PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Heat Flow and Magnetic Profiles on the Mid-Indian Ocean Ridge

R. P. Von Herzen and V. Vacquier

Phil. Trans. R. Soc. Lond. A 1966 **259**, 262-270
doi: 10.1098/rsta.1966.0011

Heat flow and magnetic profiles on the Mid-Indian Ocean Ridge*

By R. P. von Herzen† and V. Vacquier

Marine Physical Laboratory of the Scripps Institution of Oceanography, University of California, San Diego

Sixty heat flow values were measured along nine profiles across the Mid-Indian Ocean Ridge. The results were roughly of the same character as the ones previously reported for the South Atlantic Ridge. The correlation of high heat flow with the centre of the ridge was less pronounced. The scatter of heat flow values when plotted as a function of distance from the ridge was even greater. The average of all values is 1·35 μcal cm^{-2} s^{-1}, indicating that over the surveyed area the heat flow is normal. The cause for the low values on the flanks of the ridge remains unknown. A right lateral displacement of about 200 km across the Vema Trench was measured from the offset of the magnetic anomaly on the ridge crest.

On the third voyage of the R.V. *Argo* of the Scripps Institution of Oceanography as a contribution to the International Indian Ocean Expedition, geological and geophysical observations were carried out during nearly 2 months between September and October 1964. During the first month of this part of the voyage, called Dodo Expedition, the observations consisted of continuous bathymetric and magnetic recordings under way and measurements of heat flow through the ocean floor at selected stations. This study principally consists of a series of transverse profiles across a portion of the Mid-Indian Ocean Ridge, over which these measurements were carried out, and therefore is similar in scope and content to a study made previously on the South Atlantic Ridge (Vacquier & von Herzen 1964). The purpose of this paper is to describe and discuss the measurements on the Indian Ocean Ridge and to compare them with previous results in the South Atlantic.

In figure 1 is shown part of the track of *Argo* between the ports of Port Louis, Mauritius Island, and Colombo, Ceylon, in the western part of the Indian Ocean. The values of heat flow are shown in units of μcal cm^{-2} s^{-1} along the ship's track. The crest of the ridge system is shown as a heavy black line, and successive profiles across the ridge are designated by circled numbers. In addition, there are three areas shown enclosed by dashed lines which are discussed below.

The topographic and total magnetic intensity profiles plotted against longitude are shown in figure 2. The profiles labelled 'Lusiad *Argo*' and 'Monsoon *Argo*' are located on figure 1 by profiles of previous heat flow stations which cross the ridge axis near $5\frac{1}{2}°$ S and 16° S latitude, respectively. Except for the oblique trend near profile 1, the ridge axis covered by the profiles everywhere appears to deviate less than about 15° from a north–south direction, as was also true for the South Atlantic region; so that the profiles plotted versus longitude should represent sections nearly normal to the ridge axis. The position of the crest of the ridge was chosen to correspond to the position of the centre of the wide magnetic anomaly which is known to be characteristic of all oceanic ridges. Some profiles

* Contribution from the Scripps Institution of Oceanography, University of California, San Diego.
† Present address: U.N.E.S.C.O., Place de Fontenoy, Paris 7, France.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

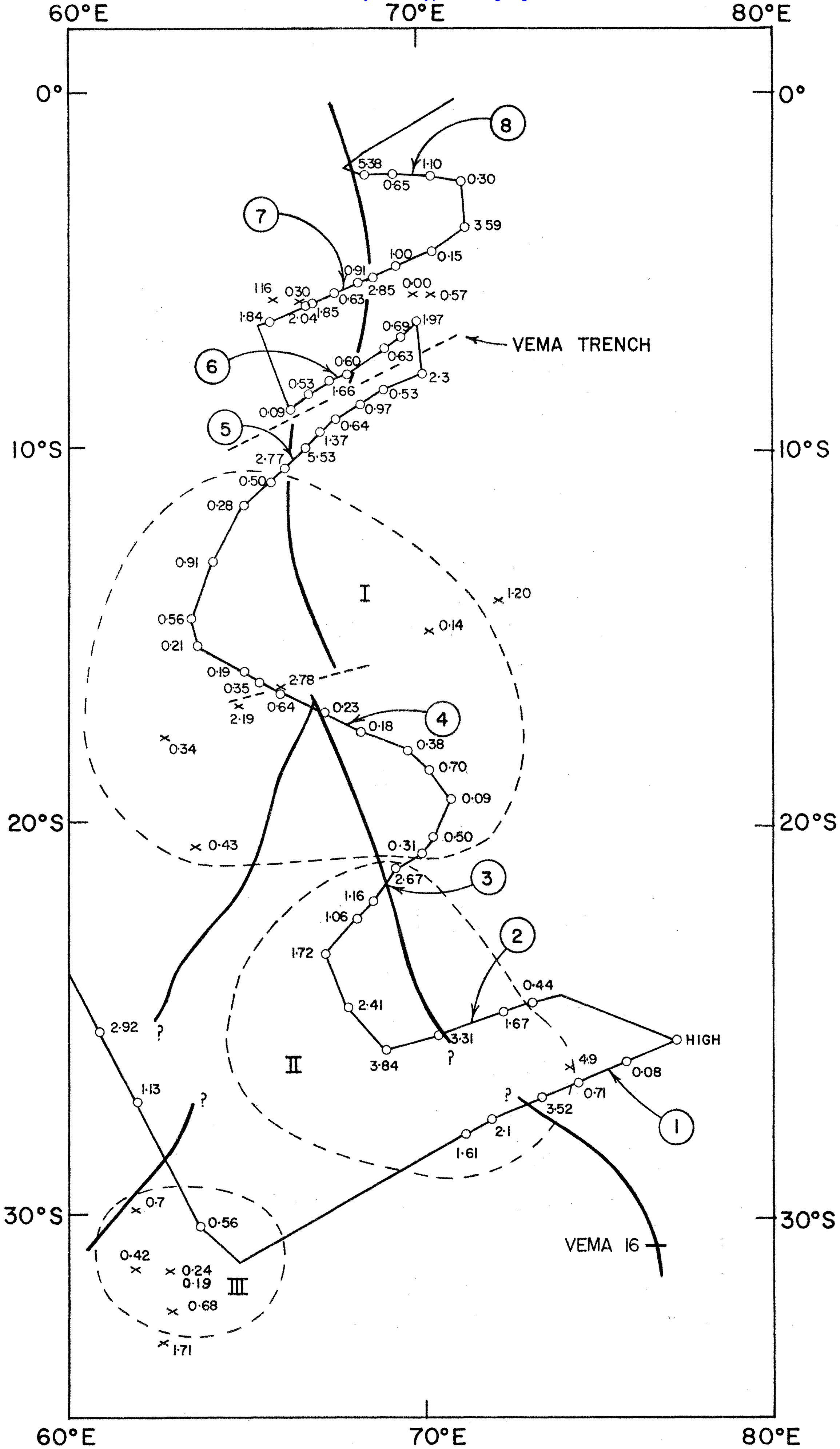
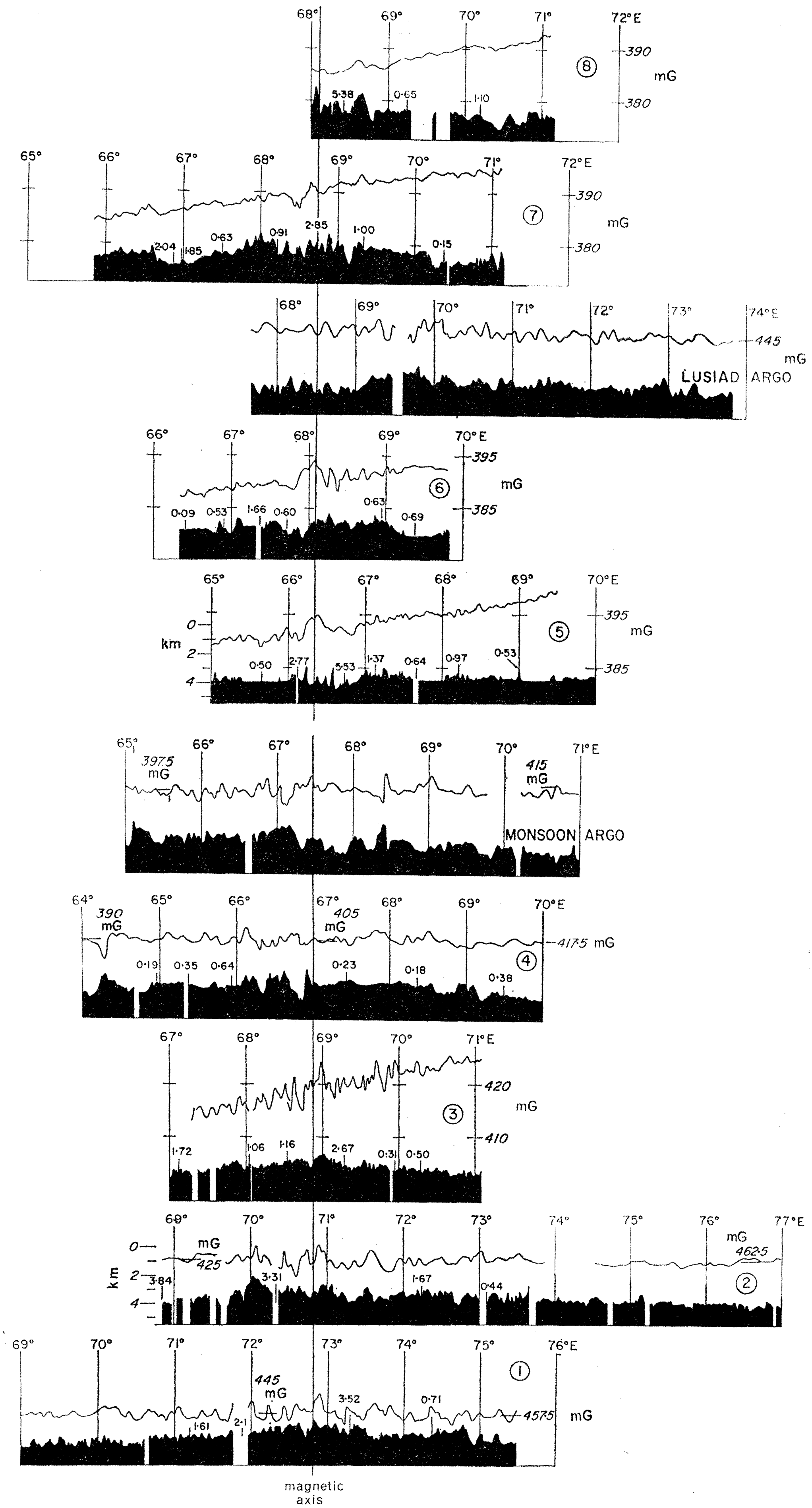


FIGURE 1. Track chart. Circled numbers designate successive crossings of Mid-Indian Ocean Ridge. Other numbers near station locations are heat flow values in microcalories per square centimetre per second. Crosses are heat flow stations previously reported by von Herzen & Langseth (1965). Location of ridge crest was established from bathymetric and magnetic profiles of figure 2.



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

FIGURE 2. Total magnetic intensity and bathymetric profiles across Mid-Indian Ocean Ridge plotted against longitude as horizontal coordinate. Circled numbers indicate crossings shown on figure 1. The profiles have been shifted east–west to line up the crest axis vertically. The bottom of each bathymetric section is at depth of 4·75 km. Numbers along bathymetric profiles are heat flow values in microcalories per square centimetre per second. The magnetic intensity profiles that do not have a milligauss scale on the right-hand side had a constant gradient subtracted as indicated by the numbers in milligauss at the two ends of the profiles.

show the central magnetic anomaly more clearly than others. For example, on profiles 1, Monsoon and Lusiad, both the magnetic intensity and the topography were used to estimate the position of the ridge axis. On profile 4 only the topography was used. In this instance, the rift valley lies about 15 mi. west of the 'magnetic axis'. This was done because in most cases where both the magnetic anomaly and the rift valley were present, the latter was displaced to the west of the anomaly. A possible explanation for the lack of magnetic expression near the ridge crest on some of the profiles may be that the track passed near regions of transverse displacement of the ridge axis, in one case of which the magnetic anomaly was lacking in the previous study of the South Atlantic Ridge (Vacquier & von Herzen 1964, profile 13).

Figure 1 illustrates transverse displacements of the ridge axis which have been deduced from the topographic and magnetic 'axes' chosen in figure 2. The displacement of the axis between profiles 5 and 6 occurs across the Vema Trench (Heezen & Nafe 1964) and was chosen principally on the basis of magnetics on these profiles. The displacement is in the same sense and of about the same magnitude as that shown on Heezen & Tharp's (1964) physiographic diagram of the Indian Ocean; it is probably the best established of the transverse displacements on the Indian Ocean Ridge. Near 16° S latitude, the displacement was determined by profile 4 and a previous line (Expedition Monsoon, R.V. *Argo*) to the north. Near 26° S latitude is indicated a possible displacement of both branches of the ridge, perhaps by the same fault or fracture zone. Heezen (personal communication, 1964) believes that both branches may be displaced near these regions by north–south trending faults, rather than east–west, which would imply the two hypothesized displacements are independent.

The new heat flow values shown in figure 1, 60 in all, are listed in table 1. For comparison this table includes most of the same features listed in the measurements of the South Atlantic study. As before, parentheses around values of thermal conductivity indicate the value was assumed from measurements obtained on cores at nearby stations. Partial penetration of the temperature gradient probe is indicated for a few of the heat flow values, and the distance of each station measurement from the ridge axis is taken from figure 2. Except for a few measurements, there is a remarkable uniformity of measured values of thermal conductivity, as on the South Atlantic Ridge; the additional error due to assumed values of thermal conductivity is estimated not to exceed a few per cent.

The profiles across the Indian Ocean Ridge are relatively short; they extend to a maximum of only about 350 km from the ridge axis. In fact, on most of the profiles, this distance cannot be much greater owing to definition and geographical necessity. The locations of the many ridges of the Indian Ocean are such that station distances greater than 300 to 400 km are not possible in most areas without being closer to another ridge system. A plot of heat flow versus distance from the Mid-Indian Ocean Ridge axis for both the new and previous (von Herzen & Langseth 1965) measurements is given in figure 3. This figure shows the large scatter of the values plotted in this way and the large number of relatively low heat flow values. There appears to be some tendency for the higher values to occur closer to the ridge axis, but low values also occur in considerable numbers nearly up to the ridge crest. Only very few measurements were obtained at distances of 300 to 600 km from the ridge axis, in which zone for the South Atlantic Ridge

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Table 1. Heat flow measurements

station no. Dodo	position		depth (m)	dist. from ridge axis (km)	therm.† cond.	heat‡ flow
	S. lat.	E. long.				
1	25° 20′	60° 44′	4940	—	(1·74)	2·92
2	27° 04′	61° 51′	4610	—	1·74	1·13
3	30° 19′	63° 35′	4400	—	(1·74)	0·56
7B	27° 57′	71° 11′	3410	165	1·93	1·61
8	27° 36′	71° 53′	3420	95	2·09	2·1
9	27° 03′	73° 19′	2955	46	2·23	3·52
10	26° 39′	74° 23′	3370	133	(2·33)	0·71
11	26° 07′	75° 52′	3385	261	2·33	0·08
12	25° 38′	77° 11′	3900	416	(2·33)	(high) pp
13	24° 42′	73° 06′	3715	248	2·29	0·44
14	24° 51′	72° 15′	3100	172	(2·29)	1·67
15	25° 25′	70° 23′	3370	16	2·20	3·31
17	25° 50′	68° 47′	3135	158	2·24	3·84
18	24° 40′	67° 49′	3070	188	(2·24)	2·41
19	23° 20′	67° 05′	3600	220	2·10	1·72
20	22° 28′	68° 01′	3140	114	(2·24)	1·06
21	22° 01′	68° 32′	2770	48	(2·26)	1·16 pp
22B	21° 11′	69° 17′	3030	34	2·26	2·67
23	20° 40′	69° 57′	3325	85	(2·26)	0·31
24	20° 24′	70° 17′	3500	173	(2·26)	0·50
25B	19° 25′	70° 43′	3675	262	1·96	0·09
26	18° 38′	70° 11′	3400	236	(1·96)	0·70
27	18° 09′	69° 31′	3785	206	1·97	0·38
28	17° 42′	68° 22′	3130	97	2·21	0·18
29*	17° 10′	67° 14′	3130	21	(2·21)	0·23
30	16° 37′	65° 57′	3135	127	(1·99)	0·64
31	16° 16′	65° 22′	3200	179	(1·99)	0·35
32	16° 03′	64° 58′	3065	249	(1·98)	0·19
33	15° 18′	63° 42′	3160	345	1·98	0·21
34	14° 14′	63° 29′	3375	333	(1·98)	0·56
35*	12° 56′	64° 11′	4120	240	2·13	0·91
36	11° 29′	65° 00′	3980	135	2·02	0·28
37*a	10° 52′	65° 38′	4065	58	1·91	0·50
38	10° 28′	66° 07′	3720	21	(1·97)	2·77
39	9° 56′	66° 44′	4295	48	1·93	5·53
40	9° 35′	67° 08′	3570	87	1·98	1·37
41	9° 12′	67° 39′	3750	134	(2·04)	0·64
42	8° 46′	68° 13′	3460	216	(2·04)	0·97
43*a	8° 18′	69° 01′	3980	108	2·10	0·53
44	7° 56′	70° 03′	3715	211	(2·10)	2·3 pp
45*a	6° 22′	69° 54′	3505	156	(2·10)	1·97
46*a	6° 47′	69° 22′	3920	113	(2·10)	0·69
47	7° 07′	68° 57′	2810	74	2·15	0·63
48*	7° 53′	67° 43′	3840	22	(2·00)	0·60
49	8° 07′	67° 22′	3360	65	(2·00)	1·66
50	8° 24′	66° 54′	3340	108	(1·95)	0·53
51	8° 52′	66° 19′	3515	173	1·95	0·09
52	6° 22′	65° 42′	4005	294	(2·00)	1·84
53	5° 51′	66° 58′	4090	166	2·02	1·85
54*	5° 54′	66° 53′	4360	185	2·02	2·04
55	5° 37′	67° 30′	3430	104	2·21	0·63
56	5° 17′	68° 13′	3565	34	2·07	0·91
57	5° 04′	68° 43′	3185	0	(2·09)	2·85
58	4° 47′	69° 20′	3380	76	2·09	1·00
59	4° 18′	70° 23′	3920	196	(2·09)	0·15
60	3° 47′	71° 14′	3420	301	(2·10)	3·59
61	2° 27′	71° 08′	3920	316	2·12	0·30
62	2° 20′	70° 20′	3940	222	2·09	1·10
63	2° 15′	69° 15′	3495	113	(2·09)	0·65
64	2° 10′	68° 25′	3895	31	(2·09)	5·38

† 10^{-3} cal °C^{-1} cm^{-1} s^{-1}. ‡ 10^{-6} cal cm^{-2} s^{-1}.

* Bottom topography varies less than 20 m within 10 km of station along ship's track.
*a Bottom topography varies less than 20 m for more than 10 km from station along ship's track.
pp = partial penetration of temperature gradient probe.

many low values were measured. Some of the low values may result from effects of the topography or sedimentation on the ocean floor, as previously noted for some regions of the Pacific (von Herzen & Uyeda 1963), but some effort was made on Dodo Expedition to avoid such unusual areas; as denoted in table 1, only a few of the measurements were made in locally flat basins, which have been correlated with low heat flow values elsewhere.

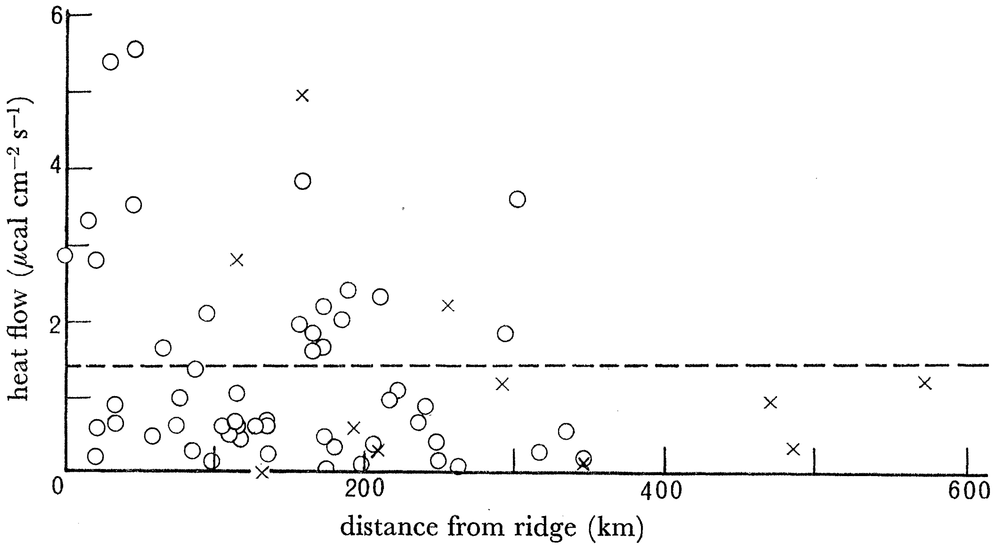


FIGURE 3. Heat flow values versus distance from ridge crest as given on figures 1 and 2. Crosses are previously reported values. The horizontal dashed line is approximate oceanic average, 1·4 μcal cm^{-2} s^{-1}.

The systematic distribution of heat flow values versus distance from the ridge crest is shown more clearly in figure 4. In this figure the heat flow is plotted for zones 0 to 100, 100 to 300 and 300 to 600 km distant from the ridge axis. The values plotted are those at the 75, 50 and 25 percentile points of all the values for each zone shown in figure 3. The numbers above each set of points shows the number of values for each zone. For example, in the zone between 0 and 100 km, 75 % of the 19 values are smaller than 2·8 μcal cm^{-2} s^{-1} whereas 25 % are greater. In the same zone, 50 % of the 19 values are greater than 1·2 and 50 % are smaller; and so on. This representation clearly shows the systematic decrease of heat flow away from the ridge axis, although there are relatively few measurements (8) for the zone 300 to 600 km distant from the axis. Similar plots for the mid-Atlantic Ridge and the East Pacific Ridge show a similar distribution (von Herzen & Langseth 1965), although the high heat flow appears to occur over a broader zone near the crest of the East Pacific Rise.

Most of the high values appear to represent rather localized hot spots on the ocean floor. Figure 3 shows that some of the high values are located at considerable distances from the ridge axis; some of these may result from a poor location of the ridge axis, and others may be located in unrecognized fracture zones. The succession of measurements from Dodo 23 to Dodo 37 inclusive, is most unusual in that all values in this series are less than 1·0 μcal cm^{-2} s^{-1}. These include profile 4 across the ridge crest, and some of these low values are located quite close to previous high values (von Herzen & Langseth 1965), probably indicating the localization of the high heat flow areas. It is interesting that the average of all values on Dodo Expedition is 1·35 μcal cm^{-2} s^{-1}, which is close to the average over the whole of the Indian Ocean (von Herzen & Langseth 1965). On several of the Dodo profiles it was not possible to obtain measurements on some areas of rugged topography near the ridge crests. There were no measurements obtained between Dodo 3 and 7B, a distance of about 775 km, owing to a lack of penetrable sediment on the ocean floor (the missing station numbers represent unsuccessful attempts). Such areas may be regions of relatively high heat flow and may give a considerable increase to the heat flow average near the ridge crest.

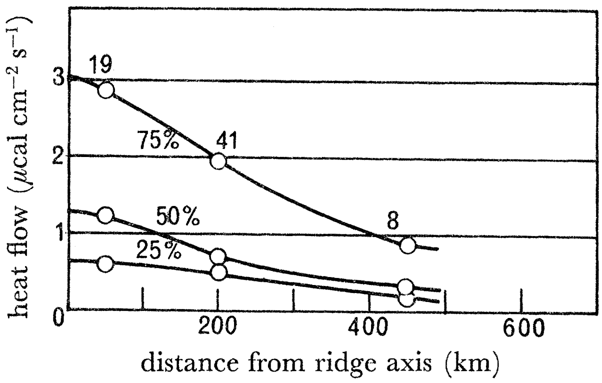


Figure 4. 75, 50 and 25 percentile heat flow values plotted against distance from crest of Mid-Indian Ocean Ridge.

Another way of looking at the data presented in figure 1 is to arrange them into zones of relatively different heat flow. Three such possible zones are shown on figure 1, labelled I, II and III. The 20 values in zone I average 0·60 μcal cm^{-2} s^{-1}, considerably less than the normal oceanic average. In a similar way, the 12 values enclosed within zone II average 2·50 μcal cm^{-2} s^{-1}, making it a region of considerably higher-than-normal heat flow. Also, zone III, although smaller in area than zones I and II, appears to have consistently low values, the average of the five values at different localities (assuming an average value of 0·22 μcal cm^{-2} s^{-1} at the locality with the two measured values of 0·24 and 0·19 μcal cm^{-2} s^{-1}) being 0·52 μcal cm^{-2} s^{-1}. These three zones which differ in average heat flow range from approximately $2{\cdot}5\times10^{5}$ to $1{\cdot}1\times10^{6}$ km^{2} in area and are apparently the only zones of this size in the region of figure 1 which are delineated by the presently existing measurements.

An argument against this interpretation is that the zones as shown appear to have little correlation with the major structural features of the region. Zones I and II each include the crestal region, flanks and lower flanks of a major oceanic ridge (including regions of the crest which show transverse displacements) although the low heat flow of zone III may be principally confined to a lower ridge flank and adjacent basin, with which low heat flow has been previously correlated (Vacquier & von Herzen 1964; von Herzen & Langseth 1965). The values within both zones I and II therefore show little or no correlation with distance from the ridge axis. The two high values previously measured (von Herzen & Langseth 1965) in zone I must be localized to a small region, as they are only a short distance from low values obtained on Dodo Expedition. Also, near the northern boundary of zone II at the crest of the eastern branch of the ridge, M. G. Langseth (personal communication, 1964) has found a few very high heat flow values. These were apparently close to locations of our stations Dodo 21 and 22B, which gave normal and moderately high values, respectively, indicating again the high values are probably localized. We could not exclude the possibility that some of these local hot spots (or strips) were missed in our crossings of the ridge in zone I on Dodo Expedition. However, the existence of such local anomalous hot spots might cause us to divide up zone I into several smaller zones, perhaps similar in area to zone III, but each of which would show a lower-than-normal heat flow.

Therefore, perhaps the principal discovery in this region, as well as the vicinity of the South Atlantic Ridge, is the presence of areas of the ocean floor through which the heat flow is *less* than normal, as well as those through which it is *greater* than normal. The high heat flows can be explained as regions of local magmatic intrusions, although the question of the origin of these intrusions goes begging. But how do we now account also for regions of low heat flow? Without going into the detailed mechanism, three different possibilities seem evident: (i) *Heat flow refraction.* McBirney (1963) suggests that anomalies of thermal conductivity in the mantle may produce areal heat flow anomalies at the surface. However, calculations by Uyeda & Horai (1964) indicate the expected differences in heat flow would be small. (ii) *Mantle convection.* The slow movement of material in the mantle has often been used to account for heat flow anomalies at the surface, especially the hypothesized upward movement of rock material and heat beneath the oceanic ridges. The downward movement of material may as well explain areas of low heat flow. If the zonal pattern of figure 1 holds, which has little relationship to the existing ridges, then perhaps a new regime of convection has been established since the formation of the ridges. The linear dimensions of several hundred to *ca.* 1000 km across the zones imply convection may be limited to the upper part of the mantle. (iii) *The serpentinization of rock.* This hypothesis, recently advanced by Hess (1962), can account for high and low heat flow areas through the release or absorption of heat at depth by the change of olivine to or from serpentine. Since movement of rock is generally required, this hypothesis is similar to that of convection and has been briefly reviewed by Uyeda & Horai (1964) as an explanation for heat flow measurements in Japan.

We acknowledge the assistance of Mr F. S. Dixon, Mr R. E. Warren, and Dr C. G. A. Harrison of the Scripps Institution of Oceanography and Mr John Sclater of Cambridge University, England. Mr P. T. Taylor of Stanford University made the thermal conductivity measurements on the cores and some of the computations of the heat flow values. This research was supported by the National Science Foundation under grant NSF-G 22255 and by the Office of Naval Research under contract Nonr 2216(05).

References (von Herzen & Vacquier)

Heezen, B. C. & Nafe, J. E. 1964 Vema trench: Western Indian Ocean. *Deep-Sea Res.* **11**, 79–84.

Heezen, B. C. & Tharp, M. 1964 *Physiographic diagram of the Indian Ocean.* Geol. Soc. Amer.

Hess, H. H. 1962 History of Ocean Basins. In *Petrological studies*, pp. 599–620. Buddington Vol. Geol. Soc. Amer.

McBirney, A. R. 1963 Conductivity variations and terrestrial heat flow distributions. *J. Geophys. Res.* **68**, 6323–6329.

Uyeda, S. & Horai, K. 1964 Terrestrial heat flow in Japan. *J. Geophys. Res.* **69**, 2121–2141.

Vacquier, V. & von Herzen, R. P. 1964 Evidence for connection between heat-flow and the Mid-Atlantic Ridge magnetic anomaly. *J. Geophys. Res.* **69**, 1093–1101.

von Herzen, R. P. & Langseth, M. G. 1965 Present status of oceanic heat flow measurements. In *Physics and chemistry of the Earth*, vol. 6. (ed. S. K. Runcorn).

von Herzen, R. P. & Uyeda, S. 1963 Heat flow through the Eastern Pacific Ocean floor. *J. Geophys. Res.* **68**, 4219–4250.