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Report on DELP 1988 Cruises in the Okinawa Trough
Part 8: Heat Flow Measurements

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Abstract

Heat flow measurements were made at 31 stations in the middle and southwestern Okinawa Trough to investigate the thermal structure and hydrothermal activity near the surface. The heat flow in the central graben of the southwestern Okinawa Trough is highly variable, ranging from 30 to 180 mW/m^2. The variability can be attributed to hydrothermal circulation associated with recent volcanic intrusions. In the middle Okinawa Trough, a detailed survey around the central axis has revealed that the area of extremely high and variable heat flow anomaly (with the average of 600 to 700 mW/m^2) is confined in a less than 10 km wide zone along the axis.

1. Introduction

The Okinawa Trough, which is a back-arc basin of the Ryukyu arc-trench system, is thought to be in a nascent stage of back-arc spreading. Extensive geophysical and geological surveys have been run in this area since 1984. In the middle Okinawa Trough, the results of the DELP-84 Wakashio cruise showed that rifting of the continental crust is occurring in the axial part of the trough (JAPANESE DELP RESEARCH GROUP ON BACK-ARC BASINS, 1986). Many heat flow measurements were made in this area in 1984 during the DELP-84 Wakashio cruise, the SO34 cruise of the R/V Sonne, and the Pop 1 cruise of the R/V Jean Charcot, and an extremely high heat flow anomaly was observed in the central rift zone (YAMANO *et al.*, 1986a; b; 1989). The anomaly is

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probably a result of the present or recent volcanism associated with rifting.

In the southwestern Okinawa Trough, former studies suggested that back-arc spreading has produced an oceanic crust along the axis (e.g. LEE *et al.*, 1980). The results of recent investigations, however, threw doubt on the existence of the oceanic crust (KATSURA *et al.*, 1986; SIBUET *et al.*, 1987). Heat flow measurements during the Pop 1 cruise demonstrated that the heat flow is low in the central graben and increases northward at about 125°E (YAMANO *et al.*, 1989). But this heat flow profile may not be a typical one because it was obtained near a transition zone between two central grabens.

During the DELP-88 cruise in July, 1988, we made heat flow measurements mainly in the southwestern Okinawa Trough to add more data to the Pop 1 results and to investigate the thermal structure beneath this area. The stations were located along a seismic survey line across the trough at about 124°30′E (Parts 2 and 3 of this report) and within the central graben (Yaeyama Graben). We also made measurements in the axis area of the middle Okinawa Trough in order to examine the extent of the high heat flow anomaly.

We also report the results of heat flow measurements conducted during the KH87-2 cruise of R/V Hakuho-Maru (Ocean Research Institute, University of Tokyo) in May 1987 in the axial high heat flow region of the middle Okinawa Trough.

2. Measurement Techniques

We used the ordinary method for surface heat flow measurements; penetrating a few meters long probe into the surface sediment to measure the geothermal gradient, taking sediment core samples to measure the thermal conductivity, and multiplying these two values together. Several types of probes were used for measuring the geothermal gradients.

(a) Ewing type probes (EL, ES, CH)

This type was used during the DELP-88 and KH87-2 cruises. The advantage is that it can collect data efficiently and can make closely-spaced measurements by allowing multiple penetrations into the seafloor during one lowering. A disadvantage is the difficulty in penetration into coarse sediment due to the large diameter (40 to 73 mm).

We used two kinds of Ewing type probes. One belonged to the Earthquake Research Institute, and it had larger (EL) and smaller (ES) versions. The large version was used during the DELP-88 cruise, and its configuration was already described by KINOSHITA *et al.* (1990), therefore omitted here. The data logger was developed by the Woods Hole Oceanographic Institution (WHOI). The small version, used during the KH87-2 cruise, was 3 m in length and about 150 kg in weight. It had six temperature sensors. The data logger was made by the Lamont-Doherty Geological Observatory of Columbia University (LDGO). Temperature data are recorded on a magnetic cassette tape. The range of temperature recorded by the LDGO logger was about 3.5 K, while the WHOI logger covered a temperature range of over 20 K.

The other was developed and has been improved by Chiba University since 1984 (NAGIHARA *et al.*, 1986), and used during the DELP-88 cruise (CH). It is similar in ability to the LDGO and WHOI data logger, and the temperature resolution is about 2 mK over a full scale of 5 K. Its weight and length are about 300 kg and about 4 m, respectively. In order to prevent loss of the whole instrument, the lance was designed to drop off in case it should suffer a large tension while being pulled out. Actually we saved the principal part of the probe by dropping off a lance during the DELP-88 cruise.

(b) **Violin Bow type** (PC)

This type was used during both the KH87-2 and DELP-88 cruises. It has a sensor string with eight thermistors mounted at 45 cm intervals, stretched like a hair of the violin bow along a 4 m-long core barrel of a piston corer as the stick. Total weight of the probe is about 450 kg, as in the case of prototype Ewing probe. With it, measurements of both the temperature gradient and the thermal conductivity are available at one time. On the other hand, it does not allow multiple penetration Either the LDGO or WHOI instrument was used as the data logger for this type probe.

(c) **Bullard type** (BL)

This type was used during the DELP-88 cruise. It was developed by Tokai University. Two pairs of temperature sensors (IC-thermo sensor) are installed in a thin probe at intervals of 1.0 m and 1.5 m. Temperature differences are measured for each pair of sensors.

Determination of Temperature Gradient

Because any type of probe is heated by friction on penetration into sediments, we extrapolated the obtained temperature data as a function of time to the equilibrium temperature, using the function $F(\alpha, \tau)$ derived by BULLARD (1954), except for the Ewing type probes. As for the Ewing type probes which have thin sensors of 3.5 mm in diameter, the $F(\alpha, \tau)$ function is approximately proportional to the inverse of time after penetration for over five minutes records, because the τ value becomes larger than 20 which satisfies the approximation condition ($\tau>5$; HYNDMAN *et al.*, 1979). Usually, the standard deviation of the temperature from the best-fit curve is a few millidegrees. The temperature gradient was determined using the least squares fit of the temperature versus depth data to a straight line, after correcting for the instrument tilt.

Thermal Conductivity

Thermal conductivity values were determined on piston core samples using the needle probe method (VON HERZEN and MAXWELL, 1959) on board. The recovered sample was split longitudinally into two halves, one of which was used for pore water chemistry analysis and the other half was used for thermal conductivity measurement and for geological studies. It was kept laid horizontally for a few hours in order to equilibrate the core temperature to the laboratory temperature, taking care not to lose interstitial water. Measurements were made at depth intervals of 30 cm; they were repeated twice in order to reduce errors. The results were corrected for the temperature and pressure conditions at the sea floor after RATCLIFFE (1960).

In the case where we did not obtain in-situ thermal conductivity values (i.e. except for 'PC' probe), we used a value or appropriate combination of values of thermal conductivity obtained in the vicinity.

3. Results

We tried measurements at 5 stations during the KH87-2 cruise and at 26 stations during the DELP-88 cruise, including 17 stations located along and across the Yaeyama Graben in the southwestern Okinawa Trough and the other 14 stations in the Iheya Deep area, which is the central rift region of the middle part of the trough (Fig. 1). The geographical coordinates and the data obtained at successful stations are listed in Table. The alphabet after the number of the station name indicates multiple penetrations.

Fig. A-1 in the appendix shows the temperature versus depth profiles. Solid lines represent the least-squares fit of the data to a straight line. For the station KH87-2 CB-1E, two lines were drawn to represent the two extreme possible values of the instrument tilt. Most of the profiles are linear, with non-linearity at several stations (KH87-2 CB-5C, DELP-88 HF5A, HF13B, HF15A, B, D, and HF26B). In some cases, the non-linear profiles may result from unreliable data points due to possible movement of the probe in mud or failure of the sensors.

The thermal conductivity values from core samples are plotted in

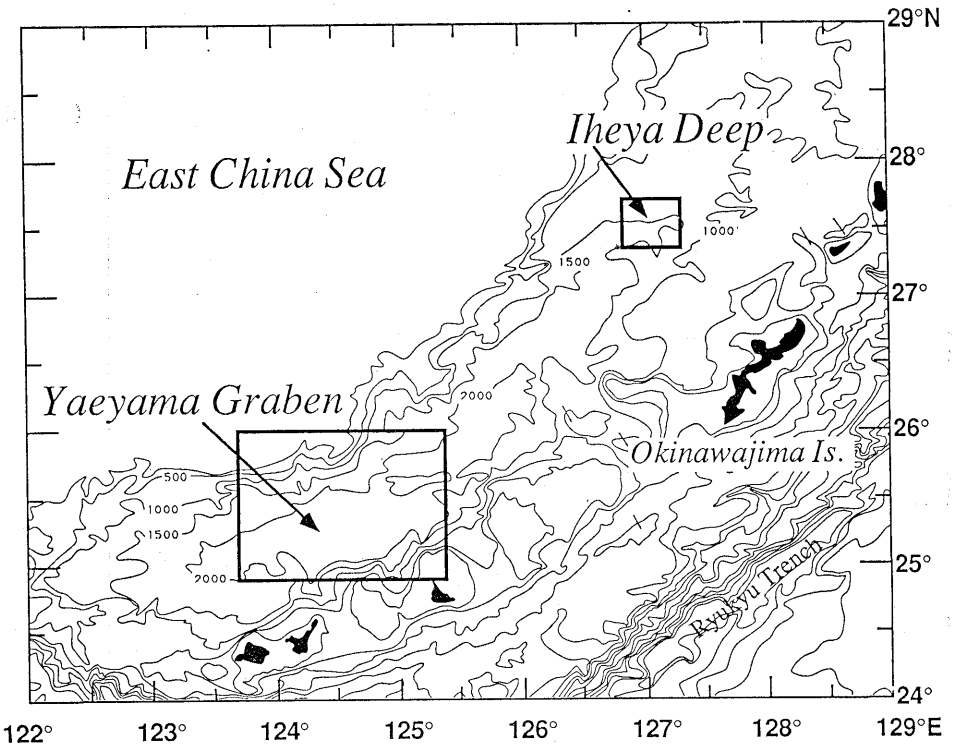

Fig. 1. Yaeyama and Iheya areas in the Okinawa Trough. Heat flow data in the boxes are shown in Figs. 2 and 4.

Fig. A-2 in the appendix. Within sandy layers, the measured thermal conductivity is higher than that in other parts (e.g. uppermost section of DELP-88 HF23).

3.1. Yaeyama Graben Area

The Yaeyama Graben is a depression extending in an E-W direction at the axis of the southwestern Okinawa Trough (Fig. 2). There is a small knoll in the graben at about 25°16′N, 124°25′E (Yaeyama Central Knoll). Seismic surveys were carried out along a NNW-SSE line across trough, which crosses the Yaeyama Graben at the knoll. We tried heat flow measurements along this line except in the vicinity of the knoll where heat flow data had already been obtained on the SO56 cruise of the R/V Sonne in June, 1988 (KINOSHITA *et al.*, 1990). North of the graben, however, penetration was successful only at two stations (DELP-88 HF5 and HF15) due to coarse surface sediments. At DELP-88 HF10, the Bullard type probe penetrated into sediment, but temperature data was not obtained because of damage to the recorder. We also made

Table. Results of heat flow measurements

Station	Latitude N	Longitude E	D m	PR	PEN m	N	G mK/m	K W/mK	Q mW/m^2
KH87-2									
CB-1E	27°33.8′	127° 9.7′	1630	ES		5	(119-154)	0.8 *	(95-123)
CB-5A	27°35.6′	127° 8.2′	1780	ES	2.5	5	419	0.8 *	335
CB-5B	27°35.6′	127° 8.1′		ES	2.5	5	75	0.8 *	60
CB-5C	27°35.7′	127° 8.1′		ES	1.5	4	246	0.8 *	197
CB-5D	27°35.7′	127° 8.3′	1650	ES	2	4	271	0.8 *	217
CB-8	27°35.5′	127° 8.8′	1780	PC	4	8	>1000	0.81	>800
DELP88									
HF5A	25°18.9′	124°28.3′	2200	CH	3.5	5	(182)	0.97*	(177)
HF8A	25° 7.4′	124°27.4′	2100	CH	3.5	5	183	0.93*	170
HF6	25°15.1′	124°21.0′	2300	PC	3	5	52	0.84	44
HF7A	25° 2.2′	124°30.1′	2005	EL	4.5	6	65	0.93*	60
7B	25° 2.0′	124°29.8′	2010	EL	4.5	6	69	0.93*	64
HF9A	25°15.6′	124°36.6′	2260	EL	4.5	5	65	1.03*	67
9B	25°15.5′	124°36.3′	2260	EL	4.5	5	68	1.03*	70
HF10	25°21.6′	124 25.3′	2140	BL				(0.83)	
HF11A	25°13.0′	124°44.8′	2290	EL	4.5	7	55	1.05*	58
HF12	25° 5.2′	124°28.7′	2070	PC	2	5	(49)	0.93	(46)
HF13A	25°13.5′	124°14.6′	2300	CH	4	3	194	0.84*	163
13B	25°13.4′	124°14.6′	2300	CH	4	3	(198)	0.84*	(166)
HF14	25°26.4′	124 25.3′	2080	PC				(1.02)	
HF15A	25°25.1′	124°25.7′	2100	EL	1.5	3	(79)	0.89*	(70)
15B	25°25.0′	124°25.6′	2090	EL	3.5	5	98	0.89*	87
15D	25°25.3′	124°25.8′	2080	EL	1.5	4	110	0.89*	98
HF18A	27°38.3′	127°15.6′	1690	EL	1.5	3	239	0.8 *	191
18B	27°38.1′	127°15.6′	1690	EL	1.5	3	288	0.8 *	230
18C	27°37.9′	127°15.4′	1690	EL	4.5	6	322	0.8 *	258
HF20A	27°35.3′	127° 3.3′	1650	EL	3.5	6	94	0.8 *	75
20B	27°35.4′	127° 3.2′	1640	EL	2	3	111	0.8 *	89
HF21	27°35.4′	127° 9.2′	1760	PC	4	6	1304	0.76	991
HF22	27°34.6′	127°12.8′	1740	PC	3.5	5	291	0.76	221
HF23	27°34.5′	127°11.5′	1750	PC	3	4	411	0.78	321
HF24B	27°32.5′	127°12.4′	1560	CH	2	2	(184)	0.8 *	(147)
HF25A	27°31.0′	127° 0.8′	1650	EL	4	5	33	0.8 *	26
25B	27°31.0′	127° 9.0′	1645	EL	1.5	3	(28)	0.8 *	(22)
25C	27°31.0′	127° 9.1′	1640	EL	1.5	3	67	0.8 *	54
HF26A	27°32.4′	127° 2.7′	1700	EL	4	3	35	0.8 *	28
26B	27°32.4′	127° 2.6′	1700	EL	4.5	7	36	0.8 *	29
26C	27°32.5′	127° 2.9′	1700	EL	4.5	7	25	0.8 *	20

D is the uncorrected water depth; PR is the type of heat flow probe (ES, EL, PC, CH, and BL are ERI-short, ERI-long, HFPC, Chiba, and Bullard type respectively); PEN is the estimated penetration of the lowermost temperature sensor; N is the number of active temperature sensors in mud; G is the temperature gradient; K is the thermal conductivity (* represents values measured at nearby stations); Q is the heat flow. Values in parentheses are less reliable.

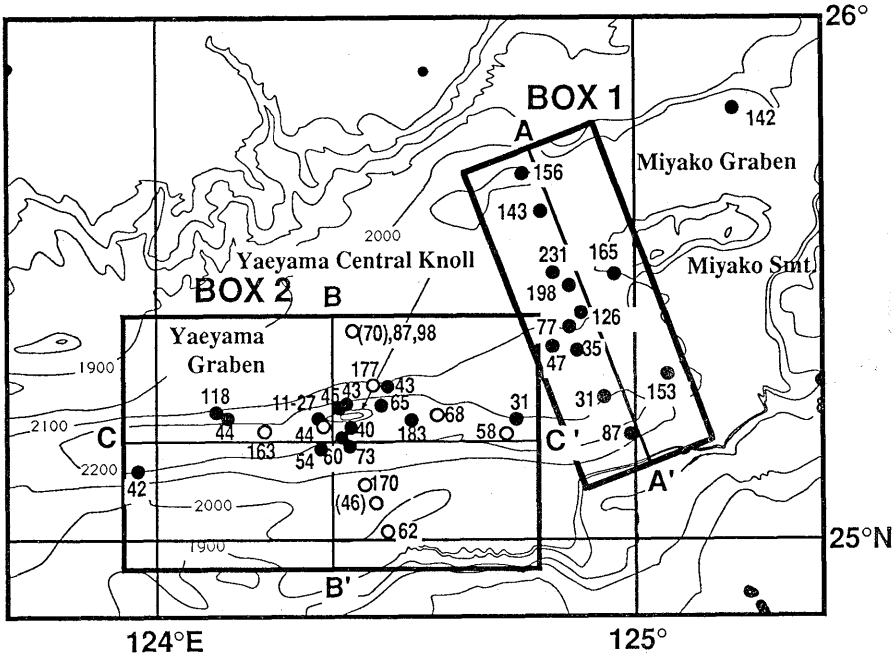

Fig. 2. Heat flow data in the Yaeyama Graben area, southwestern Okinawa Trough (mW/m²). Solid circles: obtained by previous studies; open cirdes: obtained by this study. Bathymetry contours are based on Oshima *et al.* (1988).

measurements within the graben to the east and the west of the knoll.

All the available heat flow data around the Yaeyama Graben are plotted on a bathymetry map in Fig. 2. In order to examine characteristics of the heat flow distribution in the Yaeyama Graben area, we constructed heat flow profiles in two boxes in Fig. 2. The data in the eastern box were projected along the line A-A′ and the data in the western box were projected along the lines B-B′ and C-C′ (Fig. 3). In the eastern box, which is located at the eastern end of the Yaeyama Graben, the heat flow increases northward from about 30 mW/m² in the graben to over 200 mW/m², as pointed out by YAMANO *et al.* (1989).

The heat flow in the western box shows a complicated pattern. The heat flow is lower than 50 mW/m² within 2 km of the foot of the Yaeyama Central Knoll (KINOSHITA *et al.*, 1990), but higher than 150 mW/m² values also exist in the Yaeyama Graben (Figs. 2 and 3b). Higher heat flow values can be seen north and south of the Yaeyama Central Knoll as well (Figs. 2 and 3c). It looks as if the low heat flow in the vicinity of the knoll is surrounded by the higher heat flow.

3.2. Iheya Deep area

The Iheya Deep is located in the central rift zone of the middle

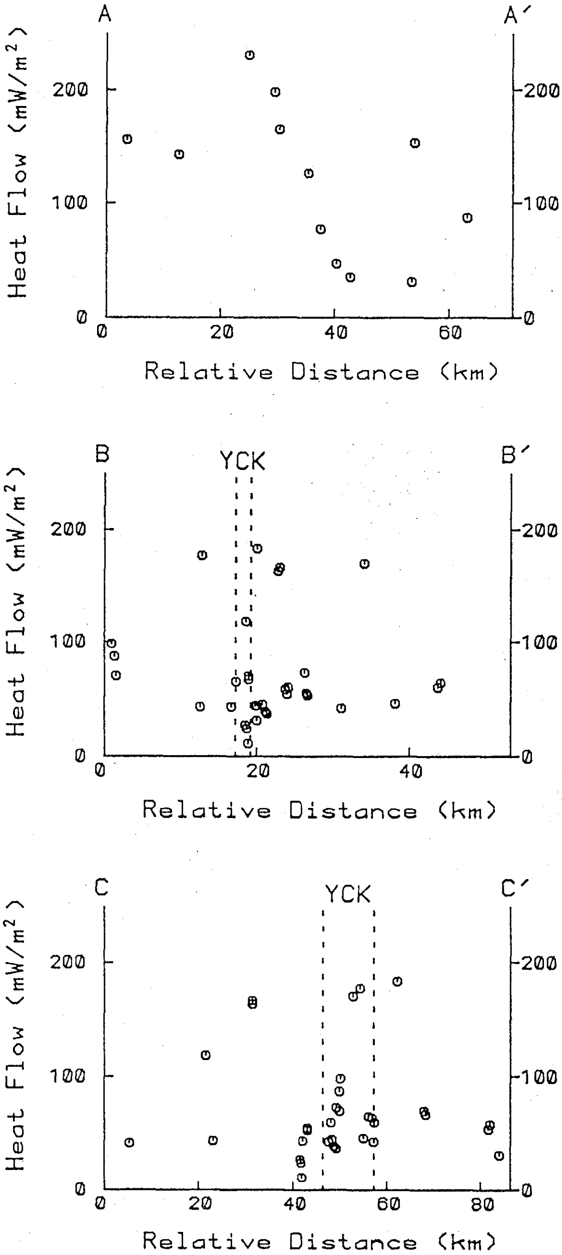

Fig. 3. Heat flow profiles along the three lines in Fig. 2.
(a) Data in the eastern box projected onto the line A-A′.
(b) Data in the western box projected onto the line B-B′.
(c) Data in the western box projected onto the line C-C′.
The location of the Yaeyama Central Knoll (YCK) is indicated by pairs of broken lines.

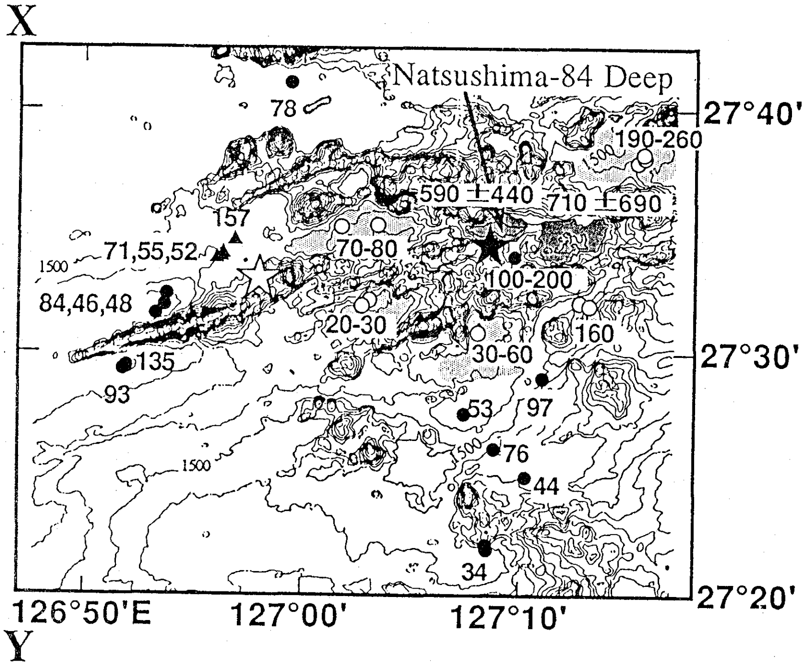

Fig. 4. Heat flow data in the Iheya Deep area, middle Okinawa Trough (in mW/m^2). Solid and open stars represent the locations of active hydrothermal mounds (KIMURA *et al.*, 1988) and hydrothermal vents (TANAKA *et al.*, 1989) respectively. Bathymetry contours are based on OSHIMA *et al.* (1988).

Okinawa Trough, and characterized by a topography lineated in an ENE-WSW direction parallel to the trough axis (Fig. 4). An extremely high heat flow anomaly was found in a small depression, Natsushima-84 Deep, at about 27°35′N, 127°09′E during the 1984 cruises (YAMANO *et al.*, 1986a; b). The average and standard deviation of sixteen values obtained in the deep was about 600 and 400 mW/m^2, respectively. The high and variable heat flow indicates the existence of hydrothermal activity in this region. Discovery of active hydrothermal mounds on a small knoll just south of the deep (solid star in Figs. 4 and 5, KIMURA *et al.*, 1988) supported this inference.

During the KH87-2 cruise, we made heat flow measurements in the Natsushima-84 Deep and its vicinity. One of them was a 'PC' station (KH87-2 CB-8), and the temperature gradient could not be determined because the temperature exceeded the recording range of the LDGO data logger (more than 3.5 K above the bottom water temperature). From the distance between the seafloor and the topmost sensor, which was inferred from the recovered core sample, temperature gradient was estimated to be higher than 1000 mK/m. At all the stations outside the

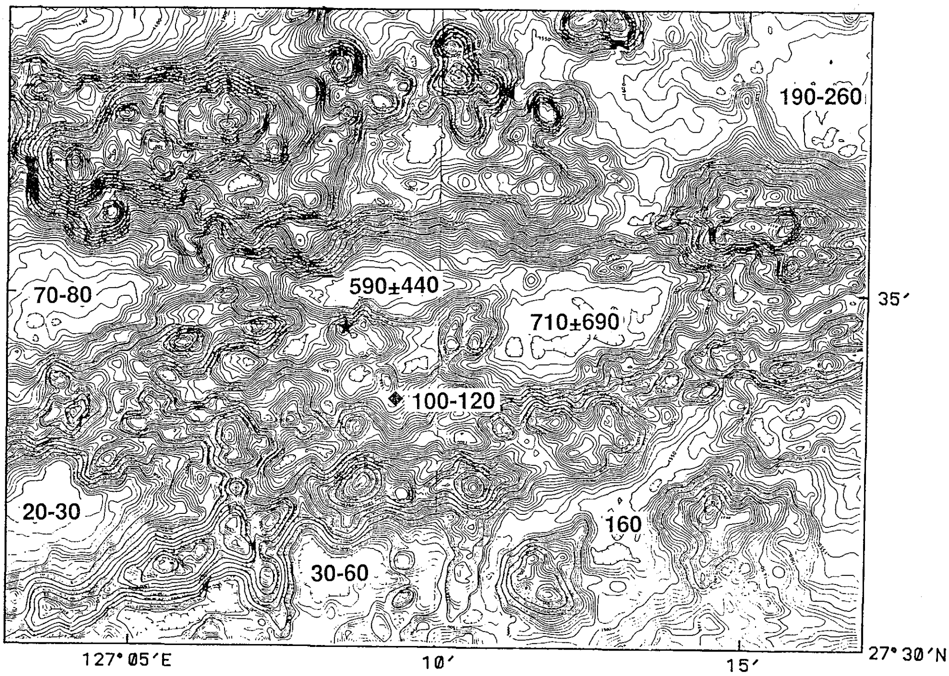

Fig. 5. Detailed bathymetry map by the Hydrographic Department, Maritime Safety Agency, Japan and heat flow data (mW/m^2) around the Natsushima-84 Deep and the eastern deep. Solid star represents the location of active hydrothermal mounds (KIMURA *et al.*, 1988).

deep, the temperature probe fell down or tilted.

Measurements during the DELP-88 cruise were carried out mainly in similar small depressions surrounding the Natsushima-84 Deep (Fig. 5) to examine whether and how this high heat flow anomaly extends outward. The ‘PC’ stations were located in the Natsushima-84 Deep and in a similar depression at about 27°34′N, 127°13′E, just east of the Natsushima-84 Deep (termed the eastern deep below), where high and variable heat flow was measured on the SO56 cruise (KINOSHITA *et al.*, 1990). The purpose for conducting these ‘PC’ stations was to study pore water chemistry which should reflect the feature of hydrothermal activities, and to check possible correlation with the temperature gradient. The result thereof will be reported later.

The heat flow results obtained in the Iheya Deep area are summarized in Figs. 4 and 5. To represent the values in each small depression, the average and standard deviation of heat flow values are shown. Where the numbers of values are small, the range of heat flow values is presented with the maxima and minima. It is clear that the heat flow is very high and variable in the Natsushima-84 Deep (590 ± 440 mW/m^2) and in the eastern deep (710 ± 690 mW/m^2). On the other hand, the heat flow values in the depressions, located to the north and south of the Natsushima-84 Deep and the eastern deep, are low as compared to that in these two basins, though the highest value reaches about 250 mW/m^2. The high heat flow anomaly area is restricted in these two deeps in the Iheya Deep area.

4. Discussion

YAMANO *et al.* (1989) attributed the high heat flow anomaly in the Natsushima-84 Deep to the present or recent volcanism in the central rift zone. The results of the present study suggest that the anomaly extends along the trough axis and confined in a narrow zone, probably less than 10 km wide. It appears, therefore, that the heat source of the anomaly is very shallow and extends in an ENE-WSW direction. The heat source, probably magma chambers or solidified intrusions, may be continuous or distributed in spots beneath the trough axis. Such a high thermal activity must be a manifestation of the rifting in the middle Okinawa Trough.

In contrast, the heat flow is rather low in the central graben in the southwestern Okinawa Trough. It may be partly due to rapid sedimentation. According to Letouzey and KIMURA (1986), the graben is covered only by Pleistocene sediments with a thickness of 3000 m to 4000 m, giving an average sedimentation rate of about 2 mm/year. The resulting decrease in surface heat flow is estimated to be about 30% (VON HERZEN and UYEDA, 1963). Thus, the sedimentation effect cannot explain the large difference in the heat flow at the trough axis between the middle and the southwestern Okinawa Trough. It suggests that the present thermal activity at the axis is probably lower in the southwestern part than in the middle part.

There are still some indications of the existence of hydrothermal circulation in the Yaeyama Graben. The Yaeyama Central Knoll is believed to be a young volcanic feature extruded in the graben, and benthic communities were found on the knoll with a deep sea still camera (KATSURA *et al.*, 1986). It suggests that discharge of warm water is under way on the knoll, and the low heat flow around the knoll may result from the recharge of the circulating water (Fig. 6). The highly variable heat flow observed in a small area near the western foot of the knoll (KINOSHITA *et al.*, 1990) may also result from the existence of pore water flow. It is possible that the higher heat flow values in the Yeayama Graben area are related to unknown volcanic intrusions and the

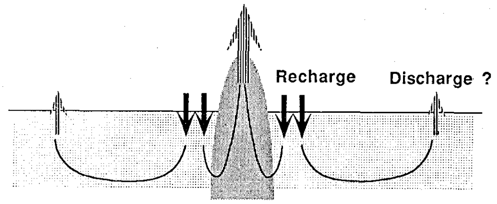

Fig. 6. Schematic model of the probable hydrothermal circulation system around the Yaeyama Central Knoll.

associated hydrothermal circulation.

The monotonous northward increase in heat flow along the Line A-A′ in Fig. 2 is rather enigmatic. GENTHON *et al.* (1990) suggested a hydrothermal circulation cell with a very high aspect ratio to explain the trend, but it is difficult to produce the high aspect ratio circulation without assuming an unusually anisotropic structure. We need further geophysical and geological information including heat flow data to discuss the thermal structure beneath the trough floor.

5. Conclusions

The present study revealed that the extremely high heat flow anomaly in the central rift zone of the middle Okinawa Trough is confined within the close vicinity of the trough axis. In the two small deeps along the axis, the average heat flow reaches 600 to 700 mW/m^2, while the heat flow is 20 to 250 mW/m^2 in the surrounding small depressions. We believe that this axial high heat flow is caused by volcanic activity along the axis and extends westward to the Iheya Ridge, though we can not measure heat flow on the ridge.

In the southwestern Okinawa Trough, there is no significant heat flow anomaly correlated with the central graben. The heat flow in the Yaeyama Graben ranges from 30 to 180 mW/m^2, while the highest value on the trough floor outside the graben exceeds 200 mW/m^2. We may conclude that the present thermal activity is higher in the middle part of the trough than in the southwestern part.

The highly variable nature of the heat flow inside the Yaeyama Graben, a typical example of which is the Yaeyama Central Knoll, and the low heat flow surrounding the knoll may result from hydrothermal circulation associated with discrete volcanic intrusions.

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Appendix: Temperature and thermal conductivity profiles obtained by this study

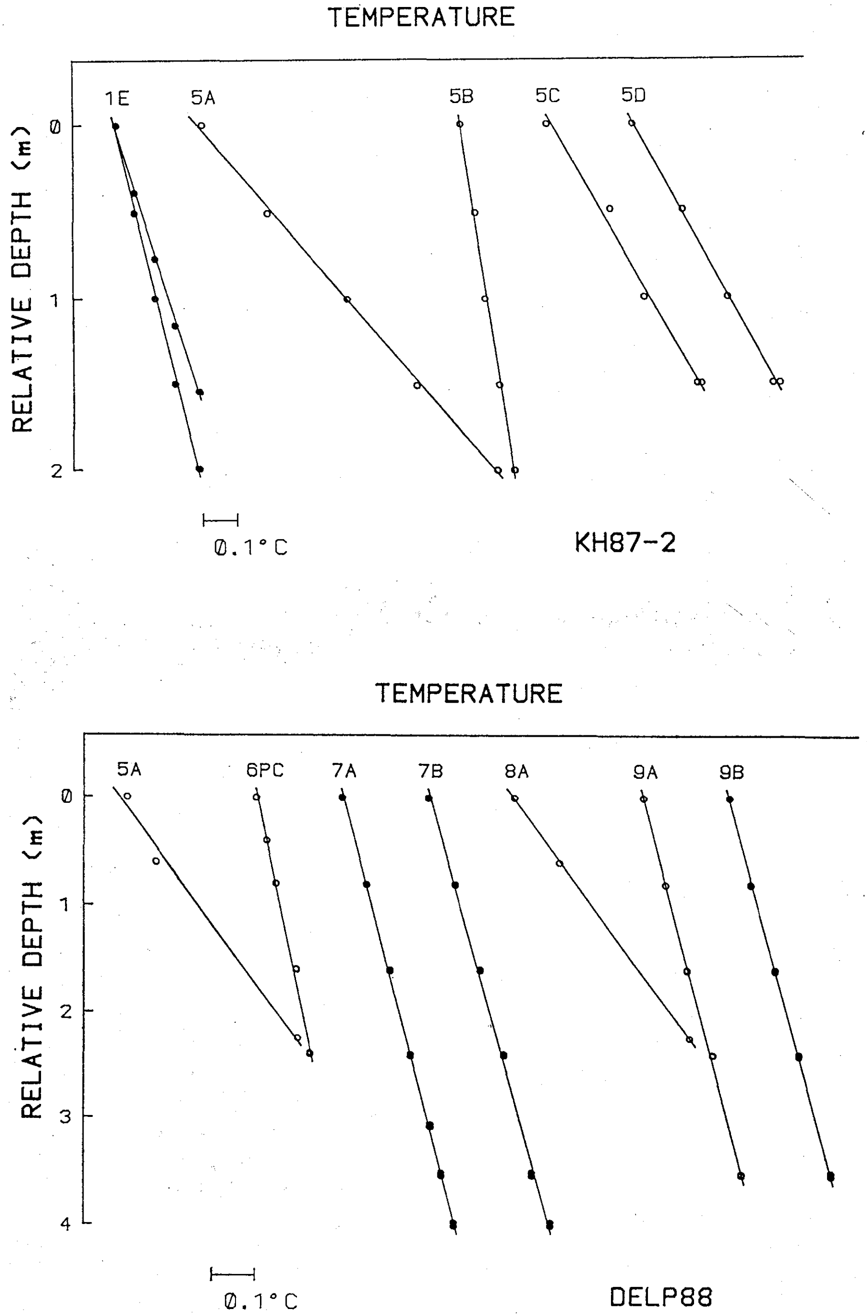
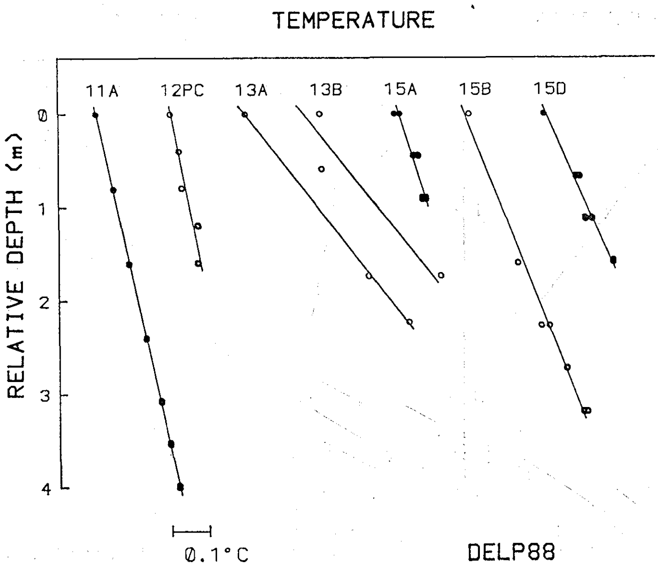


Fig. A-1



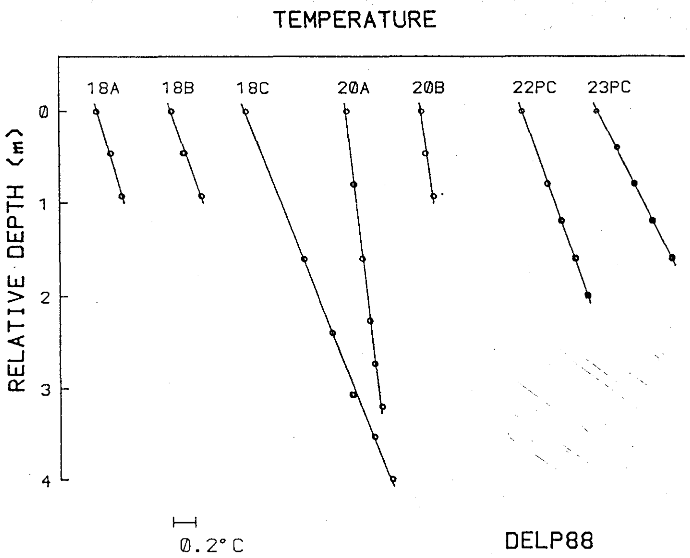


Fig. A-1 (Continued)

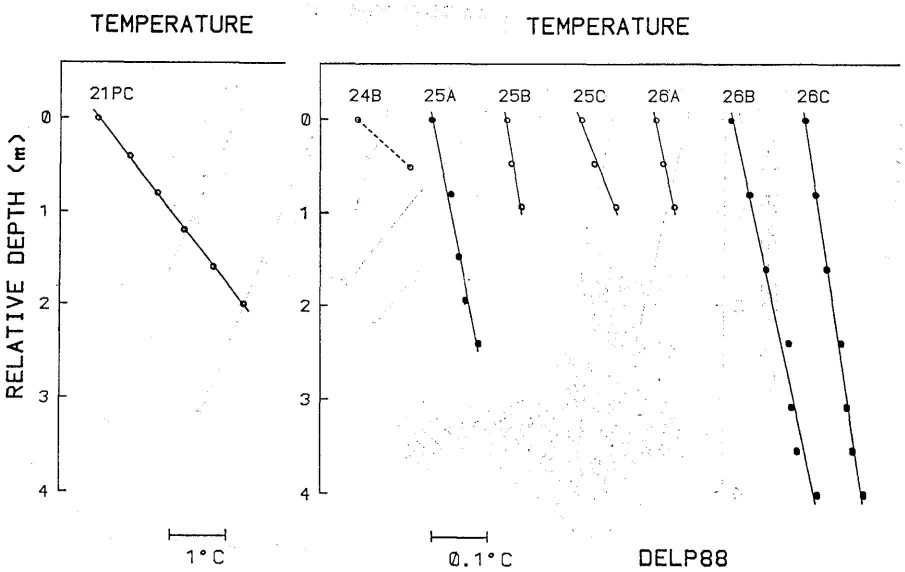


Fig. A-1. Temperature versus depth profiles. Cruise name is attached at the bottom of each figure, and number with alphabets on top of each profile corresponds to the station name in Table. Solid lines show the larst-squares fit to straight lines.

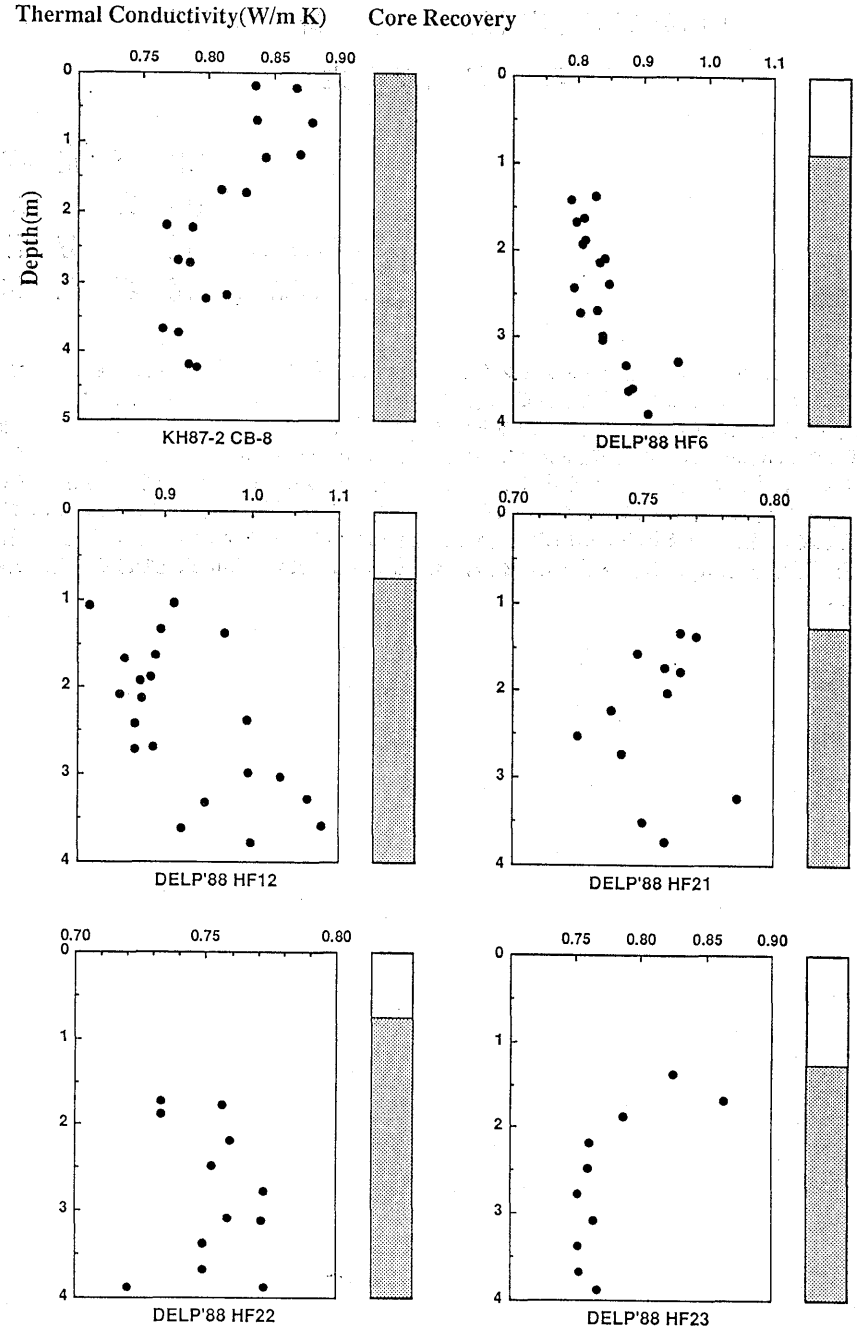


Fig. A-2. Thermal conductivity versus depth profiles with the positions of the corresponding cores.

DELP 1988年度沖縄トラフ海域研究航海報告

8. 地殻熱流量測定

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沖縄トラフでは現在大陸地殻のリフティングが進行中であるとされるが，その熱的構造と表層での熱水循環について調べることを目的として，南西部及び中部沖縄トラフの合計31地点において地殻熱流量測定を実施した．その結果，南西部沖縄トラフでは，中軸部に東西に延びる八重山地溝内の熱流量は 30-180 mW/m² と，中部沖縄トラフでの熱流量値に 1000 mW/m² を超すものがあるのに比べてかなり低く，中軸での熱的活動度が中部より低いことを示唆している．その一方で，熱流量のばらつきは非常に大きく，地溝内に存在する貫入岩体にともなって熱水循環が起こっているのではないかと考えられる．また，1984年の DELP 航海で発見された中部沖縄トラフ中軸部の高熱流量異常域は，軸と平行な方向にはある程度延びているが，その幅はせいぜい 10 km 以内であることが明らかになった．