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Heat Flow in the Aegean Sea

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Summary

Heat flow measurements taken in the Aegean Sea indicate a high heat flow in the northern and central Aegean. Nine stations at which a linear thermal gradient was measured give a mean value of 2·08 HFU. Four stations in the southern Aegean at which the gradient was non-linear gave limits to the heat flow in this area of between 1·0 and 1·6 HFU. Two high values in the north are associated with a deep bathymetric feature and intense magnetic anomalies. The high heat flow in the Aegean Sea is considered to be due to underthrusting of oceanic crust similar to that which occurs in the marginal basins of the north-west Pacific.

Introduction

The Aegean Sea is regarded as a Volcanic Island Arc system (Giermann 1966; Ryan 1969; Maley & Johnson 1971), and has recently been postulated to form part of a small rapidly moving plate (McKenzie 1970, 1972). The geological and geophysical aspects of the Aegean Sea are similar to those of the marginal basins inside the Volcanic Arcs of the western Pacific (Nicholls 1971; Ninkovich & Hays 1972). These marginal basins such as the Sea of Okhotsk and the Sea of Japan have received much attention since they were discovered to be regions of high heat flow (see Sclater 1972). To determine whether the Aegean Sea exhibits a similar high heat flow, a total of 20 stations of which 13 were successful were occupied in November 1972 (Fig. 1) using the Cambridge heat flow apparatus previously used by Lister (1963).

Method and results

The stations are located in the deeper depressions with depths ranging from 750 to 2373 m. The recording apparatus was used in conjunction with standard coring techniques. Three outrigger probes containing thermistors were spaced 1 m apart along the core barrel. Thermal gradients in the sediments were obtained by using the relative rises in temperature of the probes before and 10 min after entry of the corer into the sediments. The core was sampled immediately upon recovery at intervals of 30 cm, and the sediment samples were stored in air-tight bottles. The sediments consisted of calcareous lutites which in the cores from the southern Aegean were interbedded with volcanic ash layers and sapropelic mud horizons. The water content of these sediments was obtained by oven-drying them in the laboratory. The thermal conductivities were found from the water contents using the relationship obtained by Ratcliffe (1960). The validity of using this method is discussed by Bullard (1963) and the maximum probable error in the thermal conductivities so obtained is estimated to be 55 per cent.

The results of the heat flow measurements are shown in Tables 1 and 2 and Fig. 1.

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Table 1

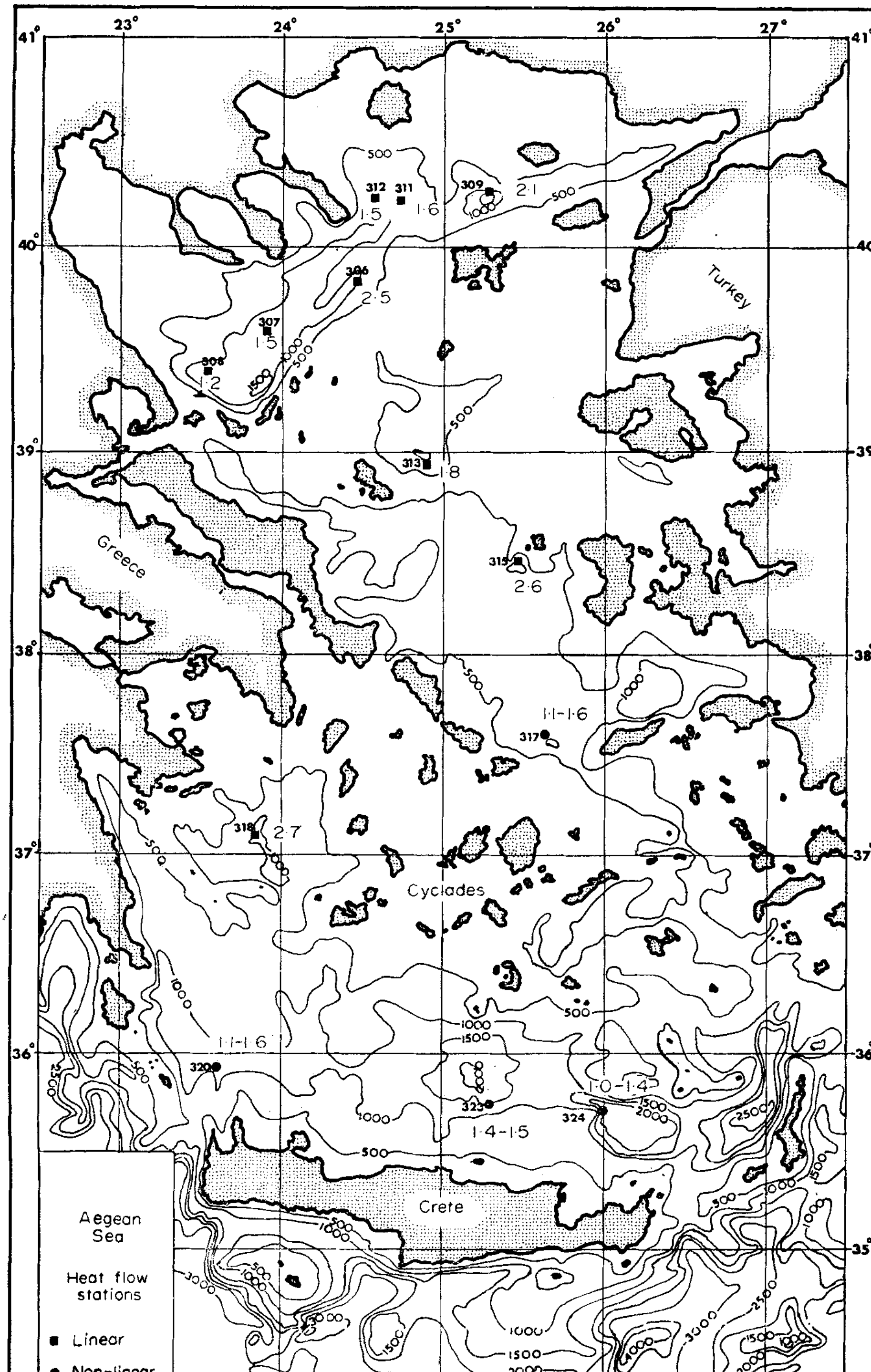
Heat flow stations in the Aegean Sea (linear gradients)

Station No.	Position	Depth (m)	Penetration (m)	Thermal conductivity ($\times 10^{-3}$ cal cm^{-1} s^{-1} °C)	Gradient (°C m)	Heat flow (μ cal cm^{-2} s^{-1})	Standard error
306	39° 50·7′N 24° 27·5′E	1198	3·29	2·22	0·112	2·52	0·10
307	39° 35·4′N 23° 53·0′E	1278	3·66	2·37	0·066	1·56	0·06
308	39° 24·2′N 23° 32·0′E	1248	2·29	2·13	0·058	1·24	0·06
309	40° 15·8′N 25° 16·4′E	1506	4·02	2·20	0·098	2·15	0·11
311	40° 13·5′N 24° 41·2′E	926	3·75	2·10	0·078	1·62	0·10
312	40° 20·2′N 24° 34·3′E	751	4·43	2·06	0·076	1·56	0·08
313	38° 56·3′N 25° 27·2′E	860	4·14	2·06	0·087	1·79	0·09
315	38° 24·8′N 25° 27·2′E	928	3·46	2·22	0·118	2·61	0·14
318	37° 6·0′N 23° 49·7′E	909	3·59	2·21	0·123	2·73	0·13

Table 2

Heat flow stations in the southern Aegean (Non-linear gradients)

Station No.	Position	Depth (m)	Penetration (m) L. Probe	Thermal conductivity U. Pair L. Pair	Gradient (°C m^{-1}) U. Pair L. Pair	Diffusivity (cm^2 s^{-1})	ΔT (°C)	Heat flow (cal cm^2 s^{-1}) U. Limit L. Limit
317	37° 37·7′N	860	4·02	2·12	−0·002	0·0027	0·3	1·64
	25° 36·4′E			2·32	0·089			1·08
320	35° 54·1′N	1265	3·00	2·32	−0·004	0·0029	0·15	1·61
	23° 35·1′E			2·49	0·083			1·08
323	35° 44·1′N	1210	3·09	2·37	−0·002	0·0030	0·15	1·52
	25° 17·4′E			2·45	0·096			1·42
324	35° 43·1′N	2180	3·00	2·49	−0·011	0·0035	0·15	1·42
	25° 58·9′E			2·69	0·077			1·01



Aegean Sea
Heat flow stations
Linear
Non-linear
Greece
Turkey
Cyclades
Crete
41°
40°
39°
38°
37°
36°
35°
34°
23°
24°
25°
26°
27°
312
311
309
306
307
308
313
315
317
318
320
323
324
1·5
1·6
2·1
2·5
1·5
1·2
1·8
2·6
1·1–1·6
2·7
1·1–1·6
1·0–1·4
1·4–1·5
500
1000
1500
2000
2500
3000
3500
4000

Penetration of the lowermost probe, which was deduced from the mudmarks at the top of the corer, varied between 2·29 and 4·43 m. Thermal conductivities ranged from 2·06 to 2·69 $\times 10^{-3}$ cal cm^{-1} s^{-1} °C^{-1} with generally a slight increase with depth. At nine of the thirteen stations which were successfully occupied, a linear gradient was obtained. For seven stations it was possible to compare the gradients obtained from the relative rises in the temperature of the probes against absolute temperatures. The observed difference between the absolute temperatures of the bottom water and at the depth in the sediment measured by the upper probe was at each station found to be more (average of 20 per cent) than the difference predicted from the product of the measured gradient and the upper probe depth. This provides a good indication of the validity of the results. At four stations in the central eastern and southern Aegean, non-linear gradients were measured, which are thought to be caused by an annual temperature variation in the bottom waters. Poor penetration of the corer in this region has made this effect noticeable.

The linear stations

The nine linear stations give heat flow values which range between 1·24 and 2·73 HFU (cal cm^2 s^{-1}), and except for station 308 they are all higher than the world average of 1·46 HFU for oceanic and 1·45 HFU for continental areas determined by using grid elements of equal area, (Von Herzen & Lee 1969). The mean of these stations is 2·08 HFU with a standard deviation of 0·24 HFU. This value is much higher than the mean value of 1·0 HFU for the eastern Mediterranean (Erickson 1970; Ryan *et al.* 1971).

Environmental corrections

A number of different local disturbances of the environment near the seafloor affect heat flow measurements made at sea (Bullard, Maxwell & Revelle 1956; Von Herzen & Uyeda 1963). These disturbances are due to sedimentation or erosion (Jaeger 1965), local topography and irregular sediment cover (Sclater, Jones & Miller 1970), bottom water temperature variations, biogenic activity or water movement within the sediments. In the cores taken with the heat flow measurements no evidence was found of biogenic or water movement. The other disturbances at the heat flow stations in the Aegean all tend to lower the equilibrium geothermal gradient.

The stations are located in depressions which are sediment ponds as shown by seismic reflection profiles run concurrently and during earlier cruises (Maley & Johnson 1971). Published sedimentation rates in the Aegean vary between 15 and 75 cm/1000 years (Wong & Zarudski 1969; Opdyke *et al.* 1972; Ninkovich & Heezen 1965) and the sedimentation appears to have started in the Pliocene (Holmes 1965; Wong & Zarudski 1969). Using a conservative estimate of 10 cm/1000 years for the rate and a 10-My period of sedimentation one can calculate (Carslaw & Jeager 1959 (p. 388); Von Herzen & Uyeda 1963) that the geothermal gradient would be decreased by 10–15 per cent. Sudden deposition of sediment layers such as the volcanic ash layers found in the southern Aegean (Ninkovich & Heezen 1965; Opdyke *et al.* 1972) is of minor importance since they are generally less than 1 m thick and the most recent deposition of such a layer occurred 3400 years BP (Opdyke *et al.* 1972) so that

FIG. 1. Station numbers, locations and heat flow values determined in the Aegean Sea. Stations with linear gradients are shown by squares while those at which non-linear gradients were measured are shown by circles and the limiting values of the heat flow are indicated. The bathymetric contours are after Allen & Morelli (1971) converted to metres. The contour interval is 500 m.

recovery of the initial gradient would be virtually complete (Von Herzen & Uyeda 1963).

The effect of topography and sediment thickness at the stations can be estimated by using the results of Sclater *et al.* (1970) and Von Herzen & Uyeda (1963). For a basement to sediment ratio of between 2 and 3 with thicknesses of sediments of 1 km in depressions with diameters of 20 km, a 20 per cent reduction to the equilibrium gradient could occur. However, since the basement highs are also covered with thicknesses of sediment of up to 500 m this reduction is probably in the order of 10 per cent.

Variations in bottom water temperatures may also have affected the heat flow measured at the Aegean stations. Mean surface temperatures over the last 70 years do not show significant differences in the Mediterranean region (Pollack 1951; Ovchinnikov & Plakhin 1965) and it seems likely that the mean bottom water temperatures have been stable for this period. For temperature variations with much longer periods of several hundreds to thousands of years it is possible to estimate a correction by using the palaeo-temperature and climatic curves (Emiliani 1955; Emiliani *et al.* 1963; Cita *et al.* 1973a, b) obtained for the Aegean and Mediterranean area. Such an estimate based on a Fourier analysis of these curves (Ciaranfi, Loddo & Mogelli 1973) shows that the maximum disturbance to the temperature gradient at the surface is about $-8°C\ km^{-1}$. This disturbance will be less at the bottom of the Aegean Sea and since the observed gradients are between $58°C\ km^{-1}$ and $123°C\ km^{-1}$ the reduction is probably less than 10 per cent.

This discussion of the environmental corrections shows that for the nine linear stations in the Aegean these corrections would all increase the already higher than normal heat flow values which were observed. The equilibrium heat flow values are probably higher by 10 per cent and perhaps as much as 30 per cent.

Non-linear stations

At four stations in the southern Aegean non-linear thermal gradients were measured. These stations, at which penetration was poor, exhibited a small negative gradient between the upper and middle probe and a high positive one between the middle and lower probe. The occurrence of maximum bottom water temperatures at the time of measurement, i.e. November (Bruce & Charnock 1966), the interval of 2 m within which this non-linearity could be observed, combined with shallow depths and the large area affected are all features which suggest that an annual temperature variation in the bottom waters causes this non-linearity.

The solution of the problem is well known (Carslaw & Jaeger 1959, p. 65). A thermal disturbance at the sediment interface, $z = 0$, which is sinusoidal with time about a mean temperature, T_1, so that the temperature at the interface, $T(0)$, is:

$$T(0) = T_1 + \Delta T \cos(\omega t)$$

(where ΔT is the amplitude, and $\omega = 2\pi/P$, where P is the period of the variation) is propagated into the sediment having a uniform thermal diffusivity κ, and in which a temperature gradient g is present in accordance with the damped wave equation so that at time t and depth z the temperature will be:

$$T(z, t) = T_1 + gz + \Delta T\, e^{-kz} \cos(\omega t - kz).$$

Here $k = (\omega/2\kappa)^{1/2}$, and the wavelength $\lambda = 2\pi/k$.

For the sediments in the Aegean, κ varies between 0·0025 and 0·0035 cm^{2-1}, and hence the wavelength of the annual temperature variation is between 10 and 11 m. The amplitude of the oscillation falls off as $e^{-kz} = e^{-2\pi/\lambda}$. At a depth of one wavelength the amplitude will be $0{\cdot}0019\Delta T$. The temperature gradient at a depth z and at a time t is

$$(\partial T/\partial z)_t = g + \sqrt{2}\Delta T k e^{-kz} \sin(\omega t - kz - \pi/4).$$

By differentiating this expression with respect to time t we find that the gradient in the sediment at a certain depth z will vary between the maximum and minimum values of $g + \sqrt{2}\Delta T ke^{-kz}$ and $g - \sqrt{2}\Delta T ke^{-kz}$. The measured gradient is the difference of the temperature divided by the probe separation. This is always less than or equal to the maximum gradient at the depth of the shallower probe. Similarly, the measured gradient is always more than or equal to the minimum gradient at the shallower depth. Thus, if g_{m1} and g_{m2} are the gradients measured between the upper and middle and middle and lower probes respectively, and the depths of the probes are z_1, z_2 and z_3 then the geothermal gradient g lies between the following limits

$$g_{m1} + \sqrt{2}\Delta T k\, e^{-kz_1} \geqslant g \geqslant g_{m2} - \sqrt{2}\Delta T k\, e^{-kz_2}.$$

The evaluation of these limits to the geothermal gradient involves a knowledge of the magnitude of the bottom water temperature variations. From data collected over the last 20 years, obtained from the British Oceanographic Data Centre, the maximum temperature difference in the bottom waters below 1000 m is 0·3°C. Studies of the autumn and spring temperatures (Bruce & Charnock 1966; Miller, Tchernia & Charnock 1970) indicate that the annual variation is probably less than this. For the shallower area around station 317 the temperature variation from the available data appear to be as high as 0·6°C. The resulting limits to the heat flow at the four non-linear stations and the values used in the calculations are shown in Table 2 and Fig. 1. The values of the thermal diffusivity were obtained from the average water contents of the sediment by using the empirical relationships of Bullard (1963). Station 323 is an attempt to reoccupy an earlier heat flow station done by Erickson in 1961 (Erickson 1970), for which a value of 1·05 HFU was reported. The limits of heat flow obtained in this study are higher (1·42–1·52 HFU) which may be partly due to a refraction effect since station 323 was on the flank of a sediment pond and 640 m shallower than Erickson's station. The thermal gradient determined by Erickson was between two probes only and hence non-linearity was not detected. A value very close to Erickson's of 1·12 HFU would have been obtained in this study if only the upper and the lower probe readings had been used.

The results shown in Table 2 indicate a normal heat flow of between 1·64 and 1·01 HFU at these four stations in the southern Aegean. Sedimentation corrections for these values would raise these limits by about another 10 per cent. The heat flow in this area is higher than that of the eastern Mediterranean south of Crete, but the values are lower than the results from the northern Aegean shown in Table 1.

Discussion

Summarizing all the 13 measurements in the Aegean Sea it may be concluded that the heat flow is high in this area. The highest values occur within and behind the volcanic arc of the Cyclades. In the extreme northern Aegean two very high values (>2 HFU) are associated with intense magnetic anomalies, which are thought to be caused by intrusions (Vogt & Higgs 1969; Allen & Morelli 1971). Rifting and generation of new crust similar to the production of the sea-floor of the Red Sea has been postulated (McKenzie 1970, 1972; Allen & Morelli 1971) for this area and the high heat flow values support this hypothesis. As mentioned earlier the geophysical properties of the Aegean Sea are very similar to those of the marginal seas behind the Island Arcs in the Pacific and from this study it can be concluded that the heat flow is no exception. The heat flow values plotted against distance from the Hellenic Trench, i.e. the zone of crustal subduction, exhibit an increase away from and inwards of this zone (Fig. 2). Combined with the heat flow in the eastern Mediterranean

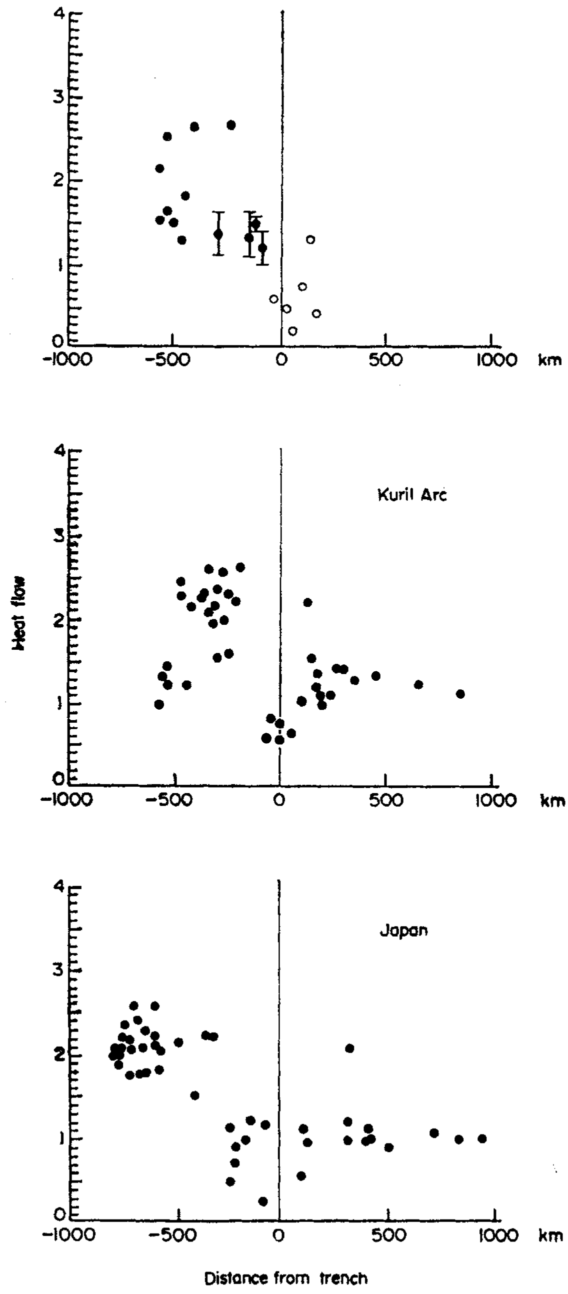


FIG. 2. Heat flow values obtained in the Aegean (black dots) combined with the values obtained by Erickson (1970) south of Crete (circles) plotted against distance from the Hellenic Trench. Negative distance for stations on the northern concave side of the trench. Profiles across the Kuril Arc and across Japan (after Vacquier *et al.* 1966) are shown for comparison. Here the distance is negative if a station is on the continental side. In all three cases the heat flow is high on the inside of the trench.

south of the trench this plot is similar to those of the Kuril Arc and across Japan (Vacquier *et al.* 1966).

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