the temperature sensors. Probes devoted exclusively to heat-flux measurements are typically limited to lengths of a few meters, but they have several distinct advantages. They allow thermal conductivity to be measured under in situ conditions and at depths that are co-registered with temperature measurements, and they allow transects of many measurements to be made efficiently during single instrument lowerings. A typical multipenetration heat-flux probe (Figure 1b) employs a heavy strength member that resists bending during repeated penetration and withdrawal from the sediment, and a small-diameter, rapidly responding tube containing thermistor sensors and a linear heater element. In situ temperatures are estimated by extrapolating transient decays following probe penetration, and conductivities are determined from the rate of change of temperature following steady or impulsive activation of the heater. A typical data record is shown in Figure 2, as are the resulting determinations of temperature and thermal conductivity. Heat flux is determined as the linear regression fit of temperature versus cumulative thermal resistance, *R:*

$$R = \sum [\Delta z / \lambda(z)]$$

where λ is thermal conductivity measured at a series of depths, z, and Δz is the depth interval assumed to be represented by each measurement. This is equivalent to calculating heat flux as the product of thermal gradient and the harmonic mean of thermal conductivity between temperature measurements, as was done in early marine heat flow studies. Errors associated with possible bottom-water temperature variations are evaluated by examining systematic deviations from linearity as a function of the number of thermistors included in the fit, working progressively up toward the shallowest measurement point. Complete descriptions of instruments and discussions of data reduction methods can be found in Lister (1979); Hyndman et al. (1979); Davis (1988), Wright and Louden (1989), and Villinger and Davis (1987).

Deep borehole measurements

Where observations are needed in hard formations or at depths greater than can be penetrated with a gravity-driven device, drilling is required. For research objectives, this has been done primarily through the Deep Sea Drilling Project, the Ocean Drilling Program, and the Integrated Ocean Drilling Program. In relatively unconsolidated sediments (typically the uppermost 50–100 m below the seafloor), hydraulically driven piston corers are deployed from the bottom of the drill string, and temperatures are measured at the tip of the core barrel (Horai and Von Herzen, 1985). At greater depths below the seafloor, high-strength probes can be pushed in with the weight of the drill string sufficiently far below the bottom of the hole (c. 1 m) to gain an unperturbed measurement (Uyeda and Horai, 1980; Davis et al. 1997a) (Figure 1c). Deeper than a few hundred meters in sediment, or at any level in crystalline rock, bottom-hole measurements are not feasible; instead, long-term borehole measurements are required to discriminate the natural formation thermal state from the commonly large and long-lived perturbations from drilling and subsequent fluid flow into or out of the hole. The most reliable method for determining the natural thermal state of crustal rocks has been to seal holes and install thermistor strings for long-term monitoring (Davis et al., 1992) (Figure 3).

Example studies

Bottom-water temperature perturbations

Seafloor heat-flux measurements rely on the assumption that both long- and short-term bottom-water temperature variations are small; the volume of ocean bottom water is very large and the temperature of the source in polar regions is regulated by the formation of sea ice. Many early measurements were made with temperatures determined at only three depths over a span of a few meters, however. Good checks on the validity of this assumption were not possible until temperature observations began to be made in deep-sea boreholes and long records of

bottom-water temperature were acquired (Hyndman et al., 1984; Davis et al., 2003). An ideal suite of observations that would allow errors associated with bottom-water temperature variations to be quantified throughout the world's oceans – one that is broadly distributed both geographically and with ocean depth – does not yet exist, but the available data show that gradients measured a few meters below the seafloor generally do permit accurate determinations of heat flux in large areas of the oceans where depths are greater than ~2,000 m. One example where errors are demonstrated to be small is illustrated in Figure 4, where closely colocated seafloor probe and borehole observations are compared. Significant bottom-water temperature variations are ruled out by the linearity of the plots of temperature versus cumulative thermal resistance, and by the agreement between the shallow probe and deep borehole determinations. This illustration also shows the importance of precise colocation when doing such a comparison, given the local spatial variability of heat flux as defined by neighboring probe measurements.

A more direct approach uses observations of bottom-water fluctuations. An example from a 5,000-m-deep site in the western Atlantic (Figure 5a) shows that in this area, oceanographic perturbations might have a modest influence on measured gradients. Estimated gradient perturbations at depths of less than 2–3 m below the seafloor range up to 10 mK m^{-1} (Figure 5b), that is, up to 20% of the geothermal gradient if the heat flux were 50 mW m^{-2}. A second example from a 2,600-m-deep site in the eastern Pacific shows smaller variability (Figure 5c), although perturbations estimated at a depth of 2 m could still result in a heat-flux determination error of up to 10%. Observations like these are clearly useful for guiding measurement strategy (e.g., depth of penetration) wherever heat flux is low and precise determinations are required.

Heat-flux signals from hydrothermal circulation

Hydrothermal circulation is a major source of error when determinations of deep-seated heat flux are sought, but it is also an important geological process. Hence it has been the focus of a large number of studies. Instructive examples of the influence of hydrothermal circulation are shown in Figure 6, where closely spaced measurements were made along transects striking perpendicular to basement structure. The first (Figure 6a) is in an area where sediment cover is continuous over a broad region spanning several tens of kilometers. Locally, heat flux varies inversely with sediment thickness. Such variations are common in areas of young seafloor, but can occur across relatively old seafloor as well (Embley, 1980; Von Herzen, 2004; Fisher and Von Herzen, 2005). They are the consequence of thermally efficient, local convection in permeable igneous rocks beneath low-permeability sediment cover. If the permeability of the igneous "basement" formation is high, vigorous convective flow maintains nearly constant temperatures at the sediment/basement interface despite variations in the thermal resistance of the overlying sediment layer. In this instance, the average seafloor heat flux is close to that expected from the underlying lithosphere, suggesting that from a thermal perspective, the circulation in the upper igneous crust is sealed in by the extensive sediment cover. The second transect (Figure 6b) crosses a sediment-covered area immediately adjacent to an area of outcropping igneous crust (where measurements are impossible). Local variations like those in Figure 6a are present, but even more apparent is a systematic variation of a larger scale, with heat flux increasing with distance from the area of basement outcrop, opposite to the expected trend of decreasing heat flux with increasing seafloor age. Temperatures estimated at the top of the igneous section increase systematically as well, suggesting that heat is transported laterally by fluid circulation and mixing in the sediment-sealed igneous crust. Heat exchange between the well-ventilated and sediment-sealed areas, indicated by the heat-flux deficit in this example, suggests a lateral heat-transfer scale of 20 km. Examples elsewhere suggest that the effects of advective heat loss may be felt laterally as far as 50–100 km (e.g., Fisher et al., 2003).

Ever since the early work of Lister (1972), the mere presence of local variability has been used as a diagnostic indicator of hydrothermal circulation in both young and old areas (e.g., Figure 6c), but with widely spaced observations, neither of the signals exemplified in Figure 6a and b could be resolved coherently; values were simply scattered and averages were often low. When systematic, detailed transects of observations began to be completed in context of colocated seismic data, the vigor of the convection could be inferred quantitatively from the nonconductive thermal regime (Fisher and Becker, 1995; Davis et al. 1997b), and the amount of heat lost from the crust by fluid advection could be estimated with growing confidence (e.g., Anderson and Skilbeck, 1980; Stein and Stein, 1994; Harris and Chapman, 2004).

Two major lessons are learned from detailed observations like these for drawing conclusions about deep-seated heat flux. First, to ensure that observations do not suffer from the bias caused by convective ventilation, it must be demonstrated that there are no exposures of permeable rock at faults or volcanic edifices within distances of several tens of kilometers. Second, large numbers of closely spaced observations must be made, ideally colocated with seismic reflection data, so that the local variability can be understood and meaningfully averaged, and the locally relevant lateral transport scale can be assessed (e.g., Sclater et al., 1976; Davis et al., 1999).

Lessons learned about the way that the seawater interacts with the oceanic crust are far-reaching and continuously expanding. Estimates for the temperatures of circulation, the chemistry of the fluids, the volumetric rates of exchange between the crust and the ocean, and the consequent effects on crustal alteration and ocean chemistry have become reasonably well understood (e.g., Mottl and Wheat, 1994; Elderfield and Schultz, 1996). Studies of

the actual distribution of crustal permeability, the percentage of rock affected by hydrothermal alteration, and the potential for chemosynthetic microbial populations are the focus of current investigations.

Dependence of heat flux on age and the global average

With the potentially large influence of hydrothermal circulation in mind, it is clear that a simple compilation of heat-flux data will provide a deceiving view of global heat loss. Except in old ocean basins, values are likely to be scattered and low relative to the heat loss expected from the underlying lithosphere. But by taking only those measurements that are sufficiently far from known permeable crustal outcrops and sufficiently numerous to provide a reliable local average, a subset of data can be gathered that provides a reliable determination of deep-seated heat flux. When considered in the context of lithospheric age, the results have been found to be consistent with both the characteristics of age-dependent seafloor subsidence and with simple lithospheric cooling theory (see entry on Oceanic Lithosphere: Thermal Structure). In young areas, heat flux is found to decline linearly with the inverse square root of age, following the simple relationship $Q = \mathrm{C}\, t^{-1/2}$ (where Q is heat flux in $\mathrm{mW\,m^{-2}}$, t is age in Ma, and C is a constant estimated between 475 and 510; Lister et al., 1977; Harris and Chapman, 2004). High-quality observations in older regions ($>$100 Ma) are generally uniform, in the range of 45–50 $\mathrm{mW\,m^{-2}}$ (Lister et al., 1990), suggesting that the thermal structure of the lithosphere may become stabilized in a state regulated either by the convectively supplied heat flux from the underlying asthenosphere, or by the combination of a compositionally established lithospheric thickness and the relatively uniform temperature of the vigorously convecting asthenosphere.

With the relationship between heat flux and age thus defined, the problems of the unknown bias and large scatter in young areas and the sparse distribution of measurements in large portions of the oceans can be overcome. A reliable estimate for the total heat flow through the floor of the ocean can be had by using the area/age relationship for the oceans defined by seafloor magnetic anomalies (e.g., Parsons, 1982; Wei and Sandwell, 2006), along with a robust heat-flux/age relationship. Several such estimates have been made (e.g., Williams and Von Herzen, 1974; Sclater et al., 1980; see summary in Jaupart et al., 2007), and all fall in a relatively narrow range centered around 32 TW (with contributions from marginal seas and hotspot swells included). This yields an average seafloor flux of roughly 107 $\mathrm{mW\,m^{-2}}$, a number that has little physical significance, but is considerably greater than that estimated in the early days of marine heat flow, and greater than the average though continents (c. 67 $\mathrm{mW\,m^{-2}}$), particularly when the latter is adjusted for the contribution of continental crustal radiogenic heat (c. 33 $\mathrm{mW\,m^{-2}}$).

With the total heat flow thus constrained, the heat lost advectively by ventilated circulation can be estimated from the difference between this and the age-binned average of unfiltered observations. Such estimates of this "heat deficit" fall in the neighborhood of 10 TW (Stein and Stein, 1994; Harris and Chapman, 2004). Most of this deficit occurs in seafloor less than 8–10 Ma in age, and it becomes insignificant on average by an age of 65 Ma. The actual age at which advective loss becomes insignificant is locally variable, depending primarily on the continuity of accumulating sediments that bury the igneous crust (Anderson and Skilbeck, 1980; Harris and Chapman, 2004), and the associated increase in spacing between basement outcrops that are essential for hydrothermal recharge and discharge on older ridge flanks (Fisher and Wheat, 2010).

The signature of subduction

Marine heat flux is used extensively to constrain deep thermal structure in studies of continental margins and marginal basins. A transect crossing the forearc prism of the Cascadia subduction zone illustrates one such application (Figure 7). This transect begins with standard gravity-driven probe measurements over the incoming plate and outermost accretionary prism, where bottom-water temperature variability is small. Where the seafloor is shallower than 1,500–2,000 m, other measurement techniques are used, including borehole measurements and estimates made using the depth to a bottom-simulating seismic reflector (BSR), which marks the limit of methane-hydrate stability. This reflector defines a unique set of pressure-temperature conditions, and with constraints on seismic velocity and thermal conductivity of the section above the BSR, the thermal gradient and heat flux can be estimated. Alternatively, a small set of seafloor heat-flux measurements can be used as a "calibration." In either case, the travel-time depth to BSRs can serve as a widespread proxy for thermal data (e.g., Yamano et al., 1982). This technique is valuable where bottom-water temperature variability is too large to permit accurate heat-flux determinations with shallow probes, where sediments are too hard to allow probe penetration, or where there are few conventional measurements. Observations like these allow the thermal structure to be inferred deep within subduction zones, providing a critical constraint on the rheology of the rocks and the potential for seismogenic slip along the subduction thrust interface. In the example shown (Figure 7), the seafloor heat flux is variable locally, but regional values and trends are consistent with the expected thermal state of the thickly sedimented subducting plate.

In another study of the subducting Cocos Plate seaward of the Middle America Trench, variations in the thermal state of the plate are strongly influenced by regional differences in hydrothermal heat loss, and these correlate with differences in seismic processes occurring at depth (Newman et al., 2002; Fisher et al., 2003). One part of

the plate is extensively cooled by hydrothermal circulation before the Cocos Plate is subducted, and earthquakes observed within the subduction wedge in this area are relatively deep (>20 km). Earthquakes tend to be shallower (<20 km) along an adjacent segment of the subduction zone, where there is no evidence for regional advective heat extraction. One explanation for the different earthquake depths is that cooling of part of the Cocos Plate slows dewatering and the transition of smectite to illite in subducting sediments (Spinelli and Saffer, 2004). Illite-rich sediments are more likely to undergo brittle deformation at depth, so the delay in heating associated with hydrothermal circulation in the crust prior to subduction causes a landward shift of the locked region where earthquakes are most likely to occur.

Summary

Seafloor heat flux can be measured with high accuracy in most deep-ocean settings with gravity-driven probes that penetrate a few meters into seafloor sediment. Improvements in heat-flux measurement technology, improvements in navigation, and integration with swath bathymetric, seismic, and other data that provide geological context for heat-flux measurements have greatly advanced our understanding of many global, regional, and local heat flow processes. Comparison of seafloor and borehole data has demonstrated that measurements made with short probes are accurate, provided that bottom-water temperature variations are relatively small. Compilations of global heat-flux data show that heat flux tends to vary systematically with seafloor age, following a $t^{-1/2}$ relation, at least until seafloor age exceeds 100 Ma, after which heat flux tends to become relatively constant. Determining the deep-seated lithospheric heat flux requires quantification of the potentially large influence of hydrothermal circulation in the permeable igneous rocks of the upper oceanic crust. This is best accomplished through closely spaced transects of heat-flux measurements colocated with seismic reflection profiles that constrain the hydrologic structure, and regional maps that allow identification of basement outcrops. This approach has been applied in numerous settings, providing valuable constraints on the flow of water within the oceanic crust, the exchange of water, heat, and solutes between the crust and the oceans, the formation of hydrothermal mineral deposits, the accumulation of gas hydrates, and the development and maintenance of a subseafloor microbial biosphere. Individual heat-flux measurements and transects of measurements can be extended across broad regions using the depth to bottom-simulating seismic reflectors. These and other applications were never imagined by those who developed the original techniques for acquisition of seafloor heat-flux data 6 decades ago, but they illustrate how acquiring this kind of data has remained valuable for multidisciplinary studies of thermal, hydrogeologic, tectonic, and microbiological conditions and processes within the lithosphere.

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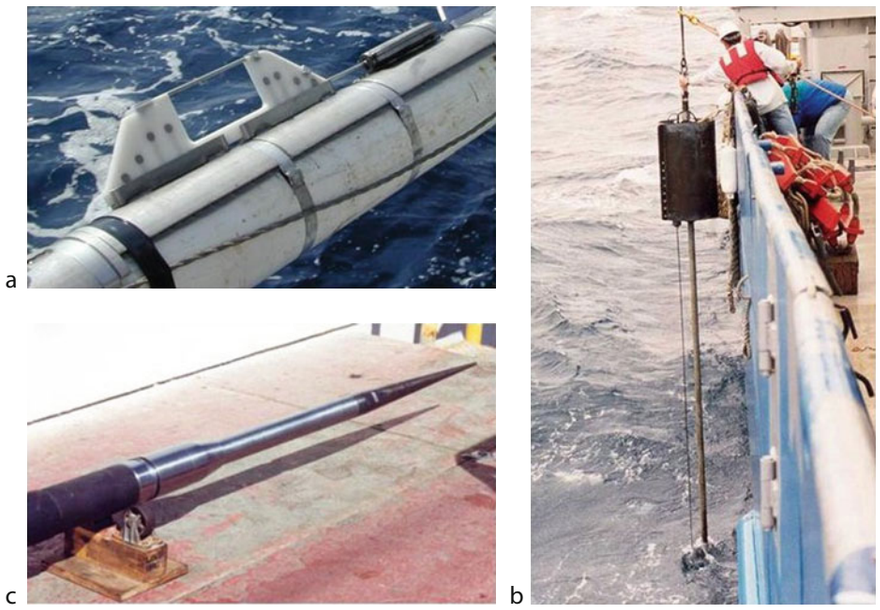
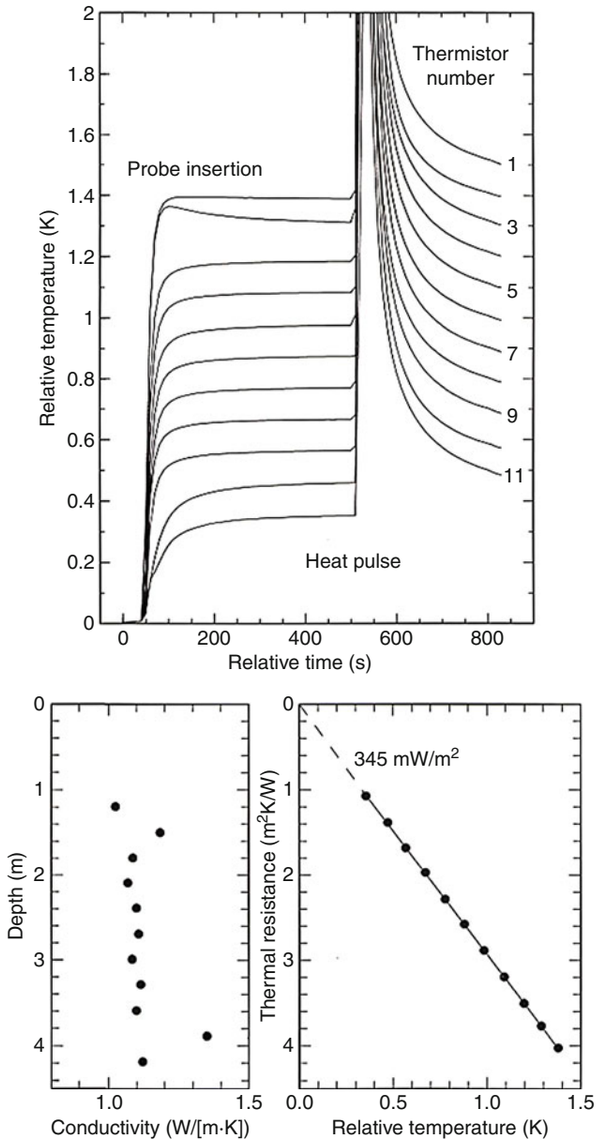
Cross-references

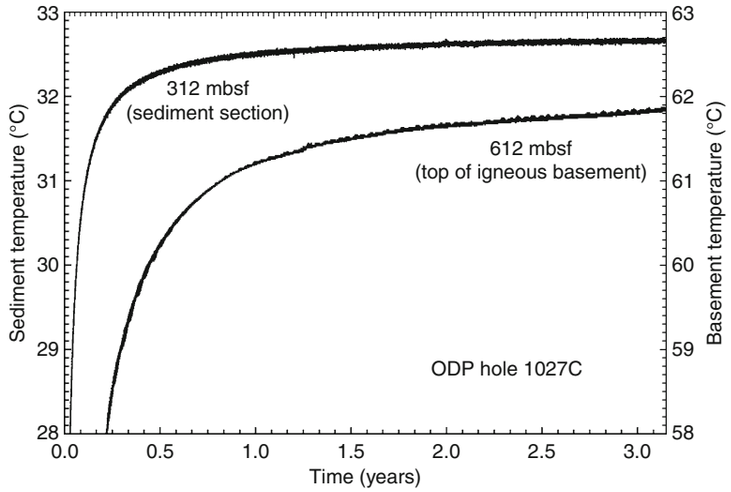
Heat Flow, Continental
Heat Flow, Continental: Measurement Techniques
Oceanic Lithosphere: Thermal Structure



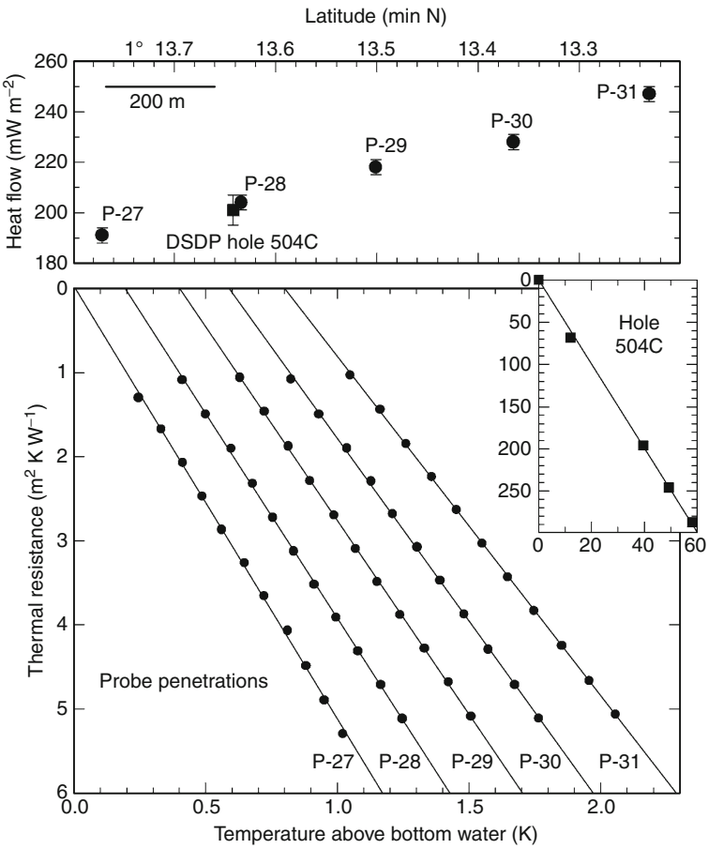
Seafloor Heat Flow: Methods and Observations, Figure 1 Sensors and probes for measuring temperatures and thermal conductivity in marine sediments, including (**a**) outrigger temperature sensors mounted to the outside of a sediment corer (core barrel is 12 cm diameter), (**b**) a devoted heat-flux probe for measuring sediment temperatures and thermal conductivities (total length is 4.5 m), and (**c**) a high-strength probe that extends below a drill bit for bottom-hole temperature measurements (length is 1.2 m, tip diameter 1 cm).



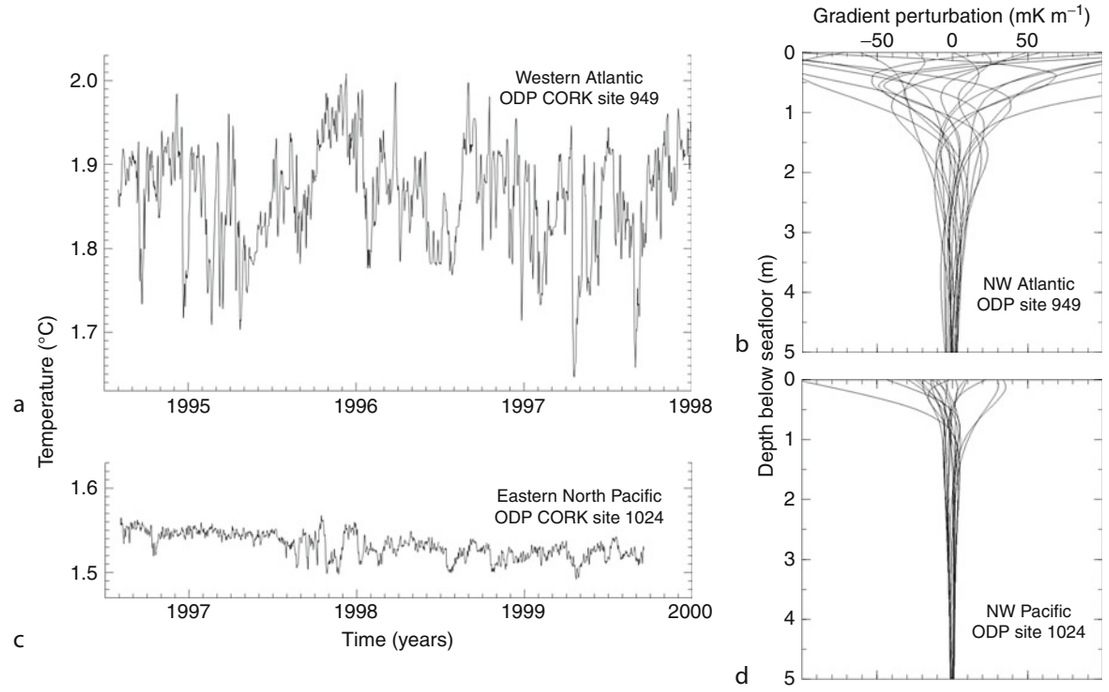
Seafloor Heat Flow: Methods and Observations, Figure 2 Typical data (upper panel) collected with a marine heat-flux probe like that shown in Figure 1b. Thermal conductivities are determined from the rates of decay following the metered pulse of heat, and natural sediment temperatures are determined by extrapolating the transients following probe insertion. In this example, high conductivities associated with two turbididic sand layers are present.



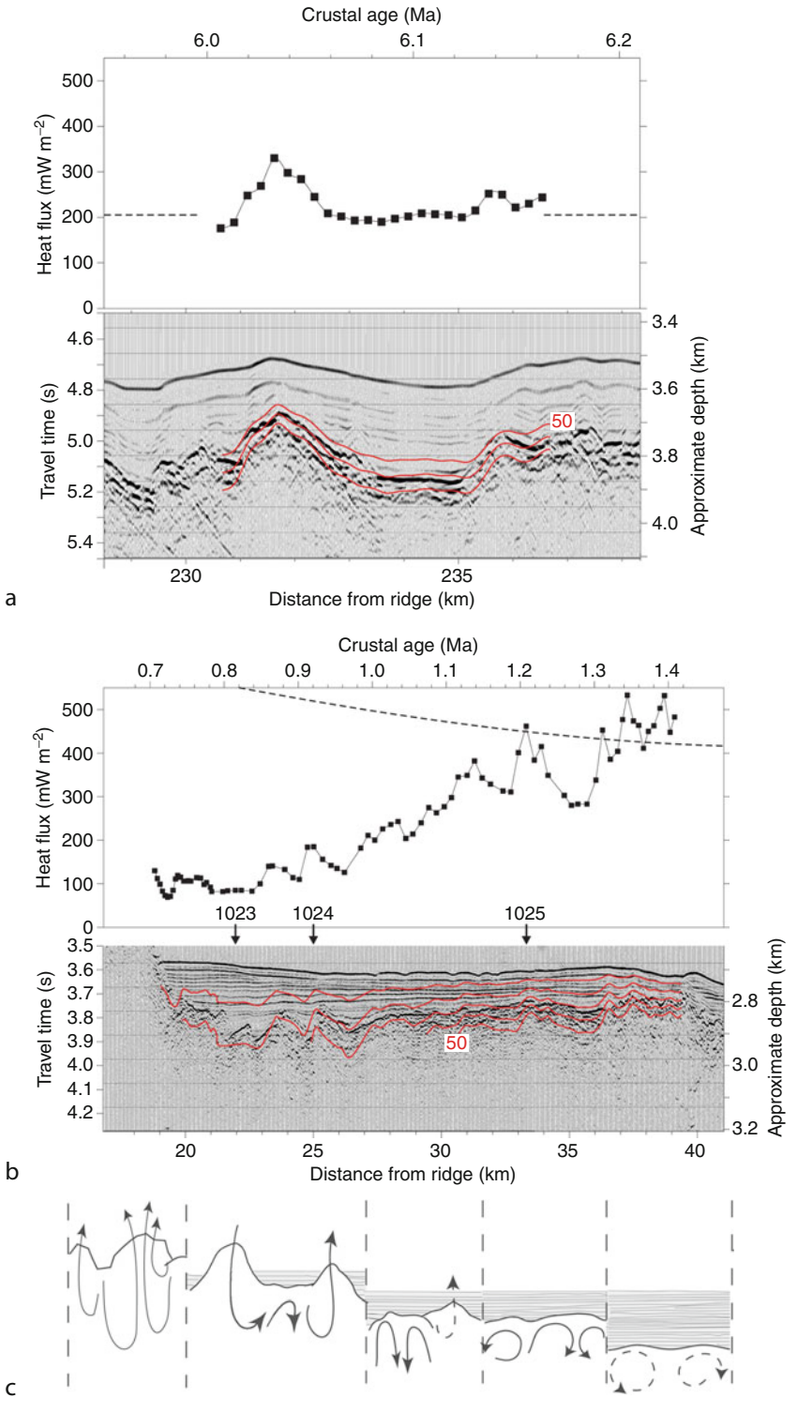
Seafloor Heat Flow: Methods and Observations, Figure 3 Two records from a 10-thermistor cable suspended in a borehole that penetrates a c. 600-m-thick sediment layer and into the underlying uppermost igneous oceanic crust. The longer recovery time at the deeper level reflects the large volume of water that invaded the uncased and permeable igneous section during the 5 days between the time of drilling and when the hole was sealed and instrumented.



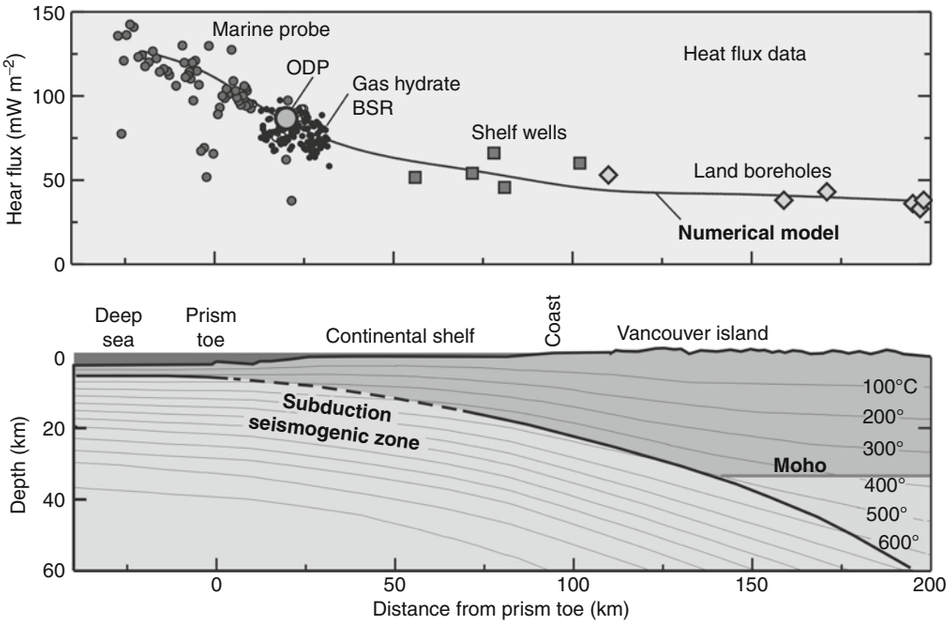
Seafloor Heat Flow: Methods and Observations, Figure 4 Comparison of colocated seafloor probe and borehole heat-flux observations. Variations in probe measurements along the transect adjacent to the borehole site illustrate how carefully such comparisons must be done.



Seafloor Heat Flow: Methods and Observations, Figure 5 Bottom-water temperature variations observed in the Atlantic (**a**) and Pacific Oceans (**c**), and estimated perturbations of the geothermal gradient as a function of depth (**b** and **d**) stemming from the variations, calculated at an evenly distributed suite of times during the temperature time series.



Seafloor Heat Flow: Methods and Observations, Figure 6 Transects of heat flux on the flanks of the Costa Rica Rift (**a**) where an extensive sediment cover is present, and Juan de Fuca Ridge (**b**) striking away from an area of extensive basement at the left end of the figure. Both show the effects of hydrothermal circulation on conductive seafloor heat flux and on the crustal thermal regime. Heat flux estimated on the basis of the local lithosphere age (see text) is shown as the dashed lines. Temperatures estimated below the seafloor are shown at intervals of 10 °C. The cartoons in (**c**) show the influence of sediment burial on hydrothermal circulation and advective heat loss under a variety of burial states.



Seafloor Heat Flow: Methods and Observations, Figure 7 Structural and heat-flux transect across the Cascadia subduction forearc, with temperatures estimated from a numerical model for underthrusting and sediment thickening, constrained by the heat-flux data (following compilation of Hyndman and Wang, 1993).