9. A HEAT FLOW MEASUREMENT ON THE FALKLAND PLATEAU[1]

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ABSTRACT

At Hole 511, on the margin of Maurice Ewing Bank, eastern Falkland Plateau, successful bottom hole temperature measurements were made at 52.5 and 113 meters below the seafloor. The results show a regular increase of temperature with depth of 0.074°C m^{-1}.

Conductivity measurements on core samples, made on board ship and at the Lamont-Doherty repository, gave a mean value of 0.842 W °$C^{-1}m^{-1}$. The heat flow indicated by these observations is 62.3 mW m^{-2} (1.49 HFU), a value that is compatible with the geological evolution of the plateau.

EXPERIMENTAL TECHNIQUE

Temperature measurements are made in sediments at the bottom of the hole using the Tokyo/DSDP T-probe (Yokota et al., 1979). The instrument is lowered to the bottom of the drill string on the sand line during a pause in drilling. The electronic recorder, enclosed in a special core barrel that serves as a pressure-proof vessel, records temperature while the probe is being lowered down the pipe and during hoisting. When the core barrel is latched into the bottom of the drill string, the probe, carrying a thermistor in its tip, projects about one meter below the bottom of the bit.

Temperature in the sediments is measured by driving the probe into the sediments at the bottom of the hole. The probe is left undisturbed in the sediments for a period of 15 to 20 minutes, which allows sufficient time for the probe to equilibrate with the surrounding sediments.

While hoisting the probe back to the surface, a stop of several minutes is made just above the seafloor to allow the thermistor to equilibrate with the bottom water. This measurement provides a valuable data point, seafloor temperature, and an *in situ* check of instrument calibration, since the bottom water is usually known from nearby hydrographic data.

For measurements in Hole 511, temperatures were recorded every minute, and up to 128 temperatures were recorded per lowering.

HOLE 511 MEASUREMENTS

Two successful temperature measurements were carried out at Hole 511. The heave compensator was used during the drilling and produced a stable bottom hole assembly in the unconsolidated sediments penetrated by the thermistor probe. The temperature records during lowering, penetration, a 20-min. wait on bottom, and hoisting back up the pipe are shown in Figure 1. In Figure 2 we show the temperature profile at a nearby hydrographic station INDOMED Leg XIII (SIO Data Report). Notice that the T-probe recorded the temperature minimum at 200–400 meters and a bottom water temperature of 0.7°C, both in excellent agreement with the hydrographic results. For some reason the recorder stopped functioning during hoisting, for both measurements. For the measurement at 52.5 meters (Measurement I), it stopped about 10 min. after the probe was extracted from the sediments.

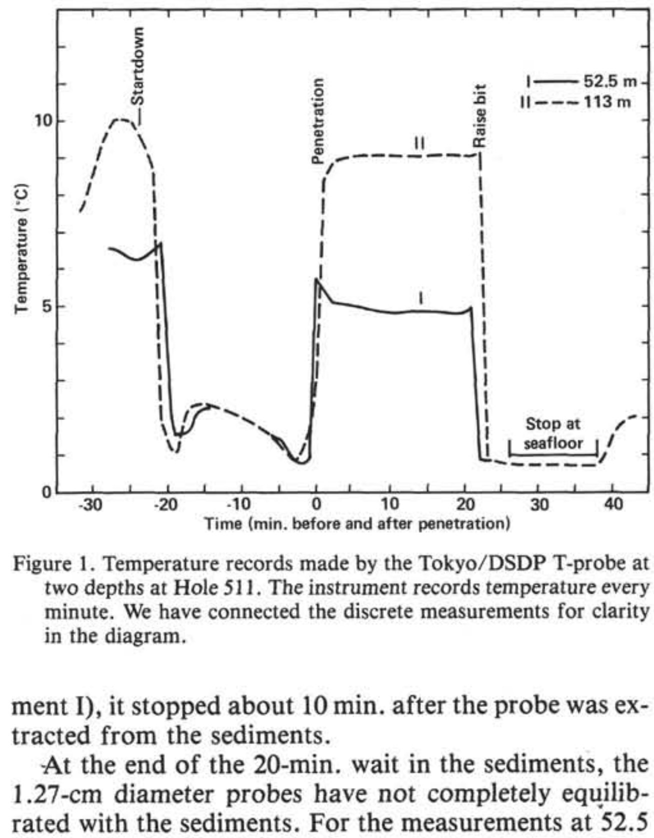

Figure 1. Temperature records made by the Tokyo/DSDP T-probe at two depths at Hole 511. The instrument records temperature every minute. We have connected the discrete measurements for clarity in the diagram.

At the end of the 20-min. wait in the sediments, the 1.27-cm diameter probes have not completely equilibrated with the sediments. For the measurements at 52.5 meters the thermistor is still cooling slowly while it loses the initial heat of penetration, whereas it warms after penetration at the 113-meter measurement. The temperature curves can be used to estimate a final equilibrium temperature based on the theory of cooling of a cylindrical probe (Jaeger, 1956). After about 5 min. in the sediments, the rate of temperature decrease with respect to the reciprocal of time elapsed is uniform. Thus temperature plotted versus 1/time will yield a straight line, and the intercept at $1/t = 0$ provides an estimate of the equilibrium temperature. Plots of this type for the two measurements at Site 511 are shown in Figure 3.

The measurement at 52.3 meters shows a reasonable fit to a straight line, and the estimate of the equilibrium

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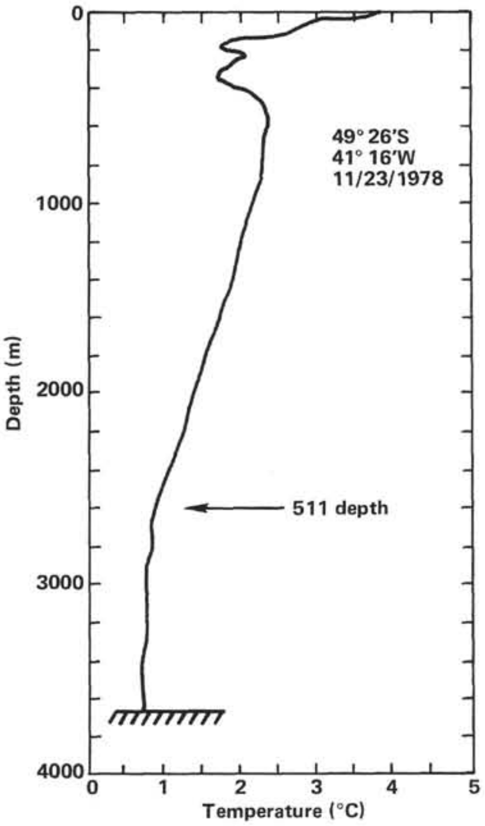

Figure 2. The temperature profile in the water column at a nearby hydrographic station (INDOMED Leg XIII Station 21D). Notice the temperature minimum at about 100 meters that is also recorded by the T-probe.

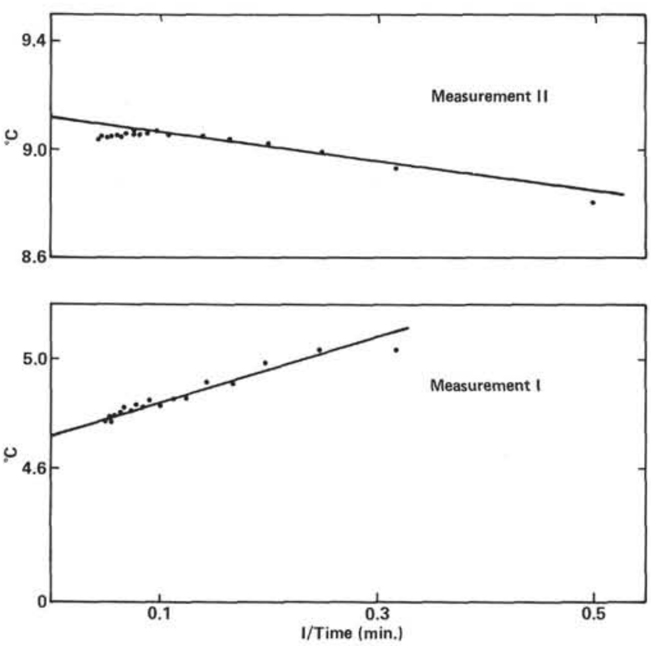

Figure 3. Temperatures recorded while the T-probe is in the sediments, plotted versus the reciprocal of time since penetration. The lines are fitted by eye. The intercept at 1/time = 0 is an estimate of the final equilibrium temperature.

temperature is 4.73°C. The temperature history during the 113-meter measurement shows warming of the probe; the temperatures do not describe a straight line on the 1/time plot but appear to equilibrate more rapidly than expected. We think that this is due to the superposition of two transient phenomena: (1) the equilibration of the initially cold probe to the surrounding warmer sediments and (2) the flow of heat upward along the 10-cm-long probe body to the massive 6-cm diameter lance on which the probe is mounted. This second effect is thought to be the cause of the perceptible tailing away of the points from a straight line after 10 min. If this is what actually occurs, the apparent final value of 9.04°C may underestimate the equilibrium temperature. Extrapolation of the first 5 min. of the record gives 9.12°C. The error bars in the plot of these temperatures versus depth (Fig. 4) reflect these uncertainties, which introduce very small errors in the gradient determination. The final gradient values are as follows: from the seafloor to 52.5 meters, $0.0764 \pm 0.0004°C\ m^{-1}$ and from 52.5 to 113 meters, $0.072 \pm 0.0008°C\ m^{-1}$. The difference is apparently real and attributable to an increase in mean conductivity from the upper to the lower interval.

THERMAL CONDUCTIVITY MEASUREMENTS

Four thermal conductivity measurements were made on core samples from Hole 511 in the interval between the seafloor and 113 meters sub-bottom, the interval over which the gradient was measured. The measurements made onboard ship with a needle probe apparatus (Von Herzen and Maxwell, 1959) are judged to be unreliable because a correlation of the measured conductivity against water content shows that the values are not in

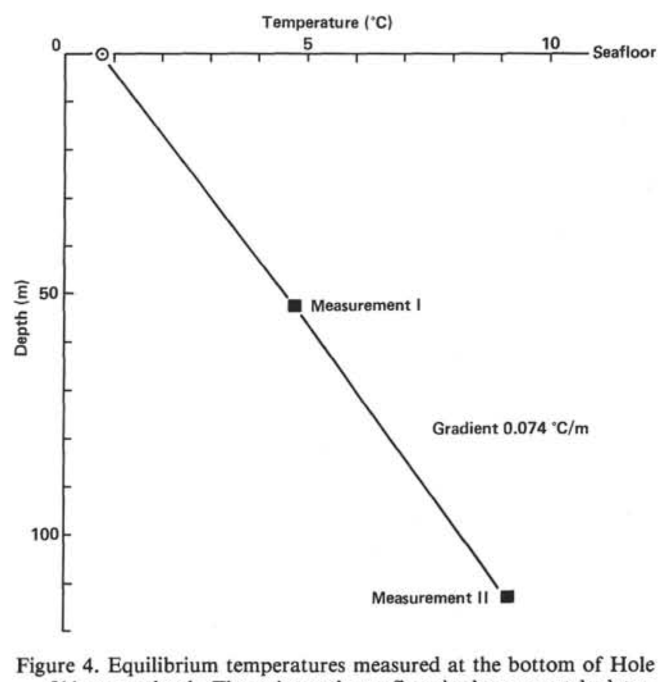

Figure 4. Equilibrium temperatures measured at the bottom of Hole 511 versus depth. The point at the seafloor is also accurately determined.

accord with relations usually found for seafloor sediments. As a result, we made 25 additional measurements of conductivity on the core samples after they were returned to the core repository at L-DGO. The data from these measurements are given in Table 1 and plotted in Figure 5.

Because of concern that the sediments may have lost considerable moisture during their stay in the repository, we made measurements of the water content at each measurement location. Comparison of these values with the water contents measured onboard ship (Table 1) shows no significant loss of water; therefore no adjustment was made in the values measured at L-DGO.

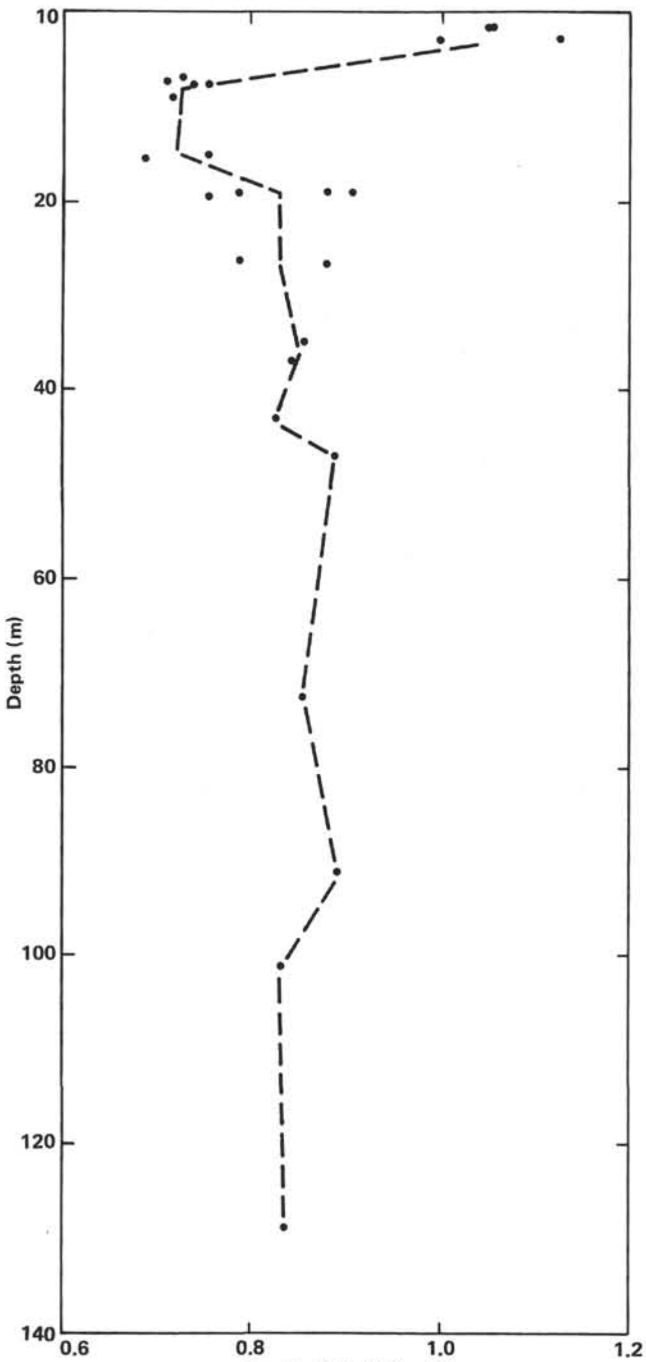

Figure 5. Thermal conductivity of sediments versus depth. The dashed line connects the mean conductivity at the levels where the line breaks.

A plot of the thermal resistivity (i.e., the reciprocal of thermal conductivity) versus the water content in percentage of wet weight is shown in Figure 6. Simple theory suggests that this relationship should be linear. A linear regression of the 25 data points yields a relation $\varrho = 1/k = 0.302 + 1.64\ W$, where ϱ is the resistivity in °C m W^{-1}, k is the thermal conductivity in $Wm^{-1}\ °C^{-1}$, and W is the water content in fraction of the wet weight.

This linear relation is not significantly different than that of Lachenbruch and Marshall (1966), who made a

Table 1. Thermal conductivity and water content data at Site 511.

Core/ Section	Sub-bottom Depth (m)	K (*in situ* $Wm^{-1}\ °C^{-1}$)	Water Content % (%, L-DGO)	Water Content (%, shipboard)
1-2	1.75	1.054	38.10	
1-2	2.60	1.000	—	54 (1-4)[a]
1-2	1.76	1.059	38.10	
1-2	2.64	1.123	—	
2-2	6.75	0.713	65.80	
2-2	7.84	0.756	63.94	
2-2	6.72	0.723	65.80	
2-2	7.77	0.740	63.94	
2-3	8.65	0.719	64.99	63 (2-3)
3-1	15.37	0.755	61.68	62 (3-2)
3-1	15.35	0.688	61.68	
3-4	19.10	0.782	55.23	
3-4	19.88	0.758	—	58 (3-5)
3-4	19.11	0.880	55.23	
3-4	19.87	0.903	—	
4-2	26.22	0.878	54.07	58 (4-1)
4-2	26.00	0.783	—	
5-2	35.83	0.852	—	
5-2	36.06	0.851	54.94	55 (5-2)
6-1	43.72	0.823	55.14	55 (6-1)
6-3	46.52	0.887	53.52	55 (6-4)
9-1	72.45	0.852	54.98	55 (9-3)
11-2	91.75	0.887	52.46	53 (11-2)
12-2	101.25	0.825	52.87	55 (12-2)
15-1	129.45	0.835	56.78	57 (15-1)

[a] Numbers in parentheses refer to core and section.

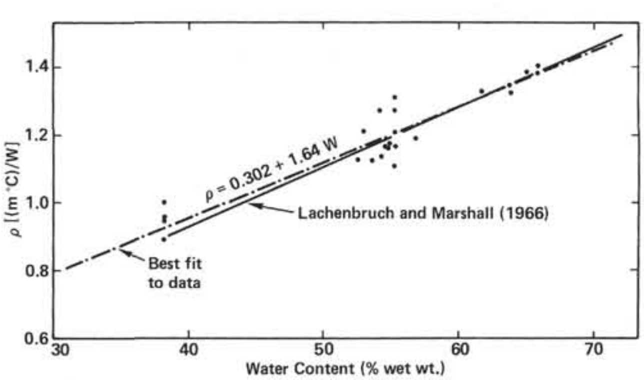

Figure 6. Thermal resistivity (1/conductivity) of sediments versus water content for the 25 measurements made on samples from Hole 511 at the L-DGO repository. The best-fitting linear relation is shown and compared to that discovered by Lachenbruch and Marshall (1966) for sediments in the Arctic Ocean.

similar study of seafloor sediments in the Arctic Ocean, using a much larger group of data. The agreement of these data with earlier results supports their accuracy.

The conductivity shows some variation with depth. In the upper three meters there is an unusual layer of high conductivity sediments that corresponds to a layer of gravelly sand with a low water content. A 15-meter layer of low conductivity is found below this, and at depths greater than 19 meters the conductivity is remarkably uniform. We calculate the effective conductivity by the equation

$$\frac{1}{k_e} = \frac{1}{z'} \int_{0'}^{z'} \frac{dz}{k(z)},$$

where k_e is the effective conductivity and z' is the depth of the deepest temperature measurement. We have estimated the integral in this expression by calculating the area to the left of the broken line curve in Figure 5 and dividing by the depth. The value of k_e calculated is 0.842 $W\,m^{-1}\,°C^{-1}$.

HEAT FLOW

Combining the determinations of the gradient, 0.074° C m^{-1}, and the effective conductivity, 0.842 W m^{-1} $°C^{-1}$, we calculate a heat flow of 62.3 mW m^{-2} (1.49 HFU) at Site 511. Because of the large depth interval over which the gradient is measured and the consistency of the conductivity results, we feel that this is an accurate value—the first accurate value of heat flow measured on the Falkland Plateau.

DISCUSSION

The Falkland Plateau is a sediment-filled basin formed by marginal flexures of the Falkland Islands Platform on the west, a narrow, subsided continental ridge on the north, and a subsided continental block called Maurice Ewing Bank on the east (Ludwig, this volume). The basin is floored by oceanic crust. The North Scotia Ridge provides partial closure of the basin on the south. Drilling on the western flank of Maurice Ewing Bank at Site 330 recovered 576 meters of Mesozoic and Cenozoic sediment above continental basement (Barker, Dalziel, et al., 1977). From the Middle to Late Jurassic to the late Early Cretaceous (Aptian), shallow marine sedimentation, sometimes under euxinic conditions, prevailed on the Bank. Predominantly pelagic deposition was established over the Bank during Albian time, when open ocean circulation occurred and the Bank subsided.

Our heat flow measurement in Hole 511 is located on the buried flank of Maurice Ewing Bank, on the back slope of a cuesta-type sedimentary ridge and about 10 km south of Hole 330. The configuration of seismic reflectors and the lithology in Hole 511 indicate shallow marine coastal downlap of sediments against a basement continental slope to the south, followed by slope front fill and draping by biogenic sequences.

Reconstruction of Gondwanaland to the time of opening of the South Atlantic by Tucholke et al. (1981) places the northern edge of the Falkland Plateau against the present southern edge of Agulhas Bank and the eastern and southern margins of Maurice Ewing Bank against the western Mozambique Ridge. They believe the northern Agulhas Plateau to have been attached to the southwestern edge of the Mozambique Ridge and the southern side of the Falkland Plateau.

There are no reliable heat flow measurements in the Agulhas Bank or the Mozambique Ridge area to compare with the heat flow value determined at Hole 511. The mean of nine terrestrial heat flow values south of 29°S in Africa is 60.4 ± 5.3 mW m^{-2} (1.44 ± 0.13 HFU), which agrees well with the Maurice Ewing Bank value. Geothermally, the two terrains are similar.

Figure 7 is a map of bathymetry showing nearby seafloor measurements of the thermal gradient in the upper 10 meters of sediment. Two of these values, 0.071°C m^{-1} at V18-36 on the North Scotia Ridge and 0.073°C m^{-1} at V32-36 just north of the Falkland Fracture Zone, are in good agreement with the measurement at Hole 511. A measurement south and east of Maurice Ewing Bank (C16-76) indicated a significantly lower gradient; however, the likelihood of a transient disturbance to this shallow penetration seafloor measurement is high.

It is interesting to compare the Maurice Ewing Bank measurements with measurements in the Argentine Basin to the north. Except for a gradient value of 0.047 °C m^{-1}, the values range from 0.061 to 0.068. The conductivity at these stations averages about 0.75 W m^{-1} $°C^{-1}$. This would indicate a mean heat flow for the western Argentine Basin of 49 mW m^{-2} (1.17 HFU).

The age of the Argentine Basin north of the Falkland Plateau has been well determined from magnetic anomalies (Ladd et al., 1973; Rabinowitz and LaBrecque, 1979). North of the plateau, the age varies from about 80 Ma in the east to 130 Ma in the west. Thermal models of a cooling oceanic lithosphere (e.g., Parsons and Sclater, 1977) predict a heat flow over this age range of 43–54 mW m^{-2} (1.03–1.29 HFU). Thus, these four measurements are in good agreement with the expected value.

The difference between the Maurice Ewing Bank heat flow and that observed in the Argentine Basin probably results from heat production by radioisotopes in the continental crust of the Bank. Thus, even though the oceanic crust of the Argentine Basin is younger than the terrain of the Maurice Ewing Bank, the heat flow of the Bank is higher because of the enrichment of long-lived radioisotopes of uranium, potassium, and thorium in continental-type crust. This difference could be considered as further support for Maurice Ewing Bank being a continental block.

Several workers have shown a clear correlation between heat flow in continental areas and the age of the last orogenic event (Chapman and Pollack, 1975). These correlations show that heat flow values of 60–65 mW m^{-2} (1.43–1.55 HFU) are characteristic of terrain of Hercynian age (late Paleozoic to early Mesozoic). The heat flow value measured on Leg 71 should provide a reliable datum from which to calculate the temperatures of deep layers in the basin slope and basin floor provinces of the Falkland Plateau.

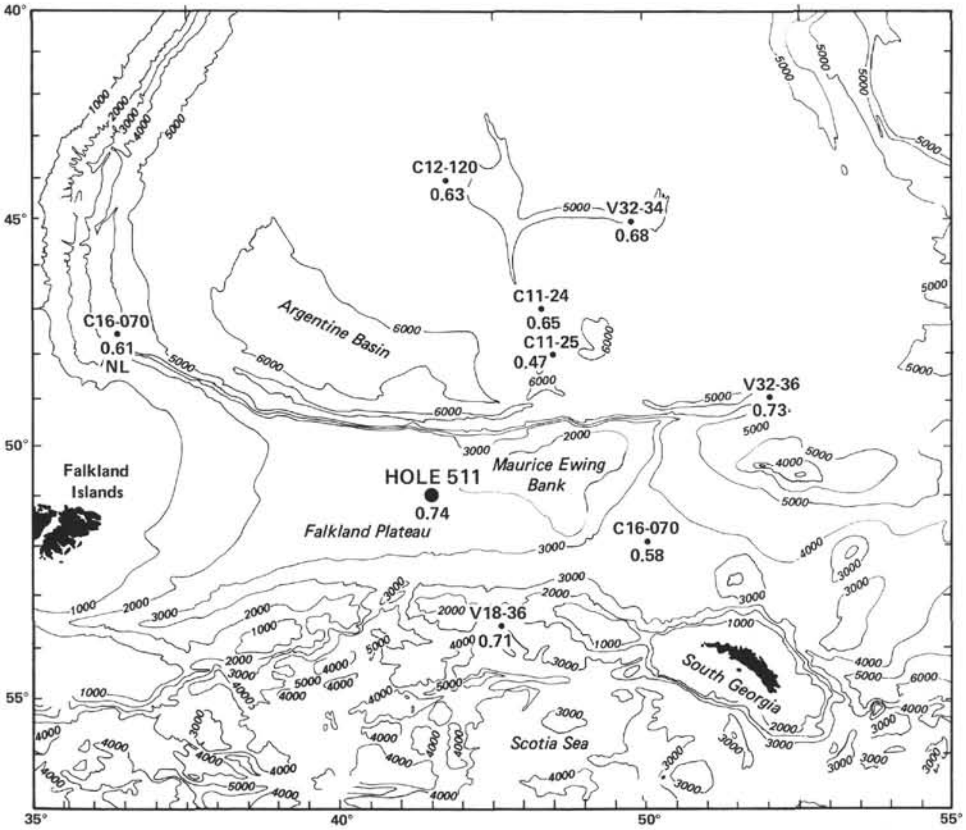

Figure 7. Geothermal gradients at stations in the vicinity of the Falkland Plateau. Except for the measurement at Hole 511, all of the measurements were made using the Ewing thermograd technique. Gradients are in °C per 10 meters, and the number over each point is the station number.

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