5. TEMPERATURE MEASUREMENTS IN HOLE 395A, LEG 78B[1]

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ABSTRACT

During Leg 78B, we measured borehole temperatures in Hole 395A down to depths of 600 meters below the seafloor, more than five years after the hole had been drilled during Leg 45. Our attempts to measure an equilibrium temperature profile immediately after the initial re-entry were only partly successful, but we were able to obtain an apparent equilibrium profile by extrapolation of a subsequent pair of continuous temperature logs. This profile features an isothermal zone extending from the seafloor to 250 meters sub-bottom, or over 150 meters into basement, indicating a vigorous, pressure-driven downhole flow of bottom water into the upper levels of the basement. This flow probably began when the hole was first drilled through the relatively impermeable, 93-meter-thick sediment cover during Leg 45. We were unable to quantify the rate of flow during Leg 78B, partly because we could not reliably determine the geothermal gradient in the sediments in the adjacent Hole 395B.

In the deepest 100 meters of Hole 395A, the temperature gradient approaches the predicted gradient for conductively cooling, 7.3-Ma-old crust. In combination with the extremely low permeability measured in this zone by Hickman et al. (this volume), this indicates predominantly conductive heat transfer deeper than about 500 meters below the seafloor. Low temperatures above 500 meters suggest shallow, lateral hydrothermal circulation in the permeable upper 300–400 meters of the basement, as modeled by Langseth et al. (this volume).

INTRODUCTION

Temperature measurements were an important part of the downhole measurements program on DSDP Leg 78B. Hole 395A provided a particularly good opportunity for temperature studies because it had been undisturbed during the five years since it was drilled. During Leg 45, the hole was cored to a sub-bottom depth of 664 meters, 571 meters into basement, over the period 9 December 1975 to 10 January 1976, without temperature logging. The five-year interval before Leg 78B was more than ample time for the thermal drilling disturbance to dissipate. An equilibrium geothermal condition should have been reached if the thermal equilibration proceeded by conductive processes only (e.g., Bullard, 1947). Evidence from other ridge flank sites indicates, however, that drilling into basement may result in complicated processes of water movement in the hole. Temperature logs in several holes that penetrate the basaltic crust have indicated a downward flow of ocean bottom water through the hole into apparently underpressured basement (e.g., Holes 335, 396, 454A, 504B; Hyndman et al., 1976, 1977; Erickson and Hyndman, 1979; Uyeda and Horai, 1982; Becker, Langseth, and Von Herzen, 1983; Becker, Langseth, Von Herzen, and Anderson, 1983). If sufficiently fast ($\geq$1–2 m/hr. or $\geq$100 ℓ/hr.), such downhole flow will result in depressed borehole temperatures unrepresentative of the geothermal gradient in the surrounding sediments and basement.

Hole 395A is in a small sediment pond in crust about 7.3 Ma old, on the western flank of the Mid-Atlantic Ridge. The sedimentary and thermal environment is similar to that in the above-mentioned holes where downhole flow has been observed, so our temperature measurements were planned to test whether such flow was active in Hole 395A or whether borehole temperatures reflected conductive heat transfer in the surrounding crust. The sediment cover in the sediment pond is roughly 0–300 meters thick. This range spans the typical value of 100–200 meters generally thought to be sufficient to seal off hydrothermal circulation through the sediment cover (e.g., Sclater et al., 1976; Anderson and Hobart, 1976; Anderson et al., 1977). We assume that the 93 meters of sediment in Hole 395A, and the thicker sediment throughout most of the sediment pond, are relatively impermeable, so that any hydrothermal circulation is largely confined to basement.

With one exception, the eight site-survey heat-flow measurements of Hussong et al. (1979) are tightly clustered about a mean of 37 ± 3 mW/m^2. Three of these measurements were taken close to Site 395 (Fig. 1); the exceptional value of 120 mW/m^2 appears to pertain to thin sediment unrepresentative of the conditions at Site 395. Typical of sediment ponds in young ocean crust, the measured surface heat-flow values are significantly less here than the heat transfer of 175–185 mW/m^2 predicted from cooling-lithospheric-plate models for 7.3-Ma-old crust (e.g., Parsons and Sclater, 1977; Lister, 1977). We attribute this discrepancy to the unmeasured advection of heat to the ocean by hydrothermal circulation through nearby basement outcrops.

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[1] Hyndman, R. D., Salisbury, M. H., et al., *Init. Repts. DSDP*, Vol. 78B: Washington (U.S. Govt. Printing Office).

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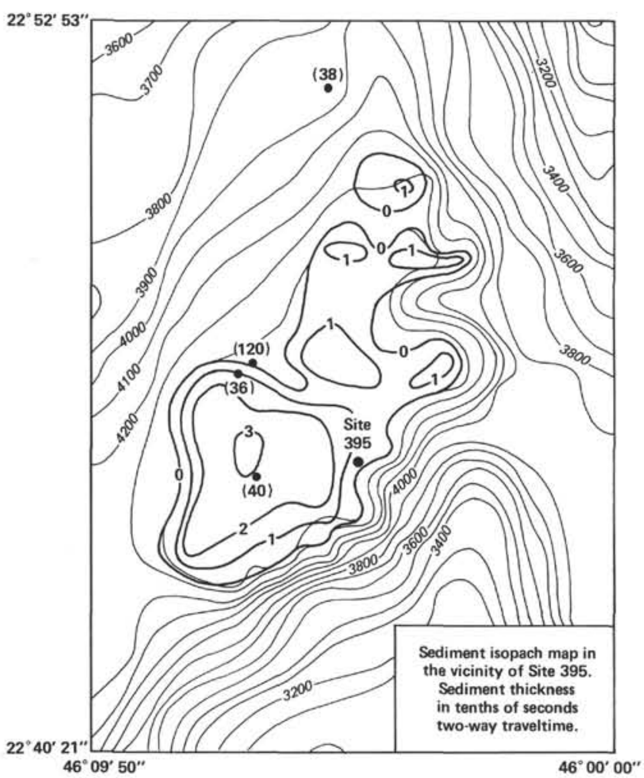

Figure 1. Site-survey surface heat-flow measurements (in parentheses) in the immediate area of Hole 395A. Values in mW/m^2. Bathymetry in meters. Sediment isopachs are shown as heavy contours. Map after Hussong et al. (1979).

Neglecting the exceptional value, the uniformity of the low measured site-survey heat-flow values is somewhat puzzling, considering the large range of sediment thickness within the sediment pond. Hyndman et al. (1976, 1977) observed a similar situation in a sediment pond on 3.5-Ma-old North Atlantic crust drilled during Leg 37. They showed that the uniformly low heat flow could not be a result of thermal refraction or topographic effects. Later in this paper we interpret our downhole temperature data in terms of lateral convection in the upper basement, beneath the relatively impermeable sediment cover. Such processes should, however, produce nearly isothermal temperatures at the sediment/basement contact, resulting in higher heat-flow values where the sediment cover is thinner.

To gain a complete understanding of hydrologic and thermal conditions in the hole and surrounding crust required measurement both of the equilibrium geothermal flux through the sediment near the hole and of undisturbed water temperatures in the hole. The latter required that temperature measurements be made immediately on re-entering the hole, before any disturbance of the thermally equilibrated water column in the hole. We obtained undisturbed borehole temperature measurements over only one 30-meter section of the hole, and no reliable sediment temperatures. Our interpretation of thermal conditions in Hole 395A relies primarily on (1) a pair of temperature logs from a later stage of the measurement program, (2) site-survey heat-flow measurements, and (3) a bottom-hole temperature value obtained from a thermistor in the downhole seismometer deployed at the end of the measurement program (Ballard et al., this volume).

METHODS

Immediately after re-entry, the DSDP downhole temperature probe (T-probe) was used to measure undisturbed temperatures just ahead of the bit as it was eased down the hole. Of the five lowerings with this instrument, only one yielded reliable temperature measurements. During the subsequent logging program, however, two continuous Gearhart-Owen Differential Temperature (GO-DT) logs were run, and these could be roughly extrapolated to yield the undisturbed temperature profile. To determine the essential boundary condition for interpreting temperatures in the hole, that is, the predrilling, equilibrium heat flow through the surrounding sediment, the T-probe was also used to obtain a sediment temperature reading at Hole 395B, offset about 100 meters from Hole 395A. Table 1 summarizes the conditions and data quality for each of these measurements.

The DSDP T-probe is described in detail by Yokota et al. (1980). The sensor housing has subsequently been modified for greater strength and a faster time constant. This device records 128 resistance values of a single thermistor at 1- or 2-min. intervals. It has a precision of 10 ohms, providing a nominal temperature resolution of 0.01–0.02°C. The thermistor is encased in a 1.25-cm-diameter steel tip, with a time constant of about 2 to 3 min., depending on the sediment or water thermal diffusivity. The thermistor had been calibrated several years previously over a 0–50°C temperature span. On the basis of results of

Table 1. Leg 78B temperature measurements in Hole 395A with the Barnes pore-water sampler/DSDP T-probe.

Lowering no.	Time	Depth of temperature measurement (m sub-bottom)	Method of lowering (pump rate, strokes/min.)	Temperature results
HF-1	1300–1512 20 March	29–105	Free fall (5) 3-min. stops every 10 m	No data—recorder reset by spurious pulse
HF-2	1557–1715 20 March	105–219	Free fall (5) 3-min. stops every 10 m	Poor data—thermistor cable damaged
HF-3	1957 20 March– 0620 21 March	2–248	Lower on sandline (No pump) 8 stops	No data—recorder reset by spurious pulse
HF-4	0718–0916 21 March	371–400	Lower on sandline (5) 4 stops	Good data
HF-5	1032–1244 21 March	514–543	Lower on sandline (No pump) 4 stops	Poor data—spurious shifts in digital record
HF-6 (Hole 395B)	0853–1053 26 March	70	Wash to 68 m, lower on sandline	Good record, but probe in disturbed sediments

a shipboard ice-bath calibration, a −0.34°C correction was applied to the recorded temperatures.

As used normally, the probe latches into the bottom-hole assembly, so that it protrudes about 1 meter ahead of the drill bit. It can then be pushed into soft sediments for temperature measurements undisturbed by the drilling process (Erickson et al., 1975), as at Hole 395B. Alternatively, it can be lowered in several steps through the drilled hole, to obtain discrete readings of water temperature at depth; this is how it was used during the first five measurements in Hole 395A. However, because of the possibility of blockages in the re-entered hole, we modified the probe so that it extended only about 25 cm ahead of the bit during the measurements in Hole 395A. Depth control was accurately determined from total drill-string length below the ship.

For the first two of the five T-probe lowerings, the instrument was allowed to fall free down the pipe to the bit. Since the instrument suffered some mechanical damage on deceleration when landing in the bit, the last three lowerings were made on a wire. Although this is a safer method, the measurement interval is then limited to about 30 meters, the length of pipe that can be drawn up into the derrick beforehand. In addition, with this technique the tool must be pumped down the pipe to avoid tangling the wire; the pumping may produce a thermal disturbance in the hole some distance ahead of the bit.

The GO-DT logging tool also uses a calibrated resistance element. It is encased in a smaller probe than the DSDP T-probe, so its time constant (<1 min.) is considerably faster. The GO-DT tool is slowly lowered on a logging cable while the temperature is continuously recorded. The delay in the response of the GO-DT probe introduces a bias error in recorded hole temperatures, but the effect is small (<0.05°C) at slow winch speeds, so we have not applied any correction. All the data reported here were obtained on downgoing logging runs. Depth measurement was provided by the logging winch counter, which was checked using hole-bottom depth readings, giving an estimated accuracy of about ±5 meters.

MEASUREMENT RESULTS

DSDP T-probe

The T-probe recorder worked properly only during the fourth of five lowerings. The first and third lowerings yielded no data, because the solid state memories were erased, probably a result of a shorting contact between the two main circuit boards. During the second lowering the wire to the thermistor was abraded, and a significant seawater shunting resistance of about 60 kΩ developed across the thermistor, so accurate temperatures were not obtained. Nevertheless, the data indicated that the temperature was nearly constant over the interval measured, 103–217 meters sub-bottom. This conclusion was later verified by the two GO-DT logs.

The fourth lowering (see Figs. 2 and 3) yielded temperatures at four levels in the interval 369–398 meters sub-bottom; of these the maximum and deepest temperature reading was 7.24°C. The gradient indicated over this interval extrapolates to the bottom-water temperature at a depth well below the seafloor, suggesting that there is a rather rapid increase in the gradient deep in the hole. This feature of the profile was later verified by the continuous temperature log run in the hole.

The fifth lowering yielded a record with large, spurious step increases in apparent temperature, and no reliable temperature record was obtained.

Gearhart-Owen Differential Temperature Logs

Two GO-DT logs were run, one at 1800 hours on 21 March and the second 39 hours later at 0900 hours on 23 March, after the other logging operations were completed. A temperature correction of −0.44°C was applied to the data, based on an ice-bath calibration before the second log. The corrected logs are shown in Figure 3.

In the upper 250–275 meters of the hole, the temperature is nearly constant and equal to the bottom-water

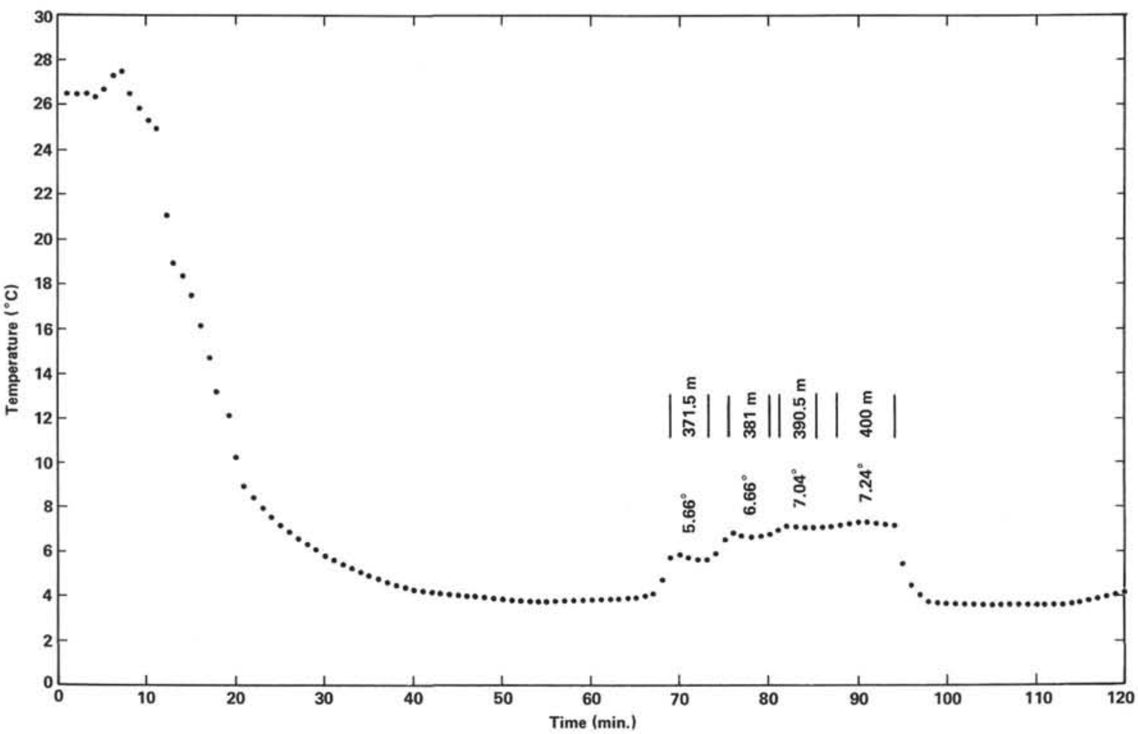

Figure 2. Temperature-vs.-time record for the fourth lowering of the T-probe.

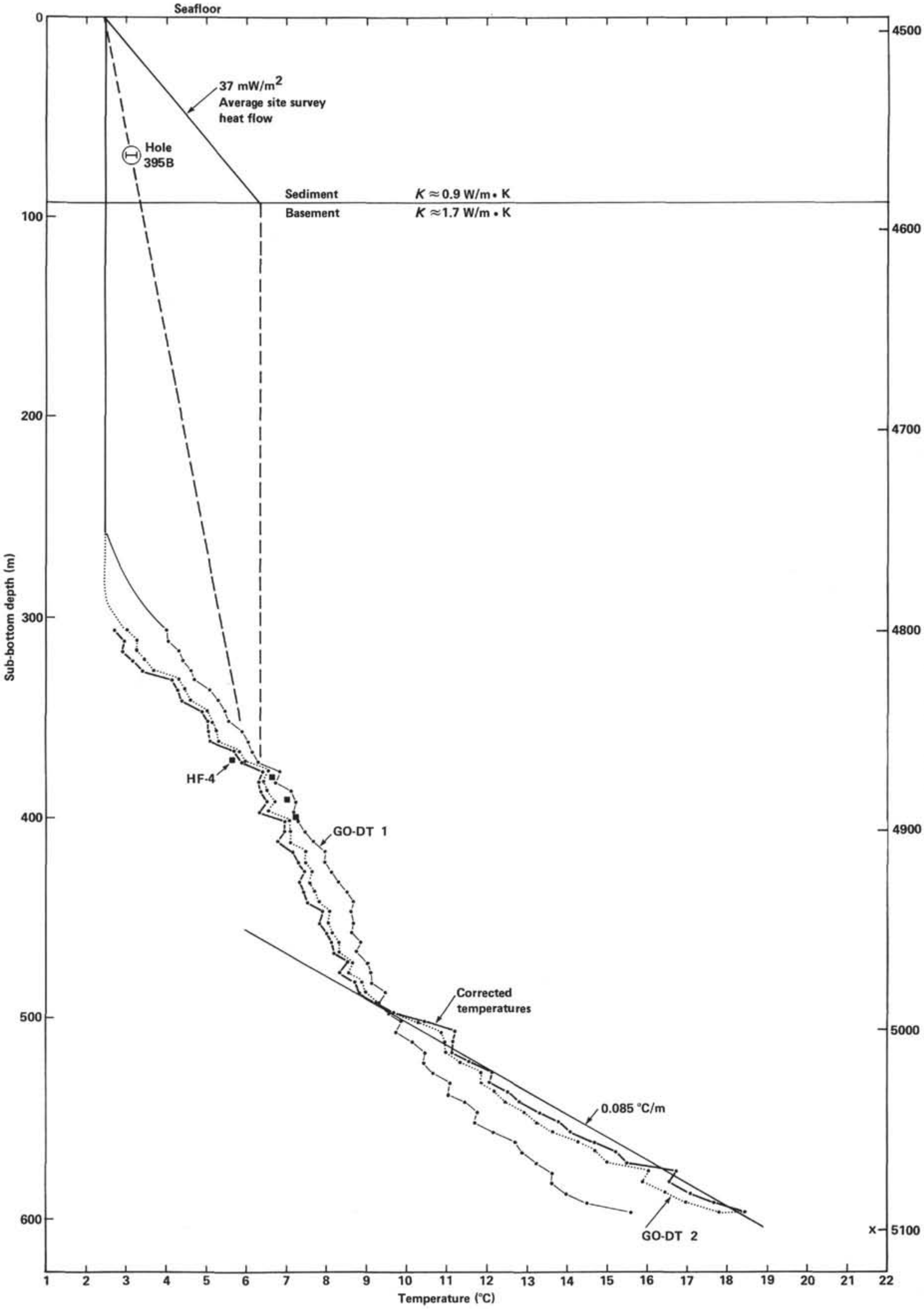

Figure 3. Borehole temperatures measured in Hole 395A during Leg 78B using the T-probe (■), continuous temperature logs (●), and a temperature sensor in the borehole seismometer (×). The continuous temperature logs were extrapolated to apparent equilibrium temperatures using the $F(\alpha,\tau)$ method of Bullard (1954) shown in Figure 4. Dashed lines represent possible temperature profiles in the upper part of the section prior to drilling.

temperature. Between 275 and 495 meters sub-bottom, the measured temperatures increase with depth at a relatively uniform rate (0.03–0.04°C/m). Over this zone, the second log showed temperatures 0.6–1.0°C lower than the first. Deeper than 495 meters, however, the second run shows a considerably steeper gradient and higher temperatures. At a depth of 600 meters, temperatures measured on both logs increase abruptly to a value of about 22°C. We speculate that this may have resulted from penetration by the thermistor of a thin, insulating layer of mud overlying a blockage in the hole.

The temperature differences between the two GO-DT logs were larger than expected, considering that every attempt was made to minimize the disturbance to downhole temperatures during the re-entry and logging operations on Leg 78B. We expected that the greatest disturbance to the temperature should come from periods of slow circulation required during tool lowering. Nevertheless, the two GO-DT logs differ in three important respects (Fig. 3): (1) the isothermal (bottom-water temperature) zone extended 30–40 meters deeper during the second log; (2) below this level to about 495 meters sub-bottom, the second log recorded lower temperatures; (3) deeper than 495 meters the second log recorded higher temperatures. These effects could have been caused by some combination of pumping before and/or between the GO-DT logs. Before we ran the logs, the pipe had been run down to the bottom of the hole and then back up into the casing. During the logging program the logging tools were pumped down only to the bottom of the pipe, which was held within the casing. We reasoned, therefore, that the major thermal disturbance to the water within the borehole occurred before the GO-DT logs were run, and we interpreted these logs neglecting any possible disturbance during the time interval between them.

From the sense of the temperature change between the two GO-DT logs—temperatures decreasing with time between 275 and 495 meters sub-bottom, and increasing with time deeper than 495 meters—we reasoned that the prior disturbance to the hole might have been a relatively quick overturn of the water column in the hole. Since the deeper part of the formation is exceptionally impermeable (Hickman et al., this volume), we assumed that such a disturbance occurred when the pipe was run down to the bottom of the hole, displacing warmer water upward. We modeled this disturbance as an instantaneous temperature change, and applied Bullard's (1954) $F(\alpha,\tau)$ theory to correct the measured temperatures to undisturbed values. This is the standard theory that describes the temperature decay, $T(t)$, measured by an oceanic heat-flow probe, as the temperature returns to the original formation temperature, T_o, after an instantaneous temperature change, ΔT, caused by frictional heating on penetration:

$$T(t) - T_o = \Delta T F(\alpha,\tau)$$

where

$$F(\alpha,\tau) = \frac{4\alpha}{\pi^2} \int_0^\infty \frac{du\, e^{-u^2\tau}}{u\left\{[uJ_0(u) - \alpha J_1(u)]^2 + [uY_0(u) - \alpha Y_1(u)]^2\right\}}$$

and where u is the variable of integration, and J_0, J_1, Y_0 and Y_1 are Bessel functions of the first and second kind.

In this case, the parameter α is defined as twice the ratio of the heat capacity of the borehole seawater to that of the surrounding crust. Using values for crustal properties from Hyndman et al. (this volume), we find $\alpha \approx 1.25$ for a hole in basaltic crust, compared with the typical value of ≈ 2 for heat-flow probes in sediment. The time constant $\tau \equiv \kappa t/a^2$, where κ is the thermal diffusivity of the crust (about 0.65 mm²/s), a is the radius of the borehole (14–20 cm; Mathews et al., this volume), and t is the time since the disturbance. A plot of $F(1.25,\tau)$ is given in Figure 4.

The time of the disturbance to Hole 395A was taken to be the time of the last pumping while releasing the bit, when the pipe had been run to the bottom of the hole. The temperatures in the bottom 300 meters of the hole were logged about 5 and 42 hours later, or about 0.5 and 5 hole time-constants later. After 5 time constants, the temperature disturbance should have decayed considerably (Fig. 4), and the extrapolated equilibrium temperatures were quite close to those measured during the second temperature log (Fig. 3).

Sediment Temperature Measurement at Offset Hole 395B

One sediment temperature measurement was attempted at a sub-bottom depth of 70 meters in Hole 395B, about 100 meters northwest of Hole 395A. The T-probe was held for 5 min. at the seafloor, and then lowered into the sediments at the bottom of the hole, where it was left for 23 min. The temperature recorder performed well, but the soft sediments apparently did not support the bottom-hole assembly well, and disturbed temperature measurements were obtained (Fig. 5). Within 3 min. of penetration, the temperature record shows a large spike, which rises 6°C and then rapidly falls to 1–2°C above the bottom-water temperature. The remainder of the record to minute 80 appears to be made up of short pulses followed by a minute or two of decay, with an average

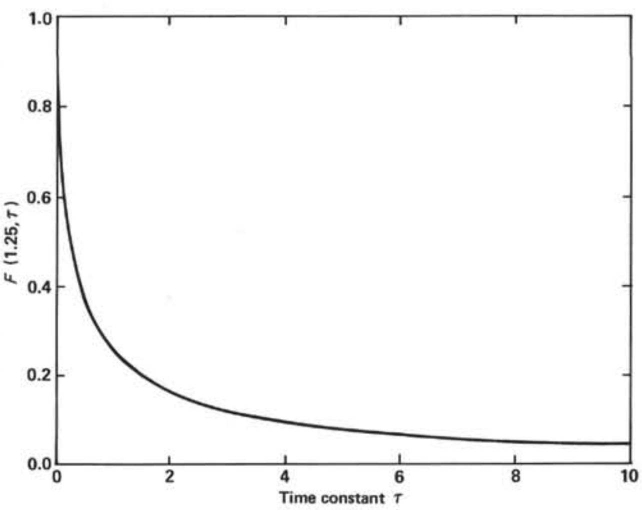

Figure 4. Bullard's (1954) $F(\alpha,\tau)$ function for conditions appropriate to a seawater-filled borehole in basaltic crust, where $\alpha \approx 1.25$.

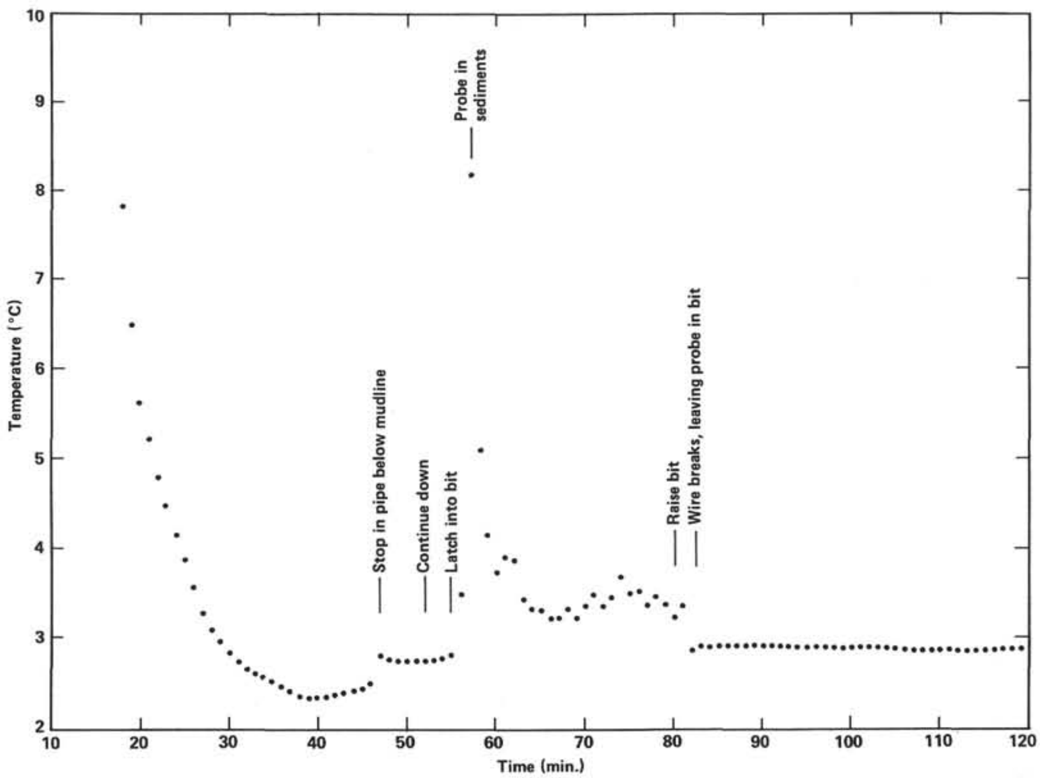

Figure 5. Temperature-vs.-time record for T-probe measurement 70 meters into the sediments in Hole 395B.

temperature of about 3.25°C, about 0.7°C above the bottom-water temperature. Settling of the bit and probe at short intervals over the 24-min. measurement period is suggested by the temperature spikes and by the shipboard bit-load record. It seems likely that some bottom water was mixed with the sediment to produce a cooler slurry unrepresentative of *in situ* temperatures. A plot of measured temperatures against the appropriate decay function—Bullard's (1954) $F(2,\tau)$—confirms this and indicates that a valid formation temperature probably cannot be obtained (Fig. 6). The average measured temperature of approximately 3.25°C might be interpreted, however, to be an uncertain lower bound on the *in situ* temperature.

Downhole-Seismometer Temperature Record

Further information about the equilibrium temperature at the bottom of Hole 395A was provided by the DARPA downhole seismometer, which contained a thermistor thermally coupled to the pressure case (a 20-cm-OD steel cylinder with 2.5-cm-thick walls). Over a two-day period, a steady increase in temperature was recorded. Figure 7 shows the temperature history at the bottom of the hole plotted against the reciprocal of time (long-time assymptote of $F[\alpha, \tau]$ function) from the last time water was vigorously circulated down the hole. After a few time constants of the instrument case, the points plot as a fairly straight line with an intercept of 21.7°C, which provides an estimate of the equilibrium hole-bottom temperature.

This estimated equilibrium temperature is in excellent agreement with that recorded by the logging tool at the bottom of the hole. Thus, the seismometer thermistor provides supporting evidence that a temperature of 22°C existed 600 meters sub-bottom before our first re-entry.

DISCUSSION

Partial constraints for models of the thermal and hydrologic conditions in Hole 395A and the surrounding crust were provided by three successful data sources: (1) re-entry temperatures measured over a single 30-meter interval before any disturbance to the hole; (2) two complete temperature logs run after the hole had been disturbed by limited circulation; and (3) the bottom-hole temperature record for a 40-hour period at the end of the downhole measurement program. It is clear that the temperatures in the hole have been strongly influenced by the flow of water downhole during the five years since the hole was drilled, and that pumping during the Leg 78B operations further altered the temperatures.

Thermal and Hydrologic Regime Prior to Re-entry

The clearest evidence for downhole flow comes from the two GO-DT logs, both of which show temperatures that are uniform and equal to the bottom-water temperature to a depth of about 250 meters below the seafloor (Fig. 3). These uniform temperatures can only be maintained by a strong flow of water down the hole, particularly in the cased section through the relatively impermeable sediments. On the basis of a model described by Becker, Langseth, and Von Herzen (1983), we estimate that a volume flux of at least 1000 ℓ/hr. (a linear rate of 10–20 m/hr.) is required to maintain isothermal condi-

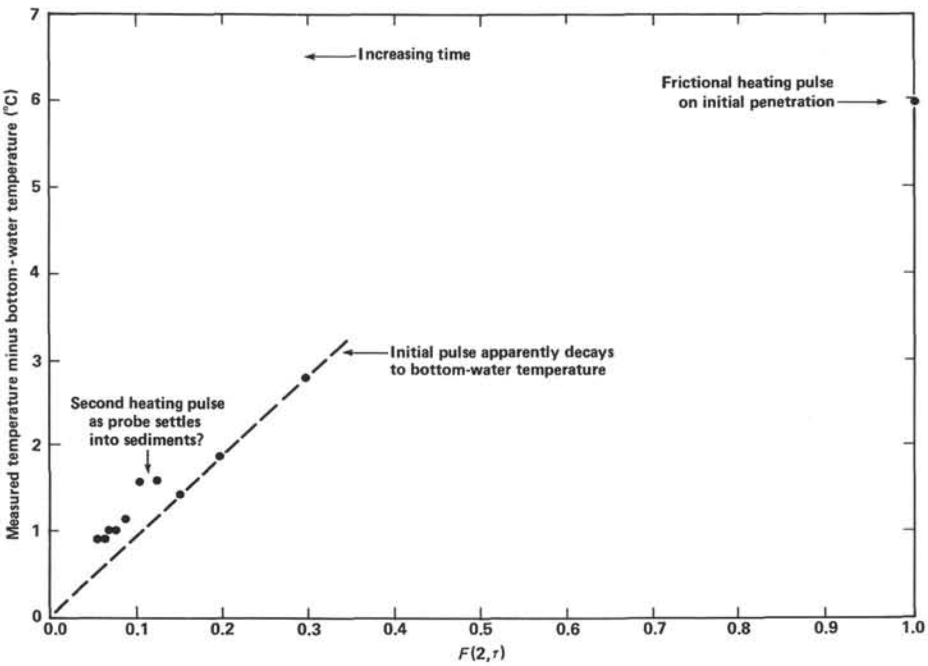

Figure 6. Hole 395B temperatures plotted against Bullard's (1954) $F(\alpha,\tau)$ function, with $\alpha = 2$, $\kappa \equiv 0.25\ mm^2/s$. The initial frictional heating pulse on penetration appears to extrapolate to the bottom-water temperature, suggesting mixing of bottom water around the probe.

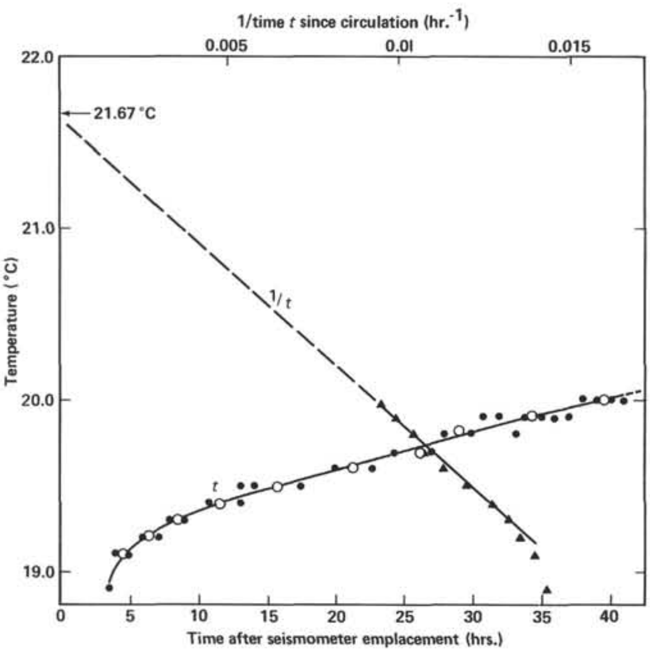

Figure 7. Temperatures measured by the thermistor in the DARPA seismometer, which was emplaced 609 meters below the seafloor. Temperatures are plotted against two time axes: time after emplacement of seismometer, shown as solid and open circles, and the inverse of time since the last circulation disturbance in the hole, shown as triangles.

tions. We believe that this flow began at the time the hole was drilled and has continued for at least five years.

A more precise estimate of the downhole flow rate would require both an accurate value for the geothermal gradient in the sediments and a measurable temperature increase with depth through the casing, where the flow rate must remain uniform with depth. Since we did not reliably determine the heat flow, and since no temperature increase was observed to the bottom of the casing, we can only assert that an exceptionally vigorous downhole flow exists in Hole 395A.

The uniformity of temperatures to about 250 meters sub-bottom (about 150 m into basement) indicates that the downward flow continues at a high rate to this depth. It is possible, nevertheless, that a significant fraction of the downhole mass flux could be lost into the formation over this interval, without allowing a noticeable rebound of temperatures from isothermal conditions. Below 250 meters sub-bottom, the temperatures increase slowly with depth. This requires that the downward flow significantly decrease with depth, by percolation into the permeable formation. A similar phenomenon was observed in Hole 504B on the Costa Rica Rift, but there the water appears to exit into the basement over a more restricted section of the hole (about 100 m), and the change in the gradient of measured temperatures is much sharper (Becker, Langseth, and Von Herzen, 1983; Becker, Langseth, Von Herzen, and Anderson, 1983). As at Hole 504B, the downhole flow in Hole 395A is driven by underpressure of the basement pore fluids (Anderson and Zoback, 1982; Hickman et al., this volume) and not caused by thermal buoyancy convection.

Thermal and Hydrologic Regime in the Crust before Drilling of Hole 395A

Our extrapolation of the GO-DT logs appears to indicate three distinct temperature zones in Hole 395A before the Leg 78B re-entry: (1) an isothermal zone through the casing and about 150 meters into basement; (2) from

250 to 495 meters sub-bottom, a zone with a fairly uniform but small gradient, partly disturbed in the zone of recovery from the downhole flow; and (3) from 495 to 600 meters sub-bottom, a zone with a larger, nearly linear gradient. In the deepest section, a linear regression through the extrapolated temperatures yields a minimum gradient of 0.085°C/m. The predicted plate heat flow of 175–185 mW/m² (Lister, 1977; Parsons and Sclater, 1977) would produce a gradient of 0.10–0.11°C/m, assuming an *in situ* thermal conductivity of 1.7 W/m·K. The pattern of the extrapolated temperatures—gradient increasing with depth—and the high temperature of 22°C measured at 600 meters sub-bottom suggest that the gradient in the deep section approaches the theoretical value. We therefore interpret our measurements to indicate that the heat flow in the crust deeper than 500–600 meters was predominantly conductive, at approximately the predicted cooling-plate value. This is consistent with the permeability measurements of Hickman et al. (this volume), which indicate that the deepest section penetrated by Hole 395A is effectively impermeable to hydrothermal circulation.

Shallower than 500 meters sub-bottom, the gradient significantly decreases. We cannot determine from the temperature measurements to what extent this may have been caused by the downhole flow, which has been active since the hole was drilled. A gradient at the predicted value, which intersects 22°C at 600 meters sub-bottom, would extrapolate, however, to well below the bottom-water temperature at the seafloor, suggesting significant advective heat transfer and hydrothermal circulation in the basement shallower than 500 meters. This would be consistent with the apparent indications—from both our poorly determined Hole 395B sediment temperature and site-survey heat-flow measurements—of heat flow lower than the predicted value through the sediments. Hydrothermal circulation in the uppermost crust is also strongly indicated by the $\delta^{18}O$ calcite equilibration temperature data for samples from Holes 395 and 395A (Lawrence et al., 1979). These data, like our temperature measurements, indicate that the basement is nearly isothermal, with a temperature of approximately 6°C to about 300 meters into basement, below which the temperature increases sharply to about 20°C.

Our preferred model of heat transfer at Site 395 requires a vigorous, but fairly shallow, lateral hydrothermal circulation (Fig. 8). This model is similar to that proposed by Hyndman et al. (1976, 1977), except that the circulation is confined to the upper part of the basaltic layer. A more detailed, mathematically tractable model is presented by Langseth et al. (this volume). The heat transfer before the drilling of Hole 395A was con-

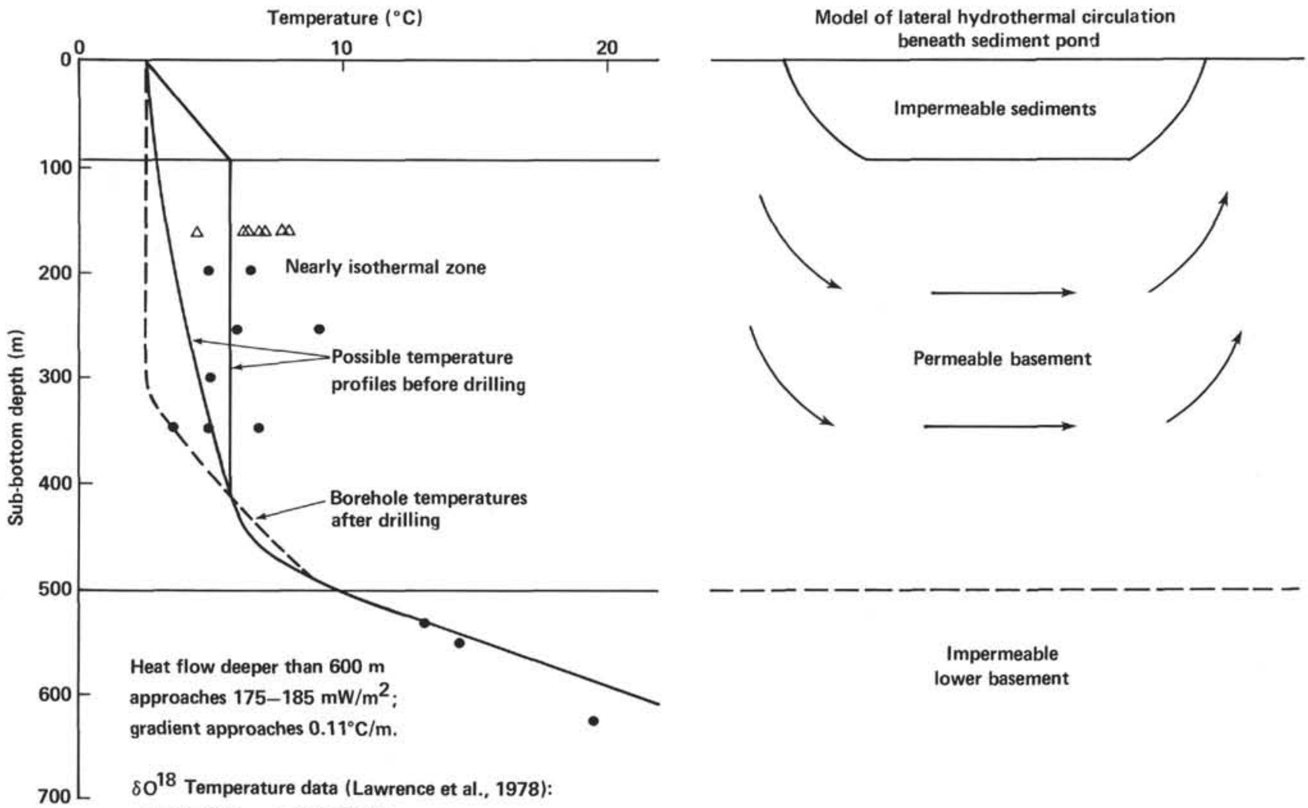

Figure 8. Preferred model of heat and mass transfer at Site 395. See also the model of Langseth et al. (this volume). The temperature data do not constrain the temperature profile in the cool upper section of the basement. Two possible predrilling profiles are sketched, based on two possibilities for heat flow in the sediments: the average site-survey value, 37 mW/m², or a tenuous value of about 10 mW/m², assuming a minimum temperature of about 3.25°C at 70 meters sub-bottom in Hole 395B. The solid circles and open triangles give the δO^{18} data from Lawrence et al. (1978) using the glacial reference (see McDuff, this volume).

trolled by a stratification of permeability: a relatively impermeable sediment cover about 100 meters thick overlies 300–400 meters of permeable basement, which is underlain by impermeable basalt. Hydrothermal circulation is effectively limited to the permeable upper basement, and must involve a strong lateral component of heat transfer beneath the sediment pond. The directions and rates of such hydrothermal circulation cannot be determined from available data, but the circulation is probably controlled by nearby basement exposures surrounding the sediment pond. In the impermeable basement beneath the zone of circulation, a conductive gradient reflects the predicted heat transfer. The depressed seafloor intercept of this gradient indicates long-term (on the order of 10^5 y.?) re-equilibration to nearly isothermal conditions in the circulation layer in the upper crust. Thus, a nearly steady-state circulation system probably existed in the upper part of the basement, keeping temperatures there below 10°C. The low and nearly constant temperature gradient in the sediment pond indicated by the site survey heat-flow data and the borehole data reflects the imposition of two nearly isothermal boundary conditions: the bottom-water temperature at the mudline, and a temperature of 4–10°C in a near-horizontal horizon just below or at the sediment/basement contact. The latter condition is controlled by the circulation; thus, the low heat flow through the sediment reflects only a small proportion of the theoretical plate heat flow.

A very important result of the Leg 78B experiments is the apparently shallow extent (300–400 m) into basement of the hydrothermal circulation at Site 395. This deduction is supported by our temperature measurements, the permeability tests of Hickman et al. (this volume), and the logging results (particularly electrical resistivity) of Mathews et al. (this volume). In a similar manner, a shallow depth of circulation is indicated in Hole 504B, where the best-documented case of downhole flow exists (Anderson and Zoback, 1982; Anderson et al., 1982; Becker et al., 1982; Becker, Langseth, and Von Herzen, 1983; Becker, Langseth, Von Herzen, and Anderson, 1983). A distinction should be drawn between the two types of water movement at these holes: hydrothermal circulation in the crust, and pressure-driven flow of bottom water downhole and into the upper crust. Whereas both types of water movement apparently occur at Site 395 (and Site 335; Hyndman et al., 1976, 1977), the downhole flow in Hole 504B is apparently superimposed on a predominantly conductive heat transfer mechanism. This may be a direct consequence of the large lateral extent of the 250–300-meters-thick sediment seal at Site 504.

Despite the difference between the predominant mechanisms of heat transfer, Holes 395A and 504B share the feature of pressure-driven downhole water flow directed into the upper levels of the basement. But whereas the flow down Hole 504B decayed during three years to only about 2% of its original rate of 6–7 kl/hr. (Becker, Langseth, and Von Herzen, 1983; Becker, Langseth, Von Herzen, and Anderson, 1983), the flow down Hole 395A has remained vigorous for at least five years. Becker and colleagues (references just cited) argued that a sediment layer 200–300 meters thick is a poor seal against diffusion of pressure differentials, so that a continuous, nontectonic process is probably required to explain the basement underpressures. If we speculate that the driving underpressures of basement pore fluids are related to the pressure differentials that may arise in a hydrothermal circulation system, it would then follow that the strongly decaying downhole flow in Hole 504B might be related to a weak convection system in the predominantly sealed young crust of the Costa Rica Rift. Conversely, the vigorous downhole flow in Hole 395A might be related to an extensive circulation system (such as that modeled by Langseth et al., this volume) in the incompletely sealed young crust extending under the Site 395 sediment pond.

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