TAO, Supplementary Issue, 305-317, May 2001

Heat Flow of the Southwestern End of the Okinawa Trough

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(Manuscript received 15 February 2001, in final form 15 March 2001)

ABSTRACT

Detailed heat flow measurements were carried out around the ODP contingency drilling site KS-1 (24°48'N, 122°30'E) located on the southern slope of the southwestern end of the Okinawa Trough. A total of 26 heat flow values were obtained. Within about 10 km of the site, the heat flow is lower than 50 *mW/m*². **Heat flow increases southward to about 65 *mW/m*² on the south edge of the trough. Due to the extraordinarily high sedimentation rates, the sedimentation-corrected heat flow values have increased by as much as 76%, so only the most recent surface sedimentation effects are considered. Distribution of heat flow patterns shows that high heat flow values are associated with igneous activities and are observed in both the northern and southern flank and the western end of the Okinawa Trough. Heat flow values in the E-W trending central rift zone, on the other hand, appear to be lower. This is probably due to hydrothermal activities in the rift zone. The correlation between the heat flow and bathymetric contours is discernable, but with a slight southward shift in the heat flow pattern. Considering the fact that abnormally high and low heat flows are observed near volcanic intrusions, extrusions and faults, and that much higher heat flows would be expected if the full sedimentation effects were eliminated, we suggest that the magma associated with the extension of the southwestern Okinawa Trough has at least extended into the southwestern end of the Okinawa Trough, in northeast Taiwan.**

(Key words: Southwesternmost Okinawa Trough, Heat flow)

1. INTRODUCTION

The Okinawa Trough is a curved backarc basin which is convex to the southeast, and located behind the Ryukyu Trench and Ryukyu Islands. It extends from the Ilan Plain in northern Taiwan to Kyushu Island in southern Japan. Its width increases from 60-100 km in the south to 230 km in the north. The maximum water depth is 2300 m in the south, progressively

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decreasing to 200 m in the north. Tectonically, the Okinawa Trough, formed by extension within the continental lithosphere (Uyeda 1977), is linked to the subduction of the Philippine Sea plate beneath the Eurasian plate. The bending of the Okinawa Trough at its southwestern end is due to the collision between the Luzon volcanic arc riding along the western edge of the Philippine Sea plate and the passive continental margin of the Eurasian plate. South of Taiwan, the Philippine Sea plate overrides the Eurasian plate, whereas northeast of Taiwan the Eurasian plate overrides the Philippine Sea plate. In the southwestern part of the trough, geological evidence suggests that the backarc was initially rifted in the mid-to-late Miocene, and after 5 my cessation of tectonic activity, the second rifting restarted during Pliocene (Kimura 1985; Sibuet et al. 1995). The backarc extension is believed to have started very recently (upper Pleistocene), as shown by the presence of en echelon (Sibuet et al. 1987; Park 1996; Sibuet et al. 1998). Seismic refraction profile shows that the southern Okinawa Trough is still in a continental rifting stage and the extent of oceanic crust is restricted to the trough axis (Hirata et al. 1991). The west end of the Okinawa Trough is joined to the Lishan trough (Sibuet et al. 1998), a northeast extension of the Lishan fault which was recently identified beneath the Ilan Plain (Hsu et al. 1996b). Numerous normal faults in the Lishan trough are ENE-WSW trending while further east, in the southern flank of the southwestern Okinawa Trough, normal faults associated with volcanic intrusions are oriented in an E-W direction, roughly parallel to the extension axis of the Okinawa Trough. Present-day earthquakes are active and suggest that the present-day extension is still in a N-S direction. Continuous spreading and volcanism in the mid and southern Okinawa Trough is indicated by high heat flows. Heat flow values in the Okinawa Trough are relatively high (about 110 mW/m^2 on the average) and very variable (from 9 to 437 mW/m^2), as observed in young ocean basins (Yasui et al. 1970; Lu et al. 1981). In the southwestern part, heat flow seems to be lower in the vicinity of the central rift zone than that in the surrounding areas. Around 126°E, there is a high heat flow area proposed by Vander Zouwen (1984) and Yamano et al. (1989). An extremely high (600 mW/m^2 on the average) and localized heat flow anomaly was observed in the central rift zone which was probably caused by present or recent igneous activity (Yamano et al. 1989).

A major ocean current, the Kuroshio (Black Current), passes through the passage between Taiwan and the southernmost part of the Ryukyu Island Arc and flows northeastward along the Okinawa Trough (Ono et al. 1987). It is the biggest western boundary surface current in the western Pacific and plays an important role in the meridional transport of heat, mass, momentum and moisture from the western Pacific warm pool to the high latitudes of the North Pacific. Its role in the Pacific is as important as the Gulf Stream in the North Atlantic. Lack of knowledge of the past history of this important current system has hindered us from building a complete scenario for the Pleistocene climatic evolution of the Western Pacific. In order to understand the variability of the Kuroshio that combines both the study of surface ocean circulation records from the Okinawa Trough sediments and modeling of atmospheric and oceanic responses to different boundary conditions, as inferred from the geological records, a scientific group from Taiwan studying the southernmost part of Okinawa Trough, recently proposed a drilling site to the Ocean Drilling Program (ODP). The site, KS-1, is located at 24° 48.24'N, 122°30'E at a water depth of 1270 m (Fig. 1). Downhole temperature and thermal conductivity are measured on most of the ODP legs. This site, if drilled, could provide valuable data on the thermal structure of this area and for the prediction of a stretching model of the continental lithosphere.

Although the southwestern Okinawa Trough has been surveyed using gravity, magnetic, seismic and swath-bathymetric profiles (Pascouet 1991; Huang et al. 1992; Hsu et al. 1996; Sibuet et al. 1998), few heat flow measurements in this region have been published. Between 122°E and 124°E in the trough, no more than ten heat flow measurements have been made and most of these are concentrated near the central rift zone. None have been made within 10 nautical miles of the KS-1 drilling site.

The purpose of this paper is to provide the results of recent heat flow measurements at and in the vicinity of the KS-1 drilling site (Fig. 1), and to establish the thermal characteristics at the southwestern end of the Okinawa Trough. On the other hand, the opening of the Okinawa Trough may continue onto Taiwan but the relation between the opening of the trough and the occurence of a nearby onshore geothermal field remains unsolved. This study can provide more information to help understand their thermal interaction.

2. FIELD MEASUREMENTS

In July and September of 2000, 26 heat flow measurements were made on board R/V Ocean Researcher I. Twenty-one of them were chosen along pre-existing seismic profiles, that provide good structural and stratigraphic control of the measuring sites. The heat probe used was developed at the Institute of Oceanography, National Taiwan University. It employs the 'Violin bow' strength member and parallel sensor string configuration suggested by Lister (1979). It permits multiple 'pogostick' penetrations on each lowing and measures in situ thermal conductivity, as well as temperature gradient, over the same interval. Although the heat probe has the capability of multipenetration, due to the time constraint, only one penetration was attempted at most of the sites in this study, except at Sites 1 and 2 where two measurements were taken. During each penetration, the instrument remains undisturbed in the sea floor for about 30 minutes to measure temperature and in situ thermal conductivity (12 minutes for the temperature gradient; 18 minutes for the thermal conductivity). Meticulous mechanical and electronic designs allow temperature resolution better than $0.1m^{\circ}K$ in the range of -1°C to 25°C. Thermal conductivity is obtained by a least-squares best fit of the observed temperature curve generated from a heat pulse to the cylindrical decay function (Bullard 1954) through successively adjusting the thermal conductivity and the origin time. Two decimal resolution in for the conductivity reduction is achieved.

3. TEMPERATURE GRADIENTS

The temperature gradients measured are given in Fig. 2. In general, they show little, if any, departure from linearity. Together with the bottom water temperature, these gradients were also used to determine the temperature at the penetration depth. Average gradient values are determined from the best linear fit of equilibrium temperatures for each thermistor versus depth. Temperature gradients at Sites 1, 10, 11, and 16 are significantly higher than those at others, which may be related to the nearby presence of volcanic intrusions, extrusions or base-

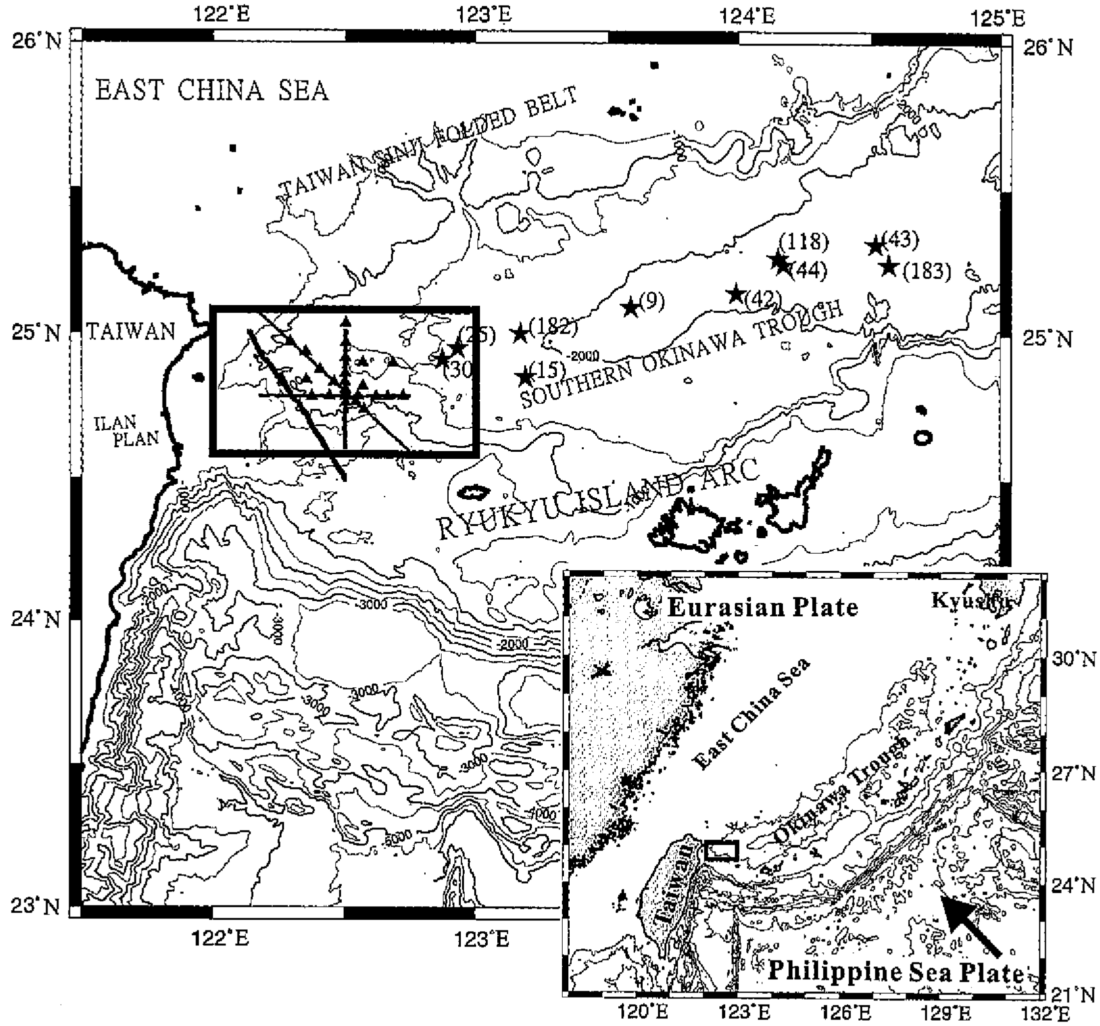


Fig. 1. Locations of heat flow sites in the southern Okinawa Trough. Stars (★) represent previous measurements (Yasui et al. 1970; Lu et al. 1981) and the corresponding heat flow values in mW/m^2 are shown. Triangles (▲) and lines (—) in the box area are the heat flow sites and seismic tracks for this study. ODP drilling site KS-1 is located at the intersection of the N-S trending and NW-SE trending seismic tracks. Heat flow values at the sites are shown in Fig. 3.

ment outcrops. Lower temperature gradients at Sites 17, 18, 21, and 22, on the other hand, are results of thick sedimentary layers. Reversal temperature gradients displayed on top of Sites 2, 7, and 17 could be attributed to the inlet of seawater induced by hydrothermal circulation in surface sediments, and thus are excluded from the heat flow calculation.

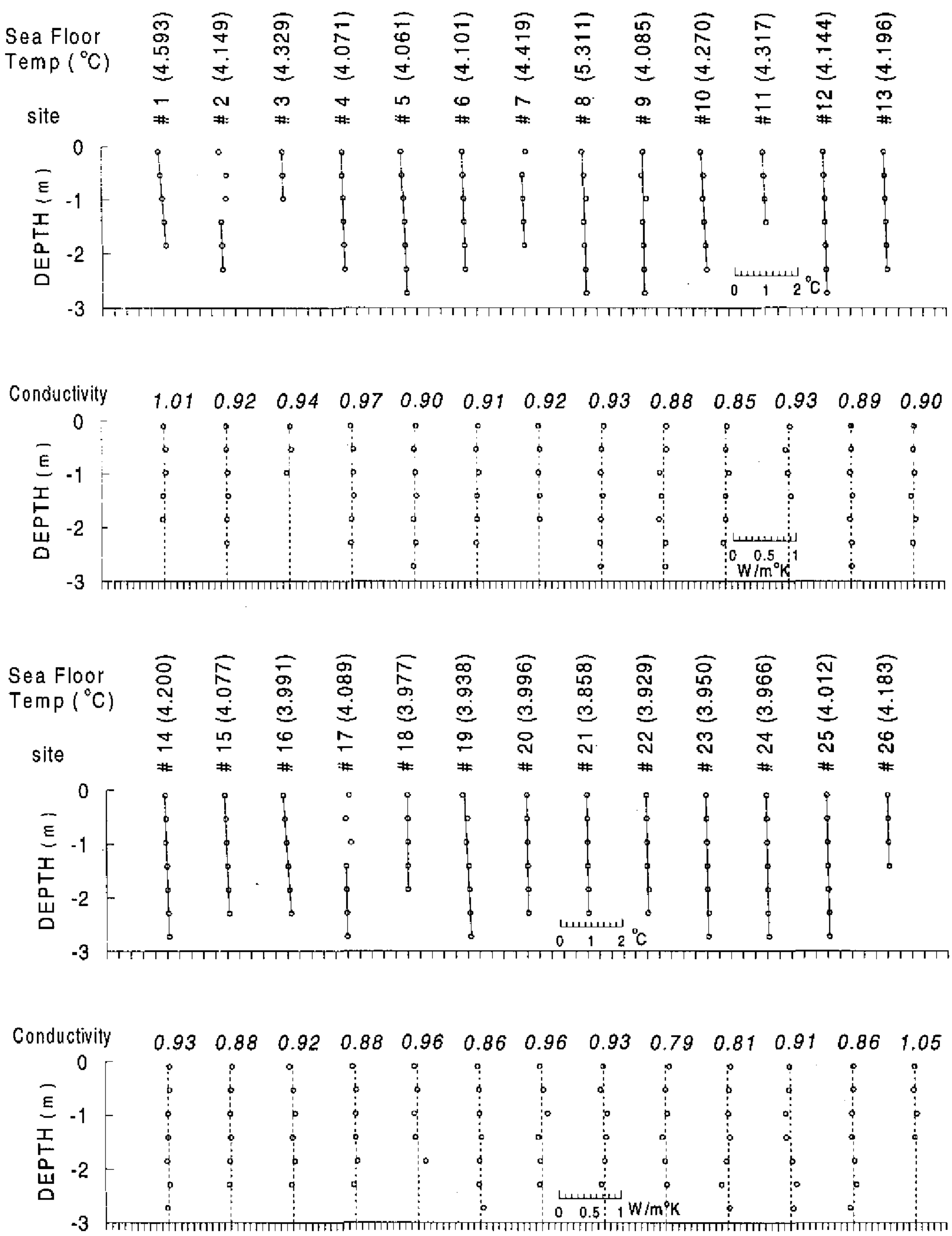


Fig. 2. Temperature and corresponding thermal conductivity profiles for each heat flow site. Origin of the depth axis is the position of the ocean floor. Temperatures in °C on the ocean floor are parenthesized at each site.

4. THERMAL CONDUCTIVITIES

Minerealogical data (Lin and Chen 1983) suggest that the muddy sediments in the southwestern Okinawa Trough are mainly terrigenous in nature, derived from China, Taiwan and the Ryukyu Arc. As biogenic and volcanic contributions are quite small, Lin and Chen (1983) conclude that the continent-derived sediments are transported and dispersed from the East China Sea by bottom currents. Chung and Chang (1995) proposed a possible sedimentation by boundary scavenging, coupled with the Kuroshio water flowing through the area. Sediments, on the lower slope of the trough are of clayey silts and silty clays (Lin et al. 1992). The thermal conductivity of the sediment at each site is well constrained and almost invariable through the penetration depth. The observed temperature gradients also show great linearity (Fig. 2 and Table 1). Thus for a given depth interval, the multiplicity of temperature gradient and its corresponding thermal conductivity equals a constant, as would be expected for uniform heat flow over a site.

Most of the variations with respect to the mean value of conductivity at all sites are less than 10%. An extraordinarily high value occurred at Site 26 which is about 15% higher than the mean and may reflect lateral variation in sediment types or their physical properties on the southern slope of the Okinawa Trough.

For the other 25 sites, except site 22 which is 0.788 $Wm^{-1}K^{-1}$, the conductivities are generally uniform with a mean value of 0.91 ± 0.1 $Wm^{-1}K^{-1}$, which is similar to that of typical marine sediments. Although there are some differences in mean conductivities between sites, variation with respect to depth is not obvious at most of the sites, with the exception of Sites 18, 23, and 25 (Fig. 2).

5. EFFECTS OF SEDIMENTATION

Since the heat flow measurements are made by means of heat probes that penetrate the sea floor sediment at the ocean bottom, we must also consider the effect of the sediment accumulated over a long period of time. Each grain of sediment arrives at the sea floor at the temperature of the water through which it has been falling, and as the water-sediment boundary is slowly raising, the temperature at every point below it must adjust upward towards a new equilibrium value. This means that part of the conducted heat must be used to warm the material through which it is passing, and the heat flow value at the sea floor surface is reduced. The sedimentation rates estimated from the excess Pb-210 profiles of the cores range from 0. 09 to 0.52 *cm/yr* for the lower slope, and decrease toward the deeper part of the southwesternmost end of the Okinawa Trough (Chung and Chang 1995). With this extremely high sedimentation rate (normal rate in the deep sea is of the order of 10^{-4} to 10^{-3} *cm/yr*), the temperature disturbance becomes significant in comparison with measurement errors. In order to correct the sediment effects, the sedimentation rates at the heat flow measurement sites are interpolated from coring locations nearby. The thickness of the recent deposited sedimentary layers at each site are estimated from seismic reflection profiles. Calculations are then made to incorporate the sedimentation effects into the equations of Jaeger (1965; adapted by Kappelmeyer and Haenel 1974).

Table 1. List of heat flow results provided in this study in the southwest Okinawa Trough.

Site	Latitude °N	Longitude °E	WD m	K W/m°K	G °K/m	Q mW/m^2
1	24.83768	122.26247	1075	1.005	0.144	145.0
2	24.83893	122.35394	1252	0.930	0.047	43.7
3	24.97097	122.29325	1113	0.943	0.039	36.9
4	24.93485	122.35153	1409	0.980	0.054	52.5
5	24.87524	122.40536	1374	0.905	0.066	60.0
6	24.83271	122.45861	1318	0.905	0.049	44.6
7	24.76370	122.54090	1161	0.923	0.055	50.6
8	24.73700	122.57186	758	0.924	0.073	67.5
9	24.78354	122.72112	1361	0.869	0.050	43.1
10	24.78249	122.66281	1198	0.841	0.099	83.6
11	24.78271	122.61754	1172	0.920	0.084	76.8
12	24.78349	122.55094	1252	0.888	0.049	43.1
13	24.78341	122.44201	1224	0.897	0.056	50.1
14	24.78300	122.37476	1181	0.927	0.067	61.7
15	25.03369	122.50239	1381	0.880	0.067	58.8
16	24.96599	122.50263	1488	0.926	0.118	108.8
17	24.89713	122.68273	1541	0.892	0.029	25.7
18	24.90003	122.56740	1523	0.929	0.009	8.6
19	24.81816	122.56749	1324	0.861	0.046	40.0
20	24.91469	122.50164	1505	0.982	0.035	33.9
21	24.86175	122.50100	1472	0.939	0.028	26.1
22	24.83120	122.50029	1340	0.788	0.028	22.1
23	24.80463	122.50059	1278	0.811	0.048	39.1
24	24.79549	122.50144	1262	0.929	0.034	31.3
25	24.78218	122.50081	1220	0.868	0.038	32.6
26	24.76126	122.50189	1122	1.052	0.045	47.8

WD=water depth, K=thermal conductivity, G=temperature gradient, Q=heat flow.

6. HEAT FLOW DISTRIBUTIONS

Figure 3 shows the locations of the heat flow measurement sites and seismic reflection profiles in the study area. Most of the sites are along seismic reflection lines which provide information on the thickness of the sedimentary layers and distribution of the volcanic bodies (Fig. 4). Excluding the tectonically active zone, the average heat flow for the ocean basin is about 62 mW/m^2. After sedimentation correction, high heat flows of 110.3, 103.3 (Fig. 4a), 172.5 (Fig. 4b) and 98.8 (Fig. 4c) mW/m^2 are observed either on the summit or in the vicinity of volcanic intrusions or extrusions; while 76.2 and 180.1 mW/m^2 are on a basement outcrop and volcanic rock with little sediments on it (Figs. 4c and 4d, respectively). For the four high heat flow sites that do not have seismic profile control, their sedimentation-corrected heat flow values of 93.5, 74.6, 98.8 and 92.7 mW/m^2, are respectively, derived from the nearby seismic lines. Low heat flows of 46.1, 34.5, 41.4 and 54 mW/m^2 located along the N-S trending multichannel seismic profile EW9509-1 (Fig. 4b) could be explained by sea water circulating in the interstice of normal faults developed in the central rift zone. This process absorbs heat and reduces the temperature of the rocks. Although there are no seismic profiles along Sites 17 and 18, since both are located in the central rift zone, we believe that hydrothermal circulation may also explain their low heat flows of 40.8 and 13.7 mW/m^2, respectively (Fig. 3).

The uncorrected and sedimentation-corrected heat flows are contoured in Fig. 5. In general, the correlation between the heat flow and the bathymetric contours is discernible but with a slight deviation in trending. The zone of relatively low heat flow is NE-SW trending, while the topography of the southwestern end of the Okinawa Trough is NEE-SWW trending. The low heat flow zone is surrounded by three heat flow highs (Fig. 5). Since these values are measured at sites covered by thin sediments, we believe that the heat flows of most of the other sites, particularly those situated over thick sediments, would be higher if better seismic data were available. The sedimentation-corrected heat flow values observed on the seismic profile QCS 524-30 across the southwestern end of the trough range from 46.1 to 98.8 mW/m^2(Figs. 3 and 4c), and show that the higher heat flows occurred where sediment is thicker. The results imply that the continental crust in the southwestern end of the Okinawa Trough is being stretched. We suggest that the magma associated with the rifting of the southwestern Okinawa Trough has at least extended to the southwestern end of the trough.

7. CONCLUSIONS

Twenty-six heat flow sites located in the southwestern end of the Okinawa Trough are surveyed. In general, most of the measured temperature gradients and thermal conductivities are linear and almost invariable through the penetration depth. The reversal temperature gradients that appeared at Sites 2, 7 and 17 are the results of pore-water advection caused by hydrothermal circulation commonly occuring in rifty backarc basins. The advection cools sediments from below.

Due to the extremely high sedimentation rates (0.09 to 0.52 *cm/yr*) in the survey area, we have incorporated the sedimentation correction in the measured heat flows. The correction

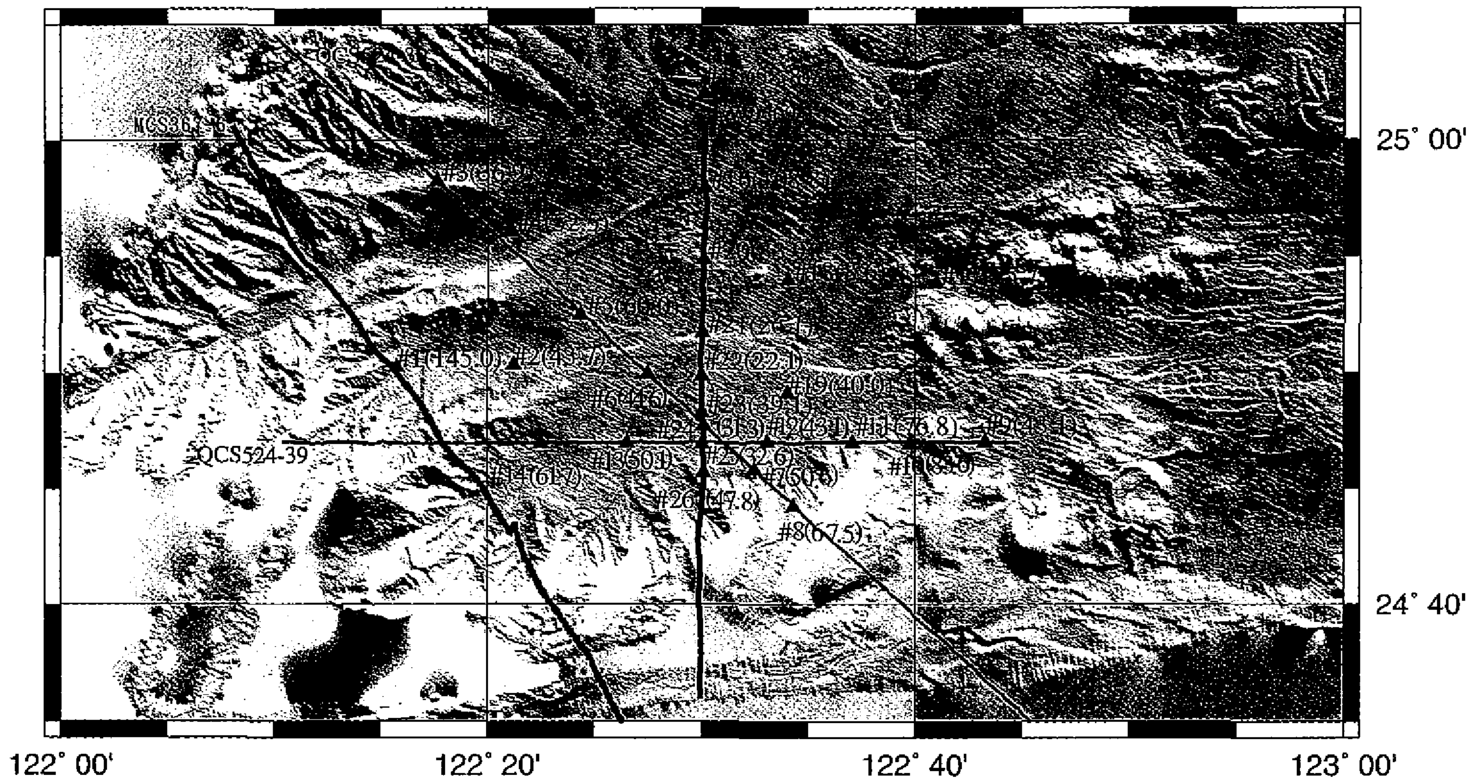


Fig. 3. Multichannel (EW 9509-1 and MCS 367-6) and 4-channel (QCS 524-30 and QCS 524-39) seismic reflection lines and heat flow sites are mapped on the NE simulated hillshading bathymetric map of the southwestern end of the Okinawa Trough. Parenthetical values at each site are heat flows in mW/m^2. Locations of heat flow sites and the corresponding seismic profiles are shown in Fig. 4. The contigency ODP rilling site KS-1 (#24) is located at the intersection of seismic lines EW9509-1 and QCS524-30.

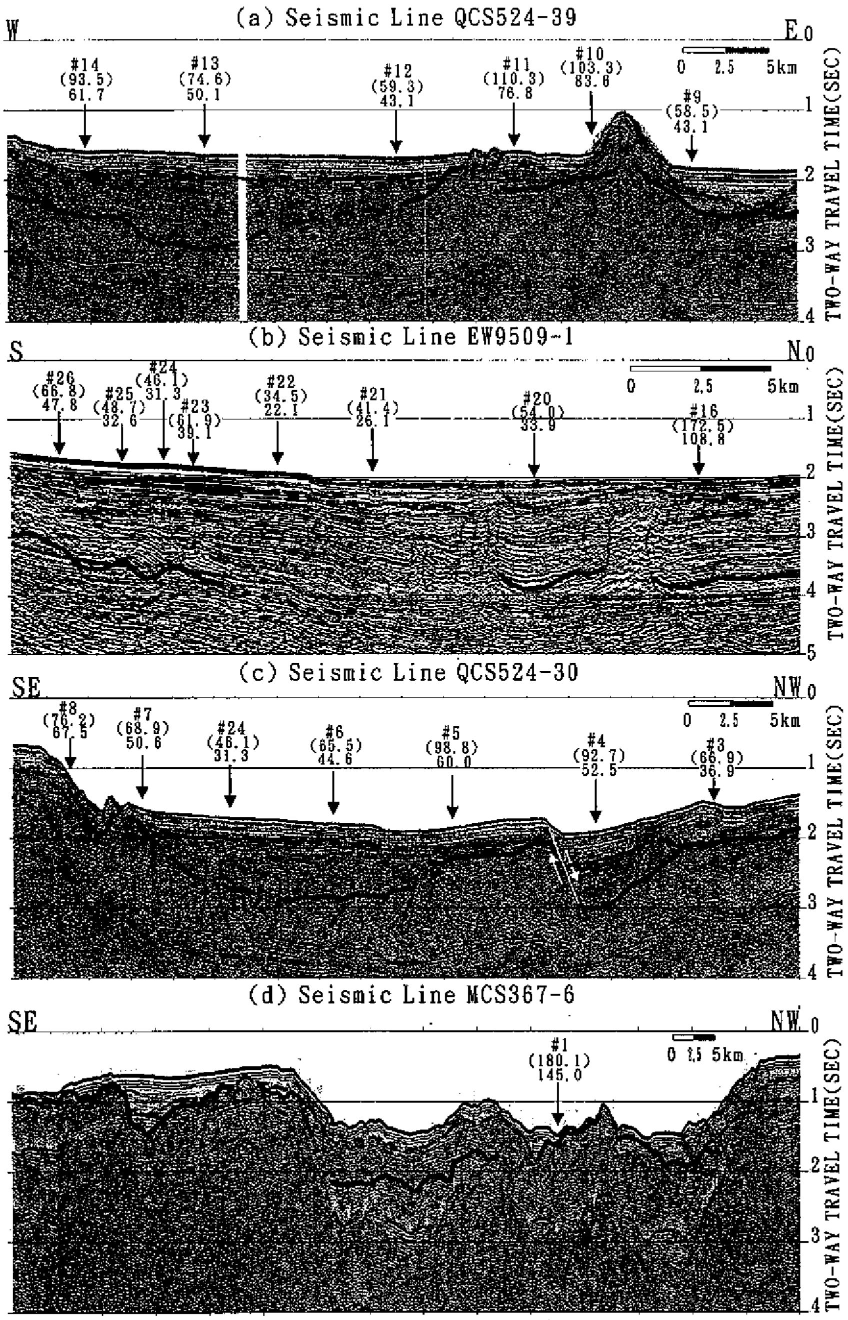
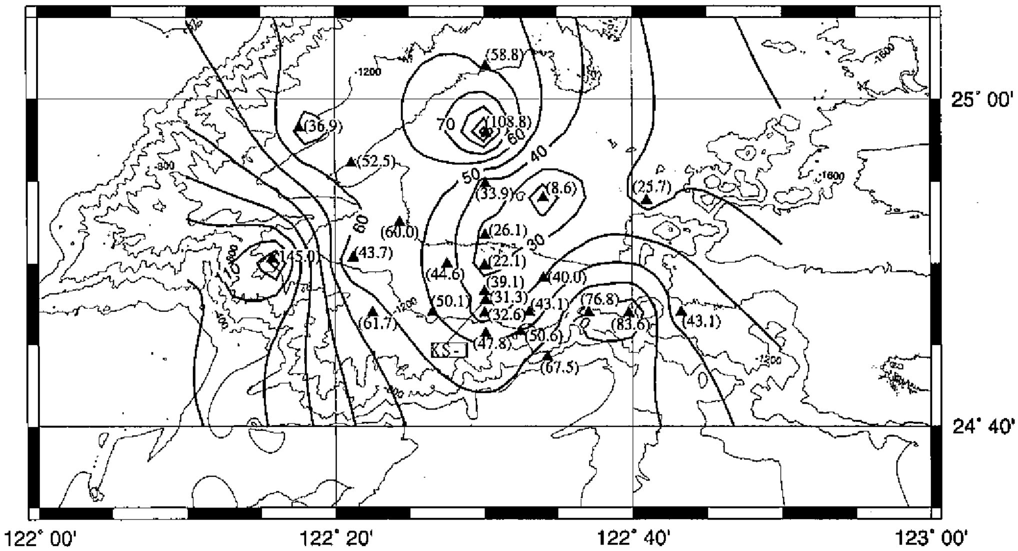


Fig. 4. Locations of heat flow sites (↓) along the corresponding seismic profiles. Heat flows are in mW/m^2. Parenthetical values are the sedimentation-corrected heat flows. The recent deposited sedimentary layers, indicated by dashed lines, have been considered for the sedimentation correction.

(a)



(b)

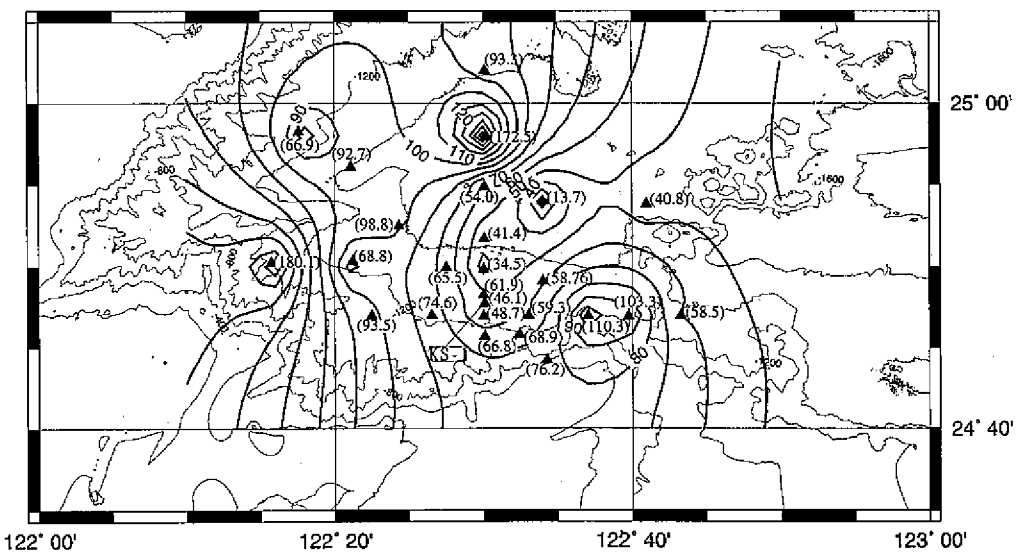


Fig. 5. Sedimentation-uncorrected (a) and -corrected (b) heat flow contour maps in and around ODP KS-1 site which has a corrected heat flow value of 46.1 mW/m^2. Contour interval is 10 mW/m^2.

has increased the heat flow value by as much as 76%. The sedimentation-corrected high heat flows, range from 74.6 to 180.1 mW/m^2, and generally occur on the summit or in the vicinity of the volcanic bodies.

The low heat flows, ranging from 46.1 to 54 mW/m^2 across the trough from south to north, correspond to the faults where heat has been absorbed due to hydrothermal circulation of interstitial seawater.

The correlation between the heat flow pattern and topography at the southwestern end of the Okinawa Trough is discernible, except that the former is trending slightly southward. We believe that the sedimentation-corrected heat flows could be higher than that calculated in this study because only the most recent surface sedimentation effects have been considered, due to the limited penetration depth of the available seismic data. That is, the present heat flow study supports the idea that the backarc rifting magma has at least extended westward into the southwestern end of the Okinawa Trough, northeastern Taiwan. On the other hand, temperatures and temperature gradients are relatively low at or near drilling site KS-1 proposed for ODP Contigency Program.

Acknowledgements We wish to thank the efforts of electronic engineers H.I. Chang and C. C. Lai in the construction of the recording system of the instrument. We also appreciate the help of Mr. S.D. Chiou of the Ocean Research I Precious Instrument Center and the officers, crew and shipboard technicians of the R/V Ocean Researcher I. C.P. Lo and Y.C. Cheng deserve special thanks for their help in heat flow data acquisition and editing seismic reflection data. The study was supported by the National Science Council of the Republic of China, under grants NSC89-2611-M-002-016-ODP and NSC89-2611-M-002-045-ODP.

REFERENCES

Bullard, E. C., 1954: The flow of heat through the floor of the Atlantic Ocean. *Proc. Roy. Soc. London*, A, **222**, 408-429.

Chung, Y., and W.-C. Chang, 1995: Pb-210 fluxes and sedimentation rates on the lower continental slope between Taiwan and the South Okinawa Trough. *Continental Shelf Res.*, **15**, 149-164.

Hirata, N., H. Kinoshita, H. Katao, H. Baba, Y. Kaiho, S. Koresawa, Y. Ono, and K. Hayashi, 1991: Report on DELP 1988 cruises in the Okinawa Trough. Part III: Crustal structure of the southern Okinawa Trough. *Bull Earthquake Res. Inst.*, Univ. Tokyo, **66**, 37-70.

Hsu, S.-K., J.-C. Sibuet, S. Monti, C.-T. Shyu, and C.-S. Liu, 1996a: Transition between the Okinawa trough backarc extension and the Taiwan collision: new insights on the southernmost Ryukyu Subduction zone. *Mar. Geophys. Res.*, **18**, 163-187.

Hsu, S.-K., J.-C. Sibuet, and C.-T. Shyu, 1996b: High-resolution detection of geologic boundaries from potential field anomalies: an enhanced analytic signal technique. *Geophysics*, **61**, 373-386.

Huang, S.-T., H.-H. Ting, R.-C. Chen, W.-R. Chi, C.-C. Hu, and H.-C. Shen, 1992: Basinal framework and tectonic evolution of offshore northern Taiwan. *Pet. Geol. Taiwan*, **27**, 47-72.

Jaeger, J. C., 1965: *Application of the theory of heat conduction to geothermal measurements.* In: W. H. K. Lee (Ed.), Terrestrial heat flow, Am. Geophys. Union, Washington, DC, 7-23.

Kappelmeyer, O., and R. Haenel, 1974: Geothermics with Special Reference to Application. Borntraeger, Berlin.

Kimura, M., 1985: Back-arc rifting in the Okinawa Trough. *Mar. Pet. Geol.*, **2**, 222-240.

Lin, F.-J., and J.-C. Chen, 1983: Textural and mineralogical studies of sediments from the southern Okinawa trough. *Acta Oceanologica Taiwanica*, **14**, 26-41.

Lin, S., K. K. Liu, M. P. Chen, P. Chen, and F. Y. Chang, 1992: Distribution of organic carbon in the KEEP area continental margin sediments. *TAO*, **3**, 365-376.

Lister, C. R. B., 1979: The pulse-probe method of conductivity measurement. *Geophys. J. R. Astron. Soc.*, **57**, 451-461.

Lu, R. S., J.-J. Pan, and T.-C. Lee, 1981: Heat flow in the southwestern Okinawa Trough. *Earth Planet. Sci. Lett.*, **55**, 299-310.

Ono, T., S. Yamamoto, and H. Ujiié, 1987: Fluctuation of carbonate and interstitial-exchangeable elements in sediments from the ocean surrounding the Ryukyu Islands. *Compass*, **64**, 195-206.

Park, J.-O., 1996: Seismic stratigraphy and tectonic evolution of the southern Ryukyu island arc. Ph. D. thesis, Ocean Res. Inst., Univ. of Tokyo, Tokyo, Japan.

Pascouet, A. P., 1991: Something new under the water, the bubbleless air gun. *Leading Edge*, **10**, 79-81.

Sibuet, J.-C., B. Deffontaines, S.-K. Hsu, N. Thareau, J.-P. Le Formal, C.-S. Liu, and ACT party, 1998: Okinawa Trough backarc basin: early tectonic and magmatic evolution. *J. Geophs. Res.*, **103**, 30245-30267.

Sibuet, J.-C., S.-K. Hsu, C.-T. Shyu, and C.-S. Liu, 1995: *Structural and kinematic evolution of the Okinawa trough backarc basin.* In: B. Taylor (Ed.), Backarc Basins: Tectonics and Magmatism, Plenum, New York, 343-378.

Sibuet, J.-C., J. Letouzey, F. Barbier, J. Charvet, J.-P. Foucher, T. W. C. Hilde, M. Kimura, L.-Y. Chiao, B. Marsset, C. Muller, and J.-F. Stephan, 1987: Backarc extension in the Okinawa Trough. *J. Geophys. Res.*, **92**, 14041-14063.

Uyeda, S., 1977: *Some basic problems in trench-arc-back-arc-system.* In: M. Talwani and W. C. Pitman (Eds.), Island Arcs, Deep Sea Trenches and Back-Arc Basins, Maurice Ewing Ser., AGU, Washington D.C.,1,1-14.

Vander Zouwen, D. E., 1984: Structure and evolution of Okinawa Trough. M. Sc. Thesis, Texas A & M Univ., College Station, Tex., USA.

Yamano, M., S. Uyeda, J.-P. Foucher, and J.-C. Sibuet, 1989: Heat flow anomaly in the middle Okinawa Trough. *Tectonophysics*, **159**, 307-318.

Yasui, M., D. Epp, K. Nagasaka, and T. Kishii, 1970: Terrestrial heat flow in the seas around the Nansei Shoto (Ryukyu Islands). *Tectonophysics*, **10**, 225-234.