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15. TEMPERATURE MEASUREMENTS AT SITE 395, ODP LEG 109[1]

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ABSTRACT

Borehole temperatures in Hole 395A were continuously logged during Leg 109, over 10 years after the hole was drilled during Leg 45 and about 5 years after temperatures in the hole were previously measured during Leg 78B. The more precise Leg 109 data are basically consistent with temperatures measured during Leg 78B, except at intermediate depths of 300–500 mbsf. Temperatures measured during Leg 109 indicate a vigorous flow of ocean bottom water down the 112 m of casing and into the permeable upper basement, at a rate virtually undiminished since Leg 78B. The temperature gradient in the sediments was measured at the nearby Hole 395C, allowing the rate of flow down Hole 395A to be estimated at about 10–100 m/hr. The fine-scale structure in temperature gradients in Hole 395A indicates that the water outflow occurs predominantly in the basement above 300 mbsf, with additional outflow zones between 430 and 530 mbsf. Below 450 mbsf, the gradient profile is affected by flow within the borehole, but indicates predominantly conductive heat transfer. The temperature gradient in the deeper section is consistent with a heat flow of about 200 mW/m^2, close to the value predicted for the 7.3-m.y.-old crust at the site.

INTRODUCTION

Temperatures in Hole 395A and the surrounding sediments were logged during Leg 109 of the Ocean Drilling Program (ODP), with the purpose of characterizing the geothermal and hydrological regime at the site. Hole 395A had been drilled over 10 years earlier during Leg 45 in 1975–1976, in 7.3-m.y.-old crust under an isolated sediment pond in which heat flow is low and variable (Fig. 1; Hussong et al., 1979). The hole was cored through 93 m of sediments and 571 m of mostly basaltic basement (Melson, Rabinowitz, et al., 1979); the upper 112 m is cased, and the deepest 58 m of the hole have filled with cavings since the hole was drilled (Hyndman, Salisbury, et al., 1984; Detrick, Honnorez, Bryan, Juteau, et al., 1988).

Temperatures in Hole 395A were previously measured when it was reentered during Leg 78B in 1981 (Fig. 2), although some of these measurements were marred by instrumental failures and disturbances to the borehole. Despite these problems, Becker et al. (1984) concluded from the Leg 78B data that: (1) cold ocean bottom water was flowing down the 112 m of casing into the basement, as indicated by nearly isothermal temperatures from seafloor to about 300 m below seafloor (mbsf), and (2) the gradient in the deepest section of the hole was probably conductive, consistent with the heat flow predicted for conductively cooling 7.3-m.y.-old crust.

The temperature measurements conducted during Leg 109 were designed to verify these conclusions, to monitor the patterns of flow of ocean bottom water down the hole and into the formation, and to determine the equilibrium gradient in the deeper section of the hole. A continuous, high-precision temperature log was run in Hole 395A, both to locate the zones into which the downhole flow is directed and to accurately determine the conductive gradient deep in the hole. In addition, as was attempted during Leg 78B, temperatures in the sediments were measured at the uncored "Hole" 395C offset 110 m from Hole 395A. The difference between temperature gradients measured in the cased section of Hole 395A and in the undisturbed sediments at Hole 395C allows the rate of downhole flow in Hole 395A to be estimated.

MEASUREMENT DEVICES

Several tools were used for the temperature measurements during Leg 109, including the ODP WSTP (water sampler, temperature, pressure) tool, the ODP APC (advanced piston corer) heat flow tool, a German high-precision logging tool, and a sensor included in a Japanese magnetometer. The ODP tools are designed so that a single thermistor protrudes a short distance ahead of the bit for temperature measurements in sediments or in open hole (e.g., Erickson et al., 1975; Hyndman et al., 1987; Becker, 1988). The WSTP tool, formerly known as the Uyeda probe (Yokota et al., 1980), incorporates a thermistor encased in a 12.5-mm-diameter steel probe that extends 0.6 m ahead of the bit; during Leg 109, it was programmed to sample the resistance of this thermistor every minute during a 2-hr deployment. The APC tool (Horai and Von Herzen, 1986) incorporates a thermistor within an APC cutting shoe that extends 0.3 m ahead of the bit; it was programmed to sample the resistance of this thermistor every 15 s during deployments lasting 3 or 4 hr. During Leg 109, the APC tool worked much more reliably than the WSTP tool, and only data from the APC tool are shown here.

The German high-precision temperature-logging device was developed at the Bundesanstalt fur Geowissenschaften und Rohstoffe (BGR, or Federal Institute for Geosciences and Natural Resources), Hannover, Federal Republic of Germany. The BGR tool basically consists of a probe with a 200-ohm platinum sensor of very short response time, a high-resolution digital multimeter for four-wire resistance measurement, and a desk-top computer with plotter (Kopietz, 1984). The overall accuracy of this device is about 0.01°C. The resolution of the temperature measurements is about 0.001°C, and the depth resolution ranges from 1 to 20 cm (selectable depth intervals). The probe was modified for logging ODP boreholes to withstand pressures up to 1 kb and temperatures up to 320°C. Before temperatures in Hole 395A were logged, the entire system (including logging winch and cable) was calibrated, yielding a correction for the cable of about +0.1°C to the sensor calibration constants. As a routine check immediately before and after logging, proper functioning of the measurement system was confirmed by testing against a reference resistor. Temperatures in Hole 395A were sampled at depth intervals of 2 cm at a downward logging speed of 5 m/min.

The Japanese magnetometer (Hamano and Kinoshita, this volume) includes a platinum sensor (KT6-7) in the bottom section of its pressure case. The temperature resolution is about 0.005°C, over a

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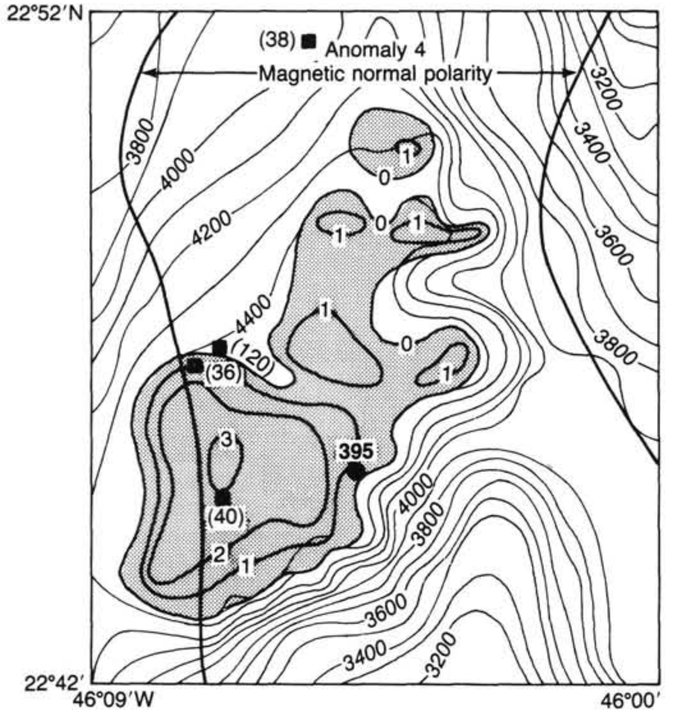

Figure 1. Bathymetry in corrected meters and sediment isopachs in seconds of two-way traveltime near Site 395. Heat flow stations of Hussong et al. (1979) are shown as solid squares, with values in mW/m^2. After Salisbury and Hyndman (1984).

range of about 0–300°C. Temperatures were sampled at 2 m intervals in Hole 395A while logging upward with this device at a speed of 2 m/min.

OPERATIONS

Hole 395A

It was planned to run the temperature log as soon as possible after reentering Hole 395A, to minimize any disturbance to the equilibrium temperatures in the borehole, which had not been reentered during the previous 5 years. However, it was not possible to continuously log borehole temperatures with the BGR probe until after a pipe run to clean the hole, a precaution against the possibility of bridges in the hole.

Instead, borehole temperatures were measured first using the ODP tools near the bottom of the casing, where accurate temperature data would best resolve the rate of flow of ocean bottom water down the hole. Immediately after reentry, the pipe was run slowly and without circulation to 100.6 mbsf, near the bottom of the casing at 112 mbsf. With two joints of drill pipe made up in the derrick, a tandem combination of the ODP WSTP tool plus APC heat flow tool was lowered on a wire rope to the bit, pausing first for a calibration point against bottom water temperature at the seafloor. With the probes seated in the bit, the pipe was slowly lowered, pausing at each joint for 10-min readings of borehole temperatures at 100.6, 109.2, and 118.8 mbsf (Fig. 3A).

The probe was retrieved, and the pipe was run slowly and without circulation or rotation to 544 mbsf. Another lowering of the paired WSTP and APC tools was attempted at this depth, but neither temperature recorder worked properly. The pipe was then lowered until the bottom of the hole was encountered at 606 mbsf. The hole was found to be completely clean, and no rotation or circulation had been required to this point. Therefore, the disturbance to the equilibrium borehole temperatures during this pipe run was minimal. The pipe was pulled slightly off bottom, to 592 mbsf, and the BGR temperature probe was used to obtain a high-precision temperature log within the pipe from seafloor down to 582 mbsf (Figs. 2 and 4).

After this log, the hole was conditioned for an extensive logging program by circulating for 30 min before pulling the pipe up into the casing. This was probably the only significant disturbance to borehole temperatures during the logging program. About 3 days later, the Japanese magnetometer was run, obtaining a continuous record of borehole temperatures while logging up the hole (Fig. 4). A second run of the BGR probe in open hole was planned for the end of the logging program, to check the results obtained during the first log in the pipe, but insufficient time precluded this repeat log.

Hole 395C

After 4 days were spent logging Hole 395A, the pipe was pulled out of the hole and offset 110 m northwest. Hole 395C was spudded solely to measure the background geothermal gradient in the sediments at Site 395, which had not been accurately determined in a similar attempt during Leg 78B (Becker et al., 1984). The ODP APC heat flow tool was permitted to fall freely down the pipe and latched into the bit. The bottom-hole assembly was then washed and pushed into the sediments, pausing to measure temperatures at three depths, 31, 58, and 94 mbsf.

The resulting temperature record (Fig. 3B) reflects the fact that the measurement technique in Hole 395C was quite different than the normal method for deployment of the APC tool, during which it records temperatures before and after the instantaneous penetration of the APC cutting shoe into sediments. Instead, when the bit was about 5 m above each measurement depth, circulation was stopped, and the probe was slowly pushed into sediments undisturbed by circulation and presumably at *in-situ* temperature. The sensitive heave compensator was used to maintain the minimum weight required on bit to hold the probe in stable position; the precise depth of measurement was therefore a function of the strength of the sediments.

Given that it took several minutes to push the tool to each measurement depth, it is questionable whether the approach of the measured temperatures to *in-situ* temperature can be adequately described by the decay curve after instantaneous penetration (Horai and Von Herzen, 1986). Nevertheless, the estimated *in-situ* temperatures shown in Figure 3B were approximated by fitting the measured data to this theoretical decay curve in a least squares sense.

INTERPRETATION OF RESULTS

A comparison of the temperature logs from Leg 109 with those from Leg 78B (Fig. 2) shows that the two data sets are basically consistent in the upper and lower sections of Hole 395A, but are distinctly different in the intermediate depths of 300–500 mbsf. It is likely that this difference is related to the circulation and thermal disturbance to the borehole fluids that apparently occurred during the Leg 78B measurement program (Becker et al., 1984); this difference may also be related to possible transient temperatures associated with the development of the strong downhole flow since the hole was drilled. Below 500 mbsf, the Leg 78B data approach estimated equilibrium temperatures in close agreement with Leg 109 temperatures, which may represent *in-situ* temperatures before the section was drilled.

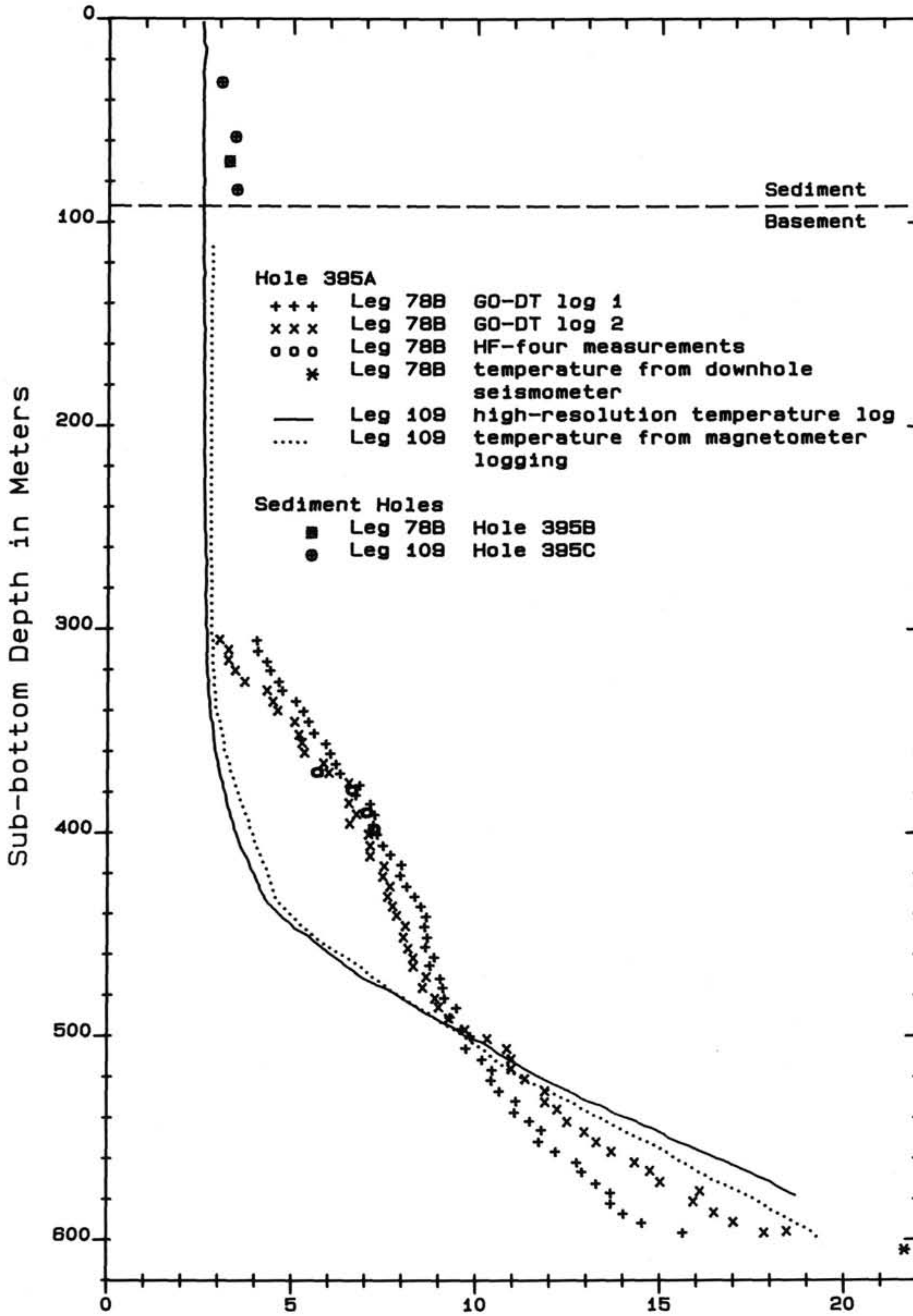

Figure 2. Temperatures measured at Site 395 during Legs 78B and 109. Temperatures measured in the sediments at Holes 395B and 395C are significantly greater than isothermal values measured at corresponding depths in Hole 395A during Legs 78B and 109. In the basement section, the Leg 78B logs were measured at disequilibrium caused by some disturbance of the fluid in the borehole (Becker et al., 1984), whereas the Leg 109 BGR data (solid line) represent virtually undisturbed borehole temperatures.

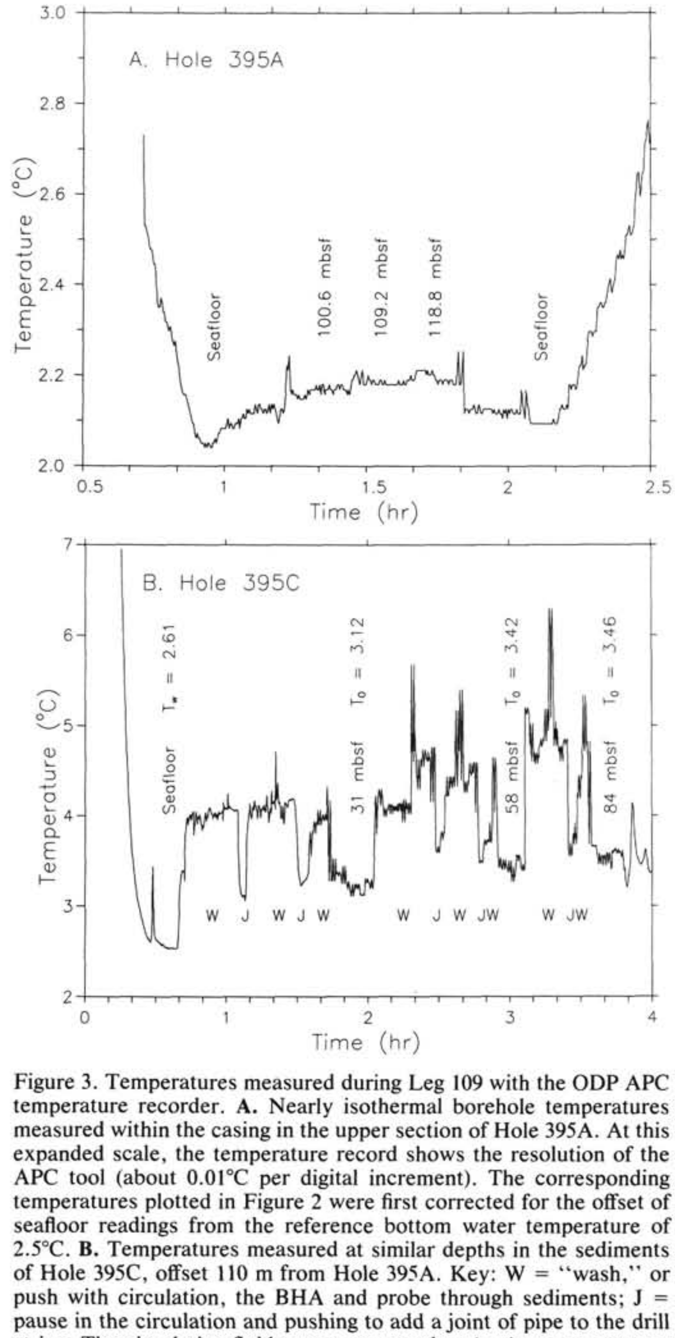

Figure 3. Temperatures measured during Leg 109 with the ODP APC temperature recorder. **A.** Nearly isothermal borehole temperatures measured within the casing in the upper section of Hole 395A. At this expanded scale, the temperature record shows the resolution of the APC tool (about 0.01°C per digital increment). The corresponding temperatures plotted in Figure 2 were first corrected for the offset of seafloor readings from the reference bottom water temperature of 2.5°C. **B.** Temperatures measured at similar depths in the sediments of Hole 395C, offset 110 m from Hole 395A. Key: W = "wash," or push with circulation, the BHA and probe through sediments; J = pause in the circulation and pushing to add a joint of pipe to the drill string. The circulating fluids were warmer than *in-situ* temperatures; therefore probe temperatures were also warm during the periods of circulation, but dropped to near *in-situ* values when circulation was stopped, either to add joints of pipe or at the three measurement depths.

Temperature gradients measured in Hole 395A

The temperature logs measured during both Legs 78B and 109 show nearly isothermal profiles from seafloor down to a depth of about 300 mbsf (Figs. 2 and 4). A linear regression applied to the data obtained during Leg 109 with the BGR high-precision probe inside the drill pipe in this depth range yields a gradient and standard deviation of 0.25 ± 0.003 mK/m. From 300 to about 430 mbsf, the BGR log shows a smooth increase of gradient to about 25 mK/m (Figs. 2 and 4). In the deeper section of the hole, the gradient increases to about 120 mK/m, apparently in steps of up to 45 mK/m at the three depths of about 430, 475, and 530 mbsf (Fig. 4). At the final logging depth of 585 mbsf, a temperature of 18.9°C was measured. The data obtained with the sensor in the Japanese magnetometer during upward logging in open hole after slight circulation yielded essentially consistent results (Fig. 4).

Downhole flow of ocean bottom water into basement

The nearly isothermal temperature gradient down to a depth of about 300 mbsf indicates that a vigorous flow of ocean bottom water has persisted for over 10 years since Hole 395A was drilled. The ocean bottom water must flow at a uniform rate down the casing, and then exit laterally into the basement section that the hole penetrates. The temperature profile may be sensitive to the position(s) of specific zone(s) in basement into which the mass flux is directed. Similar thermal flowmeter methods have been developed for precise determination of fluid inflows and outflows from transient temperature changes in fluid injection wells (Murphy, 1977; Schellschmidt and Haenel, 1987), but their applicability is limited under quasi-stationary conditions as in Hole 395A.

The position of some of the outflow zones in Hole 395A can be deduced from changes in the temperature gradient. However, when the downhole flow is vigorous as in Hole 395A, outflows are possible without significantly affecting borehole temperatures, as the remaining downhole flow may maintain a nearly isothermal gradient in the borehole. Outflow zones and resultant changes in the temperature gradient can only be resolved at depths below which the downhole flow falls below a certain threshold rate, as can be seen from temperature measurements in Hole 504B (Becker et al., 1983a, 1983b, 1985).

To investigate some of the zones in Hole 395A into which seawater flows from the borehole into the formation, the fine-scale structure in temperature gradients was evaluated from the BGR high-resolution measurements by applying a sliding regression using different window widths (Fig. 5). Below about 300 mbsf, the BGR temperature gradient profile clearly shows variations with higher amplitudes and frequencies. This probably reflects a considerable decrease in the downhole mass flux by water outflow into the formation above 300 mbsf. Steep increases in the gradient at depths of about 300, 430, 475, and 530 mbsf (Fig. 5) probably mark outflow horizons or sections.

Estimation of Rate of Downhole Flow in Hole 395A

The rate of flow of ocean bottom water down Hole 395A can be estimated from the difference between temperature gradients measured in the sediments of Hole 395C and in the cased section of Hole 395A. The temperature record for Hole 395C shows the strong effects of circulation as the probe was moved between measurement depths, but shows relatively stable readings during the short periods when circulation was stopped and the probe was held in undisturbed sediments (Fig. 3B). The estimated *in-situ* temperatures suggest a background geothermal gradient of 0.01 K/m, and a temperature at the bottom of the casing (112 mbsf) of 1.3°C above bottom water temperature. In contrast, temperatures actually measured during Leg 109 at this depth in Hole 395A exceeded bottom water temperature by only 0.1°C on the initial reentry (Fig. 3A) and only 0.03°C during the BGR log (Fig. 6). Using quasi-steady-state models of Ramey (1962) and Becker et al. (1983a, Eq. 7), these gradient values yield estimates of the downhole flow rate ranging from 10 to 100 m/hr, corresponding to volume fluxes of 700 to 7000 L/hr. If the rate of downhole flow is assumed to have held constant during the 10 years since Hole 395A was drilled, the total volume flux down

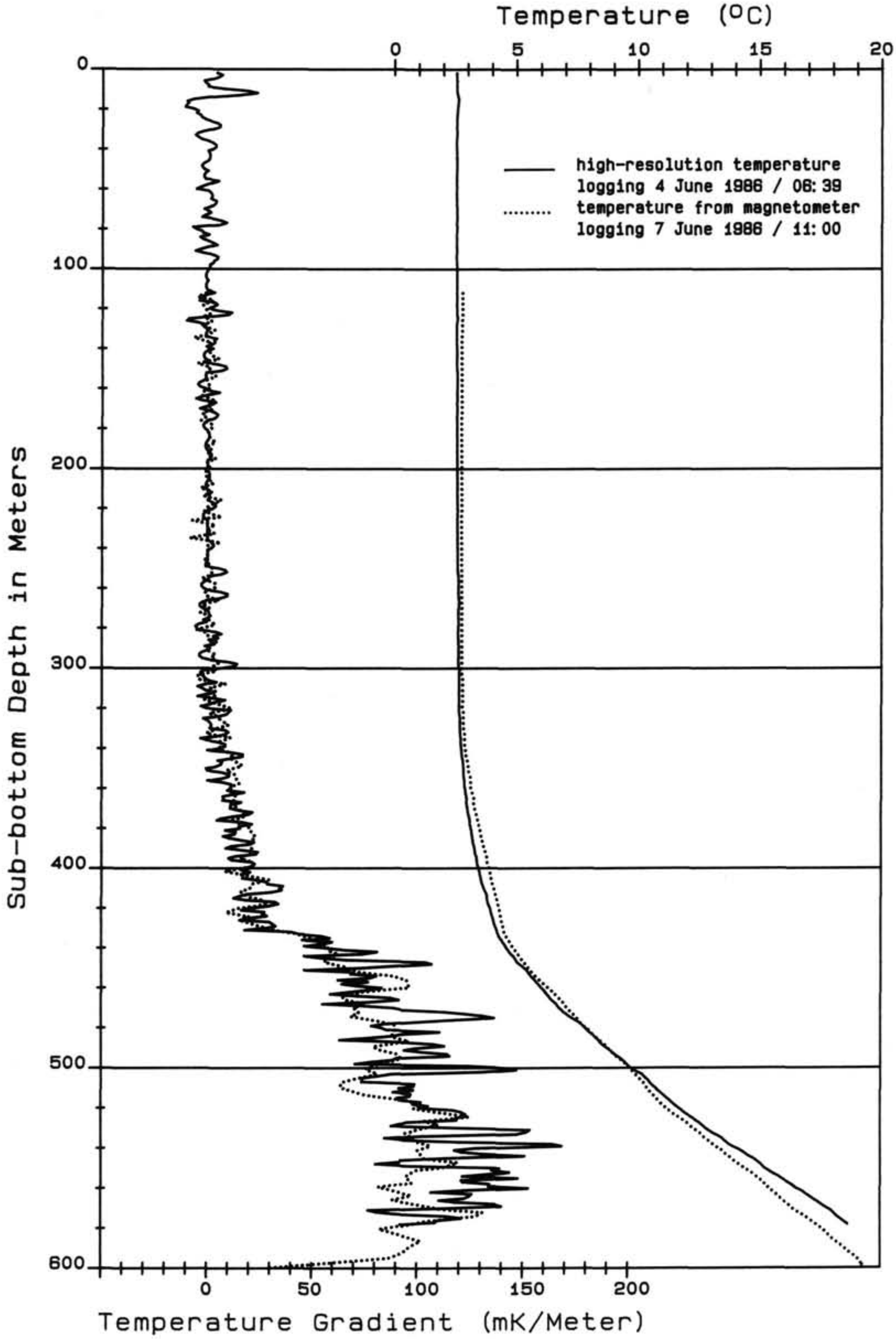

Figure 4. Logs of temperature and temperature gradient measured in Hole 395A during Leg 109.

Hole 395A and into the surrounding formation has been at least 10^8–10^9 L of seawater.

Conductive gradient deep in Hole 395A

The temperature gradient deeper than about 450 mbsf in Hole 395A shows zones with more stable mean values of the gradient (Figs. 2, 4, 5). Although advective processes may still affect the measured temperatures, the stability of the gradient is interpreted as the transition to mostly conductive heat transfer deep in the hole where electrical resistivity increases, porosity decreases (Becker, this volume; Moos, this volume), and permeability is very low (Hickman et al., 1984). The

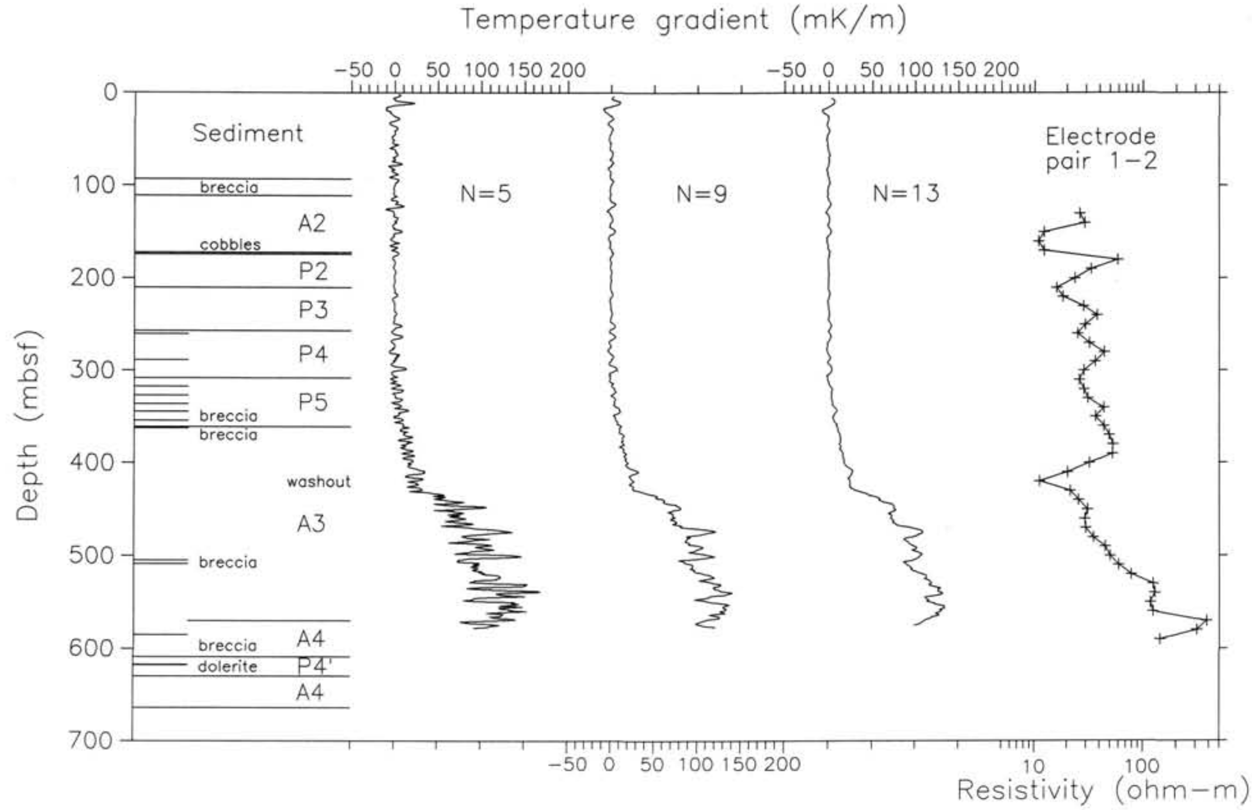

Figure 5. Logs of temperature gradient in Hole 395A compared to the core lithology on the left and a resistivity log on the right. The temperature gradient logs were constructed from the high-resolution BGR temperature log conducted during Leg 109, by applying sliding regressions using different window widths N, where N is the number of temperature-depth data within the window. Lithology summarized from Shipboard Scientific Party (1979), who identify 23 lithologic units (delimited by short horizontal lines on left), most of which belong to nine major chemical/magnetic types (delimited with long horizontal lines on left). These chemical/magnetic types are composed mostly of aphyric (A2–A4) or phyric (P2–P5 and P4') pillow lavas, with some minor flows, and are sometimes separated by breccias or cobbles. The resistivity profile is that obtained with the shortest-spaced electrode pair in the large-scale resistivity experiment conducted during Leg 109 (Becker, this volume).

gradient measured in this section is about 100–120 mK/m. Using the average thermal conductivity measured on basalt samples from Hole 395A, 1.8 W/m-K (Hyndman et al., 1984), this yields a heat flow of 180–216 mW/m^2. With a slight negative correction to *in-situ* conductivity for the effect of porosity, the estimated heat flow is consistent with the value of 175–185 mW/m^2 predicted for conductively cooling 7.3-m.y.-old crust (Lister, 1977; Parsons and Sclater, 1977).

CONCLUSIONS

Temperatures measured in Hole 395A during Legs 78B and 109 reflect two different processes in the shallow and deep sections of the hole. From seafloor to about 300 mbsf, the nearly isothermal temperatures indicate a vigorous downhole flow of ocean bottom water at a rate virtually undiminished in the 5 years between Legs 78B and 109. Using the background gradient of 0.01 K/m measured in the nearby sediments at Hole 395C, the rate of downhole flow is estimated to be 10–100 m/hr, or 700–7000 L/hr, over 10 years since Hole 395A was first drilled.

The fine-scale structure in temperature gradients in Hole 395A indicates outflow of the water flowing down the hole into the formation at depths of 300, 430, 475, and 530 mbsf. Outflow of this water into the formation above 300 mbsf is likely without significantly affecting the borehole temperatures, which remain depressed by the vigorous downhole flow. The greater part of the downhole mass flux has probably exited into the basement section from 112 to 300 mbsf.

Deeper than 400 mbsf, the effect of the downhole flow on measured temperatures diminishes, and the gradient increases to a value consistent with conductive plate heat transfer. Variations in the temperature gradient measured in this section show no clear correlations with lithology. However, the increasing gradient deep in the hole correlates with decreasing porosity and increasing sonic velocities, electrical resistivity, and permeability.

The thermal observations made during Leg 109 are quite consistent with those made during Leg 78B, and with the indications that Hole 395A penetrates two hydrologically different sections: (1) the permeable, upper few hundred meters of basement, in which advective processes are active, and (2) the relatively impermeable section below, in which conductive processes predominate. These results support the hydrogeological models of Langseth et al. (1984), who suggest that the upper few hundred meters of basement around Site 395 is being cooled by lateral flow of pore waters beneath the sediment cover. In this context, the strong downhole flow of ocean bottom water revealed by the temperature measurements results because the hole bypasses the sediment cover and taps directly into an active hydrogeological system beneath the isolated sediment pond.

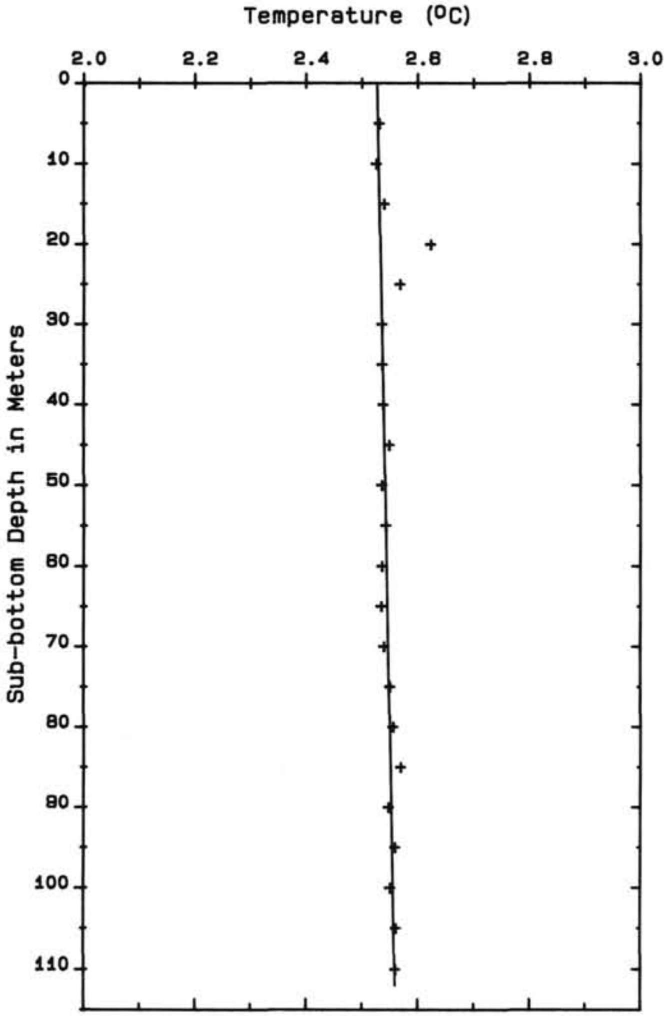

Figure 6. Expanded view of temperatures measured with the BGR tool inside the drill pipe within the cased section of Hole 395A.

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