- Original paper -

Heat flow distribution on the floor of Nankai Trough off Kumano and implications for the geothermal regime of subducting sediments

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During three research cruises (KY05-14, KY07-01 and KY08-01) using JASMTEC R/V *KAIYO*, we obtained 13 heat flow data with piston core samples across the Nankai Trough and the Kashinosaki Knoll (KK). Subbottom temperatures were measured by precise thermometers attached to the piston corer. Thermal conductivity, color reflectance and vane shear strength were measured for the cored samples onboard *KAIYO*. Surface heat flow in the Nankai Trough north of KK ranges from 90-135 mW/m². With the sedimentation effects considered, basal heat flux beneath the Nankai Trough off Kumano is roughly estimated as 100-130 mW/m², most likely as 120-130 mW/m². In the Shikoku Basin south of KK, heat flow ranges 120-147 mW/m², (average~135 mW/m²), significantly higher than the theoretical value (110 mW/m²) estimated from the age of the Shikoku Basin. Possible cause for the heat flow anomaly is either the postspreading volcanism at KK, thermal disturbance by tectonic compression at KK, or subseafloor fluid migration. More intensive study, including scientific drilling is necessary to estimate the accurate thermal structure of the incoming Shikoku Basin.

Keywords: Heat flow, Nankai Trough, turbidite deposit, NanTroSEIZE, Shikoku Basin

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1. Introduction

The thermal regime within the accretionary sediments and underlying oceanic basement has an important effect on the seismogenic characteristics along the megathrust at the convergent plate boundary. Hyndman et al. (1995) simulated temperature along the plate interface in the Nankai Trough and suggested that the updip limit of the seismogenic zone approximately coincides with the location of a 150°C isotherm. Their temperature estimate largely depends on surface heat flow data on the incoming Shikoku Basin as well as in the accretionary prism and forearc basin.

Yamano et al. (2003) show that the heat flow values are approximately 100 mW/m^2 on the floor of the Nankai Trough off Kumano (Tonankai region), indicating that the thermal structure of the incoming plate off Kumano is basically consistent with theoretical estimates from the age of the Shikoku Basin.

However, it is necessary to consider some local disturbances that affect the thermal regime near the seafloor, such as rapid sedimentation on the trough floor (e.g. Hutchison, 1985), the volcanism of seamounts, or time variation in bottom-water temperature variation. At least we

need to know the heat flow in the incoming Shikoku Basin that is not affected by these local effects.

Recently many seismic profiles were acquired at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in the Kumano region as a site survey for the Integrated Ocean Drilling Program (IODP) in the Nankai Trough (Tobin et al., 2006; Kinoshita et al., 2006). These Multi-Channel Seismic (MCS) profiles were studied and documented in detail, especially on the variation in basement relief and sediment thickness in the Shikoku Basin (Ike et al., 2008a) and around the Kashinosaki Knoll (KK;Fig. 1) (Ike et al., 2008b). Turbidite sedimentation in the Shikoku Basin is controlled by basement relief, leading to the local variation of turbidite units deposited during the middle Oligocene to the middle Miocene.

In this paper we present newly obtained heat flow data in the Nankai Trough off Kumano, mainly seaward of the frontal thrust, along the MCS line KR9806-02 (IFREE database center) (Fig. 1). In addition, we attempt to interpret the result and infer the thermal regime of the incoming (subducting) Shikoku Basin.

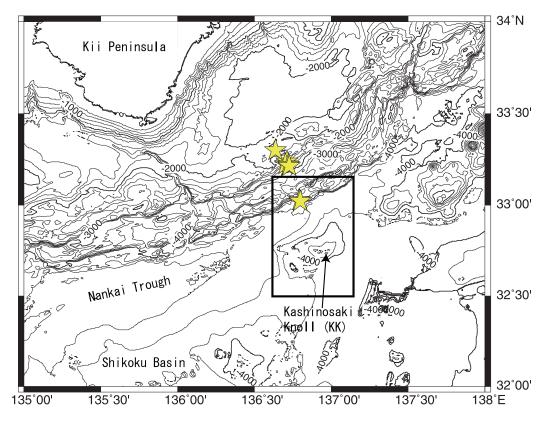


Fig. 1 (a) Index map showing the survey area in this study. Yellow stars are IODP sites during NanTroSEIZE Stage 1 (Tobin et al., 2006).

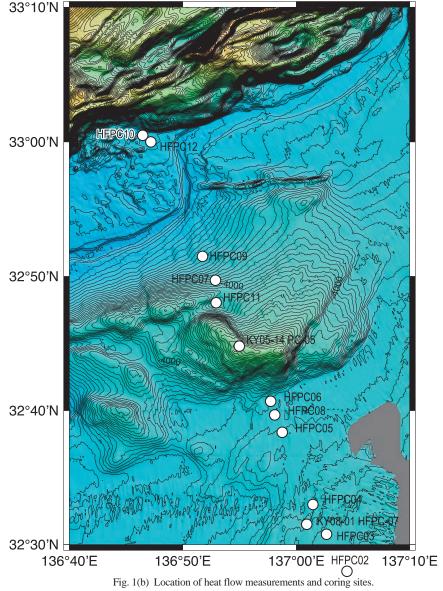
2. Data acquisition

New heat flow data were acquired through three research cruises KY05-14, KY07-01 and KY08-01, using R/V KAIYO of JAMSTEC.

The KY05-14 cruise was carried out using the 'Navigable Sampling System' (NSS) of the Ocean Research Institute, University of Tokyo. NSS is a special purpose ROV that can carry a piston core sampler or a heat flow probe to the seafloor, and can make an accurate penetration to the point of interest through 2 video cameras attached to NSS. One heat flow measurement with core sampling was conducted near the summit of KK on the trough floor.

Table 1. Specifications of the heat flow probe

Sensor	thermistor (6 k Ω at 0 °C)
Sensor diameter	4 mm
Resolution	about 1mK
Accuracy	about 10mK
Recording interval	30 sec.
Number of sensors	5-8
Sensor vertical interval	50-80 cm
Typical probe length	4-6m
Measurement time	10-20 min.



During the KY07-01 cruise 12 piston core sampling and heat flow measurements were simultaneously made along the MCS line KR9806-02, along which most IODP NanTroSEIZE drillsites are located. During the KY08-01 cruise one heat flow datum was added south of Kashinosaki Knoll.

2.1. Heat flow

In the deep sea, heat flow through the seafloor can be determined by multiplying the vertical thermal gradient and thermal conductivity of the upper few meters of sediment below the seafloor (e.g. Bullard, 1954). This is because the disturbance of subbottom temperature due to fluctuation of bottom-water variation is normally much smaller than the temperature difference between uppermost and lowermost sensors. For instance, temperature difference of 4-m probe below seafloor with 50 mW/m² heat flow is ~200 mK. We can generally expect that the bottom-water temperature variation is smaller than that, thus we can extrapolate measured surface heat flow to some depths below seafloor.

We use either Ewing or violin-bow type geothermal probes that are attached to a steel rod or to a piston core sampler (Table 1; Fig. 2). These probes are lowered from the ship to the seafloor with the steel wire string mounted on the deep-sea winch. In order to obtain reference temperature data the probe is left still for 5-10 minutes about 30 meters above the seafloor before it penetrates the sediment. Penetration is attempted by spooling out the wire as quickly as possible, or by using a mechanical trigger used for a piston core sampler (e.g. Hyndman et al., 1979). In either case, a significant amount of frictional heat is generated, and we need to leave the probe in the sediment for 10-20 minutes to allow the heat to diffuse away from the sensors and to avoid the heat generated by the steel rod or core pipe that are about 5 cm away from the sensors. The typical time constant for the heat dissipation of 5 cm distance is about 30 minutes (assuming the thermal diffusivity of marine sediment as 10⁻⁶ m²/s), so the correction for frictional heating has to be applied in order to obtain insitu formation temperature (Bullard, 1954) (Fig. 3).

The vertical temperature gradient is estimated by a weighted least-squares fit, where the weight is calculated from uncertainties due to frictional heat correction.

Thermal conductivities were measured on core samples, using the full-space needle probe method or half-space method (e.g. Von Herzen and Maxwell, 1959). In both

measurements, calibration was applied using three standard samples (rubber, glass and silicon blocks). Correction for insitu temperature and pressure is not applied. It should be noted that the overall error or uncertainty of heat flow can be as large as 10%, partly because of the uncertainty of thermal conductivity.

2.2. Color reflectance

The color reflectance of the halved core surface was measured at every 2 cm using a Minolta Photo-spectrometer CM-2002 in order to quantify the sediment color. The color reflectance data were described by CIE (Commission Internationale de l'Eclairage) L*a*b*color model. L* represents lightness which can range between 0 (black) to 100 (white). The other two variables represent the colors; a* representing green (negative values) to red (positive) and b* representing blue (negative) to yellow (positive values). Sediment color is one of the fundamental data that reflects chemical composition and, in some degree, the physical condition of sediments, such as water content. It is therefore useful to document the lithologic characteristics. As shown in Fig. 5, changes in color data appear to reflect variations of the core lithology recognized visually.

2.3. Vane Shear

In order to measure the shear strength of core samples, we conducted a vane shear test. Shear strength is measured using a four-wing-bearing torque driver of 2 cm in height and 1 cm in width. The measurement was done as follows; 1) all the wings of the torque driver penetrated directly into the split surface of the working half core sample, 2) the torque driver was rotated slowly, 3) the torque force was record at 1 second interval. Each test was done for approximately 20 seconds. If the sediment samples were too stiff to measure, the penetration depth of the wings was changed from 2 cm to 1 cm, and measured again for 20 seconds at the new surface.

The shear strength is calculated from the shear friction working during rotation of the driver. According to the vane rotation length, it is calculated that one unit on the driver is equal to 4.54 kPa. The shear strength C (kg/cm^2) is calculated as :

$$C = Mtmax/\pi D^2 (H/2 + D/6),$$

where Mtmax is the torque moment $(kg \cdot cm)$, H the wing height (cm), and D the total wing width (cm).





Fig. 2 Heat flow probes.

- (a) Ewing type outrigered sensors are attached to the core barrel.
- (b) Violin-bow type thermistor string is attached to the piston core sampler.

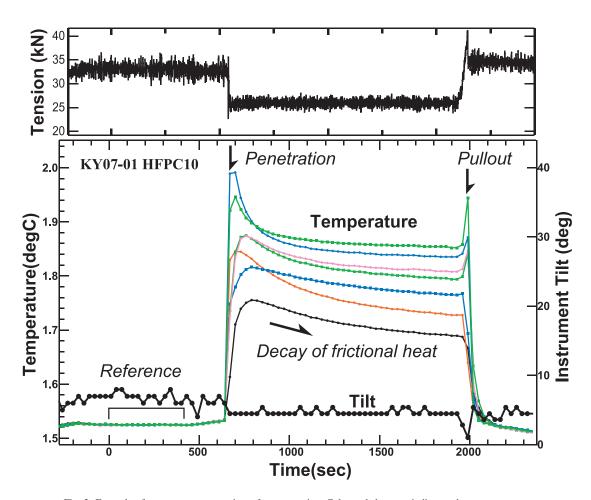


Fig. 3 Example of temperature versus time after penetration. Color-coded curves indicate subottom temperatures measured by the sensors at different depths. An instrument tilt and tension applied to the wire is also plotted.

3. Results and discussion

Fig. 4 shows the core photographs and visual core description obtained during the KY07-01 cruise. Fig. 5 shows the summary diagram of the core description, vane shear, color reflectance and thermal conductivity during the KY07-01 cruise. Hemipelagic mud has a dark, greenish color, and its thermal conductivity ranges 1.0-1.2 W/m/K. Turbidite sediment is characterized by darker color and high conductivity values (>1.2 W/m/K). Intervals with pumice fragments have brighter and yellowish color. Ash layers have stronger vane shear.

Based on the bathymetry, MCS profiles and piston core samples obtained during the KY07-01 cruise, our studied area is designated into three regions: the Nankai Trough floor filled with turbidite (KY07-01 HFPC-10 and 12), the Kashinosaki Knoll (KK) and its northern and southern slope (KY05-14 PC-5; KY07-01 HFPC-5, 6, 7, 8, 9, 11), and the Shikoku Basin to the south (KY07-01 HFPC-2, 3, 4; KY08-01 HFPC-7). Lithology around KK is dominated by yellowish silty clay with pumice fragments and occasional massive pumice layers. They should be the debris flow deposits originated from KK. On the Shikoku Basin and on the Nankai Trough hemipelagic sediments are dominant with a volcanic ash layer. The ash at the Shikoku Basin sites is supposed to be of AT (Aira-Tn ash) origin, based on the refractive index of glass involved in these ash layers (Fig. 4b). Ash layers at other sites could not be identified as AT, but there is a good chance that all ash layers are also of AT origin. The sedimentation rates can be estimated from

the age (24,330 year before present; Murayama et al., 1993) and the depth to the ash layers; they are 20-40 m/Ma in the Shikoku Basin (HFPC02-05) and 70-80 m/Ma in the northern end of the Nankai Trough (HFPC10 and 12). The latter estimate, however, would be too low for Quaternary turbidite sedimentation as shown for the case in the Nankai Trough off Muroto (e.g. Shipboard Scientific Party, 2001).

3.1. Heat flow on the Nankai Trgough

Table 2 shows the result of heat flow measurements. We obtained 13 reliable heat flow values in the Kumano region. Fig. 6 is the temperature versus depth profiles obtained during the KY07-01 and KY08-01 cruises. The heat flow distribution in this region is mapped in Fig. 7, including previous and newly obtained data. In the next section, we provide some interpretation in the trough floor and Shikoku Basin only.

The sediment sequence of the Nankai Trough and the Shikoku Basin consists of continuous hemipelagic sediment (Upper and Lower Shikoku Basin Sequences) and overlying turbidite during the middle Oligocene to the middle Miocene and present trench-fill turbidite (Ike et al., 2008a).

Unfortunately we do not have enough heat flow on the trough with trench-fill turbidite in the Kumano region near KK. This is partly because a deep-sea channel erodes off surface sediment and makes penetration more difficult, and partly because of relatively dense telecommunications cables lying on the seafloor. The average heat flow on the

Station	Latitude		Longitude		Water	N	Pen	Temperature		Thermal		Heat flow	Quality	Area	Comment	
Station		Longitude		Depth	1 1 1 1		Gradient		conductivity			iicat iiow	Quality	Alea	Comment	
		('N)		('E)	(m)		(m)	(mK/m)	error	$Wm^{-1}K^{-1}$	n	sdev	mW/m^2			
KY05-14																
PC-05	32 °	44.84	136 °	55.02	3480	6	2.5	163		0.97			158	good	Kashinozaki Knoll	68 hours meas.
KY07-01																
HFPC02	32 °	28.04	137 °	4.49	4062	3	1	142.7	8	1.03	4	0.04	147	poor	Shikoku Basin	tilt>45deg
HFPC03	32 °	30.82	137 °	2.70	4084	3	1	133	6.5	1	10	0.05	133	poor	Shikoku Basin	only 2-3min
HFPC04	32 °	33.03	137 °	1.50	4127	7	3	131	0.2	1.03	14	0.06	135	excellent	Shikoku Basin	T3 outlier
HFPC05	32 °	38.41	136 °	58.79	4167	2	1	122	1.3	0.99	7	0.03	121	fair	Shikoku Basin	only 2 sensors
HFPC06	32 °	40.73	136 °	57.80	4178	2	1	125	2.5	1.02	4	0.02	128	fair	Kashinozaki Knoll	only 2 sensors
HFPC07	32 °	49.74	136 °	52.93	4063	4	2	112	0.8	0.99	7	0.03	111	excellent	Nankai Trough	
HFPC08	32 °	39.72	136 °	58.17	4184	5	2	141	1.1	1.03	12	0.04	145	excellent	Shikoku Basin	
HFPC09	32 °	51.52	136 °	51.77	4245	5	2	104	1.9	1.06	2	0	110	good	Nankai Trough	
HFPC10	33 °	0.51	136 °	46.52	4334	7	2.5	82	0.7	1.13	19	0.08	93	good	Nankai Trough	
HFPC11	32 °	48.08	136 °	53.01	3984	2	0.5	144	9.1	1.02	6	0.06	147	fair	Kashinozaki Knoll	only 2 sensors
HFPC12	33 °	0.02	136 °	47.22	4347	8	2.5	115	0.6	1.18	9	0.11	136	good	Nankai Trough	
KY08-01																
HFPC-07	32 °	31.55	137 °	0.98	4112	6	3	141		1.03			145	good	Shikoku Basin	

Table 2. List of heat flow obtained during the KY05-14, KY07-01 and KY08-01 cruises around the Nankai Trough off Kumano.

Note: N; number of sensors in the sediment, Pen; penetration depth, n (in Thermal conductivity); number of conductivity measurements on core samples. Quality (best to worst); excellent, good, fair, poor.



HFPC10 HFPC12 PL09 HFPC07 HFPC01 HFPC08 HFPC08 HFPC03 HFPC03 HFPC01 HFPC01 HFPC01 HFPC01 HFPC01 HFPC01 HFPC01 HFPC01 HFPC02 HFPC01 HFPC01 HFPC03 HFPC02 HFPC01 HFPC01 HFPC03 HFPC03 HFPC03 HFPC03 HFPC02 HFPC01 HFPC01 HFPC03 HFPC

216 cm

(b)

Brownish yellow silty clay: Oxidized layer

Pumice layer

Yellowish silty clay with pumice fragment: Debris flow deposits from Kashino Knoll

Grayish silty clay: Hemipelagic sediments

Flow-in

348

Fig. 4 (a) Core photos and (b) core description, obtained during the KY07-01 cruise.

cm

220

196 cm

Grayish silty clay: Turbidity sediments

Green band, Yellow band: Volcanic ash?

Sand layer: Turbidity sediments

Volcanic ash: AT

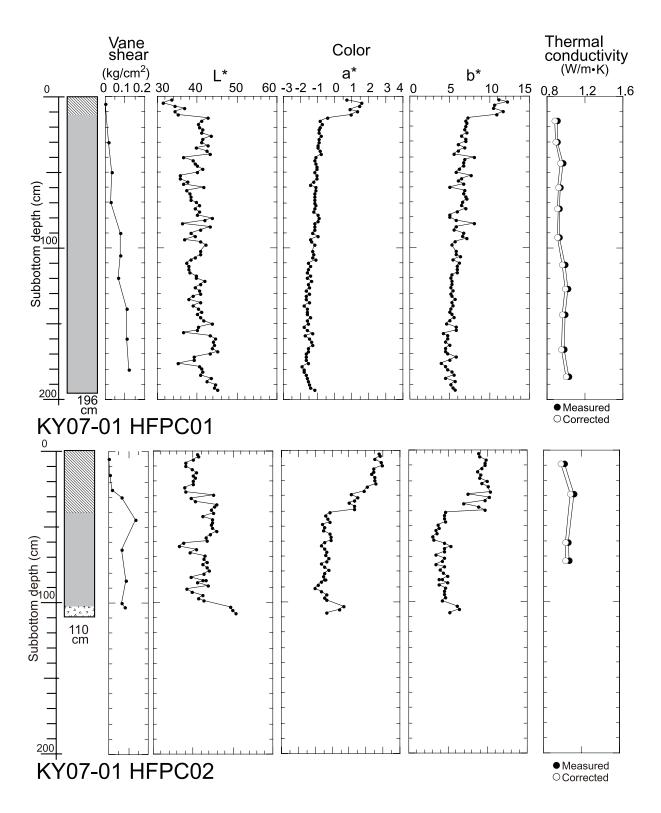


Fig. 5 (a)

Fig.5 Summary diagram of core description and data during the KY07-01 cruise. Note that the sample "PL-01" is taken with a pilot corer at site HFPC09. The HFPC01 samples were taken from the Kumano Basin.

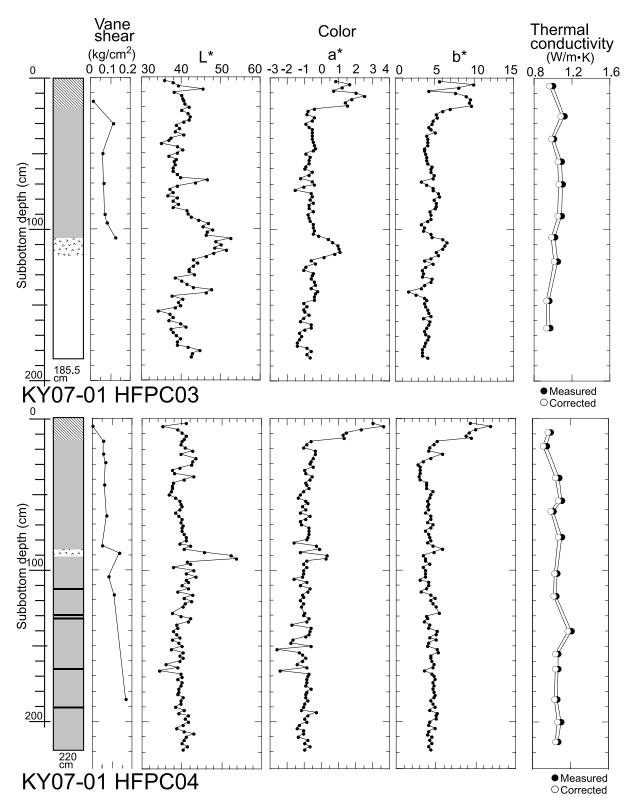
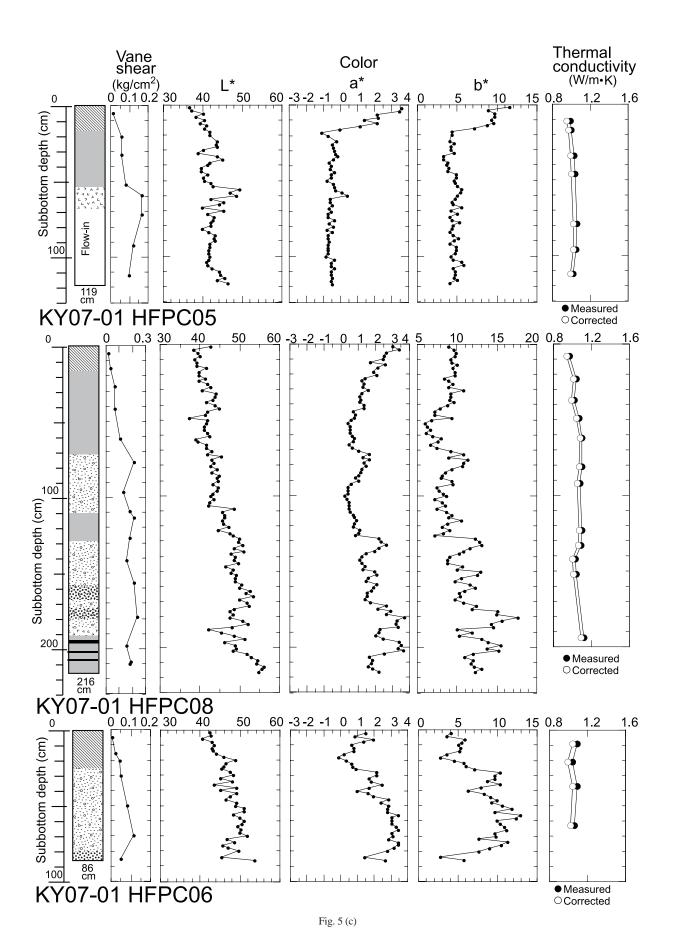


Fig. 5 (b)



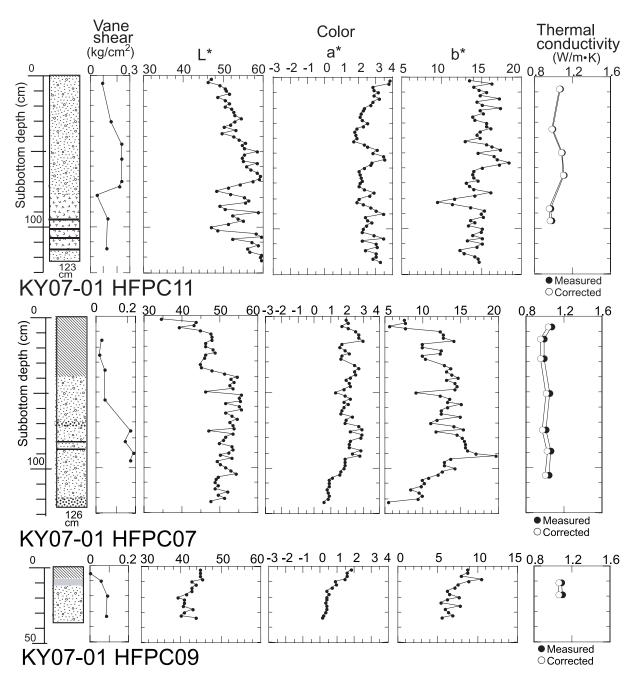


Fig. 5 (d)

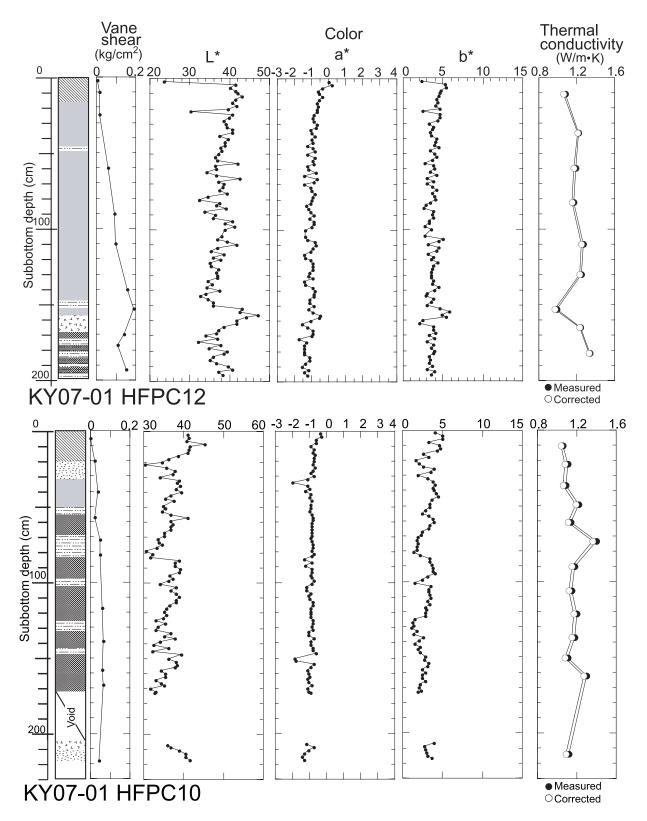


Fig. 5 (e)

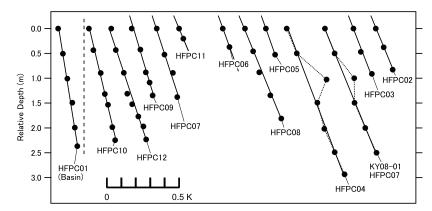


Fig. 6 Temperature versus depth profiles obtained during the KY07-01 and KY08-01 cruises in the Nankai Trough off the Kumano region. Vertical axis indicates depth from the shallowest sensor in the sediment. Note that the profiles are aligned from landward (left-hand side) to seaward (right-hand side).

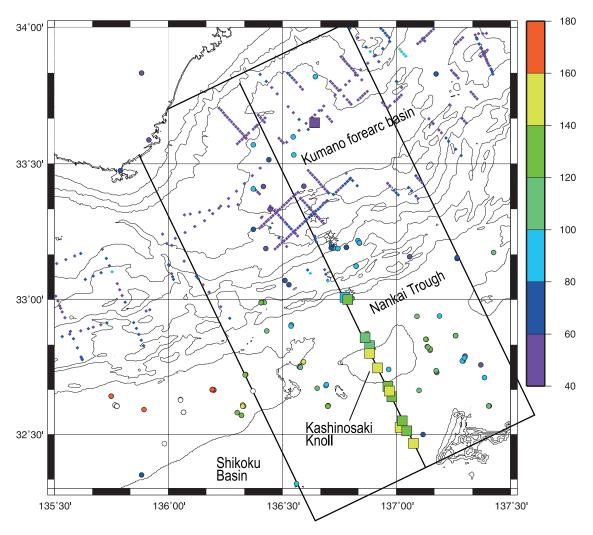


Fig. 7 Heat flow distribution on the floor of the Nankai trough off Kumano. Heat flow values are classified by a color code on the right (unit: mW/m^2). Squares; heat flow obtained by this study, circles; previous results and results prepared by Hamamoto et al. (in prep), dots; estimates from gas hydrate BSRs (Ashi et al., 2002).

trough floor in the Kumano region is $100-110 \text{ mW/m}^2$, whereas it is as high as 200 mW/m^2 at about 50 km westward (Yamano et al., 2003.).

Two heat flow values obtained on the probable landslide deposits just seaward of the frontal thrust (HFPC-10 and 12) are 90 and 135 mW/m², respectively. At HFPC-10 the core sample includes large amount of turbidites, whereas the lithology at HFPC-12 is dominated by hemipelagic mud. Thus the difference in heat flow may be attributed to the difference in the depositional environment.

HFPC-07 and 09 are located on the trough floor but also on the northern lower slope of Kashinosaki Knoll, one at NanTroSEIZE NT1-7A (Kinoshita et al., 2006; for location see http://www.jamstec.go.jp/chikyu/eng/Expedition/Nantro SEIZE/stage1b.html) (HFPC-07), and the other on its downslope side by 2 miles (HFPC-09). Cores from both sites include pumice fragments (Fig. 4), probably the debris flow from KK, so the sediments should be thermally disturbed. Although heat flow values at the two sites are quite similar to each other at about 110 mW/m², we should be careful about extrapolating heat flow at depth in the oceanic basement.

Overall, surface heat flow in the Nankai Trough region ranges from 90 - 135 mW/m². On the Nankai Trough, the sedimentation rate of Quaternary trench turbidite can be as high as 600m/My or even higher (e.g. Shipboard Scientific Party, 1991; Shipboard scientific Party, 2001). Under such conditions, sediment near the surface is deposited rapidly before it is thermally equilibrated to the geothermal gradient. Accordingly, the surface temperature gradient is reduced by about 15 % from the basal heat flux (e.g. Hutchinson, 1985), i.e. the theoretical value estimated from the age of oceanic crust. Likewise, surface heat flow in an area covered with slope failure deposits or debris flow can be lower than the basal heat flux, depending on the sedimentation rate and thickness, and thermal diffusivity. With these factors considered, the basal heat flux beneath the Nankai Trough off Kumano is roughly estimated as 100 - 130 mW/m², and most likely as 120-130 mW/m².

3.2. Heat flow in the Shikoku Basin/Kashinosaki Knoll

Kashinosaki Knoll is supposed to be an isolated basement high of volcanic origin on the subducting Philippine Sea Plate (Ike et al., 2008b). Piston core samples taken from the Shikoku Basin sediment during the KY07-01 cruise consist of approximately 1-m-thick hemipelagic sediment underlain by approximately 10-cm-thick ash layer.

Heat flow at stations HFPC02 through HFPC06 and HFPC08 (KY07-01), and HFPC07 (KY08-01) is 120-147 mW/m², (average~135 mW/m²). Furthermore, previous heat flow measurement obtained eastward or westward of this transect are lower around 90 - 120 mW/m² (Fig. 8). Particularly, one previous heat flow in the Shikoku Basin was obtained close to HFPC02 and HFPC03 (Fig. 7), and it was 62 mW/m². Although the quality at HFPC02 and 03 is not sufficient (see Table 2), other nearby stations also show silimilarly high values. We anticipate that this previous value (station="TAK68204"; temperature gradient=80 mK/m, thermal conductivity=0.76 W/m/K) may not be reliable.

The heat flow to the south of KK ranges 130-140 mW/m². Core samples suggest that these three sites are affected by slumping from KK. Interestingly, these heat flow values are similar to those in the Shikoku Basin to the south (HFPC02-05 of KY07-01).

During the KY05-14 cruise we obtained one heat flow datum on the summit of KK (158 mW/m^2). Visual observation of the seafloor near the summit shows some outcrops of volcanic rocks.

3.3. Cause for high basal heat flow

Fig.8 is the MCS section KR9806-02 and heat flow cross section acquired so far. As described above, surface heat flow in the Shikoku Basin south of KK and the inferred basal heat flow beneath the Nankai Trough north of KK are 120-158 mW/m² and 120-130 mW/m², respectively. Both values are significantly higher than the theoretical value (110 mW/m²) estimated from the age of the Shikoku Basin (20 Ma; Okino et al. 1999).

Postspreading volcanism may have made the heat flow at the summit of the knoll higher than the surrounding region. The oceanic crust across KK may have been reheated by the postspreading volcanism, possibly at KK. According to the classical half-space cooling model by Lister (1974), the age of KK is 13 Ma (for 140 mW/m²) or 10 Ma (for 160 mW/m²). Hydrothermal circulation must have followed this volcanism, in which case the volcanic heat was escaped more rapidly. Thus these age estimates provide maximum values, i.e. the postspreading volcanism must have occurred even more recently.

Ike et al. (2008b) propose that KK was formed soon after the crust was formed by seafloor spreading in the middle Miocene (20 - 21 Ma), because the lowest sedimentary unit (LSB-T subunit) onlaps the basement flank of KK, indi-

cating that the knoll was already in place before LSB-T sedimentation began. This is not consistent with inference from heat flow. It is necessary to determine the age of oceanic crust near KK, either by dredge sampling of outcrops or through drilling.

Another possibility is that this knoll was formed by the thrust faulting dipping to the north. The asymmetrical structure across KK, recognized on the MCS profile (Fig. 8), might support this inference. If this is the case, a simple thermal conduction model predicts that the hanging wall side (the northern side) should have a reduced heat flow, whereas the heat flow on the footwall side increases. This hypothesis may reasonably explain the lower heat flow (110 mW/m²) to the north of the knoll and higher heat flow to the south. However, the southward distance of the high heat flow "zone" to the south is at least 40 km, which seems too long to be caused by thrusting. Besides, Ike et al. (2008b) reject this idea because KK is structurally discontinuous from the Zenisu Ridge which is of volcanic origin with tectonic overprint of thrust faulting.

It could also be possible that subseafloor fluid in the

accretionary prism or from the deeper portion migrates along permeable channels, such as the turbidite layer, décollement or frontal thrusts. A certain amount of heat is also carried with the fluid, increasing the surface heat flow values. Probably a combination of volcanism, tectonic compression, and fluid flow would have caused the high heat flow.

4. Summary

13 new heat flow data were obtained on the Nankai Trough off Kumano and on the Shikoku Basin near the Kashinosaki Knoll (KK). Surface heat flow in the Nankai Trough north of KK ranges from 90 - 135 mW/m². With the sedimentation effects considered, basal heat flux beneath the Nankai Trough off Kumano is roughly estimated as 100 - 130 mW/m², most likely as 120-130 mW/m². In the Shikoku Basin south of KK, the average heat flow is about 135 mW/m²), significantly higher than the theoretical value (110 mW/m²) estimated from the age of the Shikoku Basin. Furthermore, previous heat flow data obtained eastward or westward of this transect are lower around 90 - 120 mW/m².

A possible cause for the heat flow anomaly is the

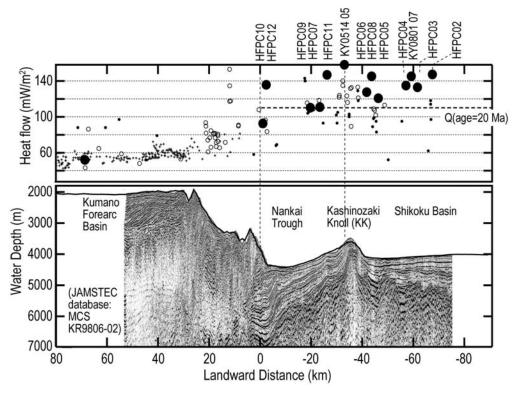


Fig.8 Depth-converted MCS section KR98096-02 and heat flow cross section acquired so far. Solid circles; heat flow obtained by this study, small and open circles; previous results and results prepared by Hamamoto et al. (in prep), dots; estimates from gas hydrate BSRs (Ashi et al., 2002). Horizontal broken line shows theoretical heat flow (110 mW/m²) corresponding to 20-Ma-old oceanic crust.

postspreading volcanism, which made the heat flow at the summit of the knoll higher than the surrounding region. According to the half-space cooling model the age of KK is estimated as 13 to 10 Ma. This is not consistent with the age suggested by Ike and others, who propose that KK was formed soon after the crust was formed by seafloor spreading in the middle Miocene (20 - 21 Ma). Other interpretations are either that KK is thermally disturbed by tectonic compression, or that surface heat flow is affected by subseafloor fluid migration.

Heat flow from the subducting oceanic crust can be as high as 130 - 150 mW/m², which can affect the frictional property of seismogenic zone fault. More intensive studies are necessary, including point-by-point assessment of the sedimentation effect on the surface heat flow, and determination of the age of oceanic crust at and near KK, either by dredge sampling of outcrops or through scientific drilling.

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