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Heat flow in the northwest Indian Ocean and Red Sea

By J. G. Sclater

Department of Geodesy and Geophysics, University of Cambridge

Twenty-four measurements of the heat flow through the ocean floor were made in the Indian Ocean and three in the Red Sea. A critical analysis of the effects of fluctuations of bottom-water temperature on the geothermal gradient in the Red Sea shows that these fluctuations do not invalidate the measurements of heat flow. The mean value for the Gulf of Aden (this includes five previous measurements) is $3{\cdot}89 \pm 0{\cdot}49$ μcal cm^{-2} s^{-1}. This high value, combined with the shape of a profile across the Gulf, suggests a region of unusually high temperature at a depth of less than 10 km below the bottom. The seventeen heat flow measurements made by R.R.S. *Discovery* and R.V. *Vema* between the African coast and the Seychelles show little variation about a mean value of $1{\cdot}17$ μcal cm^{-2} s^{-1}. The comparison of these observations and the deep structure, as determined by a series of seismic lines, shows a constant heat flow across the continental margin.

The author is indebted to Mr R. Belderson of the National Institute of Oceanography for a brief description of the cores taken on the cruise.

I.I.O. Expedition

In August 1963, R.R.S. *Discovery* during her contribution to the International Indian Ocean Expedition sailed from Aden to carry out a geological and geophysical survey of two areas, one over the median valley and another over the flanks of the Carlsberg Ridge. This was followed by a series of seismic profiles, shot in conjunction with H.M.S. *Owen*, designed to investigate the deep structure between the Seychelles and the African coast. On the return voyage magnetic and heat flow profiles were obtained in the Gulf of Aden and the Red Sea.

During the expedition more than thirty cores were taken and the heat flow apparatus was attached on all lowerings. A summary of the results and the positions of the stations from the present work is given in table 1. The station positions were determined by astronomical methods. Figure 1 presents a map of these and of previously published heat flow observations in the northwest Indian Ocean (von Herzen & Langseth 1965).

The possible depth of the sources of heat between the African coast and the Seychelles might be inferred by comparing the deep structure obtained from a series of seismic profiles with the heat flow measurements. A critical analysis is given of the possible changes of temperature gradient in the sediment of the Red Sea caused by variations in the temperature of the deepest water. The similarities of the topography, the magnetic profiles, and the seismicity between the Carlsberg Ridge and the Gulf of Aden suggest a comparison of the heat flow.

The heat flow at each station has been calculated from the temperature gradient found between pairs of probes on outriggers attached to a gravity corer. The thermal conductivity of the sediment column was determined from the water content (Ratcliffe 1960; Gerard, Langseth & Ewing 1962; Lister 1963; Bullard 1963).

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TABLE 1. HEAT FLOW STATIONS

station	position lat.	position long.	depth (m)	thermal conductivity (10^3 c.g.s.)	heat flow (10^6 c.g.s.)	accuracy (S.D.)
5116	05° 35′ N	61° 57·1′ E	3560	2·02	1·34*	±0·30
5122	05° 35′ N	61° 56′ E	3560	2·01	1·29	±0·12
5125	02° 45′ N	60° 15′ E	4806	1·70	0·45	±0·07
5135	02° 55′ N	59° 53′ E	4697	1·77	0·73	±0·07
5139	01° 54′ N	56° 10′ E	4812	1·73	1·26	±0·09
5144	01° 41′ S	42° 13′ E	2255	2·00	1·40†	±0·30
5149	02° 24′ S	43° 24′ E	3552	1·96	1·26	±0·09
5152	02° 32′ S	44° 56′ E	4160	1·86	1·15	±0·20
5155	20° 48′ S	47° 03′ E	4812	1·77	1·08	±0·11
5160	03° 30′ S	49° 40′ E	5042	1·77	1·28	±0·12
5165	03° 33′ S	51° 29′ E	5100	1·70	0·71	±0·15
5171	02° 10′ S	57° 25′ E	4402	2·26	0·50	±0·25
5177	02° 12′ S	57° 20′ E	4402	2·12	1·10	±0·12
5180	06° 39′ S	54° 16′ E	3824	2·06	1·54	±0·09
5190	02° 51′ S	47° 00′ E	4800	1·82	1·20	±0·15
5194	02° 34′ S	44° 53′ E	4180	1·91	1·14	±0·12
5201	01° 42′ S	42° 15′ E	2046	2·04	1·25†	±0·30
5204	03° 31′ S	48° 23′ E	4940	1·80	1·37	±0·30
5207	03° 34′ S	50° 29′ E	5082	1·83	1·30	±0·11
5215	02° 25′ S	54° 45′ E	4360	(2·00)	1·50*	±0·50
5226	11° 07′ N	54° 03′ E	4028	2·08	1·55	±0·13
5227	11° 39′ N	47° 50′ E	1900	2·14	3·85	±0·25
5229	12° 29′ N	47° 02′ E	2197	2·29	6·15	±0·60
5230	12° 56′ N	46° 36′ E	1600	2·16	3·25	±0·19
5231	15° 58′ N	41° 31′ E	1735	2·31	4·18	±0·30
5232	18° 24′ N	39° 47′ E	1480	2·62	1·06	±0·15
5234	20° 27′ N	37° 55′ E	870	2·75	high*	

* One probe only measured temperature in sediment.
† Corer penetrated twice.
( ) Thermal conductivity assumed.

THE CORES

The cores were taken with a free fall gravity corer weighing about 500 kg of which the barrel was 4 m long with an outside diameter of 6·3 cm and an inside diameter of 5·1 cm.

The cores from the Somali Basin, Carlsberg Ridge and Seychelles areas consisted essentially of foraminiferal lutites with interbedded graded turbidites. Those from the Somali Basin taken along the Kenya–Seychelles line contained blue-grey terrigenous pelagic material and a variable turbidite content, ranging from 0 on the steepest part of the continental slope to nearly 40% on the flattest part of the abyssal plain. These Somali Basin turbidites originate from the gullied African continental slope. The cores from the Seychelles and Carlsberg Ridge areas were grey to pink in colour, with a mean turbidite content of about 40%. These turbidites were probably derived by way of slumping from the steep flanks of local seamounts, or in some cases the slopes of the Seychelles Bank where these are the up-slope from sampled regions of ponded sediments.

The Gulf of Aden cores and the southernmost of the Red Sea cores were composed of compact, mottled grey-green foraminiferal lutites. Of the remaining Red Sea cores, the two from the shallowest depths consisted of creamy pink to creamy grey pelagic lutites with a high content of micro-organic remains; and the two from the deeper water consisted of a series of lutite bands ranging in colour from light to dark grey and brown to

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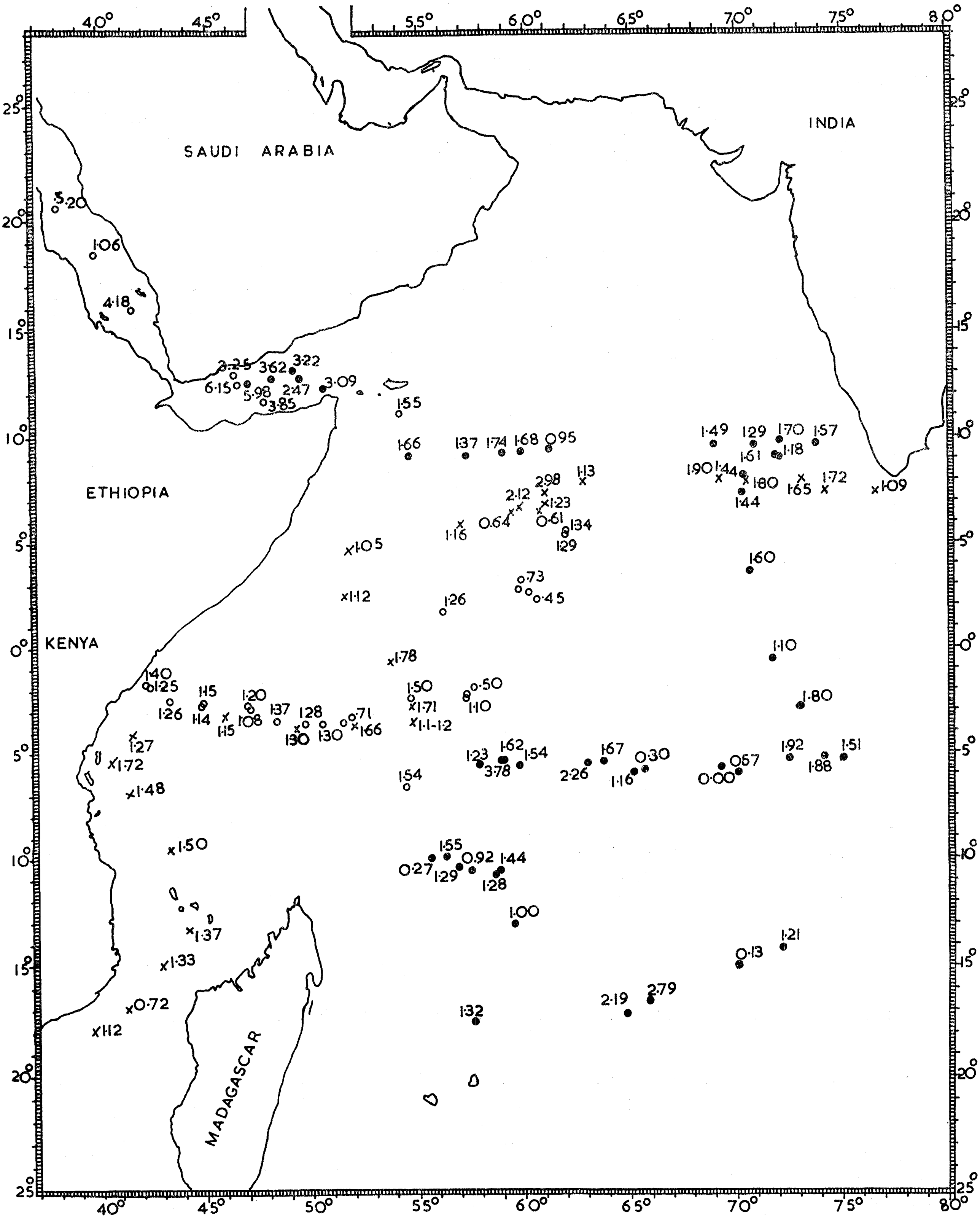

FIGURE 1. Indian Ocean heat flow (units μcal cm^{-2} s^{-1}). ×, R.V. *Vema*; ○, R.R.S. *Discovery*; ●, R.V. *Argo* and R.V. *Horizon*.

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yellow and orange, with a varying content of organic remains (including pteropods). All four cores contained layers of small lumpy or plate-like jagged calcareous concretions.

The core of Station 5165, the most easterly of a line of coring stations between the African coast and the Seychelles, shows a significantly lower turbidite content than the two nearest cores taken 80 km due west. This is not surprising as the topographic profiles between the African coast and the Seychelles show this station to be on the foothills of the Seychelles Bank and not the abyssal plain of the Somali Basin.

The interpretation of the results

The Indian Ocean is so extensive that the four main regions investigated by R.R.S. *Discovery*, the Somali Basin between Kenya and the Seychelles, the Carlsberg Ridge, the Gulf of Aden and the Red Sea, are treated individually in the interpretation of the results.

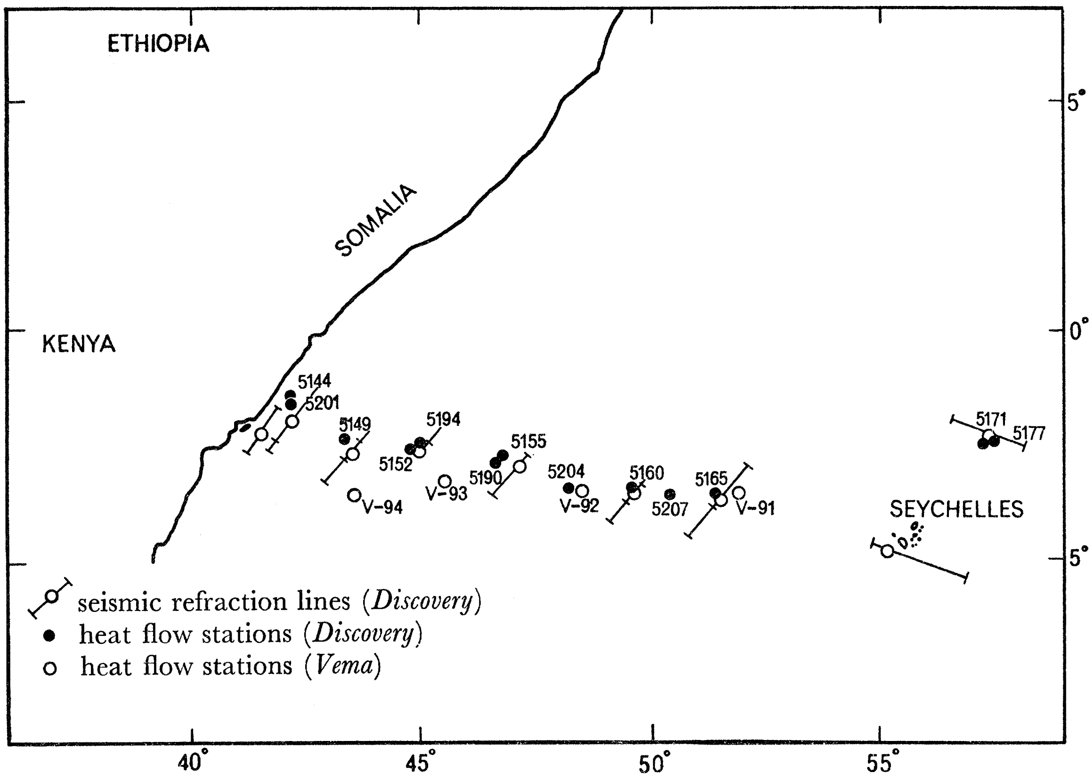

Figure 2. Map showing heat flow and seismic stations between the African coast and the Seychelles.

(*a*) *African Coast–Seychelles.* Figures 2 and 3 present the positions and results of a combined seismic and heat flow profile between the African coast and the Seychelles (Francis, Davies & Hill, p. 240 above). Four heat flow measurements made by R.V. *Vema* (cruise 19) (von Herzen & Langseth 1965) are included in the heat flow profile. No correlation is observed between the structure computed from the seismic velocity profiles and the heat flow observations. The mean value of the stations is 1·17 μcal cm^{-2} s^{-1} with a mean deviation of 0·17. This small variation about the mean suggests that the isotherms beneath the line are roughly horizontal over its whole length. The observations of heat

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flow at sea have shown that the average through the oceans is similar to that through the continental regions. The measurements between the African coast and the Seychelles suggest that this similarity can be extended to include the continental margins.

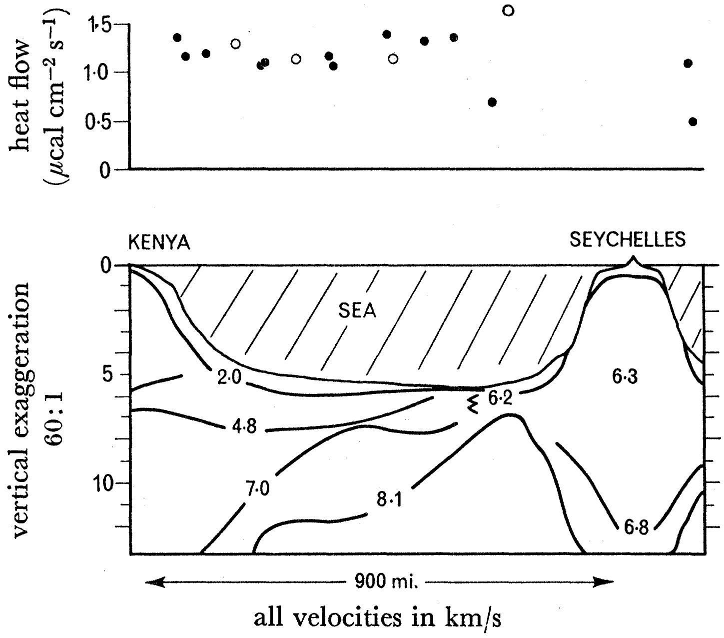

FIGURE 3. Profiles of structure and heat flow between Lamu and the Seychelles. (●, *Discovery*; ○, *Vema*.)

The four measurements nearest to the Seychelles, *Discovery* Stations 5165, 5171 and 5177 and *Vema* Station 91, were taken in areas of irregular topography and varying sediment cover.

(*b*) *The Red Sea.* On passage from Aden to U.K., five cores and three heat flow measurements were obtained in the Red Sea.

Water of an unusually high temperature and salinity has been reported in a small depression in the Red Sea (Swallow & Crease 1965; Charnock 1964; Miller 1964). The occurrence of this abnormal water and the possibility that the temperature of the bottom water might vary seasonally (Defant 1961) require an analysis of the effect upon the heat flow measurements of both sharp and seasonal variations of the bottom water temperature. Bullard, Maxwell & Revelle (1956) give an estimate of the disturbance in the heat flow caused by a sharp fluctuation of bottom water temperature ΔT. Table 2 gives the values of ΔT necessary to account for a gradient of 4×10^{-4} degC/cm in the top 5 m of sediment assuming the thermal conductivity to be $2{\cdot}5\times10^{-3}$ cal cm^{-1} s^{-1} degC^{-1} after a time T has elapsed.

TABLE 2

ΔT (degC)	time (y)
0·16	½
0·21	1
0·36	3
0·89	10

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Carslaw & Jaeger (1959) discuss the disturbance of the heat flow caused by a periodic change of amplitude δT in bottom-water temperature. The wavelength of the seasonal disturbance in the Red Sea sediments is 10 m. The corer penetrated $7\frac{1}{2}$ m of sediment at both Stations 5231 and 5232 thus the uppermost probe penetrated to a depth of approximately 5 m. The amplitude of the seasonal temperature variation at this depth is $\frac{1}{10}\delta T$.

Temperature measurements of the bottom water carried out in the northern half of the Red Sea by *Atlantis II* (July/August 1963), *Discovery* (November 1963, February and March 1964), *Albatross* (May 1948), *Will. Snellius* (April 1929, reported by Charnock (1964) and Defant (1961)) show the seasonal changes in temperature to be less than 0·2 degC. The temperature variation is not necessarily seasonal but real variations can hardly be much bigger (Charnock 1964). Thus large sharp fluctuations in temperature can be ruled out and the abnormal water found by Swallow & Crease (1965) appears to be restricted to a small area near 21° 17′ N, 38° 02′ E. The maximum effect of a seasonal change in the bottom water of 0·2 degC produces a temperature difference of 0·02 degC between a pair of probes 2 m apart and the uppermost at a depth of 5 m. This gives a maximum error of 15 % in Stations 5231 and 3 % in Station 5232. These are approximately the same as the errors already quoted for these stations. Thus both stations give an accurate representation of the outward flow of heat. At Station 5231 the lower two probes were torn off when penetrating a layer of jagged concretions 6 to 8 cm thick at a depth of 60 cm. The uppermost probe remained working throughout but only penetrated to an approximate depth of $1\frac{1}{2}$ m. The uncertainty in depth of penetration of this probe and the possible variation in the temperature caused by seasonal effects at the sediment surface makes this station only a qualitative estimate of the outward flow of heat. The results of these measurements show the existence of high heat flow values in the southern half of the Red Sea.

(*c*) *Gulf of Aden.* A continuous magnetic profile (see Laughton, p. 150 above) starting at 12° N, 47° E and three heat flow measurements were acquired during a NNW crossing of the Gulf of Aden. Figure 4, a plot of the bathymetric, smoothed magnetic and heat flow profiles taken on the crossing, shows that the highest heat flow values are associated with the maximum of the magnetic anomaly. This is similar to the findings of fourteen crossings of the mid-Atlantic Ridge between 30° and 6° S by R.V. *Argo* (Vacquier & von Herzen 1964). These reveal that nearly all the high heat flow values lie within 100 km of the apex of the magnetic anomaly. von Herzen & Uyeda (1963) suggest that regions of unusually high temperature at a depth of about 10 km beneath the ocean floor could explain the high heat flow zones on the East Pacific Rise. The similarity of the heat flow profile of figure 9 to those predicted by the methods of von Herzen & Uyeda indicate a similar source of heat for the large geothermal gradient found in the Gulf of Aden.

The large magnetic anomalies which exist in the centre of the Gulf of Aden suggest a number of dykes extending upwards to the ocean floor. These could be derived from a region of high temperature beneath the surface.

If a steady state is assumed one geological interpretation of these regions is a liquid magma body which is being continually supplied from the interior. In a non-steady state the heat flow could result from a past intrusion which is now cooling. The heat sources could then be shallower and of lower temperature (von Herzen & Uyeda 1963).

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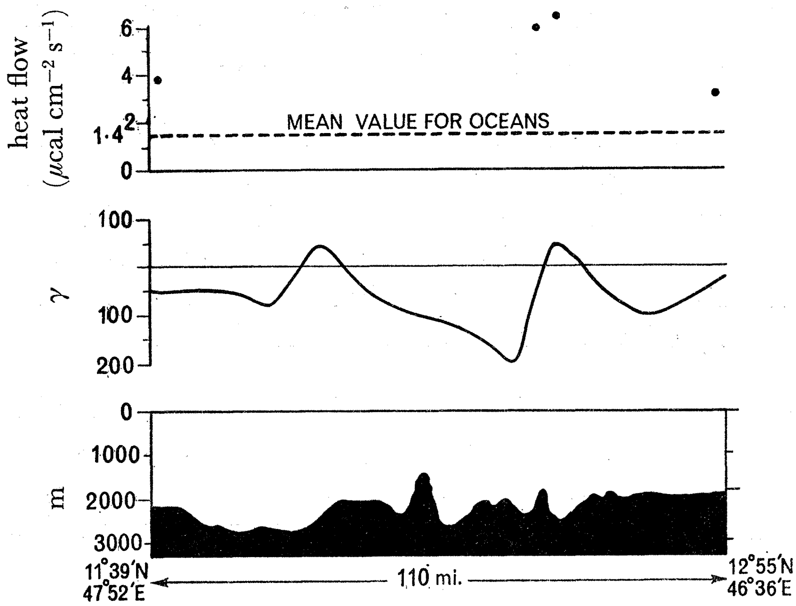

FIGURE 4. Section across the Gulf of Aden illustrating the relation between heat flow, smoothed total magnetic field and topography (– – –, mean value for oceans).

A COMPARISON OF THE CARLSBERG RIDGE AND GULF OF ADEN

The magnetic profiles obtained by H.M.S. *Owen* in the Gulf of Aden indicate that the strip of rugged topography in the median valley is associated with very large magnetic anomalies. An anomaly of comparable range and width is known to occur over the Carlsberg Ridge (see Matthews, p. 172 above, and von Herzen & Vacquier, p. 262) but nowhere else in the Arabian Sea. The narrow bank of seismic epicentres which follows the median valley of the ridge undergoes an abrupt change in direction at 10° N, $57\frac{1}{2}$° E before continuing into the Gulf of Aden. These striking similarities in the magnetics, topography and seismicity (Matthews 1963) would also suggest a comparison of the heat flow of the two regions.

Four heat flow measurements, two on the flanks, and two in the median valley, were obtained during the geological and geophysical investigation of the Carlsberg Ridge. The observed values are all lower than the mean for oceans and are similar to measurements made by R.V. *Argo* and R.V. *Vema* (von Herzen & Langseth 1965). The average value for the Gulf of Aden is approximately twice the largest measurement taken on the Carlsberg Ridge (figure 1). This difference suggests that if there is any source of heat on the Carlsberg Ridge, it must be more localized.

It is difficult to draw conclusions about a region as large as the northwest Indian Ocean on so few measurements. Nevertheless, some points have been stressed in this paper:

(i) The effects of variations in bottom-water temperature do not invalidate the measurement of heat flow in the southern half of the Red Sea.

(ii) The small variation shown about the mean by the heat flow observations between the African coast and the Seychelles suggests that the similarity between the average heat flow on land and that through the oceans can be extended to include the continental margins.

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(iii) The heat flow profile across the Gulf of Aden indicates that the high outward flow of heat could be explained by a region of unusually high temperature at a depth of less than 10 km.

(iv) The observations in the Indian Ocean do not show any large scale areas of high flow. The absence of such regions in the deep oceans, other than on the East Pacific Rise, suggests that the measurement of the outward flow of heat offers little direct evidence of thermal convection in the mantle. The narrow zones of high values on the mid-oceanic ridges indicate the existence of anomalously high temperatures at shallow depths. These could be the secondary effects of the mechanism of convection.

I should like to thank Professor Sir Edward Bullard, F.R.S. and Dr M. N. Hill, F.R.S. for their help, encouragement and suggestions; the captain, officers and crew of R.R.S. *Discovery* for their splendid co-operation at sea, and Messrs J. Cleverly, R. Belderson and R. B. Whitmarsh for the hard work that made the measurements possible.

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