15. THERMAL MEASUREMENTS AND SEAWATER DOWNFLOW INTO 35-Ma-OLD OCEAN CRUST, CENTRAL NORTH ATLANTIC[1]

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ABSTRACT

Measurements of temperature gradients in sediments, thermal conductivity and drill-hole temperatures (by wireline logging) were made in three holes drilled into basement in 35-Ma-old crust in the central North Atlantic during DSDP Leg 82. The temperature gradient and thermal conductivity values make a reliable estimate of the ambient heat flow value possible. Downhole temperatures measured by wireline logging after drilling indicate cooling of the hole in excess of that expected from the drilling process. This excess cooling effect is interpreted as a result of a substantial downflow of ocean water; a lower limit to the necessary volume of flow is derived from the data.

If the downflow is a secondary effect of hydrothermal circulation within oceanic crust, these data support the increasing body of evidence that hydrothermal circulation continues within ocean crust to considerable ages covered by a blanket of sediment allowing only conductive heat flow.

INTRODUCTION

DSDP Leg 82 was designed to drill a grid of holes along isochrons and flow lines from the Mid-Atlantic Ridge crest to the southwest of the Azores Triple Junction and to locate geochemical anomalies in the igneous rocks recovered. The holes actually drilled (Fig. 1) all lie on the western flank of the ridge. Although the objective was to find relationships with the Azores hot spot, all holes are sufficiently distant from this feature so that its thermal anomaly was not detectable in the elevation of the ocean crust. The sites were not surveyed in detail before Leg 82 but all underway profiling and bathymetry (Cande et al., this volume) show that the thermal evolution of the ocean crust has followed the expected age-depth relationship (Parsons and Sclater, 1977). In a regional context it is reasonable to view thermal measurements from this area as representative of crust produced from a slow-spreading ridge free from major subcrustal thermal perturbations.

Deep penetration into volcanic basement was only achieved at three sites (556, 558, and 564). These were all drilled within the width of Magnetic Reversal Anomaly 13 or in troughs to either side of it, indicating an age range of 35 ± 2 Ma. Palaeontologic dates from recovered sediments are compatible with this age range. Given the similar ages, the thermal evolution of ocean crust at these three sites should be very closely comparable. At each site the location was chosen to avoid basement topographic highs, and depths to basement are quite consistent. Also, at each site, the basement was overlain by between 280 and 460 m. of calcareous pelagic ooze and chalk (Fig. 2). Physical property measurements of the sediments show little significant variation between sites (Hill and Cande, this volume).

Over recent years the importance of hydrothermal circulation of seawater as a heat-transfer mechanism in young ocean crust has been well demonstrated (e.g., Fyfe and Lonsdale, 1981; Hyndman et al., 1977; Becker et al., 1983). As the crust becomes older, the effectiveness of such hydrothermal circulation may be reduced by two different processes. Firstly, the convective pathways within the volcanic crust may become restricted or blocked by such processes as growth of authigenic minerals or physical compression by increasing hydrostatic load. Secondly, the convective regime is blanketed by a layer of effectively impermeable sediment that allows only conductive heat transfer to the ocean water. When the sediment blanket becomes several hundred meters thick, surface heat flow measurements do not clearly resolve the effects of any hydrothermal circulation within the ocean layer. Hence, the age to which such circulation can persist is poorly known. The data discussed below allow some indirect inferences to be made concerning this question.

THERMAL MEASUREMENTS

A determination of the ambient geothermal gradient and heat flow was only made at Site 556. A temperature probe protruding ahead of the drill bit was used here to measure temperatures of undisturbed sediments at the mudline and at three depths well distributed in the 460 m sedimentary column. Measurements were made with the DSDP digital thermal instrument and are described in detail elsewhere (Site 556 report, this volume). Figure 3 shows a typical data record from these measurements, and Figure 4A shows the linearity of the thermal gradient determined, with a value of 0.036°C/m. Coring of the sediment was not carried out at Site 556, but was performed at Sites 558 and 563. Comparison of wireline logging data between Sites 558 and 556 reveals little dif-

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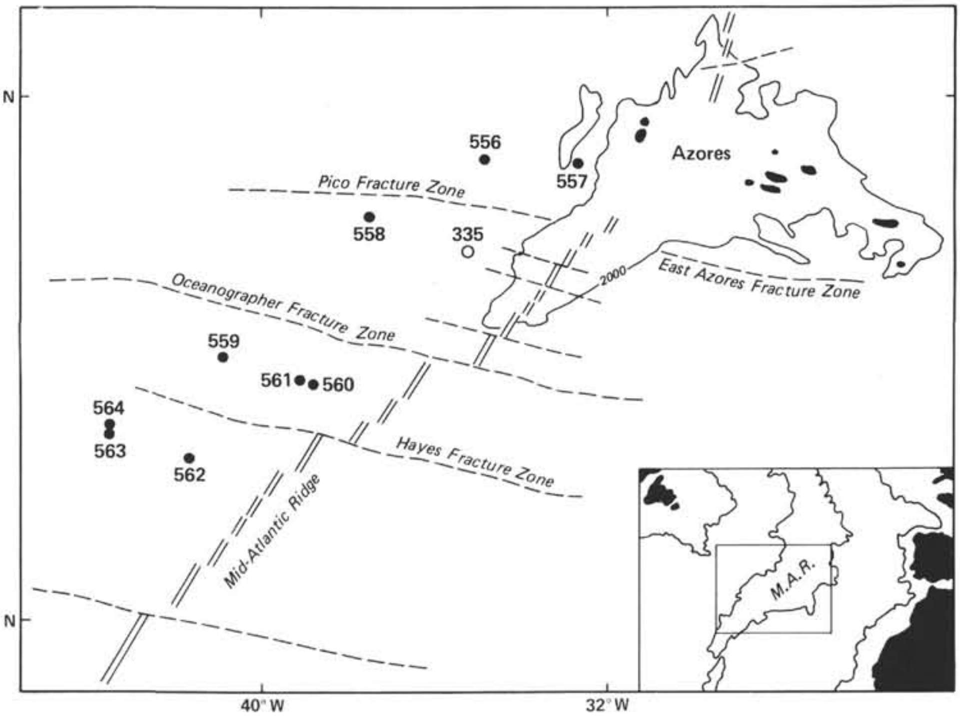

Figure 1. Location of DSDP Leg 82 drill holes.

ference in physical properties, with very good correlation between even fine details of the log curves (Hill and Cande, this volume). This correlation, the geographical proximity, and the similar depositional environments justify the use of thermal conductivity values measured at Site 558 to derive a heat flow value for Site 556. This leads to a value of 45 mW/m^2 with a likely error of ±10% deriving mainly from the errors in determination of thermal conductivity values (Site 558 report, this volume).

The remaining thermal measurements were made as part of the downhole logging program after drilling had been completed. We used the standard Schlumberger High Resolution Thermister probe (HRT), a small-diameter tool normally used in the oil industry for logging cased holes. During Leg 82, this tool was modified to improve its ease of use in uncased holes with poor sidewall stability (typical of DSDP conditions) by mounting it inside a modified core barrel (Site 564 report, this volume). This increased the tool weight and protected the thermister probe from a mud coating, which considerably affects the time constant of the probe. These modifications were purely mechanical and did not affect the accuracy or precision of the tool. The precision is better than 0.01°C but absolute calibration was considerably poorer. The thermister was recalibrated during the cruise against mercury in glass thermometers at 0 and about 20°C, and the calibration derived was used throughout Leg 82. The calibration of the DSDP probe was believed reliable but was similarly checked at 0°C and found to be accurate. The only direct comparison of the data from both instruments is the mudline temperature determined by both at Site 556. Although these determinations were separated by a time interval of about 150 hours, it is likely that the bottom water would remain at constant temperature over this period. Comparison of Figures 3 and 4A shows the mudline temperatures to be 2.1 and 2.4°C, respectively. From these data it is concluded that the accuracy of the HRT is on the order of ±0.5°C, although there is no reason to dispute the specification sensitivity of 0.01°C. The difference in bottom water temperatures at Sites 556, 558, and 564 is shown in Figure 4. The variation between 2.1°C at Site 556 and 0.5°C at Sites 558 and 564 is regarded as outside the measurement error, but its cause is uncertain. It is probably not related to any drilling circulation effects because it was first measured after only a few hours of drilling disturbance, when penetration was only about 100 m.

During drilling, the hole is flushed with seawater pumped down the drill string from the surface to the bit, then vented from the hole at the sea bed. The water cools to within a degree or so of bottom water temperature as it travels down the drill string. Thus the hole is flushed and cooled by water at the temperature of ocean bottom water. Once drilling and the associated water circulation have finished and in the absence of other complicating factors, the hole will begin to reequilibrate with the preexisting geothermal gradient. Because measurements with the HRT took place at intervals on the order of one day after circulation ceased, the temperature in the holes will still be reequilibrating.

Figure 4 shows that none of the measurements show a temperature gradient similar to the undisturbed one measured in Hole 556. Indeed the thermal gradients are all very low. Hole 556 shows constant temperature with depth to 360 m sub-bottom. Below this, the temperature rises slightly until just below the basement interface where there is a sharp rise of temperature of 2°C. It would

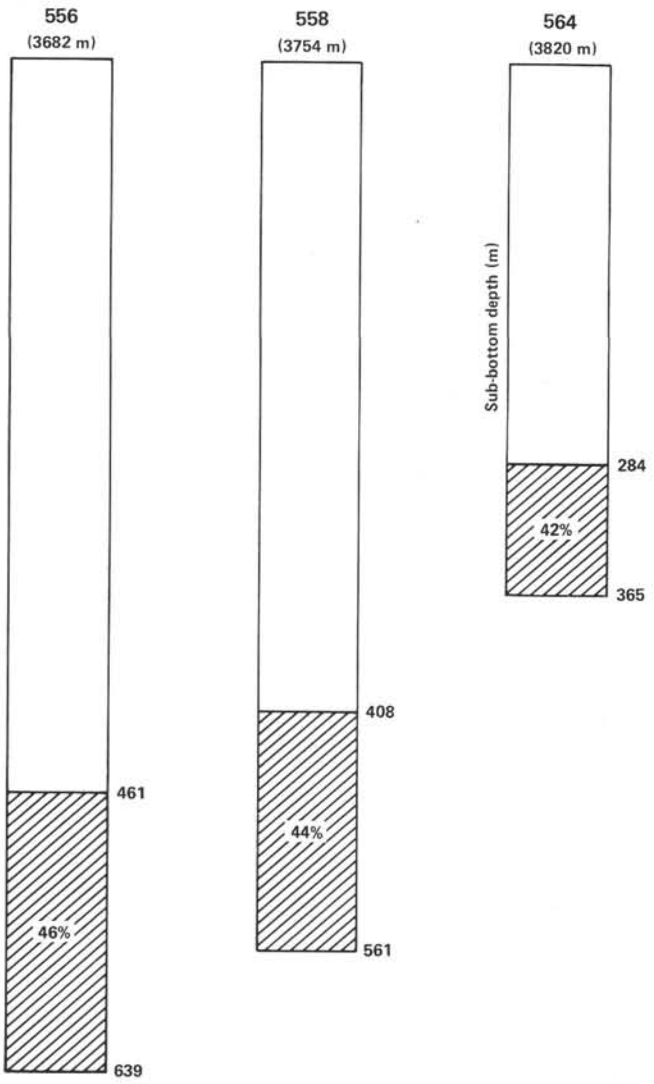

Figure 2. Depths drilled in holes in 35-Ma-old crust. Sedimentary section blank, basement hatched. Basement interface and total depth shown in m sub-bottom. Percentage recovery of basement core shown.

seem that there is little or no thermal recovery in the sedimentary section, whereas the basement section either recovered relatively quickly or was less chilled. Hole 558 shows two curves of fairly similar shape. Between measurements, the hole was flushed with water and mud and this disturbance may explain the difference in the recorded curves. On both HRT runs, the tool could not be lowered below 220 m sub-bottom because of hole cave in. The curves suggest the hole is slowly undergoing thermal reequilibration. Hole 564 was not subject to cave in or flushing between the two HRT runs and showed three interesting features. Firstly, the temperatures measured through the sediments between 200 and 280 m sub-bottom are identical on both runs. Secondly, the temperatures within 50 m depth of 100 m sub-bottom are substantially different. Thirdly, the basement temperatures on Run 2 are lower than those measured on Run 1. The second feature can be related to motion of the end of the drill string within the hole. The level was changed between the two runs as shown in Figure 4C, and it is highly likely that the heave motion on the drill string may have heated the hole or caused some local water circulation. A similar, but much less marked, effect can be discerned in the data for Hole 556, where the sea conditions during logging were much calmer than at Site 564. The other two effects suggest that the hole did not recover thermally within the lower sedimentary section and had cooled within the basement.

Given these effects in Hole 564 coupled with the zero temperature gradient recorded in Hole 556, it is possible that the holes may be experiencing continued cooling and that this could be due to continued downflow of bottom water.

THERMAL MODELS OF BOREHOLES

A simple summary of the thermal effects of drilling has been given above during the consideration of the HRT results. Because the effect of drilling and the recovery after drilling ceases are time dependent, the best way to study these phenomena quantitatively is to make repeated thermal measurements over a long period of time. The length of time required depends on the drilling history and the thermal properties of the surrounding rock, but for DSDP holes, periods of 20 days or more are generally required for fairly complete thermal recovery. Because of operational constraints, such measurement intervals are impractical in most cases, and the discussion of thermal state must be conducted with reference to physical models. In the present case, the only initial requirement is to establish whether the data are compatible with a model in which there is no cooling of the hole after circulation associated with drilling is terminated. If, however, the data show further cooling, then we may consider the effects of likely cooling mechanisms.

We will assume that the sedimentary sequence is impermeable. This is reasonable in the light of previous studies of similar pelagic oozes and chalks (Bryant et al., 1981). Some interstitial water movement is likely due to compaction and should result in the slow upward migration of pore water from the depths at which major compaction is occurring, but this is a very slow process and may be neglected for the present purpose. The thermal conductivity and density of sediments were measured from recovered core at Hole 558. Bulk values for permeability, density, and thermal conductivity for the basement have not been determined. The thermal model can, however, be restricted to a consideration of the sedimentary section of the hole, with the assumption that there is no water flow into or out of basement formations and no thermal convection within the hole. The problem thus simplifies into a consideration of the thermal perturbation in the sediments.

Because the hole is drilled downward from the top, there is normally a considerable difference in the duration of cooling in the lower parts of the hole compared to the top. The time sequence of drilling operations in the three holes is shown in Table 1. It can be seen here that this is not a major effect. Hole 556 is the best documented example for thermal modeling. The hole was washed down through sediments in 25.5 hr. In fact, the washing and associated water circulation were suspend-

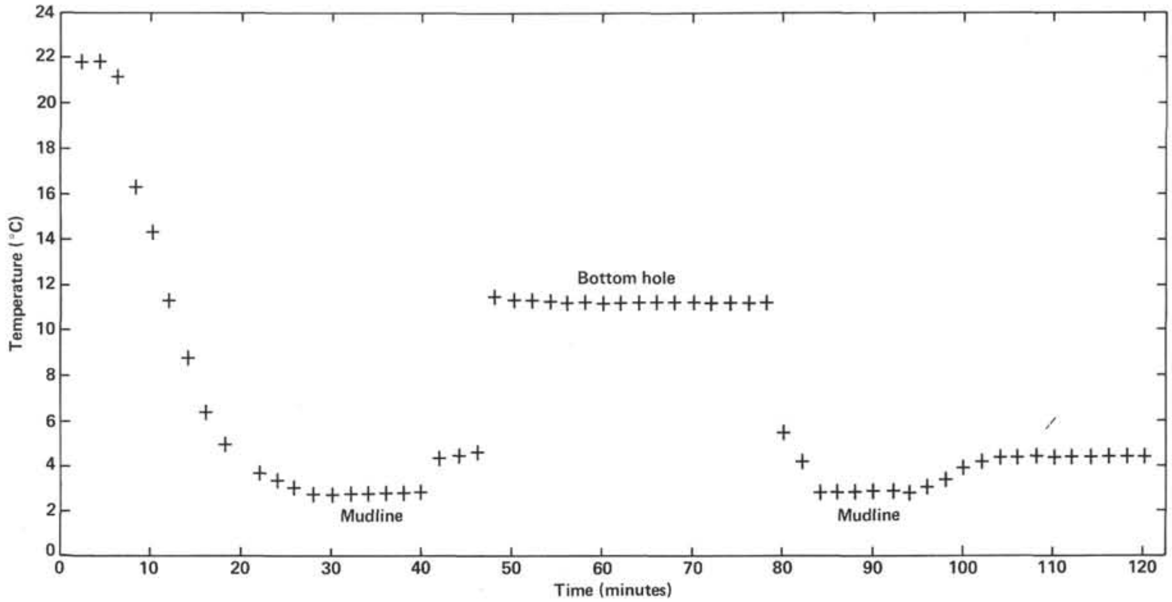

Figure 3. Typical record of DSDP downhole thermal probe (for measurement at 192 m sub-bottom, Hole 556). Note mudline temperatures as well as bottom-hole temperature measured over 15-minute equilibration period.

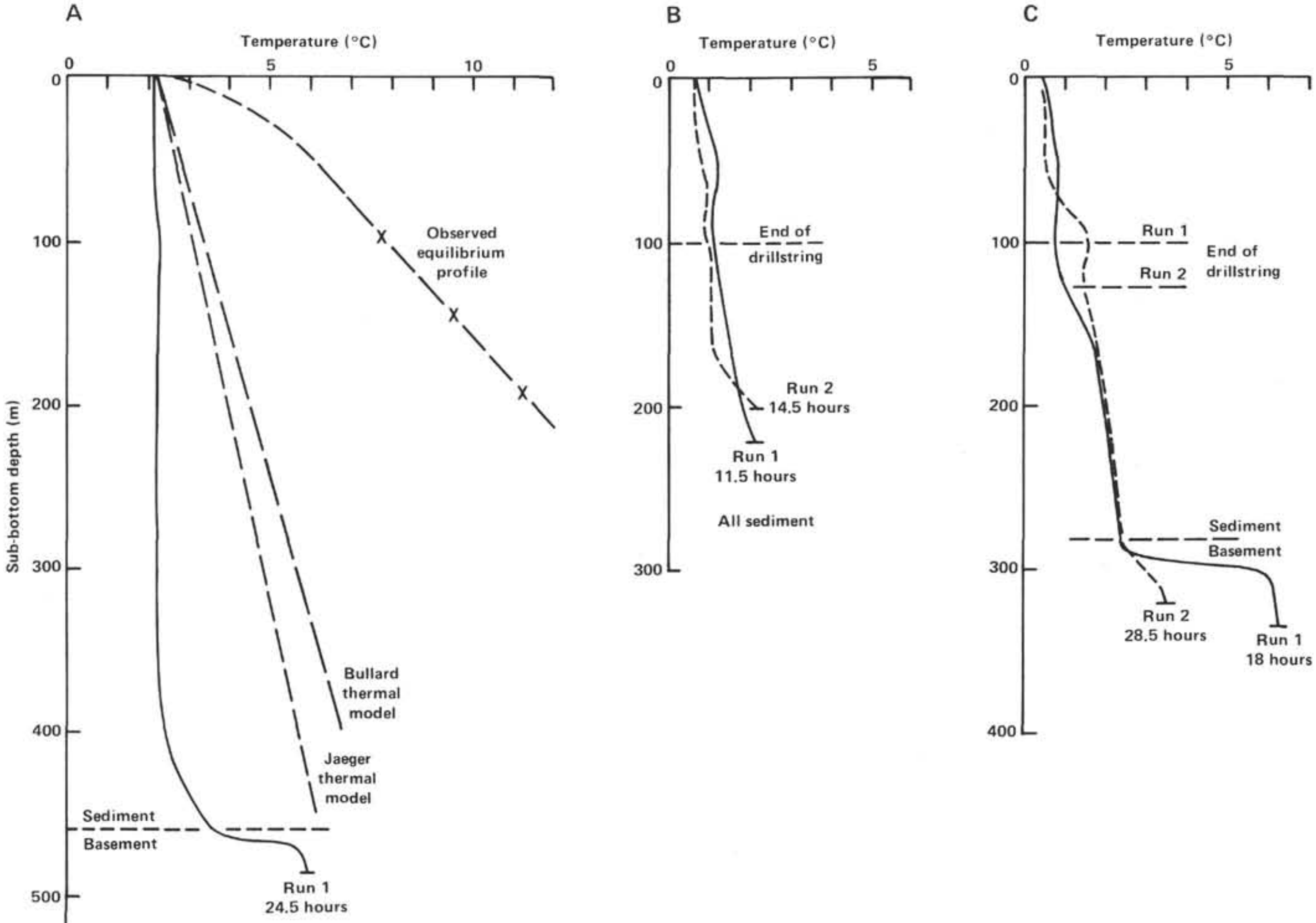

Figure 4. Thermal profiles obtained with downhole logging tool (Schlumberger High-Resolution Thermister) for Holes 556 (A), 558 (B), and 564 (C). Each tool run is annotated with elapsed time since last circulation in the hole. Thermal gradient determined for undisturbed sediment shown in A. Dashed lines show calculated thermal profiles from models of Bullard (1947) and Jaeger (1956) as noted.

Table 1. Time scale of drilling and logging operations at Holes 556, 558, and 564.

Hole	Time/Date	Operation	Elapsed time (hours)
556	1800/22 Sep	Spud in	0
	1930/23 Sep	Basement reached	25.5
	1925/27 Sep	Last Core	121.5
	2100/27 Sep	Pipe drawn to 100 m sub-bottom, circulation ceased	123
	0200/28 Sep	Logging started	128
	2130/28 Sep	HRT run	147.5
558	2122/03 Oct	Spud in	0
	1600/05 Oct	Basement reached	42.5
	0745/09 Oct	Coring ended	130.5
	1430/09 Oct	Circulation ceased	136.5
	1600/09 Oct	Logging started	138.5
	0130/10 Oct	HRT Run 1	148
	0400/10 Oct	Wash to base of hole flush with mud	150.5
	0815/10 Oct	Circulation stopped	155
	1130/10 Oct	Logging started	158
	2300/10 Oct	HRT Run 2	169.5
564	1743/28 Oct	Spud in	0
	0305/28 Oct	Basement reached	9.5
	1600/30 Oct	Circulation stopped	46.5
	1800/30 Oct	Logging started	48.5
	1000/31 Oct	HRT Run 1	64.5
	2030/31 Oct	HRT Run 2	75

Note: HRT = high resolution thermister probe.

ed for approximately 8 hours during this period while the sediment temperature measurements were made. Circulation then proceeded for 97.5 hr. during coring of the basement. The assumption will be made that the time of cooling was constant for the complete sedimentary section. The rate of heat loss will depend on the temperature of the circulating water and the flow rate as well as the properties of the formation and dimensions of the hole. Jaeger (1961) conducted a detailed study of the cooling effect of circulating fluids during drilling. If circulation rates are low, the drill string can act as an annular heat exchanger between the cool down-flowing water and the heated return flow. For usual pumping rates with rotary drilling, however, the flow rate is sufficient if the circulating water does not heat up appreciably and the heat exchange is negligible. There was no attempt to restrict water circulation during drilling of any of the holes considered here, and we will assume that circulation was sufficient to keep the holes cooled to near bottom water temperature. The very low temperature gradients measured in the sedimentary sections of all three holes show that the circulating water must have a temperature very close to that of bottom water.

The model required is, thus, one that will predict the cooling effect of a borehole held at constant temperature for a known time period within a uniform impermeable layer through which there is a known initial temperature gradient. In addition, the temperature must be known at any time after cooling is stopped and thermal equilibrium is allowed to return. The simplest treatment of this is to consider the drillhole as a line source of heat that acts in a homogeneous medium for time t_1 and calculate the remaining thermal perturbation at time t after t_1. The approximate solution for this case was derived by Bullard (1947) to give the expression:

$$\frac{T}{T_o} = \frac{[\ln(1 + t_1/t)]}{[\ln(4\kappa t_1/a^2) - 0.577]},$$

where

T = temperature disturbance at time t after t_1;
T_o = temperature disturbance at time t_1, end of drilling;
a = radius of drillhole; and
κ = thermal diffusivity of the medium.

The mean diameter of the borehole is known from wireline caliper logs to be.0.2 m, the conductivity is taken to be that measured at Hole 558 (1.6 W/m K) and the diffusivity is calculated as 6.3×10^{-7} m^2/s (Hyndman et al., 1979). Using these values and the times from Table 1, we get a value for T/T_o of 0.75. Applying this ratio to the deepest point in the hole at which the undisturbed temperature gradient was measured (192 m sub-bottom, we get a predicted temperature at time of logging of 4.4°C. This is over 2°C above the measured value.

A fuller treatment of the same problem has been given by Jaeger (1956). In this study, the exact expression for the temperature distribution in a medium of uniform diffusivity caused by a cooling borehole of finite radius is derived. This is evaluated numerically and the results tabulated in terms of the dimensionless parameters;

$\tau_o = \kappa t/a^2$
$R = r/a$ (r is distance from axis of hole).

Using the values as above, we get a value for τ_o of about 7. These values lead to a prediction that considerable chilling of the wall rocks occurs to distances of the order of 1.2 m from the hole. The reequilibration of the borehole after disturbance is a similar case of conduction but with initial conditions determined by the thermal state determined as above for a perturbation time t_1. To calculate this it is assumed that the hole $r<a$ is filled by conducting material at the perturbed temperature. The temperature perturbation for this reequilibration case has been tabulated by Jaeger in terms of τ_o and n, where the reequilibration time is nt_o (see Table 2). Applying the data from Hole 556 with $\tau_o = 7$ and $n = 0.2$ gives a per-

Table 2. Values of thermal perturbation in a borehole after time $n\tau_0$, tabulated for parameters τ_0 and n (from Jaeger, 1956). See text for explanation.

	n			
τ_0	0.1	1	10	100
1	0.988	0.543	0.095	0.010
10	0.722	0.252	0.038	0.004
100	0.477	0.143	0.020	0.002
1000	0.324	0.098	0.014	0.001

turbation of about 0.8 and a temperature of 3.9°C for the documented point at 192 m sub-bottom. However, this calculation assumes the material within the borehole is a perfect conductor and makes no allowance for the thermal capacity of this material. When the borehole is filled with water, the temperature rise will be affected by the requirement to heat the contained volume of water. This effect is only appreciable when the product $n\tau_0$ is less than 100; in this particular case, the value is about 1.5. In physical terms, the effect of the thermal capacity of the borehole fluid is only negligible when the rates of heating or cooling are low.

The heat flux into a borehole that has been cooled by being filled with fluid at a constant perturbing temperature for a known time period can be calculated from a result derived by Carslaw and Jaeger (1959, Section 13.5 [8]) to be

$$[4K(T_1 - T_0)/a^2]\ \mathrm{I}\ (\kappa t/a^2),$$

where K is thermal conductivity and I is an integral involving Bessel functions. It is this heat flux into the borehole that must heat the borehole fluid, and if this flux is large compared with the thermal capacity of the fluid, then appreciable heating will occur. Using the values previously given, and the tabulated values of I from Jaeger and Clark, (1942) results in a heat flux of 45 W at 192 m sub-bottom. This heat flow is easily adequate to heat the contained water at a rate of many degrees per hour. This, of course, will not happen because as soon as the water starts to heat, the temperature structure of the cooled rock will also have to adjust, but at least the thermal capacity of the water will not have a great delaying effect upon the heating.

Considerably more elegant models of the thermal effects surrounding boreholes have been advanced. Lachenbruch and Brewer (1959) extend the treatment of Jaeger (1956) and include a detailed assessment of the likely errors introduced by the departures of real formations and hole conditions from the idealized models studied. Hyndmann et al. (1977) review the relative merits of particular models for DSDP holes, and Burch and Langseth (1981) extend the treatments above to calculate corrections for thermal gradients measured in unequilibrated holes. Unfortunately, none of these methods is directly applicable to the present data set because they either require measurements at greater durations after drilling or detailed recording and control of parameters such as fluid circulation rate during drilling. The aim of the more complex models is to derive the equilibrium thermal gradient from measurements taken during the thermal recovery period. For the present data set, the equilibrium thermal gradient is known, and all that is required is to determine whether cooling in excess of that provided by drilling process is necessary to account for the observed thermal profiles.

Having established the errors involved in applying the theoretical models for borehole temperature recovery to this case, we can compare the calculated temperature profiles to the observed data in Figure 4A. Allowing for the lag caused by the thermal effect of the borehole fluid, there should be a temperature gradient down the hole reaching values of at least several tenths of a degree at the 192 m depth. The foremost feature of the Hole 556 data is the lack of any gradient to depths below 350 m. This measurement is independent of any calibration error of the HRT discussed earlier. There must be some mechanism to remove the heat that is entering the hole above these depths. Comparison with results from Hole 558 (Fig. 4B) emphasizes this point. The drilling and cooling history of Holes 556 and 558 are similar (Table 1); Hole 558 was cooled for a slightly longer period than Hole 556. On logging after a shorter equilibration period, we measured a thermal gradient. If we compare this gradient to computed gradients as described above, the two can be seen to be compatible, with the real data still showing a slower reequilibration than the models because of the thermal capacity of the hole fluid. The situation for Hole 564 is more complex: the thermal gradient measured is broadly compatible with the models, but shows no change in the depth interval between 190 and 280 m sub-bottom 18–28.5 hours after circulation. Above this range the temperatures are clearly affected by the end of the drill string. In the basement section of the hole, the decrease in temperature between the two runs is interesting. Great efforts were made to ensure that the tool was at the indicated cable depth and not hung up on the rough basement sidewalls. However, this would be the simplest explanation of the apparent temperature decrease.

SEAWATER DOWNFLOW

The differences between the measurements in Holes 556 and 558 could be explained by continued downflow of seawater at bottom water temperature after drilling had ceased. At Hole 558, the hole rapidly caved in and was blocked to logging tools at about 200 m depth. The flushing of the hole, which interrupts logging operations, was accompanied by lowering of the drill string in attempts to clear the hole. Despite these disturbances the hole was blocked again at the time of the second HRT run. Thermal recovery was taking place in this hole. In Hole 556, the hole remained open throughout the logging operations and no thermal recovery took place.

It could be argued that the basic model is wrong and that the flow rate of drill fluid is insufficient to chill the formations to its own temperature; and therefore, the thermal recovery is much slower than calculated, so little change is seen in Hole 564. This is quite possible but makes the explanation of the lack of a thermal gradient in Hole 556 more important because the hole will have to have been actively cooled after cessation of drilling rather than prevented from reheating. The argument hinges on the assumption of physical similarity of the sediment formation at the two holes, which is shown by logging results to be reasonable (Hill and Cande, this volume). Whereas the data set for any one hole can be explained in a variety of ways, the only consistent explanation of all the data presented above requires the existence of some cooling mechanism for at least Hole 556 and possibly Hole 564. The simplest mechanism is the seawater downflow that has been observed in many holes in young ocean crust.

This inference is supported by the temperature gradients in the basement at Site 556. The temperature rose very sharply immediately below a zone identified by the logging as being of high porosity and low seismic velocity. This also correlates with a zone of carbonate breccia associated with pillow basalts identified in the recovered core. It is likely that such a zone could provide a highly permeable pathway where downflowing water could flow out of the hole into the surrounding formation. Below this zone a more normal temperature gradient existed that could be explained by a much lower or zero flow rate of water in this section of hole after drilling ceased. It may be significant that the high temperature gradient in the basement of Hole 564 is similarly identified with a zone of high porosity and low velocity on log curves and pillow basalts in recovered core material.

Accepting seawater downflow as a model for cooling, we can make a crude calculation of the minimum rate of flow required to produce the uniform temperature in Hole 556. This can be calculated as the volume throughput of water necessary to carry away the heat flux through the hole walls in this zone without measurable heating of the water. The heat flux can be calculated with the equation given above. Because this relationship between heat flux and temperature perturbation ($T_1 - T_0$) is linear, as is the initial temperature gradient, the mean heat flux for the top 350 m of Hole 556 can be calculated, and thus the total flux. Using a mean perturbation of 8.5°C and other values as above, we get a total heat flux of 14 kW. This value will, of course, rapidly decay as the sediments become progressively chilled. To remove this flux with a temperature rise of less than 0.2°C would require a flow rate of at least 3.5 liters/s. The heat flux into the hole at any level will increase linearly with depth. The slight rise in water temperature in the hole below 350 m sub-bottom may indicate that here the heat flux is sufficiently high to appreciably warm the water flowing past and to suggest that the flow rate is unlikely to be much larger than the minimum value required by the upper portion of the hole.

CONCLUSION

The data set of thermal measurements presented above is far from an ideal one for a clear interpretation of the thermal regime in each borehole. However, if the uniformity of the sedimentary layer and its thermal properties within and between holes is accepted, it is possible to seek a single consistent model that will fit all the data. This model is one that involves substantial water downflow a Hole 556 and possibly a lower flow rate at Hole 564.

Because such flow is not forced by the drilling process, it can only exist if the pressure at the base of the hole is less than the hydrostatic pressure of the water column in the borehole. Such underpressure in oceanic basement has been directly observed at Hole 504B (Anderson and Zoback, 1982), at which hole downflow of seawater is very well documented (Becker et al., 1983). The origin of this underpressure, which drives the downhole flow, is not clearly understood. Becker et al. (1983) consider the ability of the sediment layer at Hole 504B to allow "pressure diffusion" through the pore waters and concluded that the observed basement underpressure, about 8 bars, would dissipate in approximately 1000 years unless dynamically maintained. Both of the above analyses lend support to the idea that the pressure is a secondary effect of hydrothermal convection occurring within ocean basement under an impermeable seal of sediment through which the heat is transmitted by convection. The length of time for which convection may continue in this way is not known, but Embley et al. (1983) suggest that this may occur to ages of 80 Ma.

The data reported here documenting downflow of water demonstrate the existence of basement underpressure. This can be used to infer the presence of hydrothermal convection in 35-Ma-old crust under the assumptions above. However, definitive proof of this convection would require a suite of considerably more sophisticated experiments, such as those conducted at Hole 504B. The importance of establishing the existence of this convection, and the extent of its interchange with the oceans as inferred by Embley et al. (1982), lies in the implication of thermal and chemical exchange with ocean water. This data adds to the body of evidence suggesting that detailed study of convective systems should be conducted in older ocean crust as well as in flanks of active ridges.

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REFERENCES

Anderson, R. N., and Zoback, M. D., 1982. Permeability, underpressures and convection in the oceanic crust near the Costa Rica Rift, eastern equatorial Pacific. *J. Geophys. Res.*, 87:2860–2868.

Becker, K., Langseth, M. G., Von Herzen, R. P., and Anderson, R. N., 1983. Deep crustal geothermal measurements, Hole 504B, Costa Rica Rift. *J. Geophys. Res.*, 88:3447–3457.

Burch, T. K., and Langseth, M. G., 1981. Heat-flow determination in three DSDP boreholes near the Japan Trench. *J. Geophys. Res.*, 86:9411–9419.

Bryant, W. R., Bennett, R. H., and Katherman, C. E., 1981. Shear strength, consolidation, porosity and permeability of oceanic sediments. *In* Emiliani, C. (Ed.), *The Sea* (Vol. 7): New York (John Wiley and Sons), 1555–1616.

Bullard, E. C., 1947. The time necessary for a borehole to attain temperature equilibrium. *Monthly Notices, R. Astron. Soc., Geophys. Suppl.*, 5:127–130.

Carslaw, H. S., and Jaeger, J. C., 1959. *Conduction of Heat in Solids, 2nd. Ed.:* London (Oxford University Press).

Embley, R. W., Hobart, M. A., Anderson, R. N., and Abbott, D., 1983. Anomalous heat-flow in the North Atlantic: a case for continued hydrothermal circulation in 80 Ma crust. *J. Geophys. Res.*, 88:1067–1074.

Fyfe, W. S., and Lonsdale, P., 1981. Ocean floor hydrothermal activity. *In* Emiliani, C. (Ed.), *The Sea* (Vol. 7): New York (John Wiley and Sons), 589–638.

Hyndman, R. D., Davis, E. E., and Wright, J. A., 1979. The measurement of marine geothermal heat flow by a multipenetration probe with digital acoustic telemetry and in situ thermal conductivity. *Mar. Geophys. Res.*, 4:181–205.

Hyndman, R. D., Von Herzen, R. P., Erickson, R. J., Jolivet, J., 1977. Heat flow measurements, DSDP Leg 37. *In* Aumento, F., Melson W. G., et al., *Init. Repts. DSDP*, 37: Washington (U.S. Govt. Printing Office), 347–362.

Jaeger, J. C., 1956. Numerical values for the temperature in radial heat flow. *J. Math. Phys.*, 34:316–321.

———, 1961. The effect of the drilling fluid on the temperature measured in boreholes. *J. Geophys. Res.*, 66:563–569.

Jaeger, J. C., and Clarke, M. E., 1942. A short table of I (0, 1; x). *Proc. R. Soc. Edinburgh, Sec. A*, 61:229–230.

Lachenbruch, A. H., and Brewer, M. C., 1959. Dissipation of the temperature effect of drilling a well in arctic Alaska. *Geol. Surv. Bull.*, 1083-C.

Parsons, B., and Sclater, J. G., 1977. An analysis of variation of ocean floor bathymetry and heat flow with age. *J. Geophys. Res.*, 82:803–827.

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