HEAT FLOW IN THE WESTERN EQUATORIAL PACIFIC OCEAN

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ABSTRACT

Eighty-eight previously unpublished measurements are added to our knowledge of heat flow in the western equatorial Pacific Ocean. The mean of 32 values obtained between the Line Islands and the Marshall, Gilbert, and Ellice island groups is 1.15 ± 0.06 (standard error of mean) HFU and is comparable to the means obtained for other deep-ocean basins. Heat flow just northeast of the Solomon Islands is low (0.83 ± 0.09 HFU, 10 measurements), while to the southwest it is high (1.99 ± 0.17 HFU, 15 measurements). An apparent dichotomy exists in the geological-geophysical relations across the Solomon Islands arc, i.e., the heat flow distribution and the island geology suggest a trench and subduction zone on the Pacific Ocean (northeast) side of the arc, but the seismic, bathymetric and crustal thickness data show a trench and subduction zone exists on the Coral Sea (southwest) side. These contradictions may be reconciled if it is assumed that the subduction of a down-going plate, at that time on the northeast side of the arc, was stopped by the thick crust (> 35 km) of the Ontong Java Plateau, which collided with the arc. Continued crustal consumption being necessary because of plate tectonics, a new subduction zone was formed on the southwest side of the arc. The observed heat flow distribution is then viewed as a relict feature of a pre-existing island arc-

trench configuration.

Heat flow in the New Britain, North Solomon, North New Hebrides, and Marianas trenches is low (0.57 ± 0.17 HFU, 6 measurements). Heat flow in the Palau Trench is abnormally high (2.21 HFU), and four high values obtained east of the Palau Trench agree well with high values previously found in the West Caroline Basin.

INTRODUCTION

Heat flow measurements are one of the basic tools available to the geophysicist in his efforts to learn more about the earth's interior. Under steady-state conditions, geothermal flux, q , is defined as:

$$q = K \frac{\Delta T}{\Delta Z}$$

where K is the thermal conductivity, and $\frac{\Delta T}{\Delta Z}$ is the rate of temperature increase with depth. Involved in the measurement of heat flow is thus the accurate determination of two parameters: (1) the temperature gradient over a vertical interval; and, (2) the thermal conductivity of the material in the same interval. The commonly used units of geothermal heat flow are 10^{-6} cal/cm² sec (hereafter denoted HFU, after Simmons, 1966).

Wooster and Volkman (1960) estimate that the temperature of the deep-ocean bottom water in the Pacific Ocean ranges from 0.90°C south of 50°S Latitude to 1.60°C in the eastern North Pacific. This remarkable thermal stability makes the oceanic bottom water an excellent environment for the measurement of heat flow.

The discovery of the large, positive gravity anomaly that lies in the Solomon Sea southeast of New Britain Island was the impetus for intensive geophysical study of the Solomon Islands region by the Hawaii Institute of Geophysics (Figs. 1 and 3). It was believed that an understanding of

Figure 1. Map of the western equatorial Pacific area. The delimited areas within the figure locate Figures 3, 4, and 5.

the relations between the Solomon Islands arc-trench system and the adjoining tectonic plates would help our understanding of the complex geologic and tectonic problems of this area. The Solomon Islands-New Hebrides Islands ridge is probably the only area in the world where a trench lies on the continental side of an island-arc system. This study of heat flow in the western equatorial Pacific was begun in 1967.

The heat flow data presented in this paper were collected by two groups: Scripps Institution of Oceanography on earlier cruises "PROA," "MONSOON" (MSN), and "LUSIAD" (LSDH), and the Hawaii Institute of Geophysics on cruises "SOLIS '68" and "MAHI 700422."

DESCRIPTION OF MEASUREMENTS

Eighty-eight new heat flow measurements taken in the area under study are presented in Table 1. New and previously published data pertinent to this area (Watanabe et al., 1970; Sclater and Menard, 1967; Lee and Uyeda, 1965) are shown in Figures 2, 3 and 4.

The accuracy of the station positions for the PROA, MSN, and LSDH data is that usually expected from celestial navigation augmented by topographic control i.e., to within a few nautical miles. The celestially determined SOLIS positions have been adjusted with the aid of VLF-OMEGA navigation data and where applicable by bathymetric control.

TABLE 1
HEAT FLOW MEASUREMENTS IN THE
WESTERN EQUATORIAL PACIFIC OCEAN

Station Number	Region ^a	Latitude	Longitude	Depth ^b	Thermal Conductivity ^c	Heat Flow ^d
PROA-1		12°42'N	142°16'E	4150	1.67	0.20±.07
PROA-2	F	11°30'N	142°19'E	10480	(1.81)	0.36±.05
PROA-3		10°28'N	143°06'E	5110	1.72	0.87±.06
PROA-4		9°54'N	142°52'E	4705	1.65	0.76±.09
PROA-5	G	6°08'N	136°13'E	4740	1.72	2.05±.14
PROA-6	G	6°58'N	134°59'E	4720	1.62	2.76±.44
PROA-7		7°45'N	134°59'E	8040	1.81	2.21±.22
PROA-8		8°21'N	133°46'E	4370	1.80	0.71±.07
PROA-9		9°35'N	137°09'E	4700	1.52	2.28±.23
PROA-10		9°26'N	139°00'E	4700	1.55	1.30±.30(pp)
PROA-11		9°05'N	143°05'E	4065	1.76	0.63±.06
PROA-12		2°59'N	147°58'E	4480	1.70	1.03±.04
PROA-13	F	7°19'S	148°45'E	6130	(2.13)	1.07±.16(pp)
PROA-14	D	8°02'S	152°09'E	5290	(2.00)	1.70±.32(pp)
PROA-15	D	6°53'S	151°44'E	5120	(2.00)	2.20±.60(pp)
PROA-16	F	6°16'S	151°35'E	7660	2.13	0.07±.02
PROA-19	C	4°44'S	153°25'E	4570	(2.00)	0.60±.20(pp)
PROA-20	C	5°04'S	153°56'E	3610	2.00	0.83±.05
PROA-21	D	11°38'S	164°40'E	4500	1.75	1.35±.12
PROA-22	D	12°49'S	163°53'E	4115	1.82	1.89±.15

TABLE 1. (continued) HEAT FLOW
MEASUREMENTS IN THE WESTERN
EQUATORIAL PACIFIC OCEAN

Station Number	Region ^a	Latitude	Longitude	Depth ^b	Thermal Conductivity ^c	Heat Flow ^d
PROA-33		14°29'S	176°33'E	3100	(1.7) min	3.6 ^e
PROA-34		12°30'S	176°18'E	3000	(1.95)	0.52
PROA-36		10°01'S	175°12'E	5035	1.69	1.24
PROA-37		7°47'S	174°28'E	5320	1.70	0.49
PROA-39		9°01'S	177°47'E	5100	1.63	1.19
PROA-40		3°07'S	174°25'E	4950	1.62	0.97
PROA-41		2°04'S	172°29'E	4270	2.05	0.80
PROA-42		2°06'S	171°20'E	4045	2.14	0.72
PROA-43		2°16'S	170°19'E	4230	2.09	0.99
PROA-44	A	3°40'N	176°15'W	4995	1.65	0.44
PROA-45	A	1°57'N	178°01'W	5330	(1.68)	1.22
PROA-46	A	0°15'N	179°42'W	5400	1.72	1.40
PROA-47	A	1°23'S	178°24'E	5400	1.62	1.27
PROA-48	A	8°00'S	175°38'W	5350	1.62	1.13
PROA-49	A	9°35'S	176°14'W	4865	(1.62)	1.28
PROA-50	A	12°25'S	173°09'W	4650	1.76	1.04
PROA-51	A	11°03'S	170°04'W	5125	1.61	0.04
PROA-53	A	6°39'S	167°22'W	5090	1.59	1.17
PROA-54	A	4°03'S	165°25'W	4020	2.06	0.54
PROA-55	A	6°23'N	172°32'W	5840	(1.74)	1.14
PROA-56	A	8°52'N	169°32'W	5300	1.67	1.30

TABLE 1. (continued) HEAT FLOW
MEASUREMENTS IN THE WESTERN
EQUATORIAL PACIFIC OCEAN

Station Number	Region ^a	Latitude	Longitude	Depth ^b	Thermal Conductivity ^c	Heat Flow ^d
PROA-57	A	9°59'N	167°05'W	5250	1.71	1.10
PROA-58	A	10°33'N	165°32'W	4340	2.27	1.11
MSN-10	D	12°34'S	164°22'E	4260	1.83	1.81±.12
LSDH-50	E	13°58'S	151°47'E	4655	1.89	1.63±.06
LSDH-51	E	15°43'S	154°44'E	4160	2.09	1.50±.08
LSDH-52	E	14°47'S	155°57'E	2985	2.15	1.04±.05
LSDH-53	D	11°19'S	158°03'E	3025	2.03	1.34±.07
LSDH-54	D	9°54'S	159°00'E	4850	2.07	3.00±.18
LSDH-56	C	7°44'S	160°49'E	3410	(2.02)	0.63±.05 (pp)
LSDH-57	C	6°40'S	163°11'E	3570	2.08	0.83±.03
SOLIS-22	C	04°47'S	157°57'E	1700	(2.1)	0.71±0.15
SOLIS-28	B	01°17'S	160°10'E	2535	2.05	1.37±0.15
SOLIS-29	B	01°37'S	158°47'E	2015	2.08	2.00±0.35
SOLIS-31		04°44'S	155°08'E	2530	(2.1)	>0.9 (pp)
SOLIS-41	A	00°36'N	172°13'W	5620	1.40	1.11±0.06
SOLIS-43	A	02°13'N	166°27'W	5520	1.81	1.21±0.14
SOLIS-44		08°45'N	160°32'W	4805	1.43	0.43±0.08
SOLIS-45	A	07°41'N	164°48'W	4970	1.49	1.12±0.09
SOLIS-47	A	05°26'N	173°06'W	5740	1.42	1.14±0.07
SOLIS-48		04°12'N	178°04'W	5155	(1.5)	>0.9 (pp)
SOLIS-49	A	03°55'N	179°33'W	5428	1.43	1.04±0.07

TABLE 1. (continued) HEAT FLOW
MEASUREMENTS IN THE WESTERN
EQUATORIAL PACIFIC OCEAN

Station Number	Region ^a	Latitude	Longitude	Depth ^b	Thermal Conductivity ^c	Heat Flow ^d
SOLIS-50	A	04°45'N	175°17'E	5100	1.38	1.09±0.08
SOLIS-51		06°10'N	173°00'E	4890	(1.8)	0.23±0.24
MAHI-47	A	09°12'S	173°59'W	4455	1.59	1.94±0.11
MAHI-49	A	03°50'S	169°04'W	4872	1.61	1.66±0.19
MAHI-50	A	00°34'S	167°36'W	5320	1.53	1.09±0.08
MAHI-51	A	01°34'S	167°43'W	5645	1.49	1.25±0.11
MAHI-58	C	10°06'S	163°46'E	3120	2.03	1.38±0.29
MAHI-60	D	13°15'S	160°27'E	3480	2.11	1.52±0.31
MAHI-61	D	12°13'S	158°56'E	3375	1.97	1.32±0.21
MAHI-62	D	09°60'S	155°54'E	3430	1.97	1.77±0.14
MAHI-63	D	09°04'S	157°15'E	3945	1.88	3.42±0.62
MAHI-64	D	08°06'S	156°00'E	4970	2.01	1.39±0.14
MAHI-65	D	08°04'S	154°35'E	3850	1.91	2.96±0.35
MAHI-66	D	07°37'S	153°56'E	4475	1.87	1.80±0.24
MAHI-67	D	06°55'S	153°29'E	5030	1.74	2.37±0.43
MAHI-68	F	06°22'S	153°10'E	4765	1.91	0.65±0.08
MAHI-71		04°30'S	147°47'E	2000	1.84	2.56±0.40
MAHI-72		04°04'S	148°44'E	2014	1.88	0.90±0.13
MAHI-79	C	04°22'S	153°28'E	2160	2.26	1.18±0.26
MAHI-81	B	01°09'S	154°43'E	2880	(2.30)	1.22±0.29
MAHI-82	B	00°04'S	155°01'E	2360	2.40	1.85±0.35

TABLE 1. (continued) HEAT FLOW
MEASUREMENTS IN THE WESTERN
EQUATORIAL PACIFIC OCEAN

Station Number	Region ^a	Latitude	Longitude	Depth ^b	Thermal Conductivity ^c	Heat Flow ^d
MAHI-83	B	00°34'S	154°52'E	2910	2.26	1.15±0.15
MAHI-84	C	03°20'S	155°30'E	1915	2.06	0.45±0.09
MAHI-84	C	03°16'S	155°24'E	1915	2.01	0.84±0.18
MAHI-87		04°34'N	142°01'E	2320	(2.00)	1.14±0.29
MAHI-88	G	06°11'N	139°51'E	4095	1.86	2.03±0.25

^aRegions discussed in the text and summarized in Table 2: A = Central Pacific Basin; B = Northern Ontong Java Plateau; C = 200 km band northeast of Solomon Islands; D = 500 km band southwest of Solomon Islands; E = Coral Sea; F = Marianas, New Britain, North New Hebrides trenches; G = West Caroline Basin.

^bDepth in uncorrected meters.

^cUnits of thermal conductivity are $\times 10^{-3}$ cal/cm sec °C. Values in parentheses indicate K was assumed from a nearby station.

^dUnits of heat flow are HFU ($\times 10^{-6}$ cal/cm² sec). (pp) indicates partial penetration of the probe.

^eIndicates minimum estimate; temperature gradient recorder off scale.

Figure 2. Heat flow distribution in the Central Pacific Basin. The dashed line indicates the approximate crest of the Darwin Rise (Menard, 1964). In Figures 2, 3 and 4 heat flow units are HFU (10^{-6} cal/cm² sec), depths are in kilometers (after unpublished chart compiled by T. Orwig), solid dots indicate data presented here, open dots indicate other data (referenced in text).

Figure 3. Heat flow distribution in the Solomon Islands region. The dashed lines indicate limits of bands of heat flow averaged north and south (regions C and D of Tables 1 and 2) of the Solomon Islands discussed in the text.

Figure 4. Heat flow distribution in and near the Yap, Palau, and Marianas trenches.

Except for station 44, where instrument failure caused an estimated uncertainty of eight nautical miles, the positions are probably accurate to one nautical mile. Uncertainties of less than one mile are estimated for station positions of the MAHI data since a satellite navigation system was then operational.

THERMAL CONDUCTIVITY

The needle-probe technique (Von Herzen and Maxwell, 1959) was used to measure the thermal conductivities listed in Table 1 for PROA, MSN, LSDH, and MAHI. The thermal conductivity of the SOLIS data was determined by using the water content method of Bullard and Day (1961). This method utilizes an empirical relation between thermal resistivity, R (thermal conductivity is the reciprocal of R), and the water content [$w = 100$ (wet weight-dry weight)/wet weight]. The relation is:

$$R \text{ (cm sec}^\circ\text{C/cal)} = 168 + 6.78 W$$

A comparison of the needle-probe technique with steady-state techniques was made by Lachenbruch and Marshall (1966), using sediment samples taken from the Arctic Ocean. The comparison indicated that the empirical relation found by Bullard and Day gave thermal conductivities which were 5 to 20 per cent too low. When we compared the relation developed by Bullard and Day with the results of the

Figure 5. Graph showing the relations between water content and in situ thermal conductivity after Bullard and Day (1961) and Lachenbruch and Marshall (1966).

The probe is 2 m long and contains four thermistor sensors arranged in two differential alternating current bridges. One pair of sensors has 1 m separation and the other pair 1 1/2 m. Since the temperature gradient is measured over two different length-intervals an estimate of gradient linearity is possible.

In practice, the Scripps instrument was lowered on a winch to a point just above ocean bottom where the water is approximately isothermal, and a zero temperature gradient was recorded for about 10 minutes. Following this measurement, the instrument was lowered into the ocean bottom penetrating the sediments, left to record for a period of about 10 minutes, and then recovered aboard the ship. A corer was subsequently lowered to obtain a sediment sample for the thermal conductivity determination. The SOLIS and MAHI data were collected using the temperature probe as the trigger weight for a Ewing-type piston corer. The probe and corer were lowered together; held near 100 m above bottom for about 10 minutes recording of zero temperature gradient; lowered into the sediment for about 30 minutes; withdrawn; and held near 100 m for an additional 10 minutes before recovery. In all cases 30 minutes of undisturbed recording apparently was sufficient to gain equilibrium, and the gradient was measured directly from the record (i.e., no extrapolation was applied). The method used for determination of the errors shown with the heat flow

values in Table 1 are summarized in Appendix 1.

DISCUSSION

Central Pacific Basin

From a summary of geological-geophysical studies, Menard (1964) postulated the existence of a former oceanic rise, the Darwin Rise. His major evidence for its existence is the decrease in the depth of the flat-topped seamounts (presumably, a sea-surface erosion phenomenon) that is observed as one progresses away from the axis of the hypothesized former rise. In addition, seismic refraction data indicated the existence of a thick "second" layer, perhaps the result of extensive volcanism which has occurred during the time when the rise was emergent.

A number of heat flow measurements were obtained as part of more recent geological-geophysical investigations in this area conducted by the Hawaii Institute of Geophysics. Included here are data from the central portion of the Darwin Rise bounded by the Line Islands on the northeast and the Marshall and Gilbert and Ellice islands to the southwest. As shown in Figures 2 and 6, the heat flow over this large, topographically variable region (Table 2) is below the Pacific Ocean average (1.50 HFU, Von Herzen and Lee, 1969) and remarkably constant, indicating that the area is no longer tectonically active. The data shown in Figure 6 cover

Figure 6. Frequency distribution of 32 values of heat flow in the central Pacific Basin between the Line Islands and the Marshall and Gilbert and Ellice islands. The mean is 1.15 HFU, the standard error of the mean is 0.06, and standard deviation is 0.35.

TABLE 2.
STATISTICAL SUMMARY OF HEAT FLOW BY REGIONS

Region ^a	Mean (HFU)	Standard Error of Mean	Standard Deviation	No. of Observations	Remarks
(A) Central Pacific Basin (Fig. 2)	1.15	0.06	0.35	32	
	1.15	0.04	0.24	30	Excluding two values which are > 2 s.d. from mean (1.94 and 0.04 HFU)
(B) Northern Ontong Java Plateau (Fig. 3)	1.52	0.17	0.38	5	
(C) 200 km band northeast of Solomon Islands (Fig. 3)	0.83	0.09	0.27	10	
(D) 500 km band southwest of Solomon Islands (Fig. 3)	1.99	0.17	0.67	15	Excluding 3 values in the New Britain Trench (0.07, 1.07 and 0.65 HFU) and one in the North New Hebrides Trench (0.71 HFU)
(E) Coral Sea (Fig. 3)	1.48	0.11	0.26	6	
Japan Trench (Northeastern Honshu)	0.70	--	0.15	--	From Uyeda and Vacquier, 1968
Japan Sea	2.01	--	0.38	--	From Uyeda and Vacquier, 1968
(F) Marianas, New Britain, North New Hebrides Trenches (Figs. 3 and 4)	0.57	0.17	0.38	5	
(G) West Caroline Basin (Fig. 4)	2.20	0.05	0.15	7	Including five values from Watanabe <i>et al.</i> , 1970

^aLetters are those used for regional identification in Table 1.

approximately 2×10^6 square nautical miles. The two extreme values in this population are located near the southern boundary of the area and, therefore, may not be representative. Disregarding these two measurements does not alter the mean (1.15 HFU), but decreases the standard error of the mean from ± 0.06 to ± 0.04 , and the standard deviation from ± 0.35 to ± 0.24 . Two other low values, not included in the mean, were also measured; one (0.43 HFU) just east of the Line Islands and the other (0.23 HFU) near the Gilbert Islands. Both of these values are located near bathymetric highs, and may be depressed by the effects of rapid sedimentation.

The thermal conductivity in this region is extremely low, seismic reflection profiles show a layer of acoustically transparent sediment, characterized by unusually high water content (generally greater than 75 per cent), and Fan (1970) has suggested that the high porosity of these sediments may be due to the presence of interlaced siliceous spicules.

Solomon Islands Region

Intense interest in this region (Fig. 7) was initially generated by the discovery of a large positive gravity anomaly from studies of satellite orbital perturbations (Rose et al., 1968). Land gravity measurements were begun in 1961 (Laudon, 1968). Since then several cruises have been conducted in the region, and the gravity and magnetic fields are now rather well known (Rose et al., 1968).

Figure 7. Location map of the geographic features of the Solomon Islands.

In addition, accurate bathymetric and sediment-thickness maps are now available in some areas (Kroenke, in preparation).

From crustal seismic refraction studies of the oceanic crust and upper mantle in the region, Furumoto et al. (1970) differentiate three types of crustal areas:

1. Thick crust with normal mantle velocities northeast of Malaita and Santa Isabel islands;
2. Thin crust and low mantle velocities southwest of New Georgia Island;
3. "Normal oceanic" crustal structure southwest of Bougainville Island.

The thick crust northeast of Malaita and Santa Isabel has since been extended both in area (to include most of the Ontong Java Plateau) and in thickness (35 to 42 km, A. Furumoto, personal communication). The crustal seismic data of Furumoto et al. (1970) and the gravity data of Rose et al. (1968) correlate very well, with the exception of the data for New Georgia Sound, which lies between Santa Isabel, New Georgia, and Guadalcanal islands. Here, where water depths are less than 1 km, the seismic data indicate a mantle depth of 14 km, while the low (+ 50 mgal) Bouguer gravity anomaly indicates a mantle depth of 28 km.

Coleman (1970) has completed a thorough review of the geology of the Solomon Islands, and on the basis of structure and rock type has divided this autochthonous geologic system into three provinces: the Volcanic, the Central, and the Pacific.

1. The active and recent volcanoes of the Solomon Islands define the Volcanic province (Fig. 8) on the southwest side of the island arc, which includes Bougainville, the Shortland group, the New Georgia group, Russel, Savo, and the western end of Guadalcanal. The most typical part of the province is the New Georgia group where lavas range from highly mafic picrite (olivine-rich) basalts to hornblende andesites, the most common being olivine basalts, pyroclastics, and basaltic andesites. On Bougainville basalts are rare, the dominant lavas being hornblende andesites. The structural trend is exemplified by three sets of faults: in the west, trending mainly northwest-southeast approximately parallel to Bougainville; in the east, trending dominantly northeast-southwest; and in New Georgia, the central portion of the province, the two former sets intersecting with a third east-west tensional set. This intersection apparently provides the controlling factor in the location and development of New Georgia.

"The Volcanic Province, in terms of the continuing development of the Solomons, may be regarded as a youthful extension, a young version of the Central Province" (Coleman, 1970, p. 296).

Figure 8. Map of the Solomon Islands showing the boundaries of the Pacific, Central and Volcanic provinces (after Coleman, 1970).

2. The Central Province has a metamorphosed basal complex of Cretaceous age consisting of greenstones, amphibolitic schists, and less-altered lavas and pelagic sediments. These rocks are intruded and overlain by later lavas (up to 1 km thick) mainly consisting of subaerial and submarine basalts but also some andesites. This sequence has been faulted (by two sets of faults, one trending north-west the other west) into a horst and graben structure, the grabens receiving the erosional products of the horsts (derived from uplifted older rocks). There were four periods of increased disturbance in this region: late Paleocene; Oligocene; Upper Miocene; and Quaternary. A prominent fault system considered to be the boundary between the Pacific and Central provinces (best exposed on Santa Isabel) is the locus of a belt of serpentine rock, the erosion products of which first appear in Lower Miocene sediments.
3. "The Pacific Province contrasts markedly with the rest of the Solomon Block. It shows best on Malaita. Here there are highly basic basal lavas (postulated as original sea-floor) which are overlain concordantly; but irregularly, by deep-water foraminiferal oozes of Upper Cretaceous age. These, in turn, are overlain by about 1300 meters

of foraminiferal organogenic calcilutites of Cainozoic age, without apparent break. Some of the Eocene sediments were intruded by contemporaneous submarine lavas. They include highly mafic types akin to alnöite and ankaratrite..." (Coleman, 1970, p. 299).

Older sediments consist of various marine derived constituents including some radiolarian chert bands and marine manganese. "Malaita did not experience subaerial erosion before the Pliocene" (Coleman, 1970, p. 299). This sequence has been faulted and folded, probably being deformed almost continuously from early Tertiary but with major episodes in the Eocene and in the Upper Miocene.

"In general, the contrast between the Pacific and Central provinces at least suggests that the two may once have occupied different relative positions. The postulate is that Malaita, at least, began a westward movement relative to the Central Province, probably in the Upper Miocene" (Coleman, 1970, p. 299-300).

Studies of the seismicity of the Solomon Islands-New Britain Island regions delineate the presently active motions within the lithosphere (Isacks and Molnar, 1971; Santo, 1970; Denham, 1969). The distribution of shallow earthquake epicenters is concentrated along the north coast

of Papua-New Guinea, the southeast coast of New Britain and the south coasts of the Solomon Islands. Intermediate- and deep-focus earthquakes are less scattered than the shallow-focus earthquakes and suggest a focal plane which dips about 45 degrees northwest under New Britain and northeast under the Solomons. The focal plane appears to steepen with depth to become nearly vertical under the Solomon Islands. A notable gap in the earthquake foci locations exists in the Solomon Islands at depths between 225 and 380 km (Denham, 1969), posing the possibility that the subducting lithosphere has parted and the deep-focus earthquakes (rare under the southeastern half of the Solomons) are caused by a disjoined section of lithosphere encountering the more resistant mesosphere. First-motion studies in the region suggest that lithosphere in the Solomon Sea and Coral Sea is underthrusting beneath the Solomons and New Britain (Isacks and Molnar, 1971).

The attenuation of short-period seismic shear waves is normally considerably higher across the concave (continental) side of island-arc systems and lower across the convex (oceanic) side (Molnar and Oliver, 1969). This pattern of low Q has been found associated with the Japan, Bonin, Marianas, and Tonga Kermadec arc-trench systems. A low Q zone is also found associated with the Solomon arc-trench system, but here it is found on the convex (trench) side.

Some definite trends are apparent in the heat flow measurements in the Solomon Islands region (Fig. 3 and Table 2). Northeast of the Solomon Islands the heat flow, about 0.8 HFU near the islands, increases to normal (1.5 HFU) across the Ontong Java Plateau to the north. Immediately southwest of the Solomon Islands the heat flow is above normal (2.0 HFU). Two high values (3.00 and 3.42 HFU) are found southwest of Guadalcanal and the New Georgia Islands. Farther south in the Coral Sea Basin the heat flow appears to be normal (1.5 HFU).

In general, some of the geophysical relations in the Solomon Islands region are as would be expected in an island arc-trench system if the system is reversed with respect to the ocean basin, i.e., the trench feature, the seismic zone, and the convex arcuate shape are toward the continental (Coral Sea) side of the island-arc system rather than toward the ocean basin.

Typically, heat flow associated with an island arc-trench system is near normal under the ocean basin adjacent to the trench, low near the trench axis, and above-normal on the continental side. A typical example is the Japan arc-trench system, where the heat flow in the trench, east of northeastern Honshu averages 0.70 HFU, and that in the Japan Sea (continental side) averages 2.01 HFU (Uyeda and Vacquier, 1968). The low in the trench is easily explained by the effects of subduction of the lithospheric plate

(Minear and Toksöz, 1970) and/or disposition of sediments at the bottom of the trench. The high heat flow behind arc-trench systems is more difficult to explain. McKenzie and Sclater (1968) discuss the possible causes of high heat flow behind island arcs and show that all the models have inconsistencies. One of the two most likely causes, upward movement of molten magma from depth, is discounted because of the enormous quantities of magma that would have to be extruded and/or intruded in the crust to sustain the observed heat flow anomalies. The necessary quantities of magma are not observed in the crust. The other likely cause, stress-heating along the downgoing slab, could only be important if all the energy is dissipated within the material and the effective thermal conductivity is significantly higher than previously assumed and, therefore, able to transport the heat to the surface in a geologically reasonable time.

In the Solomon Islands arc-trench system, although as expected, values within the trench proper are low, the heat flow pattern appears to be reversed for its present geographical configuration; i.e., low on the side opposite the trench (Pacific Ocean side) and high on the trench side (Solomon Sea). Any acceptable crustal model suggested for the Solomon Islands region must, therefore, account for the following, sometimes apparently inconsistent, observations in the geological-geophysical data:

1. The location of the trenches on the Solomon Sea (continental) side of the island-arc system rather than on the Pacific Ocean (oceanic) side.
2. The arcuate shape of the island-arc being convex toward the Solomon Sea rather than toward the Pacific Ocean basin.
3. The apparent dip of the seismic zone toward the Pacific Ocean basin rather than away from it.
4. The unusual thickness of the crust (35 to 42 km, A. Furumoto, personal communication) beneath the Ontong Java Plateau northeast of the Solomon Islands as compared to normal oceanic crust (12 km).
5. The low heat flow on the Pacific Ocean side of the island-arc and high heat flow on the Solomon Sea side of the arc.
6. The low Q zone associated with the Solomon Sea (convex) side of the island arc.
7. The distinct change in geology of the island-arc between the Pacific Province to the northeast and the rest of the arc to the southwest.
8. The location of volcanism on the edge of the New Britain-South Solomon trenches on the southwest side of the Solomon Islands.

The tenets of new global tectonics suggest that in the southwest Pacific, the Australian Plate is moving in a northeasterly direction and impinging in some manner upon

the northwesterly moving Pacific Ocean Plate (LePichon, 1968; Isacks et al., 1968). The position of the New Britain and South Solomon trenches, as well as those on the North and South New Hebrides trenches, plus the position and dip of the seismic plane (except possibly for the deep earthquakes) in the Solomon Islands region, all suggest that the Australian Plate is now underthrusting the Pacific Ocean Plate. However, except for low values in the presently active trench, the observed pattern of heat flow is opposite that expected for such a tectonic regime. This apparent dichotomy in these geophysical relations may be explained if one considers that both the heat flow pattern observed at the surface today and the geology of the Solomon Islands result from a pre-existing tectonic regime.

We suggest that in the past there existed in the Solomon Islands region a normal island arc-trench system, with the Pacific Plate being consumed in a subduction zone on the Pacific Ocean side of the islands. More recently a block of crust of the order of 40 km in thickness i.e., the Ontong Java Plateau, collided with the island-arc and because of its buoyancy effectively stopped the subduction. Since it was necessary for lithospheric consumption to continue, the Australian Plate to the southwest began being consumed beneath the Pacific Plate with the attendant development of the trenches and seismic zone as observed today in the Solomon Sea. This sequence of events is illustrated in

Figure 9. A similar model was considered by Dewey and Bird (1970) in their discussion of the phenomenon of continental-island arc collision.

Our model appears to explain most of the observed geological and geophysical relations. The geological history of the Pacific province of the Solomon Islands differs greatly from that of the other provinces--as though this province were part of the Ontong Java Plateau and only recently became juxtaposed. In addition the presently active volcanic province is on the Solomon Sea or "trench" side of the arc, whereas, typical examples of island arc-trench systems frequently have a lineation of active volcanoes about 100 to 300 km back from the trench axis. The distance from the axis of the volcanic province to the northeast coast of Malaita is 200 to 250 km. Although the cause is not clear, the high heat flow in the Solomon Sea is comparable to that observed in other marginal seas landward of island arcs. The low heat flow band observed on the northeast side of the Solomons is similar to the low heat flow associated with the trenches of other island arcs. Both of these heat flow patterns are believed caused by the pre-collision arc-trench system. Although no detailed calculations have been made, it is reasonable to expect that the original pattern could be preserved for at least the order of 10^7 years. The zone of low Q is at least spatially associated with the high heat flow and, therefore, is also

Figure 9. Diagram showing the hypothesized geologic history of the Solomon Islands arc-trench system (a) pre-collision, (b) at collision, (c) post-collision.

attributable to the pre-collision arc-trench system.

The location of the New Britain and South Solomon trenches and the low heat flow measured in them is attributed to the presently active post-collision arc-trench system. The arcuate shape convex toward the Solomon Sea is probably also caused by the presently active system, as is the location and dip of the shallow- and intermediate-focus seismic zone. We suggest that the concentration of deep earthquakes lying nearly vertically below the deepest of the intermediate-depth earthquakes, may be caused by a disjoined piece of lithosphere encountering the more viscous mesosphere, perhaps a remnant of an original slab of Pacific Plate lithosphere descending from the northeast.

The origin of the Ontong Java Plateau is a complex problem and beyond the scope of this paper. The geology of the Ontong Java Plateau is the subject of a dissertation in preparation by Loren Kroenke for the University of Hawaii.

Heat Flow in Other Western Equatorial Pacific Trench Areas

Elsewhere in the western equatorial Pacific, heat flow measurements are not entirely normal. A series of five heat flow measurements across the Marianas Trench are all low, three immediately south of the trench being higher (0.87, 0.76, and 0.63 HFU, Fig. 4) than the one measurement in the trench (0.36 HFU) or the one immediately to the north (0.20 HFU). These measurements correlate rather well with

two low measurements (0.54 and 0.45 HFU, Fig. 4) in the basin to the north (Watanabe et al., 1970). In marked contrast, one measurement on the axis of the Palau Trench (depth 8040 m) is high (2.21 HFU) as is one measurement just to the south of the trench (2.76 HFU). In addition, one measurement between the Palau Ridge and the Yap Trench is high (2.28 HFU). Two measurements in the northern part of the West Caroline Basin are high (2.05 and 2.03 HFU), and correlate very well with a series of previously published measurements across the southern part of the basin including the Euripik Rise (Watanabe et al., 1970). Three measurements along the western margin of the West Caroline Basin are low (Watanabe et al., 1970).

Correlation Between Seismic Energy and Heat Flow

As mentioned above, previous investigations have suggested that the heat flow in trenches is low, whereas the heat flow of the marginal seas on the continental side of trenches is high. However, the Palau Trench and the trench-like bathymetric deep between the New Britain and South Solomon trenches are both areas of anomalously high heat flow; in addition they exhibit significantly less seismicity than adjacent well-developed trenches having expectedly low heat flow. These observations suggest a correlation between heat flow and seismicity.

Figure 10. Histogram of the relationship between total seismic energy released, within a radius of 200 km and 100 km depth, of the heat flow station and the heat flow value. Error bars (standard error of mean) indicate that the lack of heat flow data seriously detracts from the reliability of the data.

Investigating further, we developed a program to calculate the seismic energy released during some period of time (in this case the ten-year period from 1961 to 1971) "near" each of the heat flow stations presented in this paper and have attempted to correlate heat flow with the total seismic energy released. "Near" is defined as a right circular cylinder of varying radius from 10 to 200 km, and varying depth, from 15 to 100 km. Figure 10 shows the average seismic energy released, within a radius of 200 km and 100 km depth, of stations having heat flow values with the given interval (0.25 HFU). The relationship suggests a possible bimodal correlation between low heat flow and high seismic energy, and high heat flow and high seismic energy. The correlation between low heat flow and high seismic energy might be expected since, typically, trenches are seismically active areas and have low heat flow. The correlation between high heat flow and high seismic energy is somewhat surprising, if it is real. The marked paucity of heat flow data in the high and low ranges casts a good deal of doubt on these correlations--as shown by the error bars in the figure. (For this reason analyses using smaller volumes are not discussed here.) However, the plot does indicate that regions of average to sub-average heat flow (0.75 to 1.75 HFU) are areas of low seismic energy release. Further comparisons of this sort utilizing all available data are planned.

Summary

The average heat flow in the Central Pacific Basin is similar to that for other ocean basins, but individual measurements are significantly more variable than those in the North Atlantic reported by Reitzel (1963). This may be in small part due to different methods of handling the error statistics, but is believed to be largely the result of the significantly more variable topography in the Central Pacific Basin.

The heat flow and most of the other geophysical data in the Solomon Islands region can be explained by an arc-trench system which operated at some time in the past in a geographic configuration reversed from the present. The collision of the Ontong Java Plateau with the arc-trench system brought about the reversal, perhaps in Upper Miocene.

The heat flow in the Marianas, New Britain, and North New Hebrides trenches is low. The heat flow in the Palau Trench is high, as is the heat flow in the bathymetric depression between the New Britain and South Solomon trenches. In both these areas where we would expect the heat flow to be low and the seismicity to be high, we find in fact the reverse.

Appendix 1

The errors shown with the heat flow values in Table 1 are essentially subjective estimates made by the investigators following the basic guidelines listed below. The appropriate errors were applied to each measurement of thermal conductivity and of temperature gradient, and the resulting estimated error in the heat flow determination computed. To be on the conservative side individual contributions to the heat flow error were added rather than computed root mean square. Following is a summary of the guidelines used.

PROA-MSN-LSDH DATA

- a. Standard deviation of the individual thermal conductivity determinations on the core.
- b. Length of the core obtained.
- c. Uncertainty of partial penetration.
- d. Uncertainty of constants used in the extrapolation procedure.
- e. Magnitude and scatter of points in the extrapolation procedure.
- f. Possible systematic error in the needle-probe thermal conductivity measurement ($\pm 2\%$).

- g. Calibration errors of the temperature gradient recorder ($\pm 1\%$).

SOLIS-MAHI DATA

- a. Standard deviation of the individual thermal conductivity determinations on each core.
- b. No core available at recording site, thermal conductivity assumed from nearby data ($\pm 15\%$).
- c. On the SOLIS data only from the uncertainty in the empirical water content-thermal conductivity relation.
 - (1) When water content is greater than 65% ($\pm 5\%$).
 - (2) When water content is less than 65% ($\pm 10\%$).
- d. Thermogradmeter calibration errors ($\pm 1\%$).
- e. Record-reading error ($\pm 0.02 \times 10^{-3} \text{ } ^\circ\text{C/cm}$).
- f. Nonlinearity of the gradient
 - (1) $\frac{(\text{difference in gradients})}{2} = \text{error.}$
 - (2) Failure-of-one-bridge error ($\pm 15\%$).

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