35. AN ESTIMATE OF THE HEAT FLOW IN THE WESTERN NORTH ATLANTIC AT DEEP SEA DRILLING PROJECT SITE 534[1]

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ABSTRACT

A method employing both a simple relationship between total rock conductivity and the concentrations and conductivities of constituents, and an estimate of the thermal gradient based on a downhole temperature log, yielded an estimated value between 1.01 (42 mW m^{-2}) and 1.37 HFU (57 mW m^{-2}) for the heat flow at Site 534. These measurements are in good agreement with other heat-flow measurements made in the same area, indicating that this method may have a wide application in estimating heat flow at well sites.

INTRODUCTION

Hole 534 was drilled in the Blake-Bahama Basin, northwest Atlantic (Fig. 1), where the crustal age (ca. 150 m.y.) is great enough and the sediment cover thick and extensive enough that the heat flow should be unperturbed by hydrothermal circulation. This hypothesis has been verified by detailed heat-flow measurements at four sites nearby (Fig. 1), where the heat flow has been found to be extremely uniform over distances up to several hundred kilometers (E. Davis et al., unpublished data). Thus we can reasonably assume that in the absence of deep transients, the heat flow at Site 534 should be the same as that measured at the survey sites nearby.

In this study we have estimated a thermal gradient from a temperature log of the hole. In the absence of detailed thermal-conductivity measurements, we have estimated the conductivities of the sediments at Site 534 using two simple relationships between the bulk conductivity and the conductivities of the constituent phases. The resulting heat-flow estimates are then compared to heat-flow measurements obtained nearby to check the validity of the conductivity estimates.

POROSITY AND CONDUCTIVITY

Gravimetric porosity determinations were made by shipboard scientists on samples recovered from Site 534 cores at about 5-m intervals. Figure 2 shows porosity values taken from this data set at intervals of approximately 10 m, plotted against sub-bottom depth. Also plotted in Figure 2 are the least-squares best fit to the complete data set; the line found by Le Douaran and Parsons (in press) to fit data from a number of holes in the North Atlantic; and the exponential curve quoted by Sclater and Christie (1980) as being a good fit to data from the North Sea. As may be readily seen, the scatter of data from Site 534 around all these lines is large, and any smooth curve through the data would be only poorly defined. For our purpose of using porosity for estimating conductivity, a mean porosity was calculated for each of the lithologies identified by shipboard scientists from the recovered cores for which porosity data were available (Subunits 2a through 7a). Then, by inspection of the smear-slide summaries, a representative mineral composition was estimated. For simplicity, the sediments were assumed to consist of sea water, quartz, clay, and carbonate.

Two methods of estimating bulk conductivity were used here. Budiansky (1970) presents a theoretical relationship among the conductivity of a composite material, K, and the volume fractions, f_i, and thermal conductivities of the constituent phases, K_i, as follows:

$$\sum_{i=1}^{n} f_i\,(2/3 + 1/3[K_i/K])^{-1} = 1$$

This relationship, derived from the solution to the analogous electrostatic problem, assumes that the composite consists of a random mixture of n isotropic components, at least $n - 1$ of which are distributed in particulate fashion. Traditionally the geometric mean, $K = K_1^{f_1} K_2^{f_2}, \ldots, K_n^{f_n}$, has been used with some success (Woodside and Messmer, 1961), and although there is somewhat less theoretical justification for its being used to model a multicomponent system, we have employed it here also. In practice, the conductivity of sediments and sedimentary rocks is not likely to be described accurately by either theoretical relationship over a very wide range of porosities. At high porosities, grain to grain contacts will be few, and the bulk conductivity will be controlled by the interstitial water. The correct mean value would perhaps best be described by a series (weighted harmonic) mean of the conductivities of the constituents. At low porosities, grain to grain contacts will be common, and a Budiansky-type mean may be reasonable,

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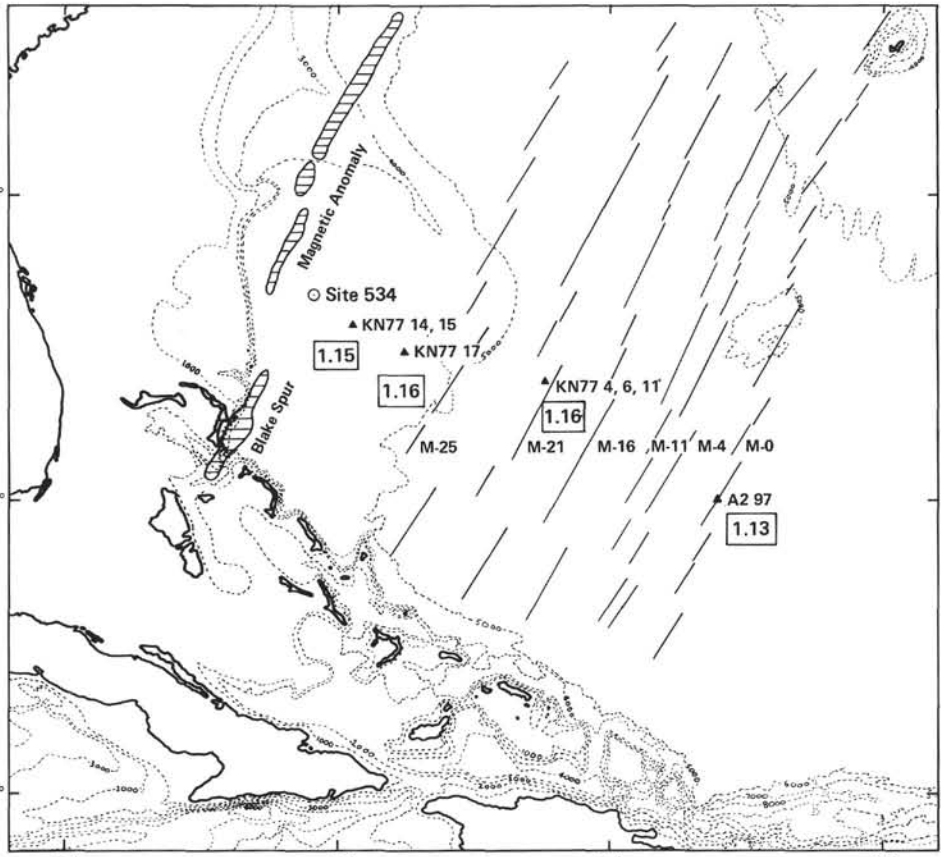


Figure 1. Map showing location of Site 534 (open circle) in relation to other heat-flow stations (solid triangles) and identified magnetic anomalies. (Dashed lines are contours of water depth at 1000-m intervals. Boxed numbers are heat-flow values.)

but the thermal contact resistance between the grains will lower the effective conductivities of the constituents. The effect of layering in sediments will be to reduce the vertical thermal conductivity of a sedimentary unit. Detritally preferred orientation of any isotropic mineral grains will influence the effective conductivity of that constituent. In summary, then, it is probably unreasonable to approach in a purely theoretical way the problem of predicting bulk conductivity accurately. A reasonable estimate may be obtained, however, using a theoretical relationship with empirically established "effective" constituent conductivities.

We have used the following values as estimates for "effective" grain conductivities:

K_{quartz} = 14×10^{-3} cal-cm^{-1}-s^{-1}-°C^{-1} (5.8 W m^{-1} K^{-1}) (Beck, 1965)

K_{calcite} = 7×10^{-3} cal-cm^{-1}-s^{-1}-°C^{-1} (2.9 W m^{-1} K^{-1}) (Robertson, 1979)

$K_{\text{clay, feldspar, etc.}}$ = 4.5×10^{-3} cal-cm^{-1}-s^{-1}-°C^{-1} (1.9 W m^{-1} K^{-1}) (value quoted below reduced by a factor equivalent to that by which K_{quartz} and K_{calcite} have been reduced)

$K_{\text{sea water}}$ = 1.5×10^{-3} cal-cm^{-1}-s^{-1}-°C^{-1} (1.6 W m^{-1} K^{-1}) (Powell, 1958)

The values for quartz and calcite have been derived from polycrystalline aggregates. It is interesting to compare these values with typical single crystal values of conductivity to emphasize the importance of grain boundary contact resistance:

K_{quartz} = 17×10^{-3} cal-cm^{-1}-s^{-1}-°C^{-1} (7.1 W m^{-1} K^{-1}) (Birch and Clark, 1940)

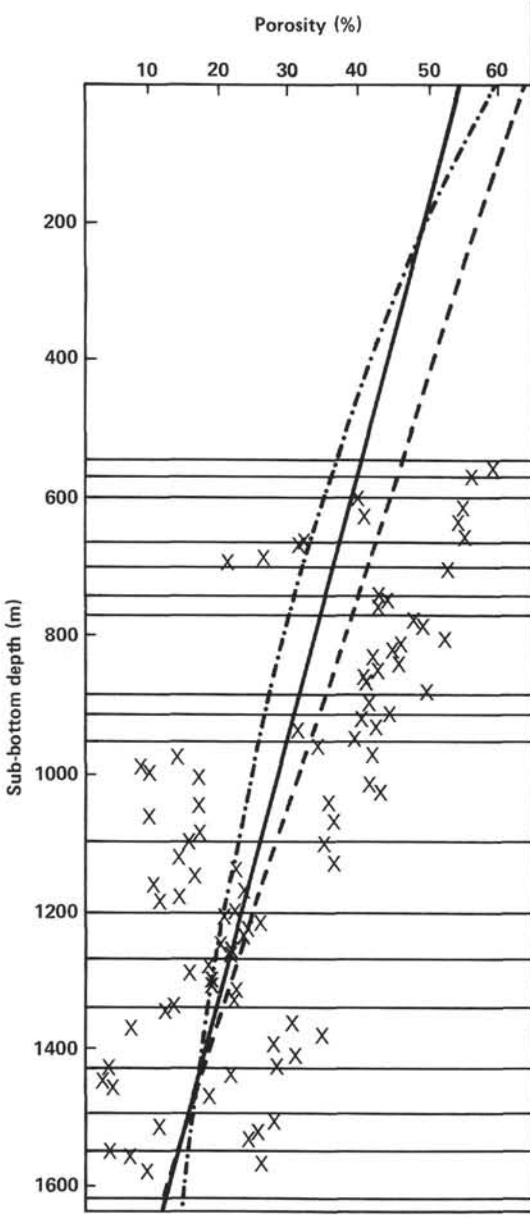
K_{calcite} = 8.6×10^{-3} cal-cm^{-1}-s^{-1}-°C^{-1} (3.6 W m^{-1} K^{-1}) (Horai, 1971)

$K_{\text{clay, feldspar, etc.}}$ = 5.7×10^{-3} cal-cm^{-1}-s^{-1}-°C^{-1} (2.4 W m^{-1} K^{-1}) (Sass, 1965)

As a "calibration" we have plotted the estimated conductivity of DSDP Sites 438 and 439 sediments in Figure 3a, using the average mineralogy of the fairly uniform sediments at the sites (Scientific Party, 1980)

$f_{\text{quartz}} = 0.05$
$f_{\text{calcite}} = 0.02$
$f_{\text{clay, feldspar, etc.}} = 0.93$

and the values of constituent conductivities given earlier. These curves are compared to direct measurements of porosity and conductivity (Carson and Bruns, 1980). The agreement is surprisingly good, in spite of the obvious uncertainties in choosing appropriate constituent conductivities; the geometric mean provides as good a fit to the data as the Budiansky curve over the full range of porosities. The latter relationship predicts conductivities that are about 5% higher at high porosities (cf.,



Lithologic unit	Thickness (m)	Porosity (%)	Composition			Estimated conductivity (T.C.U.)	
			f_{quartz}	f_{clay}	$f_{calcite}$	Budiansky	Geometric
1	545.8	(47)				(3.15)	(2.9)
2a	20.8	48.3	.02	.21	.29	3.34	3.09
b	28.4	42.53	.02	.29	.26	3.51	3.21
c	71	36.93	.03	.28	.32	3.89	3.57
d	29	24.28	.03	.36	.36	4.50	4.14
3	46.5	33.1	.04	.36	.26	3.98	3.62
4a	23	43.4	.04	.526	0	3.11	2.92
b	122.5	42.14	.15	.43	0	3.66	3.37
c	27	41.58	.06	.49	.03	3.30	3.07
d	36	34.18	.02	.40	.24	3.78	3.53
5a	148.5	23.73	.02	.35	.39	4.52	4.2
b	94.7	22.84	.02	.40	.36	4.48	4.25
c	66	22.08	.03	.46	.29	4.41	4.16
d	74	18.29	.01	.51	.30	4.42	4.27
6a	86	18.21	0	.59	.23	4.28	4.09
b	67.6	15.9	.02	.53	.29	4.62	4.39
7a	54.2	17.42	.03	.53	.27	4.56	4.36
b and c	85.5	(24)				(4.25)	(4)

Figure 2. Graph of porosity values (X), taken from the Site 534 data set at intervals of about 10 m, plotted against sub-bottom depth. (The heavy line is the least-squares best fitting straight line to the whole data set, the dashed line is that found by Le Douaran and Parsons [in press] to be a good description of porosity-depth data for a number of deep drill holes in the North Atlantic, and the dotted-dashed line is Sclater and Christie's [1980] exponential fit to data from the North Sea. The tabular material gives, for each lithologic unit, the thickness, average porosity, estimated composition [as a volume fraction of the wet rock], and two estimates of conductivity. Porosities estimated for Unit 1 and Subunits 7b and c are shown in parentheses.)

preceding discussion). We have thus gained confidence to apply the geometric mean with the appropriate constituent conductivities to Site 534 sediments. A similar plot, with estimated formation conductivities (listed in Fig. 2) and smooth curves of conductivity calculated over the full range of porosities for a sediment of average mineral composition, using both Budiansky's relationship and the geometric mean, is shown in Figure 3B for Site 534.

With the thermal conductivities thus estimated, an estimate of the total average thermal conductivity can be derived using the series, or weighted harmonic, mean:

$$K_m = \sum_{j=1}^{n} S_j \Bigg/ \sum_{j=1}^{n} S_j/K_j$$

where S_j and K_j are the thickness and conductivity of the jth layer. Using the geometric mean formation conductivities, a conductivity of 3.35×10^{-3} cal-cm^{-1}-s^{-1}-°C^{-1} (1.4 W m^{-1} K^{-1}) is obtained for the sediment column down to a depth of 1325 m (see the next section). If we were to use the conductivities calculated on the basis of Budiansky's relationship, the total average conductivity would be marginally higher.

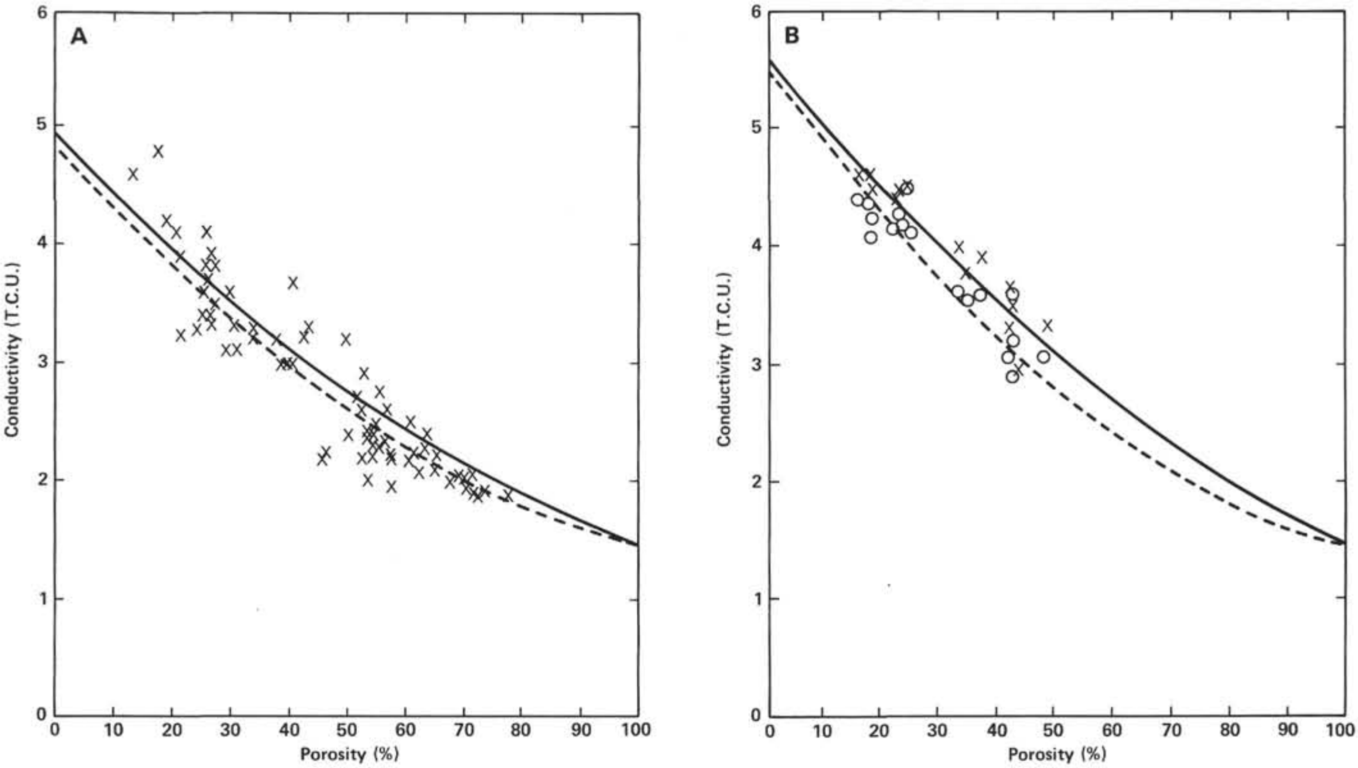


Figure 3. A. Graph of measured conductivity values plotted against measured porosities at Sites 438 and 439. (Curves are estimates of conductivity for a rock of average mineral composition [see text]. The solid line indicates conductivities estimated using the relationship described by Budiansky [1970], and the broken line indicates conductivities estimated as the geometric mean of the mineral conductivities.) B. Graph of conductivity of Site 534 Subunits 2a to 7a plotted against porosity. (Open circles show conductivities estimated via geometric mean, and crosses those estimated on the basis of the relationship delineated by Budiansky [1970]. Curves are estimates of conductivity using a rock of average mineral composition.)

TEMPERATURE LOG ANALYSIS

Approximately four days after drilling operations were terminated, a section of pipe was washed into the hole to a sub-bottom depth of 944 m in order to enable the logging tool to pass a known constriction at the Blake-Bahama Formation contact. Logging of the hole was then accomplished with a Gearhart-Owen thermal log down to a depth of 1414 m, where a bridge in the Cat Gap Formation stopped the tool. The hole had been drilled to a total depth of 1666 m sub-bottom. The resulting temperature-depth plot is shown in Figure 4.

The effects of fluid circulation during the wash-in prior to logging is clearly evident, and temperatures down to the maximum depth of the pipe are totally unreliable. Below that, temperatures are still likely to be affected by earlier drilling fluid circulation, but there the effects are we hope minor, because several days had elapsed since the most recent circulation. The temperature-depth profile in the bare part of the hole is somewhat erratic, particularly below about 1350 m; which may simply reflect differences in the rate of return to thermal equilibrium down the hole caused by variations in the hole size. Under ideal conditions, the hole diameter should be little more than 25 cm, the diameter of the bit. Where caving takes place, the hole "diameter" may be several times this size, and the thermal effects of the circulating fluid will be correspondingly greater.

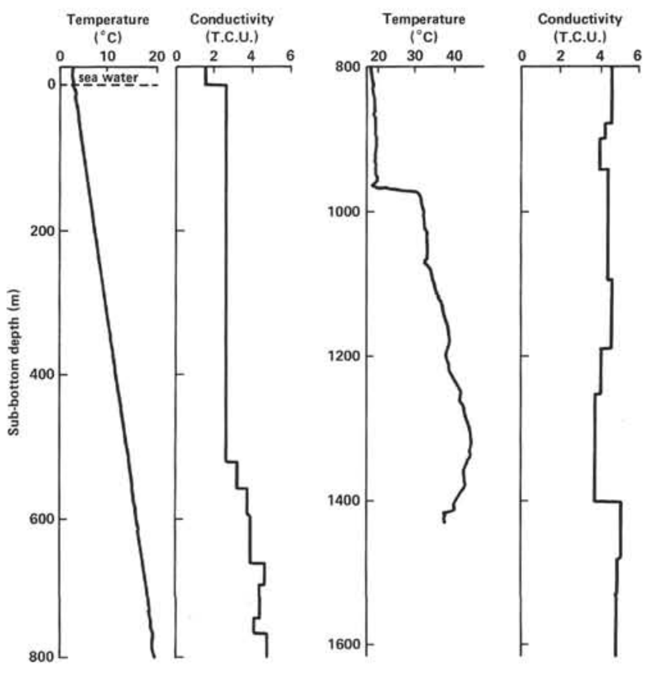


Figure 4. Sub-bottom temperatures recorded by the Gearhart-Owen logging tool, and estimated conductivities. (Note the jump in temperature at 944 m as the tool enters the bare, and less thermally disturbed, hole.)

Many techniques have been used for estimating the magnitude of drilling fluid disturbances. Hyndman et al. (1977) review several; in this study we have adopted the one chosen for their data analysis and presented by Jaeger (1961). He considers the problem to be one in which the hole of some diameter remains at some disturbed temperature for the duration of fluid circulation. The thermal effects of the disturbance during the circulation and during the subsequent decay to equilibrium are calculated for a depth of 1325 m, assuming that the thermal diffusivity of the material filling the hole (fluid, chips, and drill pipe) is the same as that of the rock. In using this correction, we have assumed that the fluid is supplied at the temperature of the bottom water, 2.8°C (justified for high rates of circulation by Jaeger, 1961), and that the disturbance time may be represented by the actual drilling time, when pumping takes place. Table 1 summarizes the timing of the disturbances we have considered, and shows their effects at the time of logging.

For the purpose of calculating a gradient, we have used the maximum observed temperature of 42.5°C at a depth of 1325 m. Applying the total correction of 27% implied by the results shown in Table 1, a gradient of 43.5 m°C m^{-1} results. With no correction, the gradient would be 30 m°C m^{-1}. This lower value is undoubtably too low, but it does provide a lower limit for the true gradient value over the 1325-m interval. The true value is probably closer to the "fully corrected" figure, although the latter may be too high, because the temperature of the circulating fluid was bound to be a certain amount warmer than that assumed (the bottom water temperature), and because circulation times are probably overestimated. If subsequent logs were available, a correction could be more confidently applied.

DISCUSSION

The heat flow, calculated as the product of the estimated thermal conductivity of the sediment column, 3.35×10^{-3} cal/cm-s-°C (1.4 W m^{-1} K^{-1}), and the minimum estimated temperature gradient, 30 m°C/m, is 1.01 HFU (42 mW m^{-2}). Using the maximum estimated temperature gradient of 41 m°C/m, we find that the estimated heat flow is 1.37 HFU (57 mW m^{-2}).

These limiting values are compared to the other nearby heat-flow determinations mentioned earlier (Davis et al., unpublished data; Galson and Von Herzen, 1981) in Table 2. It is encouraging that these values determined by Davis et al. (unpublished data) and Galson and Von Herzen (1981) fall well within the range of values estimated at Site 534. This similarity lends great credence to the technique of determining conductivity indirectly from porosity and mineralogy data, although the accuracy of the technique could have been better assessed if the temperature log had been made more carefully (cf., Burch and Langseth, 1981). Nevertheless, this method appears to provide a good estimate of the average conductivity, and it should be useful in obtaining heat-flow estimates at sites where no direct conductivity measurements are made, oil wells, for example.

There is little difference between the bulk conductivity calculated as the geometric mean of the constituent conductivities and that using a more "rigorous" derivation such as that given by Budiansky (1970). We favor the geometric mean because of its simplicity.

Table 1. Summary of postdrilling disturbances of temperature in Hole 534A at a sub-bottom depth of 1325 m caused by water circulation.

Duration of water circulation (hr.)	Time elapsed since disturbance (days)	xt_o/a^2	Log n	Fraction of disturbance remaining (Jaeger, 1961)
~20	25	2.4	1.48	0.03
52	18	6.0	0.92	0.07
~24	4.5	2.8	0.65	0.14
2	3	0.24	1.56	0.03

Note: a = 12.5 cm; $x = 0.005$ cm^2-s^{-1}; t_o = disturbance duration (s); n = time elapsed/disturbance duration.

Table 2. Comparison of estimated heat flow at Site 534 with other heat-flow measurements in the same area (E. Davis et al., unpublished data; Galson and Von Herzen, 1981).

Site 534 and heat-flow stations	Age (m.y.)	HFU
Site 534	153	1.01-1.37
A2 97	115	1.13 ± 0.05
KN77 4, 6, 11	141	1.16 ± 0.14
KN77 17	148	1.16 ± 0.12
KN77 14, 15	151	1.15 ± 0.06

Note: HFU = heat-flow unit.

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