Heat-Flow Measurements in the North Atlantic, Caribbean, and Mediterranean[1]

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Abstract. Twenty measurements of heat flow in the Caribbean Sea, the North Atlantic Ocean, and the Mediterranean Sea are described and compared with nearby measurements made by others. Heat-flow measurements in the Caribbean gave values which average about 1.2 to 1.4 μcal/cm^2 sec. East of the Antilles the value found may not be equilibrium heat flow because of past disturbance of the sediment. Values as low as 0.3 μcal/cm^2 sec were found on the flanks of the mid-Atlantic ridge, and values as high as 6.5 μcal/cm^2 sec were found at the crest. In the eastern Atlantic, normal values of about 1.2 μcal/cm^2 sec were found. In general, the agreement between measurements made by independent investigators and different instruments is good. In the North and South Atlantic, values exceeding 2.5 μcal/cm^2 sec are found only within 100 km of the crest of the mid-Atlantic ridge. The average of 32 measurements within 100 km of the ridge crest from about 30°S to 50°N is 3 μcal/cm^2 sec (twice the world average), indicating that the outflow of heat per centimeter of length from the 200-km-wide crestal region is about 2 or 3 $\times$ 10^9 cal/cm year. Possible causes of the high crestal heat flow are quantitatively evaluated.

INTRODUCTION

During the 1962 Zephyrus Expedition of the Scripps Institution of Oceanography, twenty heat-flow measurements were made in the Caribbean Sea, the North Atlantic Ocean, and the Mediterranean Sea. Preliminary values of fourteen Atlantic measurements from Martinique to the Canary Islands have been reported without discussion by *Nason and Lee* [1962]. It is the purpose of this paper to describe the twenty measurements and to discuss them in the light of other measurements in these regions [*Bullard,* 1954; *Bullard and Day,* 1961; *Reitzel,* 1961*a, b;* 1963; *Gerard et al.,* 1962; *Lister,* 1962, 1963*a, b*; *Birch,* 1964; *Vacquier and Von Herzen,* 1964; *Lister and Reitzel,* 1964; *Langseth and Grim,* 1964].

METHOD OF HEAT-FLOW MEASUREMENT

Heat flow at a given location is the rate of heat transferred across the earth's surface at that place per unit area per unit time. It is determined as the product of the thermal conductivity and the vertical temperature gradient. Temperature gradients in the sea floor were measured with a cylindrical probe which has been described by *Von Herzen et al.* [1962]. Thermal conductivities were measured on sediment cores by the needle-probe technique [*Von Herzen and Maxwell,* 1959] and corrected for ambient sea floor conditions after *Ratcliffe* [1960].

The temperature-gradient probe penetrated the ocean floor normally at all stations except numbers 8, 18, 19, and 26, as shown by cores obtained from a small corer on the instrument case. Penetration at stations 8, 18, 19, and 26 was estimated from the bend in the probe.

Thermal conductivities were measured on board the ship on gravity cores taken at the site of the temperature-gradient measurements. Three measurements were usually made on each core to obtain an average conductivity value. On most cores the different conductivity values were within 5% of the average, but at stations 8, 11, 13, 14, and 32 the individual conductivity

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TABLE 1. Heat-Flow Measurements in the Caribbean Sea, Atlantic Ocean, and Mediterranean Sea

Station	Latitude	Longitude	Corrected Oceanic Depth, m	Temperature Gradient, mdeg/cm	Thermal Conductivity, mcal/cm sec deg			Heat Flow, μcal/cm² sec	Experimental Error, %	Sedimentation Rate,† cm/1000 yr
					No.	Mean	S.D.*			
				Caribbean						
Zep-4	13°36′N	71°59′W	4232	0.72	3	2.0	0.1	1.4	15	
Zep-5	13°43′N	68°38′W	5042	0.58	3	1.9	0.1	1.1	15	
Zep-8	14°22′N	62°19′W	2877	0.70	3	1.9	0.3	(1.3)‡	35	
				Atlantic						
Zep-9	16°24′N	57°39′W	4647	0.39	3	1.8	0.1	0.7?§	15	disturbed
Zep-11	19°10′N	52°03′W	5344	0.81	3	1.7	0.2	1.4	20	0.5
Zep-12	20°12′N	49°01′W	4632	0.30	3	1.5	0.1	0.5	15	<0.5
Zep-13	21°06′N	46°30′W	3912	0.16	3	1.9	0.3	0.3	25	
Zep-14	21°04′N	44°57′W	3255	0.84	3	2.1	0.2	1.8	20	<0.5
Zep-15	21°56′N	45°46′W	3372	3.24	2	2.0	0.1	6.5	15	
Zep-16	23°06′N	45°39′W	3983	1.48	3	2.0	0.1	3.0	15	
Zep-17	23°34′N	44°14′W	4960	0.81	3	2.0	0.1	1.6	15	<0.5
Zep-18	23°57′N	44°59′W	3493	1.34	3	2.1	0.1	(2.8)‡	25	
Zep-19	23°36′N	42°28′W	4113	0.23	3	2.1	0.1	(0.5)‡	25	
Zep-20	24°16′N	39°06′W	5439	0.19	3	1.9	0.1	0.4	15	
Zep-22	25°05′N	34°13′W	5602	0.36	3	1.9	0.1	0.7	15	<0.5
Zep-23	26°14′N	26°27′W	5210	0.59	3	2.0	0.1	1.2	15	<0.5
Zep-25	26°57′N	19°58′W	4298	0.46	3	2.1	0.1	1.0	15	1.7
Zep-26	31°12′N	11°50′W	3210	0.50	2	2.2	0.1	(1.1)‡	25	
Zep-27	33°35′N	9°43′W	4340	0.45	2	2.2	0.1	1.0	15	
				Mediterranean						
Zep-32	40°37′N	5°50′E	2720	0.56	3	2.2	0.3	1.2 ?§	25	

* Standard deviation from the mean.
† From *Goldberg et al.* [1963].
‡ Partial penetration of the temperature gradient probe.
§ Heat-flow value not representative of regional flux (see Description of Measurements).

values differed by as much as 20% from the average (see Table 1). A malfunctioning resistor in the circuit of the conductivity apparatus was replaced by a less precise resistor available on the ship. This replacement increases the uncertainty of each conductivity measurement from 3 or 4% [*Von Herzen and Maxwell,* 1959] to about 10%.

Description of Heat-Flow Measurements

In the listing of our measurements in Table 1, and in the text, heat-flow values are given in units of μcal/cm² sec and thermal-conductivity values in units of mcal/deg cm sec. These units will be omitted wherever it is convenient. At a station where the temperature-gradient probe did not penetrate completely, the heat-flow value is more uncertain and is therefore listed in parentheses.

Eight of the cores in the Atlantic have been studied for rates of sedimentation by *Goldberg et al.* [1963]. Their results are listed with the heat-flow measurements in Table 1.

Our heat-flow values and the values of other investigators are plotted in Figure 1. The earthquake epicenters shown in Figure 1 on the mid-Atlantic ridge are taken from *Gutenberg and Richter* [1954] and the *International Seismological Summary* [1962] for 1954 and 1955.

Caribbean basin measurements. Stations 4, 5, and 8 are in the Caribbean Sea, where other measurements of heat flow have been made by *Gerard et al.* [1962], *Vacquier and Von Herzen* [1964], and *Langseth and Grim* [1964]. Station 4, in the Columbian basin, produced a value of 1.4. Station 5, in the Venezuelan basin, produced a value of 1.1. At station 8, west of the Antilles, the heat-flow value of 1.3 is uncertain

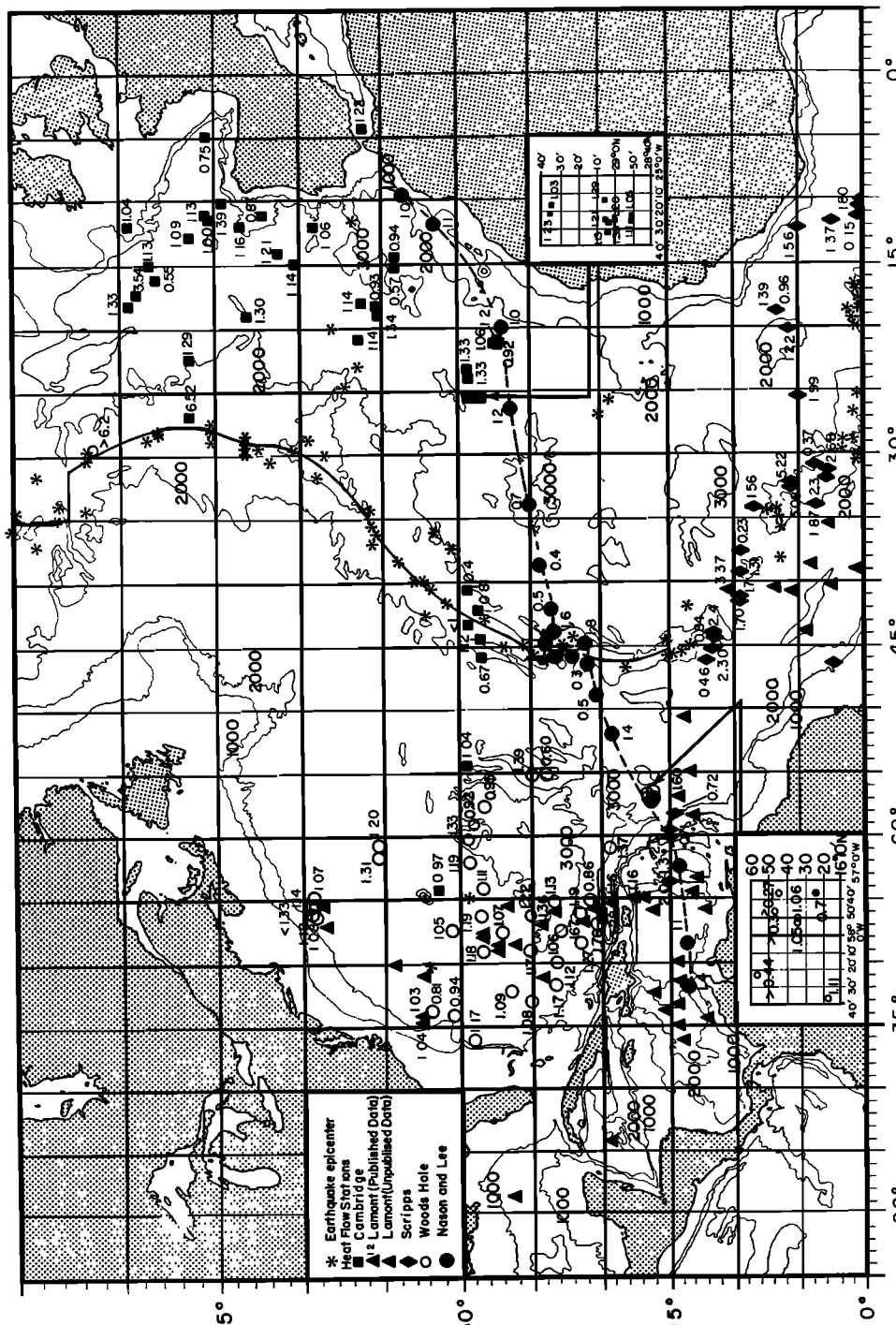

Fig.1. Map of the North Atlantic showing all heat-flow measurements (in μcal/cm^2 sec). Bathymetric contours are in fathoms. Heavy solid line shows the topographic crest of the mid-Atlantic ridge north of 13°N. Broken line indicates our ship track. References for heat-flow stations are as follows. Cambridge: *Bullard* [1954], *Bullard and Day* [1961], *Lister* [1962, 1963*a*, *b*], and *Lister and Reitzel* [1964]. Lamont: *Gerard et al.* [1962]; *Langseth and Grim* [1964]. Scripps: *Vacquier and Von Herzen* [1964]. Woods Hole: *Birch* [1964] and *Reitzel* [1961*a*, *b*; 1963]. Nason and Lee: this article.

because of incomplete penetration of the temperature-gradient probe. *Vacquier and Von Herzen* [1964] obtained a value of 2.0 about 80 km north of station 8. The average of 6 heat-flow values in the Caribbean basins (3 of ours and 3 published ones) is 1.4, and the standard deviation is about 0.3. *Langseth and Grim* [1964] obtained an average of about 1.2. The average heat-flow values of 1.2 to 1.4 in the Caribbean basins are consistent with averages found in other ocean basins [*Lee,* 1964].

East of Antilles measurements. At station 9, east of the Antilles, the temperature gradient and conductivity give a heat-flow measurement of 0.7. However, the age profile obtained by *Goldberg et al.* [1963] in the associated gravity core shows that the sediment has been disturbed or was accumulating at too high a rate for measurement. Because of the disturbance of sedimentation, the thermal conditions in the sediment are probably not at equilibrium, and hence the measured value is not equilibrium heat flow. Very near station 9, six heat-flow measurements were made by *Birch* [1964]; his values are >0.27, >0.3, >0.44, 1.05, 1.06, and 1.11. Birch's 1.05 and 1.06 values were measured about 30 km northwest of station 9. Farther to the southwest of station 9, *Vacquier and Von Herzen* [1964] obtained heat-flow measurements of 0.71, 0.72, and (2.0); whereas, with a longer probe, *Gerard et al.* [1962] obtained 1.60. The differences between these measurements are probably due to lack of thermal equilibrium in the sediment.

The heat flow of 1.4 recorded at station 11 is rather typical for ocean basins. There are no adjacent heat-flow measurements by others. Farther to the south of station 11, *Gerard et al.* [1962] obtained heat-flow values of 1.36 and 1.20 in the northern part of the Guiana basin.

Flanks of mid-Atlantic ridge measurements. Stations 12 and 13 are on the west flank and stations 19 and 20 are on the east flank of the mid-Atlantic ridge. Station 22 is at the east boundary of the flank province. All values of heat flow measured at these stations are low: 0.5, 0.3, (0.5), 0.4, and 0.7, respectively. At station 19 the temperature-gradient probe did not penetrate completely. Some 5° in latitude north of our stations, *Lister* [1962] found heat-flow values of 0.67 on the west flank and 0.4 on the east flank. *Vacquier and Von Herzen* [1964] obtained some similar low values on the east and west flanks of the mid-Atlantic ridge farther to the south, but they also found higher values of heat flow there. As the low heat-flow values were measured on local basins on the flanks of the mid-Atlantic ridge, they may not be representative of the regional heat flow. A discussion of low heat flow has been given by *Von Herzen and Uyeda* [1963]. More work is desirable to clarify the problem of low heat flow.

Crest of mid-Atlantic ridge measurements. Five heat-flow measurements (stations 14 to 18) were made along the crest of the mid-Atlantic ridge. Heat-flow values observed were 6.5 at the center, 3.0 somewhat to the west, and 1.8 and 1.6 on the eastern side. The (2.8) value was measured near an offset of the ridge crest at 24°N. The crest of the mid-Atlantic ridge is associated with high heat flow. *Bullard and Day* [1961] obtained a heat-flow value of 6.52, and *Reitzel* [1961*a*] obtained a value >6.2 on the northern mid-Atlantic ridge. To the south, *Gerard et al.* [1962] observed a heat-flow value of 3.37 and *Vacquier and Von Herzen* [1964] obtained values as high as 5.08 and 5.22. A profile about 5° in latitude north of ours by *Lister* [1962] did not have any high values. Because of the difficulty in putting the corer into the bottom, due to rough topography, the sample of Lister's stations may not be representative of the area (see Figure 2).

Eastern Atlantic measurements. At stations 23 and 25 in the Canary basin, heat-flow values of 1.2 and 1.0 were observed. A detailed survey of heat flow was made by *Lister* [1962, 1963*a*] north of station 23. His eleven heat-flow values range from 1.03 to 1.39, with an average of about 1.2 and standard deviation of about 0.1. This agrees well with our value of 1.2. Our value of 1.0 at station 25 agrees well with the values 0.92, 1.06, and 1.2, measured by *Lister* [1962] about 120 km to the west.

At stations 26 and 27, between the Canary Islands and Gibralter, heat-flow values of (1.1) and 1.0 were observed. The value at station 26 is uncertain because of poor probe penetration.

Mediterranean measurement. A measurement in the Mediterranean Sea was made on the Rhone submarine fan (station 32). However, because of the possible instability of bottom water temperature and probable high sedi-

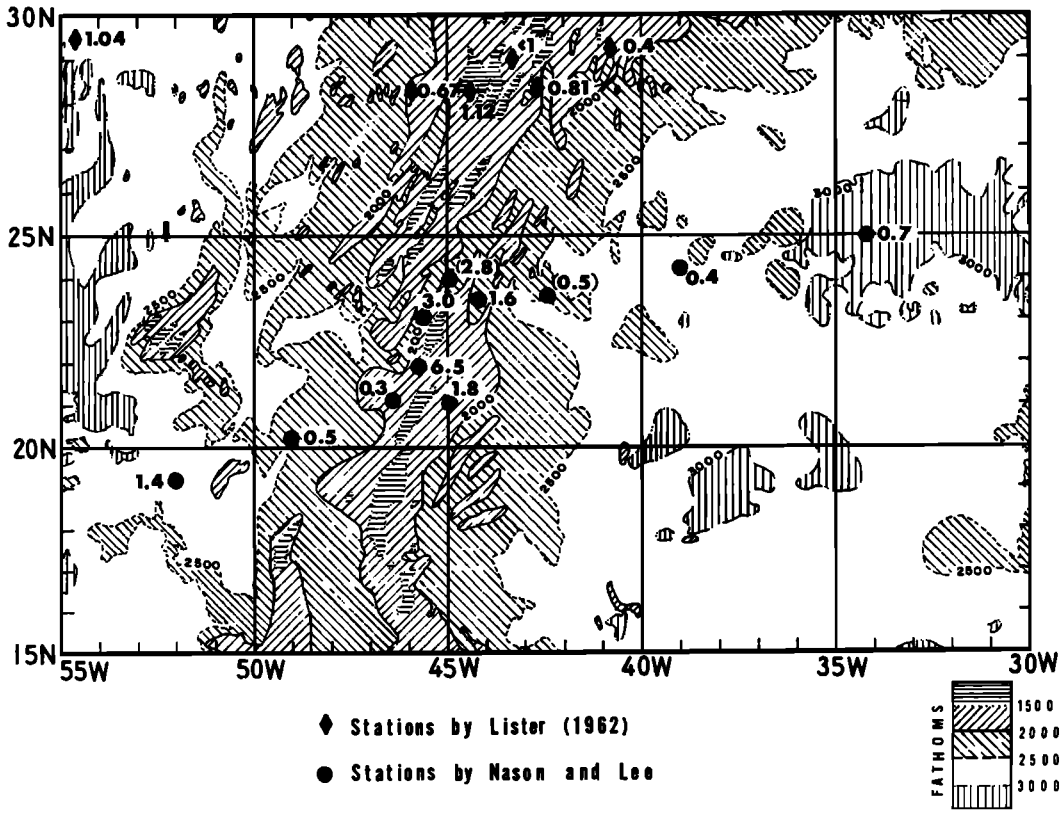

Fig. 2. Enlarged map for some heat-flow measurements (in μcal/cm^2 sec) near the crest of the mid-Atlantic ridge. Bathymetric contours are in fathoms.

mentation rate, the heat-flow value of 1.2 is uncertain. About 200 km northeast of station 32, *Lister* [1962] obtained a heat-flow value of 2.5.

Discussion

Summary of results. The results of heat-flow measurements in the North Atlantic are briefly summarized as follows:

1. Fairly uniform heat flow of about 1.2 μcal/cm^2 sec is observed in various North Atlantic basins away from the mid-Atlantic ridge.
2. Heat flow varies greatly on the mid-Atlantic ridge. The crest is associated with many high values (>3 μcal/cm^2 sec), and low values (<0.7 μcal/cm^2 sec) are often observed on the flanks.
3. Thermal conditions in sediments east of the Antilles are probably disturbed, and the heat-flow values there are probably not representative.

Evaluation of experimental technique. We used a modified Bullard-type temperature-gradient probe in which the temperature difference between two depths is measured. Recently E. A. Lubimova (private communication, 1964) has questioned the thermal stability of the water layer adjacent to the sea floor. Whether this insability has a significant effect on the temperature gradient of the sediment is yet to be determined. Nevertheless, the shortness of our probe makes it vulnerable to thermal disturbances near the water-sediment interface because the maximum penetration of the probe is only 2 meters. Measurements by longer probes with several temperature-sensing elements (such as the Ewing-type probe) are more reliable and are now more commonly used.

Heat flow and sedimentation rate. Von Herzen and Uyeda [1963] evaluated the effect of a constant sedimentation rate on heat flow. Their Figure 9, page 4236, shows that the disturbance

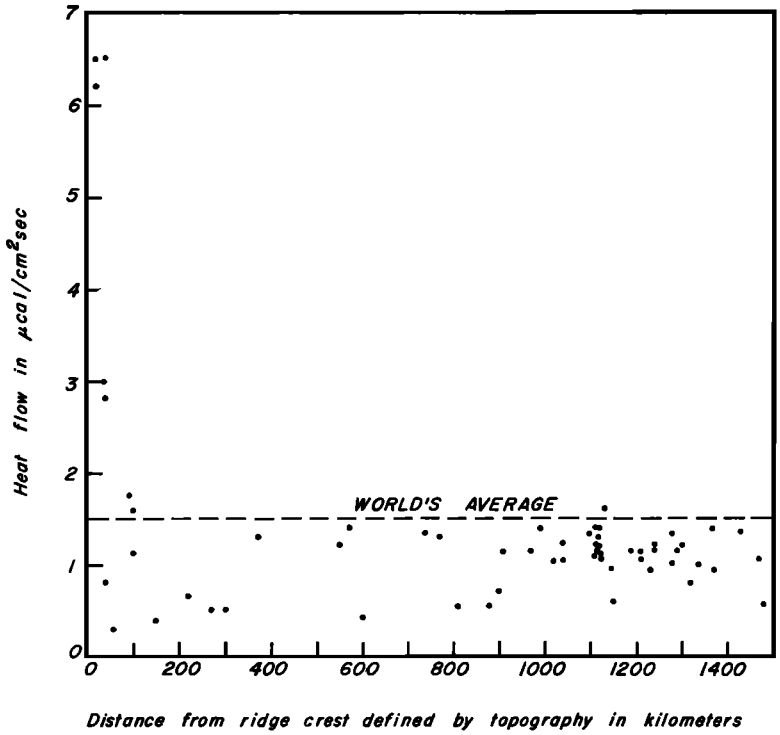

Fig. 3. Plot of Atlantic heat-flow values *north* of 13°N versus their station distances from the topographic crest of the mid-Atlantic ridge.

of heat-flow values from sedimentation at rates less than 1 cm/1000 years is insignificant. The sedimentation rates measured by *Goldberg et al.* [1963] at stations on the mid-Atlantic ridge are all less than 0.5 cm/1000 years, so the effect of sedimentation rate at these stations is negligible. The situation at station 9, east of the Antilles, has been discussed above. The sedimentation rate of 1.7 cm/1000 years at station 25, west of the Canary Islands, is possibly high enough to reduce heat flow by a minor amount (about 5%).

Outflow of heat through the crest of the mid-Atlantic ridge. In Figure 3 Atlantic heat-flow values measured *north* of 13°N are plotted versus their station distances from the topographic crest of the mid-Atlantic ridge. Figure 4 shows a similar plot from *Vacquier and Von Herzen* [1964] of Atlantic heat-flow values observed *south* of 13°N versus station distance from the ridge crest as defined by the magnetic axis. In both plots all values exceeding 2.5 μcal/cm² sec were observed within 100 km of the ridge crest, indicating that the high heat flows occur in a zone less than 200 km wide. Within this crestal zone, thirty-two heat-flow measurements from 30°S to 50°N have values ranging from 0.08 to 8.14 μcal/cm² sec. The average of these 32 values is 3 μcal/cm² sec, with a standard deviation of about 2 μcal/cm² sec.

The total *outflow of heat* from a region is calculated as the product of the average heat flow times the area. If the average heat flow from the 200-km-wide crestal zone is 3 μcal/cm² sec, the *outflow of heat per centimeter of length* along the ridge crest is 60 cal/cm sec. As the low heat-flow values may not be representative (see previous section on 'Flanks of mid-Atlantic ridge measurements'), the *apparent* average of 3 μcal/cm² sec for the crestal zone may be lower than the *true* average. From the value of the standard deviation, it appears that the true average is probably not as high as 5 μcal/cm² sec for the 200-km-wide zone. If an average of 3 to 5 μcal/cm² sec and a width of 200 km are used, the outflow of heat per centimeter of

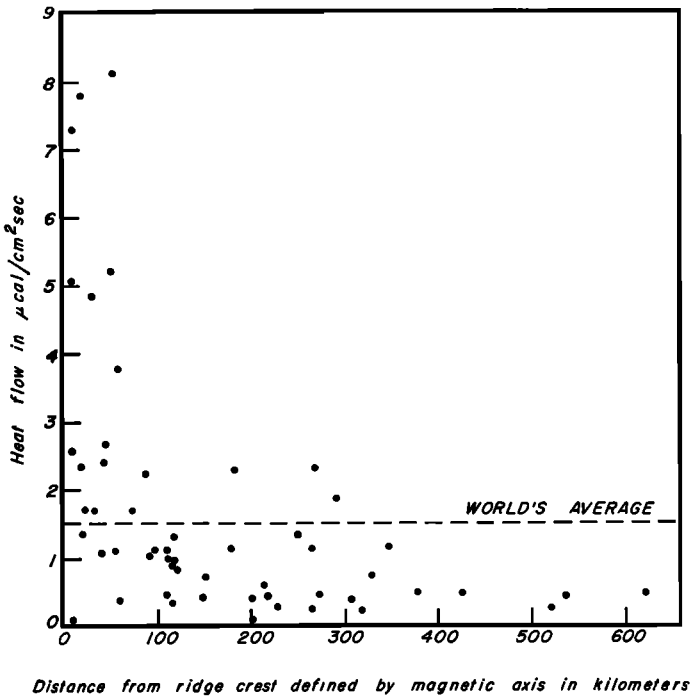

Fig. 4. Plot of Atlantic heat-flow values *south* of 13°N versus their station distances from the crest of the mid-Atlantic ridge as defined by magnetic axis [after *Vacquier and Von Herzen,* 1964].

length along the crest of the mid-Atlantic ridge is 60 to 100 cal/cm sec or 2 to 3 $\times$ 10^9 cal/cm year.

Sources of heat. From more than 780 heat-flow observations, *Lee* [1963] estimated the average heat flow for the earth to be 1.5 $\pm$ 10% μcal/cm^2 sec at the 95% confidence level. Subsequent analyses [*Lee and MacDonald,* 1963; *Lee,* 1964] with more up-to-date data (over 1300 heat-flow measurements) confirm this estimate. The observed heat flow is probably due mainly to the heat generated by radioactivity. However, we do not know the details of the distribution of radioactivity within the earth and the mechanisms of heat transfer [*Lee,* 1964]. The *apparent* average heat flow for the crestal zone of the mid-Atlantic ridge is about 3 μcal/cm^2 sec, which is *twice* the world average. It is unlikely that the radioactive elements are highly concentrated along the crest of the ridge. Therefore, we will explore other causes of high heat flow, such as intrusion of magma, convection, and serpentinization. We must bear in mind, however, that these causes and many others may be intimately related.

Intrusion of magma. A possible source of the high heat flow is the intrusion of magma into the upper mantle and crust. The heat lost from an intruding magma comes primarily from the latent heat of crystallization and from cooling. If 300 cal/g is the heat lost by crystallization and subsequent cooling of an intrusion, the outflow of heat per centimeter of length is equivalent to the intrusion of about 7 $\times$ 10^6 grams or 2 $\times$ 10^6 cm^3/cm year along the ridge crest. At this rate, every 5000 years 1 km^3 of magma would be intruded for each kilometer along the ridge. Or, if the intrusion is considered as a growing dike with a 10-km depth, the intrusion rate is equal to about 2 cm of dike width per year.

Convection. The excess heat is possibly from the cooling of material circulated by convective processes. A 100°C cooling of mantle rock yields about 100 cal of heat per cubic centimeter of material. The outflow of heat of

about 2×10^9 cal/cm year is thus equivalent to the 100°C cooling of 2×10^7 cm³ of material per centimeter per year. Cooling by a greater or lesser amount will, of course, change the requirements on volume.

If the calculated volume of 2×10^7 cm³ rises in a zone 100 km wide, the upward flow velocity in the zone is about 2 cm/year. Alternatively, convection in a *narrow* molten intrusion, as suggested by *McBirney* [1963], would require a velocity of about 20 m/year for a dike 100 m wide. Varying the volume of material cooled, cooling by a different amount, or varying the dimensions of the upflowing zone will change the deduced velocity.

That high heat-flow values have not been found more than 100 km from the ridge crest (see Figures 3 and 4) suggests that the zone of convective upflow near the surface is probably not more than 200 km wide. However, our present data are inadequate to permit us to deduce more about convection at depth.

Serpentinization. Schuiling [1964] calculated that the heat released by serpentinization of a column of rock 4 km high (to produce a 5-km-thick crust) is 1.35×10^8 cal/cm². The outflow of heat of 2×10^9 cal/cm year is then equivalent to the serpentinization of about 15 cm²/cm year, or a 15-cm-wide band along the ridge each year.

Variations in *oceanic* heat flow are primarily due to variations in temperature gradient, because the thermal conductivity of various ocean sediments is about the same. For example, in Table 1 a heat flow of 6.5 μcal/cm² sec corresponds to a temperature gradient of over 300°C/km in ocean sediments or over 100°C/km in basalt. Such high temperature gradients indicate extremely high temperatures at shallow depths under the crest of the mid-Atlantic ridge. A similar conclusion has also been reached by *Von Herzen and Uyeda* [1963] for the crest of the east Pacific rise, and they have presented several interesting explanations for the observed high heat flow.

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