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Report on DELP 1985 Cruises in the Japan Sea Part V: Heat Flow Measurements

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Abstract

Heat flow measurements were carried out in the Japan Sea at three stations on the KH82-4 cruise of R/V Hakuho-Maru and twelve stations on the DELP-85 WAKASHIO cruise. In the Yamato Basin, heat flow is very uniform and consistent with the existing data. The ages of the Yamato Basin and Tsushima Basin are estimated to be about 25 m.y. if based on the heat flow data. It was proved that the heat flow is variable in the Mogami Trough which was previously thought to be a low heat flow zone. A high heat flow value possibly associated with an anomalous reflector was obtained in the hypocentral region of the 1983 Nihonkai-Chubu Earthquake.

1. Introduction

In the Japan Sea, heat flow measurements were extensively carried out in the 1960's and over 150 values have been already reported (*e.g.* YASUI *et al.*, 1968). These data demonstrate that the heat flow in the main deep basins is very uniform and relatively high, around 100 mW/m^2, while it is lower than 80 mW/m^2 in the Yamato Rise area. Such heat flow distribution supports the idea that the basins in the Japan Sea were formed by back-arc spreading in the Miocene or Oligocene epochs and that the Yamato Rise is a continental fragment that separated from the Asian continent during the spreading.

On the DELP-85 WAKASHIO cruise, we made heat flow measurements in the Yamato Basin and in the eastern margin area of the Japan Sea (Fig. V-1). In the Yamato Basin, the stations were located along a seismic reflection survey line (Line 4 in Fig. V-1; part III of this report, TOKUYAMA *et al.*, 1987) to investigate the relationship between the surface heat flow and the basement structure. In the eastern margin area, five

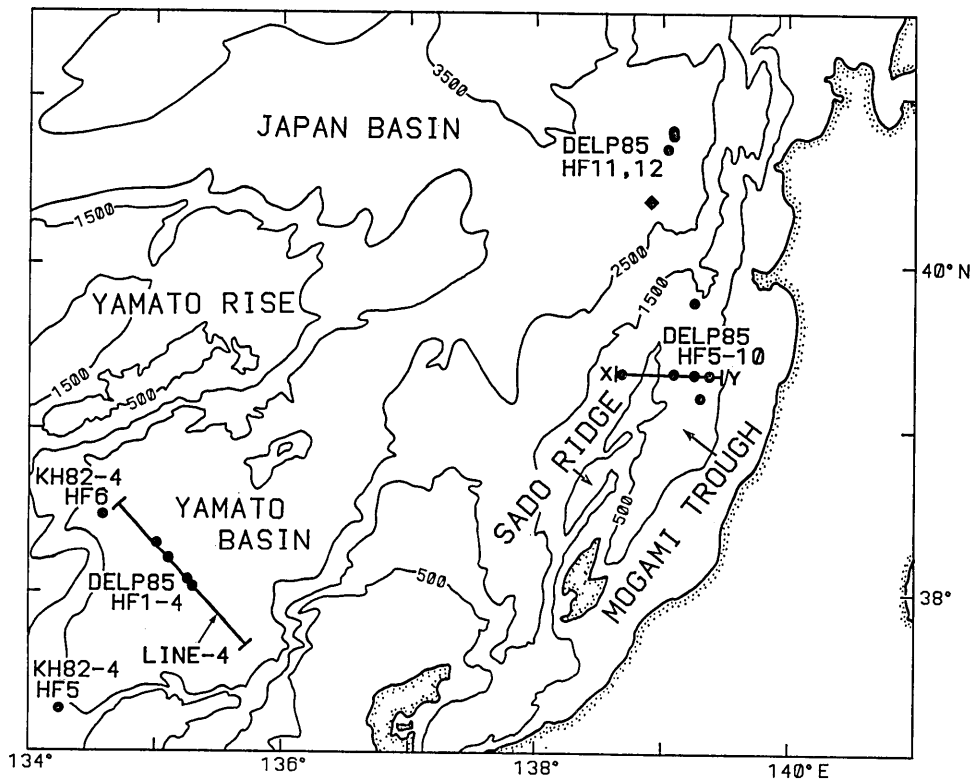


Fig. V-1. Locations of heat flow stations in the Yamato Basin and the eastern margin area of the Japan Sea (circles). Rhombus represents the epicenter of the 1983 Nihonkai-Chubu Earthquake. Contour interval is 1000 m. Seismic profiles along the Line 4 and the line X-Y are shown in Figs. V-4 and V-6 respectively.

stations were in the Mogami Trough where the existing data indicated that heat flow is lower than the mean value for the entire Japan Sea (YASUI *et al.*, 1968). The objective of these measurements was to clarify the extent of this low heat flow zone. Two stations were in the hypocentral region of the 1983 Nihonkai-Chubu Earthquake on May 26, 1983. After the earthquake, Japan Marine Science and Technology Center made a survey of this area using a deep-sea TV camera and found much yellowish material resembling hydrothermal deposits on the sea floor (HOTTA *et al.*, 1985). We intended also to detect a possible thermal anomaly related to this material.

We also report the result of heat flow measurements on the KH82-4 cruise of R/V Hakuho-Maru (Ocean Research Institute, University of Tokyo) in August, 1982, for the measurements were made in the Yamato Basin and Tsushima Basin and the obtained data should be discussed together with the results of the DELP-85 WAKASHIO cruise.

2. Methods

For measurements of the geothermal gradient on the DELP-85 WAKASHIO cruise, we used a 4.5 m long Ewing type probe, which was described by YAMANO *et al.* (1986). On the KH82-4 cruise, we used a 6 m long violin bow type probe (HYNDMAN *et al.*, 1979) manufactured by the Applied Microsystems Ltd., Canada. It consists of a thick strong lance and a parallel thin sensor tube (about 9.5 mm in diameter). Seven thermistors are equally spaced in the tube. Temperatures are recorded on a magnetic tape with a resolution of about 0.002 K.

To compensate the difference in the characteristics of the thermistors, we subtracted the bottom water temperature from the temperature recorded in the sediment for each thermistor. Then the equilibrium temperatures were estimated following BULLARD (1954). Taking account of the error in this extrapolation process, the error in the relative temperature in the sediment was about 0.006 K for the violin bow type probe on the KH82-4 cruise and about 0.004 K for the Ewing type probe on the DELP-85 WAKASHIO cruise.

Thermal conductivity of the sediment was measured by the needle probe method (VON HERZEN and MAXWELL, 1959) on piston core samples taken nearby. The obtained values were corrected for in situ temperature and pressure conditions following RATCLIFFE (1960).

3. Results

3.1. Determination of Heat Flow

Measurements of geothermal gradient were carried out at three stations on the KH82-4 cruise and twelve stations on the DELP-85 WAKASHIO cruise (Table V-1). The locations of these stations are shown in Fig. V-1 except for KH82-4 HF7 in the Tsushima Basin. At several stations, we made multiple penetrations, which are distinguished by alphabetic suffixes. The obtained temperature profiles are shown in Fig. V-2. Temperature gradients were calculated by the least squares fit to straight lines (Table V-1). Solid lines in Fig. V-2 are the best fit lines. Penetration of the lowermost thermistor in Table V-1 was estimated from the temperature gradient and the bottom water temperature.

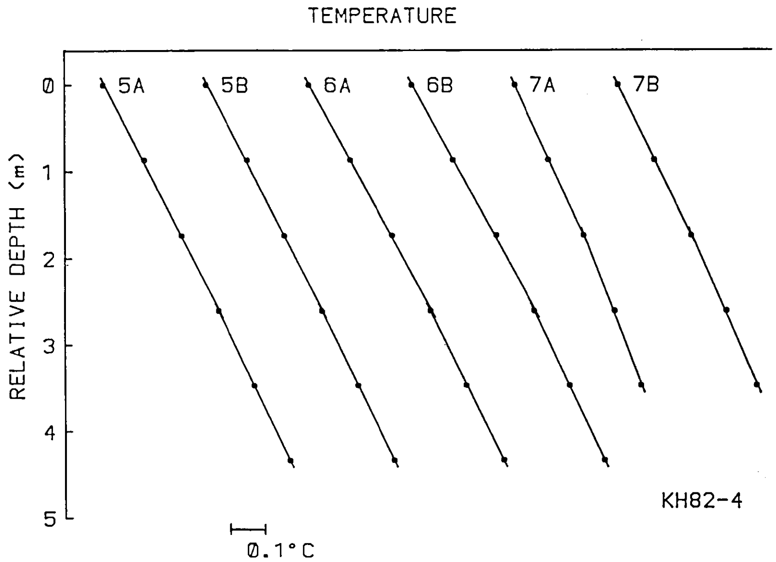
Water depths at the stations DELP-85 HF5 to HF9 are rather shallow, around 800 m. The effect of bottom water temperature variation is usually not negligible in such a shallow sea. In the Japan Sea, however, the water temperature is much more stable than in other seas. YASUI

Table V-1. Results of heat flow measurements.

Station	Latitude	Longitude	D m	PEN m	N	G mK/m	K W/m K	Q mW/m^2
KH82-4 HF5A	37°15.4′N	134°15.6′E	2430	5.0	6			
upper layer						128	0.74*	95
lower layer						119	0.84*	100
HF5B	37°15.5′N	134°15.4′E	2430	5.0	6			
upper layer						129	0.74*	95
lower layer						121	0.84*	102
HF6A	38°28.5′N	134°35.2′E	3010	5.1	6			
upper layer						136	0.74	101
lower layer						121	0.84	102
HF6B	38°28.4′N	134°35.4′E	3010	5.1	6			
upper layer						137	0.74	101
lower layer						117	0.84	98
HF7A	36° 2.4′N	131° 4.7′E	1550	4.3	5			
upper layer						122	0.78	95
lower layer						95	1.00	95
HF7B	36° 1.9′N	131° 4.5′E	1520	4.0	5			
upper layer						122	0.78	95
lower layer						109	1.00	109
DELP85 HF1	38°18.2′N	135° 0.6′E	3015	5.8	6	129	0.75*	96
HF2	38°12.3′N	135° 6.3′E	3010	5.9	6	126	0.75*	94
HF3	38° 4.5′N	135°15.4′E	2995	5.8	6	132	0.75*	99
HF4	38° 1.8′N	135°18.1′E	2990	5.9	6	122	0.75	92
HF5	39°21.5′N	138°41.2′E	785	4.2	5	172	0.80*	138
HF6	39°20.9′N	139.22.7′E	890	5.1	6	112		92**
HF7	39°12.2′N	139°17.5′E	870	4.9	6	144		118**
HF8	39°21.0′N	139°15.6′E	850	4.8	6	98		80**
HF9	39°21.5′N	139° 5.8′E	790	5.1	6	175		144**
HF10	39°47.2′N	139°15.1′E	1525	5.0	6	103	0.75*	77
HF11	40°41.7′N	139° 2.5′E	3320	0.9	2	(318)	0.79*	(251)
HF12A	40°48.6′N	139° 5.2′E	3320	5·0	6	104	0.79	83
HF12B	40°48.3′N	139° 5.3′E	3315	5.2	5	102	0.79	81
HF12C	40°47.5′N	139° 5.4′E	3310	1.5	2	(199)	0.79	(157)
HF12D	40°46.5′N	139° 5.5′E	3320	5.1	4	102	0.79	80

D is the water depth on the assumption that sound velocity is 1500 m/s; PEN is the estimated penetration of the lowermost thermistor; N is the number of thermistors in mud; G is the temperature gradient; K is the thermal conductivity (* represents values measured at nearby stations); Q is the heat flow (** represents values calculated from the temperature versus thermal resistance relations).

Values in parentheses are less reliable.



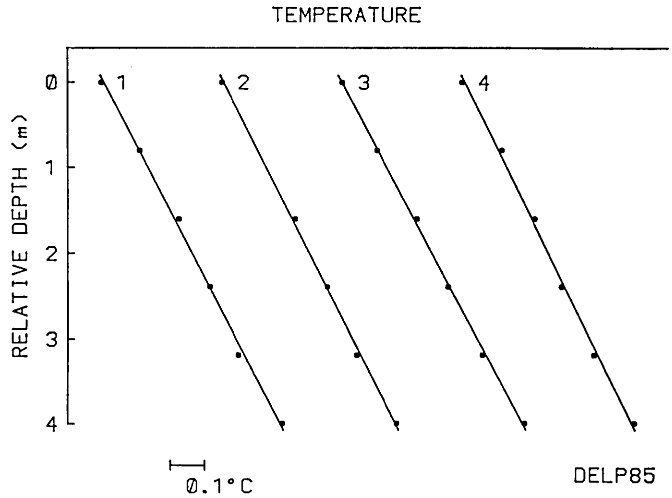
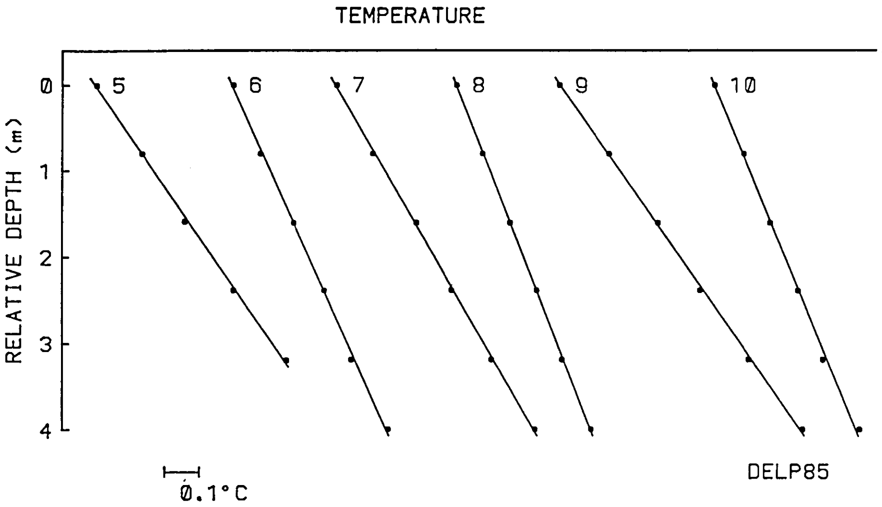


Fig. V-2. (a), (b)

and WATANABE (1965) examined the stability of the water temperature in the Japan Sea and showed that the amplitude of temperature variation at a water depth of 800 m is about 0.02 K. If it is assumed that temperature variation is annual, the amount of temperature disturbance at any subbottom depth can be estimated. When the thermal diffusivity of the sediment is $2.5\times10^{-7}m^2/s$, the disturbance will decay to about 15%



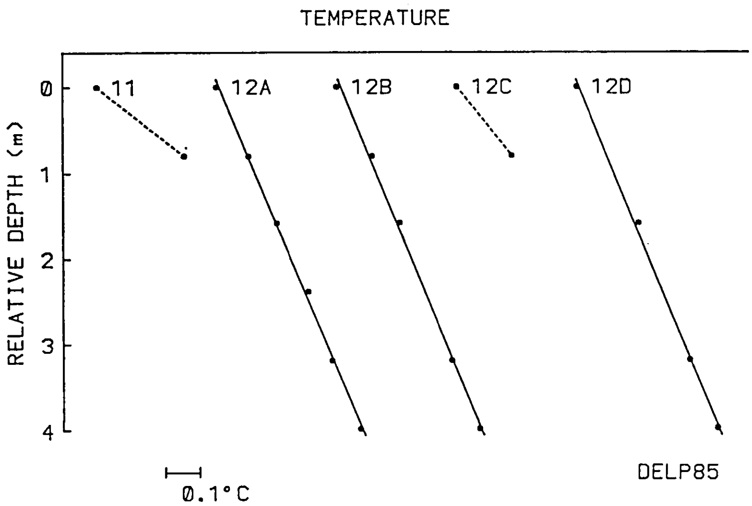


Fig. V-2. (c), (d)

Fig. V-2. Temperature versus depth profiles. Solid lines are the least squares fits to straight lines.

(a) KH82-4 cruise; (b)-(d) DELP-85 WAKASHIO cruise

and 4% (*i.e.* 3 mK and 0.8 mK) at subbottom depths of 3 m and 5 m respectively. Considering that the temperature gradients are 100 to 180 mK/m (Table V-1), the disturbance should be negligible. The observed

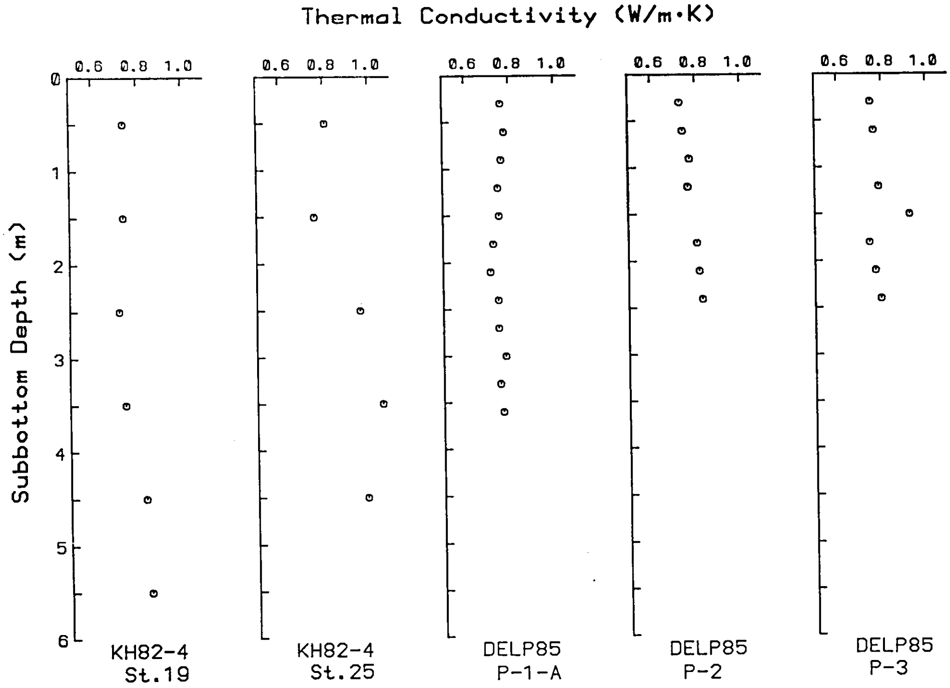


Fig. V-3. Thermal conductivity versus depth measured on piston core samples.

linear temperature profiles support this inference.

Thermal conductivity was measured at two stations on the KH82-4 cruise and three stations on the DELP-85 WAKASHIO cruise. The obtained values are plotted versus depth in Fig. V-3 and the averages are shown in Table V-2. At KH82-4 St. 19 (HF6) and St. 25 (HF7), thermal conductivity seems to change at a depth of about 4 m and 2 m respectively, though the number of measurements is small. Since the temperature gradients at these stations seem to change consistently (Fig. V-2), we calculated heat flow for upper layer and lower layer separately (Table V-1). At KH82-4 HF5, thermal conductivity is assumed to change in the same way as at HF6, since the temperature profiles are similar.

A slight increase of thermal conductivity with depth can be seen at DELP-85 P-2, but the temperature profile at the nearby station, DELP-85 HF6, seems to be linear. In such a case, we calculated heat flow from the plot of temperature versus thermal resistance. For the stations where thermal conductivity measurement was not made, the conductivities were assumed from the values measured in this study or those reported in the vicinity.

The obtained heat flow values are listed in Table V-1. The accuracy

Table V-2. Results of thermal conductivity measurements.

Station	Latitude	Longtiude	D m	LEN m	K W/m K
KH82-4 St. 19	38°29.1′N	134°34.6′E	3010	8.7	
upper layer					0.74
lower layer					0.84
St. 25	36° 2.7′N	131° 5.6′E	1570	8.8	
upper layer					0.78
lower layer					1.00
DELP85 P-1-A	38° 0.9′N	135°18.6′E	2990	3.8	0.75±0.02
P-2	39°20.9′N	139°22.7′E	890	2.4	0.78±0.04
P-3	40°48.8′N	139° 5.6′E	3315	2.8	0.79±0.06

D is the water depth on the assumption that sound velocity is 1500 m/s; *LEN* is the length of the obtained core; *K* is the average thermal conductivity and the standard deviation.

of the values depends mainly on the accuracy of the assumed thermal conductivity and is estimated to be 10 to 15%. The values in parentheses are less reliable as they were determined from only two temperature data.

3.2. Yamato Basin and Tsushima Basin

KOBAYASHI and NOMURA (1972) suggested that oxidation of sulfides and sulfuration of oxides in the surface sediments may account for the high heat flow in the main basins of the Japan Sea. WATANABE *et al.* (1977) examined the temperature profiles obtained by long probes (longer than 8 m) and the result of heat flow measurement at DSDP Site 301. They concluded that heat generation by chemical reaction is insignificant. The temperature profiles at DELP-85 HF1 to HF4 are very linear. At KH82-4 HF5 to HF7, the profiles are slightly bent, but they can be explained by thermal conductivity variation with depth as already mentioned. It means that heat generation in the surface sediment was not detected in the present study.

Fig. V-4 shows the seismic reflection profile along Line 4 in the Yamato Basin (Fig. V-1) with the heat flow values obtained at the stations DELP-85 HF1 to HF4. In spite of a large variation in the depth of the acoustic basement, the heat flow is very uniform, 92 to 99 mW/m^2. The values in parentheses are the existing data near the profile and not much different from the present results.

TAMAKI (1986) calculated the average of the reliable heat flow in each basin of the Japan Sea. He defined the reliable heat flow as the heat flow measured at the station with sediments thicker than 300 m and with no outcrops within 10 km. The mean heat flow at six new stations in

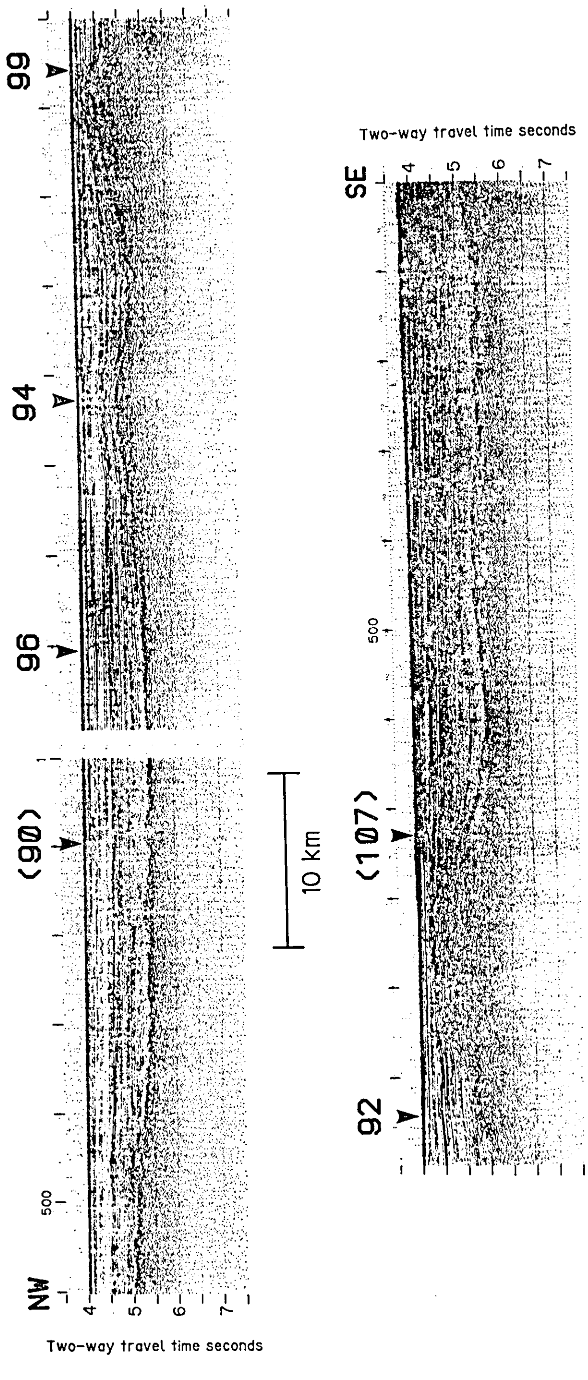


Fig. V-4. Seismic profile along the Line 4 (Fig. III-3(c) of this report, TOKUYAMA *et al.*, 1987) with heat flow values (in mW/m^2). The location of the line is shown in Fig. V-1. Values in parentheses are not on the Line 4 and projected onto the profile.

the Yamato Basin, 97 mW/m², agrees with the average of the reliable heat flow by TAMAKI (1986), 97±12 mW/m². In the Tsushima Basin, the average at KH82-4 HF7, 99 mW/m², also agrees with the average of the reliable heat flow, 96±6 mW/m².

The relationship between heat flow and age has been well determined for oceanic lithosphere (PARSONS and SCLATER, 1977; LISTER, 1977) and the same relation seems to hold for marginal basins (SCLATER *et al.*, 1980; ANDERSON, 1980; YAMANO and UYEDA, 1988). If we assume that this relationship can be applied to the Japan Sea, the ages of the Yamato Basin and Tsushima Basin are estimated to be about 25 m.y., which is much older than the age inferred by paleomagnetic studies of southwest Japan (*e.g.* OTOFUJI and MATSUDA, 1984).

3.3. Eastern Margin Area

All the heat flow data in the eastern margin area of the Japan Sea are plotted in Fig. V-5. The present study revealed that the heat flow in the Mogami Trough is not uniformly low but variable. Four of the stations in the Mogami Trough area were located along the line X-Y in Fig. V-1. Records of 3.5 kHz subbottom profiler along this line are presented in Fig. V-6 together with the obtained heat flow values. There are many faults indicating recent large vertical movement in this area. The existence of these faults and horizontal variation of sediment thickness make it difficult to obtain reliable heat flow data. Large variations of the measured heat flow may result from such environmental effects and high tectonic activity in this area (*e.g.* TAMAKI and HONZA, 1985).

In the hypocentral region of the 1983 Nihonkai-Chubu Earthquake, three good penetrations were attained (DELP-85 HF12A, B and D). The measured heat flow values, 80 to 83 mW/m², are not anomalous for the Japan Sea. The temperature profiles are, however, slightly non-linear (Fig. V-2). It might result from variation of thermal conductivity with depth. If it is assumed that the non-linearity is attributed to upward movement of pore water through sediments, we can estimate the total heat flow, sum of the conductive heat flow and the advective heat flow carried by water, based on the formulation by BREDEHOEFT and PAPADOPULOS (1965). The estimated total heat flow is 97 to 106 mW/m².

The star in Fig. V-5 represents the location of DELP-85 HF11. At this station, the bottom sediment was sandy, so only the lower two thermistors penetrated and the probe fell down about five minutes after the penetration. As a result, errors in the estimated equilibrium temperatures are large. Therefore the calculated heat flow is not very reliable, but it is anomalously high, about 250 mW/m². At HF12C, penetration was also poor, only 1.5 m, and the heat flow seems to be high, about 160

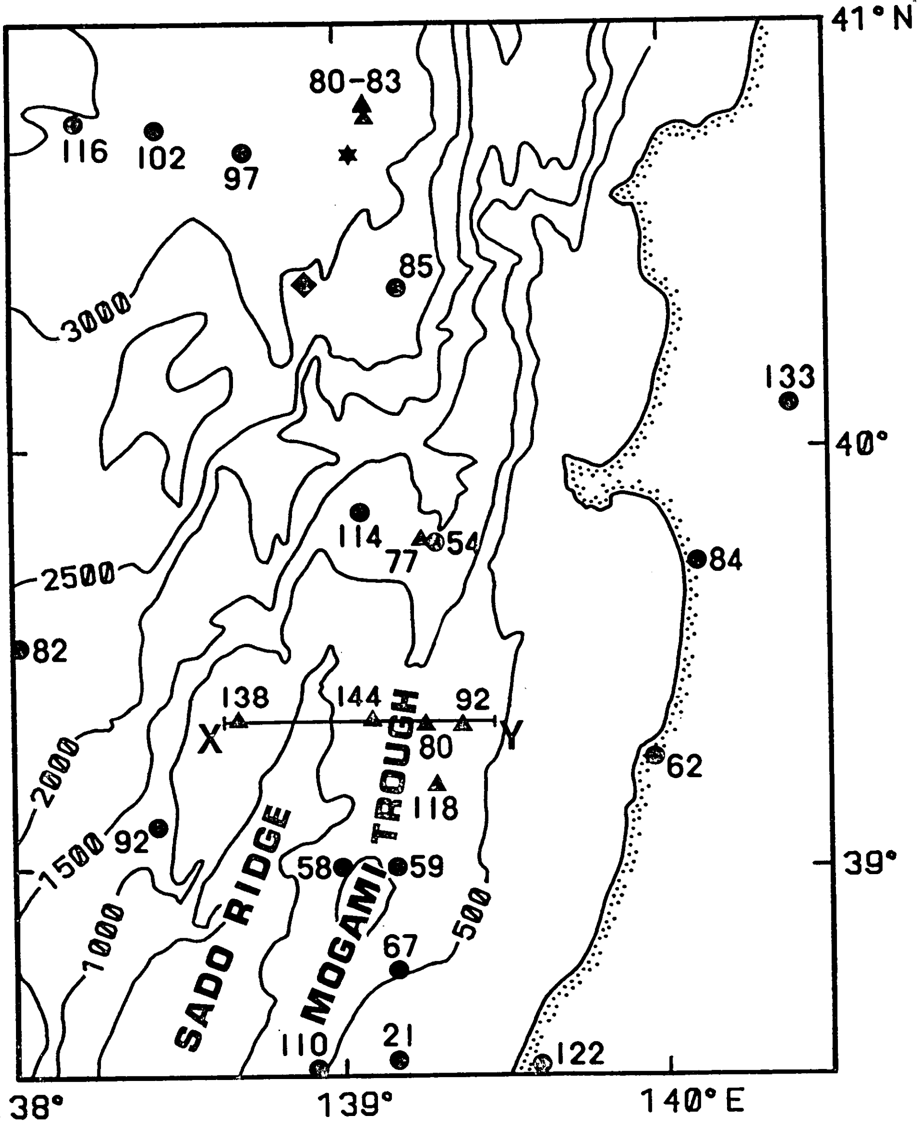


Fig. V-5. Heat flow data in the eastern margin area of the Japan Sea (in mW/m^2). Contour interval is 500 m. Circles represent previous measurements (YOSHII, 1979; unpublished data by Honda and Lamont-Doherty Geological Observatory) and triangles are results of this study. Star is the location of an anomalous reflector (Fig. V-7). Rhombus is the epicenter of the 1983 Nihonkai-Chubu Earthquake.

mW/m^2. Therefore, HF12C might be in a similar state to HF11.

At HF11, an anomalous reflection record was obtained by 3.5 kHz subbottom profiler (Fig. V-7). When this reflection was recorded, the ship was drifting without steaming. Thus the horizontal extent of the

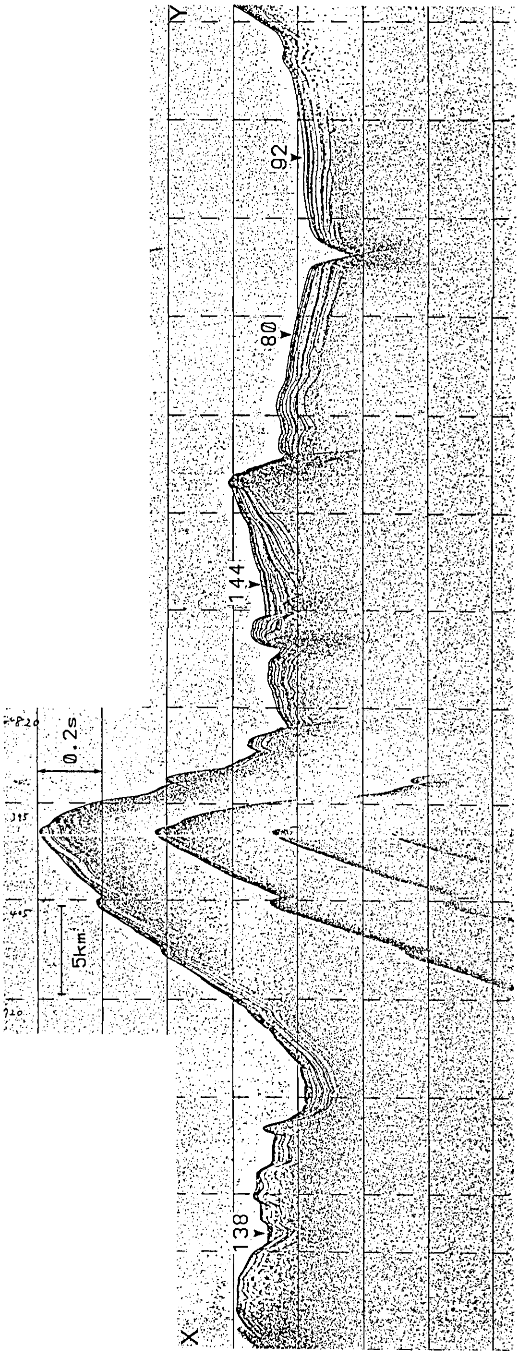


Fig. V-6. 3.5 kHz subbottom profiler record along the line X-Y in Fig. V-1 with heat flow values measured in this study (in mW/m²).

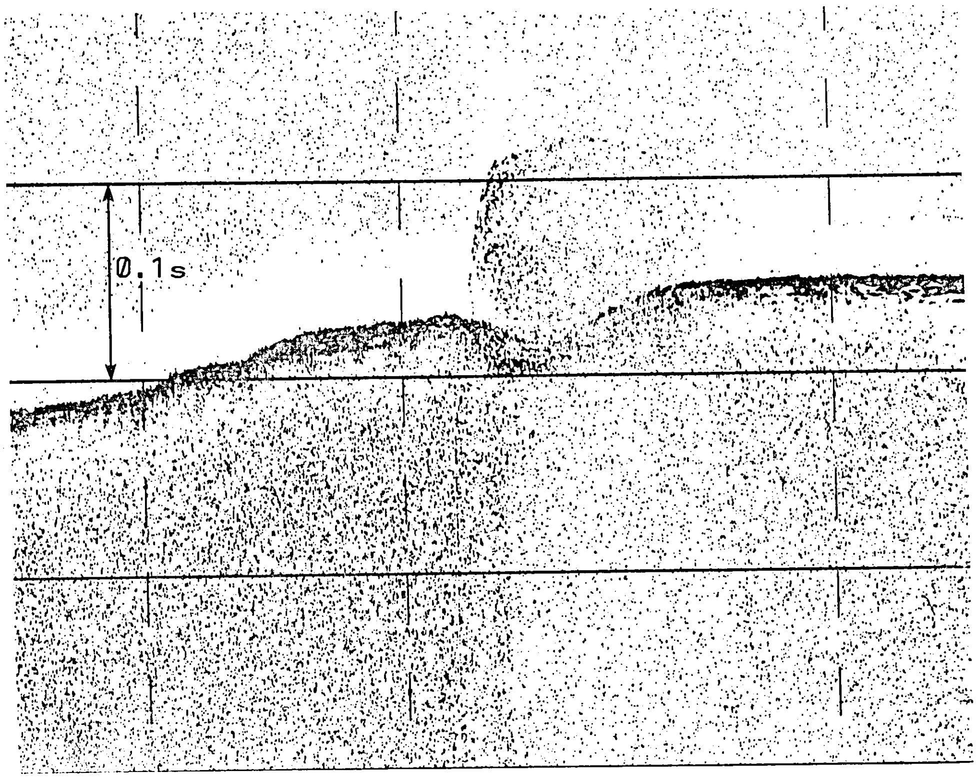


Fig. V-7. 3.5 kHz subbottom profiler record showing an anomalous reflector. Location is shown in Fig. V-5.

reflector is uncertain, but it is probably narrower than 200 m. The anomalous reflector might represent ejection of gas. Similar reflectors have been observed in subbottom profiler records in the vicinity of this station. KATO *et al.* (1986) concluded that they are side echoes caused by small hills based on the result of Seabeam surveys. Hence, the reflector at HF11 might originate from a small hill as well. Whether the reflector represents gas ejection or a small hill, it suggests upwelling of some material which may result in a high heat flow anomaly.

SATO *et al.* (1986) analyzed the sediments at HF11 recovered with the heat flow probe and concluded that they are volcanic materials which probably originated in this area (see also part VI of this report, SHIMAMURA *et al.*, 1987, for sediments recovered with the heat flow probe). As mentioned already, yellow patches were observed on the sea floor near HF11 by deep towed cameras, suggesting ejection of some material from the subbottom layers (HOTTA *et al.*, 1985). FUKUDOME and YAMASHINA (1985) reported that yellowish brown deposits were sampled and degassing was observed west of Kyuroku-shima Island, about 40 km ESE of HF11. They suggested that both the yellow deposits around HF11 and those west of Kyuroku-shima Island are products of hydrothermal activity. KATO *et al.* (1986) dredged fragments of manganese concretion with chemical and mineral compositions similar to those of hydrothermal manganese oxides from a small hill near HF11.

All these observations indicate the existence of hydrothermal activity probably due to recent volcanism in this area, which is consistent with the high heat flow at HF11.

Recently, it was proposed that the lithosphere of the Japan Sea has started to underthrust beneath northeast Japan at the eastern margin of the Japan Sea (*e.g.* KOBAYASHI, 1983; NAKAMURA, 1983). Subduction of an oceanic lithosphere will cool the surrounding mantle and make a low heat flow zone. Such a heat flow anomaly cannot be seen in Fig. V-5. It means that subduction has not taken place yet or the time passed since the initiation of subduction is too short for its cooling effect to be observed.

4. Summary

(1) In the Yamato Basin, the obtained heat flow values are very uniform and close to the mean value of the former measurements. The ages of the Yamato Basin and Tsushima Basin are estimated to be about 25 m.y. if based on the heat flow versus age relation for oceanic lithosphere.

(2) The existing data indicated that heat flow in the Mogami Trough is low, but the measurements on the DELP-85 cruise revealed that heat flow is not uniformly low. It is variable and ranges from 50 to 140 mW/m^2.

(3) A very high temperature gradient was observed in the hypocentral region of the 1983 Nihonkai-Chubu Earthquake associated with an anomalous reflection which may represent ejection of gas or a small hill. It suggests upwelling of some material in this area.

(4) Low heat flow anomaly, which may be caused by subduction of the Japan Sea lithosphere beneath northeast Japan, was not found.

Acknowledgements

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V. 地殻熱流量測定

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白鳳丸 KH82-4 航海では 3 地点，若潮丸 DELP-85 航海では 12 地点において，地殻熱流量測定を実施した．大和海盆においては，熱流量はきわめて一様であり，従来報告されている値とよく一致している．熱流量データから推算される大和海盆及び対馬海盆の年令は，約 25 m.y. である．最上トラフはこれまで低熱流量帯であると考えられていたが，今回の測定ではばらつきの大きい値が得られた．1983 年日本海中部地震の震源域において高熱流量が測定されたが，これは同じ地点での 3.5 kHz 音波探査で観測された特異な反射記録に関連している可能性がある．
