18. GEOTHERMAL MEASUREMENTS ON LEG 8[1]

R. P. Von Herzen, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts,
R. J. Fiske, Lamont Doherty Geological Observatory, Palisades, New York,
and
G. Sutton, Hawaii Institute of Geophysics, Honolulu, Hawaii

INTRODUCTION

During Leg 8 of the D.S.D.P. (October-November, 1969), several attempts were made to measure temperature and heat flow at Sites 71 and 72 in the central equatorial Pacific. The method utilized a temperature-measuring probe lowered through the drill pipe and pushed into the soft sediments below the drill bit at intervals during the drilling; this is similar to a previously-used method on the pre-Mohole project (Von Herzen and Maxwell, 1964). In addition to the measurements obtained in sediments below the drill bit, temperature information was obtained during the slow passage of the probe through the drill string. Measurements were made to depths as great as 250 meters beneath the sea floor in calcium carbonate-rich oozes. Thermal conductivity measurements were made aboard ship on the recovered cores.

A principal objective of the temperature measurements was to determine if heat-flow measurements made in deep holes agree with representative samples of the set of several thousand marine heat-flow measurements made over much shorter intervals beneath the sea floor (Langseth, 1965). This objective was not fully realized in the measurements made on Leg 8 owing to instrumental and operational difficulties. Although the interpretation of the complete set of data is ambiguous, much of it is reasonably consistent with extrapolations of thermal gradients determined by standard oceanographic techniques. The methods and equipment used here appear to have promise for much more accurate measurements on future drilling operations.

OPERATIONS

After coring was completed at Sites 71 and 72, the following general procedures were used to obtain the temperature measurements:

(1) The drill pipe and bottom hole assembly were withdrawn from the hole, so that the drill bit was suspended in the water *above* the sea floor.

(2) A new hole was drilled nearby, to the depth at which a temperature measurement was desired.

(3) The drill bit was raised a few meters off the bottom of the hole and, in most cases, water circulation through the drill pipe was shut down.

(4) The temperature measuring sonde within a special inner core barrel was lowered through the drill pipe and emplaced at the bottom of the bit, with the temperature sensor extending below the bit through the bit hole used for coring.

(5) The entire drill string was lowered to the bottom of the hole for 10 to 20 minutes for the sediment temperature measurement.

(6) Subsequently, the temperature sonde was retrieved with the logging cable, and the procedure repeated after drilling the hole to a greater depth or beginning a new one.

The configuration of the bottom hole assembly (Figure 1) was the same at both Sites 71 and 72. The drill collars provide weight (~ 1600 kilograms each) for the drill bit, and the bumper subs are collapsible sections (total movement of 1.5 meters each) which allow for vertical motions of the drilling vessel. Except for one bottom hole measurement attempt (Site 71, 250-meter hole), these bumper subs were generally ineffective in the soft calcareous oozes penetrated at these sites; this may account for much of the difficulty in measuring equilibrium temperatures. The overall physical makeup of the equipment proved workable but somewhat cumbersome, particularly during entry and exit of the probe at each end of the drill string, a period when most damage to probes was experienced.

A summary of the sequence of the relevant events during the drilling and measurements at Sites 71 and 72 is presented in Tables 1 and 2.

[1]WHOI Contribution No. 2012.

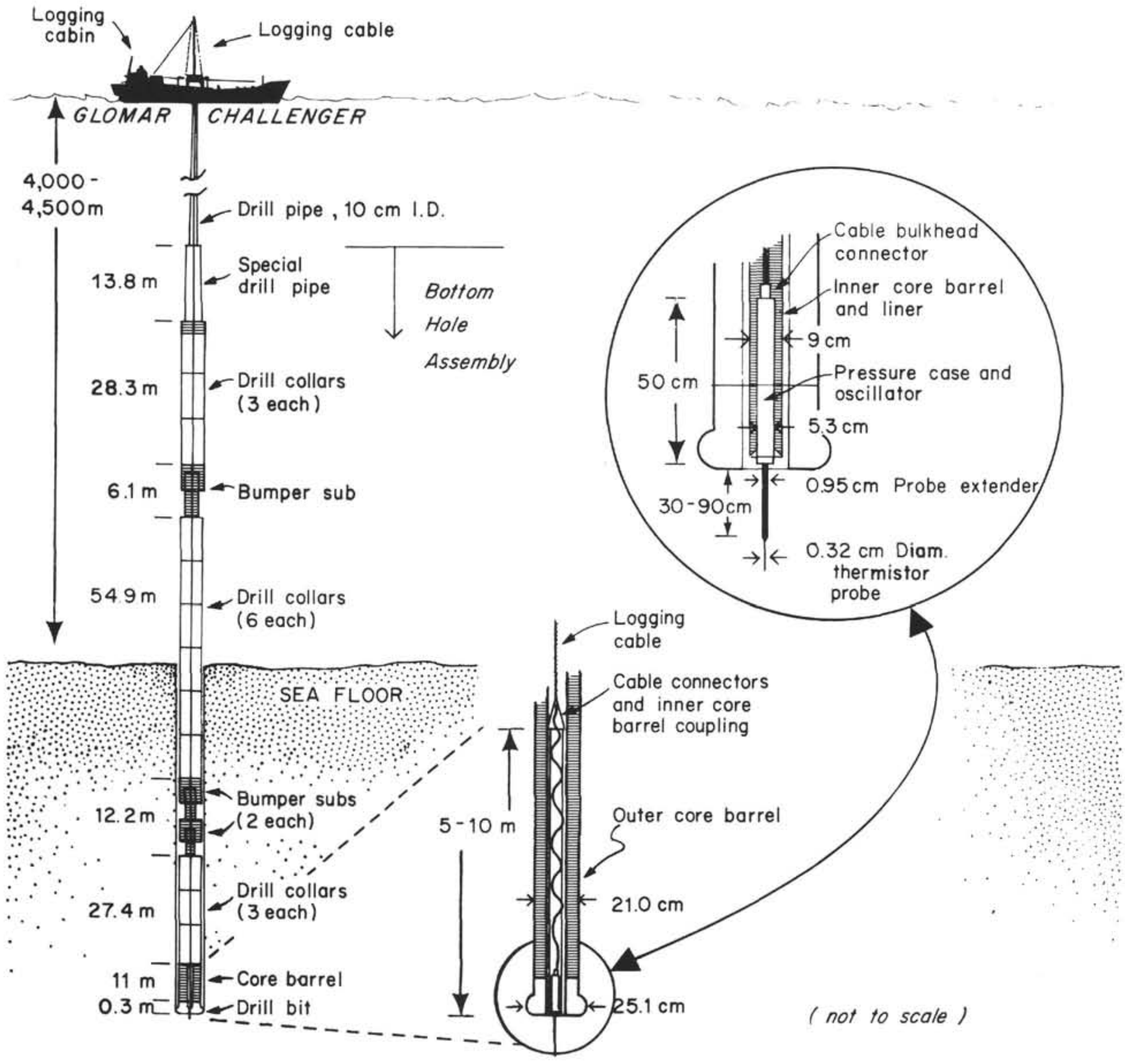

Figure 1. *Schematic configuration (not to scale) of the JOIDES drill string, bottom hole assembly, and temperature-measuring hardware.*

TABLE 1
Summary of Events at Site 71
(Location: 4° 28.28'N, 140° 18.91'W; Water Depth: 4419 meters)

Hole 71A

7 Nov., 1943 hours – Spud in and begin drilling

2010 hours – Complete drilling to 27.5 meters below bottom, stop circulation[a]

2050 hours – Insert temp. logging tool in pipe.

2239 hours – Probe entering hole.

2242 hours – Probe in bottom.[b]

2242¾ - 2244¾ hours – Period of relatively steady counts in bottom.

2246¾ hours – Lower drill pipe 1 - 2 meters.

2247 hours – Loss of signal, probably due to probe break.

Hole 71B

9 Nov., 1330 hours – Spud in and begin drilling.

1420 hours – Complete drilling to 101 meters below bottom, stop circulation[a], raise bit 10 meters off bottom of hole.

1423 hours – Start down pipe with temperature logging tool.

1623¼ - 1630¾ hours – Probe lowered from 0 to 81 meters below bottom in hole.

1636 hours – Lower bit to bottom of hole, with no apparent weight loss.

1638 hours – Being to lower probe slowly.

1640½ hours – Probe in bottom.

1649 - 1651 hours – Period of minimum relatively steady temperatures in bottom.

1654 - 1656 hours – Period of maximum relatively steady temperature in bottom.

1657 hours – Pull out of bottom.

1657 - 1710 hours – Ascend from 101 to 0 meters below bottom.

2024 - 2120 hours – Drill from 101 to 250 meters below bottom, continue circulation at 400 gal/min.

2240 hours – Stop circulation.

2241 hours – Start down with temperature probe.

10 Nov., 0037 - 0058½ hours – Lower probe 0 to 240 meters below bottom.

0112 hours – Lower drill string to bottom, lost ~10,000 kilograms weight.

0116¾ - 0118 hours – Lower probe to bottom.

0127 hours – Lower drill string ~2 meters.

0127 - 0158½ hours – Observe steady thermal decay of probe.

0158½ - 0202 hours – Raise probe from 250 to 232 meters below bottom.

0202-0207 hours – Raise probe from 232 to 185 meters below bottom.

0207 - 0216½ hours – Raise probe from 185 to 0 meters below bottom.

0358 hours – Probe removed from drill string.

---

[a]Intermittent circulation rates during drilling varied between 300 - 400 gal/min.

[b]On this hole, the drill bit remained at the bottom of the hole during probe lowering.

TABLE 2
Summary of Events at Site 72
(Location: 0° 26.49'N, 138° 52.02'W; Water Depth: 4326 meters)

Hole 72B

14 Nov., 2009 hours – Spud in and begin drilling.
2030 hours – Complete drilling to 50 meters below bottom, stop circulation.[a]
2100 hours – Start down drill string with temp. probe.
2247 - 2251½ hours – Lower probe 0-40 meters below bottom.
2305½ hours – Probe in bit, 10 meters above bottom of hole.
2312 hours – Lower bit to bottom of hole, and circulate[a] for 2-3 minutes (No weight loss).
2315 hours – Lower bit ~ 1 meters.
2321½-2323½ hours – Relatively stable readings in bottom.
2323½ hours – Start up with logging cable.
2333 hours – Frequency change, probably probe leakage.

15 Nov., 0053 hours – Probe on deck, damaged.
0050 - 0145 hours – Drill 50 to 105 meters.
0145 hours – Stop circulation.[a]
0238 - 0332 hours – Circulate ~ 300 gal/min.
0407 hours – Start down drill string with temperature probe.
0553 - 0603¼ hours – Lower probe 0-94 meters below bottom.
0607 hours – Lower probe into bit.
0614 hours – Lower bit.
0615½ hours – Change to high frequency, probably broken probe.

[a]Intermittent circulation rates during drilling varied between 300-400 gal/min.

INSTRUMENTATION

The temperature sensor consisted of a calibrated thermistor mounted in a cylindrical probe, which modulated a resistance-controlled oscillator. The oscillator was contained in a pressure case connected to and lowered with the probe inside the drill string, electrically powered and monitored from the drilling ship through a standard well-logging cable.

The free-running, thermistor-controlled oscillator in the pressure case was powered with a direct current electrical supply (±60 volts) from the ship through three conductors of the logging cable. The output frequency was returned to a counter display aboard ship with an additional conductor. The supply voltage at the oscillator was further regulated by zener diodes, providing buffering for resistance changes in the logging cable conductors owing to the effects of temperature and pressure. The oscillator was temperature compensated to within about 1 Hz over the temperature range 0°C to 25°C. The amplitude of the frequency returned to the ship (≈ 1 volt) was sufficient to interface with most commercial counters, and provided excellent noise immunity except during radio transmissions from the drilling vessel.

To minimize signal attenuation over a long cable, the oscillator was designed to operate over a frequency range of about 1 kHz to 3 kHz, corresponding to a temperature range of 0°C to 50°C of the thermistor. Over the limited temperature range encountered in these measurements (1°C to 6°C), the sensitivity remained relatively constant at about 0.025°C/Hz. Counts were made for periods of 1 second and recorded manually, so that an uncertainty of ±1 count corresponds to a (relative) temperature uncertainty of ±0.025°C. This is the uncertainty assumed for the measurements obtained within the drill pipe during transit to and from the bottom, but the bottom measurements were usually subject to other disturbances which increased their uncertainty.

The thermistor probes were made small in diameter (Figure 1) to minimize their time constant, which was determined to be about 4.5 seconds (90 percent of equilibrium) in a well-stirred water bath. An exception was the probe used for the 100-meter hole at Site 72, which had a time constant of about 16 seconds. Although some unusually low gradients were measured in the hole at this site, we believe that they were a result of causes other than the long probe time constant. The small-diameter portion of the probes had a length of about 2.5 centimeters, except for the Site 72 hole of 100 meters, where a probe of 10-centimeter length was used.

The rates of probe traverse through the drill string in the bottom varied from 10 to 20 m/min (Tables 1 and 2), so that except for the 100-meter hole at Site 72, the probes must have been in near temperature equilibrium with the water which they traversed. Even for the 100-meter hole at Site 72, the *gradients* measured in the water-filled pipe are probably nearly correct even if the long time constant probe may have incurred a small (but relatively constant) error in the temperature-depth plot of Figure 5.

RESULTS

The heat-flow measurements made at Sites 71 and 72 are divisible into two different categories according to the methods used: (1) those in which temperature gradients were measured during transit in the drill pipe in the bottom, and (2) those in which gradients are deduced from temperature measurements made in the sediments at the bottom of the drilled holes.

In the first category, the basic data are shown in Figures 2 through 5. At the 30-meter hole on Site 71 no data was obtained by this method, because the probe traversed the drill string in the hole beneath the bottom quite rapidly. In all other cases, depths are taken from the metering sheave on the logging cable. The sea-floor depth, as measured from echo sounding and drill string measurements, corresponded within a few meters to logging cable sheave measurements during descent at which significant temperature gradients were first encountered in the drill pipe. The depth at which the instrumentation reached the bottom of the drill pipe had an uncertainty of 10 to 15 meters due to the large weight ratio ($>$10:1) of logging cable to instrumentation, and elasticity of the logging cable.

The outstanding characteristics of the data in Figures 2 through 5 are the numerous linear segments of the temperature-vs-depth plots, separated by steps, or even reversals, and the overall linear trend. We have used the linear segments of the data, combined with thermal conductivity (K) measurements on cores, to deduce heat-flow values. Although there are some theoretical reasons which led us to be pessimistic about obtaining heat-flow values in this way (see Discussion below), many of the linear segments of the data give gradients which, when combined with thermal conductivity (K) measurements, give reasonable values of heat flow.

First, we discuss some of the possible reasons for the breaks in slope or discontinuities in the temperature-vs-depth plots. One theoretical possibility could be a sharp change in thermal conductivity (K) with depth, reflected by a change in the thermal gradient under equilibrium conditions. This seems ruled out at Site 71 by the significant but rather steady increase in thermal conductivity (K) from about 1.9 to 2.9 TCU (mcal/°C cm sec) between 0 and 250 meters depth, and by the rather uniform values down to almost 60 meters at Site 72 (Figures 6 and 7, respectively). The thermal conductivity values were measured on cores by the heated needle-probe technique (Von Herzen and Maxwell, 1959) and are corrected for *in situ* pressure and temperature (Ratcliffe, 1960). The cores were obtained from holes separated by at most a few tens of meters from those in which the gradients were measured; thus large uncertainties due to lateral variations in thermal conductivity are improbable.

It is more likely that the disturbances or departures from constant gradient with depth result from disequilibrium in the holes due to circulation of water. The water pumped down the drill string during drilling and afterwards (Tables 1 and 2) is probably close to the ambient temperature of deep-sea water before it enters the bottom as a result of exchanging heat with the surrounding sea water during its traverse through several kilometers of drill pipe. An indication of the lack of temperature equilibrium in the holes is given by the differences in temperatures during the "down" and "up" traverses. These differences appear relatively small for the 100-meter Site 71 data, but are quite large for the 250-meter Site 71 data. This difference probably results from the much longer period of water circulation for the 250-meter hole versus the 100-meter hole (2 hours, 15 minutes versus 50 minutes, respectively, Table 1). The same effect may cause some of the low gradients observed in the 100-meter Site 72 hole, where water circulation was continued for more than 1 hour after cessation of drilling, before the temperature measurements were made.

Another phenomenon characteristic of the 250-meter Site 71 hole, and perhaps to a lesser extent of the other holes also, is the reversal of the gradient at certain depths. We surmise that these are most likely caused by the leakage of circulating water through the bumper subs in the bottom hole assembly (Figure 1). A comparison of Figures 1 and 3 shows that the gradient reversals at 4500 meters and 4580 meters are farther apart and several tens of meters higher in the section than the locations of the bumper subs in the bottom hole assembly. This would be expected if leakage of

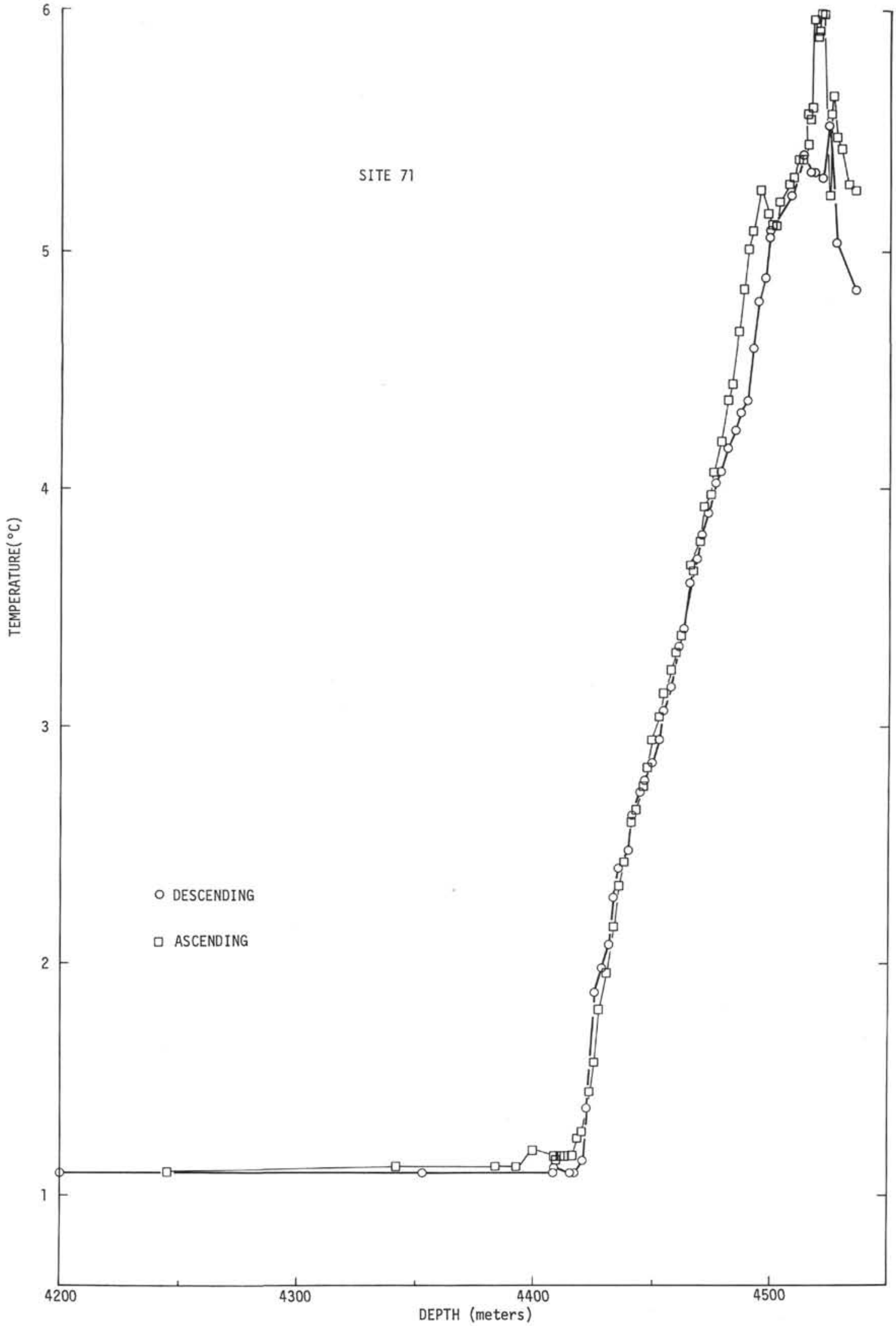

Figure 2. *Temperature vs. depth measured in the drill pipe near and below the sea floor. Site 71, 101-meter hole. Depths measured from logging cable metering sheave.*

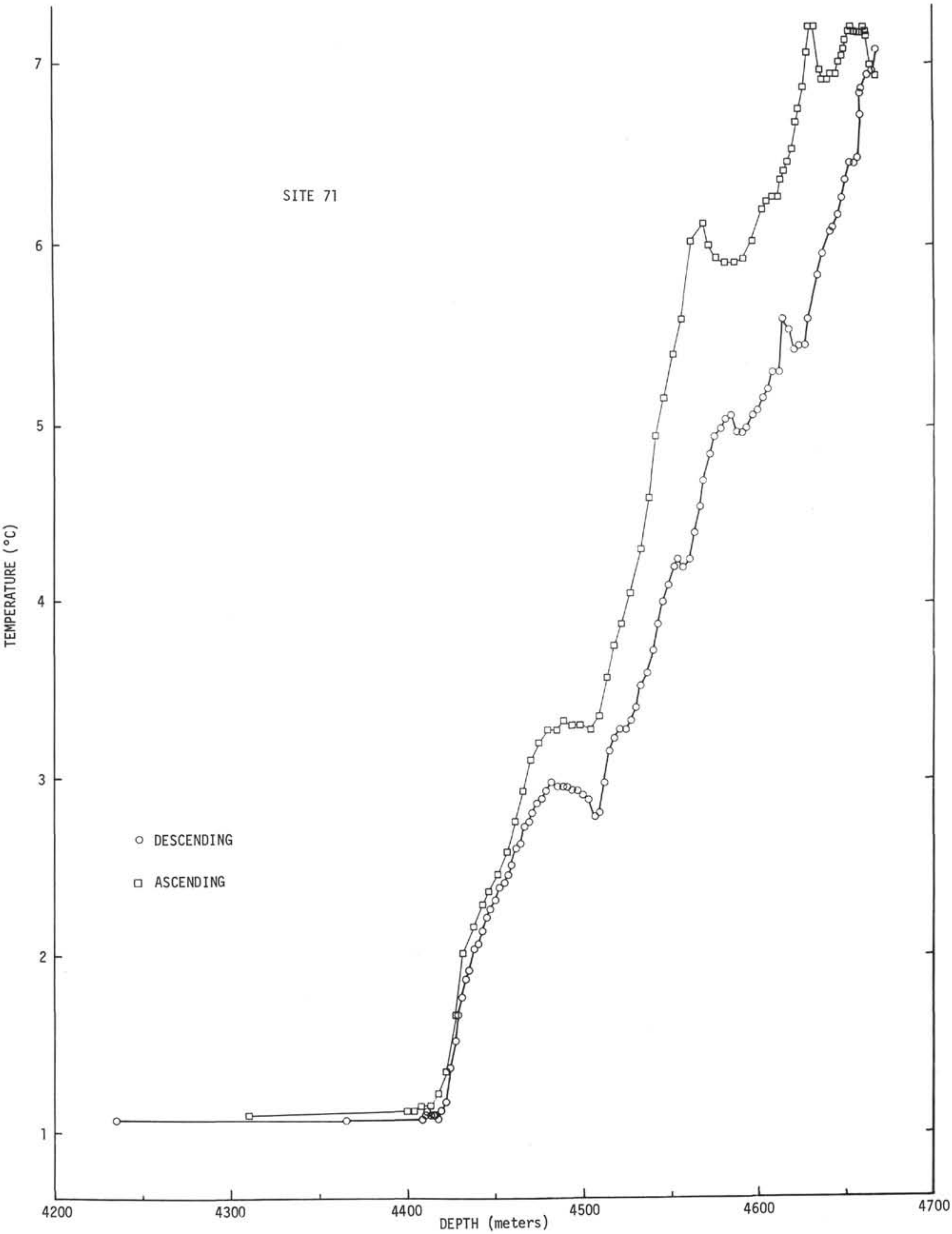

Figure 3. *Temperature vs. depth measured in the drill pipe near and below the sea floor. Site 71, 250-meter hole. Depths measured from logging cable metering sheave.*

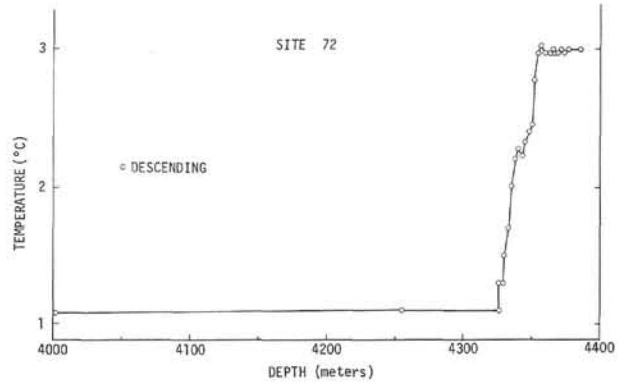

Figure 4. *Temperature vs. depth measured in the drill pipe near and below the sea floor. Site 72, 51-meter hole. Depths measured from logging cable metering sheave.*

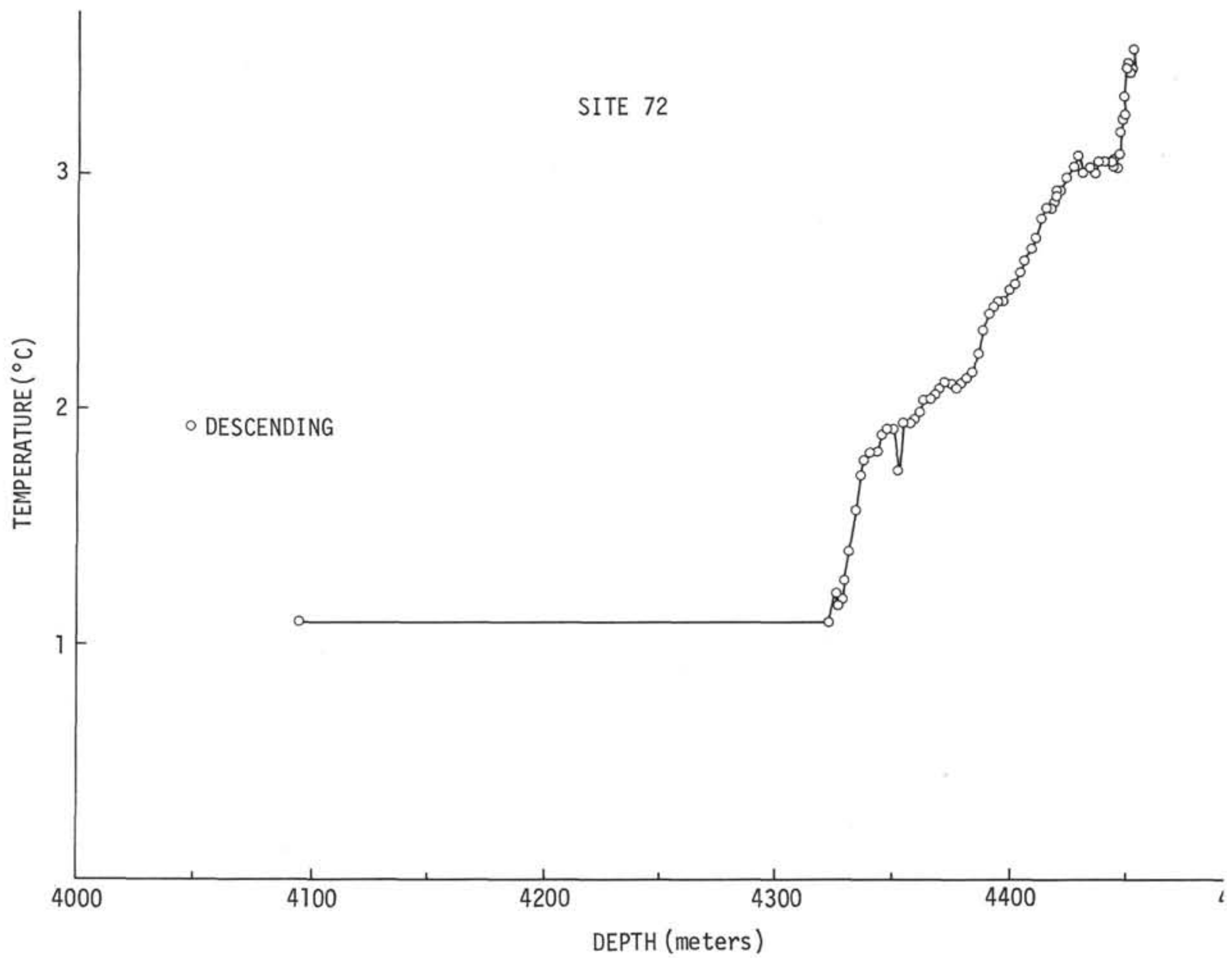

Figure 5. *Temperature vs. depth measured in the drill pipe near and below the sea floor. Site 72, 105-meter hole. Depths measured from logging cable metering sheave.*

circulating water through the bumper subs is superimposed on outflow from the bit, displacing upwards the cooling effect of water through the leaky bumper subs. The pumping action of the bumper subs, when they are being used to decouple ship motion from the drill bit, may also contribute to these observations.

The temperature measured in the drill pipe *above* the sea floor was usually reproduced within the precision of measurements where both "down" and "up" traverse data were available. However, these temperatures (1.0 to 1.1°C) are several tenths °C *lower* than those obtained nearby at similar depths with oceanographic heat-flow equipment (1.4°C, personal communication, M. Langseth). These differences are consistent with some tests made aboard ship, showing the probe reading several tenths °C lower temperature than a mercury thermometer. The thermistor probes were calibrated approximately 1 year before use, and the oscillator about 6 months before these measurements. Also, the oscillator was used on a previous leg (Leg 5), so that a combination of the previous use and elapsed time may account for some shifts in calibration. Unfortunately, all thermistor probes used were destroyed in the course of these measurements, and the oscillator was not available for subsequent recalibration.

The comparisons made with a mercury thermometer aboard ship showed relatively constant differences over the measured range of temperatures (0 to 7°C). Hence, even though the absolute temperatures in Figures 2 through 5 may be in error by several tenths °C, the *gradients* are probably not in error more than 5 per cent due to these calibration uncertainties.

The results of the gradients and thermal conductivities (K) measured over the linear portions of the temperature-depth curves are summarized in Table 3. The heat-flow (Q) errors for each interval are calculated from the departures of measured temperatures from the best straight line fits, combined with the errors inherent in digitization (±1 least count = ±0.025°C) and the standard errors of thermal resistivity for each interval. The simple means for each hole are the average of the heat flow interval values (± standard error), and the weighted means are weighted according to the depth interval over which the interval heat flows were determined. For the Site 72, a 105-meter hole, the interval from 120 to 125 meters was omitted from the mean calculations because it appears that these measurements were made during penetration of the probe through the sediments, and hence do not represent equilibrium temperatures.

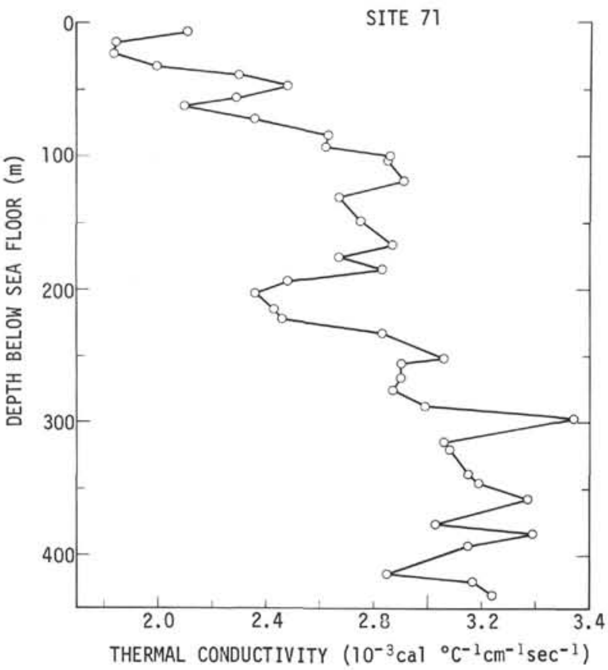

Figure 6. *Thermal conductivity vs. depth for Site 71. Values corrected for temperature and pressure.*

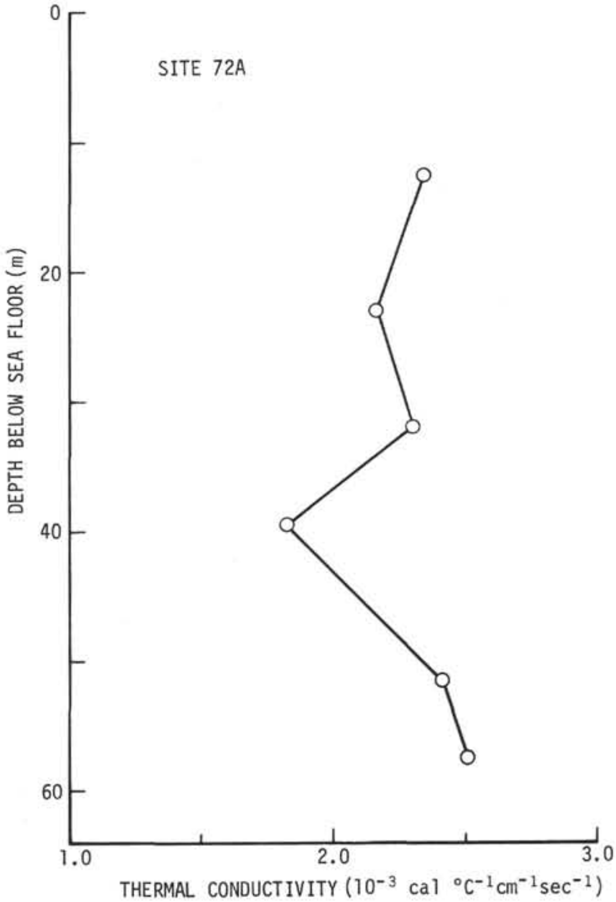

Figure 7. *Thermal conductivity vs. depth at Site 72. Values corrected for temperature and pressure.*

TABLE 3
Interval Temperature Gradients and Heat Flow Measured within Drill String at Sites 71 and 72

Depth Int. Below Bottom (m)	Number Temperature Measurements	Gradient[a]	Number K Measurements	K[b]	Q[c]
Site 71, 101 meter hole, descending					
2-17	7	0.079	2	1.97	1.56±0.20
21-68	19	0.040	6	2.15	0.87±0.06
74-81	5	0.066	0	(2.50)	1.66±0.12
Simple mean Q: 1.36±0.30, Weighted mean Q: 1.10					
Site 71, 101 meter hole, ascending					
77-65	6	0.068	1	2.36	1.61±0.09
65-24	18	0.045	5	2.22	0.99±0.06
22-0	10	0.067	2	1.97	1.31±0.02
Simple mean Q: 1.30±0.21, Weighted mean Q: 1.18					
Site 71, 250 meter hole, descending					
1-17	8	0.055	2	1.97	1.09±0.12
20-64	19	0.022	6	2.15	0.48±0.03
109-136	10	0.035	2	2.79	0.99±0.07
143-158	6	0.047	1	2.75	1.28±0.07
211-236	9	0.031	3	2.56	0.86±0.07
Simple mean Q: 0.94±0.15, Weighted mean Q: 0.83					
Site 71, 250 meter hole, ascending					
210-194	8	0.036	2	2.42	0.88±0.06
145-115	7	0.055	2	2.79	1.54±0.11
115-91	6	0.038	3	2.77	1.06±0.06
51-38	4	0.039	2	2.39	0.93±0.09
38-13	6	0.022	4	1.98	0.45±0.04
13-4	3	0.075	1	2.11	1.59±0.12
Simple mean Q: 1.08±0.19, Weighted mean Q: 1.05					
Site 72, 51 meter hole, descending					
2-14	6	0.084	1	2.34	1.98±0.12
19-31	6	0.066	1	2.16	1.42±0.16
2-31	13	0.053	2	2.25	1.19±0.12
Simple mean Q: 1.53±.29, Weighted mean Q: 1.19					
Site 72, 105 meter hole, descending					
0-12	7	0.055	0	(2.30)	1.26±0.06
19-49	13	0.008	3	2.07	0.18±0.02
62-103	20	0.018	0	(2.50)	0.45±0.02
(120-125)	8	0.091	0	(2.50)	2.28±0.22
Simple mean Q: 0.63±0.40, Weighted mean Q: 0.47					

[a]Gradient in °C/m. [b]K in mcal/°C cm sec. [c]Q in 10^{-6} cal/cm^2 sec. (HFU)

TABLE 4
Heat Flow Values at Sites 71 and 72 Derived from Sediment Temperature Measurements

Site	Hole Depth	Bottom Water Temperature[b]	Sediment Temperature[b]	t[a]	Gradient[c]	Number K Measurement	K[a]	Q[e]
71	27.5	1.00	2.58±.05	2 1/2	0.057	3	1.93	1.11±0.10
71	101.0	1.10	5.35±.07	2	0.042 (max.)	12	2.25	0.95±0.06
71	101.0	1.10	4.71±.07	2	0.036 (min.)	12	2.25	0.80±0.05
71	250.0	1.10	6.56±.03	15	0.022	24	2.44	0.53±0.03
72	51.0	1.09	4.16±.13	2	0.060	4	2.13	1.28±0.12

[a] t = time in minutes over which relatively steady temperatures were measured in the sediments.

[b] Temperature in °C.

[c] Gradient in °C/m.

[d] K in mcal/°C cm sec.

[e] Q in 10^{-6} cal/cm^2 sec. (HFU)

The other method of measuring heat flow is based on temperatures obtained in the sediments at the bottoms of the holes. The results of these measurements are summarized in Table 4. Temperatures (frequencies) were recorded at intervals of 15 seconds during the sediment measurements. With one exception, the time period over which relatively steady temperatures were measured was quite short, probably due to vertical movements of the ship transmitted through the drill string to the bit. A 15-minute thermal decay without disturbances was measured at Site 71, in a 250-meter hole; this was also the measurement at which a 10,000 kilogram weight loss of the drill string was noted during the time on bottom, suggesting that the lower bumper subs were probably taking up ship motion. Two periods of relatively steady but different temperatures were measured at Site 71, a 101-meter hole, giving maximum and minimum heat-flow values there. The errors in heat flow are calculated from the

The errors in heat flow are calculated from the uncertainties in temperature measurement at the bottom of the hole over the indicated time interval, and from the standard error of the thermal conductivity (K) measurements.

DISCUSSION AND CONCLUSIONS

A principal source of error in the measurement of *in situ* temperature and heat flow in a borehole is the disturbance caused by drilling of the hole, particularly that caused by circulating fluids. An approximate rule developed by Bullard (1947) is that reliable measurements can be made only after a period following the cessation of drilling which is at least 10 times greater than the length of time taken to drill the hole. This condition was not satisfied at any of the holes drilled at Sites 71 and 72.

Fluid circulating through the drilling pipe during or after the drilling would be expected to reduce the geothermal gradient in the pipe. The isothermal water being pumped into the drill pipe below the sea floor exchanges heat with the surrounding annulus of return circulation and with the sediments. For relatively shallow holes and/or large rates of water circulation, the temperature of water leaving the drill bit near the bottom of the holes is likely to be significantly lower than that of the surrounding sediments, whereas the water which exits from the annulus between pipe and sediments at the top of the hole will be *warmer* than sea water and near-surface sediments.

The rates and volumes of water circulation through these boreholes were estimated from the dimensions of the drill pipe and borehole (Figure 1), and from recorded rates and periods of circulation (Tables 1 and 2). The size of the boreholes was not measured, but caliper logs at other DSDP sites drilled in similar sediments indicate a diameter of about 25 centimeters (V. F. Larson, personal communication). With an inside diameter of 10 centimeters for the drill pipe and bottom hole assembly, a pumping rate of 400 gal/min will result in fluid velocities of about 200 m/min down the inside of the pipe, and about 100 m/min up the annulus between the pipe and hole walls. Such rates imply that during the many minutes or hours used for circulation during and after the drilling (Tables 1 and 2), the holes would be completely flushed with water many times over.

An approximation to the effect of water circulation on the equilibrium gradient may be obtained using the theory developed by Bullard (1954) for the oceanographic probe technique. A solution was derived for the temperature of a perfectly conducting cylinder which is suddenly immersed in an infinite homogenous medium with finite thermal properties. The return to thermal equilibrium of the probe is a function of the size and thermal properties of the probe compared to the surrounding medium. In our case, the "probe" is a borehole of 25 centimeters in diameter filled with water at an initial temperature of water at the sea floor (the bottom hole assembly within the borehole will not significantly affect its thermal properties, that is, thermal capacity). This idealized model will have zero effect on temperature at the top of the hole, and maximum effect at the bottom. The initial *gradient* in such a hole is zero, and Bullard's theory indicates that a hole of this diameter will have returned to only 60 per cent of the surrounding undisturbed gradient after 3 hours, and about 70 per cent after 6 hours. This model probably gives only *minimal* estimates of the disturbance, because circulation extended over significant time periods compared with the instantaneous source assumed in Bullard's theory.

Therefore, even with this model simplified to give a minimal effect, we would expect that measurements in the holes would give gradients and heat flows considerably less than the equilibrium values. This certainly seems to be the explanation of the low values measured in the 105 meter hole at Site 72 (Table 3), where a long period of water circulation occurred (Table 2). However, an even longer period of circulation for the 250-meter hole at Site 71 did not seem to produce a comparable effect; perhaps the greater hole depth reduced the disturbance. Nevertheless, we can see from the increased temperatures measured on the ascent of the probe as compared with the descent (Figure 3) that this hole was far from equilibrium at the time of measurements. The fact that the calibrated mean heat flows during ascent at Site 71 holes are always larger than those measured during descent (Table 3) may be a further indication of the return to equilibrium.

From the above conclusion that drilling disturbances tend to cause lower geothermal gradients in the drill holes, we could expect to find higher heat-flow values from measurements in undisturbed sediments at the bottom of the holes. Yet in only one of the holes where comparisons were possible does that seem to be the case (50-meter, Site 72 hole), and there the difference in heat flows may not be significant (Table 4). Even though a particularly long, apparently undisturbed temperature record was obtained at the bottom of the 250-meter Site 71 hole, the computed low heat flow is not consistent with the other values measured in the hole. The measured sediment temperature there was significantly lower than temperatures measured in the lower sections of that hole (Figure 3). These observations and comparisons suggest that equilibrium sediment temperatures were not measured in most of these holes, perhaps as a result of sloughing of sediments to the bottom from higher sections of the hole, or of temperature disequilibrium of the probe with the sediment due to movement of the probe.

Some comparisons can be made with nearby unpublished heat-flow values obtained with standard oceanographic techniques. A value of about 1.5 HFU was measured during a pre-site survey near Site 71 (J. Sclater, personal communication), which is higher than any measured values in the DSDP holes. On the other hand, a value of about 0.5 HFU was measured about 70 kilometers east of Site 72 (Expedition Amphitrite, Scripps Institution of Oceanography), and two measurements between Sites 71 and 72 give heat-flow values about one-half (or less) of normal (M. Langseth, personal communication). Therefore, the comparisons with the standard measurements are not definitive. Furthermore, the temperature data from the DSDP holes discussed above are too variable to determine if heat flow is constant with depth in sea-floor sediments. It is hoped that improvements in techniques and instrumentation will yield more reliable comparisons at future sites.

ACKNOWLEDGEMENTS

We are grateful for the cooperation and skills of the crew of the *Glomar Challenger*, and particularly to the assistance of the operations superintendent for Leg 8, Bill Allinder. C. Corry and W. Church assisted in development of instrumentation. V. Larson provided detailed drilling information and descriptions of equipment utilized at Sites 71 and 72, and M. Langseth and J. Sclater generously provided unpublished heat-flow data.

The D.S.D.P. staff provided generous assistance in editing and drafting of figures. A. E. Erickson provided valuable criticism of a first draft of the manuscript. Supported in part by NSF grant GA-1448.

REFERENCES

Bullard, E. C., 1947. The time necessary for a bore hole to attain temperature equilibrium. *Monthly Notices Roy. Astron. Soc.* **5**, 127.

Bullard, Sir Edward, 1954. The flow of heat through the floor of the Atlantic Ocean. *Proc. Roy. Soc. London A.* **222**, 408.

Von Herzen, R. P. and A. E. Maxwell, 1964. Measurements of heat flow at the preliminary Mohole site off Mexico. *J. Geophys. Res.* **69**, 741.

Langseth, M. G., 1965. Techniques of measuring heat flow through the ocean floor. **In** "Terrestrial Heat Flow." *Am. Geophys. Union, Monograph No. 8.* W. H. K. Lee (Ed.), 58.

Von Herzen, R. P. and A. E. Maxwell, 1959. The measurement of thermal conductivity of deep-sea sediments by a needle-probe method. *J. Geophys. Res.* **64**, 1557.

Ratcliffe, E. H., 1960. The thermal conductivities of ocean sediments. *J. Geophys. Res.* **65**, 1535.