52. DOWNHOLE TEMPERATURE MEASUREMENTS AND HEAT FLOW DATA IN THE BLACK SEA—DSDP LEG 42B

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INTRODUCTION

The origin and geological history of the Black Sea is still a highly controversial topic. Models for the origin of the Black Sea include the creations of oceanic crust by extension (Apol'skiy, 1974; Adamiya et al., 1974), subsidence and oceanization of continental crust due to mineralogic transformation and phase changes (Muratov, 1972), uplift and subaerial erosion followed by subsidence (Rezanov and Chamo, 1969; Brinkmann, 1974), and consideration of the Black Sea as a land-locked piece of the ancient Tethys sea floor (Milanovskiy, 1967).

Whatever the origin, it seems probable that the creation and subsequent history of the Black Sea was closely related to thermal processes within the mantle. Knowledge of the present rate of heat flow through the floor of the Black Sea provides an important type of geophysical data which bears directly on questions of the age and origin of the sea.

Many of the published heat-flow values in the Black Sea are either of indeterminate reliability due to lack of detailed information on the measurement procedures and techniques, or are of questionable value because of evidence for non-linear thermal gradients to depths of 10 meters or more at many locations. The opportunity to make temperature measurements to depths of hundreds of meters beneath the sea floor in holes drilled during DSDP Leg 42B provided a means of establishing highly reliable heat-flow values against which to compare the more numerous conventional oceanographic heat-flow data.

PREVIOUS WORK

Conventional shallow marine heat flow measurements in the Black Sea were reported as early as 1963 by Sysoyev (1963), and more recently by Erickson (1970), Lubimova and Feldman (1970), Lubimova and Savostin (1973), and Erickson and Simmons (1974). Although the preceding papers include all of the heat-flow data from the Black Sea known to us, many other papers exist which discuss one or more sets of these data, but never all of the data at one time (see, for example, papers by Alexandrov et al., 1972; Savostin et al., 1973).

The quality of much of the published data is difficult to evaluate, particularly in view of Erickson's observation (using from five to eight sediment temperature measurements at each of 33 heat-flow stations) of strongly non-linear thermal gradients in approximately one half of the heat-flow measurements made in the Black Sea in 1968 (Erickson, 1970; Erickson and Simmons, 1974). All other published thermal gradient measurements were made using sediment temperatures determined at only two depths below the sea-floor (Lubimova and Savostin, 1973; Sysoyev, 1963), or have been reported without a clear description of the measurement technique and apparatus (Lubimova and Feldman, 1970). There is thus no way to tell whether a thermal gradient determined from temperature data obtained at only two depths is representative of the regional geothermal flux, or whether it has been affected by any one of the numerous environmental factors reviewed by Von Herzen and Uyeda (1963) and Langseth (1965). Thermal conductivity values, estimated for some measurements by various investigators, range from 4 mcal/cm sec °C (Sysoyev, 1963) to 2 mcal/cm sec °C, (Lubimova and Feldman, 1970), the lower values being much more consistent with conductivity values measured in most shallow marine sediments.

In summary, although at least 78 conventional heat-flow values have been published for the Black Sea, it is difficult to know which of the reported values are reliable determinations of the heat flow. For comparison of the borehole heat-flow values with the surrounding conventional heat-flow values, we rely mainly upon the one set of data for which we do have sufficient information to realistically evaluate their reliability (Erickson and Simmons, 1974).

MEASUREMENT TECHNIQUE

Downhole Temperature Measurements

The measurement procedure for each borehole temperature determination was to lower a core barrel containing the temperature probe to the bottom of the drill string where it was latched into the bottom-hole assembly. The drill string then was slowly lowered, the weight of the lowermost drill collars being used to push the thermistor probe 30 to 50 cm into the undrilled sediment ahead of the drill bit. Once the weight of the bottom hole assembly was supported by the sediment, the temperature probe was allowed to remain embedded in the sediment for about 15 minutes during which time its approach to thermal equilibrium with the sediment was recorded once every 8 seconds; retrieval through the drill pipe to the surface using the wire line completed the operation.

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Estimation of the probable error of the temperature measurements can be somewhat subjective. In the case of measurements classified as "excellent," the characteristic shape of the temperature-time plot leaves little doubt that it was the actual in situ sediment temperature which was accurately determined. In other measurements, although the data may be of excellent quality, the shape of the temperature-time record makes it unclear whether the temperature was measured in thermally undisturbed sediment, disturbed sediment, a gradually warming mixture of drilling fluid and slumped sediment, or some combination thereof. In order to assist the reader to make his own judgment of the reliability of each temperature measurement, all the temperature-time records are presented in Figures 1a through 1v. Where the observed sediment temperatures did not attain thermal equilibrium during the measurement interval, they were extrapolated to equilibrium by using the 1/t technique discussed by Hyndman et al. (1974).

An estimate of the temperature of the bottom water immediately above the sediment was obtained just before the down hole temperature recorder was lowered into the subbottom portion of the drill string, on the assumption that water in the drill pipe had achieved thermal equilibrium with the surrounding seawater. Water temperatures measured in this way are in good agreement with bottom water temperatures obtained during nearby oceanographic heat-flow measurements.

Depth values cited in the text generally have precisions of ±2 meters relative to the other measurements, with the exception of the depth of the sea floor, which may be somewhat shallower than the depth determined by the driller. The latter discrepancy may be calculated by the amount of drill pipe out when the sediment began to support enough of the weight of the drill string (≈1000 kg) to cause a noticeable change in the weight of the drill string. The uppermost softness of the sediments makes it possible that the sea floor may be significantly higher than the level determined by the driller. It is noted, however, that the water depth determined acoustically and corrected for sound velocity, and the water depth determined by the drilller, are usually within a few meters of each other, except for Site 381 (Table 1). The driller's depth estimate was used for all heat-flow calculations.

Thermal conductivity measurements were made on sediment cores using the needle-probe technique described by Von Herzen and Maxwell (1959). The

TABLE 1
Comparison of Water Depths Determined by Echo Sounding and by the Driller

Site	Driller's Estimate (m)	Echo Sounding (Corr. m)
379	2171	2175
380	2115	2117
381	1750.5	1738

[a]Drilling platform is 10 meters above sea level.

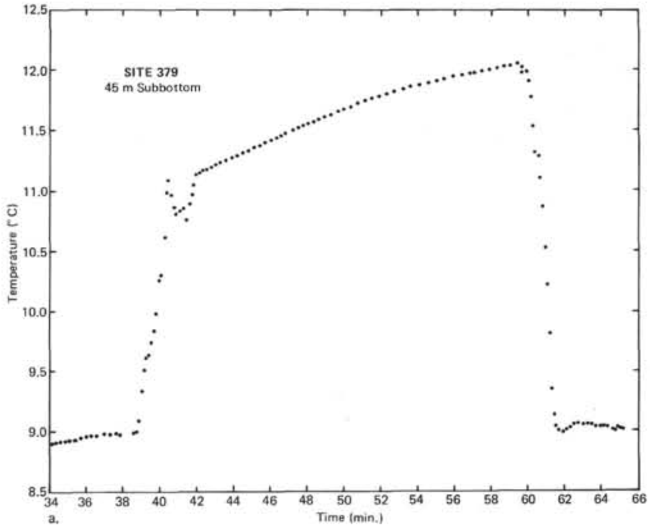


Figure 1a. *Plot of temperature versus time during the down-hole temperature measurements at Site 379, 380, and 381 in the Black Sea.*

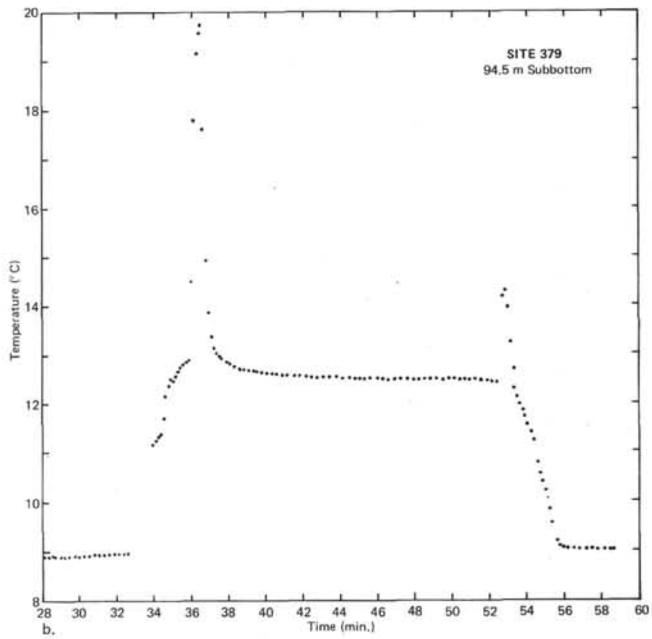


Figure 1b.

measurements were made on unopened cores soon after the cores had attained thermal equilibrium with the shipboard core loratory. Thermal conductivity values determined in this way were adjusted for pressure and temperature differences between the borehole and the laboratory conditions, using correction factors published by Ratcliffe (1960).

The effects of the high gas content of most of the Black Sea cores were visible in the form of bubbles, cracks, and voids of various sizes caused by expansion of interstitial gases as the cores were raised. Despite efforts to avoid making measurements in cores which were badly disturbed by gas expansion, it is possible that many of the thermal conductivity values reported

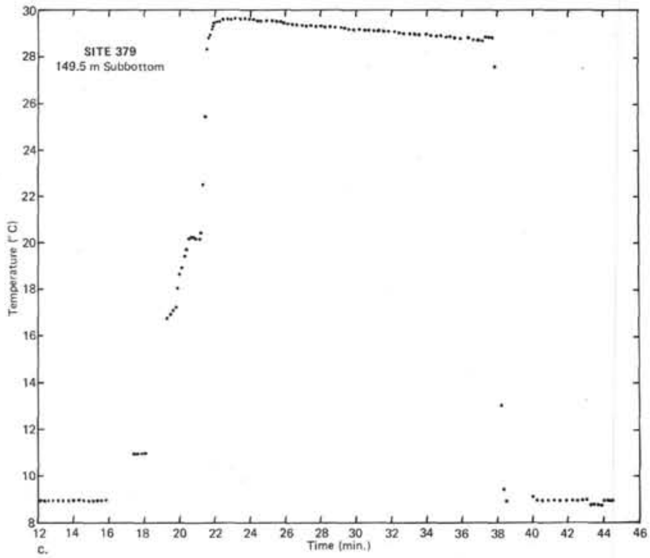


Figure 1c.

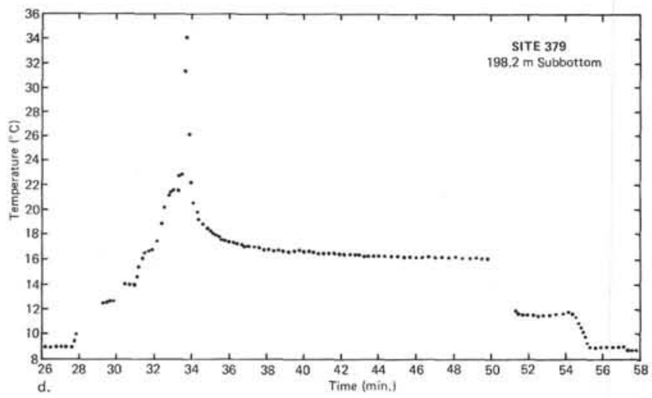
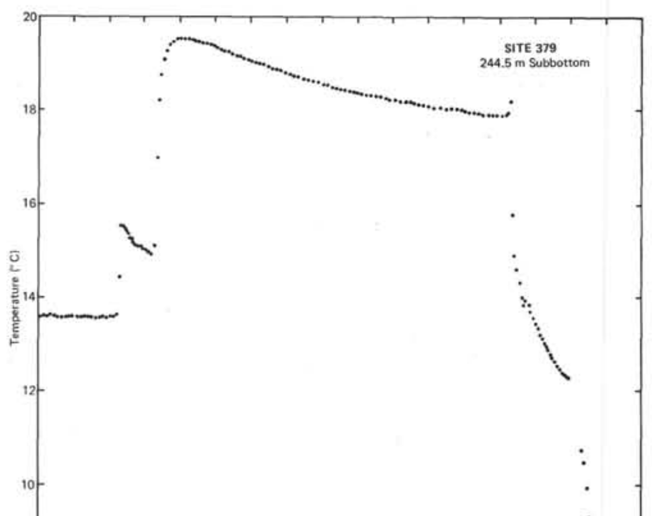


Figure 1d.



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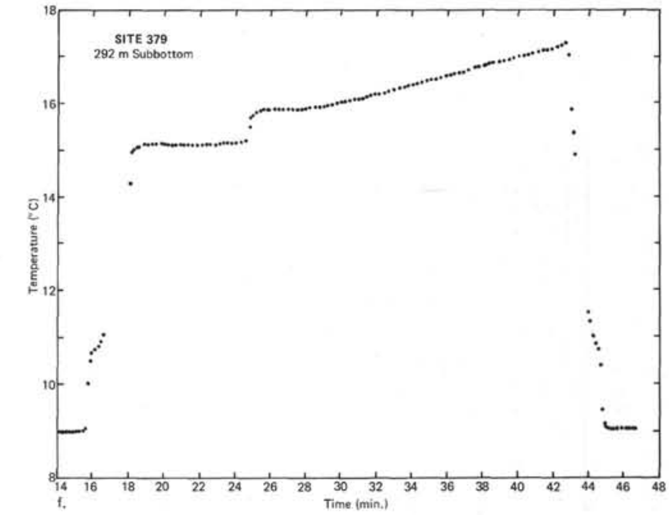


Figure 1f.

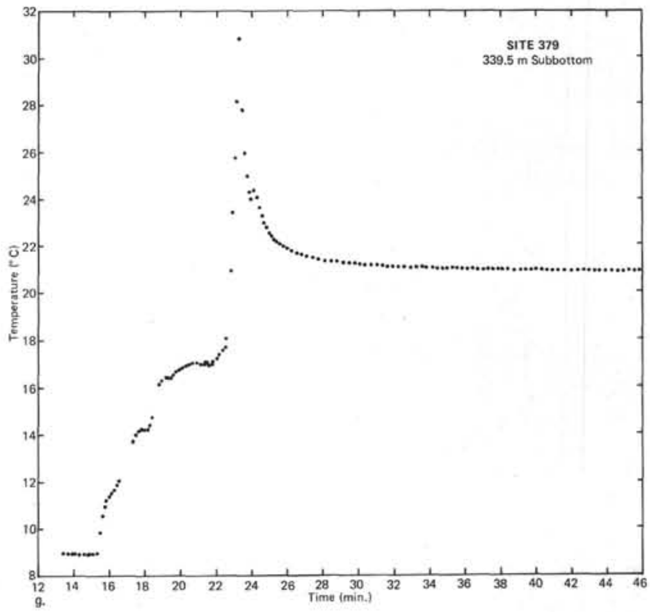


Figure 1g.

may be systematically low. However, the values observed in the Black Sea sediments are similar to values measured at other sites where gases were not noticeable, thus the effect of the interstitial gases on the thermal conductivity is presumed to be small. The conductivity data obtained at each drill site is discussed in the Physical Properties section of the respective Site Chapter (Chapters 2, 3, and 4 of this volume), and listed in (Chapter 55).

RESULTS

Site 379

Site 379 is situated in the central Black Sea on the Euxine Abyssal Plain in 2171 meters of water (Figure 2). Sediment thickness in the area of Site 379 is about 10 km (Neprochnov et al., 1974) with thin, nearly horizontal layers present to a depth of at least one km

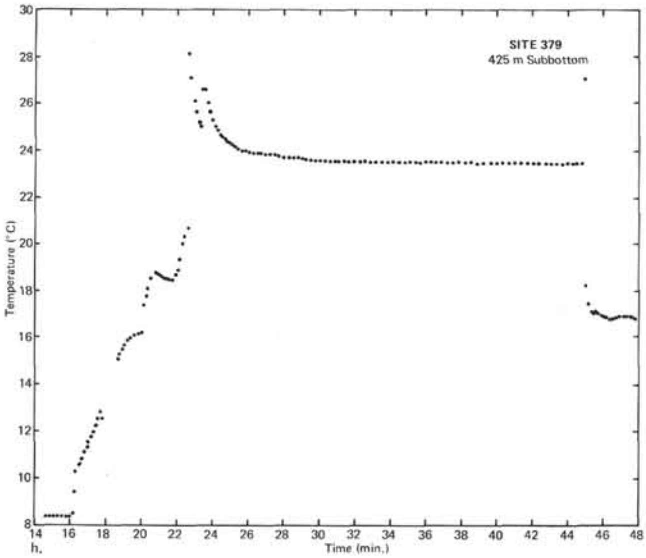


Figure 1h.

below the sea floor (Site Chapter, Site 379, this volume).

A total of 10 successful downhole temperature measurements were made between 35.0 and 624.5 meters sub-bottom at Holes 379A and 379B, resulting in the data presented in Table 2. Calm weather, stable hole conditions, and sediment which could be easily penetrated by the temperature probe permitted calculation of accurate in situ sediment temperatures for many of these measurements. All of the temperature-time records are plotted in Figures 1a through 1j, and the temperature data presented in Table 2 are plotted versus sub-bottom depth in Figure 3.

Five interval heat-flow values were calculated using bottom water temperature, and five reliable sub-bottom temperatures were measured between 35 and 425 meters below the sea floor. Interval heat flow values range from 0.77 to 1.21 $\times$ 10^{-6} cal/cm^2 sec (Table 2), with an average and standard deviation of 0.98 $\pm$0.15 $\times$ 10^{-6} cal/cm^2 sec.

The data points which do not fall on the nearly linear segments are of considerable interest. The temperature measured at 45 meters sub-bottom is significantly higher than that predicted by extrapolating the well-determined thermal gradient below, upwards to that depth. Even more remarkable is the value of 29.55°C measured at 149.5 meters, which exceeds by over 15°C the temperature expected at that depth and which is, in fact, higher than the maximum temperature measured at 624.5 meters. All indications are that the instrument did not malfunction during either measurement; all

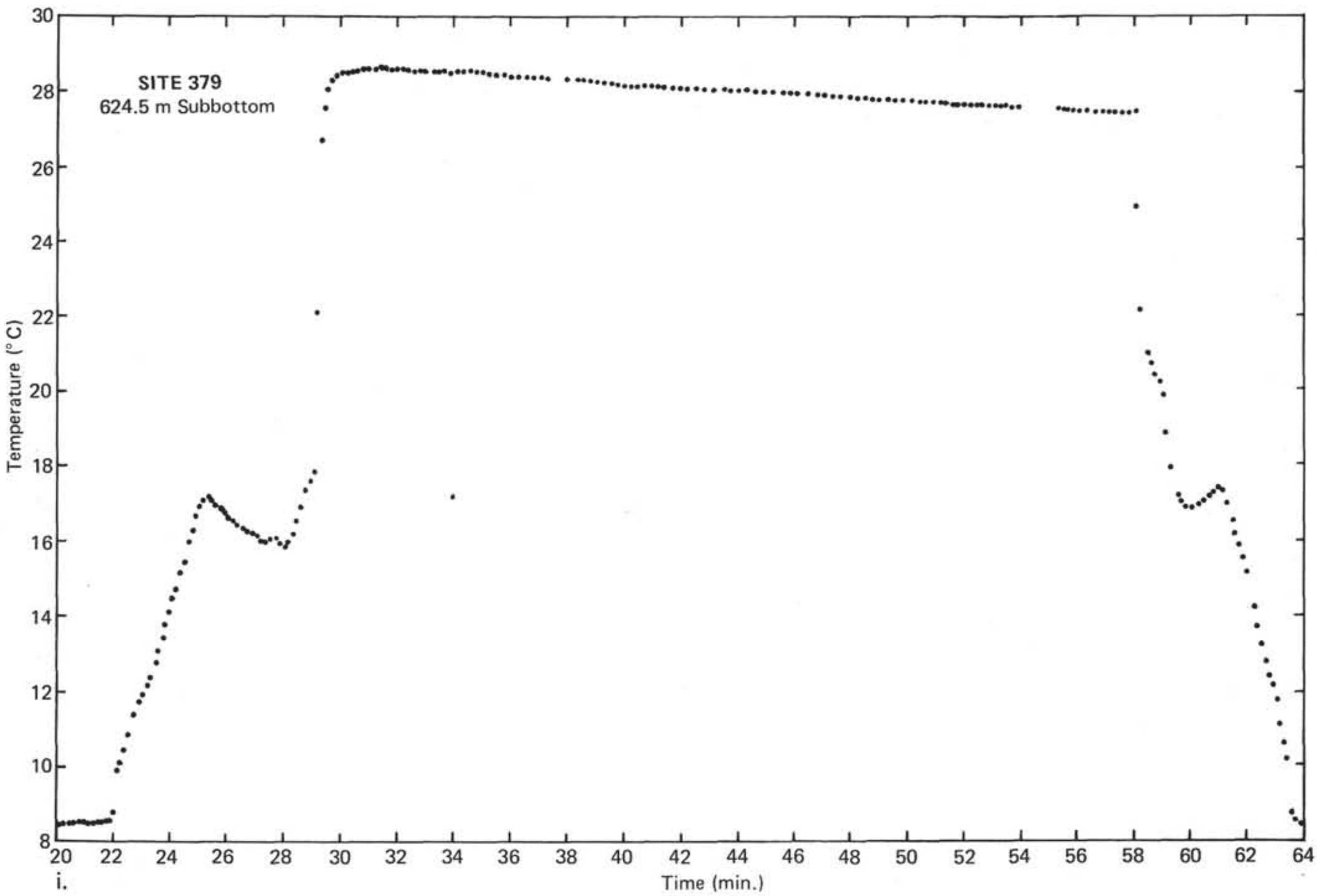
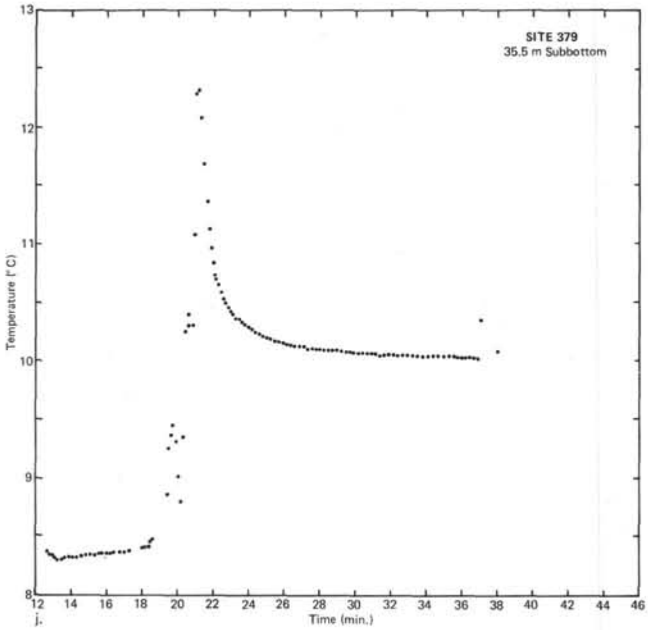


Figure 1i.



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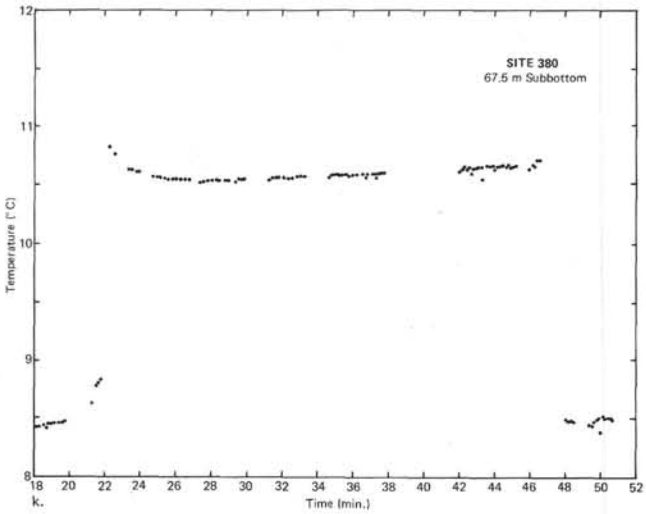


Figure 1k.

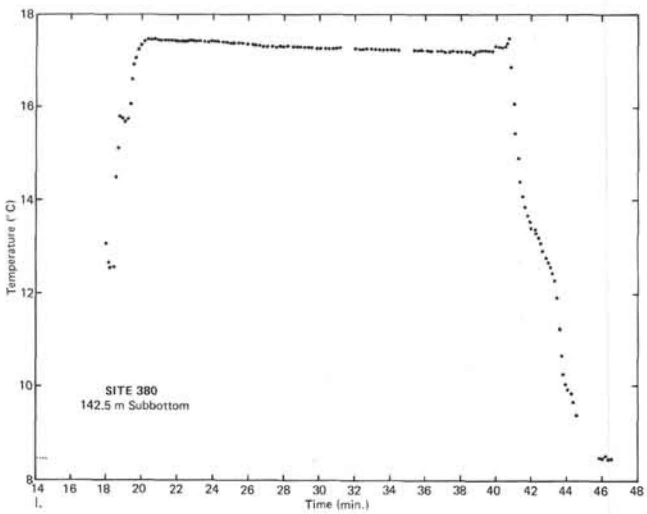


Figure 1l.

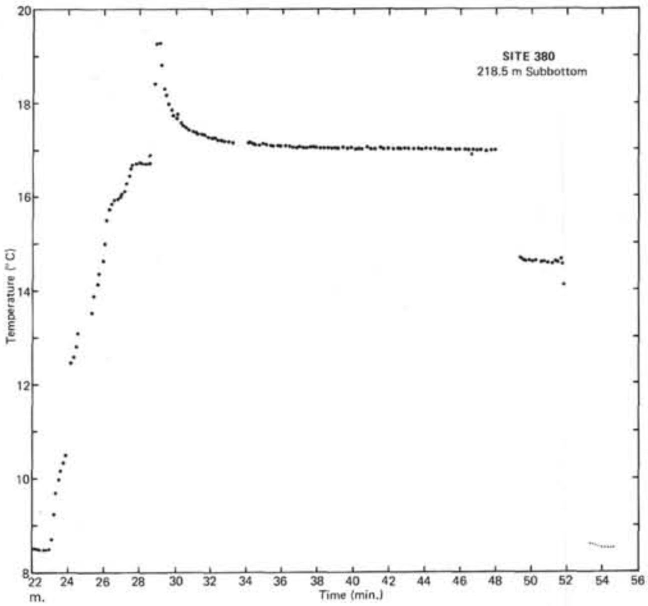
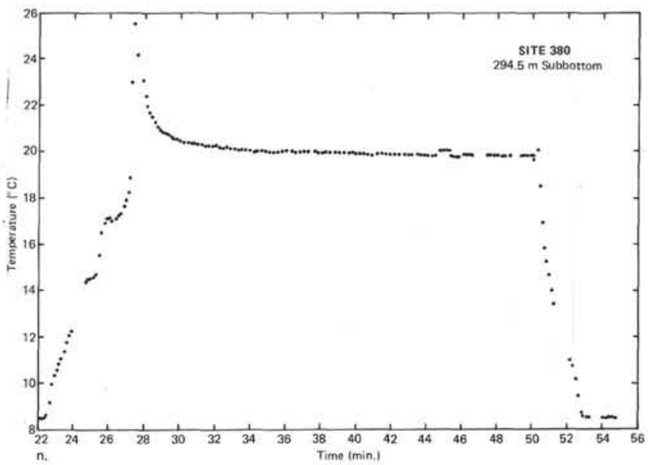


Figure 1m.



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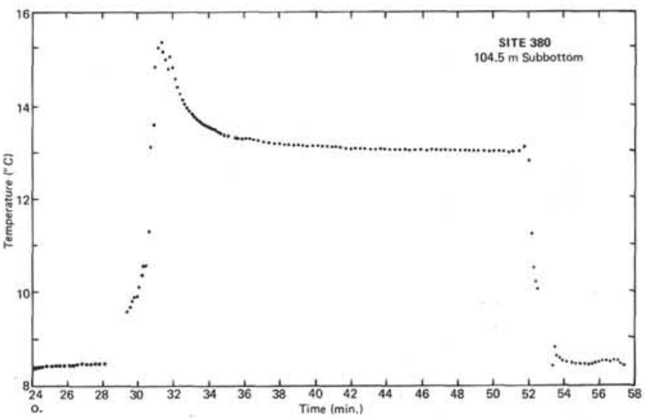

Figure 1o.

internal calibrations, and the fact that the bottom water temperatures determined before and after the anomalously high temperatures were measured, are correct. The fact that the temperature-time records show all of the characteristics expected for downhole temperature

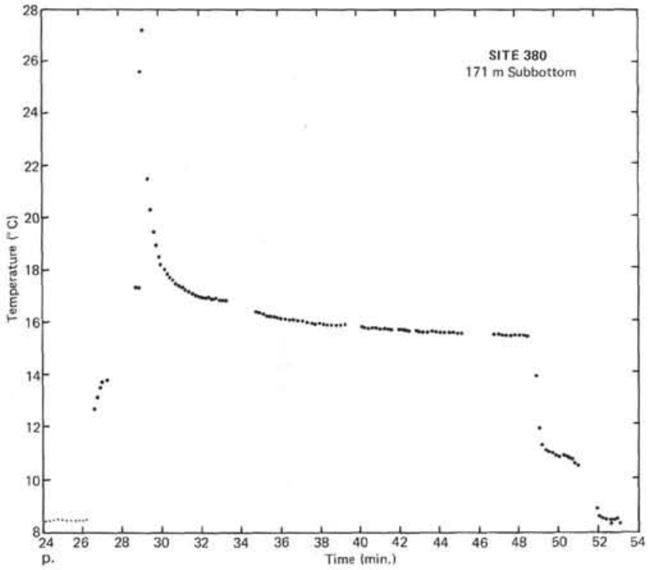

Figure 1p.

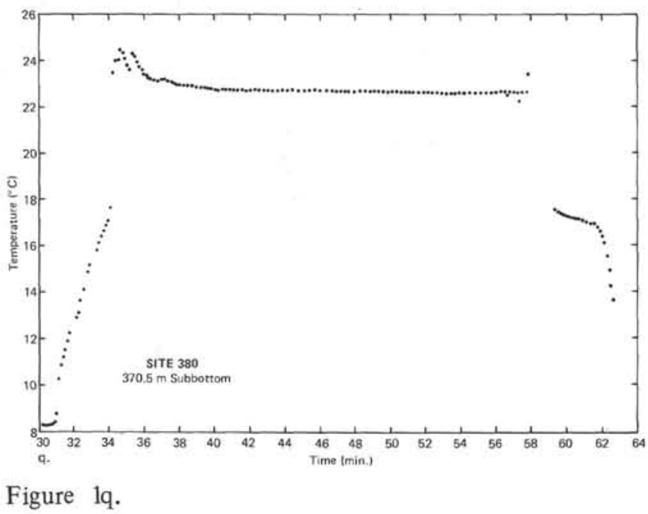

Figure 1q.

measurements strongly suggest that the instrument did in fact record anomalously high temperatures at 45.0, and more strikingly, at 149.5 meters. It is possible that these temperatures are due to frictional heating of a mixture of seawater and cuttings associated with the drilling process rather than to geological or geophysical factors.

Site 380

Site 380 is situated on the extreme southeastern edge of the basin apron near the base of the basin slope (Figure 4). The sea floor and sub-bottom reflectors in this region are smooth and slope gently up, toward the southwest, over a distance of about 20 km, whereupon the slope increases abruptly at the edge of the basin slope.

Temperatures were measured at eight depths in Holes 380 and 380A, giving five highly reliable downhole temperatures and three values which are not believed to be representative of in situ sediment temperatures. All measurements were made with the same downhole temperature instrument using two thermistors, both calibrated at the same time in the same temperature bath. Temperature-time plots of each of the measurements are shown in Figures 1k through 1r.

The measurements used to calculate interval heat-flow values (Table 3) are of extremely high quality and are believed to be representative of the in situ sediment temperatures.

Although the temperature data recorded during measurements at 67.5 and 104.5 meters sub-bottom represent true downhole temperatures, the form of the temperature-time records makes it unclear into which medium the temperature probe was immersed, or whether it was affected by long-period mechanical disturbances during the measurement interval. During the last downhole temperature measurement, at 465.5 meters sub-bottom, the pressure of the bit on the sea floor increased slowly during the 21-minute long measurement interval, implying that the ship was moving back over the bit and that the bumper subs were not effective in isolating the temperature probe from the effect of the relative movement between the ship and the bottom hole assembly. The very long period temperature increase shown in Figure 1r is believed to be due to the slow downward movement of the probe into warmer strata and to frictional heating associated with this downward movement. The similarity in the shapes of the temperature-time record at 67.5 (Figure 1k) and 465.5 meters (Figure 1r) suggest that both may have been affected in the same way.

The measurement at 142.5 meters sub-bottom is of considerable interest because of the observation of anomalously high temperature. As was the case with the measurement at 149.5 meters sub-bottom at Site 379, there is every reason to believe that the temperature probe performed correctly, as it did without modification for both earlier and later measurements. However, the measurement is anomalous both in terms of its relationship to the other downhole temperature measurements at this site (Figure 5), and because it recorded temperatures higher than those beneath it, a situation which cannot be a steady-state phenomenon. The probable cause of the anomalously high temperatures recorded at both sites is believed to be thermal disturbance caused by frictional heating during drilling.

With the exception of the unreliable temperatures discussed above, the remaining five data points between 104.5 and 370.5 meters fall in a nearly straight line defining a geothermal gradient of 0.035°C/m, only slightly less than the average gradient of 0.036°C/m determined from temperature measurements at Site 379.

Five interval heat-flow values were calculated from the bottom water and reliable sub-bottom temperature measurements (Table 3). The mean and standard deviation of these interval heat-flow values is 0.99 $\pm 0.10 \times 10^{-6}$ cal/cm^2 sec, nearly equal to the value determined at Site 379.

Site 381

Site 381 is located in 1722 meters of water on the basin slope in the southwestern portion of the Black

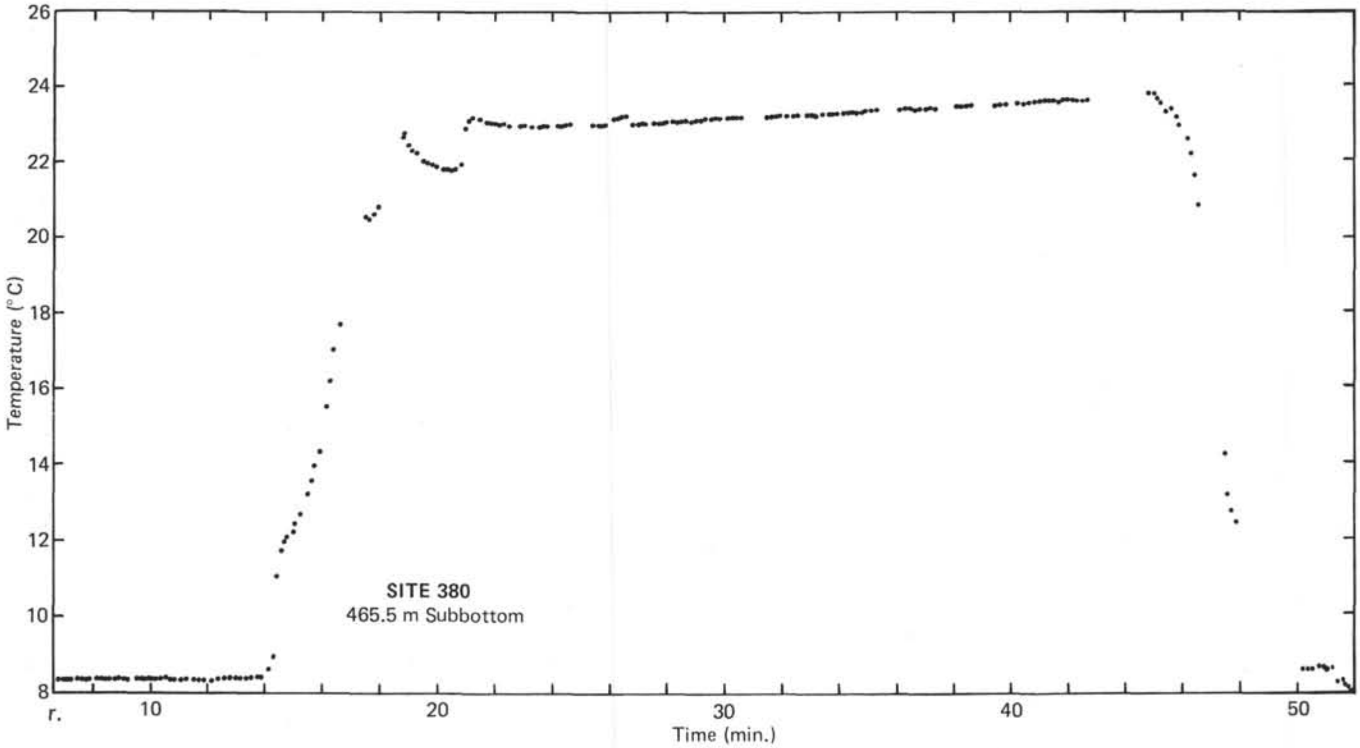

Figure 1r.

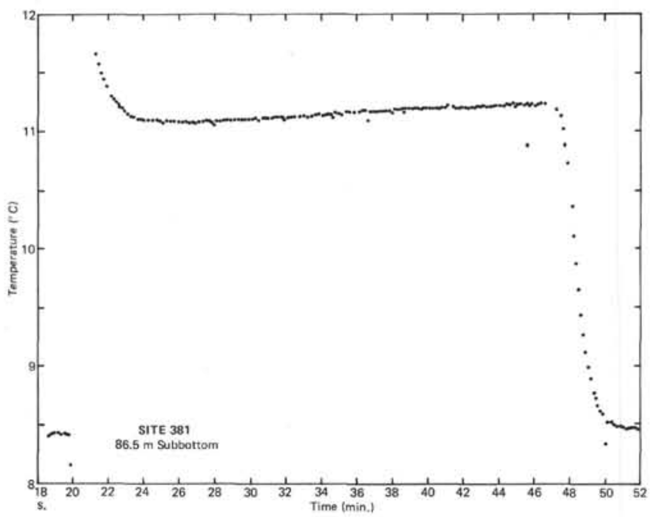

Figure 1s.

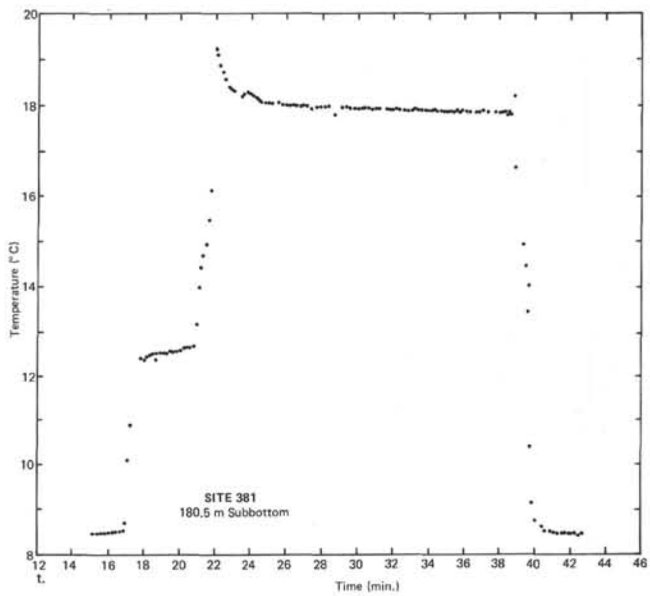

Figure 1t.

Sea (Figure 4). Sea floor topography and sub-bottom reflectors here are gently rolling, with a relief of as much as 600 meters and a horizontal wavelength of 10 to 20 km.

Four downhole temperature measurements were made at Site 381. A more uniformly spaced set of measurements was planned, but unstable hole conditions encountered below about 250 meters sub-bottom made further heat-flow measurements inadvisable until drilling had proceeded below 450 meters.

Unusually soft sediment at this site made it difficult to immobilize the bottom hole assembly by partially closing the lowermost bumper sub during the uppermost three measurements. Instead, a gradual decrease in drill string weight was noted during the course of each of these measurements, implying that the temperature probe was gradually sinking deeper into the sediment during the measurement interval. The constancy and rate of sinking varied both with the depth and time involved of each measurement. The maximum distance moved during a measurement was only a few meters and, generally, the rate of movement

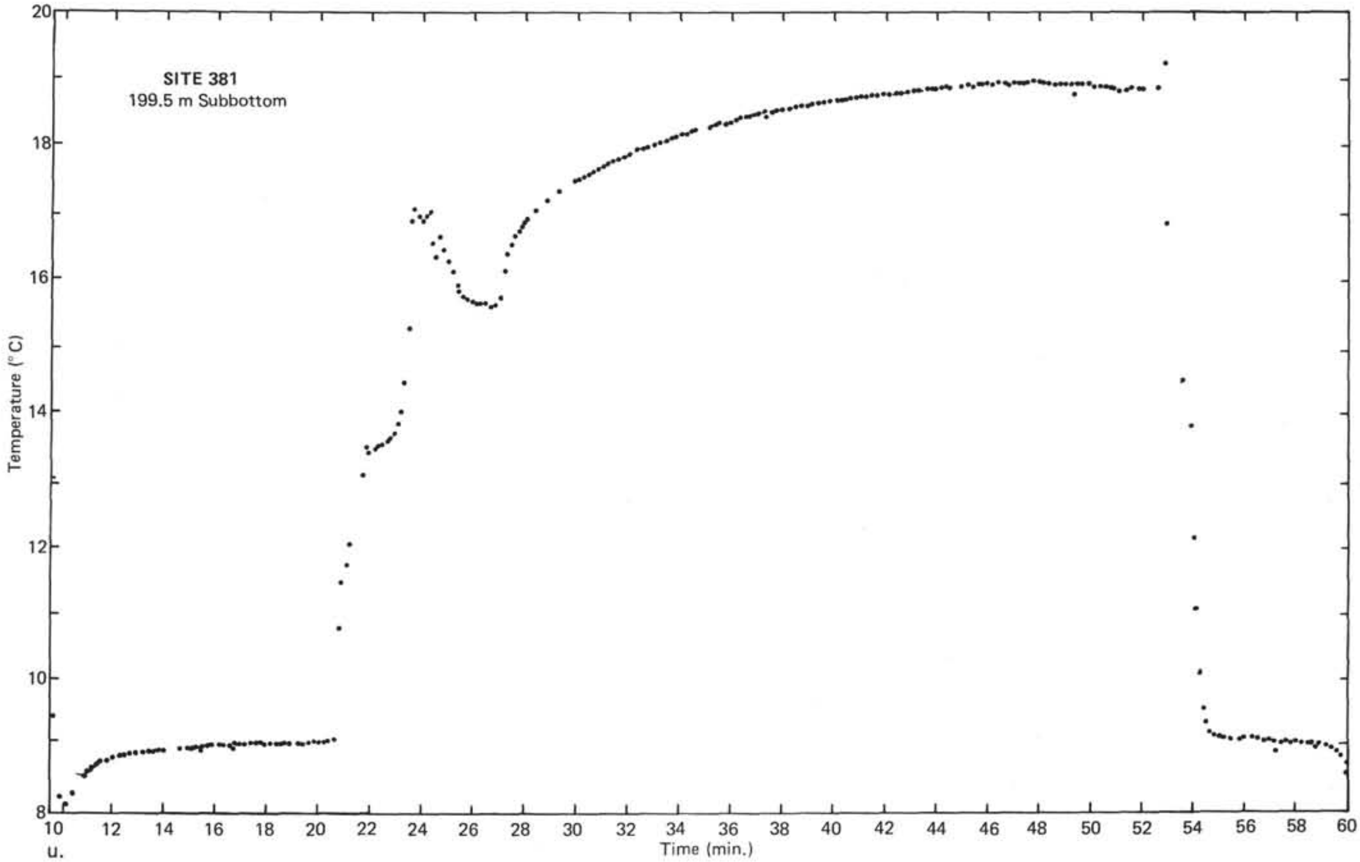

Figure 1u.

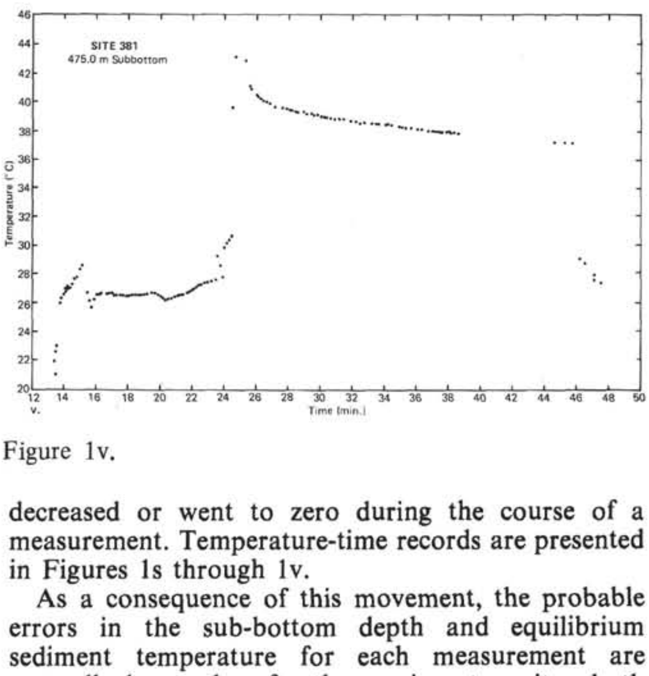

Figure 1v.

decreased or went to zero during the course of a measurement. Temperature-time records are presented in Figures 1s through 1v.

As a consequence of this movement, the probable errors in the sub-bottom depth and equilibrium sediment temperature for each measurement are generally larger than for the previous two sites; both uncertainties, however, are small compared to the total distance over which the measurements were made (475 m), and to the total temperature change observed (28.9°C); these data also provide a reasonable basis for calculation of the thermal gradient and a reliable heat-flow value at this site.

Downhole temperature and bottom water data for Site 381 are presented in Table 4 and are plotted versus sub-bottom depth in Figure 6. Bottom water temperature was again estimated as the temperature recorded in the drill pipe just before the temperature probe entered the drill hole. The form of the temperature-time records suggests that only the measurement at 180.5 meters (Figure 1t) sub-bottom provides a reliable indication of in situ sediment temperature, although the measurement at 199.5 meters (Figure 1u) may also be close to the in situ sediment temperature. It is suggested that the most reliable heat-flow value at this site is obtained by considering only the bottom water temperature and the sediment temperature measurement at 180.5 meters, and the thermal conductivity data from that interval. A heat-flow value of 1.18 $\pm 0.20 \times 10^{-6}$ cal/cm^2 sec is calculated for this site. A slightly lower interval heat-flow value (1.10×10^{-6} cal/cm sec) can be calculated using the two measurements at 180.5 and 199.5 meters sub-bottom, however the smaller depth interval and the peculiar form of the temperature-time record at the deeper measurement (Figure 1u) makes this heat-flow value less reliable than the value of 1.18×10^{-6} cal/cm^2 sec calculated for the upper interval.

CONCLUSIONS

An important objective of making heat-flow measurements is to determine the rate of heat flow from

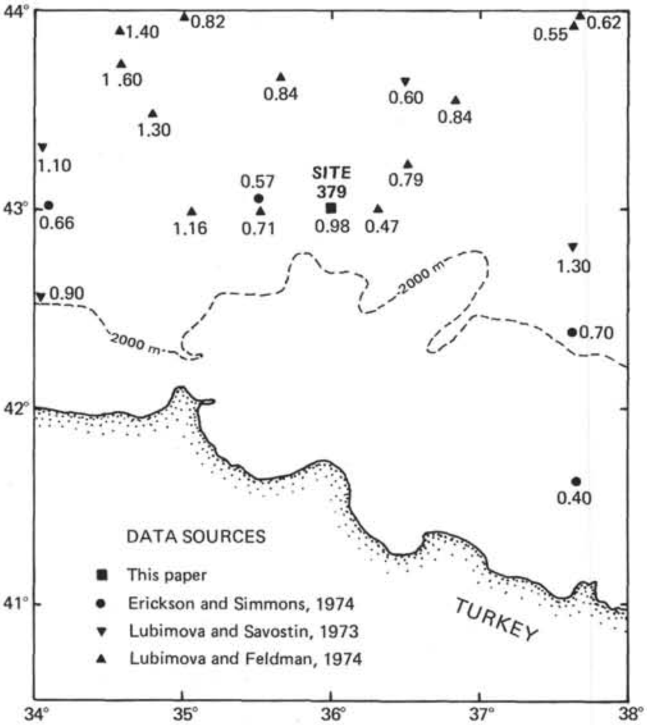

Figure 2. *Index map showing the location of Site 379 in relation to nearby conventional heat flow measurements. Heat flow values are given in units of 10^{-6} cal/cm^2 sec.*

TABLE 2
Downhole Temperature Data and Interval Heat-Flow Calculations at Site 379

Subbottom Depth (m)	Sediment Temperature (°C)	Thermal Gradient (°C/km)	Thermal Conductivity (mcal/cm sec °C)	Interval Heat Flow (μcal/cm^2 sec)
0	9.00	44.0	2.38	1.05
35.0	10.54			
45.0	(12.57	32.1	2.41	0.77
94.5	12.45			
149.5	(<29.55)	33.3	2.70	0.90
198.2	15.90			
244.5	(<17.18)	34.2	2.85	0.97
292.0	(>18.72)			
339.5	20.73	38.7	3.13	1.21
425.0	24.04)			
624.5	(27.69)			

the mantle into the base of the crust. The measured heat flow from the sea floor into the water (Table 5) may or may not be essentially the same as the geophysically relevant heat flow into the mantle, depending upon the existence of endothermic or exothermic processes within the crust, the thermal history of the bottom water, the rate and duration of sedimentation and/or erosion, whether or not heat is flowing entirely by molecular conduction or by some form of mass transport, and whether the sea floor and subsurface topography is flat or irregular, to mention some of the more important factors.

Many of these factors are either easily measured and/or are reasonably well understood in most areas of the deep ocean basins, where sedimentation rates, sediment thicknesses, and bottom water temperature changes are small. A small, relatively shallow ocean basin such as the Black Sea, with its very much greater sediment thickness, higher sedimentation rate, greater susceptibility to bottom water temperature change, and generally more complex and poorly understood tectonic history, presents a difficult problem for the geophysical interpretation of heat-flow values. Fortunately, the results of the downhole temperature measurements and sedimentological studies made during DSDP Leg 42B, as well as geophysical and geological data from other sources, can be brought to bear to estimate the probable range of environmental corrections, and thus to determine a probable range of heat flow out of the mantle.

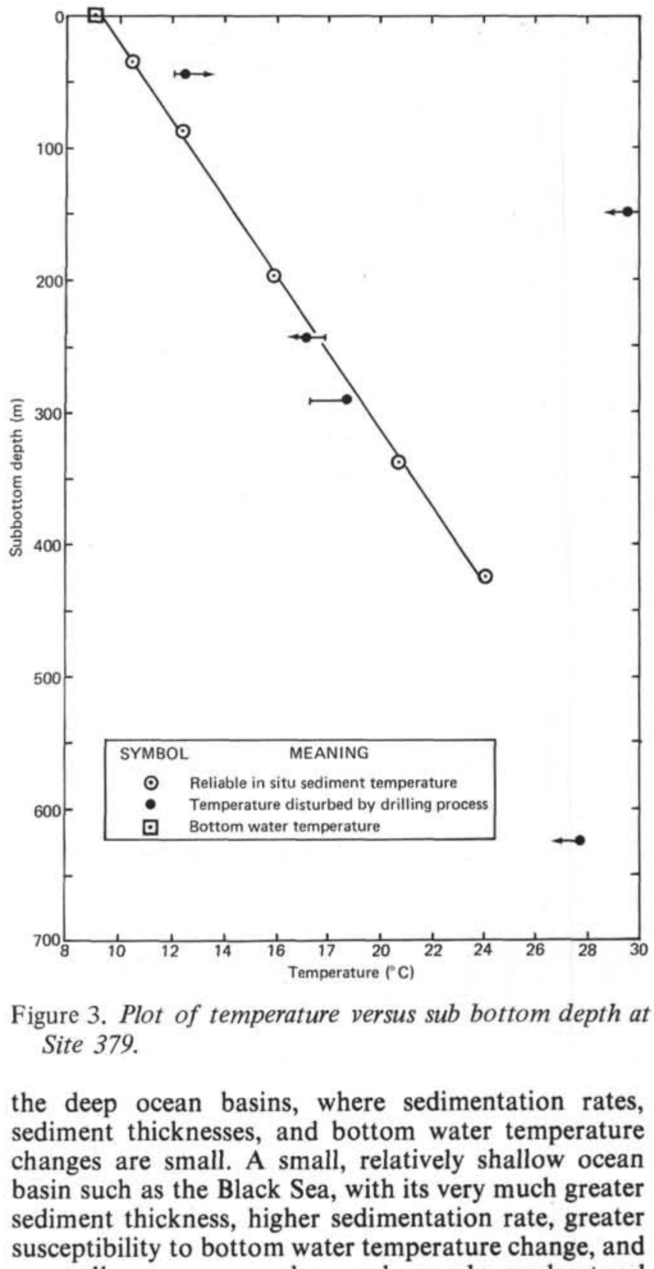

Figure 3. *Plot of temperature versus sub bottom depth at Site 379.*

Effect of Bottom Water Temperature Changes

Variations in bottom water temperature can produce a thermal gradient beneath the sea floor which can add to or subtract from the gradient which would be representative of the steady-state flow of heat through the sea floor. The amplitude and depth dependence of the thermal gradient perturbation beneath the sea floor depends upon both the amplitude and history of the

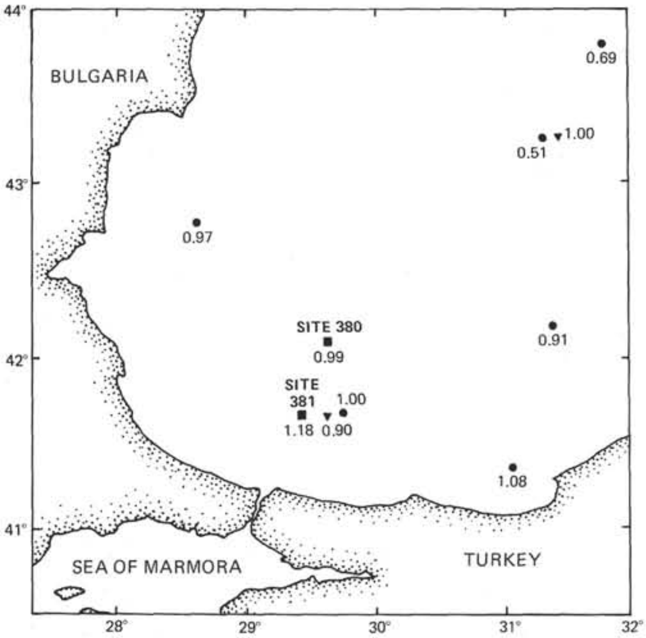

Figure 4. *Index map showing the locations of Sites 380 and 381 in relation to nearby conventional heat flow measurements. Heat flow values are given in units of 10^{-6} cal/cm^2 sec. Data sources are given in Figure 2.*

TABLE 3
Downhole Temperature Data and Interval Heat-Flow Calculations at Site 380

Subbottom Depth (m)	Sediment Temperature (°C)	Thermal Gradient (°C/km)	Thermal Conductivity (mcal/cm sec °C)	Interval Heat Flow (μcal/cm^2 sec)
0	8.43			
86.5	(>11.24)	51.2	2.31	1.18
180.5	17.67	47.4	2.32	1.10
199.5	(≤18.57)			
475.0	37.33			

bottom water temperature variations. It can be shown (Jaeger, 1965; Pugh, 1975) that harmonic temperature fluctuations which propagate downwards beneath the sea floor are attenuated exponentially with depth in a distance which depends upon the period of the fluctuation. In sediment having a constant thermal diffusivity of 0.002 cm²/sec, diurnal or annual temperature fluctuations are reduced to less than 0.2% of their surface amplitude at a distance of 46 and 890 cm below the sea floor, respectively. Whereas variations with these periods may be significant for conventional near-surface heat-flow measurements, they are clearly negligible for measurements made in deep boreholes. Longer period fluctuations may be significant at depths of hundreds of meters below the sea floor.

It seems reasonable, for example, to assume that a significant change in bottom water temperature was associated with the replacement of the cool, fresh, Black Sea water by denser, warmer, and more saline Mediterranean water when sea level rose sufficiently to permit interchange of water through the Bosporus. Study of near-surface sediments recovered from the Black Sea by Deuser (1974) indicates that Mediterranean seawater began to enter the Black Sea about 9000 years ago, and continued until about 7000 years ago. Although the actual thermal history of the bottom water is not known, some insight into the effect of the interchange can be had by study of a model in which water temperature rises, either abruptly or linearly, by 5°C between 9000 and 7000 years ago, followed by a constant rate of cooling by the same amount from 7000 years ago until the present time. At the present time the thermal effects of both models on temperatures in the sediment are nearly the same (Figure 7). The thermal gradient between the sea floor and about 175 meters sub-bottom is increased, with the magnitude of the increase being about 15°C/km in the

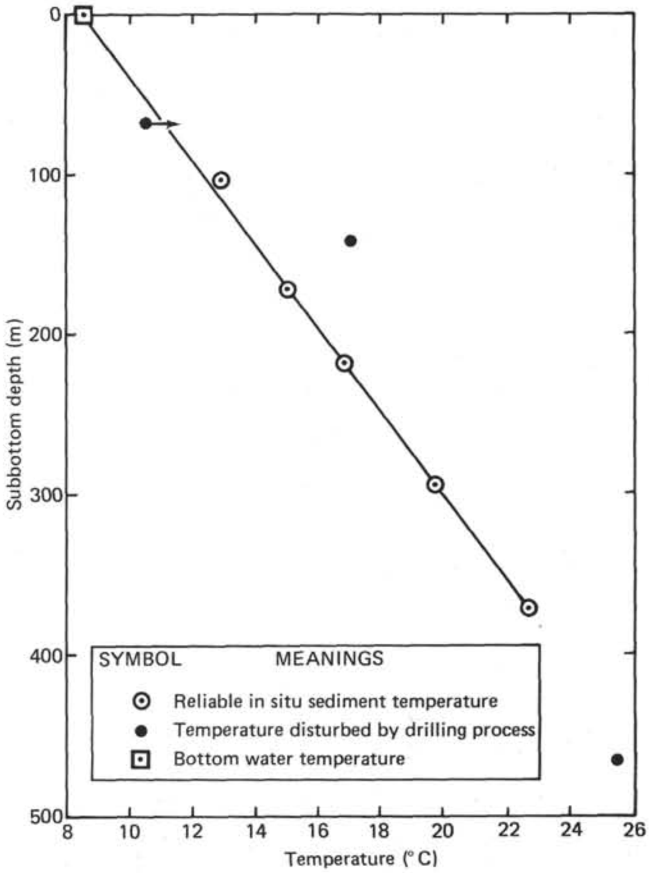

Figure 5. *Plot of temperature versus sub bottom depth at Site 380.*

TABLE 4
Downhole Temperature Data and Interval Heat-Flow Calculations at Site 381

Subbottom Depth (m)	Sediment Temperature (°C)	Thermal Gradient (°C/km)	Thermal Conductivity (mcal/cm sec °C)	Interval Heat Flow (μcal/cm^2 sec)
0	8.47	42.7	2.35	1.05
67.5	(>10.67)			
104.5	12.93			
142.5	(17.11)	31.4	2.54	0.80
171.0	15.02	39.6	2.57	1.02
218.5	16.90	37.9	2.70	1.02
294.5	19.78	38.9	2.72	1.06
370.5	22.74			
465.5	(25)			

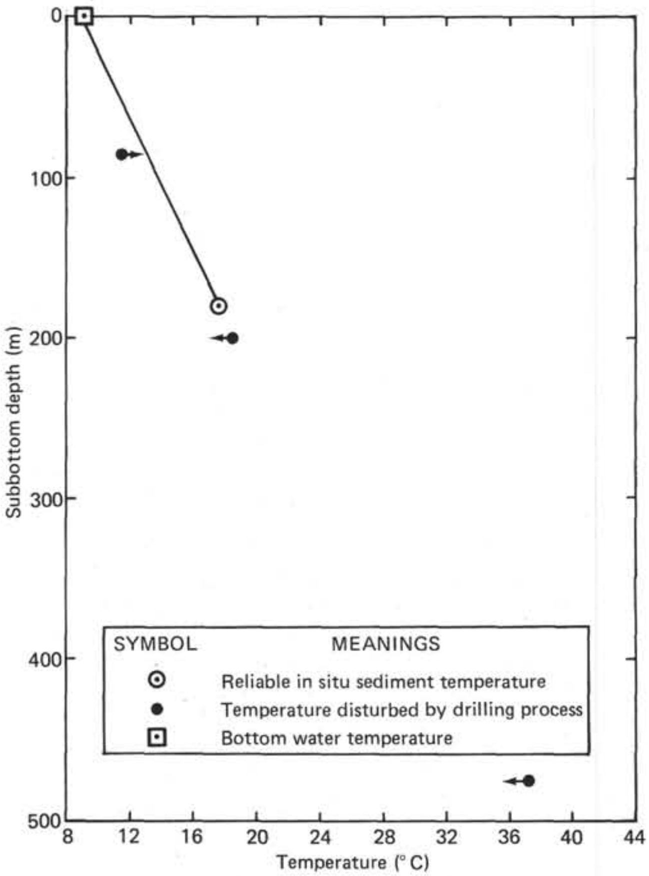

Figure 6. *Plot of temperature versus sub bottom depth at Site 381.*

TABLE 5
Summary of Heat-Flow Values Determined From Downhole Temperature Measurements and Shipboard Thermal Conductivity Determinations Made in the Black Sea During Leg 42B

Site	Location Latitude	Location Longitude	Water Depth (m)	Heat Flow (μcal/cm^2 sec)
379	43°00.29′N	36°00.68′E	2171	0.98 ±0.15
380	42°05.96′N	29°36.88′E	2115	0.99 ±0.10
381	41°40.25′N	29°24.96′E	1750	1.18 ±0.10

upper 50 meters, and falling rapidly to zero with depth. Below about 250 meters the gradient is decreased by a nearly constant value of about 3.5°C/km to depths greater than those at which reliable downhole temperatures were measured. The effect of temperature variations of this type would be to produce the observed higher heat flow in the interval immediately below the sea floor, however it would also tend to produce a downward decrease in heat flow in the intervals below 175 meters, the depth at which the inflection point of the temperature-depth curve occurs. Such a decrease with depth is not observed, and, in fact, a tendency for increased heat flow in the deeper intervals is noted, suggestive of a long-term decrease in bottom water temperature.

While they might have a significant effect on the observed geothermal gradient in the boreholes, the effects of even longer period temperature changes would not be discernible if the temperature perturbation is nearly constant or if it varies linearly with depth over the entire interval from which our downhole temperature data were obtained. Some understanding of this situation can be had by considering the effect of a unit change in temperature in homogeneous sediment having thermal diffusivity of 0.002 cm²/sec, which occurred at various times in the past. A plot of the resultant temperature perturbation versus depth (Figure 8), shows that as the temperature change is maintained for longer times, the amplitude of the temperature perturbation increases, the maximum magnitude of the disturbance to the thermal gradient decreases, and the perturbation gradually affects greater and greater depths. In our data there is no way to resolve that part of the observed geothermal gradient due to heat flow from that which has been caused by bottom water temperature variations. However, if the observed thermal gradient is due entirely to steady-state, conductive, geothermal flux and if there are no heat sources or sinks, then the heat flows calculated over any vertical interval should be equal. If the temperature distribution has been affected by a long-term change in bottom water temperature, then the product of the harmonic mean thermal conductivity

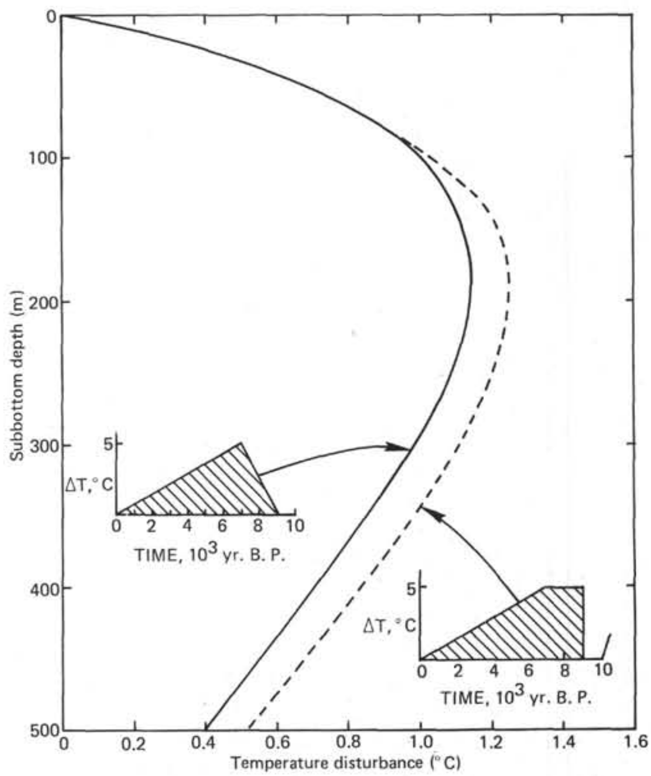

Figure 7. *Plot of the temperature disturbance versus depth below the sea floor caused by the variations of bottom water temperature shown in the two insets. A constant thermal diffusivity of 0.002 cm²/sec was assumed. These thermal histories are based on evidence for large-scale replacement of cold, fresh Black Sea water by warmer, saline, Mediterranean water between 9000 and 7000 years ago (Deuser, 1974).*

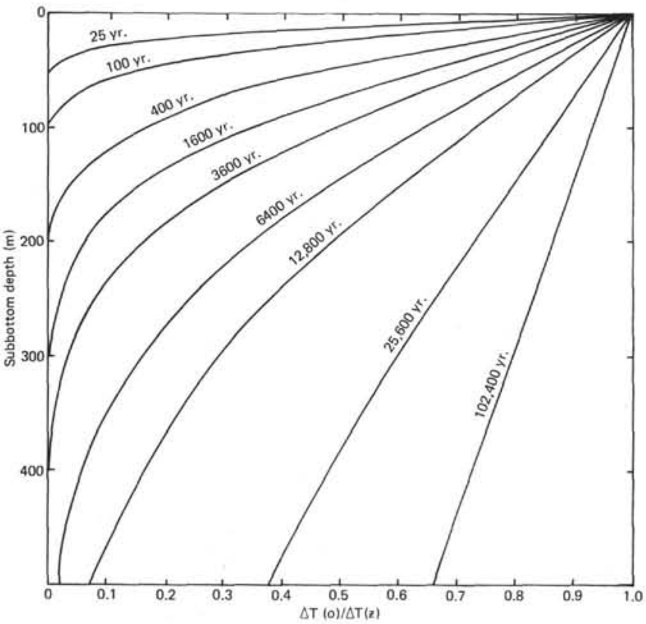

Figure 8. *The normalized effect of a sudden (step) change in bottom water temperature lasting for various lengths of time on sediment temperature below the sea floor. A constant thermal diffusivity of 0.002 cm^2/sec is assumed.*

and the thermal gradient in each interval should show either a systematic increase or decrease, depending upon whether the bottom water temperature has decreased or increased, respectively.

Examination of Tables 2 and 3 suggests that there is a tendency for higher interval heat flow in the uppermost interval, followed by a significant decrease in the next deeper interval, and for gradually increasing interval heat-flow values at greater sub-bottom depths. The increased heat flow at greater depths, although readily apparent at Site 379, is nearly negligible at Site 380. The fact that water depths at the two sites are nearly equal suggests that the thermal history of the bottom water, and thus its effect on the temperature distribution below the sea floor, should have been nearly identical at both sites. The differences observed in the distribution of the interval heat-flow values with depth at the two sites suggests that the variations in interval heat flow may not have been caused entirely by variations in bottom water temperatures. This conclusion is supported by the fact that the relatively large increase in the interval heat flow calculated through the deepest interval at Site 379 requires an unreasonably large amplitude and complicated thermal history for the bottom water.

The high interval heat flow in the uppermost interval could be attributed to one or more of the following causes:

a) Rapid cooling of the bottom water by several tenths of a degree Centigrade during the last 25 years. This seems improbable in view of the density stabilization of the Black Sea water, and the fact that, if Mediterranean water is continuing to enter the Bosporus, its temperature (14°C) would increase, rather than decrease the temperature of the Black Sea bottom water (9°C).

b) Measurement of bottom water temperatures in the drill pipe which are lower than the actual bottom water temperatures. It is difficult to visualize how temperatures lower than those characteristic of the bottom water could be measured in view that the drilling fluid used for circulation is normal Black Sea surface water, initially at a temperature of about 19°C.

c) If the water depth is actually shallower than that estimated by the driller, thus causing calculation of a higher thermal gradient than is actually present (Figure 9). An overestimate of the depth to the sea floor of about 10 meters is necessary to account for the higher gradient in the uppermost interval at both Sites 379 and 380. An error of this magnitude is not unreasonable, particularly in view of the very soft near-surface sediments, characteristic of the Black Sea. It is noted that the distinctive near-surface sedimentary units observed in the uppermost few meters of most Black Sea piston cores (Ross and Degens, 1974) were not observed in any of the punch cores taken to verify the driller's contention that the drill string had just reached the sea floor, although failure to sample these layers may also be due to the inadequacy of the sampling technique. The apparent close agreement between the corrected water depth calculated from echo-sounding records and the water depth determined by the driller may be fortuitous in view of the difficulty of making precise corrections for variations in sound velocity through water having significant variations in both salinity and temperature.

d) Occasional measurements of a temperature significantly greater than the in situ sediment temperature, as predicted from upward extrapolation

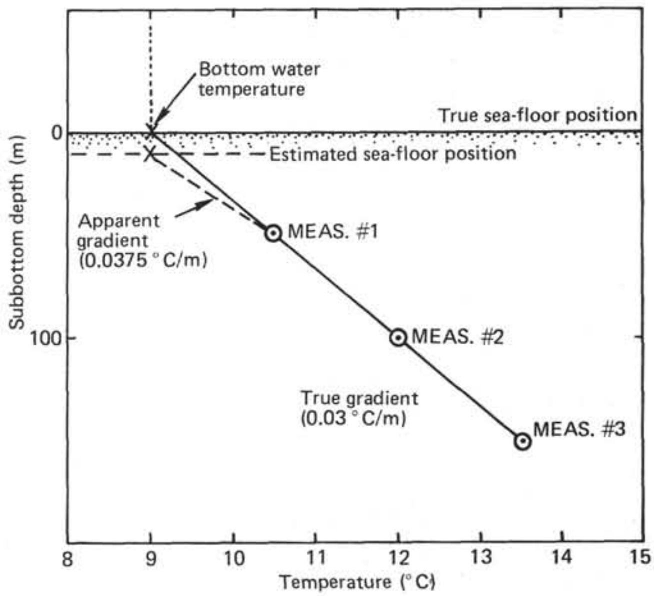

Figure 9. *The effect of an overestimate in the water depth due to the inability of the driller to detect the mudline in regions of soft sediment can produce an apparent decrease in the thermal gradient (and thus heat flow) with depth below the sea floor.*

of the nearly constant thermal gradient below 50 meters sub-bottom, are well documented at Sites 379 and 380. One of the two most clearly anomalous measurements (Figure 1d) has a temperature-time record which is significantly different from the records which are believed to be representative of the normal in situ sediment temperatures (Figure 1i), while the other (Figure 1m) does not. Although the temperature measurements used to calculate the interval heat-flow values were carefully chosen to avoid consideration of measurements whose temperature-time plots deviated from those characteristics of supposedly reliable in situ temperature determinations, it is possible that some of the temperature values used actually are higher than the true steady-state sediment temperature. This is suggested by the occurrence, at both Sites 379 and 380, of a below average interval heat-flow value immediately beneath the above average heat flow associated with the uppermost interval.

Our conclusion is that the variations in interval heat flow in the uppermost two intervals at Sites 379 and 380 are probably due to systematic measurement errors associated with failure of the driller to detect the top of the mud-water interface and/or due to measurement of sediment temperatures which may have been slightly higher than the in situ sediment temperature due to frictional heating, although the possibility of bottom water temperature changes cannot be definitively ruled out. The lack of systematic variations in interval heat flow in the deeper intervals at both sites strongly suggests that these variations are not due to long-term temperature changes, but are probably caused by making the downhole temperature measurements in material which is not at thermal equilibrium with the in situ sediment temperature.

Sedimentation and Compaction Effects

The ability of rapid sedimentation to decrease the near-surface geothermal gradient has been discussed by various investigators (Von Herzen and Uyeda, 1963; Jaeger, 1965). Thermal effects of sedimentation are due to the upward (and lateral) movement of interstitial fluids, the changing position of the mud-water interface, and the downward movement of solid particles due to compaction of sediments having different hydraulic diffusivities (Sharp and Domenico, 1976; Panda, 1973; Lubimova et al., 1965). The relationship between the heat flow into the base of an accreting and compacting layer of sediment, and the heat flow which would be calculated on the basis of temperatures measured in the upper part of the sediment layer, is a complicated and sensitive function of the sedimentary history and the lateral and vertical variations in the physical properties of the sediment layers (see, e.g., Sharp and Domenico, 1976). Where faults are present or where horizontally extensive layers of impermeable (salt or shale) and permeable (sand) sediment are interbedded, water movement due to compaction could be primarily lateral, rather than vertical (Magara, 1976). In short, the detailed correction of the observed heat flow (Table 5) for sedimentation and compaction requires far more information than is currently available for the Black Sea.

It is possible to estimate the probable magnitude of the effects of sedimentation and compaction using simplified models and assuming parameters based on the results of drilling and other types of geophysical data. The effect of sedimentation at a constant rate can be estimated if the average sedimentation rate, the length of time that sedimentation has been occurring, and the thermal diffusivity of the sediment are known or can be estimated (Jaeger, 1965; Von Herzen and Uyeda, 1963). Estimates of the rate and duration of sedimentation can be made if the age of the sediment recovered from various depths in the drill holes is known, or if the age of the "basement" and the thickness of sediment upon it can be ascertained from geologic and geophysical data. In either case a correction is required to convert "compacted" sediment thickness to "uncompacted" thickness (Hamilton, 1976).

Use of the drilling results to calculate sedimentation rates in the Black Sea is not without hazard as neither the age of the sediments nor the distribution of thermal diffusivity with depth of the sediment is well known. Use of the best estimates for the maximum age of the sediments recovered at each drill site, and assumption of thermal diffusivities of 0.002 and 0.004 cm^2/sec, typical of unconsolidated and semiconsolidated marine sediments, respectively, yields the results listed in Table 6.

It can be seen that one effect of sedimentation is to significantly reduce the observed gradient. On one hand, the magnitude of the reductions shown in Table 6 must be considered to be the minimum effects, as much greater thicknesses of sediment than were drilled are present beneath all three sites. On the other hand, assignment of a uniform thermal diffusivity is probably unrealistic, as compaction will tend to increase the diffusivity at depth.

A maximum sedimentation effect can be calculated by estimating the sediment thickness beneath each drill site using depth-to-basement maps based on seismic data provided by Neprochnova (1976). Again expanding the observed sediment thickness beneath each site (Table 7) following Hamilton (1976) and assuming various ages for the Black Sea, the sedimentation effects shown in Figures 10 a, b, and c were obtained. It is apparent that sedimentation should have significantly reduced the heat flow at all three sites and that the effect is largest for sites having the greatest sediment thickness and for decreasing duration of sedimentation. It is noted that the effect is nearly constant over the depth range in which temperature data were obtained, and is strongly dependent upon the value assumed for the thermal diffusivity of the sediment which may vary from 0.002 cm^2/sec, characteristic of unconsolidated marine sediment, to 0.010 cm^2/sec characteristic of consolidated rocks.

Although estimates for the age of the Black Sea range from Precambrian (Milanovskiy, 1967) to early Quaternary (Nalivkin, 1960), on the basis of geological and seismic data most investigators now appear to

TABLE 6
Reduction of the Steady-State Thermal Gradient Due to Sedimentation at Constant Rates Calculated from Thicknesses and Ages Determined by Drilling Results

Site	Drilling Data Max. Depth (m)	Drilling Data Max. Age (m.y.)	Expanded Thickness (m)	Sedimentation Rate (m/m.y.)	Gradient Reduction (%) $K = 0.002$ cm^2/sec	Gradient Reduction (%) $K = 0.004$ cm^2/sec
379	624	1	1080	1080	38	29
380	1000	5	2029	406	34	25
381	500	5	813	163	15	11

TABLE 7
Heat Flow Corrected for Effects of Sedimentation as Determined by Seismically Determined Sediment Thickness Beneath Each Drill Site

Site	Sediment Thickness (km) Observed	Sediment Thickness (km) Expanded	Thermal Diffusivity (cm^2/sec)	Observed Heat Flow (10^{-6} cal/cm^2 sec)	Heat Flow (10^{-6} cal/cm^2 sec) Corrected for Sedimentation for Length of Time Shown Below: 20 m.y.	40 m.y.	60 m.y.	80 m.y.	100 m.y.	200 m.y.
379	8	24	0.008	0.98	3.82	2.48	2.07	1.86	1.73	1.46
380	5	15	0.006	0.99	2.55	1.90	1.68	1.56	1.48	1.31
381	3	8	0.004	1.18	2.14	1.79	1.65	1.57	1.53	1.42

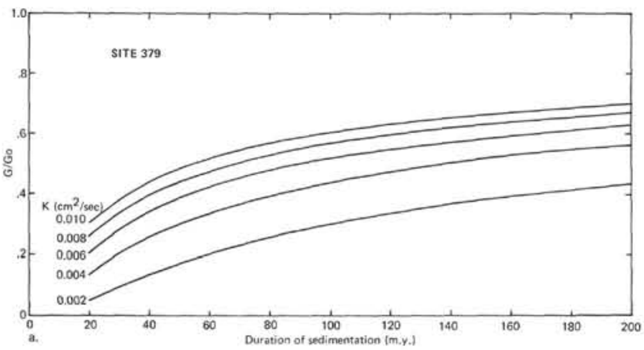

Figure 10a. *The ratio of the thermal gradient at a depth of 200 meters sub bottom to the steady state thermal gradient at Sites 379, 380, and 381, respectively. The sediment thickness beneath each site (Table 7) was deposited at a constant rate for the times shown, and that the sediment has constant thermal diffusivity K.*

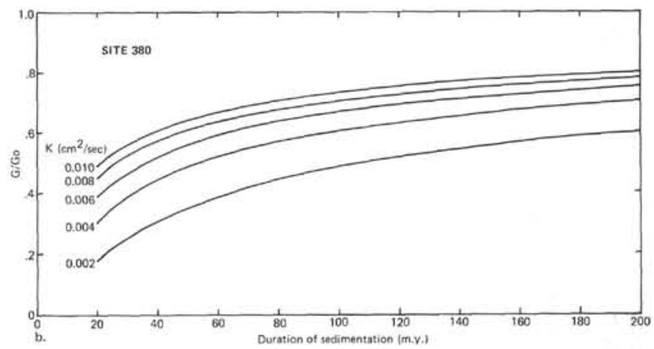

Figure 10b.

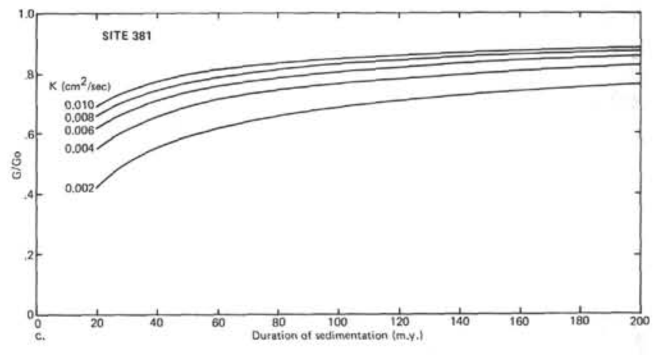

Figure 10c.

favor an origin for the Black Sea some time during the Mesozoic Era (Apol'skiy, 1974; Neprochnova, 1976; Brinkmann, 1974; Adamiya et al., 1974) with the possibility of even greater ages for localized areas of the central deep-water depressions. (Muratov, 1972). Abundant evidence exists for recent or continued subsidence along the southern, eastern, and northern margins of the basin (Ross et al., 1974), suggesting that there may be significant differences in the length of time sediment has been accumulating beneath Sites 379 and 381, located well out on the basin floor and on the continental rise, respectively.

Table 7 indicates the corrected heat flow which would be calculated from the observed heat flow for all three drill sites assuming (a) increased average thermal diffusivity with increasing sediment thickness, and (b) that sediment accumulated at a constant rate for various periods of time. It is worth noting from Table 7 that the corrected heat-flow values calculated at Sites 380 and 381, situated near and on the southern margin of the Black Sea, respectively, are approximately equal if an age of about 80 m.y. (Late Cretaceous) is assumed for the initiation of the sedimentation, but are both significantly lower than the corrected heat flow through the central basin at Site 379 if the age of the basin is the same at all three sites. It can be seen that if an age between 140 and 180 m.y. (Early to Middle Jurassic) is assumed for the basin, the corrected heat-flow values at all three sites are between 1.5 and 1.6 $\times 10^{-6}$ cal/cm²sec. No particular significance can be placed on this equality as there is no a priori reason to presume that the heat flow through the central Black Sea Basin is not actually greater than the heat flow through the margins; however, it is worth noting that the apparently greater corrected heat flow through the central Black Sea suggested by Table 7 may simply reflect the fact that all areas of the Black Sea are not of equal ages.

The thermal effect of the upward movement of water as a consequence of sediment compaction can be estimated using a relationship derived by Lubimova et al. (1965). Their model consists of a layer of permeable sediment of known thickness through which water is moving upwards at a uniform velocity. In order for a steady-state situation to exist, the velocity with which the fluid rises cannot exceed the rate at which sediment is added to the top of the compacting layer.

The effect of the upward movement of the interstitial water is to increase the thermal gradient near the top of the compacting layer by an amount which increases both with the thickness of the layer and with the velocity by which the water moves through the layer. It is possible to set limits on the thickness of the compacting layer both from the physical property data measured on the sediment drilled at these sites, and by noting the absence of a systematic downward decrease in interval heat-flow values at Sites 379 and 380 (see section on evidence for bottom water temperature variations). Specifically, porosity and water content are seen to decrease rapidly with depth in the uppermost hundred meters, and then to decrease much more slowly with increasing depth (see Physical Properties Sections of Chapters 3 and 4). It thus seems reasonable to consider that most of the compaction occurs within the upper hundred meters, at rates not exceeding the average sedimentation rates determined by the drilling results (Table 6). Based on an upward velocity of 500 m/m.y., the thermal gradient near the surfaces of uniformly compacting layers having thicknesses of 100 and 500 meters would only be increased by factors of 1.01 and 1.06, respectively, relative to the gradient at the base of the layer. Doubling the assumed upward velocity yields near-surface, thermal gradient increases by factors of 1.02 and 1.11, respectively. Clearly, the effect of steady-state compaction is insignificant in comparison to the effect of the heat absorbed by newly deposited sediment.

Thermal Refraction

In addition to the reduction in the thermal gradient caused by sedimentation, it is possible that the presence of a thick blanket of low thermal conductivity sediment beneath the central Black Sea has further reduced the average flux through the central basin and increased the heat flow around the margins relative to the flux from the mantle into the base of the sediments. The magnitude of the reduction was estimated using analytical solutions presented by Von Herzen and Uyeda (1963) for thermal refraction through circular and two-dimensional sediment-filled, hemi-ellipsoidal depressions, having major and minor axes of 95 and 14 km, respectively, and assuming that the mean thermal conductivity of the basement is twice that of the sediment. If the cross-sectional shape of the Black Sea were ellipsoidal, heat flow would be uniformly lower over the entire sediment-filled depression by 10% to 20%.

The actual non-ellipsoidal cross-sectional shape of the Black Sea Basin will cause the magnitude of the reduction to vary according to position, rather than being constant across the basin. The principal discrepancy between the real and idealized sediment distribution is that the sediment thickness beneath the margins of the deep basin is thinner than that required by the model, thus causing a reduction in the refraction effect near the continental rise where the sediment thins rather abruptly. The observed heat flow should thus be low in the central basin and slightly higher near the continental rise, as observed in both borehole and conventional heat-flow values.

Summary of Environmental Effects

It appears almost inevitable that the rapid rates of sedimentation at the drill sites have decreased the heat flow through the sea floor by 30% to 40%. It is further likely that thermal refraction has reduced the heat flow by amounts varying from as much as 20% through the central Black Sea abyssal plain (Site 379) to perhaps 10% near the edge of the abyssal plain (Sites 380 and 381). Small-scale refractive effects are considered to be negligible in view of the presence of thick, generally horizontally stratified, sediments beneath all three drill sites. The distributions of temperature and interval heat-flow values with depth cannot be convincingly interpreted in terms of bottom water temperature variations, despite independent evidence for significant changes in the water masses since the end of the last glacial epoch 10,000 years ago (Ross and Degens, 1974). The thermal effect of the upward migration of interstitial water appears to be small (less than 5%), if it is true that compaction is primarily occurring in the uppermost 500 meters of sediment and that the upward velocity of the interstitial water is less than or equal to the mean sedimentation rate.

In conclusion, the measured heat flow of 0.98 to 1.18 $\times 10^{-6}$ cal/cm²sec measured at all three sites should probably be increased to $1.6 \pm 0.2 \times 10^{-6}$ cal/cm²sec, primarily to compensate for the effects of regional sedimentation and, to a lesser extent, thermal refraction.

SUMMARY

Comparison of Borehole and Conventional Heat-Flow Measurements

Meaningful comparison of the borehole heat-flow values with the results of conventional marine heat-flow measurements is complicated by the failure of many investigators to provide sufficient information on their measurement techniques and equipment to allow an evaluation of the reliability of their data. The authors' frequent observation of strongly non-linear temperature-depth relationships in many of the conventional heat-flow measurements reported by Erickson and Simmons (1974) suggests that heat-flow values computed from gradients determined at only two depths below the sea floor may be seriously in error.

Conventional heat-flow values within 50 km of DSDP Site 379 range from 0.47 to 1.16 $\times$ 10^{-6} cal/cm²sec, with a mean and standard deviation of 0.77 $\pm 0.22 \times 10^{-6}$ cal/cm²sec (Figure 2). The value of 1.16 $\times$ 10^{-6} cal/cm²sec west of Site 379 is significantly higher than any of the remaining six values and may belong to a region of higher heat flow extending southeast from Crimea. The lowest heat-flow value (0.47 $\times$ 10^{-6} cal/cm²sec) is viewed with suspicion, although even lower values are found in other areas. After deletion of these two extreme values the mean and standard deviation of the remaining five values is 0.76 $\pm 0.10 \times 10^{-6}$ cal/cm²sec, somewhat lower than the borehole heat flow of 0.98 $\pm 0.15 \times 10^{-6}$ cal/cm²sec, but within the range of the probable error. Although additional, carefully controlled surface heat-flow measurements will be needed to determine whether or not the observed difference is significant, it is interesting to speculate on what could cause the discrepancy.

The observation of lower heat-flow values using near-surface thermal gradient measurements, rather than the much deeper borehole temperature measurements, is surprising in view of the well-documented tendency for the near-surface thermal gradient and interval heat-flow values in the uppermost 10 meters of sediment to decrease with depth (Erickson and Simmons, 1974). Based on these observations, the gradient and interval heat-flow values at greater depths should either remain low or decrease even further, contrary to what is actually observed at Site 379. Even if the sedimentation rate has increased dramatically in the last few ten thousand years or so, resulting in the deposition of a few meters of sediment at sedimentation rates between 400 and 900 m/m.y., calculated by Ross and Degens (1974) for recently deposited Black Sea sediments, the heat flow through the newly deposited layer of sediment would be very nearly equal to the flux through the underlying layer. Sudden deposition of a layer of sediment several meters thick throughout much of the Black Sea basin could reduce the thermal gradient in the uppermost sediment relative to the gradient at depth by the required amount, if the layer were deposited between 100 and 1000 years ago. However, the widespread presence of distinct, well-dated lithologic units within the uppermost few meters of the sea floor (Ross and Degens, 1974) rules out this possibility.

An increase in bottom water temperature by a few hundredths of a degree Centigrade within the last year or so, possibly associated with yet undetected seasonal variations, could result in the measurement of lower heat flow immediately below the sea floor. However, the strong density stratification characteristic of the upper few hundred meters of the Black Sea should effectively isolate the sea floor from these seasonal effects.

It is possibly significant that a similar downward decrease in heat flow was observed to depths of about 10 meters below the sea floor in almost all of the marine heat-flow measurements made in the Gulf of Mexico (Epp et al., 1970), a basin which is in some respects structurally equivalent to the Black Sea in terms of its thin "oceanic" crust and thick sediment cover (Ewing et al., 1960; Martin and Case, 1975). Epp et al. (1970) also were unable to explain satisfactorily the cause of the vertical variations in the near-surface heat flow in terms of sedimentation effects, bottom water temperature variations, the movement of interstitial water, or heat production in the sediments. Unfortunately, no borehole heat-flow values are available from the Gulf of Mexico to see if heat flow measured at greater depths is higher than that observed through the sediments immediately below the sea floor.

Only five conventional heat-flow measurements have been made in the southwestern corner of the Black Sea within 150 km of Sites 380 and 381 (Figure 4). All of the values are within the range from 0.90 to 1.08 $\times$ 10^{-6} cal/cm² sec, with a mean and standard deviation of 0.97 $\pm 0.07 \times 10^{-6}$ cal/cm²sec, and are in excellent agreement with the heat-flow values calculated at the drill sites.

The problem of the origin of the Black Sea must be approached in the much broader framework of the regional geophysics and plate tectonics of the entire Mediterranean region. The Mediterranean region is, in many ways, unique in that it is at present an active zone of continent-continent and ocean-continent convergence on a truly massive scale. As a result of the mutual interaction of the Eurasian and African plates, and the almost (?) complete subduction of the intervening oceanic lithosphere, a wide range of mineralogical and other thermally driven processes in the mantle may occur here, some of which may not occur in other, less complicated areas. Any theory for the origin of the Black Sea must take into account, as a starting point, its location at the northern edge of the zone of convergence between the Eurasian and African lithospheric plates, the abundant evidence for the present and past existence (and the subduction) of microplates (Roman, 1970; Herz and Savu, 1974; Boccaletti et al., 1974; Dewey et al., 1973), and the presence of a number of other basins or depressions stretching longitudinally from the Balearic Basin in the west through the Caspian Sea to the east, whose origins are also the subject of great geophysical inquiry and even greater speculation (Boldizsar, 1974; Bleahu et al., 1973; Menard, 1967; Auzende et al., 1973).

The corrected heat flow of 1.6 $\pm 0.2 \times 10^{-6}$ cal/cm²sec, based on the borehole heat-flow values, is significantly lower than the estimate of 2.2 $\times$ 10^{-6} cal/cm²sec computed by Erickson and Simmons (1974) from conventional heat-flow values and significantly different assumptions regarding correction of the observed heat flow for the effects of sedimentation. The magnitude of the corrected heat flow is characteristic of the heat flow through a wide variety of geophysical environments, for example: (a) through normal oceanic crust formed 40 to 80 m.y.b.p. (Sclater et al., 1976); (b) through normal continental crust which has not been orogenically active within the last 100 m.y. (Kutas, 1972); (c) through some marginal basins behind island arcs (Sclater et al., 1972).

Thus, the heat-flow data do not, in itself, allow us to distinguish between most of the hypotheses for the origin of the Black Sea other than in the most elementary manner.

The estimation of a nearly uniform heat flow of 1.6 $\pm 0.2 \times 10^{-6}$ cal/cm²sec at all three drill sites, plus the absence of any measured conventional heat-flow values greater than 1.6×10^{-6} cal/cm²sec, is in accord with other geological and geophysical data which argue against the Black Sea being a geologically young feature formed by rifting of either normal oceanic or continental crust, or by recent spreading behind a subducting plate boundary (Sleep, 1975).

Instead, it appears more likely that some or all of these basins may owe their origins to more passive processes driven directly by temperature variations in the upper mantle (Long and Lowell, 1973; Sleep and Snell, 1976). Large positive and negative temperature differences in the upper mantle appear to be inevitable consequences of plate movements associated with subduction zones (Bird et al., 1975; Andrews and Sleep, 1974) and possibly, also with contrasts in the temperature of the asthenosphere beneath continental and oceanic areas (Jordan, 1975; Sipkin and Jordan, 1975; Schubert et al., 1976).

It is interesting to speculate that the convergence of the African and Eurasian continents, once widely separated by a zone (Tethys) underlain by oceanic lithosphere and asthenosphere, resulted in the temporary heating of the cooler, continental mantle material formerly beneath the Black Sea, possibly due to viscous flow behind a former island arc (Andrews and Sleep, 1975) and/or the effects of thermal and composition differences in the upper mantle beneath oceans and continents postulated by Jordan (1975). Heating of the continental lithosphere could induce thermal expansion and phase changes resulting in the uplift and subaerial erosion of the overlying continental crust; slow subsidence of the deeply eroded crust followed as the lithosphere cooled by removal of the overlying radiogenic crustal material, cessation of subduction, the replacement of high temperature oceanic mantle material by cooler continental mantle, or some combination of the above. Estimation of a heat flow of $1.6 \pm 0.2 \times 10^{-6}$ cal/cm²sec out of the top of the sediments, and a somewhat lower value (1.2 to 1.4×10^{-6} cal/cm²sec) for the flux into the base of the sediments, suggests that the lithosphere is still cooling, also indicated by evidence for continued subsidence around the margins of the Black Sea (Ross and Degens, 1974).

Given the present state of our knowledge about the temperature distribution within and even beneath normal continental and oceanic lithospheric plates, much less within a dynamic region such as the Mediterranean, it would appear likely that the origin of the Black Sea will remain speculative for some time to come. The final solution will surely necessitate a multi-disciplined, well-coordinated combination of geological and geophysical observations on both the local and regional scales. A better understanding of the thermal regime within the Mediterranean area will play a significant role in suggesting, as well as providing constraints on, solutions to the problem of the origin of the Black Sea and surrounding basins.

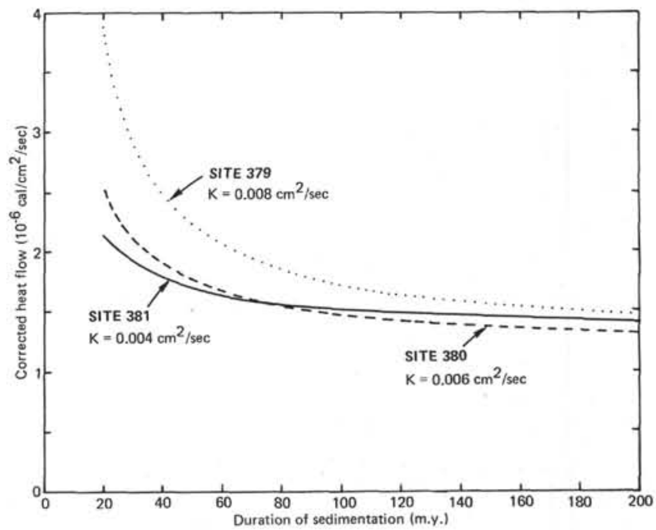

Figure 11. *Heat flow corrected for the effects of sedimentation at Sites 379, 380, and 381. The correction was made assuming that the sediment thickness beneath each site (Table 7) was deposited at a constant rate for the times shown. A constant thermal diffusivity was assumed for each site, but increasing thermal diffusivities of 0.004, 0.006, and 0.008 cm²/sec were assigned to Sites 379, 380, and 381, respectively, on the basis of the variable sediment thickness beneath the sites (Table 7).*

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