46. HEAT FLOW MEASUREMENTS ON DEEP SEA DRILLING PROJECT LEG 60[1]

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ABSTRACT

Downhole heat flow measurements were revitalized during Leg 60 by a newly developed downhole heat flow probe. Three measurements in the actively spreading Mariana Trough gave variable heat flow values indicating that active hydrothermal circulation is operative in the crust of the Trough, while two measurements in the Mariana fore-arc region showed subnormal values. Results of downhole logging conducted using the Gearhart-Owen equipment at two sites are also considered in the interpretation of our downhole measurements. The highly variable heat flow in the Mariana Trough has been confirmed by subsequent surface-ship measurements by Hobart et al. (1979).

INTRODUCTION

DSDP holes have provided an important opportunity for investigating the thermal state of the oceanic crust to a depth that is inaccessible using the conventional short probe technique. A. Erickson and R. P. von Herzen developed a downhole heat flow probe at an early stage of the Deep Sea Drilling Project, and their probe was used successfully on several cruises of the *Glomar Challenger* (e.g., Erickson, 1973; Erickson et al., 1975; Hyndman et al., 1976).

Due to mechanical troubles, however, their probe was not used during several legs prior to Leg 60, and the DSDP heat flow program was temporarily suspended. Having been informed of the unavailability of the Erickson-von Herzen probe for Leg 60, we decided to build hurriedly a new probe that would, we hoped, tolerate the inevitable rough handling. As described elsewhere (Yokota et al., 1980), the new probe utilizes IC (Integrated Circuit) memory units to record the downhole temperature. Containing no mechanically moving parts, it is likely to be much more rugged than conventional devices. The IC memory device (Daughter Instrument) can be housed in the pressure case of the existing DSDP *in situ* water sampler of R. Barnes, and the thermistor in its nose piece. Thus, it is possible to take both the temperature measurement of the bottom hole sediments and a pore water sample in a single operation. This new heat flow probe is called the Tokyo T-probe in this chapter wherever it needs to be distinguished from other types of probe.

The Tokyo T-probe can store 128 readings of thermistor resistance sampled every one or two minutes. Stored data are retrieved by a device (Parent Instrument) aboard the ship and displayed visually. Resistance readings are then converted into temperature, using the thermistor calibration data. It would be an easy matter to convert resistance into temperature data automatically, but this was not done during Leg 60 because we did not have enough time to construct the necessary device.

In normal operation, the heat flow probe, attached to the bottom of the core-barrel, is lowered by the sandline and latched in the drill bit which has been raised off the bottom. At this point, the nose of the probe is sticking out of the bit by about two feet. Then the entire drill string is slowly lowered to force the probe into the undrilled sediments, where the temperature is recorded for an appropriate period. Obviously, for this operation to be possible, the sediments should not be too hard, otherwise the nose of the probe can be damaged. Moreover, until the bulk of the bottom-hole assembly (which is about 60 meters long) is buried in a hole, the drill string system is too unstable for the operation. These conditions impose severe restrictions on the heat flow measurements, especially when the sediment cover is either thin or hard as in the case of Leg 60 drilling. When the sediments are judged to be too hard or the hole is already in hard igneous rocks, one has to be satisfied with the measurements of near-bottom water temperature keeping the drill bit off the bottom, or even with the water temperature at various levels in the drill string. In such cases, the temperatures measured are by no means the formation temperatures, but are distorted by the circulation of drilling fluid (sea water). The same is true for the downhole temperature logging. On Leg 60, Gearhart-Owen downhole logging was conducted at two sites. Ideally, if the logging is made long after the circulation of fluids, the measured temperatures may approximate the formation temperature. But usually, in the DSDP operation one cannot afford such a long wait; therefore, the recorded data have to be corrected in order to estimate the formation temperature (e.g., Hyndman et al., 1976).

The thermal conductivity of the core samples needed for heat flow estimates has been made by a QTM (Suzuki et al., 1975) and a needle probe method (von Herzen and Maxwell, 1959). A full account of the conductivity measurements during Leg 60 is given in a companion paper (Horai, this volume).

[1] *Initial Reports of the Deep Sea Drilling Project*, Volume 60.

Subsequently in this chapter, the results of heat flow measurements on Leg 60 will be reported for each site. Strong indications of hydrothermal activity in the crust of the Mariana Trough were obtained, and these findings have now been confirmed by a subsequent detailed surface-ship heat flow survey carried out by Hobart et al. (1979).

SITE 453

At this site, located in a sediment pond in the westernmost part of the Mariana Trough (5–6 m.y. old), a heat flow experiment was conducted for the first time using the new heat flow probe.

The downhole temperature was determined once at a sub-bottom depth of 75.7 meters. The probe was set for a 2-minute recording interval and lowered by the sandline into the hole. Lowering was stopped at the mudline for 10 minutes to record the bottom surface temperature; whereafter the probe was forced into the bottom sediments. It was kept there for 20 minutes before retrieval. The change in recorded temperature with time is shown in Figure 1. The temperature in the bottom sediment was 11.9°C; at the mudline it was about 2.2°C, but changing slightly with time. The thermistor might have been at the sub-bottom level. The temperature just above the mudline—which is 1.7°C—may be more representative of the bottom temperature. These data give a temperature difference of 9.7°C–10.2°C for a depth difference of 75.7 meters. The geothermal gradient is thus 12.8–13.5°C/100 meters.

The thermal conductivity of the sediments was measured by QTM on 28 core samples taken between the sea bottom and a depth of 88.3 meters. Most of the values of thermal conductivity were in the range of $1.8–2.0 \times 10^{-3}$ cal/cm s°C (Fig. 2), the geometrical mean being 1.86×10^{-3} cal/cm s°C. This value in turn was corrected for depth and temperature to give the $K_{in\ situ}$ = 1.82 cal/cm s°C, by the empirical formula (Ratcliffe, 1960):

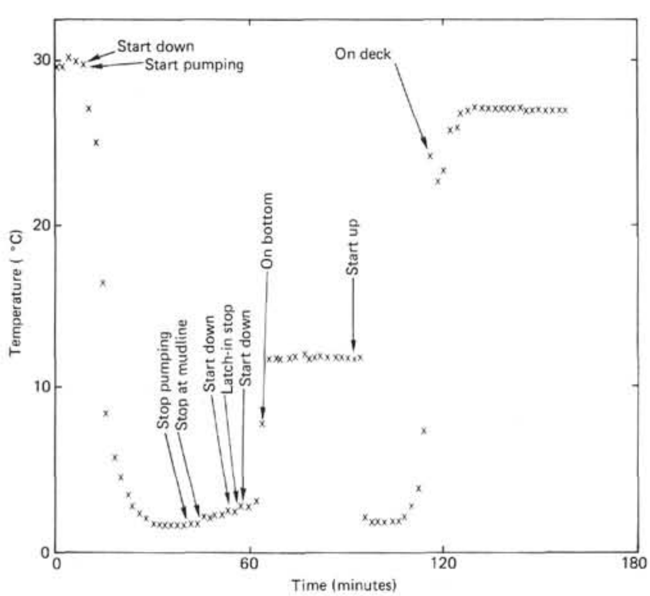

Figure 1. Downhole temperature data of Hole 453.

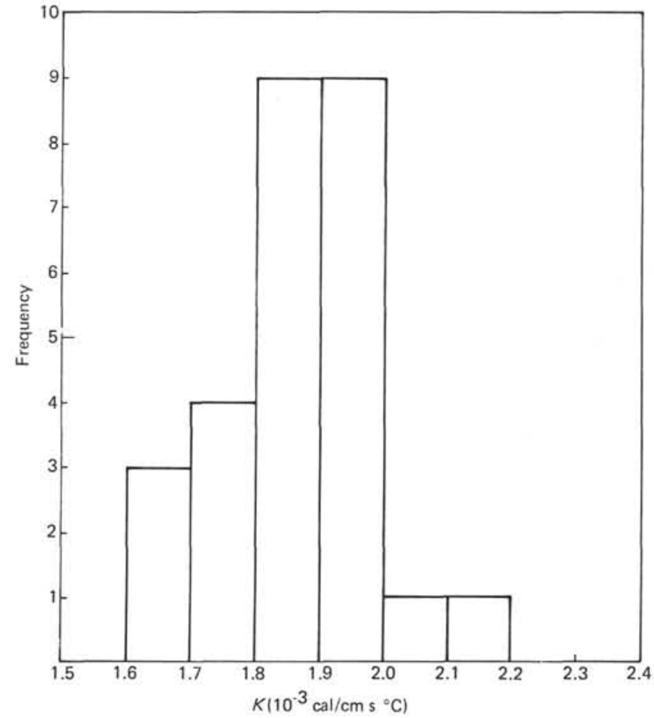

Figure 2. Frequency histogram of thermal conductivity of sediments of Hole 453.

$$K_{in\ situ} = K\left(1 - \frac{T_m - T}{400}\right)\left(1 + \frac{D}{183000}\right),$$

where K is the value measured at T_m°C in the laboratory and $K_{in\ situ}$ is the value at T°C and at the water depth D(m). Using the values for the geothermal gradient and thermal conductivity obtained, the heat flow for the depth interval 0–75.5 meters was estimated at $2.33–2.46 \times 10^{-6}$ cal/cm^2 s (HFU), the mean being 2.40 HFU (100 mWm^{-2}).

Attempts to effect measurements at other depths were not made, because at a depth of about 100 meters the sediment became too firm to be penetrated by the probe without risk of breaking it.

The heat flow value of 2.40 HFU obtained here, though estimated from only a single temperature measurement, is reliable. This value is significantly higher than the average oceanic heat flow but is reasonable for young sea floor such as the Mariana Trough (Watanabe et al., 1977), although the theoretical heat flow for a cooling plate model predicts much higher values for the 5- to 6-m.y.-old crust. However, the values obtained previously in this area by a conventional oceanic heat flow probe (Anderson, 1975) are mostly below 1 HFU (Fig. 15). In view of the possibility that the heat transfer in the young crust is largely controlled by hydrothermal circulation, local high variability is expected. The igneous rocks sampled from the bottom of Site 453 exhibited both petrologic and paleomagnetic evidence of hydrothermal alteration (see site 453 report, this volume).

SITE 454

Downhole temperature measurements were attempted in Holes 454 and 454A, which were located in a small sediment pond in the shallow central part of the Mariana Trough, the age of the basement being from 0.9 to 1.6 m.y.

The first temperature measurement was conducted in soft mud in Hole 454 at a sub-bottom depth of 27 meters. However, the instrument recorded for only 27 minutes. The temperature was in the range of 25–26°C, which does not fit the possible temperature anywhere in the hole, but fits the temperature aboard ship. We suspect that the recorder was "reset" when it was brought on deck, wiping out all the previous records, and started to record the temperature on deck. In fact, it was observed that the barrel containing the probe, on retrieval, hit fairly severely against the guide rail. The mechanical shock thus probably "reset" the elecronics by instantaneous cut-off of battery contact.

In Hole 454A we judged it to be unsafe to attempt heat flow measurements until the bottom-hole assembly was completely buried. Unfortunately, by the time the assembly was buried the bit was penetrating interbedded basalt and sediments, which made the heat flow measurement impossible.

After drilling in Hole 454A ended at 2335 7 April, we made a bottom-hole water temperature measurement. The bit was first raised 31.5 m above the maximum drilled depth (175.5 m) to get above the cuttings piled up in the hole. The probe was turned on at 0110 8 April (2-minute recording interval) and lowered into the hole immediately. It was held at 10 meters above the mudline for 7 minutes, and at the bit level for 30 minutes. The recorded temperature change with time is shown in Figure 3. The rise in temperature in the hole is remarkably small. The bottom water temperature is about 1.72°C, whereas the bottom hole temperature (d = 140 m) is 2.05°C, the difference being only 0.33°C.

At Hole 454A, Gearhart-Owen logging was conducted after our Tokyo T-probe run. The bit was released at 0530 8 April and the entire drill string was raised to 3911.5 meters (bit 83 m below the mudline) at about 0600 8 April. The temperature log was run at the beginning and the end of the series of other logging tool runs. The first and second temperature logs were made at 1000 8 April and 0500 9 April, respectively. The results shown in Figure 4, a and b indicate that in both measurements the temperature throughout the hole is almost identically low: 36.7°F (2.61°C) at mudline and 37.2°F (2.89°C) at the bottom. This indicates a 0.28°C increase in temperature in the hole.

The Gearhart-Owen temperature probe (GO T-probe) readings were slightly different from Tokyo T-probe readings. Both probes were then calibrated aboard 0°C (ice water). The GO T-probe read 33.6°F for freezing point, whereas the Tokyo T-probe read 0.0°C. When

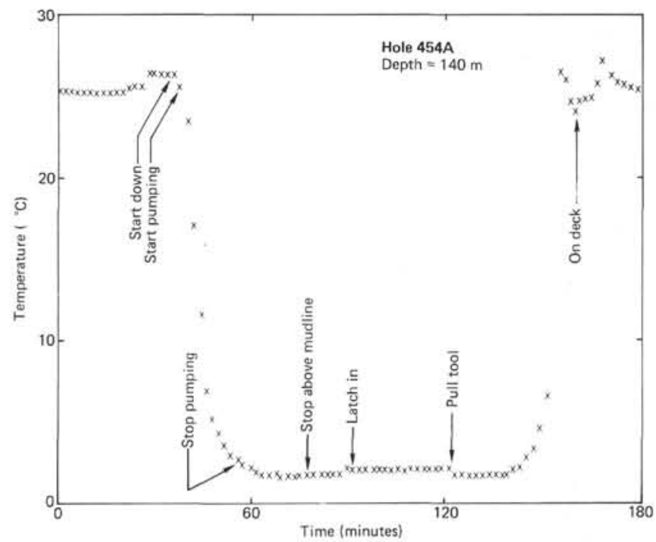

Figure 3. Downhole water temperature data of Hole 454A.

corrections were made on GO T-probe readings, they turned out to be 1.72°C for the bottom water temperature agreeing with the reading of the Tokyo T-probe, and 2.00°C for the bottom hole temperature, indicating 0.28°C for the temperature rise. If the differences in temperature in the hole recorded by the different instruments (0.33°C for the Tokyo T-probe measurement and 0.28°C in the GO logging) are real, there was a 0.05°C decrease of bottom hole temperature between the time of our log and the first GO log.

The observed low temperature and low gradient in Hole 454A—which are almost identical to the three loggings conducted at different times—are probably not due to thermal disturbance by drilling, because the thermal disturbance should decay with time. A possible explanation for the observed low temperature and low gradient may be that they represent the true natural state and that the circulating sea water did not cause any significant disturbance because its temperature was the same as the formation temperature. If this interpretation be correct and if we take the mean of the in-hole temperature rises observed, this results in a geothermal gradient of 0.2°C/100 meters. The strata penetrated by the hole consisted of about 65 meters of sediment and 105 meters of basalt. Thermal conductivity (Horai, this volume) of each is 2.24 and 3.99 × 10^{-3} cal/cm s°C, respectively, the geometrical mean thus being 2.9 × 10^{-3}. Using these values, the apparent heat flow at the site is calculated as Q = 0.06 HFU (2.5 mWm^{-2}). This value is extremely low, but probably not unreasonable for sea floor where active hydrothermal circulation is expected, as in the present case of young crust. In fact, among the heat flow values obtained by conventional oceanic techniques in the Mariana Trough (Anderson, 1975), there are many that show values less than 1 HFU. There is even one measurement showing 0.00 HFU in a sediment pond at 17°18.5′N 145°03.6′E. Lister (1972) and Williams et al. (1974) found that sediment cover is

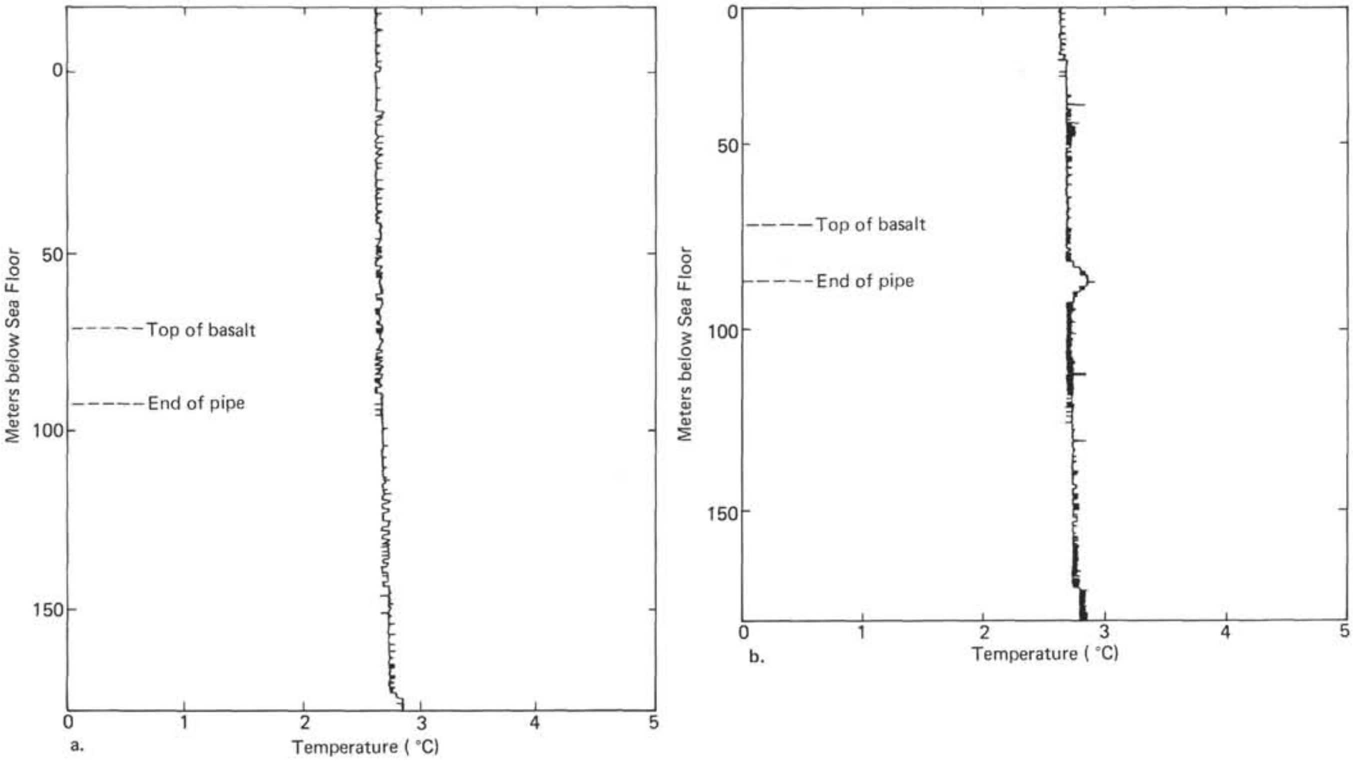

Figure 4. Gearhart-Owen temperature-log data of Hole 454A. (a) First run. (b) Second run.

an important factor in controlling the surface heat flow in a hydrothermal area, and that generally low heat flow is found in sediment troughs.

An entirely different interpretation for the low heat flow observed in Hole 454A is also possible. Similar phenomena were observed at Site 335 drilled on DSDP Leg 37 (Hyndman et al., 1976) and Site 396 drilled on DSDP Leg 46 (Erickson and Hyndman, 1979) near the Mid-Atlantic Ridge (Site 335 is about 90 miles west and Site 396 is 80 miles east of the Median Valley of the Mid-Atlantic Ridge, Fig. 5 A and B). At both sites, the temperature measured by the Erickson/von Herzen heat flow probe in sediment was found to increase with depth, although the gradient was rather small and gave apparent heat flow values of 0.49 HFU and 0.56 HFU—values much smaller than would be expected from the cooling plate model. However, after the hole had been drilled into basaltic basement, the temperature in the bottom of Holes 335 and 396 was almost the same as that of the bottom water. Their interpretation is that this strange phenomenon was caused by down-flowing of sea water into permeable basaltic crust through the hole. Because of the failure of our first heat flow measurement in Hole 454, we do not have temperature data in sediments before penetrating into the basement at Hole 454A. Although we cannot be certain that all the circumstances are similar, it is likely that the same thing as in Holes 335 and 396 happened in Hole 454A. The observed slight decrease with time of 0.05°C in the bottom hole temperature mentioned above, if real, may represent the cooling of the hole by this artificially created, local sea-water convection into the crust. If this was the case, three examples (Holes 335, 396, and 454A) seem to point out a potentially very important new phenomenon pertaining to the physical properties and the hydrothermal state of the young oceanic crust. In fact, a subsequent detailed heat flow survey (Hobart et al., 1979) obtained a surface heat flow of 0.6 HFU (25 mWm^{-2}) at Site 454, supporting our second interpretation.

SITE 456

At this site, Holes 456 and 456A were drilled about 200 meters apart in a small sediment pond on a local bathymetric high at about 37 km east of the central valley of the Mariana Trough. The age of the oldest sediment was 1.6–1.8 m.y.

Hole 456

A downhole temperature measurement was made at a sub-bottom depth of 29.0 meters by the Tokyo T-probe. During this measurement, simultaneous use of the R. Barnes in situ water sampler was first attempted. The temperature versus time record on this lowering is shown in Figure 6. The bottom water temperature is 1.75°C, as estimated from the 5-minute stationary test at 20 meters above the mudline on the way up. To estimate the minimum period needed for such a test, the response characteristics of our probe to a sudden change in temperature of the surrounding water was examined

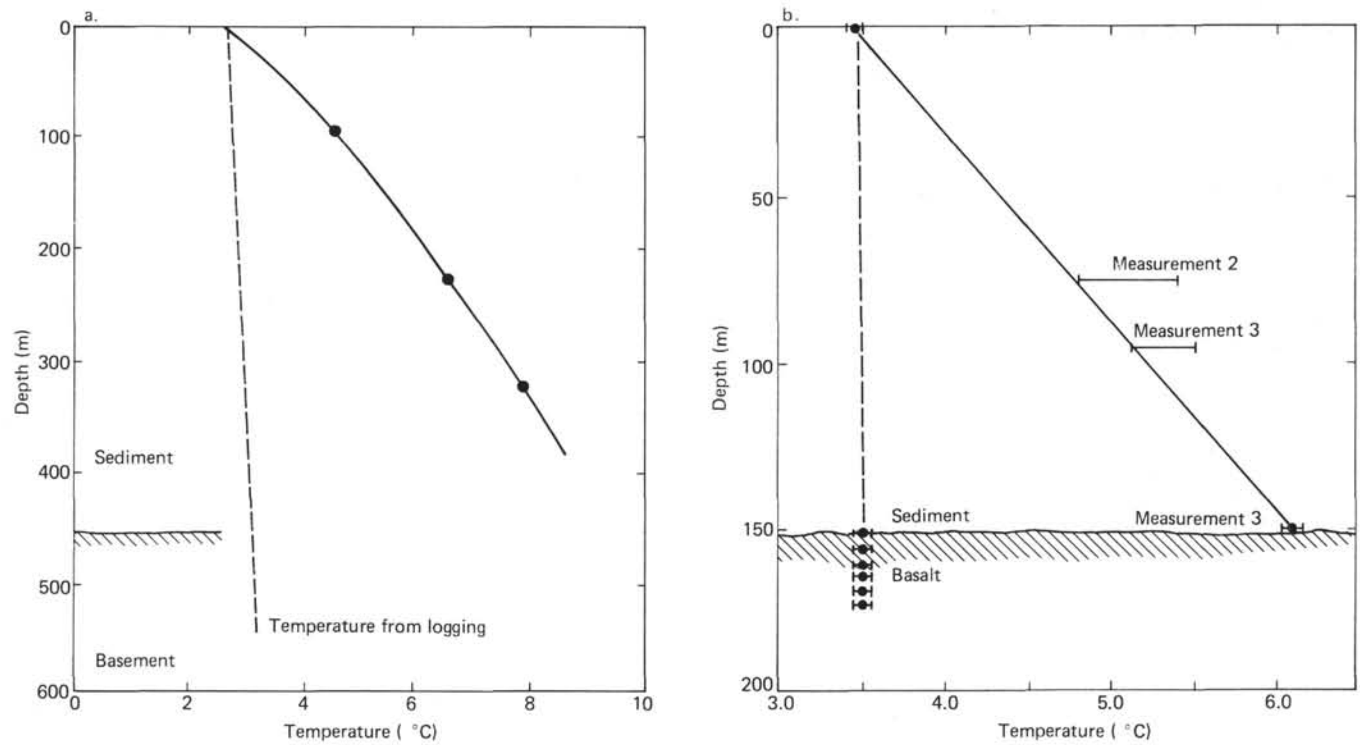

Figure 5. A. Temperature with depth at Site 335, after Hyndman et al. (1976). B. Temperature with depth at Site 396, after Erickson and Hyndman (1979).

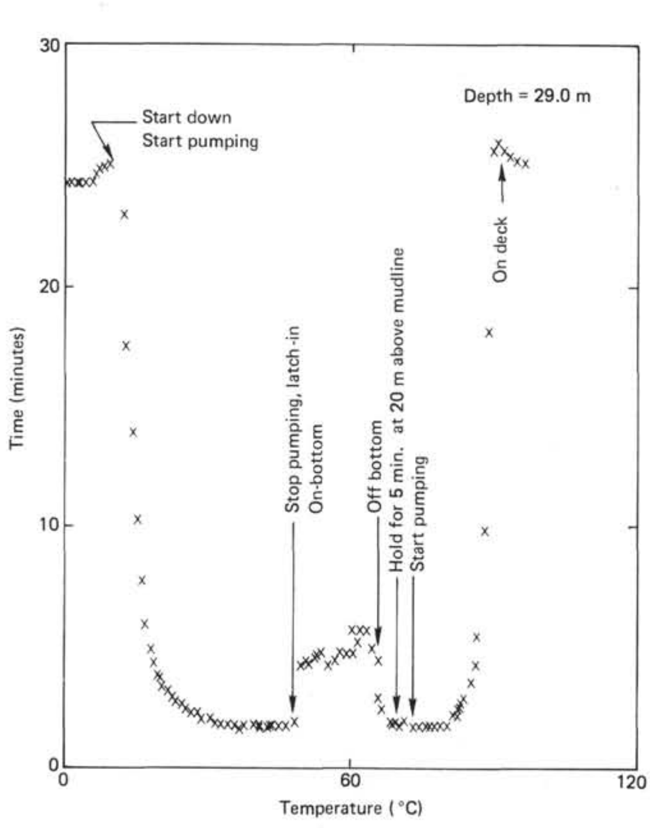

Figure 6. Downhole temperature data at Hole 456.

on board by its immersion in ice water; we found that the probe attains 90 percent of the temperature change in 80 seconds.

The temperature in the bottom sediment was found to fluctuate between 4.30°C and 5.63°C in this experiment. Although the fluctuations are probably caused by instability of the probe at the bottom, further details are difficult to evaluate. If we assume that the temperature recording mechanism was functioning properly, at least two possible reasons for the fluctuations may be considered: (1) peaks represent frictional heating; and (2) lows represent partial pull-out or interference of bottom water. Being unable to decide which possibility is the more likely, we tentatively take the mean of the maximum and the minimum for the sediment temperature—that is, 5.00°C. The temperature increase in the 29-meter interval is thus 3.25°C, giving a geothermal gradient of 11.2°C/100 meters. (If we take the minimum and maximum reading, the gradient ranges from 8.7-13.4°C/100 m).

The thermal conductivity of the sediments at this site was measured on 33 samples cored from the 1-50-meter interval (Horai, this volume). The geometrical mean value was 2.50×10^{-3} cal/cm s°C ($K_{in\ situ} = 2.42 \times 10^{-3}$ cal/cm s°C). The heat flow value at Site 456 was thus estimated to be 2.71 HFU (113 mWm^{-2}), with a possible range of 2.1-3.2 HFU (88-134 mWm^{-2}). The water sampler could not be pulled out of the pressure barrel upon returning to the deck, owing to mechanical jamming for unknown reasons. The water sampler as well as the heat flow probe had to be removed by cutting open the barrel. Part of the water sampler was damaged, but the heat flow probe was intact.

Hole 456A

A downhole temperature measurement was also made at this hole at a sub-bottom depth of 47.5 meters. The temperature versus time data are shown in Figure 7; from these data it appears that: (1) the bottom water temperature was 1.82°C; (2) the temperature at 47.5 meter sub-bottom reached a maximum of 4.18°C at 2 minutes after penetration and decreased to 3.60°C approximately linearly. As in the previous measurement, at this stage it is not certain whether the change was caused by dissipation of initial frictional heat or by partial pull-out and bottom water interference. Therefore, we tentatively take the mean value of 3.89°C as the sediment temperature, again with a possible range of 3.60°C to 4.18°C; (3) the temperature (3.60°C to 4.18°C) in Hole 456A at a depth of 47.5 meters was lower than that at a depth of 29.0 meters (4.30°C to 5.63°C) in Hole 456. Considering that the two holes are only about 200 meters apart, this is unusual.

The observed temperature increase of 2.07°C (range 1.78°C–2.36°C) in 47.5 meters gives a geothermal gradient of 4.36°C/100 meters (range 3.74°–4.96°C). The geometrical mean of the thermal conductivity values measured on 18 sediment samples (0–50 m depth) in Hole 456A (Horai, this volume) is 2.53×10^{-3} cal/cm s°C ($K_{in\ situ} = 2.45 \times 10^{-3}$ cal/cm s°C). From these values, the heat flow was obtained as 1.06 HFU (44.4 mWm^{-2}), again with a range of 0.9–1.2 HFU (38–50 mWm^{-2}). This is only about 40 percent of the value of the nearby Hole 456. This extraordinary local variation in heat flow was confirmed by the subsequent survey of Hobart et al. (1979), providing further important evidence for hydrothermal activity.

Lithification of sediments in Hole 456A prevented us from effecting sediment temperature measurements deeper in the hole. Accordingly, only measurement of the water temperature at a depth of 66.5 meters, near the bit, was attempted. The Tokyo T-probe was latched in the bit, which had been raised to 3 meters above the bottom (the tip of the probe was, then, about 2 m above the bottom), and was held there for 30 minutes from 0855 to 0925 14 April. The results indicated that the water temperature increased by about 0.35°C during the 30-minute measurement. The time of drilling at this depth—namely the beginning of fluid circulation—was about 0715 hours, and the pumping was stopped at 0820. This means that the period of disturbance was 65 minutes. The temperature measurement started 35 minutes after the cessation of the disturbance. The equilibrium temperature, if linearly extrapolated from the measurement at the 47.5 meter depth, would be about 4.7°C. This means that the disturbance still remained about 90 percent and 85 percent at the beginning and end of the measurement, respectively. This appears to be reasonable from a theoretical standpoint (e.g., Jaeger, 1961). However, an estimate of the formation temperature from these data would obviously involve too much uncertainty.

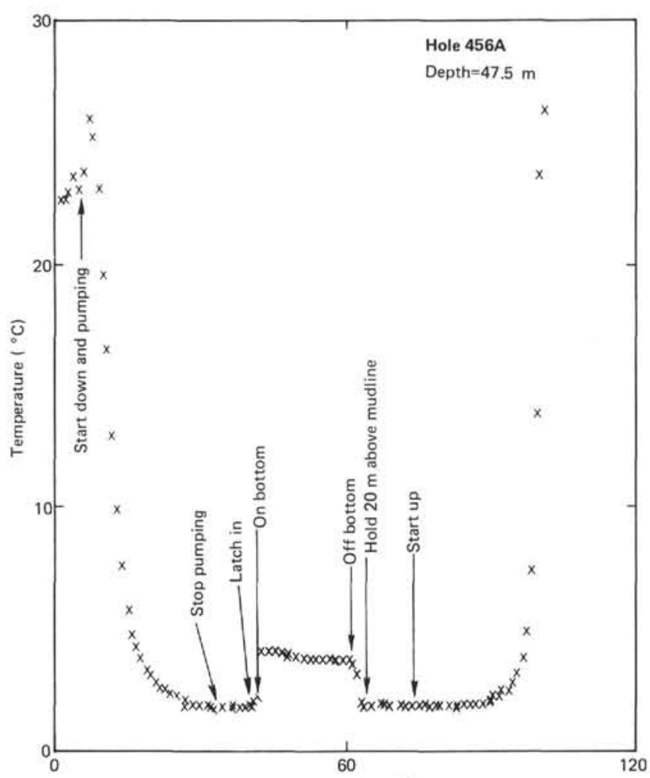

Figure 7. Downhole temperature data at Hole 456A.

SITE 458

Bottom hole sediment temperature measurements at Site 458, located on the Mariana fore-arc at a water depth of 3447 meters, were made at two sub-bottom depths, 76 meters and 142.5 meters. Although the measurements were successful, interpretation of the recorded temperature presented some difficulty.

Temperature versus time records are shown in Figures 8 and 9. At the 76-meter depth measurement, the temperature in the sediment appeared to attain a stable value of 4.25°C at 4 minutes after bottom penetration (Fig. 8); subsequently, however, it rose to about 5.3°C. The exact reason for this temperature increase is not known. However, it may be noted that the drill string had to be lowered by 1 foot and 1/2 foot, respectively, at the times indicated by arrows, because of a decrease in the bit weight. We assume, therefore, that the temperatures in the later part of the record were disturbed. (If we take the highest value, it is almost as high as the highest value at 142.5 m!)

The measurement at 142.5 meters showed an entirely different temperature versus time relationship (Fig. 9). A temperature of 5.32°C was attained on bottom penetration, but decreased continuously until pull-out. Although a little more weight was applied at the times indicated by arrows in Figure 9, there were no observable changes in temperature. We are not sure of the cause of the slow temperature decrease, but assume

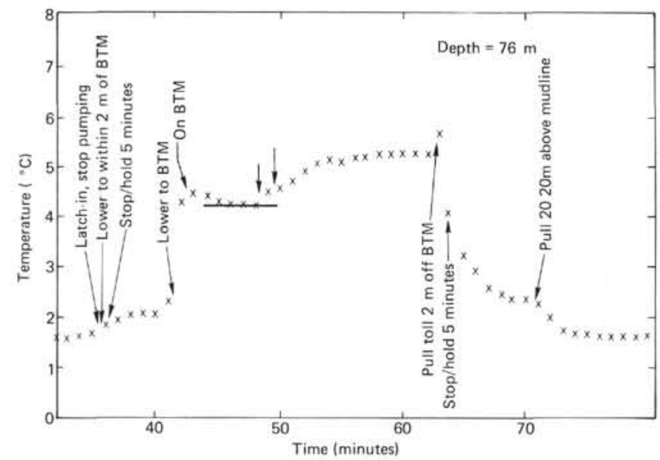

Figure 8. Downhole temperature data at Hole 458.

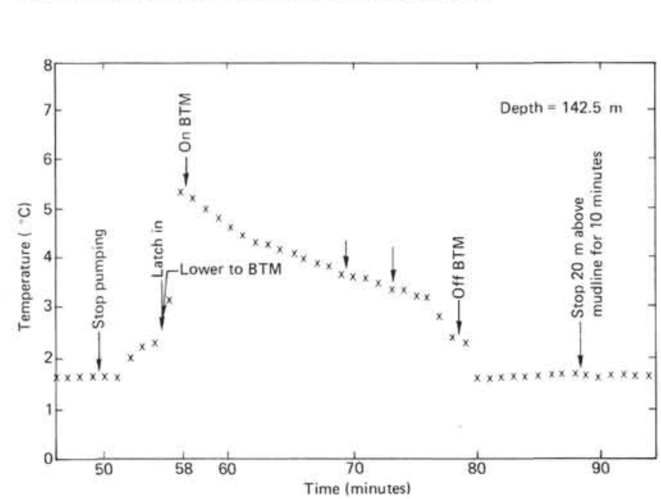

Figure 9. Downhole temperature data at Hole 458.

that, in this case, the initial highest temperature may be closest to the sediment temperature.

The reason for assuming that the lowest temperature in the 76-meter measurement and the highest in the 142.5-meter measurement are closest to the true sediment temperature is the following: The sediment at the top part of Core 9 (76.0–85.5 m) is a compact nannofossil ooze, whereas that of the Core 6 (142.5–152.0 m) consists of brittle interbedded muds, silts, and sands. We assume that any frictional heat that might be generated by movements of the probe in the compact ooze would effectively raise the temperature (76-m measurement), whereas the brittle sediments would produce cracks that would allow interference of bottom water (142.5-m measurement). The water temperature at the sea floor was taken in both experiments by holding the probe at 20 meters above the mudline for 5 and 10 minutes on the way up. Both measurements were 1.65°C.

With these assumptions, the temperature gradients for the intervals 0–76 meters and 76–142 meters are estimated to be 3.42°C/100 meters and 1.61°C/100 meters, respectively. The geometrical average values of the thermal conductivity at the intervals 0–80 meters, and 80–150 meters for this site are 2.44×10^{-3} cal/cm s°C (66 samples) and 2.77×10^{-3} cal/cm s°C (13 samples) (Horai, this volume). $K_{in\ situ}$ values are 2.36×10^{-3} cal/cm s°C and 2.68×10^{-3} cal/cm s°C. These data result in heat flow values of 0.81 HFU and 0.43 HFU for both intervals, the average being 0.6 HFU (25 mWm^{-2}). Although these values cannot be regarded as highly reliable because of the uncertainty in the temperature data, it may be stated that heat flow at this site is probably low. Such a low heat flow value seems to be a reasonable one for a fore-arc region.

During the experiment at the 76-meter depth, the probe was held for 5 minutes at 2 meters above the bottom of the hole on both descending and ascending trips (Fig. 8). The water temperature at 2 meters above the bottom of the hole on both these occasions were 2.10°C and 2.35°C. The difference (0.25°C) may represent the recovery, during the initial half hour, of water temperature in the hole after the disturbance by the circulating fluid. This compares with an increase of ca. 0.35°C/30 minutes in bottom water temperature in Hole 456A. In the case of Hole 456A at a depth of 66.5 meters, temperature measurement was started about 1/2 hour after cessation of fluid circulation, whereas in the present case pumping was stopped at about one minute before the beginning of the first holding. It is disappointing that the present experiment does not show greater initial temperature recovery.

The bottom water temperature just after stopping pumping (2.10°C) is taken as the temperature of the circulating water at this depth. This means that the circulating water was warmed from 1.65°C (sea floor temperature) to 2.10°C during descent in the pipe.

SITE 459

Sediment Temperature

This site was located on the eastern edge of the deep sediment pond immediately above the Mariana Trench slope break.

A downhole sediment temperature measurement in Hole 459B was made at a depth of 64.5 meters. The temperature versus time record is shown on Figure 10. The record was found to stop at 58 meters minutes after turn-on, at the time of pull-out from the bottom. We later discovered that the lead wire of the thermistor was cut by inadvertent slight rotation of the probe rod relative to the filter block of the water sampler.

The recorded temperature first shows a decrease with time and an apparently stationary temperature at 4 minutes after penetration. However, this temperature did not stabilize, but again started to decrease as more weight was added to the bit (arrows in Fig. 10). If we assume, on the one hand the initial highest temperature (5.75°C) and on the other, the asymptotic temperature (3.75°C), as alternative true temperatures for the depth, the gradients obtained are 5.96°C/100 meters and

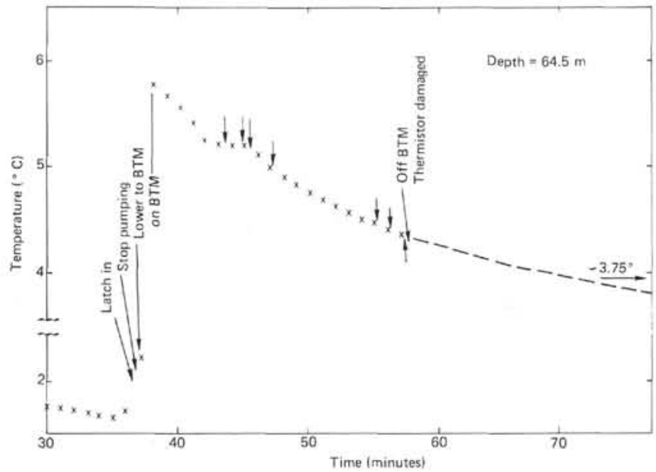

Figure 10. Downhole temperature data at Hole 459B.

2.86°C/100 meters, respectively. The geometrical mean value of the thermal conductivity between depths of 0 and 100 meters at this site is 2.60×10^{-3} cal/cm s°C (44 measurements, Horai, this volume). $K_{in\ situ}$ is then 2.52 $\times 10^{-3}$ cal/cm s°C. These values give the possible heat flow range at Site 459 as 1.50–0.72 HFU. The maximum value of 1.5 HFU seems to be too high for the fore-arc area. The top of Core 8 (64.5–74.0 m) had an approximately 1.5-cm thick and 5-cm long mass of grease from the sandline. Although the sandline used was new and greasy, such a mass was not found in any other cores. The top 30 cm of Core 8 is of more variable lithology than the section below (see the core barrel sheet in the Site 459 Report, this volume), suggesting an accumulation of materials from higher levels, fallen down the hole. Holding the probe in the bottom for a long duration (20 min.) probably resulted in the accumulation of these materials, including the mass of grease. From these observations we infer that the lithology of the section just below the disturbed zone represents that of the section penetrated by the probe. The lithology of the section is unlithified crystal vitric ash, probably incapable of brittle fracturing and highly impermeable. Therefore, the asymptotic value of the recorded temperature rather than the initial one may be close to the true sediment temperature. Based on these considerations, we tentatively take the lowest value of 0.7 HFU (30 mWm^{-2}) as the heat flow of this site.

Because the sediments shortly afterward became too firm for safe penetration of the probe at this site, no more sediment temperature measurements were attempted. Instead, only the water temperature just above the bottom of the hole was measured at 131.0 meters, 197.5 meters, and 330.5 meters.

Measurement When the Hole Reached 131.0 Meters Sub-bottom

The near-bottom water temperature was measured by the Tokyo T-probe when the hole was drilled to a depth of 131.0 meters. Henceforth, in this chapter, the time since cessation of fluid circulation will be denoted by t_l. In this case t_l = 46 minutes, as will be explained subsequently. After stopping and holding at 20 meters above the mudline for 10 minutes, to record the bottom sea-water temperature as 1.9°C, the probe was lowered into the hole and latched into the bit which had been raised to 5 meters above the bottom. Pumping had been stopped about 46 minutes before this. Within 20 seconds of latching-in, the bit was lowered to 3 meters above the bottom and held there for 30 minutes. When the T-probe latched in the bit, the temperature first rose to 4.22°C and then came down to 3.65°C during the rest of the observation period. This decrease was not expected, because the probe was simply lowered from 5 meters to 2 meters above the bottom. One possibility is that the temperature of the bit and its vicinity was locally raised by frictional heating by ca. 0.7°C, because the bit was rubbing against the wall of the hole as the ship heaved while held at the 5-meter point. Then when the bit was lowered to the 2-meter point, the temperature decreased. The situation may have been similar to that recorded by the Gearhart-Owen temperature log data at Site 454. This showed a noticeable local rise (also ca. 0.7°C) at the depth of the end of the pipe during the second temperature log after the pipe had been sitting at the same depth for some time without pumping (Fig. 4b). The temperature anomaly was not noticed in the earlier Gearhart-Owen temperature log at Site 454, which was obtained soon after the end of the pipe had been raised in the hole for logging (Fig. 4a).

Measurements When the Hole Reached 197.5 Meters Sub-bottom

Next, the temperature was recorded by step-holding at three depths—at 197.5 meters, just above the bottom of the hole, 131 meters, and 65 meters. In order to test the validity of "bit heating," the bit was held at 3 meters above bottom at this time and not moved after latching-in of the probe. As expected, the anomalous initial temperature decrease was not observed. Instead the temperature linearly increased from 3.05°C (t_l = 23 min.) to 3.37°C (t_l = 1 hr.). This increase may be the combined result of both temperature recovery and bit heating.

Presumably, heating at the bit depends on many factors, including sediment lithology and the amount of ship's heave; it varies in each case, making a simple generalization difficult. Assuming that the bit heating was small at this depth, the recovery temperatures are estimated as 3.37°C (197.5 m, t_l = 1 hr.), 2.85°C (131 m, t_l = 70 min.), and 2.05°C (64.5 m, t_l = 80 min.), respectively.

Measurements When the Hole Reached 330.5 Meters Sub-bottom

For this measurement, the probe was held at 64.5 meters, 131.0 meters, 197.0 meters, and 330.5 meters for 10 minutes each on both descending and ascending trips. The results are shown in Figure 11. The average temperatures at these depths are (for t_l = 50 min.):

Depth (m)	T (°C)
0	1.99
64.5	2.45
131.0	3.09
197.0	3.58
330.5	3.91

Gearhart-Owen T-Logging

After completion of drilling at Hole 459B at a depth of 691.5 meters sub-bottom, Gearhart-Owen engineers conducted two downhole temperature loggings. Their records are reproduced in Figure 12, a and b. The drill bit was released at a depth of 4788.5 meters at 0705 2 May 1978, and the drill string was raised to 4344 meters (120 m sub-bottom) at about 1030 the same day.

The first and second measurements were conducted at t_l = 2.4 and t_l = 20 hours, respectively. Both measurements showed very small gradients in the drill pipe and steep gradients just below the drill pipe. Below about a depth of 160 meters the gradient was relatively constant. There was 0.5 to 2° of recovery between the two measurements. Unfortunately, the logging tool could not reach the bottom of the hole because of cavings, but had to be stopped at about 40 meters above igneous basement. At about the 120-meter depth, in the second run, an anomalous temperature spike was observed. This is probably the result of "bit heating." A sharp spike is also found on the record of the first run, but it is a single measurement and is probably noise.

Summary of Downhole Temperature Logging at Site 459

All the results of temperature measurements at Site 459 are plotted in Figure 13. In this figure, A–B is the range of temperature at 64.5 meters measured by the Tokyo T-probe penetrating into the sediments. Broken lines indicate the possible extrapolated temperatures at greater depths, assuming constant thermal conductivity.

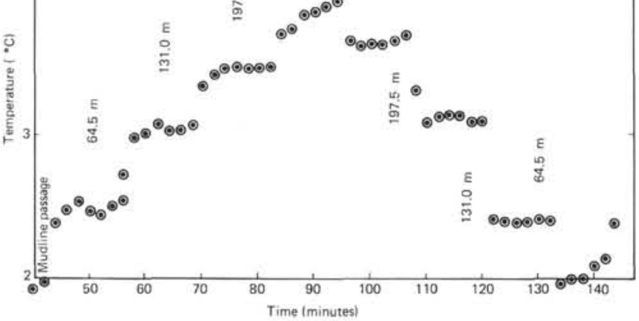

Figure 11. Downhole temperature data at Hole 459B.

As explained above, we feel A is probably closer to the actual temperature. All others are water temperatures measured at various stages of drilling at various times after cessation of disturbance (t_l):

No.	Hole depth (m)	Approximate time of measurement after last disturbance, t_l	Tool
1	131.0	1 hr.	Tokyo T-probe
2	197.0	1 hr.	Tokyo T-probe
3	330.0	50 min.	Tokyo T-probe
4	691.5	2 hrs. 30 min.	G-O T-probe
5	691.5	20 hrs.	G-O T-probe

From these results, it may be possible to conclude:

1) The Tokyo T-probe measurements at the $t_l \sim 1$ hr. are all heavily influenced by disturbance, and correction for the equilibrium temperature seems to be difficult.

2) The Gearhart-Owen T-Log, comprising a continuous record effected at about 20-hr. intervals, indicates a definite thermal recovery in the hole toward the equilibrium temperature.

3) The Gearhart-Owen log, especially the second log, shows more details of temperature-depth (T–d) relationships. For example, down to the depth of the bottom of the pipe in the hole, the effect of pumping (3–5 strokes per minute; 1 stroke = 8 gal./min.) during lowering of the tool is apparent. There is a sharp temperature anomaly at the bit level. There are also four steps in the T–d curve, possibly of some geological significance, at about 130 meters, 180 meters, 300 meters, and 410 meters (these features are more clearly seen in their original records, Fig. 12, a and b).

We have made an attempt to estimate the formation temperature from the GO-log data. When there is a set of downhole temperature data, taken at two different times (t_l and t_2) after cessation of circulation, the temperature at depth, Z may be expressed as (Bullard, 1947; Jaeger, 1961):

$$\begin{aligned} T(t_l) &= T_e + \Delta T \cdot f(t_l, \tau) \\ T(t_2) &= T_e + \Delta T \cdot f(t_2, \tau) \\ \Delta T &= T_o - T_e \text{ (initial disturbance)} \\ \tau &= kt_o/a^2, \end{aligned} \tag{1}$$

where T_e and T_o are, respectively, the equilibrium formation temperature and the temperature of the circulating fluid at the depth Z, and k, t_o and a are, respectively, the thermal diffusivity of the formation, duration of fluid circulation at Z, and the radius of the hole. The decay function f, which depends on the model is,

$$f(t, \tau) = \frac{E_i(-a^2/4k(t_o + t)) - E_i(-a^2/4kt)}{E_i(-a^2/4kt_o)}$$

$$\doteqdot \ln(1 + t_o/\tau)/[\ln(4kt_o/a^2) - 0.577] \quad (2)$$

$$E_i(-x) = -\int_x^\infty e^{-u}/u \, du \text{ (Bullard, 1947)}$$

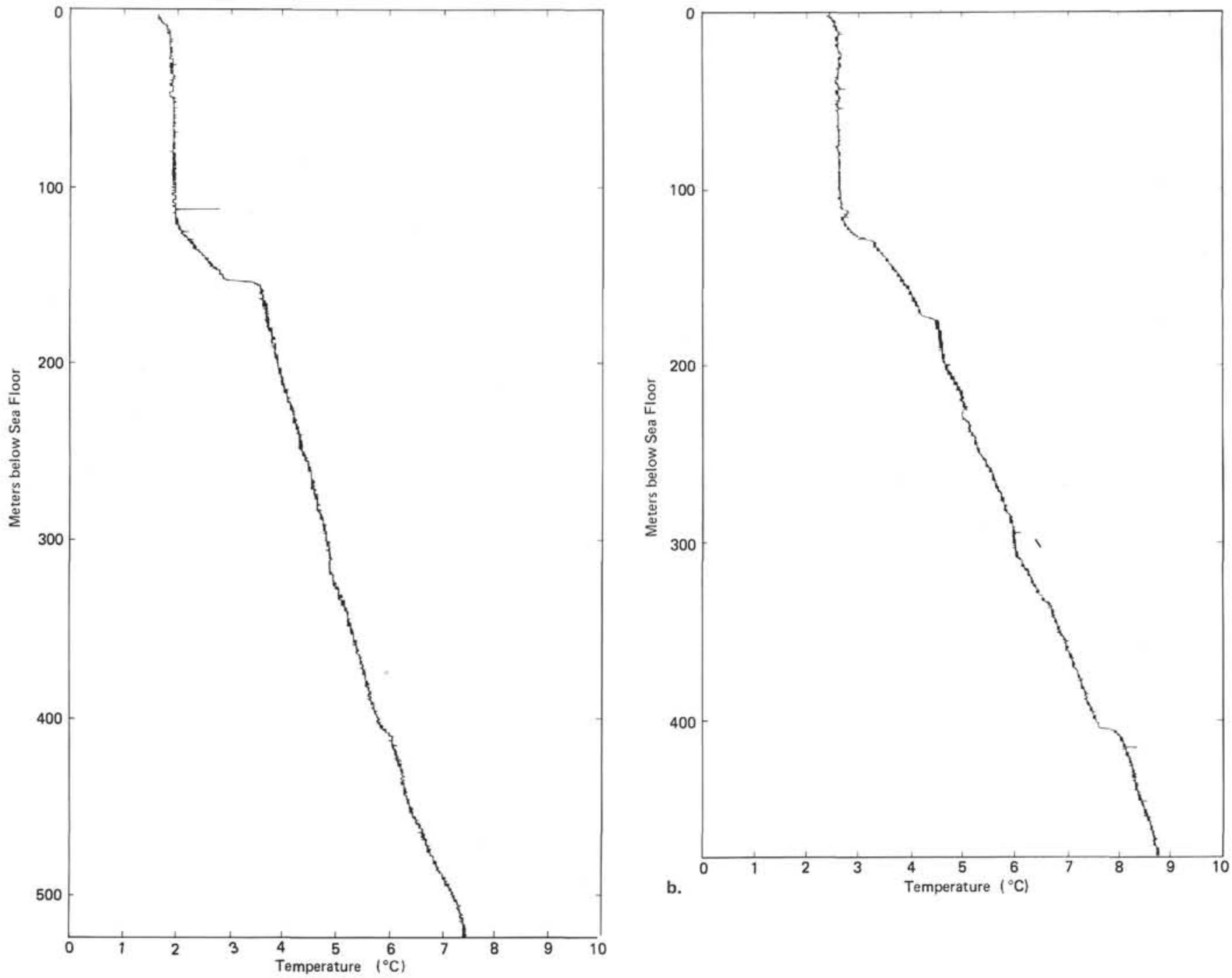

Figure 12. Gearhart-Owen temperature-log data of Hole 459B. (a) First run. (b) Second run.

or

$$f(t, \tau) = \left(1 - e^{-\frac{1}{4n\tau}}\right) + \frac{1}{4n\tau} \int_1^{\infty} e^{-\xi^2/4n\tau} \cdot g(\xi)\, d\xi \tag{3}$$

$$g(\xi) = 1 - \frac{2}{\pi} \int_0^{\infty} e^{-\tau u^2} \frac{C_o(u, \xi u)\, du}{u[J_o^2(u) + Y_o^2(u)]}$$

$$C_o(u, \xi u) = J_o(u)\, Y_o(\xi u) - Y_o(u)\, J_o(\xi u)$$

$n = t/t_o$ (Jaeger, 1961).

J_o and Y_o are the zero-order Bessel functions. From (1), we get

$$T_e = \frac{T(t_1) \cdot f(t_2, \tau) - T(t_2) \cdot f(t_1, \tau)}{f(t_2, \tau) - f(t_1, \tau)}$$

$$\Delta T = \frac{T(t_2) - T(t_1)}{f(t_2, \tau) - f(t_1, \tau)} \,. \tag{4}$$

In the case of log data at Site 459, circulation times t_o are read from the drilling record as the time differences between the drilling at Z and final cessation of circulation when the drill string was raised; Jaeger (1961)'s model (equation 3) was used for $f(t_1, \tau)$. The depths below 200 meters were considered, because the range above 200 meters appears to be disturbed by the presence of the drill string. The formation temperatures estimated at 50-meter intervals are shown by crosses in circles in Figure 13. In view of the large amounts of extrapolation, the results appear to line up fairly consistently with the lower limit of the temperature range extrapolated from the sediment measurement at the 64.5-meter depth. This result provides additional support to the favored lower thermal gradient at this site mentioned previously. From ΔT obtained by (4), the initial temperature was found to be almost indistinguishable from the first log data $T(t_1)$.

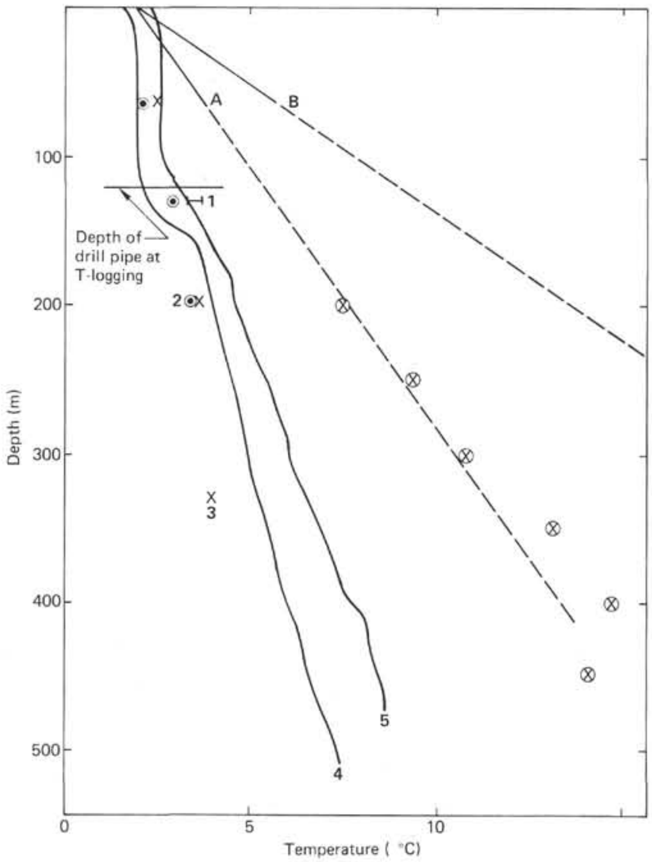

Figure 13. Summary of temperature data in Hole 459B. A, B = possible range of sediment temperature; 1 = bottom water temperature when the hole was 131.0 m deep; 2 (⊙) = water temperature when the hole was 197.5 m deep; 3 (×) = water temperature when hole was 330.5 m deep; 4 = Gearhart-Owen first temperature log; 5 = Gearhart-Owen second temperature log; and ⊗ = estimated true temperature.

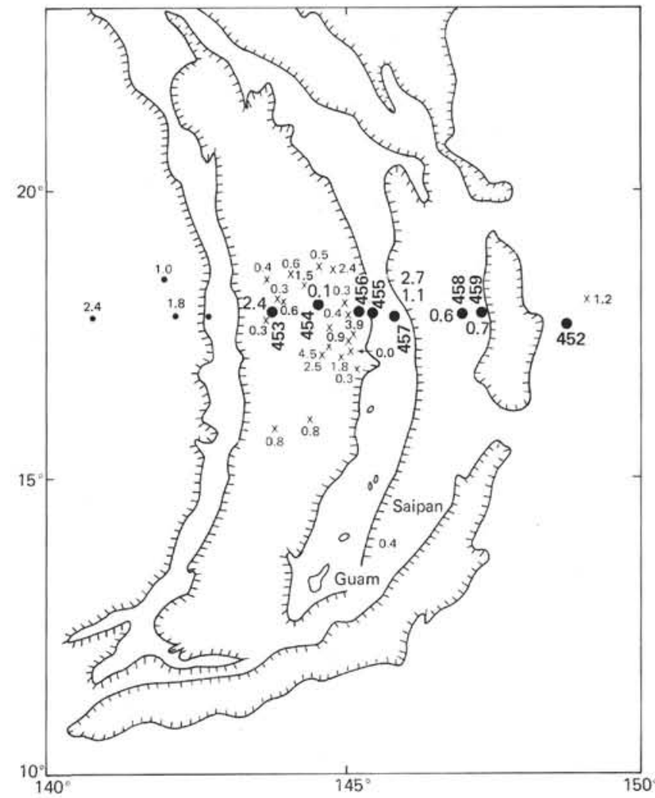

Figure 14. Heat flow in the Mariana area. Leg 60 data are superimposed on Anderson (1975).

SUMMARY

The results of terrestrial heat flow measurements performed on Leg 60 may be summarized as follows:

	Hole	Heat Flow HFU	mWm^{-2}	Remarks
	453	2.40	100	
Mariana	454A	0.06–0.6[a]	2.4–25[a]	Man-made circulation?
Trough	456	2.71	113	Holes 200 meters apart
	456A	1.06	44.4	
Mariana	458	0.6	25	
fore-arc	459B	0.7	30	Support from GO-log data

[a]Based on a subsequent survey by Hobart et al., 1979.

Of these results, only the Site 453 data are considered to be wholly reliable; all others have some doubts associated with them, as explained in the text. However, taking conventional heat flow data of the area (Anderson, 1975), it seems that heat flow in the actively spreading Mariana Trough is locally highly variable, which suggests hydrothermal circulation in the crust (Figs. 14 and 15). Indication of a man-made flow of sea water into crust at Site 454 and the extreme variability of heat flow at Site 456 are evidence for high permeability and hydrothermal activity of the crust respectively at these locations. A detailed geothermal survey conducted after Leg 60 by Hobart et al. (1979) further provided ample evidence for this. In view of the likely importance of hydrothermal activity in ocean crust, a thorough investigation of the area (including geochemical sampling) is most urgently required.

Heat flow in the Mariana fore-arc region seems less variable and below normal, generally supporting the current view on the thermal structures of island-arc regions (Uyeda and Horai, 1964; Hasebe et al., 1971; Anderson et al., 1976).

There are still many problems regarding the methodology of the DSDP measurements of heat flow, in particular the use of the Tokyo T-probe. The temperature versus time relationship in the sediment is often inexplicable. For the sake of the desired ruggedness, the present Tokyo T-probe houses the thermistor in a bulky nose piece that may have a much higher thermal time constant than the thinner Erickson-Von Herzen probe. On the other hand, to lessen the time constant, the thermistor is designed to be exposed to the external water (or sediment) in a complex configuration. Because of these factors, the thermal properties of the sensor of the Tokyo T-probe have so far not been determined. Moreover, the mechanical behavior of the probe in the sediments at the bottom of the hole is largely unknown.

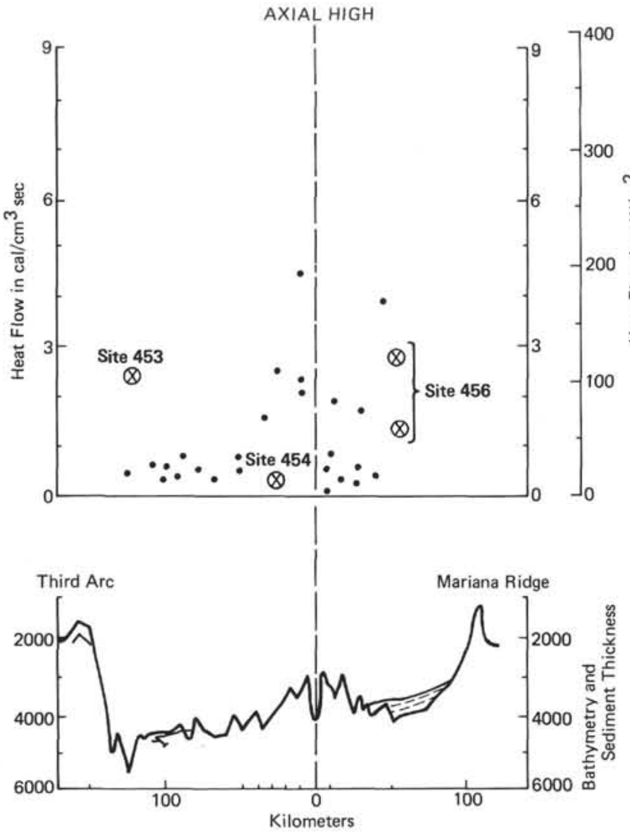

Figure 15. Heat flow versus distance from the axial high of the Mariana Trough. Leg 60 data are superimposed on fig. 6 of Anderson (1975).

There is also the question whether the ship's heave causes any movement of the probe and, if so, does it lead to frictional heating or cooling by introduction of water into the sediment/probe interface.

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