Becker, K., Sakai, H., et al., 1989
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8. GEOTHERMAL STATE OF HOLE 504B: ODP LEG 111 OVERVIEW[1]

Robert Gable,[2] Roger H. Morin,[3] and Keir Becker[4]

ABSTRACT

Hole 504B in the eastern equatorial Pacific has been the focus of five scientific drilling expeditions since it was first drilled in 1979. During these five legs, a series of temperature logs has been obtained over a time span of almost 8 yr, documenting the geothermal and hydrologic state of the oceanic crust in this region. Immediately following reentry at the onset of ODP Leg 111 operations, a high-resolution temperature probe was lowered into the borehole and a precise record of temperature vs. depth in Hole 504B was recorded down to 1300 mbsf.

As was observed during previous legs, the temperature gradient in the upper 400 m was reduced, indicating that downhole flow of cool ocean waters through the casing continued, though at a diminished rate. As subhydrostatic pressures in the upper basement have gradually diminished, the volume of flow has decayed from an estimated 6000–7000 L/hr in late 1979 to about 80 L/hr during Leg 111.

At depths below 480 mbsf, a predominantly conductive heat transfer environment enabled the temperature gradient log to be analyzed with respect to lithology on both fine and broad scales. Anomalies in the gradient log in the cased section through the sedimentary column were found to correspond to biostratigraphic age markers and/or sharp changes in sediment composition and texture. Broad variations in temperature gradient within the basement correlated with large-scale porosity trends.

Conductive heatflow estimates depict a systematic reduction with depth, ranging from approximately 196 mW/m^2 in the sediments to 120 ± 17 mW/m^2 at 1300 mbsf. Possible causes for this observation were examined from several perspectives, but none was suitably convincing. A fluid instability analysis indicated the likely existence of convection cells within the borehole and substantiated the hypothesis of mixing within the borehole postulated from isotopic and chemical studies of borehole waters. However, such mixing of borehole fluids does not provide an adequate explanation for the heatflow variations, and the disparity between surficial and deep values of heat flow remains unresolved.

INTRODUCTION

Hole 504B is located in the eastern equatorial Pacific Ocean, in 5.9-m.y.-old crust about 200 km south of the spreading axis of the Costa Rica Rift. A series of successful Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) cruises to this site has provided important data regarding the structure and composition of the upper kilometer of the oceanic lithosphere. This unique information has encouraged multiple visits to this hole, which now has become by far the deepest hole to penetrate oceanic basement. In 1979, Hole 504B was cored to a depth of 836 m below seafloor (mbsf) during Legs 69 and 70 (Cann, Langseth, et al., 1983). Reentry, coring, and logging operations continued with DSDP Legs 83 (Anderson, Honnorez, et al., 1985) and 92 (Leinen, Rea, et al., 1986). Most recently, Hole 504B was deepened by 212.3 m to a total depth of 1562.3 mbsf during ODP Leg 111 (Becker, Sakai, et al., 1988).

As the borehole was deepened and extensive downhole measurements programs were conducted, an intriguing story has unfolded concerning the evolution of relatively young oceanic crust, particularly in a geothermal and hydrological context. In this report, the temperature log obtained during Leg 111 is presented and analyzed from a temporal perspective, that is, as the latest extension of a comprehensive set of temperature profiles obtained in this hole since 1979. The temperature and geothermal gradient data are correlated with lithology and are also examined in terms of regional heat and mass transfer processes.

GEOTHERMAL SETTING AND SUMMARY OF PREVIOUS WORK

Hole 504B is located on the southern flank of the Costa Rica Rift, where the sedimentation rate is relatively high, about 50 m/m.y. Although the crust at this location is relatively young, it is blanketed with approximately 275 m of sediments, primarily composed of biogenic pelagic oozes with variable proportions of clay. From analyses of comprehensive heatflow surveys, Langseth et al. (1988) reported a mean heatflow value of 216 mW/m^2 measured through the surficial sediments near the site. This value is about 5%–10% higher than that predicted by conductively cooling plate models (Parsons and Sclater, 1977; Lister, 1977), which suggests that the thick, low-permeability sedimentary cover largely seals the fractured basement rock from interactive mass transfer with ocean waters (Anderson and Hobart, 1976; Davis and Lister, 1977). Closer to the ridge, where the sediment cover is thinner, conductive heat flow is significantly less than predicted, suggesting open hydrothermal circulation and significant convective heat loss (Langseth et al., 1983).

During Legs 69, 70, 83, and 92, numerous temperature profiles were obtained over different depth intervals in Hole 504B, when the hole was at various stages of thermal equilibrium or disequilibrium resulting from the disturbances due to drilling (Becker et al., 1983a, 1983b, 1985). The theory developed by Bullard (1947) was applied to extrapolate some of these profiles to steady-state approximations of temperature vs. depth. Based on such extrapolations, Becker et al. (1983b, 1985) estimated a conductive geothermal gradient of 70°C/km in the sheeted dikes below 900 mbsf and predicted a bottom-hole temperature of about 160°C at 1350 mbsf, the depth of Hole 504B at the first Leg 111 reentry. The composite of temperature logs shown

[1] Becker, K., Sakai, H., et al., 1989. *Proc. ODP, Sci. Results*, 111: College Station, TX (Ocean Drilling Program).
[2] Département Géophysique, Bureau de Recherches Géologiques et Minières, Avenue de Concyr, B.P. 6009, 45060 Orleans Cedex 2, France.
[3] U.S. Geological Survey, P.O. Box 25046, Denver Federal Center, Denver, CO 80225.
[4] Division of Marine Geology and Geophysics, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149.

in Figure 1 was adapted from Becker et al. (1985) and includes the latest profile obtained during Leg 111.

During Leg 69, the heat flow through the sediments at Site 504 was found to be predominantly conductive, with a value of 196 mW/m^2. After Hole 504B was drilled and cased through 274.5 m of sediments during Leg 69, borehole temperatures were strongly depressed to a depth of about 350–375 mbsf, below which point they quickly rose and approached conductive heatflow conditions. This distinctive pattern indicated that cool ocean bottom water was flowing down the borehole and radially entering the upper 100 m of basement. The volume of downhole flow was estimated to have initially been 6000–7000 L/hr in late 1979 (Becker et al., 1983a), and slowly diminished to only 150–200 L/hr almost 3.5 yr later (Becker et al., 1985). This decay in volumetric flow is thought to correspond to an equivalent decay in basement underpressure, originally on the order of 1 MPa (Anderson and Zoback, 1982) and gradually diminishing to hydrostatic equilibrium conditions. The presence of a highly permeable zone in the upper basement was confirmed directly by measurements with a packer (Anderson and Zoback, 1982), and this zone correlates with a porous interval identified from large-scale electrical measurements (Becker, 1985).

METHODOLOGY

Immediately following reentry of Hole 504B at the onset of Leg 111 operations, the temperature probe supplied by the Bureau de Recherches Géologiques et Minières (BRGM) of France was lowered into the borehole, with the drill string held stationary in the upper 105 m of the casing. The temperature probe was the first drilling or logging tool to contact the borehole fluids, thereby minimizing any thermal disturbances.

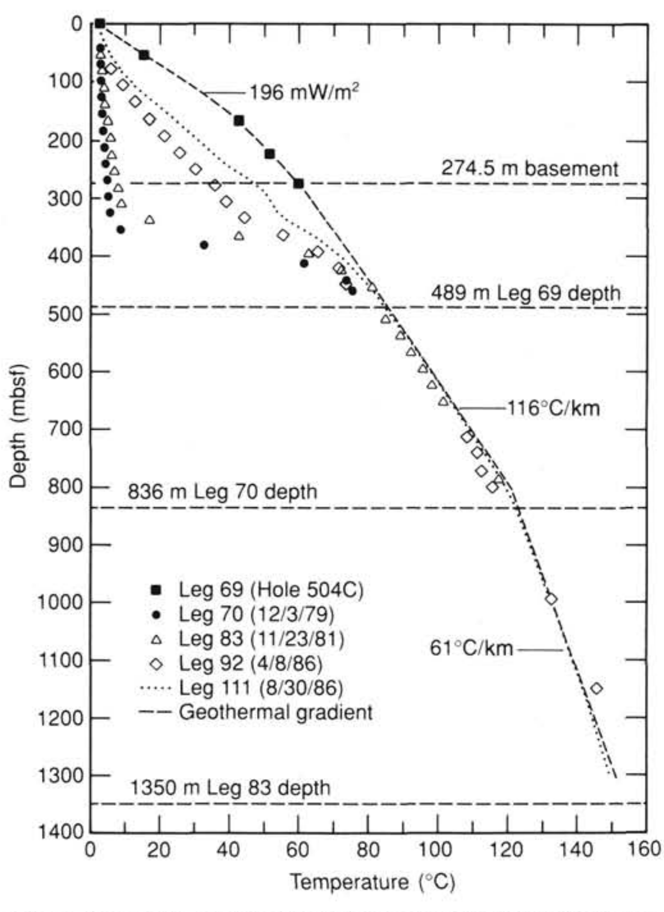

Figure 1. Composite of temperature logs measured in Hole 504B during DSDP Legs 69, 70, 83, and 92 and ODP Leg 111.

Because the borehole had last been entered almost 3.5 yr earlier during Leg 92, it could be assumed that thermal disturbances due to sampling and logging during Leg 92 had completely dissipated. Therefore, the measured water temperatures can be assumed to accurately represent the undisturbed thermal state of the borehole, which may closely represent the geothermal state of the surrounding formation.

The BRGM tool incorporates a two-thermistor design, whereby each sensor can be monitored separately or in combination for optimum sensitivity (approximately 0.001°C) over a wide range of temperatures. Temperature vs. resistance calibration data were fit to a standard function, and appropriate calibration coefficients were used to convert measured resistances to temperatures. The tool and the calibration data were fully described by the Shipboard Scientific Party (1988).

RESULTS

The temperature probe was run downward from the seafloor to the bottom of the hole at a logging speed of 5 m/min and a digitized sampling interval of 35 cm. A single thermistor was utilized to a depth of 300 mbsf and the two-thermistor arrangement was used for the deeper measurements. Temperatures in the hole were logged continuously to 1300 mbsf, where the tool reached an obstruction in the borehole that prevented logging to the bottom of the hole (1350 mbsf at that time). The resulting temperature profile is included in the composite log of Figure 1 and is also presented alongside the profile of temperature gradient in Figure 2. The temperature gradient log was computed from a nonweighted average of eight continuous temperature measurements (280-cm depth interval), with a depth shift of two measurements (70 cm) for each successive value of gradient.

After the obstruction was encountered, the probe was held stationary at 1298 mbsf for over 15 min, recording a stable temperature of 148.55°C (Fig. 3). The tool was then lifted out of the hole and another stationary measurement was recorded in the pipe 4 m above the seafloor, for calibration against the known ocean bottom water temperature of 2.01°C (Fig. 4). The data from Figures 3 and 4 demonstrate stable, accurate tool performance over a wide range of temperatures.

The temperature distribution across the lower portion of the borehole had never been measured satisfactorily because of the range and resolution limits of the tools used during DSDP. This uncertainly was compounded by the unequilibrated thermal conditions prevalent during some of the previous logging runs, some of which required extrapolation to arrive at estimates of true formation temperature. The BRGM tool provided a reliable method of measuring undisturbed borehole fluid temperature across the wide range of temperatures encountered in this hole.

DATA ANALYSIS AND INTERPRETATION

Below 400 mbsf, there is good agreement between the temperatures obtained during Leg 111 and those measured during Leg 92 (Fig. 1). For this portion of the borehole, extrapolation methods applied to temperature logs obtained during Leg 83 overestimated the geothermal gradient and predicted temperatures that were slightly high. The precise temperature profile from Leg 111 defines a geothermal gradient below 850 mbsf of approximately 61°C/km and a corresponding temperature of 148.5°C at 1300 mbsf, nearly 12°C cooler than the 160°C previously estimated for 1350 mbsf, the bottom of the hole before Leg 111 drilled deeper. The heat flow in the lower portion of the borehole (850–1260 mbsf) is computed to be 120 ± 17 mW/m^2 (Table 1). Assuming this constant value of heat flow, the temperature at the present bottom of the hole (1562.3 mbsf, after 212.3 m of subsequent drilling during Leg 111) is estimated to be 165°C (Fig. 5).

Downhole Flow of Ocean Bottom Water

Downward flow of ocean bottom water through the casing into the underpressured zone in the uppermost basement was

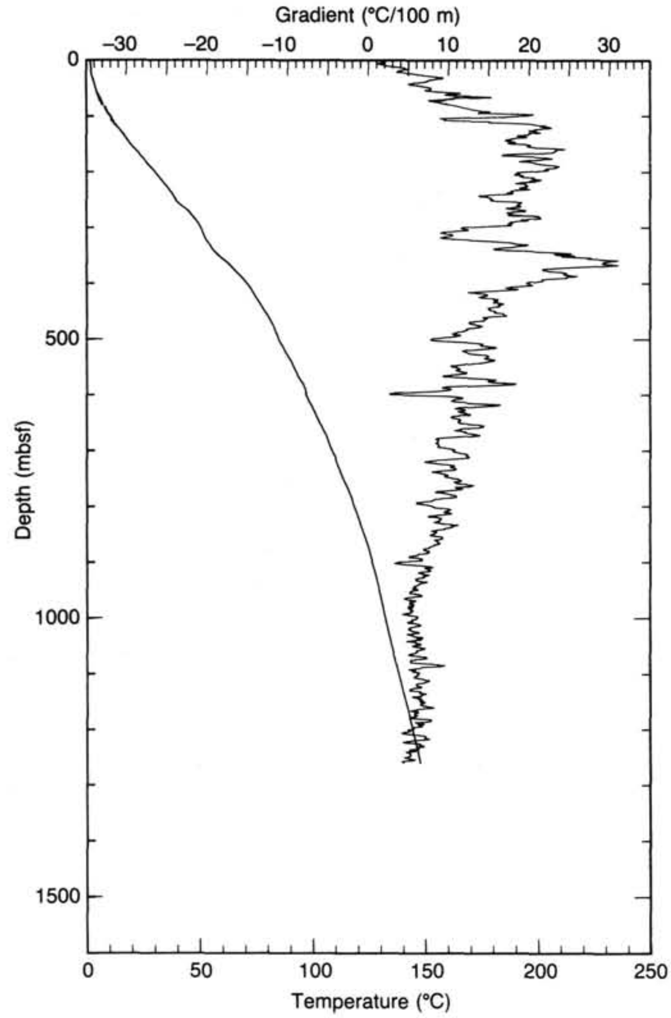

Figure 2. Profiles of temperature and gradient recorded in Hole 504B during Leg 111.

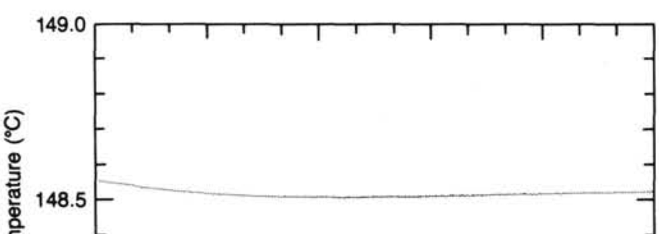

Figure 3. Temperatures recorded with the probe held stationary at 1298 mbsf, Hole 504B.

initially identified in 1979 and has been monitored with each succeeding visit to Hole 504B (Becker et al., 1983a, 1983b, 1985). Although no flowmeter logs have been run to directly measure the vertical fluid velocity through the casing, flow rates

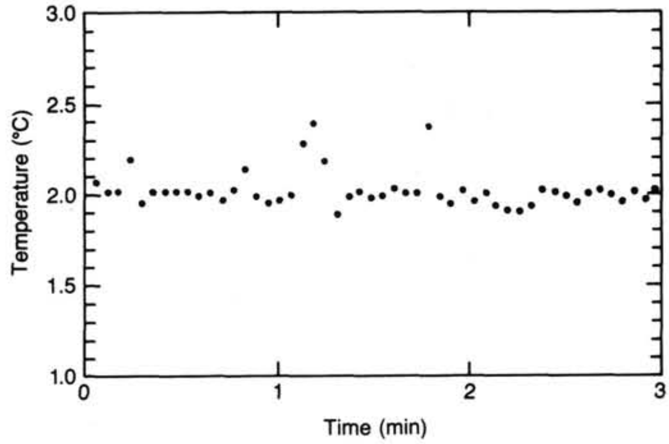

Figure 4. Temperatures recorded at Hole 504B with the probe held stationary at 4 m above seafloor, within the drill string.

were nevertheless computed (Becker et al., 1983a) by applying the solution of the analogous problem of radial conduction around an isothermal cylinder (Jaeger, 1942) to the temperature records. The profile measured during Leg 111 showed that temperatures in the upper 400 m were still slightly depressed as a result of cool ocean water flowing down the casing, but to a much lesser extent than during previous legs. The departure of measured temperatures from the geothermal gradient had greatly subsided. By Leg 111, the estimated velocity through the casing had decayed to approximately 1.1 m/hr or 80 L/hr (Fig. 6A), less than half that determined during Leg 92 in 1982 (Fig. 6B). This estimate derived from the temperature profile agrees with that predicted by Williams et al. (1986), whose three-dimensional model of hydrothermal convection in the oceanic crust around Site 504 projected an inflow rate of 50–60 L/hr by the middle of 1986. It appears that the underpressure in the upper pillow lavas, initially on the order of about 1 MPa, is gradually approaching hydrostatic equilibrium, and that the basement below this zone is too impermeable to sustain additional flow.

Correlation with Lithology

In conductive heatflow environments, the slope of the temperature log is a function of formation thermal conductivity and, as such, can provide some information about the vertical distribution of porosity and mineralogy. The temperature gradient, or delta-T, log shown in Figure 2 may be correlated with lithologic variation on both fine and broad scales. For instance, the delta-T log depicts large thermal variations in the interval from 60 to 120 mbsf (Fig. 7), that is, within the cased section. In comparison with the profiles of sediment lithology and composition constructed during Leg 69 (Beiersdorf and Natland, 1983), these variations appear to coincide with a zone marked by sharp variations in composition (Fig. 8). In addition, the low-gradient spikes evident at depths of 65 and 100 mbsf clearly delineate lithologic Subunit IB.

If the heat flow is purely conductive, decreases in temperature gradient should be accompanied by proportional increases in thermal conductivity; increases in sediment thermal conductivity translate to decreases in porosity (Ratcliffe, 1960; Pai and Raghavan, 1982). However, the porosity and thermal conductivity profiles for Hole 504 reported by Wilkens and Langseth (1983) show that porosities do not change by more than 20% across 250 m of sediments, whereas our recorded values of temperature gradient may vary by roughly an order of magnitude. Therefore, the relationship between thermal conductivity and porosity through the sedimentary column is not clearly con-

Table 1. Heat flow determinations, Hole 504B.

Depth[a] (mbsf)	Thermal conductivity[b] (W/mK)	Heat flow (mW/m^2)
853.1	1.87	168.3
862.3	1.76	149.6
870.6	1.79	136.39
888.5	2.03	101.21
898.1	1.86	72.54
904.7	1.81	117.05
910	1.82	130.44
929.2	2.20	127.74
938.8	2.16	132.14
948.6	2.10	125.01
957.8	2.05	132.13
969.4	2.09	116.2
977.2	2.14	109.35
987.3	2.16	112.53
999.7	2.14	127.11
1005.1	2.00	100.68
1013.1	1.90	117.23
1024.6	2.06	126.07
1030.8	2.03	109.82
1040.9	2.25	107.42
1049.4	2.04	110.33
1058.7	2.05	120.21
1062	1.95	108.48
1072	2.13	138.76
1081.8	1.92	154.16
1090.3	2.08	111.90
1099	1.98	118.99
1108.4	2.07	137.67
1116.8	2.07	123.62
1134.6	1.91	134.46
1144	2.03	128.50
1152.6	2.01	128.03
1153.6	2.07	131.59
1161.9	1.87	118.37
1166.6	2.05	122.18
1171.2	1.98	111.26
1185.2	1.94	134.95
1190.8	2.11	130.78
1194.2	2.18	129.77
1203.2	1.90	82.46
1208.3	2.02	115.05
1214.5	1.87	131.27
1222.9	2.02	97.13
1232.8	1.94	117.93
1241	1.96	92.7
1250	2.03	92.26
1254.4	2.13	115.44

Note: Average heat flow = 120.3 mW/m^2 ± 17 std. dev.

[a] Depths correspond to locations of core samples.

[b] Anderson, Honnorez, et al. (1985).

[c] Computed across 3-m intervals centered at the sample depth.

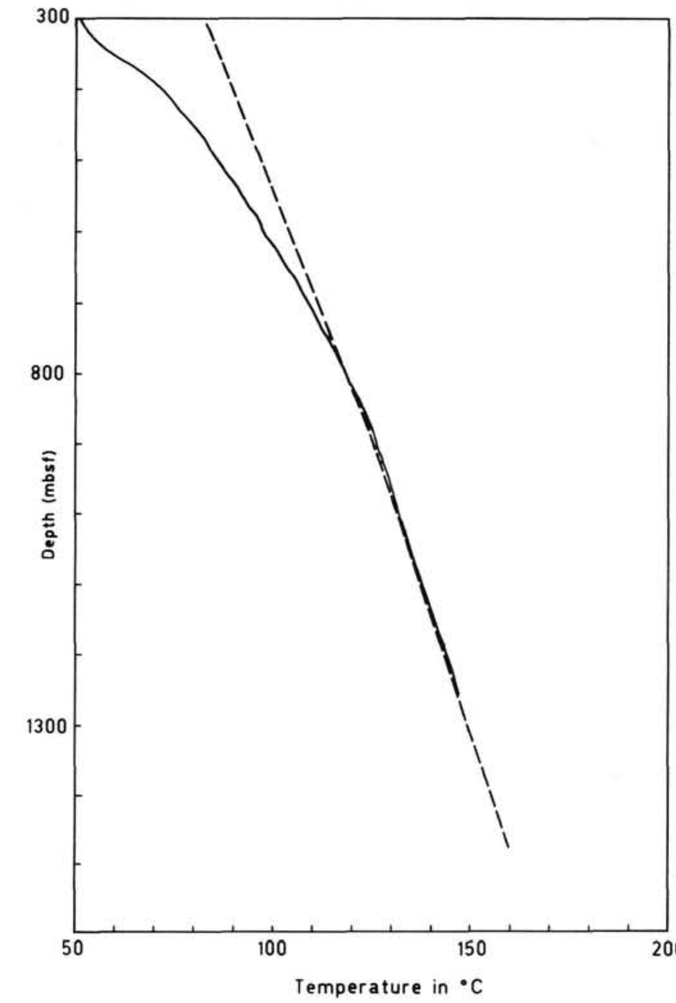

Figure 5. Temperature profile measured during Leg 111 (solid line) and extrapolation (dashed line) assuming a uniform heatflow of 120 mW/m^2 and thermal-conductivity values as measured on basalt cores from Hole 504B.

strained by the delta-T profile, particularly when there appears to be a secondary correlation with biostratigraphic age and/or lithologic unit. Perhaps downward water movement in the cased section of the hole, convection within the borehole itself (discussed in the following section), or the presence of cement around the casing could account for some of the local variability in the delta-T log.

On a broader scale, the temperature gradient log obtained in the crystalline basement rocks can be a principal indicator of porosity rather than of mineralogy, particularly if fractures compose the main component of porosity. The apparent bulk-porosity log, computed by applying Archie's (1942) law to the results of large-scale electrical resistivity measurements in Hole 504B (Becker, 1985), is plotted beside the delta-T log in Figure 9. Permeability values computed from packer experiments (Anderson and Zoback 1982; Anderson et al., 1985) are also depicted. The temperature gradient should decrease with decreasing porosity and, correspondingly, the delta-T log should parallel the porosity log to some extent. This is the case for the permeable underpressured zone in the upper basement, identified as Layer 2A in Figure 9. In this interval, it appears that low electrical resistivity corresponds to high porosity, which in turn correlates with high permeability and a high temperature gradient.

There is a sharp decrease in the temperature gradient, porosity, and permeability distributions near the bottom of Layer 2A. This indicates that a decrease in porosity within the pillow lavas and minor flows is associated with a decrease of orders of magnitude in permeability. Near the Layer 2B/2C boundary (about 900 mbsf), another sharp decrease in apparent bulk porosity is detected, accompanied by only a slight change in the temperature gradient. It appears that the "lower pillow alteration zone," which extends from 585 to 899 mbsf (Alt et al., 1986), may contain electrically conductive alteration products that erroneously indicate higher porosities when Archie's (1942) law is applied to the measured resistivities (see Pezard and Anderson, this volume). The delta-T log is not particularly sensitive to the thermal properties of a proportionally small volume of alteration products that infill fractures. Thus, this log does not reflect any significant shift in porosity. This observation also correlates well

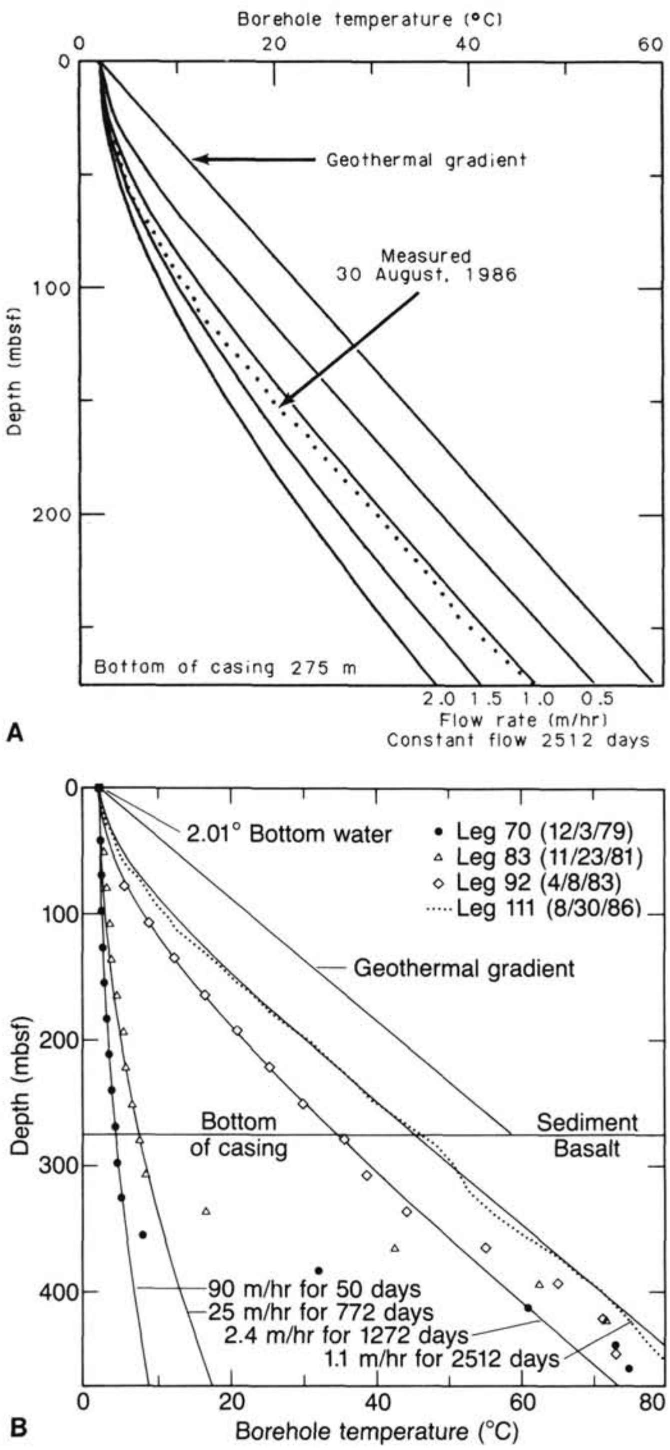

Figure 6. **A.** Estimation of rate of downhole flow during Leg 111. Temperatures measured in the cased section of Hole 504B during Leg 111 compared to profiles predicted under conditions of constant downhole flow. **B.** Decay of the rate of downhole flow since Hole 504B was initially drilled on Leg 69. Temperatures were measured in the cased section of Hole 504B during Legs 70, 83, 92, and 111; the respective matched profiles are based on conditions of constant downhole flow.

with the results of packer experiments, which define a zone of relatively uniform, low permeability below 536 mbsf (Anderson et al., 1985; Becker, this volume).

Temperature gradients in the lower portion of the hole generally exhibit smaller fluctuations and a correspondingly lower variance about the mean (Fig. 10). Intervals displaying larger variances seem to correspond to sequences of variable lithology, with interlayered pillows, thin flows, and numerous chilled contacts, as shown in the lithology log of Adamson (1985). Electrical resistivity logs obtained during Leg 111 also exhibit decreasing variability with depth (Pezard and Anderson, this volume).

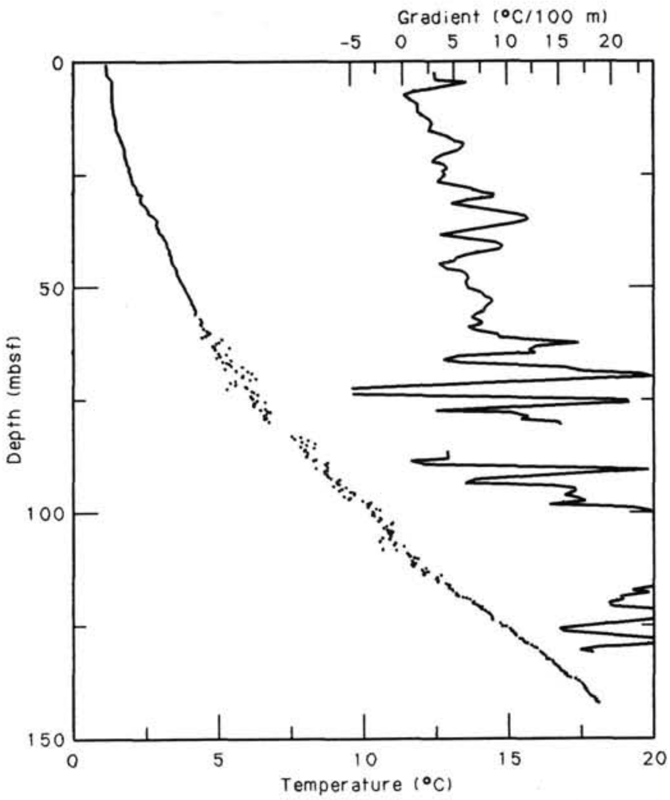

Figure 7. Temperature and temperature gradient vs. depth in the cased section through the sedimentary column, Hole 504B.

VERTICAL DISTRIBUTION OF HEAT FLOW IN HOLE 504B

The heat flow through the sedimentary column at Site 504 was determined to be 196 mW/m^2 from temperature and thermal-conductivity measurements conducted during Leg 69 in the adjacent Holes 504 and 504C. Within the basement section in Hole 504B, temperature gradients are fairly linear over limited depth intervals, but decrease in stages from approximately 116°C/km in the pillow basalts to 61°C/km in the dikes (Fig. 1). Conversely, values of thermal conductivity determined from shipboard measurements on core samples increase in stages with increasing depth (Karato et al., 1983; Becker et al., 1983b, 1985). The geothermal gradient remains relatively stable and thermal conductivity values are generally uniform from 853 to 1254 mbsf, and a corresponding average value of heat flow is computed to be 120.3 $\pm$ 17 mW/m^2 in the lower portion of the borehole (Table 1). In summary, across the 1300-m logged section of Hole 504B a decrease in temperature gradient is accompanied by a proportionally smaller increase in thermal conductivity; the product of these two trends results in an apparent reduction of heat flow with depth.

To explain this discrepancy in heatflow estimates in Hole 504B, we consider the physical significance of the distribution of borehole-fluid temperatures. Borehole temperatures measured by a logging tool are affected by a range of physical conditions, including (1) drilling disturbances, (2) hydraulically-driven water flow, (3) thermal conductivity of the surrounding formation,

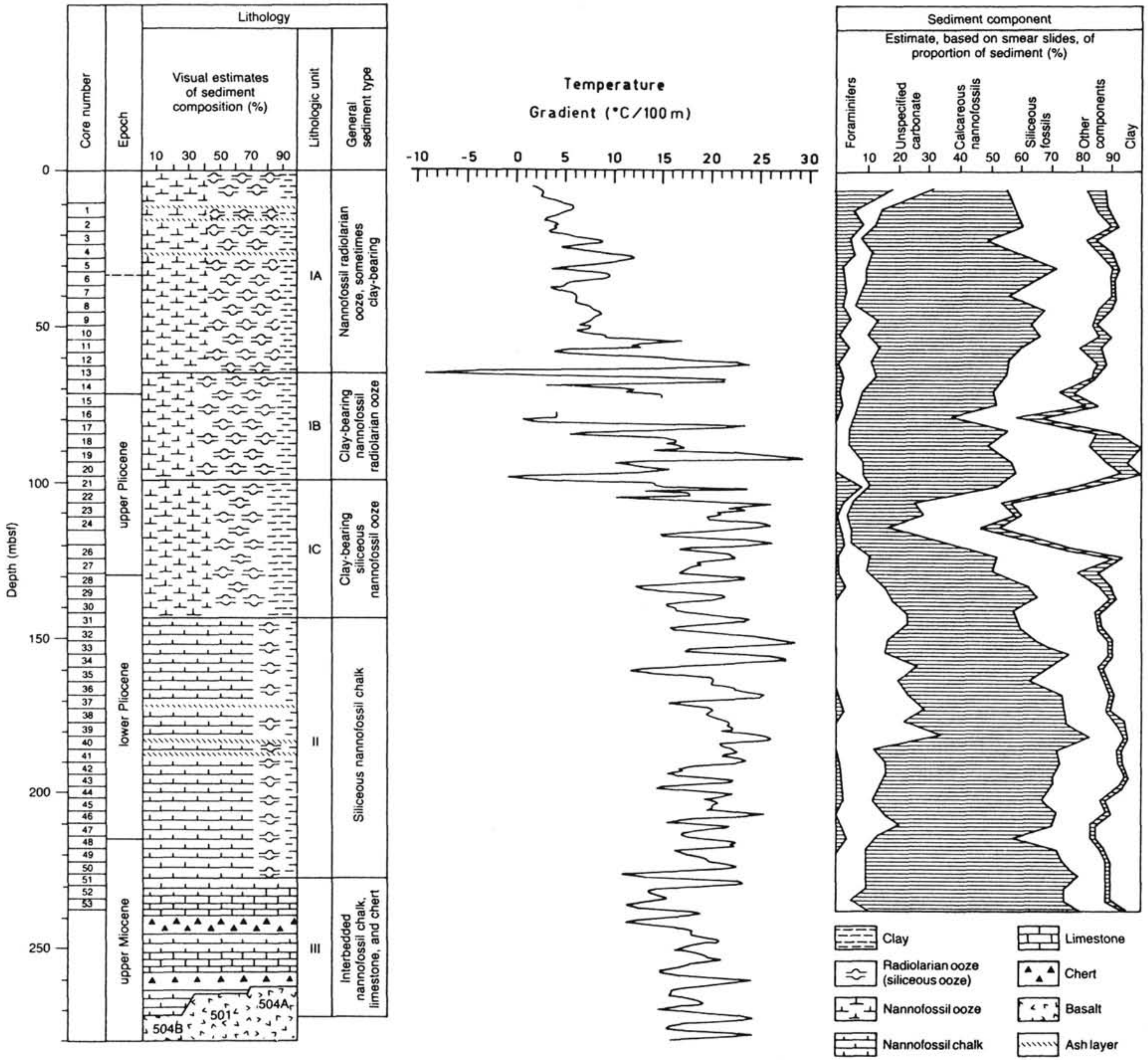

Figure 8. Comparison of profiles of temperature gradient measured in the cased section of Hole 504B with sediment lithology and composition (from Beiersdorf and Natland, 1983).

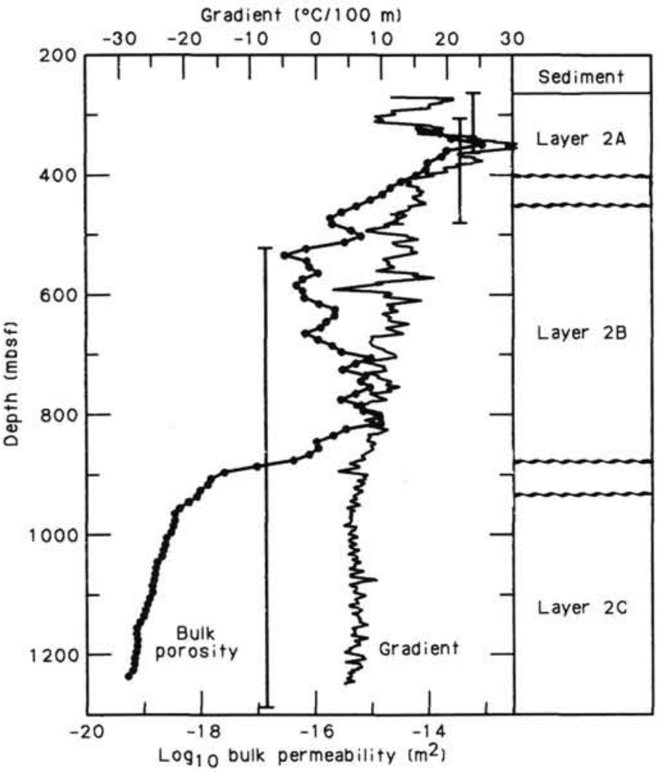

Figure 9. Composite plot of temperature gradient, bulk porosity, and bulk permeability (straight vertical lines) measured in Hole 504B.

(4) free convection in the borehole, and (5) local effects of large-scale hydrothermal convection (Conaway, 1987). The first two conditions were addressed in the preceding, and the remaining three possibilities are now discussed.

Thermal Conductivity

As noted previously, the thermal conductivity of the formation surrounding Hole 504B has been estimated from shipboard measurements performed on core samples. Morin and Silva (1984) showed that for high-porosity sediments the behavior of the liquid phase dominates the thermal-conductivity corrections for high pressures and temperatures. As with water alone, sediment thermal conductivity increases with both increasing pressure and increasing temperature. Even though the sediments and surficial, higher-porosity basalts at Hole 504B are not exposed to very high temperatures, the net effect of these adjustments to *in-situ* conditions nevertheless is a positive correction (net increase) to the thermal conductivity and a proportional increase in heat flow in the upper portion of the hole.

In the deeper section of the hole, where porosities are very low, the variations in thermal conductivity of the basalts are no longer dominated by the behavior of the fluid phase. Becker et al. (1983b, 1985) attempted to correct the values measured on cores to more realistic bulk porosities and applied pressure and temperature corrections to the pore-fluid conductivity. Their resulting estimates of formation thermal conductivity at *in-situ* conditions are slightly less than the values measured on recovered samples. Basalt conductivities increase slightly with pressure (Bridgman, 1949) and decrease with increasing temperature (Roy et al., 1981). Although these adjustments tend to offset each other, a slight negative correction (net decrease) to the thermal conductivity is evident. Thus, adjusting the heatflow estimates in Hole 504B according to thermal-conductivity corrections for *in-situ* conditions actually augments the disparity between shallow and deep values of heat flow. The high estimates of heat flow at the surface are increased slightly, whereas the low estimates in the deeper section are reduced.

Convection within the Borehole

Free convection in a borehole was addressed by Hales (1937), who demonstrated that a vertical fluid column becomes inherently unstable when its temperature gradient exceeds a threshold value that is a function of various fluid properties and the diameter of the tube. Krige's (1939) formulation of this problem has been applied to numerous field studies concerned with the proper interpretation of temperature logs (e.g., Garland and Lennox, 1962; Urban and Diment, 1985):

$$G_c = \frac{g\alpha T}{c_p} + \frac{D\nu k}{g\alpha r^4}, \tag{1}$$

where G_c is the critical temperature gradient for onset of convection (°C/cm), g is acceleration due to gravity (cm/s^2), α is the volumetric coefficient of thermal expansion (1/°C), T is absolute temperature (K), c_p is the specific heat (erg/g°C), ν is the kinematic viscosity (cm^2/s), k is the thermal diffusivity (cm^2/s), r is the borehole radius (cm), and D is a dimensionless constant equal to 216 for a borehole with a length much greater than its diameter.

The first term on the right side of equation (1) represents adiabatic compression; its value is approximately 0.2°C/km for water at 20°C and increases to roughly 0.3°C/km for water at 100°C. The second term, which is particularly sensitive to borehole size, can substantially augment the magnitude of this critical gradient. For instance, in small-diameter wells (3-5 cm), G_c can increase to values of several hundred degrees Celsius per kilometer. However, for larger diameter wells, such as Hole 504B (r = 13-16 cm), the second term in equation (1) has minimal impact on the final value of G_c.

Sammel (1968) presented curves of critical gradient vs. temperature for borehole diameters ranging from 5 to 15 cm. These can be roughly extrapolated to larger diameters or a new curve can be constructed directly from equation (1) by substituting for appropriate properties of water at high pressures and temperatures (Hamann, 1957; Lawson et al., 1959; Lawson and Hughes, 1963; Horne, 1965; Keenan and Keyes, 1967). The resulting critical gradient for a borehole with a 30-cm diameter does not exceed 0.5°C/km over a temperature range of 10° to 150°C. This value of geothermal gradient is clearly surpassed by several orders of magnitude everywhere in Hole 504B. According to Diment (1967), small-diameter (2-3 cm) holes are usually stable, larger ones (6-8 cm) approach instability, and large-diameter wells (> 10 cm) are typically unstable. Thus, according to these criteria, convective fluid movement is likely to occur throughout the water column in Hole 504B. This has been confirmed, to some degree, by water chemistry studies that reported evidence of vertical mixing and circulation in the borehole (Shipboard Scientific Party, 1988).

The vertical extent of such convection cells and the amplitudes of the resulting temperature oscillations are factors that should be considered in evaluating the precision of the Leg 111 temperature log and subsequent estimates of heat flow. Unfortunately, the behavior of these free convection cells is not well understood and not easily predicted. Sammel (1968) has presented evidence of an apparent relationship between geothermal gradient and temperature oscillations. According to these results, a gradient on the order of 100°C/km, like that measured in Hole 504B, is expected to generate temperature variations of roughly 0.03°C at a given depth. Such fluctuations are not observed in the stationary bottom-hole temperatures shown in Fig-

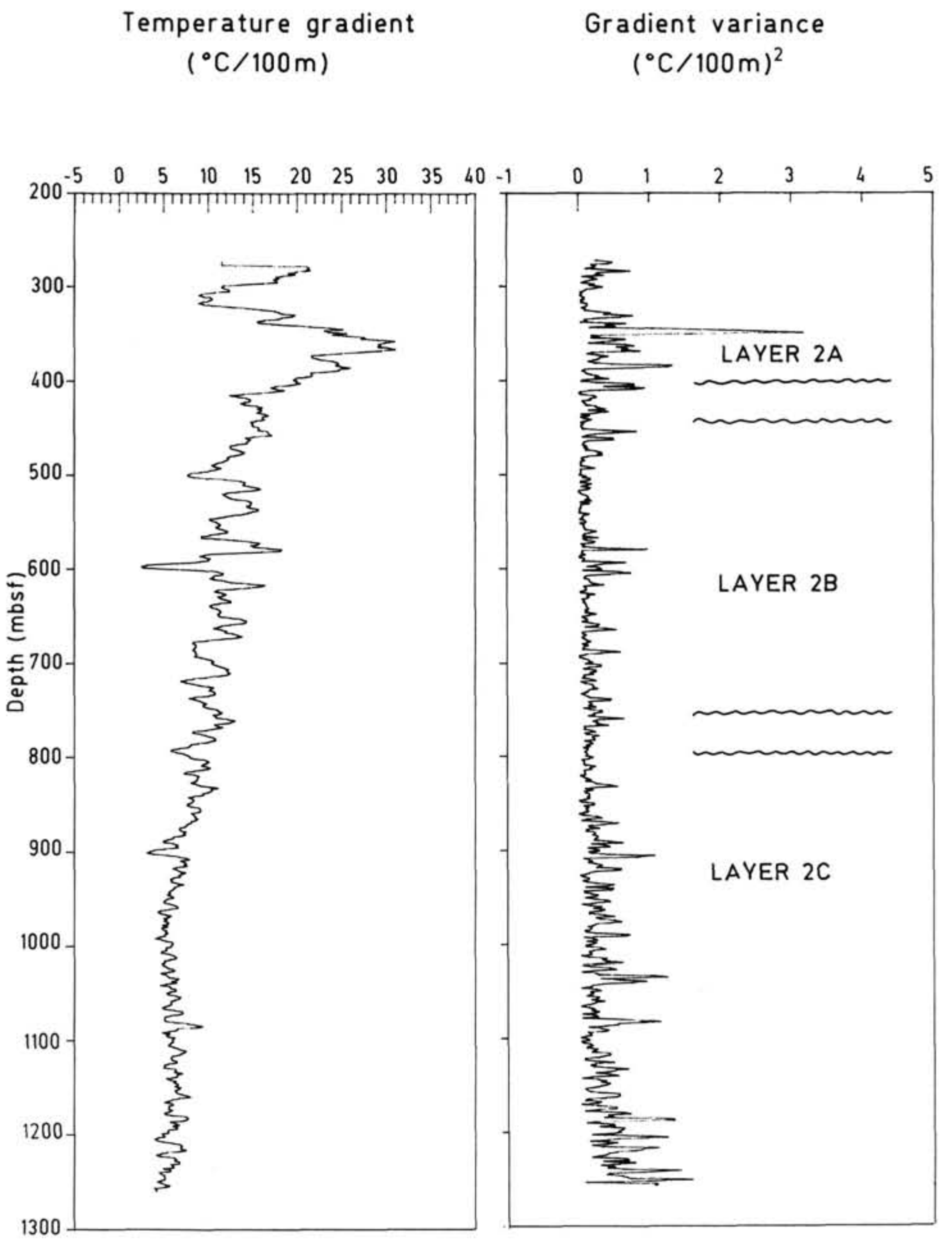

Figure 10. Temperature gradient log and a profile of its variance.

ure 3. Moreover, Urban and Diment (1980) reported that stationary temperature measurements commonly exhibit recurring patterns with periods of roughly 10 min. The data in Figure 3 were recorded for over 15 min and only display fluctuations on the order of $\pm 0.002°C$ with no obvious periodicity. It appears either that the relationship between gradient and observed temperature oscillations reported by Sammel (1968) does not apply to borehole conditions at Hole 504B or that the stationary measurements obtained at 1298 mbsf did not intercept a convection cell. In either case, the local range of possible temperature variations is too small to sufficiently account for any substantial change in the original computations of heat flow.

To help characterize convection cells in boreholes, Urban and Diment (1985) introduced a term called aspect ratio, A, defined by:

$$A = h/r, \tag{2}$$

where h is the height of the cell and r again is the borehole radius. Urban and Diment (1985) reviewed a variety of studies in which well diameters ranged from 1 to 25 cm and geothermal gradients increased to 1000°C/km. They reported that values of A typically lie between 6 and 9, although values up to 20 are common, with sporadic values of 100. By applying these results, the heights of the convection cells in Hole 504B may range roughly from 1 to 3 m, though it is conceivable that they may extend to 15 m.

Large-Scale Hydrothermal Circulation

Finally, the apparent reduction in heat flow with depth can be examined from a regional perspective, in which large-scale hydrothermal circulation in the oceanic crust may produce local anomalies in vertical heat flow (Ribando et al., 1976; Fehn et al., 1983). Langseth et al. (1988) reported the results of a detailed survey of heat flow and geochemical gradients in sediment pore waters within a 10 × 10 km area surrounding Hole 504B. They interpreted a regular pattern of heatflow highs and lows in the region to be a manifestation of active hydrothermal circulation within the shallow basement that may extend 3-4 km laterally and/or vertically. In addition, pore-water chemistry data obtained from sediment cores delineate nonlinear profiles that are directly attributable to vertical water percolation through the sedimentary column at velocities of up to 6 mm/yr (Mottl, this volume). This observation indicates that there is mass transport and open hydrothermal circulation between the permeable uppermost basement and the ocean waters.

Sediment permeabilities are estimated to be quite low (about 10^{-17} m^2; Langseth et al., 1988). Nevertheless, the relatively permeable upper basement (about 10^{-13} m^2; Anderson and Zoback, 1982) facilitates a slow mass flux through the sedimentary column. Such convection may produce the regular variations of roughly 20%-30% in surface heat flow observed across the area. Below 536 mbsf, the deeper basement is 3-4 orders of magnitude less permeable (about 10^{-17} m^2; Anderson et al., 1985; Becker, this volume), or roughly as impermeable as the sedimentary cap.

Regional convection through the basement could account for the reduction in heat flow with depth and for the surface heatflow undulations. However, it is difficult to support such a concept when permeabilities are so low in the deepest kilometer of basement penetrated by Hole 504B. Perhaps hydraulic connectivity is relatively poor in the section penetrated by the hole as a result of some type of structural discontinuity or crustal anisotropy, and permeabilities measured in the borehole are anomalously low for the region. Stephen (1985, 1988) showed that the crust on the southern flank of the Costa Rica Rift is highly anisotropic, and Morin et al. (this volume) presented data indicating that the ratio of horizontal principal stresses at Hole 504B is very high. Perhaps this particular anisotropic state of stress has produced preferential faulting on a very large scale with localized zones of high permeability away from Hole 504B. The resulting pattern of hydrothermal circulation constrained by these faults may distribute heat sources and sinks in such a way as to affect the vertical distribution of heat flow in this relatively young crust. The fact remains that heat flow decreases from approximately 196 mW/m^2 at the surface to 120 mW/m^2 at 1300 mbsf, with no clear explanation at this time.

SUMMARY

The precise temperature profile obtained from Hole 504B during Leg 111 provides a continuous record across a 1300-m vertical interval of the upper oceanic crust; these data allow the geothermal and hydrologic characteristics of the area to be assessed. Temperature logs obtained during earlier legs display a distinctively depressed profile across the upper 400 m of the hole due to flow of cold ocean bottom water down the hole into the uppermost basement. Over time, this flow has decayed as subhydrostatic pressures evident in the permeable uppermost basement have dissipated. The volume of flow down through the casing, estimated to be about 6000-7000 L/hr in late 1979, decayed to about 80 L/hr almost 8 yr later during Leg 111.

At depths below 480 mbsf, conductive conditions apparently predominate in Hole 504B, and borehole-fluid temperatures are assumed to represent true formation temperature. The temperature gradient log is related directly to thermal conductivity and, in turn, to porosity and mineralogy. As a result, correlations can be observed between the temperature gradient and lithology on both fine and broad scales. Short-wavelength fluctuations in the gradient log in the casing through the sedimentary column correspond to biostratigraphic age markers and/or sharp changes in sediment composition and texture. Over a broader range, variations in the temperature gradient in the basement correlate with large-scale porosity trends.

The apparent reduction in conductive heat flow with depth in Hole 504B is an issue that remains unresolved. Various borehole phenomena were examined in a search for possible sources of error or unanticipated limitations in the resolution of the temperature log. Small corrections to thermal conductivity at *in-situ* conditions and the inherent instability of the fluid column were considered, but the magnitudes of the respective adjustments were found to be too small to explain the disparity between surficial and deep estimates of heat flow. Regional hydrothermal circulation was also considered as a possible explanation, but the low basement permeabilities measured in Hole 504B make this concept difficult to support. However, the theoretical case for the existence of an extensive sequence of convection cells within Hole 504B does provide further confirmation for the vertical mixing of borehole fluids postulated from chemical and isotopic studies of borehole waters.

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