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Heat Flow, Depth, and Crustal Thickness of the Marginal Basins of the South Philippine Sea

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We present 51 heat flow measurements and two geophysical profiles across the West Philippine and Parece Vela basins. We show that both regions have a variable heat flow but that the scatter decreases markedly if we accept as reliable only measurements in areas of uniform sediment drape. Extending this argument to the deep ocean floor shows that the heat flow in these two marginal basins is not necessarily higher than that for deep ocean floor of the same age. On the other hand, the mean depth of both basins is greater and the oceanic crust thinner than the depth and crust of ocean floor of the same age. In the absence of a significant free air gravity anomaly over both basins, we suggest that the thinner crust may account for most of the increase in depth of the two basins. However, more refraction studies are needed to substantiate this difference before this explanation can be unreservedly accepted.

INTRODUCTION

In the marginal basins of the western Pacific (Figure 1) there appears to be a simple relationship between increasing depth, decreasing heat flow, and increasing age [*Karig*, 1971]. This relationship is similar to that shown by the midocean ridges, although the heat flow in the younger marginal basins appears to be higher than that for oceanic crust of the same age [*Sclater*, 1972]. Apart from this difference in heat flow, the general similarity in the dredged rocks and other geological and geophysical parameters has led many to suggest that the intrusion process behind island arcs is similar to that now occurring at the crest of midocean ridges.

The southern half of the Philippine Sea exhibits the classic section of oceanic crust with both active and inactive basins (Figures 2 and 3). Immediately to the west of the volcanic chain of the Mariana arc system lies the Mariana Trough. This active basin has a shallow depth of 2500–3000 m, has outcropping fresh basalt, and is a region in which crustal extension has taken place at least until the recent past [*Karig*, 1971]. A remanent arc, the South Honshu Ridge, separates this active marginal basin from the inactive Parece Vela Basin. This inactive basin has an average depth of nearly 5 km except for a slightly shallower broad volcaniclastic apron flanking the western side of the South Honshu Ridge (Figure 3*a*). A zone of high-amplitude ridges and troughs lies close to the center of the basin. These features are best developed south of 20°N but appear to continue to the northern end of the basin. Near 17°N they veer southwestward and may continue as far south as 11°N as a central feature. Sparse calcareous nannofossils at the base of two Deep-Sea Drilling Project (DSDP) holes, 53 and 54, in the basin gave a middle Oligocene to early Miocene age for the lowermost sediment section near the center of the basin.

Apart from greater size and depth, the general structure of the Parece Vela Basin is similar to that of the Mariana Basin. On the basis of these similarities and the sediment ages from the DSDP holes, *Karig* [1971] has suggested that the Parece Vela Basin is an extensional feature formed by the intrusion of oceanic crust between the late Oligocene and early Miocene. He has further suggested that the central ridge and trough feature marks the final position of the spreading center and that extension within this marginal basin is symmetrical.

The Palau-Kyushu Ridge, a supposed east-facing remanent arc associated with spreading in the Parece Vela Basin, separates this basin and the West Philippine Basin. The West Philippine Basin is by far the largest of the basins in the Philippine Sea and is the largest and the deepest (5500–6000 m) marginal basin in the world. A major system of troughs and ridges called the Central Basin Fault runs from northwest to southeast through the center of the basin. Deep-sea drilling in the West Philippine Basin yielded sediments no older than middle Eocene [*Ingle et al.*, 1975]. Careful analysis of the lineated magnetic anomalies in this basin, first observed by *Ben-Avraham et al.* [1972] and related to the magnetic time scale by *Louden* [1976], has shown that they are lineated N110°E. The anomalies are best matched by a symmetrical sequence on either side of the Central Basin Fault starting with anomaly 17 and ending with anomaly 22. On both the time scales of *Heirtzler et al.* [1968] and the modification of *Sclater et al.* [1974*a*] this sequence yields a middle to late Eocene age for the southwestern portion of the West Philippine Basin. These results are in excellent agreement with the age suggested from the analysis of piston cores in slumps [*Karig*, 1971] and from the provisional ages of the sediments at the base of the DSDP holes in the area [*Ingle et al.*, 1975]. North of the Central Basin Fault the anomalies are lineated, but identification is less certain. At present they are best matched by assuming symmetry about the fault. Unfortunately, the identification is sufficiently ill-defined so that it is possible that the anomalies could be a sequence younger than 17. Whichever interpretation is correct, we are confident that the basin is no older than Paleocene. The major question still unanswered is whether this crust was formed at a simple midocean ridge system [*Uyeda and Ben-Avraham*, 1972] or whether its tectonic environment was that of extension immediately behind an active subduction zone.

In this paper we present two each of bathymetric, seismic reflection, heat flow, and magnetic profiles and one gravity profile across the southern section of the Philippine Sea (Figure 3). We ran these profiles, concentrating on the surface heat flow, to investigate the similarities and differences between the West Philippine and Parece Vela basins and the ocean floor of the same age. We will show with a reanalysis of the relation of surface heat flow values and continuous uniform sediment cover that the high heat flow behind island arcs may not be

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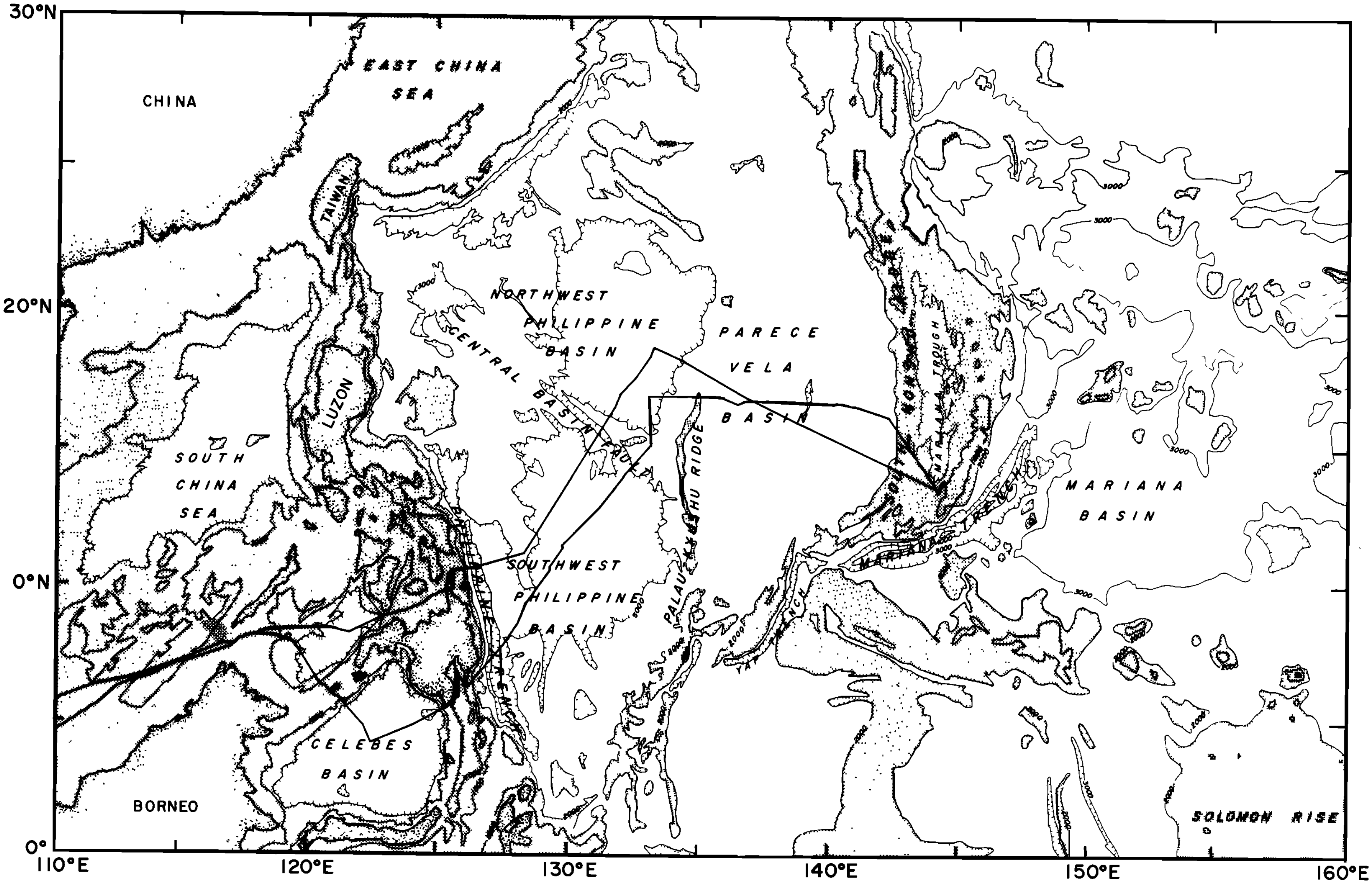

Fig. 1. A sketch of the Philippine Basin showing the principal topographic features and the track of the Antipode and Tasaday lines. The depths above 2000 fm (1 fm = 1.82 m) have been shaded.

significantly higher than that in normal oceanic crust of the same age. However, both marginal basins differ in two important features from oceanic crust of the same age. The basins are deeper and have a thinner oceanic crust. We suggest that these two features may be related.

HEAT FLOW MEASUREMENTS

In June and July 1971 we obtained 39 heat flow measurements in the marginal basins of the Indonesian region and across the Philippine Sea from the R/V *Melville* on leg 13 of expedition Antipode of the Scripps Institution of Oceanography. Twelve further measurements in this area were added during July 1973 from the R/V *Thomas Washington* during leg 7 of Scripps Institution of Oceanography expedition Tasaday. We measured all the temperatures with a 2.5-m-long Bullard probe [*Corry et al.*, 1968]. On the first expedition we determined the thermal conductivities by two methods. In the first method we measured the conductivity of sediment recovered

TABLE 1. Heat Flow Stations in the Western Pacific

Station	Location		Corrected Depth, m	Gradient, °C/m	Conductivity,* 10⁻³ cal/°C cm s	Heat Flow, μcal/cm² s	Penetration†	Tilt, deg	Type of Environment
	N	E							
Antipode 13									
176	6°34.9′	113°50.5′	2350	0.92	1.68 (N)	1.55	f	0–15	B
177	6°46.3′	114°15.3′	2863	0.80	1.67 (A)	1.33	f	0–15	A
178	6°58.3′	114°39.7′	2882	0.92	1.66 (N)	1.52	f	0–15	A
179	7°07.7′	115°07.0′	2844	0.83	1.67 (A)	1.39	f	0–15	B
180	7°51.5′	119°19.5′	3641						
181	7°17.6′	119°45.9′	3801	1.08	1.74 (A)	1.90	f	0–15	A
182	6°41.0′	120°09.0′	3641	1.02	1.74 (N)	1.77	f	0–15	B-D
183	4°55.0′	121°53.0′	4790						
184	3°58.2′	122°14.0′	4965	0.90	1.66 (N)	1.49	f	0–15	A
185	4°39.7′	123°48.5′	4942	0.88	1.66 (A)	1.49	f	0–15	A
186	5°53.5′	125°48.5′	3007	0.24	1.66 (A)	0.41	f	0–15	D
188	8°04.0′	127°46.1′	5460	0.55	1.90 (A)	1.04	f	0–15	B-D
189	8°59.5′	128°18.0′	5827	0.78	2.00 (I)	1.56	f	0–15	A
190	9°41.9′	128°45.1′	5746	0.86	1.90 (I)	1.65	f	0–15	A
191	10°30.2′	129°11.6′	5766	0.81	2.00 (I)	1.62	f	0–15	A
192	11°23.2′	129°43.9′	5470	1.03	1.90 (A)	1.96	f	0–15	A-B
193	12°13.0′	130°27.2′	5754	0.88	1.96 (I)	1.73	f	0–15	B
194	12°57.5′	131°16.5′	5752	0.60	1.83 (I)	1.10	f	0–15	B-D
195	13°43.6′	131°55.2′	5900	2.02	1.98 (I)	3.99	f	0–15	C
196	13°59.5′	132°08.9′	5959	0.86	1.90 (A)	1.63	f	0–15	C
197	14°43.8′	132°46.7′	5343	···	1.93 (I)	0.95	75 cm	>30	C
199	15°33.7′	133°14.2′	5782	0.24	2.01 (I)	0.49	f	0–15	D
200	16°26.5′	133°12.8′	5790	0.61	2.09 (I)	1.28	f	0–15	C-D
201	17°03.6′	133°15.3′	5712	0.55	1.95 (I)	1.07	f	0–15	B
202	17°03.0′	134°02.0′	5493	0.10	2.05 (I)	0.20	f	0–15	A
203	17°05.8′	134°33.7′	5398	0.87	1.98 (I)	1.72	f	0–15	A
205	17°00.0′	135°22.1′	5073	0.40	1.82 (I)	0.73	f	0–15	D
206	16°57.1′	135°54.0′	5084	0.41	1.92 (I)	0.78	f	0–15	C
207	16°49.0′	136°35.5′	4716	0.28	1.91 (I)	0.54	f	0–15	C
208	16°55.0′	136°57.5′	4797?	0.24	1.91 (I)	0.45	f	0–15	C-D
209	16°53.1′	137°24.8′	5201	0.43	1.79 (I)	0.78	f	0–15	C
210	16°53.0′	137°53.0′	4586	2.68	1.83 (I)	4.91	f	0–15	C
211	16°52.3′	138°15.8′	4171						
214	16°46.6′	140°10.2′	4609	1.50	2.07 (I)	3.11	f	0–15	C
215	16°47.2′	140°44.6′	4816	0.28	1.85 (I)	0.53	f	0–15	A
216	16°39.7′	141°24.4′	4653	1.03	1.88 (I)	1.94	f	0–15	A
217	16°31.3′	141°49.0′	4506	1.14	1.90 (I)	2.16	f	0–15	A
218	16°22.9′	142°09.6′	4170	1.10	1.89 (I)	2.08	f	0–15	A
220	16°20.2′	142°33.8′	3672	0.23	1.98 (I)	0.46	f	0–15	B-D
Tasaday 7									
01	8°17.5′	120°50.2′	3932	1.03	1.90 (A)	1.96	f	0–15	?
02	8°25.8′	121°43.1′	4857	0.31	1.90 (A)	0.59	f	0–15	D
03	13°31.8′	129°58.2′	5673	0.94	1.90 (A)	1.79	f	0–15	A
04	15°28.6′	131°12.1′	5450	1.00	1.90 (A)	1.90	f	0–15	C
05	16°43.6′	132°06.9′	5761	0.49	1.90 (A)	0.93	f	0–15	C
06	17°23.9′	132°31.0′	5958	0.38	1.90 (A)	0.72	f	0–15	D
07	18°42.8′	133°24.8′	6132	1.28	1.90 (A)	2.43	f	0–15	A
08	17°34.7′	135°49.4′	4859	0.61	1.90 (A)	1.16	f	0–15	C
09	17°18.2′	136°22.2′	5053	0.19	1.90 (A)	0.36	f	0–15	D
10	17°00.6′	137°03.0′	5072	0.37	1.90 (A)	0.70	190 cm	>30	C-D
11	16°30.8′	138°03.9′	4883	0.29	1.90 (A)	0.55	f	0–15	C-D
12	16°08.6′	138°56.1′	5120	0.47	1.90 (A)	0.89	f	0–15	C-D
13	15°52.4′	139°34.3′	5206						C

Absence of data at station 180 was caused by the instrument catching fire and at stations 183 and 211 by the instruments falling over. At station 13 no data were recorded.

* Here N indicates needle probe conductivity measurement, I indicates in situ conductivity measurement, and A indicates assumed conductivity.

† Here f indicates full penetration.

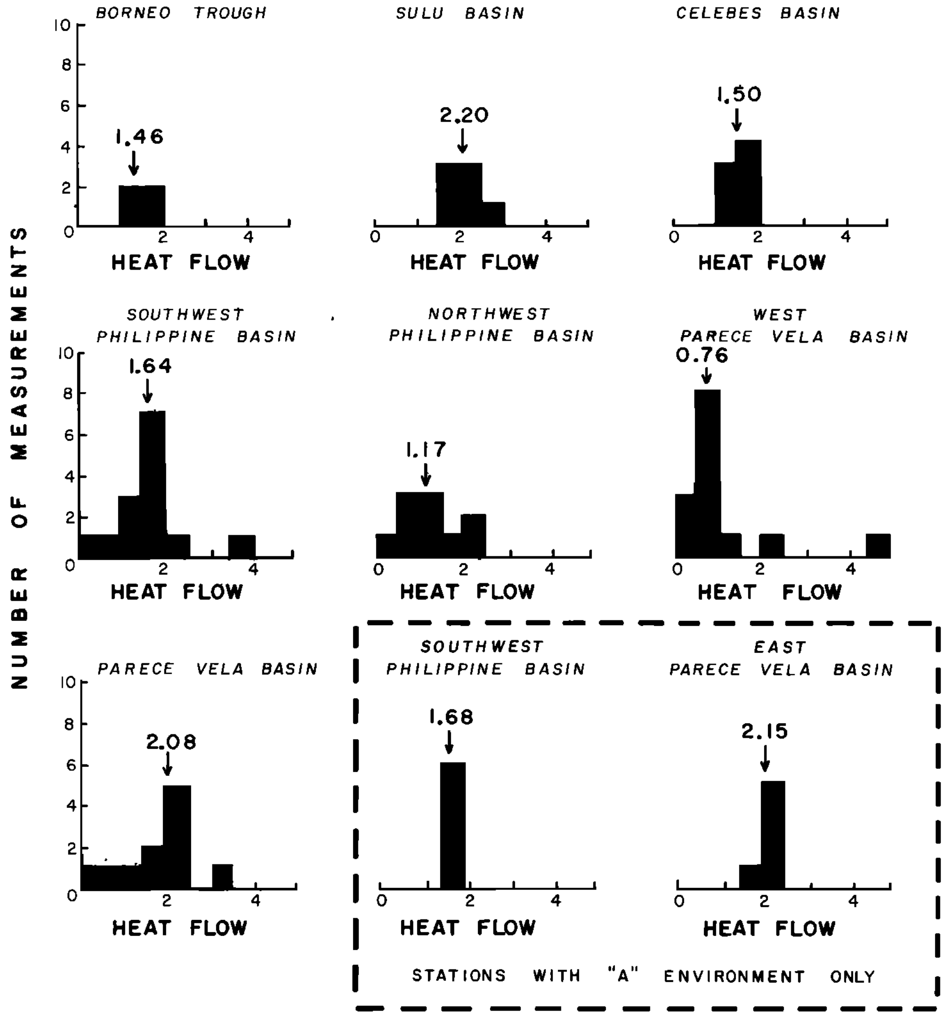

Fig. 4. Histogram of heat flow values in the tectonic provinces of the south Philippine Sea and marginal basins of the Indonesian area. The median values are presented above each histogram.

by deep-sea cores, using the needle probe technique described by *von Herzen and Maxwell* [1959]. In the second we determined the in situ conductivity while the Bullard probe was on the bottom during the temperature gradient measurement, utilizing the technique of *Corry et al.* [1968]. For the Tasaday stations in the Philippine Sea we assumed a value of 1.90 × 10^{-3} cal/°C cm s, the mean value of the conductivities measured in the south Philippine Sea. For all the stations the heat flow was taken as the product of the temperature gradient and the conductivity.

TABLE 2. Heat Flow Statistics

Area	Number of Measurements	Heat Flow, μcal/cm² s Median	Mean	Standard Deviation
		Raw Data		
Borneo Trough	4	1.46	1.45	0.12
Sulu Basin	7	2.20	2.13	0.30
Celebes Basin	7	1.50	1.51	0.23
Southwest Philippine Basin	14	1.64	1.59	0.86
Northeast Philippine Basin	10	1.17	1.24	0.69
Western Parece Vela Basin	14	0.76	1.10	1.19
Eastern Parece Vela Basin	11	2.08	1.80	0.81
All West Philippine Basin	24	1.48	1.44	0.80
All Parece Vela Basin	25	1.00	1.40	1.08
		Reliable Data		
Southwest Philippine Basin	6	1.68	1.72	0.16
Eastern Parece Vela Basin	6	2.15	2.15	0.16

Reliable data are defined as measurements taken in an area of uniform sediment drape.

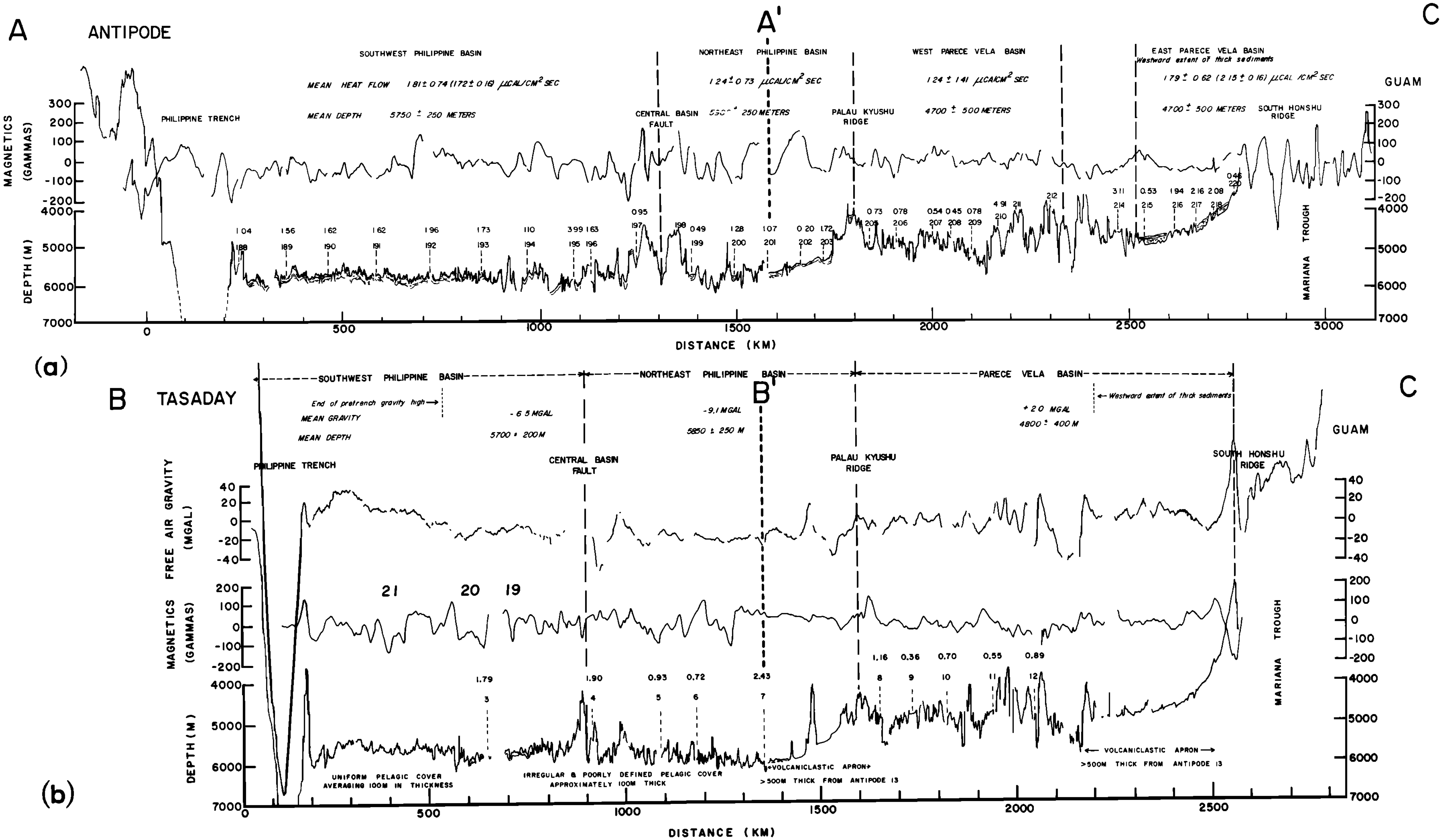

Fig. 3. (*a*) Bathymetric and line drawing of the sediments and magnetic anomalies along the Antipode 13 profile between the Philippine trench and the South Honshu Ridge. Heat flow measurements are shown along the track. Also presented are the mean heat flow and depth range for each of the separate tectonic provinces traversed by the profile. Because of instrument failure, only a magnetic profile was obtained across the Mariana Basin. (*b*) Same as Figure 3*a*, with free air gravity anomaly added for Tasaday 7 profile. (There is some evidence from cross-checking with an unpublished compilation of gravity data in the Philippine area (T. Watts, personal communication, 1975) that the gravity data west of the Central Basin Fault are 15 mGal low. The rest of the data agree with the unpublished compilation.) Also presented are mean gravity, mean depth, and range in depth for the separate tectonic provinces. Because of instrument failure, only a gravity profile was obtained across the Mariana Basin.

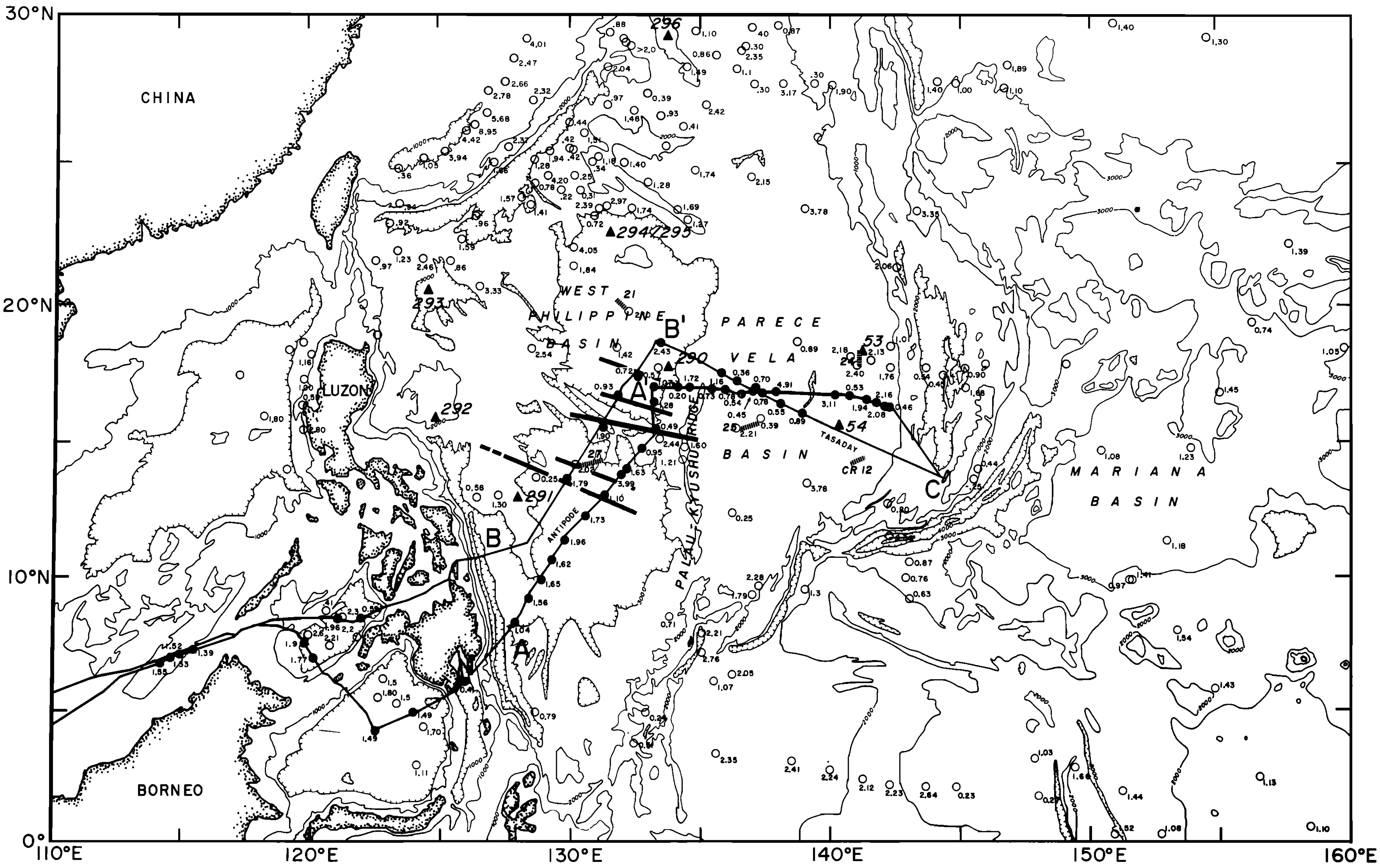

Fig. 2. Topographic chart of the Philippine Sea and marginal basins close to Indonesia. Heat flow stations, the track of Antipode 13 and Tasaday 7, and identified magnetic anomalies (after *Louden* [1976]) have been superimposed upon the chart. The solid circles are heat flow stations presented in this paper, and the solid triangles are Joides sites. Note the refraction stations.

TABLE 3*a*. Depth and Age From Joides Deep-Sea Drilling Sites

		Location			Sediment, m				Biostratigraphic Age		Magnetic Anomaly	
Basin	Site	N	E	Depth, m	Thickness	Correction	Topographic Correction, m	Corrected Depth, m	Period	Age, m.y.	Number	Age, m.y.
Parece Vela	53	18°02.0′	141°11.5′	4629	201	144	200*	~4830	Oligocene to early Miocene	32–18	...	...
	54	15°36.6′	140°18.1′	4990	294	212	...	5102	Oligocene to early Miocene	32–18	...	...
Philippine	290	17°44.9′	133°28.1′	6062	255	185	−150†	~5900	Late Eocene	45–38	<21	<53
	291	12°48.4′	127°49.9′	5217	127	93	+400†	~5600	Middle to late Eocene	50–38	21	53–49
	293	20°21.3′	124°05.6′	5599	563	405	?	~6004	?	?		
	294	22°34.7′	131°23.1′	5784	118	85	...	5869	Eocene?	54–45		

Parece Vela Basin sites are taken from *Fischer et al.* [1971], Philippine Basin sites from *Ingle et al.* [1975], and biostratigraphic ages from *Berggren and Van Couvering* [1974].

* Correction from site 53 bathymetric chart [*Fischer et al.*, 1971].

† Correction from *Chase et al.* [1970].

The heat flow measurements were taken in a wide variety of places ranging from the enclosed Borneo, Sulu, and Celebes basins to the open and deep West Philippine Basin (Figure 2 and Table 1). On initial inspection the measurements, except for those of the enclosed basins, are not consistent (Figure 4 and Table 2). Even when the results are consistent, we do not know how to interpret them. For instance, the Borneo Basin has a uniform flow of 1.45 μcal/cm^2 s. The Sulu Trough has a higher mean heat flow, 2.13 μcal/cm^2 s, than the Celebes Basin, 1.51 μcal/cm^2 s (Table 2), but the reason for this difference is not known.

The variability in heat flow values starts in the West Philippine Basin and continues through the Parece Vela Basin. In both basins (Figures 3*a* and 3*b*) there is a reasonable correlation between lack of variability and a uniform sediment cover. The West Philippine Basin south of the Central Basin Fault has a uniform sediment drape, and the heat flow has little scatter. Within the fault and to the north, the topography is rough, the sediment drape less obvious, and the heat flow more variable. A spectacular example of such variability is found in the Parece Vela Basin. This basin is cut in two by a north-south central region of peaks and troughs which is the presumed termination point of the active spreading center. Both sides of the basin are thought to be of the same age. Deep-sea drilling sites in the eastern basin gave an Oligocene to early Miocene age (Table 3). The only striking difference is that the eastern basin is covered by a uniform drape of sediments. The heat flow measurements in this well-sedimented area are high and fairly uniform (1.80 ± 0.81 μcal/cm^2 s). On the other hand, the heat flow measurements in the western basin are generally low with a few very scattered high values (1.10 ± 1.19 μcal/cm^2 s) which usually occur on top of topographic highs (stations 210 and 214 in Figure 3*a*).

This wide difference in heat flow variability in two supposedly similar tectonic basins is very disturbing. *Lister* [1972] and *Williams et al.* [1974] have suggested that because of cooling cracks and faulting the oceanic crust is permeable to fluid flow. *Sclater et al.* [1974*b*] have further suggested that if this effective permeability is never completely destroyed, then in any region of rough topography with outcropping basement highs, hydrothermal circulation will occur. These circulation patterns will cause much of the heat loss to the sea water to occur by mass transport through the permeable basement. Also, the patterns that they set up will tend to lower the conductive heat flow in the sediment ponds between the outcropping basement highs. As a consequence, conductive measurements in such regions, except in isolated cases on top of basement highs, will yield low values.

We believe that this model gives a good qualitative explanation of the heat flow across the Parece Vela Basin. In the western basin, where there is little sediment cover and a highly variable topography, most of the values lie below 1.00 μcal/cm^2 s. In fact, the median is 0.76 μcal/cm^2 s. However, in the eastern Parece Vela Basin just west of the South Honshu Ridge there is a thick sediment drape extending 200 km from the ridge (Figure 3). In this area, except for the two stations at the edge, the heat flow values show much less scatter (Figure 3*a*) and have a median of 2.08 μcal/cm^2 s.

On the basis of our qualitative explanation of the low values we reexamined the environment around each of the stations on the Tasaday, Antipode, and Scan [*Sclater et al.*, 1972] cruises in the area. We divided the environments into four groups: A, a uniform sediment drape with no nearby sediment outcrops; B, a uniform sediment drape with isolated nearby outcrops; C, very thin or no sediment drape; and D, a sediment pond in rough topography next to an outcropping basement high.

TABLE 3*b*. Depth and Age From Magnetic Anomalies and Topographic Profiles in the Philippine Basin

Area	Number of Measurements, m	Mean Depth, m	Estimated Range, m	Age Range, m.y.
Anomaly 17, Central Basin Fault	6	5050	±200	43–39
Anomaly 21, southwest Philippine Basin	5	5750	±300	53–49
Anomaly 21, northeast Philippine Basin	5	5950	±200	53–49

Topographic profiles are taken from the present paper and *Louden* [1976], and magnetic anomaly identifications from *Louden* [1976].

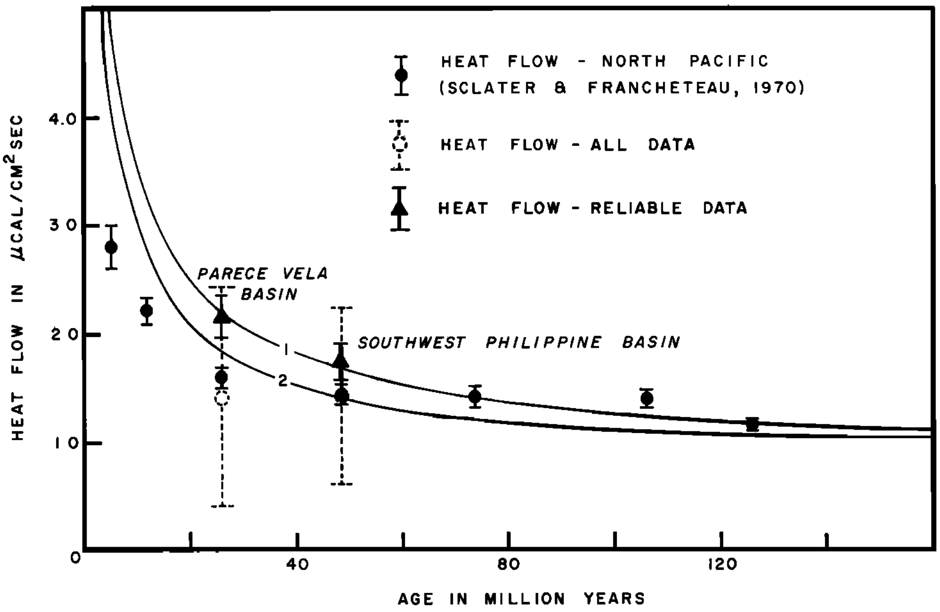

Fig. 5. The mean and standard deviation for all data and for selected reliable data from the southwest Philippine and Parece Vela basins superimposed upon a plot of mean heat flow and standard error for tectonic provinces in the North Pacific against age. Curves 1 and 2 represent the theoretical heat flow for 100-km- and 75-km-thick lithosphere plates, respectively (after *Sclater and Francheteau* [1970]).

We found six stations in the eastern Parece Vela Basin with an A environment. The median was 2.15 with a standard deviation of ±0.16 μcal/cm² s (Figure 4). The fact that the scatter has been considerably reduced by using only A environment stations is significant. It indicates that only where the sediment cover (which is presumed to be impermeable) is thick enough and sufficiently wide to stop any regional loss of heat by mass transport will reliable measurements of low scatter be obtained. We believe that the true heat flow from the eastern Parece Vela Basin is 2.15 ± 0.16 μcal/cm² s. This is high and significantly different from that in the western basin. We carried out a similar exercise for the southwestern Philippine Basin. Again, when only the A stations are considered, the scatter is low, and we obtained a value of 1.72 ± 0.16 μcal/cm² s (Figure 4).

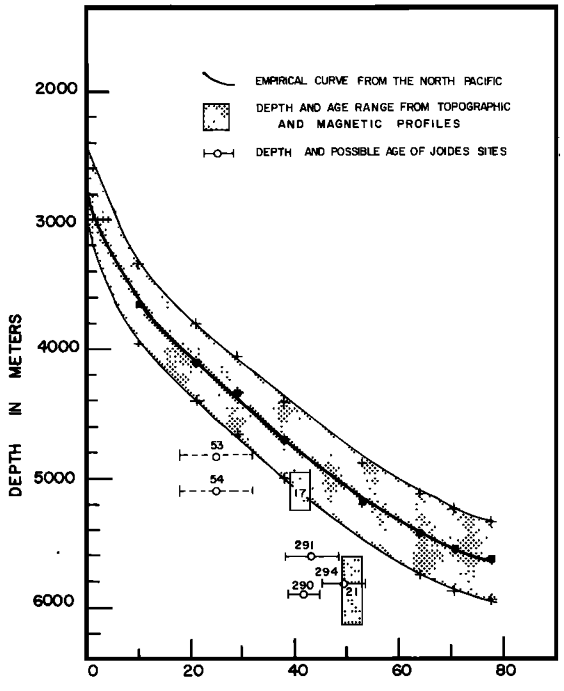

Fig. 6. Depth versus age data for the northeastern Pacific compared with similar data from the Philippine Sea. The stippled area represents a range of ±300 m about the empirical curve for the northeastern Pacific. This is the expected range for an area with no free air gravity anomaly [*Parsons and Sclater*, 1975].

This reinterpretation of data demonstrates an important and well-known fact; namely, much of the variability of oceanic heat flow measurement is a function of environment. However, if regions can be found with a uniform sediment drape of thickness greater than 100 m and an extent that is wider than that of probable hydrothermal convection cells (5–10 km), then heat flow measurements of surprisingly low scatter should be observed. If, in these areas, the effects of slumping and bottom water temperature variations can be shown to be small, then these heat flow values may be a true measure of the flow of depth beneath the oceanic crust.

COMPARISON OF HEAT FLOW AND DEPTH MEASUREMENTS

We compared the reliable heat flow average over the southern section of the West Philippine Basin and the eastern Parece Vela Basin with that over areas of the Pacific of the same age (Figure 5). Though both areas have higher heat flows than the North Pacific, the difference cannot be considered significant. In the North Pacific no account was taken of local environment, and as a consequence, the averages in the midocean ridges are almost certainly biased in the low direction. Recently, *Sclater et al.* [1975] have shown that if only heat flow values from well-sedimented areas are considered, the means when plotted against age are very close to the values predicted by a 100-km-thick lithosphere. Even the heat flow through the Parece Vela Basin is not significantly greater than the values observed over Oligocene crust in the North Pacific when the large number of unreliable low values used in determining the mean for ocean floor of the same age are removed.

TABLE 4*a*. A Comparison of Velocity and Thickness of the Crustal Layers in the West Philippine and Parece Vela Basins and the North Pacific

Area	Layer	Velocity, km/s	Thickness, km	Assumed Density, g/m^3	Data Source
West Philippine Basin	T	5.30 ±	0.92 ±	2.5	*Murauchi et al.* [1968] (stations 21 and 27)
	O	6.70 ±	4.03 ±	2.9	*Henry et al.* [1975] (station Tasaday 5-2)
Parece Vela Basin*	T	4.45	1.39	2.4	*Murauchi et al.* [1968] (stations 24N, 25W and 25E)
	O	6.81	3.00	2.9	*Gaskell et al.* [1959] (CR 12)
Western North Pacific	T	5.02 ± 0.63	2.05 ± 0.50	2.5	*Raitt* [1963]
	O	6.73 ± 0.25	5.08 ± 1.72	2.9	
North Pacific	T	5.19 ± 0.64	1.49 ± 0.98	2.5	*Shor et al.* [1970]
	O	6.81 ± 0.16	4.62 ± 1.30	2.9	
Hypothetical crust, 45 m.y. B.P.	T	5.1	1.66	2.5	*Le Pichon et al.* [1973]
	O	6.7	5.33	2.9	

T and O are the transition and oceanic layers, respectively, after *Shor et al.* [1970].

* These data are not reliable; 24S was omitted because it had an unusually thick oceanic layer.

To investigate the tectonic similarities of the basins in the Philippine Sea further, we plotted their depth as a function of age and compared the basins with the North Pacific (Figure 6). In this case, both the Parece Vela and the West Philippine basins north and south of the Central Basin Fault have depths that are significantly greater than the depth predicted by the empirical curve for the North Pacific. A possible explanation of the differences for the Parece Vela Basin is that the lithospheric plate is thinner landward of the trench because of shear stresses along the bottom of the plate [*McKenzie,* 1969]. In this case the thinner plate cools more quickly, and by 30 m.y. B.P. it has reached equilibrium. The thinner lithosphere results in a high heat flow and a depth close to 4600 m [*Sclater,* 1972]. Though this mechanism can be invoked to account for the heat flow and elevation in the Parece Vela Basin, it cannot also work for the West Philippine Basin. In this case the depths are so deep that the residual elevation anomaly (actual depth minus predicted depth for crust of the same age) cannot be caused by thinning the plate. Any decrease in thickness of the lithosphere in equilibrium crust will increase the elevation, not decrease it [*Sclater,* 1972]. Thus some other explanation must be found for the deeper than normal depths in these two basins.

Karig [1971] pointed out that there was some evidence that the oceanic crust in the marginal basins of the Philippine Sea was thinner than that under the deep oceans and that this difference could account for the greater than normal depths [*Karig,* 1974]. We also observe that the mean free air gravity anomaly over both basins is less than ±10 mGal (Figure 3*b*). Thus it appears that the basins are compensated and that the thinner crust could account for the deeper depths. To investigate this effect, we have compiled the reliable seismic data from *Murauchi et al.* [1968, *Henry et al.* [1975], and *Gaskell et al.* [1959] for the West Philippine Basin and the Parece Vela Basin. We separated the oceanic crust into three layers, sediment, transition, and oceanic, after the definition presented in Figure 1 of *Shor et al.* [1970], and we compared these with the compilations of *Raitt* [1963] and *Shor et al.* [1970] and with the theoretical northwestern Pacific crustal section of *Le Pichon et al.* [1973] (Table 4*a*). We included the three different compilations which represent the average for old ocean floor, the average for a fairly young ocean floor, and an empirical curve to give an estimate of the likely range of thickness of the two layers in normal oceanic crust. Both the West Philippine and the Parece Vela basins have a crustal thickness which is much less than that of any of the three estimates for normal oceanic crust. We have calculated (Table 4*b*) that in the West Philippine Basin this decrease in crustal thickness will produce a residual depth anomaly of between 300 and 600 m. In the Parece Vela Basin the anomaly will be slightly less, 280–570 m. Clearly, much of the extra depth in these two basins can be accounted for by a thinner crust.

Before this explanation of the excess depths in the marginal basins can be unreservedly accepted, it is necessary to point out that there are problems with this mechanism. First, the seismic data coverage in both basins is poor, and more reversed lines are needed to substantiate the evidence of a thinner crust. As a consequence, the data have a high scatter, and the differences between the means for the basins and those for oceanic crust of the same age are only marginally significant. Second, there is no evidence from dredged rocks to indicate that the oceanic crustal layers may have a different composition under the marginal basins. Finally, the deep ocean floor in the North Pacific does not have such a large variation in crustal thickness [*Shor et al.,* 1970]. Thus some new special mechanism must be advanced to explain how and why this small section of the ocean floor should have a thinner crust than that created at an oceanic spreading center.

CONCLUSIONS

We have shown that both the Parece Vela and the West Philippine basins have mean depths that are deeper and an oceanic crust that is thinner than ocean floor of the same age. Both have higher than normal heat flow, but this heat flow is not necessarily greater than that of ocean floor of the same age. Both basins appear to have been formed by crustal extension originating at the center of the basin. However, in the case of the Parece Vela Basin this extension was east-west, while in the West Philippine Basin it was north-south. The West Philip-

TABLE 4*b*. Expected Increase In Depth Resulting From Thinner Crustal Layers

	Depth Increase, m
West Philippine Basin	
with respect to western North Pacific	~110
with respect to North Pacific	~320
with respect to hypothetical crust, 45 m.y. B.P.	~500
Parece Vela Basin	
with respect to western North Pacific	~570
with respect to North Pacific	~280
with respect to hypothetical crust, 30 m.y. B.P.	~360

pine Basin has clearly identifiable magnetic anomalies showing a spreading rate during extension of 6-cm/yr half rate. Only one other marginal basin, the Scotia spreading center [*Barker*, 1972], shows more easily identified magnetic lineations, and it has a half rate of 3 cm/yr. With present information it is clear that the West Philippine Basin is different from the other marginal basins in the western Pacific. However, it also has two significant differences from deep ocean floor of the same age. Hence it is not possible at the present moment to determine the environment in which this basin was formed.

In this view it is important to realize that explanations other than crustal variations exist to explain residual depth anomalies. It is possible that in such an area behind one downgoing slab and near another, complex dynamic forces could be acting to decrease the observed depth. A similar mechanism invoking dynamic forces in the upper mantle has already been advanced by *Sclater et al.* [1975] to explain the observed correlation between free air gravity anomalies and residual elevation anomalies in the North Atlantic. One of the disturbing features of accepting the thinner oceanic crust to explain the deeper depths in the marginal basins is that it adds another hypothesis to be considered when the worldwide correlation of residual depth and free air gravity anomalies is interpreted.

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