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35. *Studies of the Thermal State of the Earth. The 16 th Paper: Terrestrial Heat Flow in the Japan Sea (1).*

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Abstract

Terrestrial heat flow has been determined at 30 localities in the Japan Sea. The average value of observed heat flow, 2.03×10^{-6} cal/cm^2 sec is higher than the world average. Though the heat flow is generally high the following features seem to exist; (a) a zone of slightly low values ($1.8-2.0\times10^{-6}$ cal/cm^2 sec) runs in the middle of the Japan Sea roughly parallel to the Japanese island arc; (b) a region with heat flow less than 1.5×10^{-6}cal/cm^{2}sec exists north of the Sado Island. However, these observations must be tested with further data.

Possible effect of annual variation of bottom water temperature on the observed heat flow was examined. When the amplitude of the annual variation is 0.02°C, the expected disturbance is about 0.1×10^{-6}cal/cm^{2}sec.

1. Introduction

Terrestrial heat flow has been measured at a number of localities both in and around Japan. The results of the measurements up to 1964 were summarized by Uyeda and Hôrai[1),2)], and the precise coincidence of the zonal pattern of heat flow and that of the Cenozoic volcanic activity of the area was made clear. These measurements are all on the land and in the North Pacific Ocean.

Heat flow work was started in the Japan Sea in late May, 1964, under a joint project of the Maizuru Marine Observatory and the Earth-

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* Communicated by T. Rikitake.

1) S. UYEDA and K. HÔRAI, *J. Geophys. Res.*, **69** (1964), 2121-2141.

2) K. HÔRAI, *Bull. Earthq. Res. Inst.*, **42** (1964), 93-123.

quake Research Institute of the University of Tokyo, on M/S Seifu Maru, 355 ton, belonging to the Maizuru Marine Observatory.

The heat flow measurements were made in two cruises in 1964, in May—June and August—September, along with the ordinary routine hydrographic work of the Observatory. The 8 stations and the ship's tracks of the first cruise are shown in Fig. 1 by dotted line and open

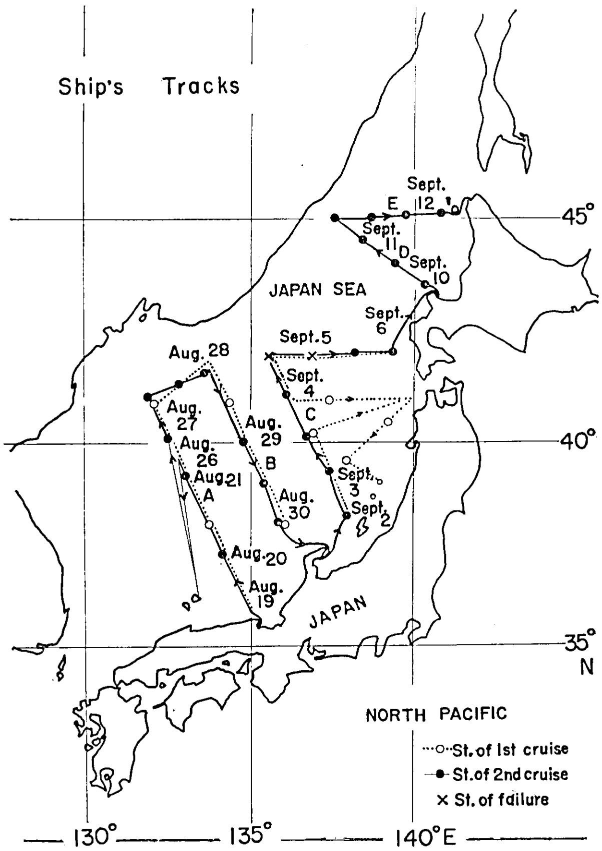

Fig. 1. Heat flow stations and ships tracks.

circles. The 22 stations and the ship's tracks are shown in the figure by bold line and closed circles.

2. The Measurements.

The geothermal gradients were measured using an improved heat-

Table 1. Data of the heat flow measurements in the Japan Sea.

Date of Measurement	Station Name	Position Latitude	Position Longitude	Station Depth (m)	Thermal Gradient (10^{-3} C/cm) 1.5 m	1.0 m	$\Delta\Theta/\Delta z$	Conductivity K (10^{-3} cal/cm·sec·deg)	Core Length (cm)	Heat Flow Value (10^{-6} cal/cm²·sec)	Plausible Error (10^{-6} cal/cm²·sec)
May 25 '64	Ako-M1	38-11N	133-45E	970	0.99	1.17	1.08±0.09	1.98±0.1		2.13	0.45
26	M2	40-47	132-04	3080	0.30	0.35	0.33±0.03	1.78±0.1		0.63	0.15
27	M3	40-48	134-24	3400	1.17	1.43	1.30±0.13	1.79±0.1		2.33	0.37
28	M4	38-01	135-57	2550	1.21	1.56	1.39±0.18	1.75±0.1		2.44	0.49
June 5	M5	40-13	136-52	2525	0.80	?	0.80±0.15	1.70±0.1		1.40	0.40
11	M6	40-59	137-24	3420	0.96	?	0.96±0.15	2.08±0.1		1.98	0.30
12	M7	40-23	139-11	2670	1.18	?	1.18±0.10	1.95±0.1		2.02	0.30
13	M8	39-29	137-59	2510	0.72	?	0.72±0.10	1.81±0.1		1.30	0.26
Aug. 20 '64	Makko-1	37-21N	134-07E	2440	1.47	1.43	1.45±0.02	1.83±0.10	58	2.66	0.18
21	2	39-10	133-02	2720	1.17	1.18	1.18±0.01	1.57±0.05	49	1.84	0.07
26	Saiko -3	40-01	132-29	3330	?	1.36	1.36±0.05	1.65±0.16	81	2.24	0.33
27	4	41-01	131-54	3470	1.29	1.36	1.33±0.04	1.59±0.10	70	2.13	0.20
28	5	41-20	132-48	3600	1.21	?	1.21±0.10	1.56±0.15	44	1.89	0.40
28	Makko-3	41-34	133-35	3650	1.26	1.32	1.29±0.03	1.56±0.2	No Core	2.02	0.40
29	4	39-55	134-50	1450	1.07	1.11	1.09±0.03	1.65±0.05	75	1.80	0.13
30	5	38-58	135-25	3180	1.17	1.14	1.16±0.02	1.69±0.13	124	2.08	0.26
30	6	38-02	135-57	2740	1.33	1.36	1.35±0.02	1.65±0.08	75	1.80	0.20
Sept. 2	7	38-13	137-52	1970	1.21	1.28	1.25±0.04	1.80±0.09	55	2.25	0.20
3	8	39-13	137-25	2340	1.09	1.03	1.06±0.03	1.96±0.09	70	2.07	0.19
4	9	40-08	136-44	2650	1.50	1.43	1.47±0.04	1.78±0.15	72	2.62	0.34
4	10	41-03	136-06	3450	1.24	1.25	1.25±0.01	1.55±0.2	No Core	1.95	0.31
6	11	42-00	138-10	3670	1.40	1.25	1.33±0.08	1.88±0.15	25	2.51	0.40
6	12	41-59	139-23	1480	1.43	1.39	1.41±0.02	1.92±0.15	30	2.70	0.45
10	13	43-32	140-20	700	1.10	1.20	1.15±0.05	1.62±0.03	111	1.87	0.18
11	14	43-59	139-20	1710	1.22	1.22	1.22±0.00	1.80±0.15	81	2.19	0.35
11	15	44-31	138-26	2430	1.14	1.11	1.13±0.02	1.72±0.15	83	1.94	0.26
12	16	44-59	137-29	1630	1.31	1.36	1.34±0.03	1.73±0.05	106	2.32	0.21
12	17	45-00	138-36	2150	0.47	0.43	0.45±0.02	1.80±0.06	35	0.8?	?
12	18	45-02	139-37	855	0.86	1.00	0.93±0.07	1.92±0.25	78	1.92	0.33
12	19	45-05	140-44	330	1.29	1.32	1.31±0.25	2.04±0.09	122	2.7?	1.30

flow probe developed by Uyeda et al.[3] Thermal conductivities of the sediments were measured by a needle probe method by the following procedures. The core-sample of seabottom sediment, which was taken in a liner (84 m/m I. D.) with an ordinary gravity core-sampler, was sealed hermatically, as soon as it came up aboard, to keep the natural water content. It was kept in the laboratory for over 24 hours to ensure its equilibrium state with the room temperature. Then, the needle-probe containing a thermistor and a heater was inserted in the specimen to measure the thermal conductivity by a transient method. A detailed account of the measurements was published by Von Herzen and Maxwell[4], and Yasui et al.[5]

The position coordinates, water depth, geothermal gradient, thermal conductivity and heat flow value are summarized in Table 1. The position coordinates of all the stations were fixed by the Loran method within an error 0.5 mile maximum. The "Ako–M" are the stations of the first cruise, and the others are of the second. The station names Ako, Saiko and Makko show, also, the names of the recorders. The same thermistor bridge was used throughout all the measurements.

Except Makko 17 and 19 stations, full penetration of the probe was attained. At Makko-17, the depth of penetration was estimated to be only 30 cm from the sharp bend and smearing of the probe. The heat flow value is unreliable. At Makko-19, a partial pull out of the probe after penetration was suspected.

For most of the stations, two thermal gradients were measured using two thermistor couples fitted in the probe as shown in Fig. 2, by means of an AC-bridge (Uyeda et al., 1961)[3]. In the column of $\Delta\Theta/\Delta z$, the

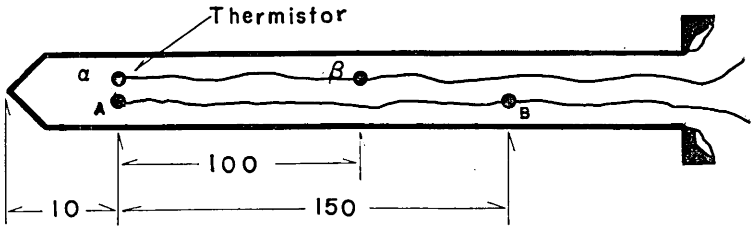

Fig. 2. Arrangement of the two thermistor bridges used in the probe.

3) S. UYEDA, T. YOMODA, K. HÔRAI, H. KANAMORI and H. FUTI, *Bull. Earthq. Res. Inst.*, **39** (1961), 115-131.

4) R. P. Von HERZEN and A. E. MAXWELL, *J. Geophys. Res.*, **64** (1959), 1557-1563.

5) M. YASUI, K. HÔRAI, S. UYEDA and H. AKAMATSU, *Oceanog. Mag.*, **14** (1963), 147-156.

ranges of the gradient indicated by the two bridges are also listed. The agreement of the two gradient values, indicated in the table, are not perfect, but are good to within 10% for 19 out of 30 stations and within 5% for 12 stations.

The electronic circuit of our instruments was designed originally for a thermistor resistance of 2.5 K ohm. In the present work, however, thermistors with 700 ohm at 0°C were used. Since this change in the load caused some malfunctioning of the oscillator of the AC bridge, a 2.0 K ohm carbon resistor was put in series to the thermistor as shown in Fig. 3, for stations Ako-M1 to Ako-M4. The sensitivity of the bridge in this case was

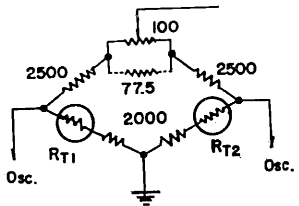

Fig. 3. Thermistor bridge used in the present work.

$$R_{T_1}-R_{T_2}=\frac{R_{T_1}-R_{T_2}-4000}{2550}\cdot r$$

where R_{T_1}, R_{T_2} and r are the resistances of the thermistors 1, 2 and the resistance of the endless potentiometer at the balance point of the bridge. It brought about a drop of the sensitivity, so from Ako-M5 to Ako-M8 another resistor (77.5 ohm) was put in parallel to the endless potentiometer, so that the sensitivity was made

$$R_{T_1}-R_{T_2}=\frac{R_{T_1}+R_{T_2}+400}{2500+\frac{77.5}{177.5}\times 50}\cdot\frac{77.5}{177.5}\cdot r$$

In the second cruise we put a buffer between the oscilator and the bridge, so that the stable oscillation may be kept for the variation of the load thermistor from 50 ohm to over 1 M ohm.

In estimating the plausible error of heat flow values in Table 1, possible effect of annual temperature variation of bottom water, as well as the accuracies of observed gradient and conductivity, was taken into consideration.

The influence of the water temperature variation was calculated as follows. We take the sea bottom as a semi-infinite and homogeneous medium without heat source. The equation of heat conduction and the boundary conditions are given as

$$\frac{\partial\Theta}{\partial t}=\kappa\frac{\partial^2\Theta}{\partial z^2} ,$$

$$\Theta=A\sin\frac{2\pi}{T}t \qquad \text{at } z=0 ,$$

$$\frac{\partial\Theta}{\partial z}=a \qquad \text{at } z=\infty ,$$

and its solutions,

$$\Theta=Ae^{-hz}\sin\left(\frac{2\pi}{T}t-hz\right)+az .$$

Observed thermal gradient should be

$$\frac{\partial\Theta}{\partial z}=-\sqrt{2}\,Ahe^{-hz}\sin\left(\frac{2\pi}{T}-hz+\frac{\pi}{4}\right)+a ,$$

where

$$h=\sqrt{\frac{\pi}{\kappa T}} ,$$

Θ ; temperature in Centigrade,
z ; depth from surface,
t ; time,
κ ; thermal diffusivity of the sediment (4×10^{-3} cm^2/sec),
A ; amplitude of temperature variation,
T ; period of variation (1 year),
a ; undisturbed geothermal gradient.

Then the expected maximum disturbance upon the thermal gradient at z becomes

$$\left|\frac{\partial\Theta}{\partial z}-a\right|_{max}=\sqrt{2}\,Ahe^{-hz} . \qquad (1)$$

When we put $\kappa=4.0\times10^{-3}$ the rate of the disturbance at various values of z is calculated as in Table 2.

In our heat flow probe, the thermistors are placed at $z=0$, 50 and 150 cm. Therefore, observed gradients are expressed as

Table 2. Thermalgradient fluctuation-depth relation.

Depth, z (cm)	$\frac{B}{A} \times 10^3$
50	4.4
100	3.5
150	2.7
200	2.1
250	1.6
300	1.3
350	0.99
400	0.77

Table 3. Heat flow disturbances, ΔQ, for various water depths in Japan Sea.

Water Depth (m)	(deg/year)	ΔQ at $z=150$ cm	ΔQ_{AB}	$\Delta Q_{\alpha\beta}$
300	0.25	1.30	2.40	1.30
500	0.10	0.50	0.96	0.50
800	0.02	0.10	0.19	0.10
1000	0.01	0.05	0.10	0.05
2000	0.005	0.03	0.05	0.03

$$\left(\frac{\Delta\Theta}{\Delta z}\right)_{AB}=\frac{A}{150}\left\{\sin\left(\frac{2\pi}{T}t\right)-e^{-150h}\sin\left(\frac{2\pi}{T}t-150\,h\right)\right\}+a$$
$$=4.8\times10^{-3}\,A\sin\left(\frac{2\pi}{T}t+C_{AB}\right)+a\;, \tag{2}$$
$$\left(\frac{\Delta\Theta}{\Delta z}\right)_{\alpha\beta}=\frac{A}{100}\left\{e^{-50h}\sin\left(\frac{2\pi}{T}t-50\,h\right)-e^{-150h}\sin\left(\frac{2\pi}{T}t-150\,h\right)\right\}+a$$
$$=2.5\times10^{-3}\,A\sin\left(\frac{2\pi}{T}t+C_{\alpha\beta}\right)+a\;. \tag{3}$$

The effect of the annual temperature variation on our measured gradients will, then, be as shown in Table 3.

In the central part of the Japan Sea, the bottom water temperature is supposed to be extremely stable. A few examples of the measured water temperatures are shown in Fig. 4 and Fig. 5. There and other

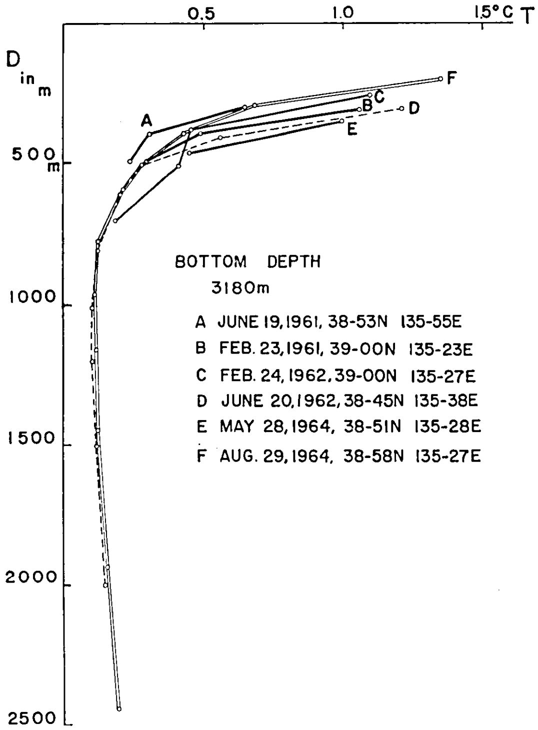

Fig. 4. Examples of water temperature distribution in the Japan Sea (After "Kaiyô Sokuhô" (Oceanographic Report) Maizuru Marine Observatory).

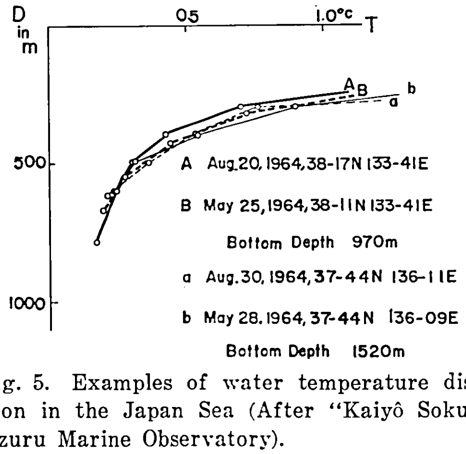

Fig. 5. Examples of water temperature distribution in the Japan Sea (After "Kaiyô Sokuhô" Maizuru Marine Observatory).

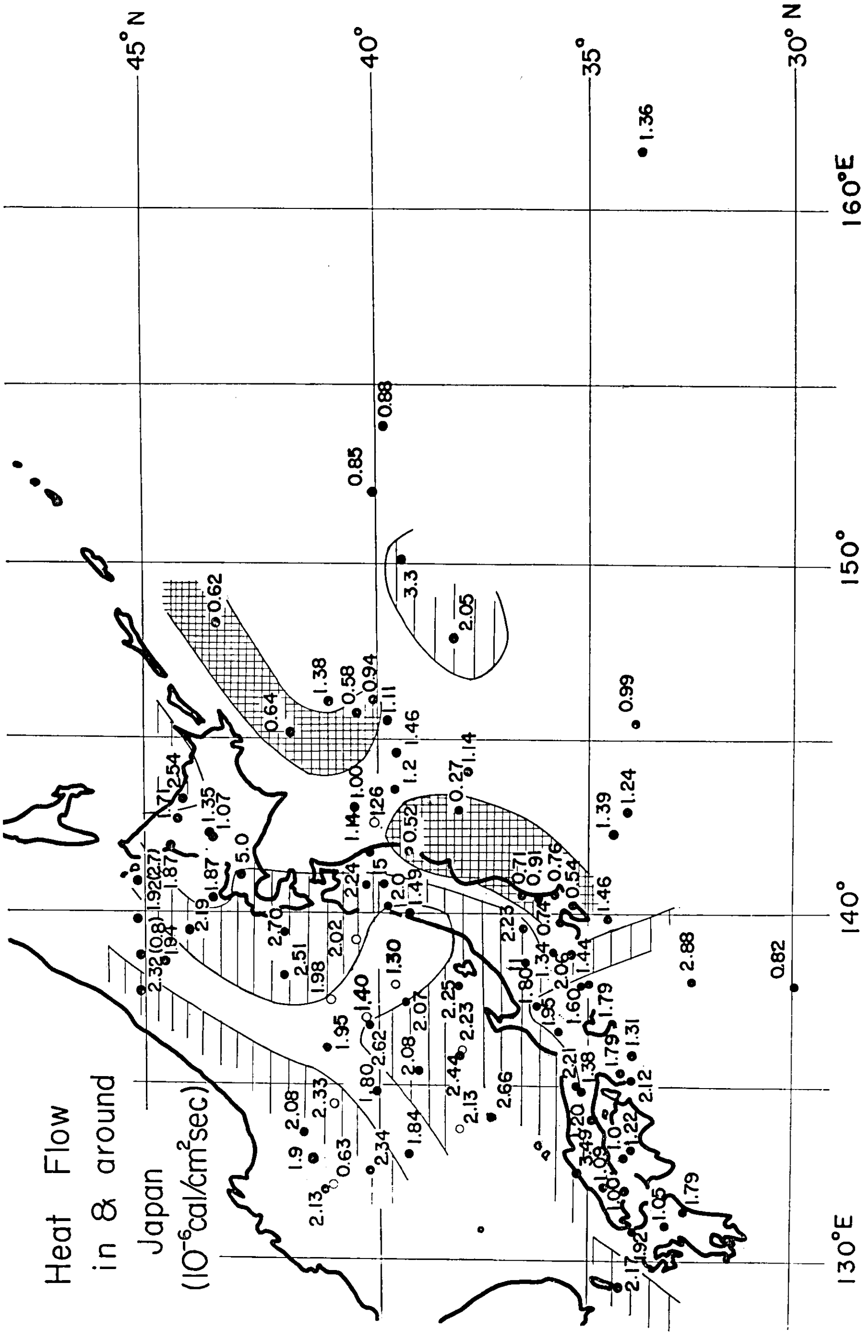

Fig. 6. Heat flow distribution in and around Japan.

evidence to be published elsewhere indicate that the values of A may be taken as a function of the water depth as shown in Table 3. In this table, the maximum values of the disturbance, i.e. the amplitude, given by Equations (1), (2) and (3) are listed. It may be observed that in the Japan Sea, the disturbance would not be greater than 0.1×10^{-6} cal/cm^{2}sec for the water depth z=800m.

3. Some preliminary discussion of the heat flow distribution.

The number of terrestrial heat flow measurements in the Japan Sea are still few, and the distance between stations, 50 to 60 miles, is too large, since, at least, less than 30 miles may be required to detect fine structures of heat flow distributions (Vacquier, 1964; private communications). In addition to these, as shown in Table 1, the error of measurements are not little at all. So it is difficult to give something conclusive here. We will mention some broad aspects only.

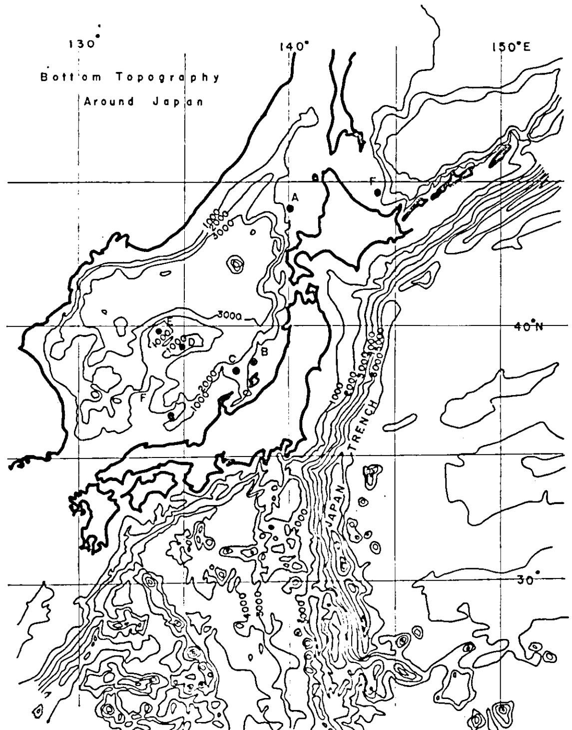

Fig. 7. Topographic map in the seas around Japan. Contours in meters. Localities A—F correspond to those in Fig. 9.

Summarized heat flow distribution around Japan is shown in Fig. 6 and Fig. 7 gives the bottom topographic map of the area. As can be seen in Table 1 and Fig. 6, heat-flow is moderately high in the Japan Sea area, giving the average value of 30 measurements as 2.03, 0.47(s.d.) $\times 10^{-6}$ cal/cm^{2}sec. The best averages to date of the world oceanic and continental heat flow values are 1.60, 1.18(s.d.) $\times 10^{-6}$ cal/cm^2 sec and 1.41, 0.55(s.d.) $\times 10^{-6}$ cal/cm^2 sec respectively (Lee and Uyeda, 1965).[6)]

Though the heat-flow values are generally high in the Japan Sea, there seems to exist a region with comparatively low heat flow, about 1.3×10^{-6} cal/cm^2 sec, at north of Sado Island.

No more features are apparent in Fig. 6, but when we draw a profile of the heat flow values along the tracks A, B, C, D and E, possible existence of another zone of slightly depressed heat-flow may be observed (Fig. 8). The trend is most characteristic in the figure along the track A. That is, starting from the land station, values 2.21 (measured by Uyeda and Horai), the heat flow value rises to 2.66, falls to 1.84, rises again to 2.24 and then slightly falls again. The same trend can be seen in the profiles B, C and D, though with profile E, this trend cannot be detected probably because the errors of the measurements there are too large. This trend indicates a comparatively low heat flow zone running along the middle of the Japan Sea roughly parallel to the island's arc.

Further discussion upon these trends should be withheld until more measurements have been made. Here a few remarks will be made of the geology of the Japan Sea in connection with its high heat flow.

On the whole, geological data is poor in the Japan Sea. We first put schematic figure of the latent fissure zones of the area after Y. Fujita in Fig. 9, (Y. Fujita; 1962).[7)] These fissure zones may be taken as representing, as far as known, the zone of Neogene volcanism. As for the land part, a correspondence of high heat flow and the volcanism has been demonstrated already (Uyeda).[8)] The dotted lines in the Japan Sea show the border of the high heat flow zone and the slightly lower heat flow zone mentioned above. The coincidence of both patterns, though not very obvious, may be noticed. There are, moreover, some pieces of information available: i.e. the results of dredging at the sites indicated in Fig. 7, and Fig. 9 as A, B, C, D, E and F. These sites are located on the banks and reeves which are numerous in the southeastern part of the Japan Sea

6) W. H. K. LEE and S. UYEDA, *Terrestrial Heat Flow* (1965).
7) Y. FUJITA, *Earth Science*, **62** (1962), 21-28.
8) S. UEDA and K. HÔRAI, *ibid.*, 1.

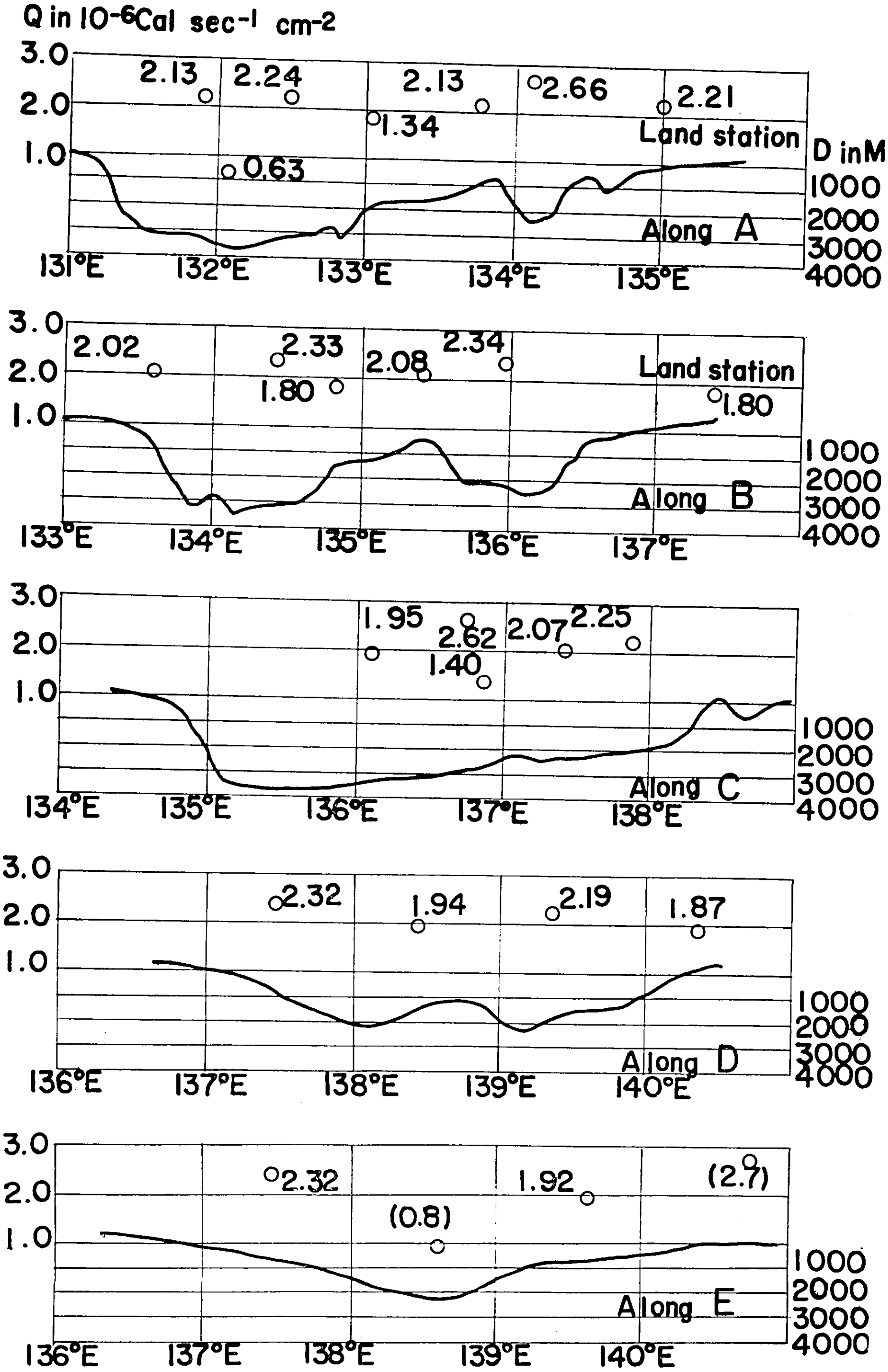

Fig. 8. Heat flow and topographic profiles along the tracks $A-E$ shown in Fig. 1.

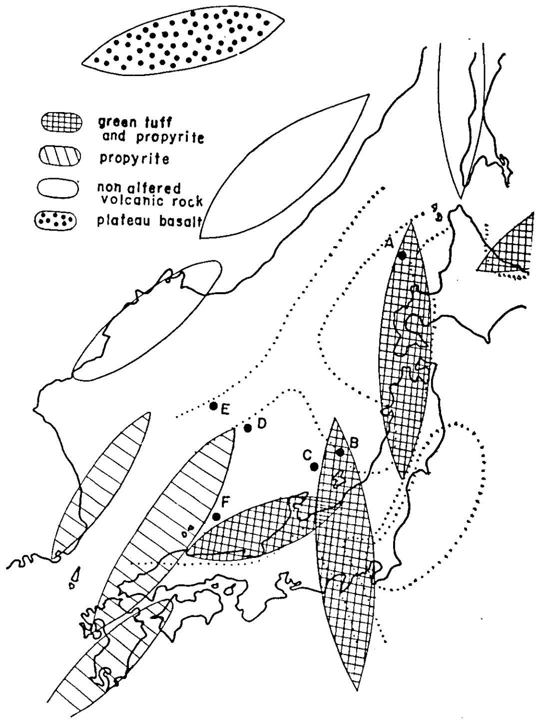

Fig. 9. Distribution of fissure zones (after Fujita) and localities of dredging mentioned in the text.

(Fig. 6). Summaries of these results are as follows:—

A : Kamui Reef. Collected igneous pieces are andesite rocks with hornblende and quartz, and granite gravels. Basement rock was believed not to be of volcanic origin.

B : Bank groups north of Sado island. Rocks are similar to those of the Green Tuff Zone on the land.

C : Hakusan Bank. Almost the same rocks as those of the Green Tuff Zone.

D : Yamato Bank.

E : Kita (north) Yamato Bank.

F : Oki Bank.

Almost the same rocks as those in the Japan Sea side of the Japanese Island were collected from these areas. On the banks, Paleozoic andesite and hornfels derived from andesite, and supposedly late Mesozoic rhyolite and granite, seem to be broadly distributed. Since rhyolites are accompanied by a large quantity of welded tuff, these areas are supposed to have been land in the late Mesozoic time. The submergence of these areas might have begun in the late Pliocene. (A, B and C by Hoshino and Satô; 1958 S, E and F by Niino; 1933, 1935, Satô and Ono; 1963)[8),9),10),11)].

According to these results, it may not be a great fault to say that at least a part of the measured high heat flow in the Japan Sea is also derived from the volcanism since the Neogene, or late Miocene times, as in the case of land heat flow.

Further discussion should await further measurements and observations not only of heat flow but also general geological and geophysical features of the area.

Acknowledgement

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8) T. HOSHINO and T. SATÔ, *Hydrographic Bull.*, **55** (1958), 29-36.
9) H. NIINO, *J. Geol. Soc. Japan*, **40** (1933), 86-100.
10) H. NIINO, *J. Geol. Soc. Japan*, **42** (1935), 675-684.
11) T. SATO and K. ONO, *J. Geol. Soc. Japan*, **70** (1963), 434-445.

35. 地球熱学 第16報 日本海における海洋底地殻熱流量 (1)

舞鶴海洋気象台 安井 正
東京大学大学院 渡部 暉彦

日本海の地殻熱流量観測は舞鶴海洋気象台観測船「清風丸」により着手され，1964年日本海のほぼ全域に亘り30点の観測を行なつた．その平均値は2.03 μcal/cm²sec という異常に高い値であるが，日本列島に沿つて日本海中央部を走る他の部分よりやや低い熱流量を示す地帯，佐渡ヶ島東北方のほぼ陸上の平均値に近い地域などの微細構造が見られるようである．より立入つた議論は1965年の諸種の観測結果を待つものであるが，日本海高熱流量のある程度の部分は新第三紀以降の火山活動によつてまかなわれうるかも知れない．

また海水温度の年変化が熱流量観測値に及ぼす影響もごく単純なモデルにおいて吟味され，海底表面の温度の年変化の振幅が0.02°C であるとき期待される観測値へのじよう乱は0.1 μcal/cm²sec にも達することが明らかになつた．