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Geothermal Measurements in Deep-Sea Drill Holes

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A method of measuring the in situ sediment temperatures in deep bore holes drilled to depths of several hundred meters or more beneath the sea floor has been developed. The technique, as presently used aboard the Deep-Sea Drilling Project (DSDP) drilling vessel *Glomar Challenger,* involves the emplacement of a temperature sensor, located below a self-contained digital temperature recorder package, a short distance into the undrilled, thermally undisturbed sediment at the bottom of the drill hole. By measuring the in situ temperature at various depths in a single drill hole it is possible to calculate the thermal gradient for various intervals in the hole. This information, in conjunction with thermal conductivity data measured aboard ship on the sediment cores recovered from the drill hole, permits computation of the heat flow through the oceanic crust. Heat flow values measured in deep drill holes in the Indian and Pacific oceans and in the Bering and Red seas are in generally good agreement with the regional geothermal flux as determined by conventional near-surface heat flow measurements, suggesting that the thousands of existent shallow heat flow values are representative of the earth's heat flux. Where multiple downhole temperature measurements made at one site permit calculation of interval heat flow values, there is no consistent indication of a significant vertical increase or decrease in heat flux, such as might be caused by long-term changes in bottom water temperature or the upward migration of interstitial fluids. We note, however, that a more detailed set of temperature measurements in a single hole is required to verify this conclusion. Downhole heat flow values made within a specific physiographic region, such as the Red Sea or the Ninety East ridge, appear to be less variable than, but equal to, the heat flow values calculated using thermal gradient measurements made at shallower depths beneath the sea floor. This observation is in accordance with theoretical considerations which indicate that temperature measurements in deep drill holes are less susceptible than conventional heat flow measurements to the disturbing thermal effects of small-scale surface topography, short-term variations in bottom water temperatures, and local sedimentary processes (slumping, erosion).

INTRODUCTION

The magnitude and geographic variation of the heat flux through the ocean floor are important geophysical parameters which provide information on the structure, composition, and processes occurring within the earth's crust and upper mantle and possibly extending down to the core-mantle boundary [*Sclater and Francheteau,* 1972]. Over 3000 heat flow measurements have been made by measuring the thermal gradient and conductivity in the uppermost 10 m of the ocean floor [*Langseth and Von Herzen,* 1971]. These measurements may be subject to systematic errors originating from near-surface effects such as past changes in bottom water temperature, movement of interstitial fluids, sedimentation, thermal refraction from sediment ponding, and small-scale topography [*Von Herzen and Uyeda,* 1963; *Sclater et al.,* 1972].

Broek [1969] has recorded deep-ocean (2000 m) bottom water temperature variations of several tenths of a degree centigrade over periods of months, and *Baker et al.* [1973] report sudden occasional changes of bottom water temperature of about 0.05°C lasting for several days at a depth of 5400 m in the Sargasso Sea. Similarly, large changes over weeks to months at shallower depths have been inferred from sediment gradient measurements in the Norwegian Sea and Baffin Bay [*Lachenbruch and Marshall,* 1968; *Talwani et al.,* 1971; *Pye and Hyndman,* 1972]. *Emiliani* [1955] has inferred Pleistocene changes of several degrees from oxygen isotope data. Whereas the effect of bottom water temperature changes on the thermal gradient may be relatively large within the upper 10 m of sediment, a temperature fluctuation is attenuated downward at a rate which is dependent upon both the form of the temperature perturbation and the thermal properties of the sediment. For this reason, heat flow measurements made in the near-surface sediments in areas of the oceans characterized by significant seasonal temperature fluctuations are difficult to interpret even in the few cases where long-term data on the thermal history of the bottom water are available [see *Talwani et al.,* 1971]. In the deep ocean these relatively short-period perturbations affect only the upper few tens of meters of sediment below the sea floor. For shallow water (e.g., continental margins), where the perturbations are of larger amplitude, conventional heat flow measuring techniques [*Langseth,* 1965] are precluded. Longer-period (Pleistocene) variations penetrate to depths of hundreds of meters and are resolvable only by precision temperature versus depth profiles to depths of at least 100 m.

Horizontal variations in the vertical heat flux can also be caused by local topographic irregularities of the sea floor [e.g., *Lachenbruch,* 1968] and by the thermal conductivity contrast between sediment and basement rock [e.g., *Von Herzen and Uyeda,* 1963; *Sclater et al.,* 1970]. Local sea floor irregularities of the order of the depth of penetration of conventional heat flow apparatus (a few tens of meters or less) are not usually detected from a surface vessel. Thermal measurements in deep drill holes located far from the easily detectable, larger amplitude topographic and basement rock irregularities

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should provide data that are more typical of the regional flux in areas where conventional data might exhibit great variability.

THEORY OF MEASUREMENT

Approach of a borehole to thermal equilibrium. The thermal effects of drilling into undisturbed sediment are primarily due to temperature changes associated with drilling fluid (seawater) flushed down the drilled hole and secondarily to frictional heating at the bottom of the hole caused by the rotary motion of the drill bit [*Bullard,* 1947]. Specifically, the flow of fluid through the hole will tend to cool the lower portion of the hole, which is warmer than the temperature of the drilling fluid, and to warm the upper portion of the drill hole. The time necessary for the entire borehole to return to thermal equilibrium with its surroundings is dependent upon the length of time during which drilling was in progress and is lower for shorter periods of drilling. On the assumption that a 30-cm-diameter hole is drilled through sediment in 1 day the hole can be expected to approach thermal equilibrium with the surrounding sediment closely enough to obtain a reliable heat flow measurement in 15-20 days [*Bullard,* 1947; *Cooper and Jones,* 1959; *Oxburgh et al.,* 1972], a length of time much greater than a ship can afford to wait.

Because the time necessary for thermal equilibrium is heavily influenced by the time during which the surrounding sediment is subjected to temperature perturbations, thermal equilibrium is achieved most rapidly at the bottom of the hole. Drilling rates in sediments soft enough to permit penetration of the thermistor probe are typically well above 1 m/h, a rate many orders of magnitude greater than the rate at which heat is conducted through sediment. Therefore the thermal effect of drilling affects the bottom of the hole only for the length of time equal to the interval between cessation of drilling and emplacement of the temperature probe in the undrilled sediment, a period which rarely exceeds 1 or 2 h. Even after this period the thermal effects of drilling are less than 1% of the temperature difference between the drilling fluid and the in situ sediment temperature for measurements made more than 20 cm below the bottom of the hole [see *Carslaw and Jaeger,* 1959, p. 63]. Our instrumentation is designed to measure sediment temperatures in the undisturbed sediments below the bottom of the hole as soon as possible after drilling has stopped at various depths.

Equipment and operational procedures. An important objective of the heat flow program has been to obtain detailed sets of temperature measurements in a few holes, rather than a few widely spaced measurements in many holes. For this reason the downhole temperature recorder and related hardware were originally designed to function along with, rather than in place of, the normal coring procedures used on the D/V *Glomar Challenger.* In this way one might reasonably expect to obtain downhole temperature measurements before each core with relatively little expenditure of ship time above that normally required for coring alone.

While a self-contained system was being designed and constructed, an interim program of downhole temperature logging was carried out on legs 5 [*Burns,* 1970] and 8 [*Von Herzen et al.,* 1971] to take advantage of measurement opportunities during the early stages of the Deep-Sea Drilling Project (DSDP) and to provide practical experience to assist in the design of the self-contained system.

The instrumentation used for logging measurements consisted of a sensing thermistor probe which projected several decimeters ahead of the drill bit. The upper end of the probe was fastened to an instrument package seated in the bottom of a core barrel which was raised and lowered by the logging cable. Thermistor resistance was converted to frequency at the bottom hole instrument, and this frequency was telemetered to the surface via the logging cable, where it was converted to temperature by the use of calibration tables. Owing to operational and instrumentation problems the data obtained on legs 5 and 8 are sufficiently variable and ambiguous to preclude any meaningful geophysical interpretation.

A prototype, entirely self-contained heat flow recorder was tested at sea on the second half of leg 14 and was subsequently used on legs 19, 21, 22, 23, and 25. These instruments are able to measure absolute temperature over the range 0°–40°C to ±0.1°C and are capable of sensing temperature changes of about 0.01°C. The instrument is turned on just before being inserted into the borehole and records temperature and calibration data in digital form on a magnetic drum every 4 s for 50 min [see *Erickson,* 1973]. Although these instruments proved to be electrically adequate, they were not rugged enough to endure the mechanical shocks frequently encountered during a measurement. New, more rugged instruments using an endless loop magnetic tape recorder rather than a magnetic drum recorder were introduced on leg 26 and remain in use.

Data read-out and processing are done at the surface by using the PDP8/S computer aboard the *Glomar Challenger* to yield a print-out of downhole temperatures as a function of elapsed time from instrument turn-on. After the data are read out, the recording instrument is readied for another temperature measurement simply by rewinding and erasing the magnetic tape.

Several types of mechanical latches have been designed to keep the temperature probe assembly, consisting of the thermistor probe and temperature recorder, firmly locked to the bottom of the inner core barrel, thus providing the force necessary to penetrate the undrilled sediment at the bottom of the hole. Upon completion of the temperature measurement the latch is designed to allow the temperature probe assembly to pass up into the inner core barrel on top of the sediment core.

As a means of obtaining reliable downhole temperature data while a reliable latch and a more rugged electronics package were being developed, another method of lowering the temperature probe, particularly applicable in hard sediments, was used on leg 22 and subsequent legs. This method involved securing the probe to the bottom of the core barrel and lowering both to the bottom of the drill string on the core wire. With the bit held above bottom the core barrel could be gently latched into the bottom hole assembly, and then the drill string could be lowered slowly to the bottom of the hole by using the weight of the bottom hole assembly to push the probe into the undrilled sediment (Figure 1). This method requires extra time because no core is obtained with the probe rigidly secured to the core barrel; however, it presently provides the most reliable means of measuring in situ sediment temperatures [*Sclater and Erickson,* 1974].

Interpretation of downhole temperature records. The thermal response of a long thin thermistor probe penetrating sediment at the bottom of the borehole is determined by (1) the frictional heating due to the passage of the probe through the sediment, (2) the initial temperature difference between the probe and the sediment, and (3) the thermal properties of the probe and sediment. If the probe has a much larger thermal

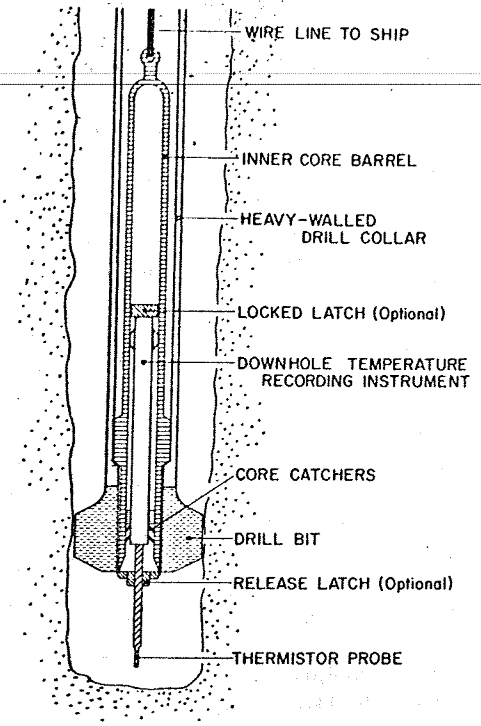

Fig. 1. Schematic drawing of the downhole temperature recorder and probe inside the inner core barrel at the bottom of the drill string. The drill bit is about to be lowered to the bottom of the hole, the thermistor probe thereby being inserted into the undrilled, thermally undisturbed sediment.

diffusivity than the sediment, as is the case for the stainless steel probes used in these measurements, the thermal response of the probe is given by the theory of heat conduction for an infinitely long, infinitely conductive rod of radius A and thermal diffusivity K_{ss} in a surrounding medium of density ρ, thermal diffusivity K, and heat capacity c [*Bullard*, 1954; *Cooper and Jones*, 1959]. The thermal response can be appropriately expressed by the dimensionless parameters α and τ, where

$$\alpha = 2\pi A^2 \rho c / m \tag{1}$$

$$\tau = K_{ss} t / A^2 \tag{2}$$

and the parameter m is the composite heat capacity per unit length of the probe.

The temperature of the thermistor probe after an initial period given by a few times the thermal time constant of the probe (about 10 s for the probes actually used) can be closely approximated as

$$T(\alpha, \tau) = T_f + \Delta T_i F(\alpha, \tau) \tag{3}$$

where T_f is the ambient temperature of the sediment, ΔT_i is the initial temperature difference between the thermistor probe and the surrounding sediment, and $F(\alpha, \tau)$ is a function describing the approach to thermal equilibrium.

If a linear relationship can be discerned in a plot of the observed temperature over a range of time versus the corresponding values of the function $F(\alpha, \tau)$ (Figure 2), it is possible to confirm the agreement between the theoretical and actual thermal responses of the probe. In addition, by extrapolating the linear curve back to $F(\alpha, \infty) = 0$, it is possible to predict the undisturbed sediment temperature to be expected after the thermal disturbance has decayed away (9.10°C, in the case of Figure 2). The success of this technique is dependent upon a sequence of undisturbed data over a period of several minutes.

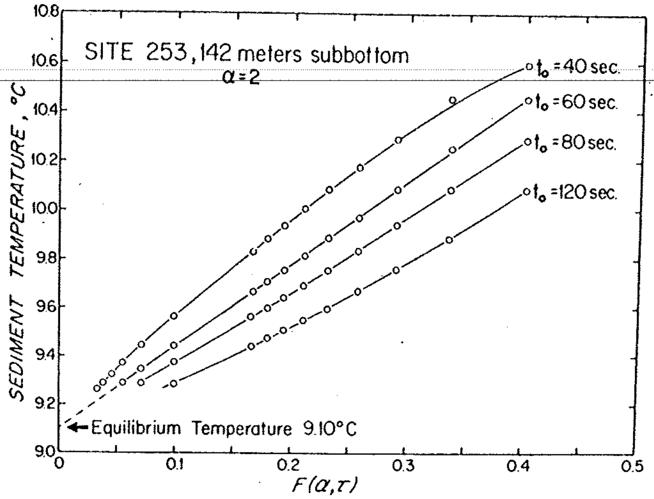

Fig. 2. Plot of $F(\alpha, \tau)$ against observed sediment temperature T (°C) for several values of the probe thermal relaxation time t_0. The linear relationship observed for $t_0 = 60$ s has been used to extrapolate the thermal decay to an equilibrium temperature of 9.10°C.

The meaningful analysis of the temperature-time records is dependent upon careful documentation of the drilling operations while the temperature probe is within the drill string. Knowledge of ship motion, positioning problems, drilling rate, bit pressure, sediment type and hardness, and many other factors associated with each measurement is essential for unambiguous interpretation of these records.

The following temperature-time records illustrate the diagnostic features of data obtained by using a mechanical release latch and a 'locked' latch. Broadly speaking, downhole temperature measurements taken with the instrument firmly locked into the inner barrel have proven easier to interpret and provide more reliable data on in situ sediment temperature than data obtained with the temperature probe held in place by any existing type of release latch.

Release latch data. The temperature-time records which suggest that the temperature probe may have been pushed up inside the inner core barrel prior to bottom contact are well represented by Figure 3, where almost no temperature increase was observed as the probe was lowered to the bottom of the drill hole. The temperature difference which would be expected between bottom water temperature and sediment temperature at a depth of 27 m subbottom is of the order of 1°C, which compares well with the temperature increase actually observed at 27-min elapsed time when warm sediment was pushed into

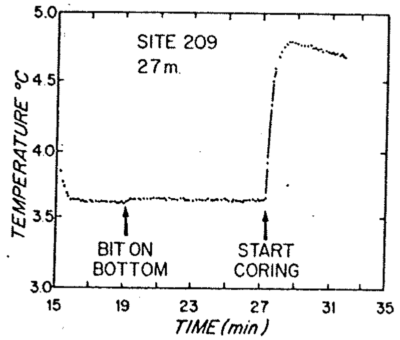

Fig. 3. Temperature versus time record obtained at site 209, 27 m subbottom. Almost no temperature increase was recorded when the drill string was lowered to the bottom of the hole at 19-min elapsed time.

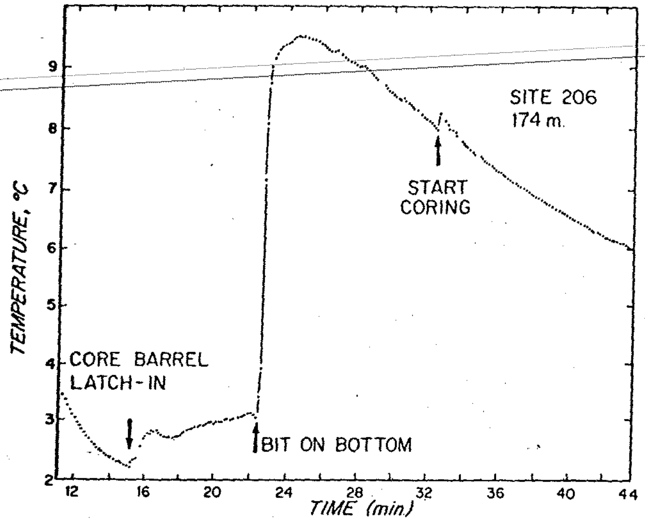

Fig. 4. Temperature versus time record obtained at site 206, 174 m subbottom. The temperature of the fluid in the borehole had increased slightly after cessation of drilling, and a further large increase was recorded as the temperature probe was slowly lowered into the sediment at the bottom of the hole. The small temperature fluctuations occurring between bottom penetration and the start of coring suggest that vertical movements of the ship were being transmitted through the drill string to the bottom hole assembly.

the core liner around the thermistor probe at the beginning of the coring process. As the sediment continued to lose heat through the walls of the core liner, the sediment and the thermistor probe gradually cooled.

The case in which the thermistor probe evidently did penetrate the undrilled sediment, but was almost immediately released up into the core barrel before acquisition of enough temperature data to define an equilibrium curve, is exemplified by Figure 4. When the probe penetrated the undrilled sediment at the bottom of the hole, an abrupt and large temperature increase occurred, followed almost immediately by a temperature decrease as the latch released prematurely and allowed the temperature probe to slide back up inside the core liner. This temperature measurement thus reflected the temperature of the sediment which had been forced a short distance into the bottom of the core barrel due to the weight of the bottom hole assembly on the sea floor, rather than the in situ sediment temperature. The fact that the small temperature fluctuations following bottom contact ceased after the beginning of coring further confirms the hypothesis that the thermistor probe had been near the bottom of the core barrel where it could sense frictional heating generated by both the coring procedure and the fluctuations in bit pressure.

Locked latch data. Downhole temperature data acquired with the temperature probe locked into the inner core barrel fall into two main categories: measurements where there is evidence of substantial frictional heating upon penetration of the thermistor probe into the undrilled sediment and measurements where there is essentially no frictional heating.

The temperature versus time plot shown in Figure 5 is typical of temperature records in which there is a large initial temperature increase as the temperature probe penetrated the sediment at the bottom of the drill hole. The temperature then decayed rapidly to about half its initial amplitude, closely following the theoretical thermal decay curve for penetration heating. The temperature dropped abruptly and then stabilized as the drill string was raised above the bottom of the hole upon conclusion of the 10-min measuring period.

The existence of substantial frictional heating appears to suggest complete penetration of the probe into undisturbed sediments. This heating as well as subsequent decay is similar to that usually observed with standard ocean temperature probes [*Langseth,* 1965] and is probably greatest in coarse or stiff sediment. Sediments at 123 m subbottom at site 253, where the temperature record shown in Figure 5 was obtained, contained up to 20% sand, for example.

Other measurements made by using the temperature probe locked into the inner core barrel show a smooth temperature increase upon penetration (Figure 6), sometimes followed by variable amounts of heating or cooling after only a few minutes. Slight frictional heating probably occurs when the probe either penetrates only a short distance into undisturbed sediment and/or penetrates fine-grained sediment where frictional heating is small. We do not fully understand why the subsequent cooling occurs. It may arise from the thermal disturbance caused by proximity of the cool drill bit or through loss of heat by longitudinal conduction along the heat probe itself (C. Lister, personal communication, 1974).

In addition to the temperature records already discussed, which provide examples for about 75% of the data obtained so

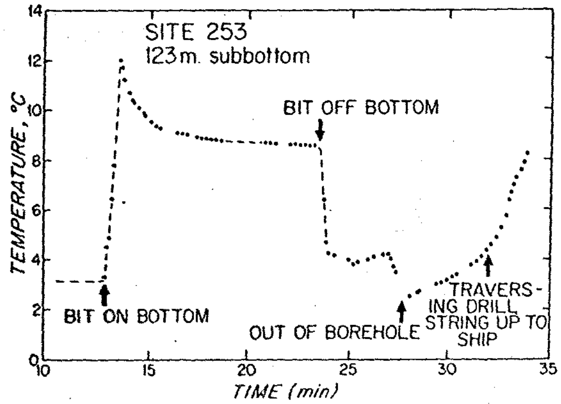

Fig. 5. Temperature versus time record obtained at site 253, 123 m subbottom. The rapid decay of the large temperature increase following bottom penetration suggests that significant frictional heating occurred during bottom penetration. The temperature increase observed while the temperature probe was traversing the drill string towards the surface reflects the upward increase in seawater temperature.

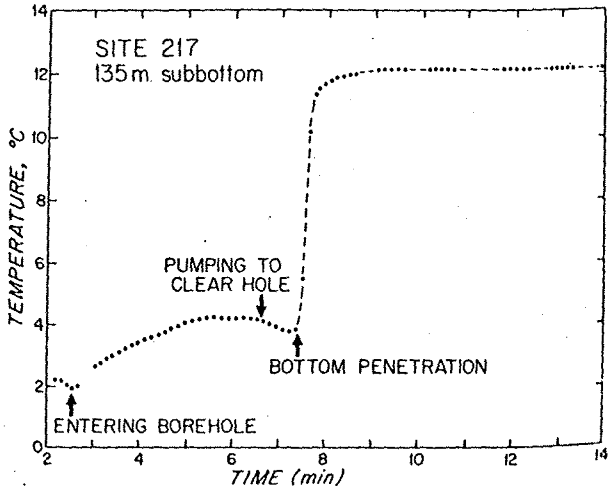

Fig. 6. Temperature versus time record obtained at site 217, 135 m subbottom. The small temperature decrease just prior to bottom penetration is due to the effect of cool drilling fluid pumped through the drill bit to ensure removal of material which had accumulated at the bottom after having fallen off the sides of the drill hole.

far, there are other more unusual records which are worth mention because of their diagnostic value in obtaining reliable data in subsequent measurements.

If the undrilled sediment is too soft to support the weight of the bottom drill collars, the bottom hole assembly and thus the inner core barrel and temperature probe will sink slowly through the sediment until either the sediment can support the weight or the entire drill string is in tension. If the drill string is in tension, the vertical oscillations of the ship will be conveyed directly to the temperature probe, as will longer-period oscillations caused by horizontal movement of the ship about the drill hole. Often a gradual temperature increase will be observed as the probe sinks, through frictional heating and through the moving of the probe deeper into warmer sediment. Similar temperature records have been observed where the sediment is too firm to allow penetration of the probe (Figure 7). Both of the problems (sediment being too soft or too hard) can be encountered using either a release latch or rigidly mounted instrumentation.

Estimation of errors and reliability. Although the accuracy and resolution of the downhole temperature recording system are about 0.1° and 0.01°C, respectively, the actual error in a temperature measurement may be much greater as a result of a multitude of other, sometimes poorly known, factors. These include the mechanical properties of the sediment, evidence for slumped material in the hole, wind and sea state, and whether the temperature probe was held in place with a release latch or firmly locked into the inner core barrel, to mention a few. Therefore our error estimates are very subjective.

One of the strongest criteria for a reliable measurement is whether the plot of the temperature versus the function $F(\alpha, \tau)$ (discussed above) is linear, this situation thereby providing a sufficient amount of good quality data to permit unambiguous extrapolation to an in situ temperature (Figure 2). When such is the case, we can determine relative temperature to a precision of ±0.02°C. There are also cases where the observed temperature-time relation does not fit the expected theory at all well. In these cases the temperature may indeed be poorly known (±1°C); however, the large vertical distance between adjacent temperature measurements often permits meaningful calculation of the thermal gradient using these data by virtue of the large absolute temperature differences encountered in the holes (Table 1).

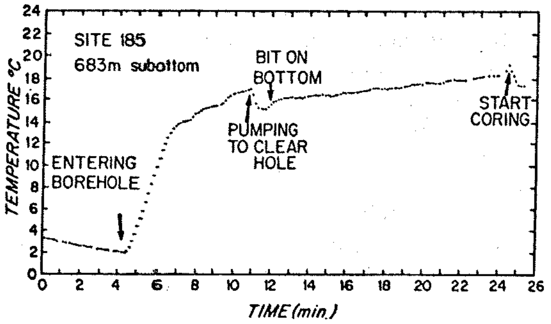

Fig. 7. Temperature versus time record at site 185, 683 m subbottom. The abrupt cooling of the probe at about 11.0 min is due to brief flushing of the drill hole prior to lowering the bottom hole assembly (11.5 min). The slow, nearly linear temperature increase measured after bottom contact is believed to reflect the absorption of geothermal heat by the drilling fluid and is a consequence of the failure of the temperature probe to penetrate the well-lithified mudstones at this depth. Small temperature fluctuations are attributed to fluid motion around the exposed thermistor probe caused by occasional movements of the drill string or by 'pumping' of seawater from higher up in the hole.

TABLE 1. Temperature-Depth Data Used in Calculating Thermal Gradients for Deep Drill Holes

Site	Depth, m	Temperature, °C
184	0	2.00 ± 0.10*
	174	16.25 ± 0.10
	342	(18.50 ± 1.00)
185	16	2.30 ± 0.20
	381	21.10 ± 0.50
	662	(25.30 ± 1.00)
204	0	1.06 ± 0.02
	86	4.79 ± 0.02
206	0	1.98 ± 0.02
	59	5.34 ± 0.06
	143	9.15 ± 0.06
	174	(9.45 ± 0.06)
	304	(11.59 ± 0.06)
209	0	2.96 ± 0.04*
	27	4.84 ± 0.04
	54	6.90 ± 0.15
210	0	1.99 ± 0.02
	54	7.16 ± 0.10
214	0	3.50 ± 0.10
	133	10.17 ± 0.10
	162	11.75 ± 0.20
	228.5	15.00 ± 0.25
216	0	2.80 ± 0.10
	215	8.74 ± 0.30
217	0	2.00 ± 0.10
	97	9.66 ± 0.10
	135	12.17 ± 0.10
225	0	22.3 ± 0.10
	19	24.2 ± 0.10
	78	29.2 ± 0.20
227	0	22.3 ± 0.10
	37	26.2 ± 0.10
	82	32.0 ± 0.20
	159	41.1 ± 0.20
228	0	22.3 ± 0.10
	25	24.7 ± 0.10
	97	40.4 ± 0.20
242	0	2.40 ± 0.10*
	141	6.25 ± 0.10
	317	11.00 ± 0.25
248	0	0.69 ± 0.10*
	130	6.50 ± 0.20
249	0	2.80 ± 0.10*
	140	8.00 ± 0.25
251	0	1.39 ± 0.10
	87.5	3.52 ± 0.10
253	0	2.50 ± 0.20*
	104	7.51 ± 0.03
	123	8.29 ± 0.03
	142	9.07 ± 0.02
254	0	3.70 ± 0.10
	137 ± 2	10.33 ± 0.03
	148 ± 2	10.85 ± 0.05
	176.5 ± 2	11.92 ± 0.10
256	0	1.14 ± 0.05
	161.5	9.87 ± 0.10
257	0	1.06 ± 0.02
	133	10.37 ± 0.05

Probable errors in depth measurements are all ±1.0 m for surface measurements and ±0.5 m elsewhere unless otherwise indicated. Downhole temperature values enclosed in parentheses are considered unreliable.

*Bottom water temperatures estimated from hydrographic data.

Relative depth determinations in the holes are, under conditions of small swell and good position control, believed to be accurate to ±0.5 m. The position of the sea floor, under the best of conditions, is less well known (±1 m) due to the difficulties of 'feeling' the soft mud with the heavy drill string. In cases where one or more of the downhole devices designed to absorb the vertical motion of the ship were inoperative, the depth uncertainty can be as great as ±5 m, depending upon the sea state (Table 1).

Thermal conductivity data. In addition to the downhole temperature measurements, thermal conductivity data are needed to calculate the heat flow. Thermal conductivity is measured aboard ship by using the transient needle probe method [*Von Herzen and Maxwell,* 1959] on sediment cores recovered from the borehole. These data are corrected for the in situ pressure and temperature beneath the sea floor, using correction factors given by *Ratcliffe* [1960], and modified for use in boreholes by *Erickson* [1973]. Last, the harmonic mean conductivity (or mean thermal resistivity) is calculated for each interval over which the geothermal gradient was determined. The geothermal flux through various intervals beneath the sea floor is the product of the geothermal gradient and harmonic mean conductivity for that interval. A subsequent paper will deal in more detail with the analysis of the thermal conductivity measurements made throughout the DSDP.

RESULTS

Melanesian region. Useful downhole temperature data were obtained at three sites (Figure 8) during leg 21 [*Von Herzen,* 1973]. Temperature measurements throughout this leg were plagued by hardware problems and resultant recording instrument difficulties, the geophysical significance of the data at some sites being left unresolved.

Site 206 was situated near the southern end of the New Caledonian basin. A total of four measurements to depths exceeding 300 m were made at this site; however, hardware malfunctions resulted in release of the temperature probe up into the core barrel before the probe attained thermal equilibrium (see Figure 4). After determining the bottom water temperature as the temperature probe passed through the drill pipe, we were able to determine interval heat flow values over four subbottom intervals (Table 2).

It can be seen immediately (Figure 9) that there is a decrease in thermal gradient below 143 m by about a factor of 4, causing the heat flow in the upper two intervals (1.27 and 1.48 HFU) (1 HFU = 1 μcal cm^{-2} s^{-1} or 41.87 × 10^{-3} W/m^2) to be much greater than the heat flux through the lower two intervals (0.29 and 0.48 HFU). *Von Herzen* [1973] examined several possible causes for this observed downward decrease (internal radiogenic or biogenic heating in the upper intervals, upward percolation of interstitial water, and large changes in bottom water temperature) and concluded that there was no obvious explanation in terms of natural phenomena.

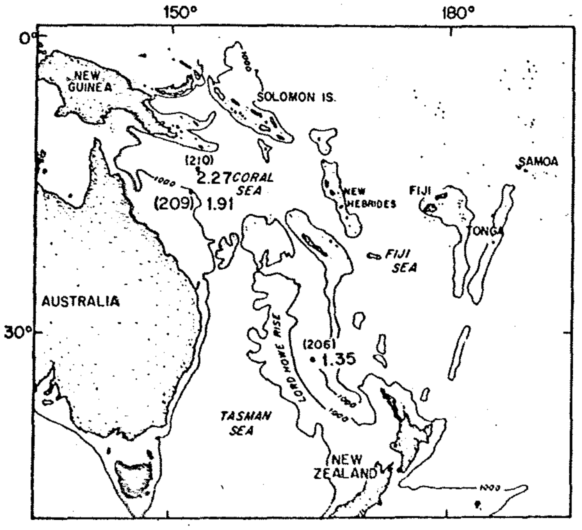

Fig. 8. Index map of the southwestern Pacific Ocean showing the locations and DSDP site numbers (in parentheses) where reliable downhole heat flow data were obtained. Heat flow values are given in heat flow units. Water depth contours are in fathoms (547 fathoms = 1 km).

It is likely that the lowermost two temperature measurements are substantially lower than the actual in situ sediment temperature. Possible explanations for the low temperatures (and gradients) are that (1) the measurement was made in cooler material which had slumped from further up in the drill hole or (2) the undrilled sediment at the bottom of the hole was too hard for the probe to penetrate or (3) the probe was prematurely released up into the core barrel. The weighted mean of the two uppermost heat flow values is 1.35 ± 0.13 HFU for site 206.

Oceanographic heat flow data are sparse in this region. Values in the northern extension of the New Caledonian basin, over 600 km north of site 206, are in excellent agreement with the heat flow measured at site 206 [*Sclater et al.,* 1972]. Heat flow measurements on the Lord Howe rise several hundred kilometers southwest of site 206 are about twice normal [*Grim,* 1969].

Site 209 was located in only 1428 m of water on the seaward edge of the Queensland plateau. Two downhole measurements at 27 and 54 m subbottom of somewhat doubtful quality, plus an estimate of bottom water temperature from hydrographic data, comprise the data at this site. Although the quality of the data at 54 m is highly suspect (both downhole measurements probably give minimum values), the interval heat flow values are self-consistent and are in good agreement with the heat flow value measured nearby at site 210 (Table 2).

The nearest oceanographic heat flow measurements are values of 1.48 and 1.89 HFU located about 200 km southwest on the Queensland plateau and about 150 km ENE in the Coral Sea basin, respectively [*Langseth et al.,* 1971]. The latter value is nearly equal to the weighted mean heat flow (1.91 ± 0.27 HFU) at this site.

One downhole sediment temperature measurement at a depth of 54 m and a bottom water temperature measurement are the only data available for calculation of the heat flow at site 210, located near the center of the Coral Sea abyssal plain in 4643 m of water. These data permit calculation of a heat flux of 2.27 ± 0.17 HFU, slightly higher than nearby values (1.72 and 1.63 HFU) measured about 100 km east and west, respectively, using standard oceanographic techniques [*Langseth et al.,* 1971; *Halunen and Von Herzen,* 1973]. *Von Herzen* [1973] examined the possibility that the discrepancy between

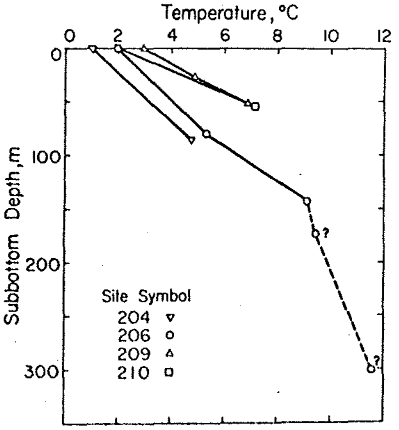

Fig. 9. Plots of temperature versus depth for downhole temperature measurements made in the Melanesian region.

TABLE 2. Summary of Downhole Temperature Measurements at DSDP Sites, Legs 19-26

	Position							Heat Flow, HFU	
Site	Latitude	Longitude	Water Depth, m	Subbottom Interval, m	Latch Type*	Gradient, °C/m	KU†	Interval	Best Value§
184	53°43'N	170°55'W	1910	0.0-174.0	R	0.0819	2.16	1.77 ± 0.07	...
185	54°26'N	169°15'W	2110	16.0-381.0	R	>0.0515	2.04	>1.05 ± 0.05	...
206	32°01'S	165°27'E	3196	0.0-59.0	R	0.0569	2.60	1.48 ± 0.10	1.35 ± 0.13
				59.0-143.0	R	0.0454	2.80	1.27 ± 0.08	
206				143.0-174.0	R	0.0097	2.99	0.29 ± 0.13	0.46 ± 0.10
				174.0-304.0	R	0.0164	2.92	0.48 ± 0.04	
209	15°56'S	152°11'E	1428	0.0-27.0	R	0.0698	2.65	1.85 ± 0.19	1.91 ± 0.27
				27.0-54.0	R	0.0762	2.73	2.08 ± 0.32	
210	13°46'S	152°54'E	4643	0.0-54.0	R	0.0958	2.37	2.27 ± 0.17	...
214	11°20'S	88°43'E	1655	0.0-133.0	R	0.0502	2.57	1.29 ± 0.07	1.31 ± 0.23
				133.0-162.0	R	0.0545	2.53	1.38 ± 0.31	
				162.0-228.5	R	0.0488	3.03	1.48 ± 0.25	
217	08°56'N	90°32'E	3010	0.0-97.0	L	0.0788	2.31	1.82 ± 0.10	1.79 ± 0.05
				97.0-135.0	L	0.0538	3.03	1.63 ± 0.20	
225	21°19'N	38°15'E	1228	0.0-19.0	L	0.100	(2.74)	2.74 ± 0.57	2.37 ± 0.44
				19.0-78.0	L	0.0847	2.74	2.32 ± 0.21	
227	21°20'N	38°08'E	1795	0.0-37.0	L	0.105	(3.39)	3.57 ± 0.51	3.52 ± 0.55
				37.0-82.0	L	0.129	3.39	4.37 ± 0.45	
				82.0-159.0	L	0.118	2.74	3.24 ± 0.25	
228	19°05'N	39°00'E	1038	0.0-25.0	L	0.0960	(3.28)	3.15 ± 0.65	4.71 ± 2.00
				25.0-97.0	L	0.218	3.28	7.15 ± 0.81	
242	15°51'S	41°49'E	2275	0.0-141.0	L	0.0273	2.54	0.69 ± 0.05	0.70 ± 0.08
				141.0-317.0	L	0.0270	2.61	0.70 ± 0.10	
248	29°32'S	37°28'E	4994	0.0-130.0	L	0.0446	2.31	1.03 ± 0.11	...
249	29°57'S	36°05'E	2088	0.0-140.0	L	0.0371	2.68	1.00 ± 0.06	...
253	24°53'S	87°22'E	1962	0.0-104.0	L	0.0481	3.20	1.54 ± 0.10	1.45 ± 0.18
				104.0-123.0	L	0.0411	3.21	1.32 ± 0.18	
				123.0-142.0	L	0.0411	3.21	1.32 ± 0.17	
254	30°58'S	87°54'E	1253	0.0-137.0	R	0.0484	2.73	1.32 ± 0.07	1.31 ± 0.45
				137.0-148.0	L	0.0471	(2.80)	1.32 ± 0.71	
				148.0-176.5	L	0.0375	2.80	1.05 ± 0.30	
256	23°27'S	100°46'E	5361	0.0-161.5	R	>0.0542	2.03	>1.10 ± 0.30	...
257	30°59'S	108°21'E	5278	0.0-133.0	L	0.0701	1.97	1.38 ± 0.06	...

*Method of immobilizing the heat probe in the drill string during a temperature measurement; R designates one of several types of mechanical release latches designed to permit a core to be obtained after the temperature measurement, and L designates a locked latch, where the heat probe is rigidly locked into the core barrel.

†Harmonic mean of all conductivity values obtained in the depth interval. Values in parentheses are assumed from available conductivity data from the next deeper depth interval. (1 KU (conductivity unit) = 1 mcal/cm s °C)

§Best heat flow estimate for the corresponding site, calculated as discussed in text.

the downhole and oceanic heat flow values might be due to recent sedimentation or warming of bottom water reducing the thermal gradient in the sediment to a depth of about 10 m below the sea floor and concluded that there were no data to substantiate either of these processes. If the measurement of high heat flow at site 210 is not an artifact of environmental factors but instead reflects above-normal flux from the mantle, the proposal that the Coral Sea basin is simply an old inactive marginal basin with normal heat flow [*Karig*, 1971] must necessarily be reconsidered. Evidence from seismic profiling [*Ewing et al.*, 1970] and deep-sea drilling [*Burns et al.*, 1972] points to an early Tertiary origin for the Coral Sea basin; thus the high heat flow may indicate the onset of a new stage of tectonic activity in this region rather than continued thermal evidence of a former extensional origin.

Southeastern Bering Sea. During leg 19, downhole temperature measurements were made at sites 184 and 185 (Figure 10) in the southeastern Bering Sea [*Erickson*, 1973]. Site 184 was located on the southwestern corner of the Umnak plateau in a water depth of 1910 m. A reliable temperature was obtained at 174 m, and a less reliable value at 342 m, where it is believed that the measured temperature was lower than the in situ sediment temperature as a consequence of the undrilled sediment's being too hard for the thermistor probe to penetrate. This seems to be the most probable explanation of a sixfold decrease in the geothermal gradient between 174 and 342 m relative to the gradient between the sea floor and 174 m (Figure 11), where thermal conductivity is relatively constant over the entire depth interval.

The best estimate for the thermal gradient at site 184 is thus obtained by using the temperature of 16.25°C measured at 174 m subbottom and the estimated bottom water temperature

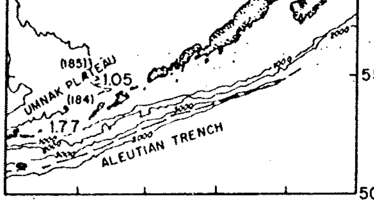

Fig. 10. Index map of the Bering Sea and northwestern Pacific Ocean, showing the locations and DSDP site numbers (in parentheses) where reliable downhole heat flow data were obtained. Heat flow values are given in heat flow units. Water depth contours are in fathoms.

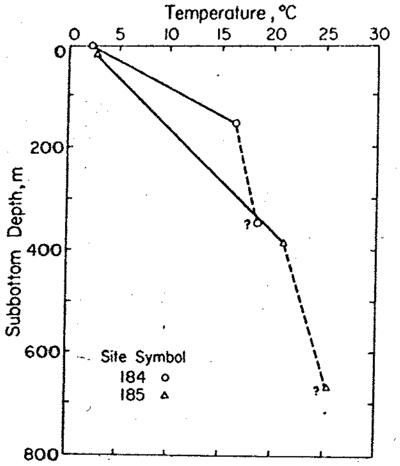

Fig. 11. Plots of temperature versus depth for downhole temperature measurements made in the Bering Sea.

(2.0°C). The resulting heat flow is 1.77 HFU (Table 2), higher than the five heat flow values (0.9–1.3 HFU) reported from the Bering Sea [*Foster*, 1962], all of which are situated over 5° west of site 184. A single heat flow value (2.64 HFU) in the Kamchatka basin reported by *Fornari et al.* [1973] is located in an entirely different tectonic province and therefore is not a valid basis for comparison.

Site 185 was located in the Bering Sea just off the northeastern edge of the Umnak plateau in 2110 m of water (Figure 10). Although five of the seven downhole temperature measurements at this site were successful in returning data, only two measurements appear to be useful for the purpose of estimating in situ sediment temperatures and heat flow. A measurement made at a depth of only 16 m below the sea floor suffered from thermomechanical disturbances caused by the slow sinking of the bottom hole assembly and temperature probe into the soft sediment, as well as from additional periodic movements of the probe due to the vertical oscillations of the drill string in response to surface wave motion and ship motion. However, the amplitude of these perturbations is small (0.2°C), and the measured temperature of 2.3 ± 0.2°C is believed to be representative of the in situ sediment temperature.

During a measurement at a depth of 381 m (Figure 12) the temperature probe assembly appears to have been released up inside the inner core barrel before acquisition of enough temperature data to allow extrapolation of the warming curve to an equilibrium temperature. It appears probable from the rapid initial temperature increase that the actual in situ sediment temperature is substantially higher than the maximum observed temperature (21.1°C). The rapid temperature increase may also be evidence of significant frictional heating during penetration; however, such heating was not observed in other measurements at this site. Thus a mean geothermal gradient at least as large as 0.0515°C/m is believed to exist in the upper 381 m. This gradient and the mean sediment thermal conductivity give a minimum heat flow of 1.05 HFU. Comments about this value are similar to those about the heat flow value obtained at site 184. Specifically, this minimum heat flow value is lower than the mean heat flow through oceanic or marginal basins but is within the range of values measured by *Foster* [1962] further west in the Bering Sea.

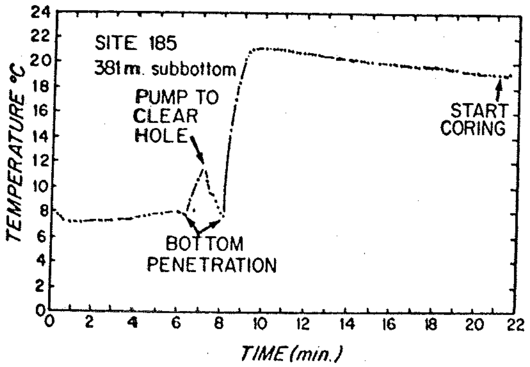

Fig. 12. Temperature versus time record obtained at site 185, 381 m subbottom.

Indian Ocean. Downhole temperature measurements were made in the Indian Ocean (Figure 13) on leg 22 at sites 214 and 217 [*Sclater and Erickson,* 1974], on leg 25 at sites 242, 248, and 249 [*Marshall and Erickson,* 1974], and during leg 26 at sites 251, 253, 254, and 256 [*Hyndman et al.,* 1974]. These measurements are discussed below as tectonic or geographic entities.

Ninety East ridge. The Ninety East ridge is a long, north-south, linear topographic high which, because of its importance in unraveling the plate tectonic history of the Indian Ocean, has received considerable attention [see *McKenzie and Sclater,* 1971; *Bowin,* 1973; *Sclater and Fisher,* 1974; *Sclater et al.,* 1974]. Heat flow data from the Ninety East ridge, reported by *Vacquier and Taylor* [1966], indicated the possibility that the ridge was the locus of high heat flow (up to 4.9 HFU). However, subsequent heat flow determinations [see *McKenzie and Sclater,* 1971] have not yielded similarly high heat flow values. The ridge is known to have been in existence since at least the Late Cretaceous (evidence reviewed by *Bowin* [1973] and *Sclater and Fisher* [1974]), and because of its lack of seismicity, relatively smooth undisturbed sediment cover, isostatic equilibrium, and normal heat flow it is not believed to be an active tectonic feature.

Five drill sites have been located on the Ninety East ridge from its northernmost extremity to slightly south of its apparent intersection with Broken ridge (Figure 13). The heat flow measurements at four of these sites are discussed below from north to south.

Site 217 is situated on the eastern flank of the Ninety East ridge near its northern termination just south of the Bengal fan. The heat flow value at this site is based upon two excellent in situ sediment temperature measurements at 97 and 135 m subbottom (Figure 6) and upon a measured bottom water temperature of 2.0°C. These temperature measurements, along with thermal conductivity data, permit calculation of the interval and weighted average heat flow values listed in Table 2.

Site 214 was located 2200 km south of site 217 on the crest of the Ninety East ridge in a water depth of 1655 m. Apparently reliable temperature data were obtained at depths of 133 and 162 m, a less reliable value at 228.5 m subbottom, and bottom water temperature was measured as the temperature probe passed through the drill pipe. These data are plotted as a function of depth in Figure 14. Although there is some question from the temperature-time plots as to whether individual temperature measurements represent the in situ temperature of the undrilled sediment, the approximately constant interval heat flux (Table 2) between the sea floor and 162 m subbottom suggests that the heat flow values are in fact highly reliable. The higher interval heat flow calculated between 162 and 228.5 m is principally due to the large increase in thermal conductivi-

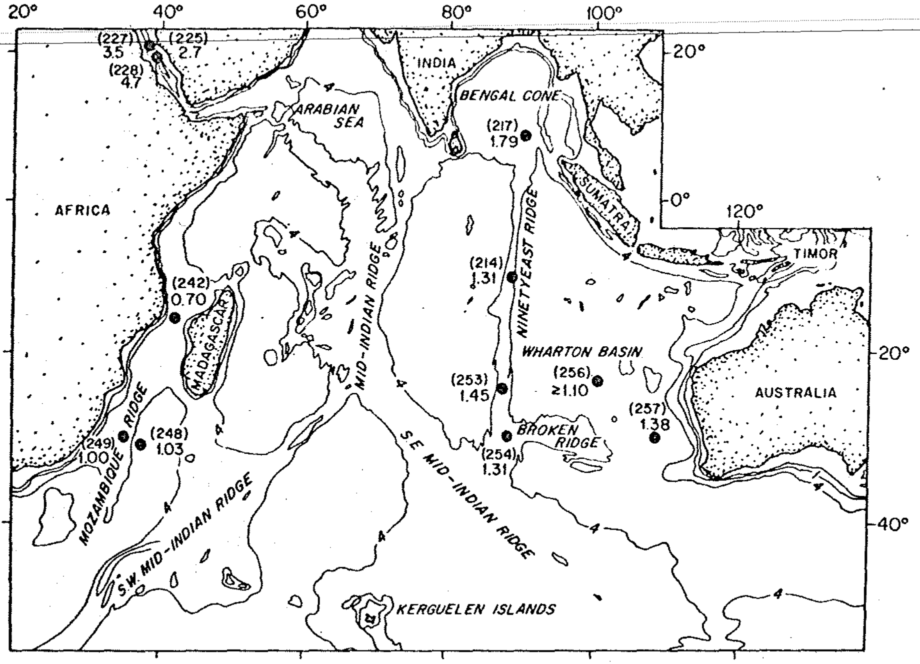

Fig. 13. Index map of the Indian Ocean and Red Sea showing the locations and DSDP site numbers (in parentheses) where reliable downhole heat flow data were obtained. Heat flow values are given in heat flow units. Water depth contours are given at 1000 and 4000 fathoms.

ty below 162 m compared with the values above 162 m, rather than to a downward increase in the thermal gradient (actually the gradient decreases in the lower interval). These high conductivity values may have been effected by convection of interstitial water during the conductivity measurement (sediments from the lower interval were noted for their unusually high water content) rather than by an actual increase in the in situ conductivity.

Site 253 is situated on the western flank of the southern part of the Ninety East ridge (Figure 13). Three excellent downhole temperature measurements (see Figure 5, for example) at 104, 123, and 142 m, plus a bottom water temperature of 2.5°C estimated from hydrographic data, were used to calculate the three interval heat flow values listed in Table 2. The best heat flow at this site is 1.45 ± 0.18 HFU.

The calculation of heat flow at site 254, located on or near the southern extremity of the Ninety East ridge at its apparent intersection with the Broken ridge, is also based upon three downhole temperature measurements. The quality of the temperature measurements at this site is not as high as that at site 253 due to movement of the temperature probe during these measurements. The heat flow at this site is estimated as 1.31 ± 0.45 HFU.

These four heat flow values determined on or near the Ninety East ridge from temperature measurements in deep drill holes range from 1.31 to 1.79 HFU, with no noticeable systematic trends with latitude. The mean and standard deviation of all four heat flow values is 1.40 ± 0.22 HFU, in good agreement with the average of four conventional oceanographic heat flow measurements on the Ninety East ridge (1.49 ± 0.26 HFU) referred to by *McKenzie and Sclater* [1971] and within the range of heat flow values (1.1–1.3 HFU) both observed and expected through oceanic crust of Mesozoic age [*McKenzie and Sclater*, 1971; *Sclater and Francheteau*, 1970].

The confirmation of normal oceanic heat flow by both oceanic and deep drill methods for the Ninety East ridge supports the conclusions presented by *McKenzie and Sclater* [1971], *Luyendyk et al.* [1973], *Bowin* [1973], and *Sclater et al.* [1974] that the ridge is old. Because of the age of the ridge, the heat flow data cannot lend support to any of the current hypotheses concerning the formation of the Ninety East ridge, specifically whether it was produced as a type of leaky transform fault along the eastern boundary of the northward-moving Indian lithospheric plate prior to the middle Tertiary [*Sclater and Francheteau*, 1970] or whether it originated due to isostatic elevation of the sea floor in response to the replacement of mantle material by high-velocity (7.04–7.94 km/s) crustal material [*Bowin*, 1973].

Southeastern Indian Ocean. Sites 256 and 257 were located in the Wharton basin in the southeastern Indian Ocean (Figure 13). The oldest datable sediments at both sites are Lower Cretaceous. Each of the heat flow values at these sites is based

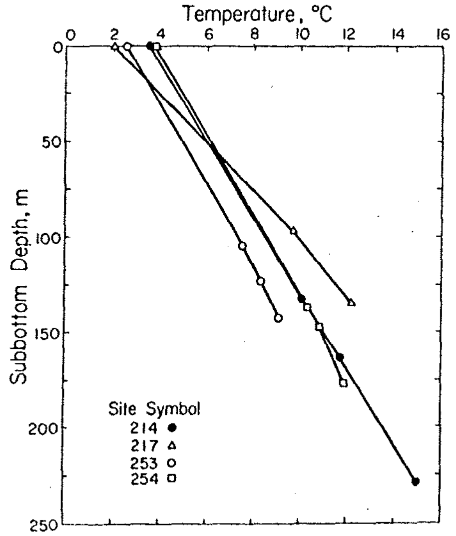

Fig. 14. Plots of temperature versus depth for downhole temperature measurements made on the Ninety East ridge.

upon only one downhole temperature measurement, and at site 256 this temperature measurement was badly disturbed and must be considered a minimum value. Bottom water temperatures were well recorded at both sites as the heat probe passed through the drill pipe. Heat flow values of 1.10 ± 0.30 and 1.38 ± 0.06 HFU have been calculated at sites 256 and 257, respectively.

These values are in good agreement with the mean of 39 conventional oceanic heat flow measurements from the Wharton basin south of 10°S (1.23 ± 0.25 HFU) discussed by *McKenzie and Sclater* [1971] and are typical for old oceanic crust [*Sclater and Francheteau*, 1970].

Western Indian Ocean. Site 242 was drilled on the eastern flank of the asymmetric and weakly seismic Davie ridge, also called the Mozambique fracture zone, between Madagascar and Africa. Two downhole temperature measurements were made at 141 and 317 m subbottom (Figure 15). Although the measurement at 141 m yielded a good record, indicating that the probe attained thermal equilibrium with the sediment, the temperature record from 317 m suggests that the thermistor probe may not have reached equilibrium with the sediment. Bottom water temperature was estimated from the temperatures recorded as the probe passed through the drill pipe. The fact that the heat flow values are nearly constant in both intervals (Table 2) suggests that the best value for this site (0.70 ± 0.08 HFU) is reliable. The nearest conventional heat flow values to the south (0.72 HFU) and north (1.33 HFU) of site 242 are subnormal and normal, respectively [*Von Herzen and Langseth*, 1966]. The heat flow at site 242 compares well with the southern value, but both values are substantially below the theoretical heat flux expected from even the oldest oceanic crust and thus require some explanation. Although low heat flow values can be caused by local environmental factors such as recent changes in bottom water temperature, very rapid sedimentation or slumping, or local sea floor topography, the presite survey and information on the type and rate of sedimentation permit us to eliminate these possible causes at site 242.

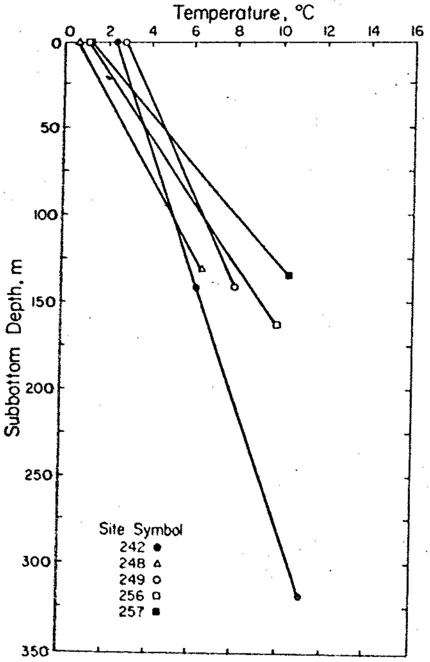

Fig. 15. Plots of temperature versus depth for downhole temperature measurements made in the southern Indian Ocean.

Site 248 was located in the northwestern Mozambique basin about 27 km east of the steep eastern slope of the Mozambique ridge. A single downhole temperature measurement was made at this site at a depth of 130 m subbottom. The record obtained is thought to give a reliable bottom water temperature and a variable, but usable, sediment temperature. Heat flow calculated at this site is 1.03 ± 0.11 HFU.

Site 249 is located about 136 km WSW of site 248 over a small, deep, sediment-filled basin close to the crest of the Mozambique ridge. Only one downhole temperature was measured at this site at a depth of 140 m subbottom. By using the bottom water temperature determined by hydrographic measurements and the single reliable downhole sediment temperature, plus thermal conductivity data, a heat flow value of 1.00 ± 0.06 HFU was computed for this site.

The heat flow values at both site 248 and site 249 are nearly equal and are well within the range of the seven nearest conventional heat flow values [*Von Herzen and Langseth*, 1966] situated within several hundred kilometers of both sites. Even after two extreme values (0.04 and 2.22 HFU) are deleted, the two deep drill hole values are well within the standard deviation of the mean of the remaining five conventional heat flow values (1.13 ± 0.24 HFU). The downhole heat flow data, in combination with conventional ocean heat flow measurements, confirm that both the Mozambique ridge and the adjacent Mozambique basin are characterized by normal or slightly subnormal heat flow.

Red Sea. Downhole heat flow measurements made on leg 23 were reported in detail by *Girdler et al.* [1974]. Sites 225 and 227 were located in the immediate vicinity of the Atlantis 2 deep (Figure 13). Usable downhole temperatures were measured at two depths at site 225 and three depths at site 227. Although the downhole temperatures were generally measured with the temperature probe rigidly latched to the inner core barrel, few of the temperature-time records show a clear-cut approach to thermal equilibrium, and most show considerable departures from the thermal behavior expected from theoretical considerations [see *Girdler et al.*, 1974]. Thus it is reassuring, as well as suggestive, that the maximum recorded temperatures are in fact indicative of the in situ sediment temperatures, that the plots of maximum recorded temperature versus depth at sites 225 and 227 (Figure 16) do indeed show a rather constant thermal gradient over the various depth intervals. These data, in conjunction with bottom water temperatures recorded while the probe was held steady in the drill pipe, and thermal conductivity data permit the calculation of reliable heat flow values at these sites.

The weighted average heat flow values determined at sites 225 and 227 (2.37 and 3.52 HFU, respectively) are higher than the average heat flow through ocean basins (1.3 HFU) and are typical of values determined on actively spreading midocean ridges [*Langseth and Von Herzen*, 1971]. We note that the heat flux at site 227, only 5 km from the thermally active hot brine pools [*Erickson and Simmons*, 1969], is 50% higher than the flux at site 225, located 11 km further to the east. This increase in flux towards the area occupied by the brine pools is consistent with the anomalously high conductive heat flow values (up to 60 HFU) measured within the brine pools by using conventional oceanographic techniques [*Erickson and Simmons*, 1969] and may be indicative of the areal extent of the thermal source. Attempts to make conventional oceanic heat flow measurements outside of, but in the immediate vicinity of, the brine pools were consistently thwarted by failure of the coring apparatus to penetrate due to the absence of sediment.

Three downhole temperature measurements were made at 25, 61, and 97 m subbottom at site 228 further south in the Red Sea on the west side of the axial valley. Inspection of the temperature-time records for these measurements strongly suggests that the measurement at 61 m was badly disturbed and never attained thermal equilibrium with the sediment. Using the data obtained at 24 and 97 m subbottom and bottom water temperature, we calculate a high heat flux (3.15 HFU) within the upper interval and an even higher (7.15 HFU) flux between 25 and 97 m (Figure 16). Instrument failures precluded verification of this apparent downward increase by over a factor of 2; however, it is certain that the heat flux at site 228 is also higher than normal. Our best value of 4.71 HFU is computed by using the water temperature and downhole temperature data from 97 m subbottom. In order for environmental disturbances to produce as rapid a downward increase in heat flow as observed one would have to postulate a relatively recent, very large bottom water temperature increase and/or a high sedimentation rate at this site. There is no evidence from geophysical or hydrographic data or other downhole temperature measurements in the Red Sea for either of these conditions.

In summary, the heat flow values determined in deep drill holes in the Red Sea (Table 2) are all above normal in agreement with other Red Sea heat flow data obtained with standard oceanic techniques and exploration drilling (reviewed by *Girdler* [1969]). The high values are consistent with the hypothesis that the axial portion of the Red Sea is an active spreading center. We note that although the means are nearly equal, there is substantially less variability in the heat flow values obtained in the three drill holes ($Q = 3.53 \pm 0.96$ HFU) than there is for Red Sea oceanic heat flow values listed in the work by *Girdler et al.* [1974] ($Q = 3.6 \pm 2.0$ HFU), thus suggesting that the deeper measurements are less susceptible to environmental effects of sea floor topography, thermal refraction, and changes in bottom water temperature.

Summary

Heat flow measurements made in deep-sea drill holes using in situ sediment temperatures are generally in good agreement with nearby heat flow measurements made in the surficial sediment using standard oceanic techniques.

In addition, where there is more than a single heat flow measurement in a deep drill hole in the same tectonic province, the scatter in the nearby conventional oceanic heat flow values is generally larger than the variability of the deep drill hole heat flow values (Table 3). We interpret this observation to indicate that heat flow measurements in deep drill holes are less susceptible to the environmental disturbances which are the source of at least some of the variability in conventional oceanic heat flow data.

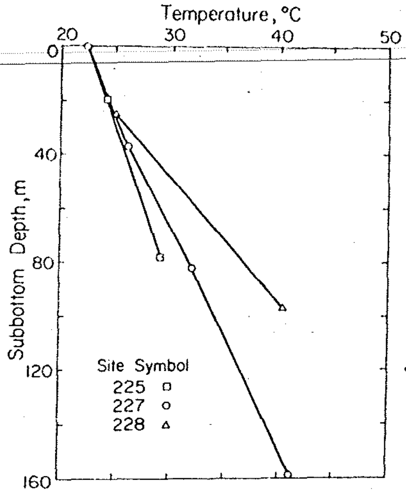

Fig. 16. Plots of temperature versus depth for downhole temperature measurements made in the Red Sea.

One of the main objectives of the heat flow program has been and continues to be the evaluation of the effects (if any) of long- and short-term variations in bottom water temperature and of heat transfer by upward migration of interstitial water in sediments on the geothermal gradient beneath the sea floor.

The detectability of an anomalous thermal gradient depends upon the amplitude of the anomalous gradient and the rate at which the anomalous gradient changes with depth. The anomalous gradient must change perceptibly between the depth intervals over which it is measured, or it will be inseparable from the steady state thermal gradient. Both of these factors depend upon the form and amplitude of the bottom water temperature changes.

In addition, the thermal gradient measured over various intervals must be corrected for variations of the thermal conductivity over the same intervals before the existence of an 'anomalous' thermal gradient can be determined. Even where the heat flow is constant with depth (i.e., where there is no anomalous gradient), the thermal gradients determined for intervals will vary if the harmonic mean thermal conductivity of the sediment in each interval varies.

Detection and definition of an anomalous gradient actually hinges on the detection of vertical variations in heat flow, and thus the threshold of detection is related to the precision with

TABLE 3. Comparison of Regional Means and Standard Deviations for Heat Flow Values Computed From Deep Drill Hole and Shallow Sediment Temperature Measurements

		Mean Heat Flow* and Standard Deviation		
Physiographic Region	Site Numbers	Downhole Data	Surface Data	Surface Heat Flow Data References
Ninety East ridge	214, 217, 253, 254	1.40 ± 15%, $n = 4$	1.49 ± 17%, $n = 4$	*McKenzie and Sclater* [1971, Table 12]
Wharton basin	256, 257	1.24 ± 11%, $n = 2$	1.23 ± 20%, $n = 39$	*McKenzie and Sclater* [1971, Table 12]
Western Indian Ocean (within 5° of sites)	248, 249	1.02 ± 1%, $n = 2$	1.13 ± 49%, $n = 5$	*Von Herzen and Langseth* [1966], *Langseth et al.* [1971]
Red Sea	225, 227, 228	3.53 ± 27%, $n = 3$	3.6 ± 56%, $n = 11$	*Girdler et al.* [1974, Table 7]

*Mean heat flow values are given in heat flow units.

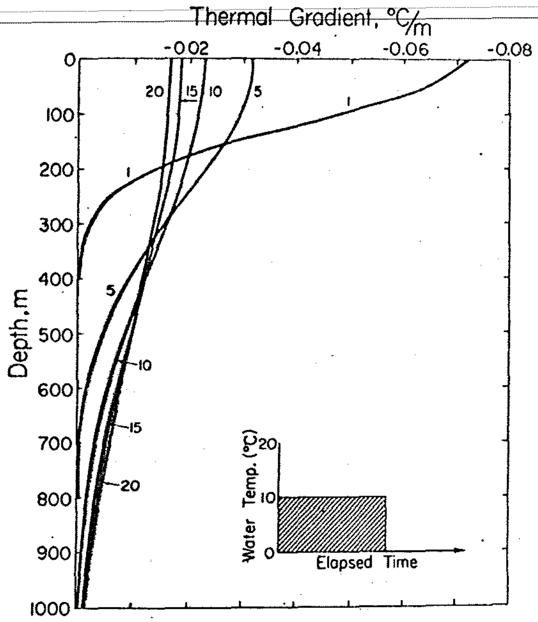

Fig. 17*a*

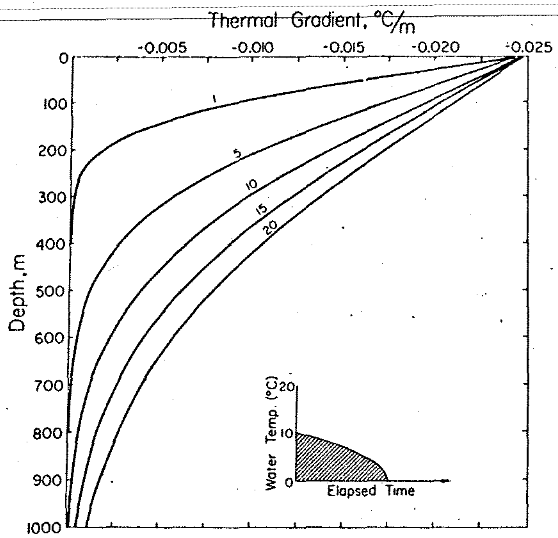

Fig. 17*c*

which both the thermal gradient and the conductivity can be measured.

In order to understand how best to position downhole temperature measurements for the purpose of detecting and defining deviations from the 'steady state' geothermal gradient and to permit us to interpret these data, we calculated the effects of a few different temporal models of bottom water temperature above a semi-infinite, homogeneous slab. Models having a stepwise, a linear, and a decaying thermal perturbation are shown in Figures 17*a*, 17*b*, and 17*c*, respectively.

Examination of the plots of anomalous thermal gradient versus depth below the sea floor indicates that the detectability of the anomalous gradient, as determined by the ratio of its amplitude to the normal geothermal gradient, is highly dependent upon the form of the bottom water temperature perturbation, as well as upon its amplitude. Thermal perturbations which have been in progress for a long time have affected the thermal gradient to greater depths than perturbations of shorter duration. Thermal perturbations which are still changing, even slowly, are more easily detectable at the relatively shallow depths accessible to downhole temperature measurements than ones which may have commenced abruptly and then remained constant for long periods of time (Figure 18).

In the preceding section we noted the difficulty, largely stemming from the absence of a sufficiently large number of interval heat flow determinations in a single drill hole, in estimating the probable error for a particular interval heat flow value. A summary of our results at drill sites where at least two interval heat flow values were computed is presented in Table 3 and illustrated graphically in Figure 19.

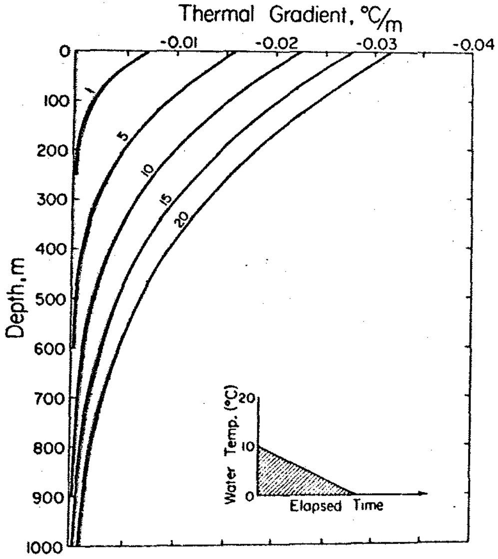

Fig. 17*b*

Fig. 17. Plots of thermal gradient as a function of depth within semi-infinite slabs whose upper surfaces have been subjected to various simple thermal histories, as shown by the insets of each figure. The numbers on the curves refer to the time elapsed (in 10^3 yr) since the onset of heating. The slab is assumed to have a constant thermal diffusivity of 0.002 cm^2/s.

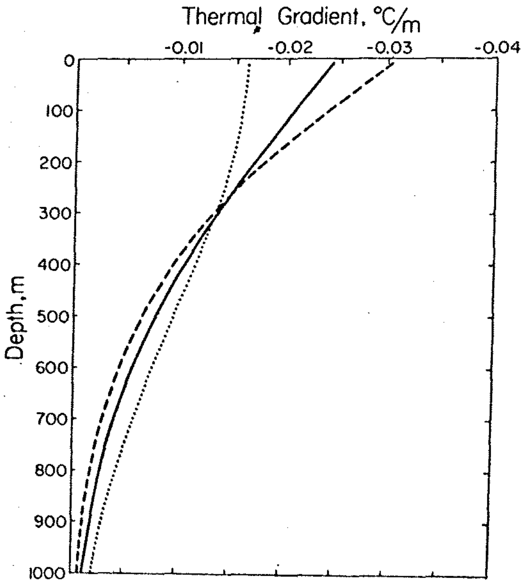

Fig. 18. Plots of thermal gradient as a function of depth within a semi-infinite slab whose surface temperature has increased 10°C over a period of 20,000 yr as a step function (dotted line), as a linear function of time (dashed line), and as the square root of time (solid line). The slab is assumed to have a constant thermal diffusivity of 0.002 cm^2/s.

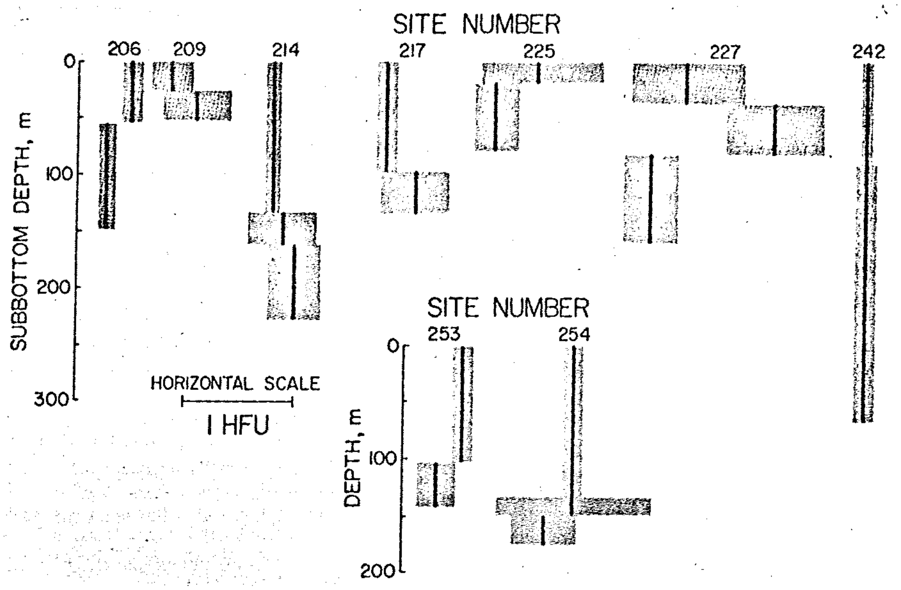

Fig. 19. Plot of heat flow versus depth for DSDP drill sites where more than one downhole temperature measurement has permitted calculation of interval heat flow values. Shaded area represents probable error associated with each interval heat flow value.

Where more than one downhole temperature measurement has been made in the same borehole, the heat flux usually remains constant within the estimated probable error of the individual heat flow determination with depth (sites 209, 214, 225, 242, 253, and 254). Marked exceptions have been observed at some sites where heat flow either increases downwards (sites 214, 217, and 228), decreases downwards (sites 206 and 217), or even varies nonsystematically with depth (site 227). In general, where significant downward heat flow variations with depth are observed (sites 209, 227, and 228), the downhole temperature-time records suggest that the data are not of the highest quality. Almost all of the intervals for which heat flow values were computed and compared are situated in the uppermost 200 m, and all are within 300 m of the sea floor. Referring back to Figures 17*a*, 17*b*, and 17*c*, we can see that even if the warming process has been in progress for 10,000 yr or more, the vertical variability of the thermal gradient is large in comparison with our estimated probable error for all but the stepwise heating model, which happens to be the least realistic of the three models. Accordingly, we make the preliminary conclusion that there is no evidence from our data for regional changes in heat flow with depth, such as might be anticipated from long-term changes in bottom water temperature or the effects of the upward migration of interstitial fluids. We note, however, that we presently lack the necessary number of downhole temperature measurements at any one drill site to unambiguously determine the existence of variations in heat flow with depth.

The acquisition of numerous (10 or more) downhole temperature measurements at a few carefully selected drill sites during subsequent legs of the DSDP will provide the data necessary to answer definitively the question of whether or not deep oceanic heat flow measurements reflect the steady state heat flux through the earth's crust. The geophysical implications of even a small (10%) systematic error, perhaps due to thermal effects of near-surface environmental factors and geological processes, may significantly alter thermal models of the lithosphere and current ideas on the distribution of radiogenic elements in the oceanic lithosphere [*Aumento and Hyndman,* 1971; *Sclater and Francheteau,* 1970].

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