Heat Flow in the Mariana Marginal Basin

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Twenty-one new heat flow measurements in the Mariana Trough delineate a central zone of high heat flow corresponding to an axial topographic high and a flank zone of low heat flow. The high heat flow is an indication that the axial high is a narrow zone of magmatic intrusion and that sea floor spreading is occurring in the Mariana Trough in a manner similar to its occurrence on midocean ridges. The low heat flow values appear to be the result of the occurrence of hydrothermal circulation in the oceanic crust of the Mariana Marginal Basin.

INTRODUCTION

Extension behind island arcs in the western Pacific has been proposed over a number of years [*Deitz*, 1954; *Carey*, 1958; *Murauchi and Den*, 1966; *Tanner*, 1968], but *Karig* [1970, 1971] provided the first detailed geological evidence for extension in marginal basins. *Karig* [1970] reported '1) steep normal fault zones bounding these basins; 2) thick sediment covers on the outer flanks of the arcs which bound the basins and an almost sediment-free area in the basin interiors; and 3) fault block morphology within the basins which can be traced ashore in places as a graben system.' *Karig* [1971] further reported (1) similar morphology, sediment distribution, and structure of the frontal and third arcs bounding the Mariana Trough (Figure 1); (2) extremely fresh pillow basalts from the central axial high of the trough; and (3) very young ages of sediments recovered in piston and gravity cores. All of these findings led *Karig* [1971] to conclude that the Mariana Trough was formed by recent intrusion and crustal extension.

Other marginal basins with past extensional histories have been discovered in the western Pacific. The Japan Sea and the Okhotsk Basin have shallow topography and high heat flow generally associated with ocean floor of young age [*Yasui and Kishii*, 1967]. The Lau Basin has high heat flow, little sediment, and oceanic-type tholeiitic basalts [*Sclater et al.*, 1972*a*; *Hawkins and Nishimori*, 1971].

While the extensional nature of these basins seems little in doubt, the exact mode of extension remains unsettled. *Karig* [1971] proposed that extension, accompanied by the intrusion of dike swarms, occurs along the central axial high of the Mariana Trough. He reported evidence of faulting on the flanks of the axial high, however, that he suggested represents decreasing rates of extension away from the center of the basin. *Hasebe et al.* [1970] proposed a mechanism of 'incipient intrusion,' or a slow rate of diapiric rise of magma throughout the basins, to account for the generally high heat flow of the marginal basins.

Sclater [1972] reported a correlation between shallower than normal sea floor depths and high heat flow in the western Pacific basins and proposed an extensional model calling for a mechanism similar to sea floor spreading to produce lithosphere below marginal seas that is thinner than that of normal oceanic plates.

Measurements from the Mariana Trough have produced evidence that conflicts with these extensional models in that the heat flow reported to date in the basin has been low. *Watanabe et al.* [1970] published three low values in the trough and acknowledging *Karig*'s [1970] evidence for recent extension, suggested that the heat flow observations had been placed into 'an anomalous, difficult situation.' *Sclater et al.* [1972*b*] reported six new measurements in the Mariana Trough, all with low heat flow values. *Sclater* [1972] in presenting his correlation between shoal topography and high heat flow in the western Pacific dismissed the low heat flow of the Mariana Trough as being 'unreliable' [*Sclater*, 1972, p. 5710, Table 1] and made no further reference to the thermal structure of the Mariana Trough.

In order to investigate this discrepancy, 21 new measurements were made in the Mariana Trough during the Scripps Institution of Oceanography expedition Tasaday. Since actively spreading midocean ridge crests have proved to have complex thermal environments frequently dominated by massive hydrothermal circulation of seawater into the oceanic crust [*Lister*, 1972; *Williams et al.*, 1974], it was necessary to obtain a precise description of the topography and sediment distribution in the heat flow survey area to evaluate the reliability of the measurements. *Karig* [1971] reported such a survey within a 2° × 2° area on the axial high at the center of the Mariana Trough. The station locations for the present

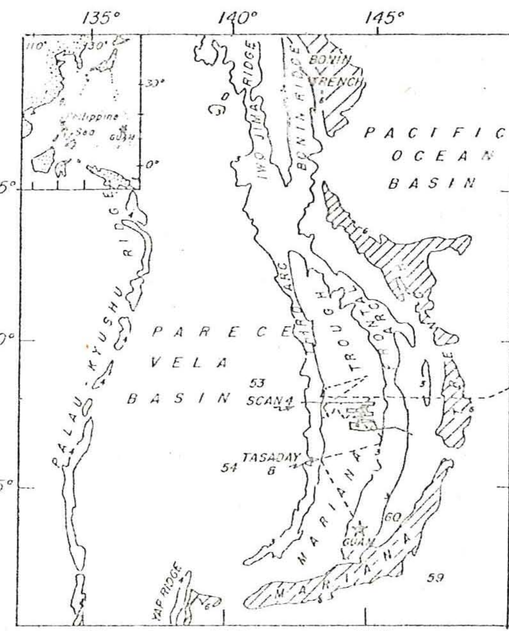

Fig. 1. Physiographic map of eastern Philippine Sea. Ship tracks are indicated for coverage of Mariana Trough discussed in this paper. High-density tracks in center of Mariana Trough are coverage within survey area of *Karig* [1971] and this report. Numbers are locations of Joides holes in area.

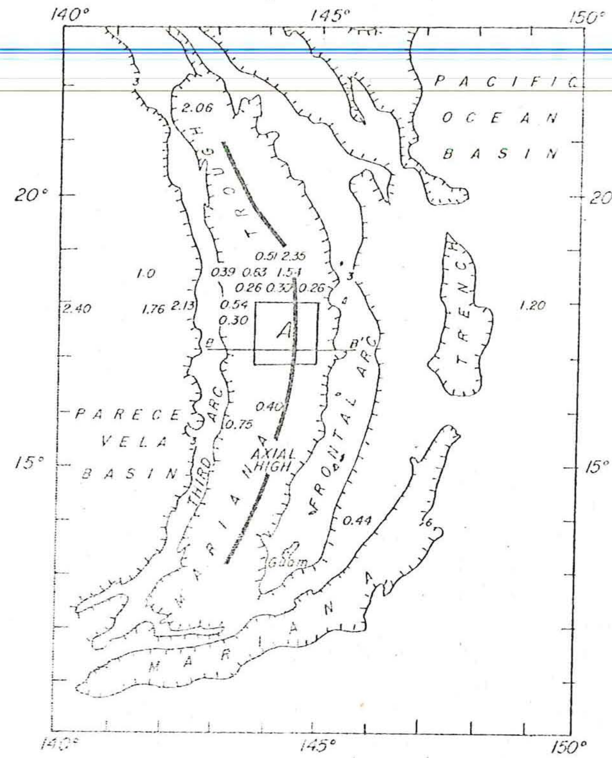

Fig. 2. Physiography of Mariana Trough. Contours are from *Karig* [1971]. Heat flow measurements are in units of μcal/cm² s from *Watanabe et al.* [1970], *Sclater et al.* [1972*b*], and this report. Square area A is the survey area of Figures 3 and 4.

study were selected on the basis of the topography and sediment thickness predetermined by this earlier survey. Measurement locations were selected to sample the thermal structures of each of the varied local environments found in the area. That is, as many stations were attempted on peaks and on the sides of hills as were attempted in sediment ponds.

TECTONIC SETTING

The north-south trending topographic depression between the Mariana island arc and the South Honshu Ridge (third arc) has many names, but the name preferred here, as was preferred by *Karig* [1971], is the Mariana Trough [*Iwabuchi*, 1963] (Figure 1). The Philippine Sea contains three marginal basins decreasing in age from west to east (West Philippine Basin, Parece Vela Basin, and Mariana Trough). Correspondingly, the West Philippine Basin is deeper and has lower mean heat flow than the Parece Vela Basin [*Sclater*, 1972]. *Karig* [1971] proposed that these basins were formed by extensional episodes that accompanied the eastward migration of the Mariana Trench relative to the Asian continent. Alternatively, *Ben-Avraham et al.* [1972] and *Uyeda and Ben-Avraham* [1972] proposed that the westernmost portion of the Philippine Sea was formed by entrapment of old sea floor during a plate boundary reorganization.

Despite the above controversy about the mode of origin of the western basins of the Philippine Sea a consensus appears to exist that the Mariana Trough is young sea floor presently being generated landward of the Mariana Trench. Is crustal extension occurring as typical sea floor spreading from a mid-

TABLE 1. Heat Flow Measurements on Tasaday Leg 8

Station	Geographic Position	Depth, m	$\Delta T/\Delta Z$, 10^{-3} °C/cm	Thermal Conductivity K,* mcal/°C cm s	Q,† μcal/cm² s	Local Environment‡
3 (HF1)	15°38.0'N, 143°49.7'E	3932	0.47	1.60A	0.75	Rough, sediment ponded, in valley
4 (HF2)	16°07.2'N, 144°23.3'E	4536	0.56	1.60A	0.90	Rough, sediment ponded, in deep trough
5 (HF3)	16°46.9'N, 145°18.7'E	3350	(bounced)			Smooth, well sedimented
6 (HF4)	16°55.3'N, 145°12.2'E	3547	0.20	1.60A	0.32	Rough; gravity core went in only 5 cm; 50-m mud show on 3.5-kHz echo sounder
8 (HF5)	17°18.5'N, 145°03.6'E	3950	0.00	1.60A	0.00	Sediment ponded
9 (HF6)	17°09.4'N, 144°55.8'E	3440	1.14	1.60A	1.82	Rough, in peak
11 (HF7)	17°11.0'N, 144°35.9'E	3600	1.55	1.60A	2.48	Rough, in survey area (Figure 3)
12 (HF8)	17°18.4'N, 144°41.7'E	4119	2.81	1.60A	4.50	See Figure 3
14 (HF9)	17°27.3'N, 145°01.7'E	3838	0.56	1.60A	0.90	See Figure 3
15 (HF10)	17°31.3'N, 145°09.9'E	3800	2.47	1.60A	3.95	See Figure 3
17 (HF11)	17°49.1'N, 145°05.6'E	3404	0.24	1.60A	0.38	On peak, in survey area (Figure 3)
18 (HF12)	17°36.7'N, 144°46.2'E	4133	5.28	1.60A	8.45	In pond (Figure 3)
20 (HF13)	17°47.0'N, 143°40.4'E	4420	0.20	1.50B	0.30	Rough; bottom of basin; piston core station located here also
21 (HF14)	18°04.9'N, 144°00.8'E	3619	0.40	1.50B	0.60	Rough; into side of peak; sediment pond only
22 (HF15)	18°19.7'N, 144°20.9'E	4256	0.96	1.60A	1.54	In sediment-filled basin
23 (HF16)	18°38.15'N, 144°49.3'E	4283	1.47	1.60A	2.35	Rough, in sediment-filled basin
24 (HF17)	18°39.78'N, 144°36.2'E	4534	0.34	1.50B	0.51	Rough, in sediment-filled basin
25 (HF18)	18°34.5'N, 144°04.5'E	4272	0.42	1.50B	0.63	West basin, well sedimented, but basement rough
26 (HF19)	~18°28.'N, ~143°42.'E	4215	0.26	1.50B	0.39	West basin, well sedimented, but basement rough
28 (HF20)	18°02.8'N, 143°52.8'E	4123	0.16	1.60A	0.26	Rough, on peak
30 (HF21)	18°04.2'N, 145°00.0'E	3838	0.16	1.60A	0.26	Rough, in 1371-m sediment valley
31 (HF22)	18°08.6'N, 149°02.8'E	5619	0.60	2.00C	1.20	Smooth, flat, well sedimented

All locations were satellite-navigated. Depths are in corrected meters. All stations except HF17 had full penetration of 2.5-m probe.
*A, 17°32.8'N, 144°22.9'E; B, 17°47.2'N, 143°40'E; and C, assumed from averages of nearby stations.
†1 μcal/cm² s = 41.85 mW/m².
‡Descriptions were made from analyses of seismic reflection and 3.5-kHz echo sounder records near each station. Except for detailed survey area A (stations 6–18), descriptions represent only a two-dimensional view of each station. This view, though perpendicular to strike of the general topographic trend of the Mariana Trough, suffers from not being three dimensional.

ocean ridge-type crestal intrusion zone, or is more diffuse extension occurring that involves intrusion throughout the trough? Alternatively, the Mariana Trough may be undergoing a recent rejuvenation of spreading within the 50- to 100-km-wide axial high.

Topographically, the Mariana Trough is a series of very rough peaks and troughs shoaling by nearly 1 km to a discontinuous central axial high. The sediment cover is patchy and ponded near the axial high, increasing to a uniformly thick blanket of volcanoclastic sediments at the edges of the trough [*Karig*, 1971]. The sediment distribution may be a function of distance from the rapidly eroding frontal and third arcs rather than a function of age. The Mariana Trough has no magnetic anomaly lineations that are continuous for more than a few kilometers. No sea floor spreading magnetic anomalies have been identified to date. If a process similar to sea floor spreading is occurring in the Mariana Trough, the characteristic magnetic anomaly signature is disrupted by the extremely rough topography and by the many transverse fracture zones. A detailed magnetic study of survey area A of Figure 2 shows the disconcordant nature of the magnetic anomalies (Figure 3) [*Karig*, 1971]. Therefore, to date, there is no compelling evidence for a central intrusion zone in the Mariana Trough.

HEAT FLOW MEASUREMENTS

Twenty-one new heat flow measurements (Table 1) were made in the Mariana Trough to determine if the low heat flow measured at nine previous locales was representative of the general thermal structure of the basin. Nine of these new measurements were between 17°–18°N and 144°–145°20′E, an area that had been surveyed previously by *Karig* [1971].

South of the survey area, two low heat flow measurements were recorded (Figure 2). Both stations were occupied in sediment-filled valleys. *Von Herzen and Uyeda* [1963] showed that the effects of excessive sedimentation rates or sediment slumping can give a low bias to heat flow measurements. Reasonable statistical considerations of the odds of sampling suggest that this effect should not lower the heat flux in a pond by more than 15–30% (unless a sediment slump >10 m thick occurred in that spot within the last 10 years [*Von Herzen and Uyeda*, 1963]). Refraction of heat flow from low-conductivity sediment valleys to high-conductivity peaks can produce a biasing of low measurements. The above effects probably were

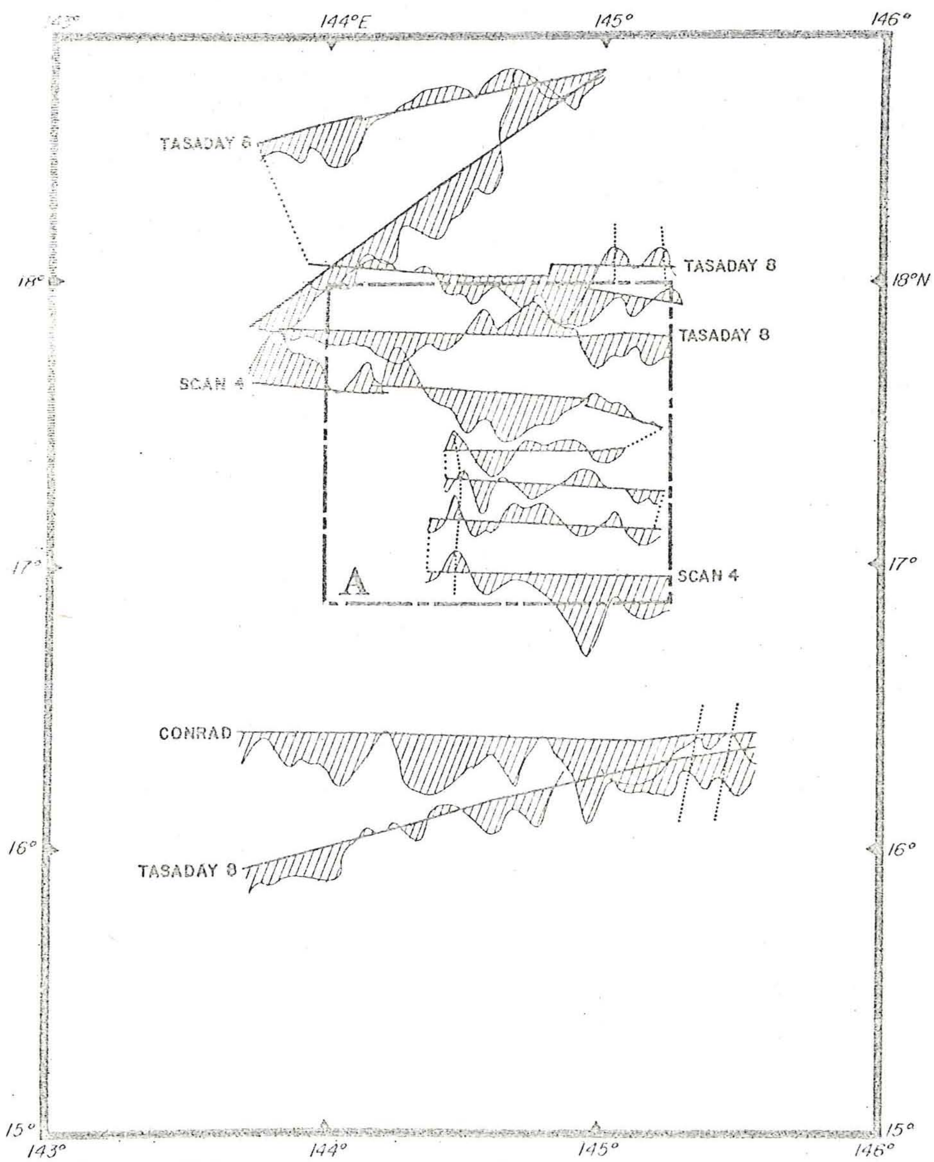

Fig. 3. Magnetic anomalies in and around survey area A in Mariana Trough. Scale is 500 γ (nT)/in. (2.5 cm) (plotted about the zero base line).

not dominant causes of the low heat flow values because the measurements on peaks away from the axial high were low also (e.g., station 6 in Table 1). Hydrothermal circulation has been found to be of sufficient magnitude to cause geographic variations of up to 1 order of magnitude [*Lister*, 1972; *Williams et al.*, 1974]. Low heat flow zones found at the crests of midocean ridges are most probably caused by hydrothermal circulation of seawater into the oceanic crust. *Lister* [1972] and *Williams et al.* [1974] found that sediment cover was an important factor to be considered in attempting to make representative heat flow measurements in a hydrothermal area. They reported large scatter when sediment cover was only spotty, low measurements nearly always being found in sediment troughs. When the sediment cover uniformly draped the basement away from the spreading center, variability of adjacent measurements greatly decreased. *Lister* [1972] suggested that this decrease in variability was caused by the impermeability of the sediment cover draping the basement. Then free interchange of circulating hydrothermal fluids and bottom water was stopped, and the conductive heat flux measured in the ocean floor became equal to the total heat flow from below.

All new heat flow measurements in the Mariana Trough outside the survey area were low values with the exception of a measurement of 2.35 HFU (μcal/cm^2 s) in a sediment pond on the axial high north of the survey area (Figure 2). Local environments of all stations are given in Table 1. Variability of locations relative to basement highs is sufficiently large that one can conclude that the heat flow is low on both flanks of the axial high regardless of whether stations were taken in sediment ponds, flat sedimentary blankets, or topographic highs or lows. For instance, station 20 was taken on a topographic peak capped with sediment. The heat flow value for this station was 0.26 HFU.

At least three hypotheses exist for these low heat flow measurements: (1) the basin has been inactive for a very long time; (2) massive hydrothermal circulation is occurring in the Mariana Trough today; and (3) asthenospheric convection is producing a heat sink at depth in some manner. The mean heat flow for these 10 flank values is 0.48 ± 0.23 (s.d.) HFU. The mean for the oldest sea floor in the world's ocean basins is ~1.1 HFU [*Sclater and Francheteau*, 1970]. Thus the fact that the trough has much lower heat flow than the oldest sea floor argues against the inactivity hypothesis. The elevated topography is an argument against the third alternative of asthenospheric anomalies. Also, this latter process must have been occurring for many millions of years to be affecting the surface heat flow today. Although there is no doubt that the downgoing slab affects the asthenosphere beneath the Mariana Trough, the zone of high seismic attenuation (low Q) observed below marginal basins argues for high rather than low heat flow [*Oliver et al.*, 1973].

We cannot dismiss hydrothermal circulation so easily, however. *Williams et al.* [1974] reported a crestal heat flow survey of the Galapagos Spreading Center. They found a distinctly bimodal heat flow distribution varying with a wavelength of 6 km away from the spreading center. Measurements were generally very low or very high. On the flank of this same ridge, *Sclater et al.* [1974] reported a low heat flow zone that they concluded was related to an irregular sediment cover and hydrothermal circulation in the oceanic crust. In crust with an expected heat flux of >4.0 HFU (for its age) no value >2.0 HFU was measured.

If we are in fact observing the same sort of flank low in the Mariana Trough, what is the crestal distribution of heat flow like? In order to answer this question a total of 13 heat flow measurements were made within the *Karig* [1971] crestal sur-

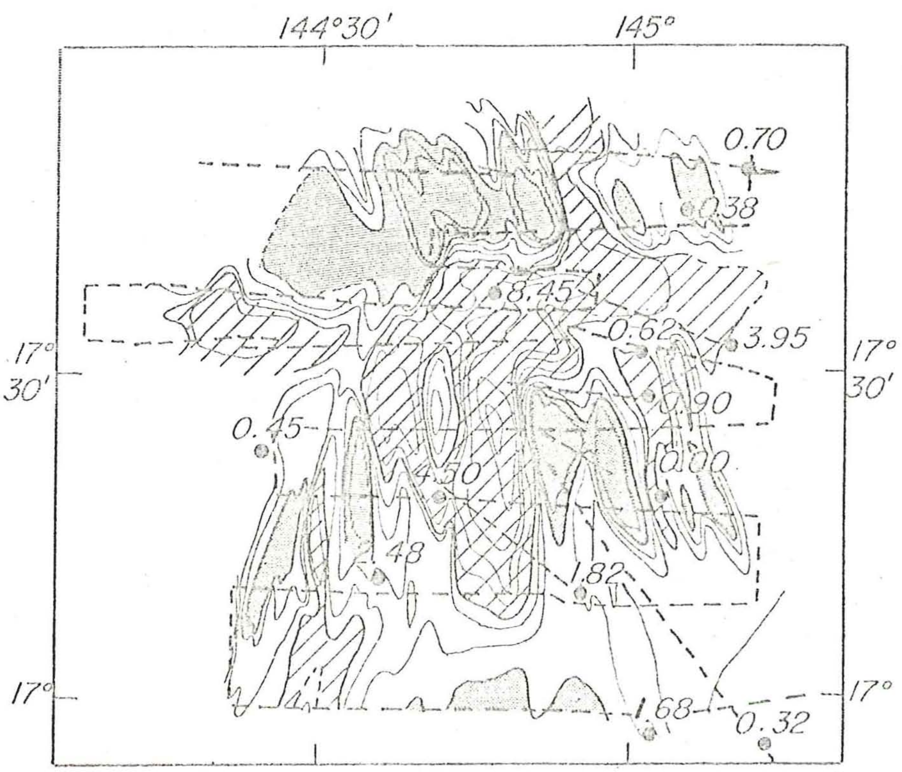

Fig. 4. Heat flow measurements (black dots) within the topographic survey area A of *Karig* [1971] and Figure 2. Contours are in corrected meters. Contour interval is 200 m. Shaded areas are topographic peaks shoaler than 3200 m; hatched areas are deeper than 3800 m; the entire survey is located on the axial high.

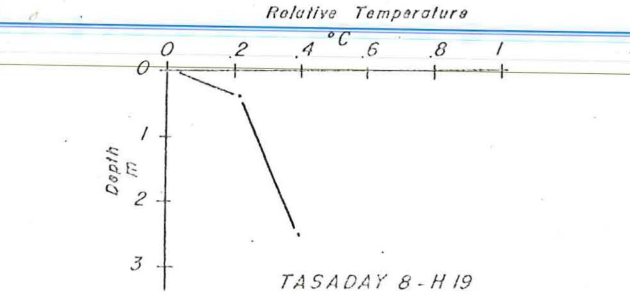

Fig. 5. Thermal gradient measured at station HF19 in sedimented valley just to northwest of survey area. Bottom water temperature is 0.2°C colder than mud, so that while heat flow value is low, sediment temperatures are high. The penetration depth of the first gradient was determined by the position of the thermal conductivity slider and by the 'mud mark' on the probe.

vey area: 1 by *Watanabe et al.* [1970], 3 by *Sclater et al.* [1972*b*], and 9 by the present study.

The axial high in this portion of the Mariana Trough is marked by a double peak and a very deep central trough (Figure 4). This axial high meets an E-W striking fracture zone at 17°37'N. Heat flow measurements on peaks and troughs outside this central axial high produced only low values (Figure 2). Measurements in the central trough, however, produced values of 4.50 and 8.45 HFU, the latter being at the fracture zone intersection. A measurement on the western peak of the axial high measured 2.43 HFU. Not only does the central ridge-trough complex have high heat flow, but so does the fracture zone. To the east of the intersection the fracture zone relief is buried by the thick sedimentary apron from the frontal arc. All previous measurements on this apron were low. A single measurement in line with the fracture zone but on the apron produced a value of 3.95 HFU.

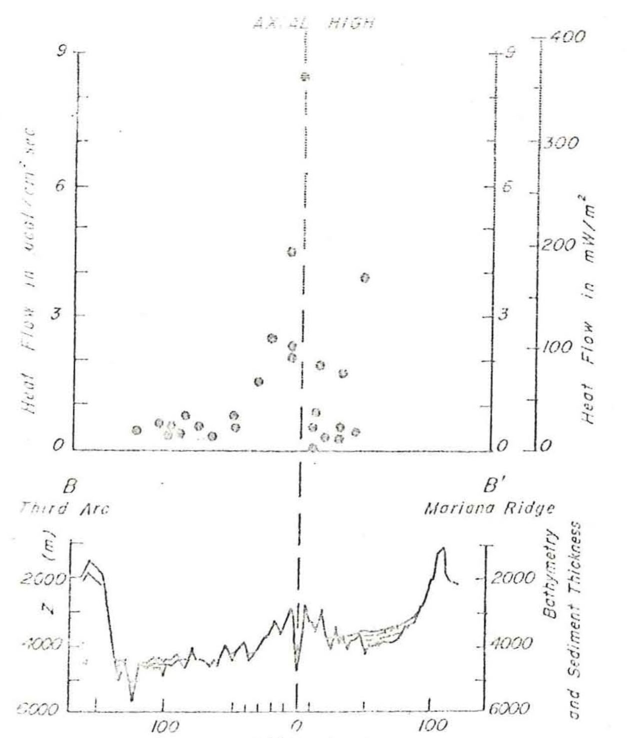

Fig. 6. Compilation of heat flow versus distance from the axial high of the Mariana Trough plotted above topography and sediment thickness from a composite of Tasaday, leg 8, profile B-B' of Figure 2. Representative seismic reflection profile across this area is shown by *Karig* [1971, Figure 7].

The high thermal anomaly is confined to the axial high. For example, measurements in the trough just to the east of the axial high have values of 0.62, 0.90, and 0.00 HFU (Figure 4). The 0.00 value was from a station with full penetration. Similar values have been reported only in active hydrothermal areas associated with downwelling of cold seawater into the oceanic crust [cf. *Von Herzen and Uyeda*, 1963; *Williams et al.*, 1974]. Further indications of hydrothermal activity might be seen in thermal gradients of nearby heat flow stations. *Sclater et al.* [1972*b*] reported low heat flow in scan 4, station HF7, where high sediment temperatures relative to the temperature of the bottom water accompanied the low thermal gradient measurement. Tasaday 8 station HF19 found similar results (Figure 5). In order to produce this observed gradient as an artificial remnant of the experiment, superpenetration of the probe by ~1 m would be required. No indication of this superpenetration was recorded on the case or probe (mud would have lodged in the top of the instrument). Similar thermal gradients were found in the Galapagos Spreading Center hydrothermal area [*Williams et al.*, 1974]. Further, hydrothermally altered diabases were recovered from the northern scarp of the fracture zone at ~145°E by both *Karig* [1971] and the Tasaday expedition.

The thermal structure of the Mariana Trough is illustrated in Figure 6. Measurements of high heat flow have been recorded on the axial high; low heat flow has been measured on the flanks. The only exception so far is the high value found in the extension of the 17°37'N fracture zone.

CRESTAL SPREADING IN THE MARIANA TROUGH

We can suggest on the basis of high heat flow, recent volcanism, and lack of sediments that the axial high is a narrow zone of magmatic intrusion and that sea floor spreading activity in the Mariana Trough is centered on this axial high. Thus it appears that the sea floor spreading process in marginal basins might be very similar to that on midocean ridges (although on a smaller scale). The thermal structure of the remainder of the basin may be dominated by hydrothermal activity. As such, the Mariana Trough is a prime locale to search for deposits of metalliferous sediments, since similar heat flow provinces in other areas have been found to have anomalously high metal concentrations. Examples are the East Pacific Rise Crest [*Corliss*, 1971] and the Bauer Deep [*Anderson and Halunen*, 1974].

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