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Heat flow and fluid flow regime in the western Nankai accretionary prism

M. Yamano [a], J.-P. Foucher [b], M. Kinoshita [c], A. Fisher [d], R.D. Hyndman [e] and ODP Leg 131 Shipboard Scientific Party [1]

[a] *Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113, Japan*
[b] *IFREMER / CB, BP 70, 29263 Plouzane, France*
[c] *School of Marine Science and Technology, Tokai University, 3-20-1 Orido, Shimizu 424, Japan*
[d] *Ocean Drilling Program, 1000 Discovery Drive, Texas A&M University Research Park, College Station, TX 77840, USA*
[e] *Pacific Geoscience Centre, Geological Survey of Canada, P.O. Box 6000, Sidney, B.C. V8L 4B2, Canada*

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ABSTRACT

The thermal structure of the western Nankai subduction zone has been studied through surface heat flow measurements with conventional geothermal probes and estimation of heat flow from depths of gas hydrate bottom simulating reflectors. Temperature and thermal conductivity measurements at ODP Site 808, located at the toe of the Nankai accretionary prism, added important information on any variation in heat flow with depth and thus on thermal effects of pore fluid flow in the prism. Surface heat flow is generally higher than 130 mW/m^2 on the floor of the Nankai Trough. Such high heat flow cannot be explained simply by conductive cooling of the subducting Shikoku Basin lithosphere. Recent closely spaced probe measurements revealed that the heat flow on the trough floor shows local variation, with particularly high values near the deformation front. The heat flow distribution suggests that warm fluid flows seaward possibly along the décollement and locally rises toward the seafloor along some channels, resulting in both the regional and local high heat flow anomalies. Contrary to this inference, no active localized fluid flow was detected at Site 808. The temperatures measured at six depths down to 347 m below seafloor (mbsf) just below the frontal thrust can be well explained by conductive heat flow of 125–130 mW/m^2. No geochemical anomaly associated with present-day pore fluid movement was observed in cores recovered from the frontal thrust or the décollement. On the other hand, the high heat flow at Site 808 requires some heat source below 350 mbsf. There is a possibility that the fluid flow in the Nankai accretionary prism is localized and transient, and thus was not detected at this single drill site.

1. Introduction

The Nankai accretionary prism has developed in a subduction zone where the Philippine Sea plate (Shikoku Basin) is underthrusting beneath the Southwest Japan arc. Expulsion of pore water must occur inside and beneath the prism as a result of sediment compaction associated with the

[1] A. Taira, I. Hill, J. Firth, U. Berner, W. Brückmann, T. Byrne, T. Chabernaud, T. Gamo, J. Gieskes, D. Karig, M. Kastner, Y. Kato, S. Lallemant, R. Lu, A. Maltman, K. Moran, G. Moore, G. Olafsson, B. Owens, K. Pickering, F. Siena, E. Taylor, M. Underwood, C. Wilkinson and J. Zhang

Correspondence to: M. Yamano, Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113 (Japan)

accretion and subduction processes. Recent submersible studies provided direct evidence of fluid expulsion in the eastern part of the Nankai accretionary prism [1,2]. Such fluid flow may affect the thermal structure of the subduction zone and be reflected in the surface heat flow distribution.

Heat flow anomalies caused by pore fluid movement in accretionary prisms have been reported in several subduction zones [3,4,5]. One of the best studied area is the Barbados Ridge accretionary complex, where anomalously high and variable surface heat flow was observed, suggesting the existence of fluid flow along the décollement and thrust faults [6,7]. Temperature measurements in ODP drill holes also revealed that the thermal structure of the accretionary complex is strongly influenced by transient fluid flow along local conduits [8].

In the western part of the Nankai subduction zone, the most prominent feature of the heat flow distribution is a high heat flow zone on the floor of the Nankai Trough [9,10], where surface heat flow is generally higher than 130 mW/m^2 (Fig. 1). Conductive heat flow near a trench axis with a thick sediment cover should be dominated by the thermal structure of the subducting plate, and the generally high heat flow in the Nankai Trough is thought to result mainly from cooling of the young Shikoku Basin lithosphere. Heat flow expected from the age of the Shikoku Basin (about 20 m.y.) is, however somewhat lower, about 110 mW/m^2, indicating that some other mechanism is necessary for sustaining the high heat flow anomaly [10]. Advective heat transfer by pore fluid movement may be an explanation.

Recently, detailed surface heat flow measurements were carried out in the Nankai Trough area to investigate the regime of subsurface fluid movement [11]. We also made temperature measurements in deep-sea drill holes at ODP Site 808

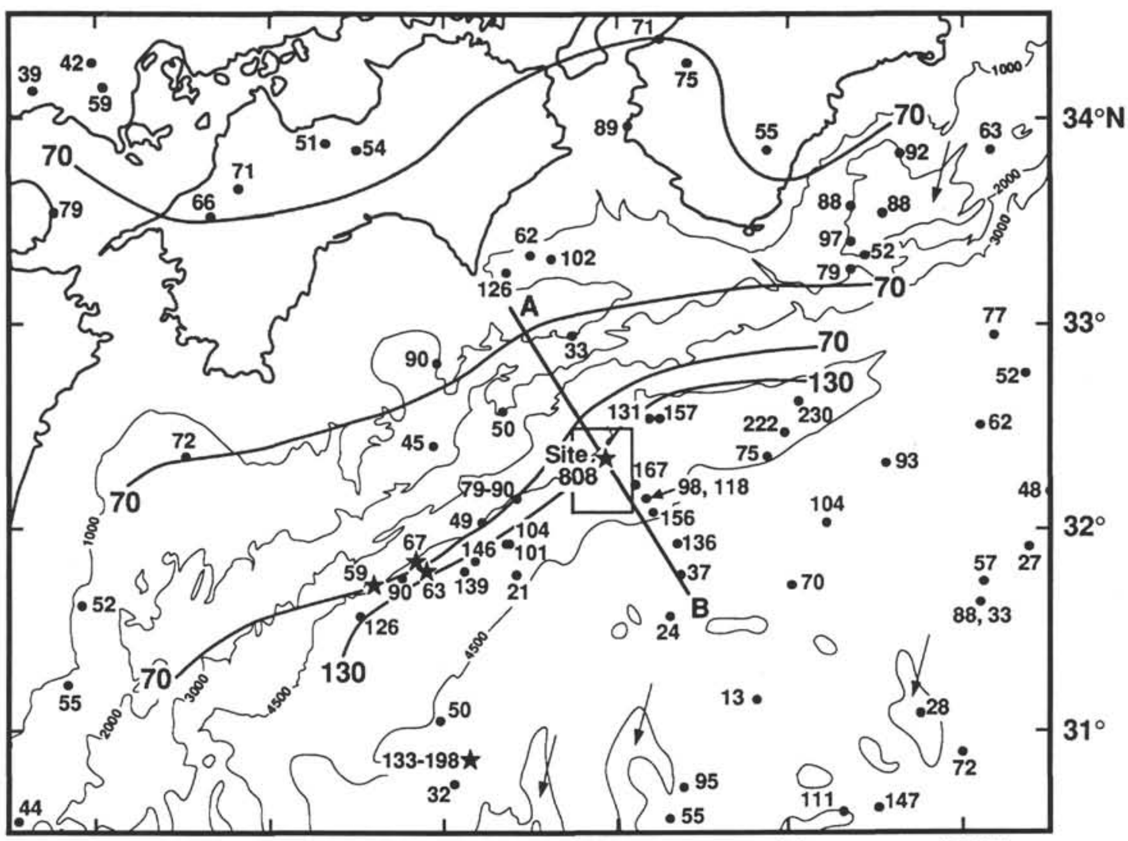

Fig. 1. Heat flow data in the western Nankai subduction zone [11,13] (in mW/m^2). Stars are DSDP and ODP drill holes. The data in the rectangle at around 32°20′N, 135°00′E are shown in Fig. 2. Contours are drawn taking BSR heat flow into consideration.

[12]. Bottom simulating reflectors (BSRs) produced by the base of gas hydrate layers are widely distributed on the Nankai accretionary prism and they provide a third source of information on temperatures inside the prism. In this paper, we review these geothermal data and discuss effects of fluid expulsion on the thermal structure of the western Nankai subduction zone, especially around Site 808.

2. Heat flow data

2.1. Seafloor measurements

Heat flow measurements with conventional marine geothermal probes have been made in the Nankai Trough area since the 1960s and have revealed that heat flow is very high on the floor of the trough [9]. Yamano et al. [10] compiled seafloor heat flow data and delineated the regional pattern of the heat flow distribution. In the last several years, more detailed measurements were carried out using multipenetration-type probes [11]. The stations were located mainly along a line extending from the Shikoku Basin to the accretionary prism at about 135°E (line A–B in Fig. 1) in order to detect local anomalies due to fluid flow near the toe of the prism and to investigate the transition between the high heat flow on the trough floor and the lower and scattered heat flow in the Shikoku Basin.

All of the seafloor heat flow data in the western Nankai subduction zone are shown in Figs. 1 and 2. There are only few data on the landward slope of the trough because the hard bottom prevented good penetration of probes. Errors in the heat flow values are estimated to be generally ±10–15%. The data measured in the area where the water depth is less than 2000 m may be less reliable, because nonlinear temperature profiles were observed at some stations, suggesting influence of variation in the bottom water temperature. In the deeper area, most of the temperature profiles were linear.

2.2. Measurements in DSDP holes

In the Nankai Trough area, temperature measurements in deep-sea drill holes were made at Sites 297 and 298 on DSDP Leg 31 [14] and at Sites 582 and 583 on DSDP Leg 87 [13] before

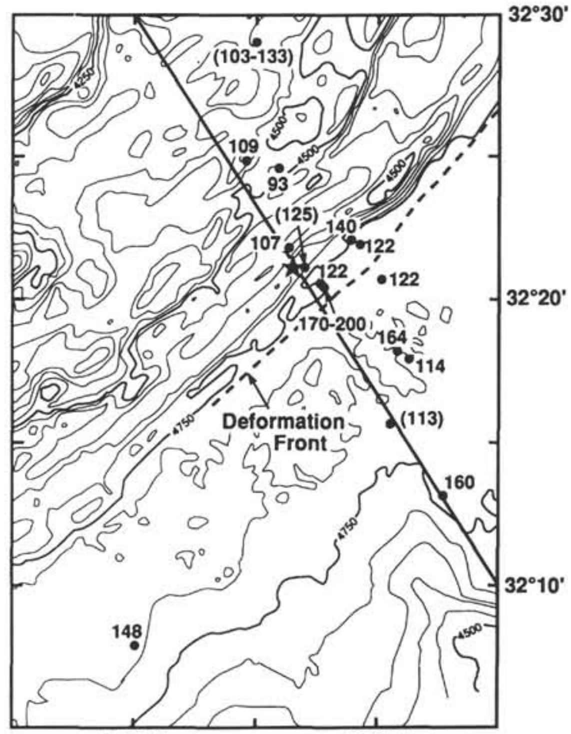

Fig. 2. Heat flow data in the rectangle in Fig. 1 [11,13] plotted on a Seabeam bathymetric map. Star represents ODP Site 808. Solid line is a part of the line along which the heat flow profile in Fig. 7 is constructed, and broken line shows an approximate location of the deformation front.

our measurements at Site 808 on ODP Leg 131 (stars in Fig. 1). These borehole measurements can provide information about vertical variation in conductive heat flow, and may reflect effects of advective heat transfer by fluid movement.

At Site 297 on the outer rise of the trough and Site 298 located on the lowermost part of the landward slope (near 133°35'E), heat flow was determined from one sediment temperature measurement and the seafloor temperature. The values are 130–200 mW/m^2 and 59 mW/m^2 at Sites 297 and 298 respectively, but are not very reliable.

Site 582 is on the trough floor seaward of the deformation front (at about 133°55'E). Temperature was measured at four depths down to 508 m below seafloor (mbsf) in two holes, the locations of which are within 50 m of each other. The temperature gradient appears to be higher in the upper 150 m than in the lower part.

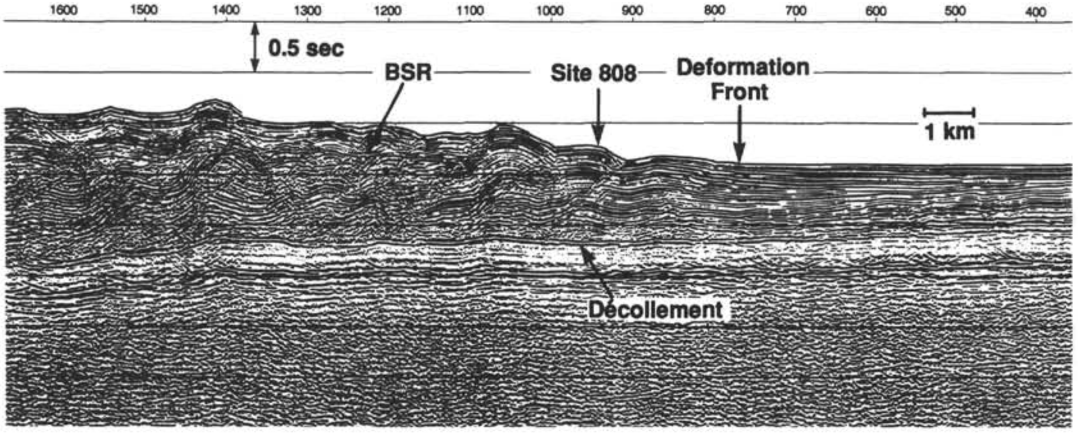

Fig. 3. Multichannel seismic reflection profile NT62–8 through ODP Site 808 (from Moore et al. [15]).

Site 583 is located at the toe of the accretionary prism, about 5 km northwest of Site 582. Fifteen temperature measurements were successful down to 172 mbsf in four holes which are about 150 to 900 m apart from each other. The temperature data are very scattered above 50 mbsf. This may partly result from measurement errors, but also suggests the possibility that heat flow is highly variable, both vertically and horizontally around Site 583.

The heat flow calculated from the average gradient is 63 and 67 mW/m^2 at Sites 582 and 583 respectively. These are relatively low values as compared with the high surface heat flow on the trough floor, although there are no surface measurements in the close vicinity of these sites for direct comparison.

2.3. Measurements at ODP Site 808

During ODP Leg 131, seven holes were drilled at Site 808, located at the toe of the accretionary prism above the frontal thrust (Fig. 3). We made temperature measurements at this site mainly using the water sampler, temperature, pore pressure (WSTP) tool [16,17]. The tool had a temperature probe with a diameter of 1.27 cm at its bottom end. The probe was penetrated into the bottom of the hole, about 1 m ahead of the drill

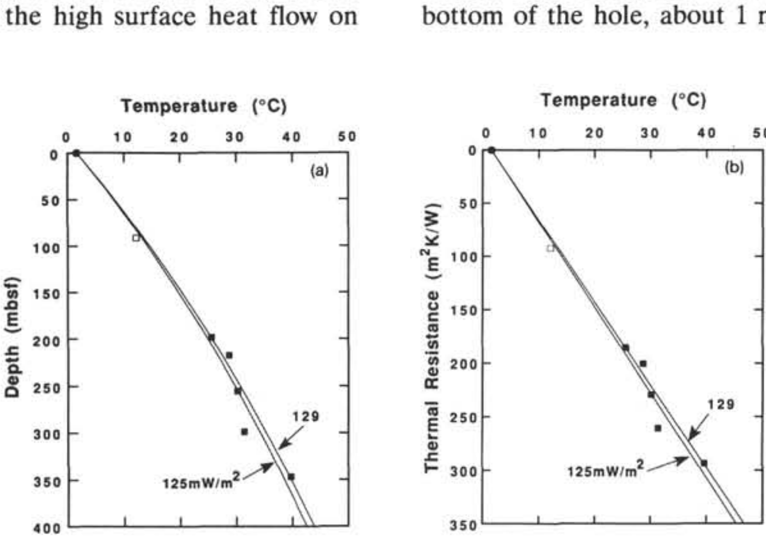

Fig. 4. Temperature data measured with the WSTP tool at ODP Site 808 [12] plotted against subbottom depth (a) and thermal resistance between the seafloor and the measurement depth (b). Black squares are measurements in Hole 808B, white squares are those in Hole 808F. Dot represents the bottom-water temperature. Lines are temperature profiles expected for purely conductive heat flux.

bit, and kept in undisturbed sediment for about 15 minutes. The recorded temperatures were extrapolated to the equilibrium following the theory of Bullard [18] (for details, see Shipboard Scientific Party [19]).

Of the eleven measurements with the WSTP tool attempted, six were successful, five in Hole 808B and one in Hole 808F. The deepest data were obtained at 347 mbsf in Hole 808B, just below the frontal thrust that was penetrated between 336 and 341 mbsf in Hole 808B. Hole 808F was drilled about 250 m away from 808B but in a similar position with respect to the structure of the prism. We thus treat the measurement in Hole 808F together with those in 808B in the present analysis. The temperatures are plotted versus subbottom depth in Fig. 4a, with the seafloor temperature at 1.6°C. Because of the possibility of conduction or advection of heat from the borehole to the depth of the probe measurement the temperature values are probably minima. Recognized errors in the equilibrium temperatures are ± 0.1–0.2 K.

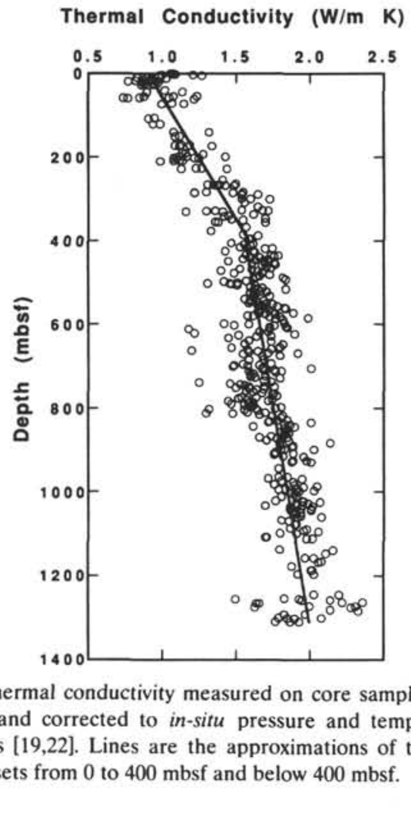

Fig. 5. Thermal conductivity measured on core samples from Site 808 and corrected to *in-situ* pressure and temperature conditions [19,22]. Lines are the approximations of the data sets from 0 to 400 mbsf and below 400 mbsf.

Thermal conductivities were measured on recovered core samples by the needle probe method [20]. Measurements for lithified sediment and hard rock samples were made in half-space configuration [21]. The measured raw conductivities were converted into true conductivities based on measurements of several standard samples, and then corrected for *in-situ* temperature and pressure conditions [19,22].

Thermal conductivity generally increases with depth as porosity decreases due to compaction (Fig. 5). The relatively large scatter in the upper 100 m results from high conductivity in sandy layers and low conductivity due to cracks in the samples produced by gas expansion. There may be a bias to low conductivities because of core disturbance and preferential recovery of muds in this section. Several extreme low values between 600 and 820 mbsf are those measured on ash layers and volcaniclastic sandstones. We approximated the average thermal conductivity versus depth relationship by straight lines as shown in Fig. 5: $k = 0.91 + 0.0017\,z$ (for 0 to 400 mbsf) and $k = 1.38 + 0.00048\,z$ (for 400 to 1400 mbsf), where k is thermal conductivity in W/m K, and z is depth in mbsf.

To obtain a conductive heat flow estimate, the temperature data were plotted versus thermal resistance between the seafloor and the measurement depth calculated from the average conductivity–depth function [23]. The best fit to the all six WSTP measurements forced through the seafloor temperature gives a heat flow of 125 mW/m^2 (Fig. 4b). The low temperature at 299 mbsf as compared with the other data might be a real temperature anomaly but there is also a possibility that it is a result of insufficient penetration of the probe or cooling by water which mixed into the sediments below the bottom of the hole along cracks. If we exclude this measurement, a conductive heat flow of 129 mW/m^2 well explains the WSTP data (Fig. 4).

Temperature measurements were also made by wireline logging in several holes down to about 800 mbsf (Fig. 6). The temperature profiles were obtained only a few hours after long periods of circulation, and were strongly affected by this activity. They all exhibit the expected cooling in the deeper parts and warming in the shallower parts of the holes. Computation of the true temperature profiles by correcting for this disturbance is in progress [24]. The preliminary results indicate that the equilibrium temperature in Holes 808C and 808E is much higher than the temperature profile calculated for a conductive heat flow of 129 mW/m^2 (solid curve in Fig. 6).

2.4. Estimation from gas hydrate BSRs

Clear gas hydrate BSRs are widely observed in seismic reflection records on the western Nankai accretionary prism (e.g., Fig. 3). These reflectors occur at the base of the hydrate stability field [e.g., 25,26] and represent the temperature–pressure limit condition in sediments for hydrate to occur. Therefore, it is possible to determine heat flow from the depth of a gas hydrate BSR if (a) the temperature–pressure field for hydrate stability, (b) the thermal resistance between the seafloor and the BSR and (c) the seafloor temperature are known [27]. The stability field for pure methane and 3.5% NaCl is thought to be appropriate to most BSRs and has been used in this study. However, field calibrations of BSRs recently made suggest that the pure water–methane conditions may be applicable [26]. If we apply the pure water stability field, heat flow will be higher by 5–10%. Considering errors in thermal conductivity estimation, heat flows obtained by this method (termed "BSR heat flow" below) have estimated overall errors of 20–25%.

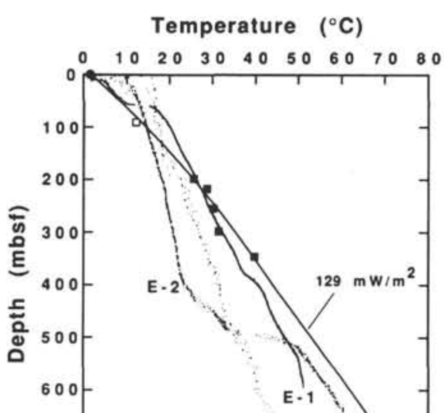

Fig. 6. Temperature logs obtained at Site 808 [12] with the WSTP temperature data and the bottom-water temperature (cf. Fig. 4). C, E-1 and E-2 denote the log in Hole 808C, the first log in Hole 808E and the second log in Hole 808E respectively. Solid line is the temperature profile for conductive heat flow of 129 mW/m^2 calculated using the approximate thermal conductivity–depth function shown in Fig. 5.

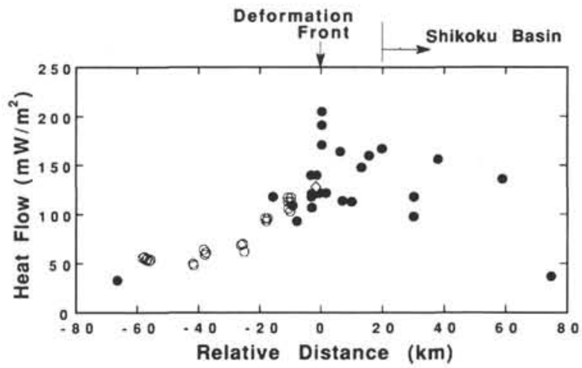

Fig. 7. Heat flow profile across the Nankai Trough along the line A–B in Fig. 1. Dots are surface probe data within 30 km of the line, circles are BSR heat flow estimated along the line, and rhombus represents the value determined at Site 808.

BSR heat flow has been calculated along many seismic profiles available in the Nankai accretionary prism [28,29]. It fills the gap in probe measurements on the landward slope of the trough (cf. Fig. 7). Seeing as BSR heat flow is determined from the temperature at the reflector (about 200–800 mbsf in this area), it represents the thermal structure of layers that are deeper than those represented by seafloor heat flow. Only a few seafloor heat flow values were obtained in the area where BSRs exist and they agree with the BSR heat flow within about 20%.

3. Heat flow distribution

After integrating the probe, drill hole and BSR data, features of the heat flow distribution in the western Nankai Trough area can be delineated. Heat flow is generally higher than 130 mW/m^2 on the floor of the Nankai Trough, with a maximum of 230 mW/m^2 (Fig. 1). The eastern limit of this high heat flow zone is not well determined because there are few data east of 136°E. To the south of the trough, heat flow is highly variable in the Shikoku Basin, and this is probably due to active hydrothermal circulation in the basement and/or through the sediment cover [10]. The heat flow distribution on the landward slope of the trough was revealed primarily by estimation from gas hydrate BSR depths (contours in Fig. 1 are drawn taking BSR heat flow into consideration). BSR heat flow decreases landward from about 100 mW/m^2 at the toe of the accretionary prism to about 50 mW/m^2 on the upper part of the slope (cf. Fig. 7). In addition to this general trend, BSR heat flow varies along the strike of the trough [28,29], although small variation in BSR heat flow might be attributed to variation in physical properties of sediment and/or composition of the hydrate.

Recent surface probe measurements were mainly concentrated in an area surrounding ODP Site 808 (Fig. 2; [11]). On the trough floor, heat flow is higher than 100 mW/m^2 but rather variable. For example, heat flow of 164 mW/m^2 and 114 mW/m^2 was measured at stations close to each other (within 1 km). The highest values in this area, 170–200 mW/m^2, were observed in the vicinity of the deformation front. The conductive heat flow obtained at Site 808, 129 mW/m^2, agrees well with the average of surface heat flow at nearby stations.

We constructed a heat flow profile along line A–B in Fig. 1, crossing the trough from the Shikoku Basin to the accretionary prism (Fig. 7). Surface heat flow data within 30 km of the line are projected together with the data from Site 808 and BSR heat flow obtained along the line. The profile clearly demonstrates that BSR heat flow monotonously decreases upslope from about 120 mW/m^2 at the toe of the prism to 30–50 mW/m^2 60 km landward of the deformation front. Heat flow on the trough floor ranges from 100 to 200 mW/m^2, and it appears that there is no clear boundary between the higher heat flow on the trough floor and the lower heat flow in the Shikoku Basin.

4. Discussion

4.1. High heat flow on the trough floor

In order to discuss the origin of the high heat flow on the floor of the Nankai Trough, it is necessary to consider the thermal structure of the subducting Shikoku Basin deep lithosphere. Heat flow observed in the Shikoku Basin is very scattered, indicating the existence of hydrothermal circulation. We therefore cannot estimate the deep thermal structure from the surface heat flow data.

The relationship between heat flow and crustal age for marginal basins was examined by compiling reliable heat flow data, which were measured at stations with a thick sediment cover and far from outcrops, and was shown to be consistent with that for ocean basins [30,31]. This indicates that the thermal structure of marginal basin lithosphere is not significantly different from that of the oceanic lithosphere with the same age.

The age of the Shikoku Basin subducting at around 135°E, the youngest part of the basin, is estimated to be 14–16 m.y. based on magnetic anomaly lineations [32,33]. Drilling at ODP Site 808 reached the basaltic basement of the Shikoku Basin, and nannofossils sampled from sediment just above and within the basalt indicate that the age of the basement is about 15 m.y. [12]. If we apply the heat flow–age relationship for ocean basins [34,35], heat flow expected from the crustal age of 15 m.y. is 120–130 mW/m^2, not much different from the values observed on the trough floor. The rapid sedimentation in the trough, however, should suppress the surface heat flow.

We calculated the sedimentation effect on heat flow using the model presented by Hutchison [36], which takes account of the process of sediment compaction. The sedimentation history used was derived from the biostratigraphy at Site 808 corrected for displacement by the frontal thrust [12]. Calculations were made for several sets of reasonable thermal property values and porosity–depth functions. The results show that the surface heat flow should be reduced by about 20% and is expected to be about 100 mW/m^2. Therefore, some other heat source and/or heat transfer mechanism is necessary to reproduce the observed heat flow of 130 mW/m^2 or more. It is possible that the thermal structure of the Shikoku Basin lithosphere is different from that of normal oceanic lithosphere of the same age for some unknown reason [10], but we will consider other possibilities in the following.

Bray and Karig [38] demonstrated that deposition of turbidites in the trough loads and thus causes rapid dewatering of the Shikoku Basin hemipelagic sediments. They argued that the high heat flow may be explained by expulsion of hot water from the dewatering sediments. Here we assume that the average porosity of the hemipelagites decreases from 61% to 43% [38] in the 20-km-wide trough floor part of the Shikoku Basin, the thickness of the hemipelagites before the dewatering is 400 m, and the convergence rate in this area is 4 cm/yr [39]. With these assumptions the average rate of fluid expulsion is about 8×10^{-12} m/s. If pore fluid flows upward through 400-m-thick turbidites at this rate, the effect on the surface heat flow is estimated to be less than 1% using the simple model of Bredehoeft and Papadopulos [40]. Although this estimation is crude, we need a more than one order of magnitude higher flow rate to attain the observed high heat flow. If significant upward flow exists, it could be detected by detailed temperature measurements in drill holes. The decrease in temperature gradient with depth observed at DSDP Site 582 possibly represents upward flow [38], but more dense and reliable measurements are necessary.

Another possible cause of the high heat flow anomaly is heating by warm fluid flow along the décollement zone, which originates from a landward and deeper—thus hotter—part of the accretionary prism (Fig. 8). Upward diffusive flow from the décollement zone may increase the efficiency of heating. Heat flow higher than expected from the age of the subducting plate was also reported in the Barbados subduction zone both seaward and landward of the deformation front, and interpreted as resulting from hot water flowing along the décollement zone [6,7,8]. A problem in this model is that the amount of water brought

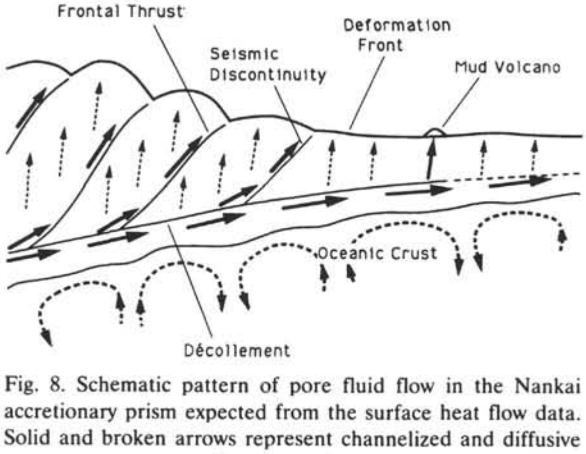

Fig. 8. Schematic pattern of pore fluid flow in the Nankai accretionary prism expected from the surface heat flow data. Solid and broken arrows represent channelized and diffusive flow respectively.

into the Nankai prism by subduction and accretion is not enough to produce the broad high heat flow anomaly in the trough [10].

The large scatter of heat flow on the trough floor indicates that localized upward fluid flow is also occurring there (Fig. 8). This inference is supported by the existence of several mud volcanoes seaward of the deformation front, which were discovered through an ocean floor imaging survey with the IZANAGI sonar system [41].

Hydrothermal circulation in the Shikoku Basin crust is thought to be sealed by the thick sediment cover in the Nankai Trough. However, it is probably still active in the basement and redistributes heat laterally (Fig. 8). Such sealed hydrothermal circulation may also result in the scattered heat flow in the trough and contribute to the lateral heat transport necessary to give the high heat flow anomaly to some extent.

4.2. Thermal structure of the accretionary prism

The most important factors controlling the thermal structure of the Nankai accretionary prism are subduction of the Shikoku Basin lithosphere and the landward increase in the prism thickness. Kinoshita and Kasumi [42] calculated the subsurface temperature structure along the line A–B in Fig. 1 using a simple two-dimensional conduction model, which only takes account of the motion of the subducting lithosphere and the shape of the prism. The calculated heat flow near the surface agrees well with the BSR heat flow when the heat flow from the deep crust is assumed to be 110–120 mW/m^2, close to the value expected from the age of the subducting plate. However, movement of sediments in the prism and frictional heating should also affect the thermal structure [6], and a simulation with a more comprehensive model is necessary for further discussion.

Expulsion of pore water in the accretionary prism may occur both by regional diffuse flow and by localized flow. In the northern Cascadia accretionary prism, the surface heat flow is consistently about 35% higher than the BSR heat flow, and it can be explained by regionally uniform upward fluid flow [5]. The flow rate required for this difference is, however, much higher than that expected from sediment compaction [43], and the difference may result partly from uncertainty in the hydrate stability field. In the Nankai prism, the surface heat flow data are too sparse to be compared with the BSR heat flow (e.g., Fig. 7). More surface probe measurements are necessary for detecting diffuse flow in this way.

The existence of localized flow in the protothrust zone is indicated by the extremely high seafloor probe heat flow (170–200 mW/m^2) in the vicinity of the deformation front (Figs. 2 and 7). A landward dipping seismic discontinuity is imaged just landward the deformation front in a seismic reflection profile through Site 808 (Fig. 3; [15]). Warm fluid may rise from the décollement zone, flow upward along a discontinuity of this type, and result in the local heat flow anomaly (Fig. 8). Similar anomalies are expected to occur associated with major thrust faults in the prism, since they are probably more suitable for fluid flow paths. Such heat flow anomalies have not been detected, but there are too few measurements to resolve such localized flow.

Minshull and White [4] reported that the BSRs in the Makran accretionary complex curve up into thrust faults. This curvature may be attributed to water expulsion along the faults. In the Nankai prism, no similar upwarping of BSRs is observed in association with thrust faults [29], so any flow along such faults in the Nankai area must be at a slower rate.

The temperature data obtained at ODP Site 808 provide important information about the thermal structure of the Nankai prism. The temperatures measured with the WSTP tool are consistent with conductive heat flow of 125–130 mW/m^2 (Fig. 4). This value agrees with the surface heat flow at stations close to Site 808 and at stations located at similar positions with respect to the frontal thrust (120–140 mW/m^2) (Fig. 2).

The sedimentation effect must be considered in order to discuss the implications of these data. We calculated the temperature structure of the sediment layers at Site 808 with the sedimentation history both corrected and uncorrected for the thrust displacement, using the Hutchison model [36]. The surface heat flow is reduced by about 20% in the thrust-corrected case, and additional 3–4% reduction occurs in the uncorrected case. Heat flow increases with depth, but the rate is almost negligible, less than 1%/500 m. This result is consistent with the observation that heat flow does not significantly vary with depth. Thus the thermal regime at Site 808 appears to be nearly conductive, at least down to 350 mbsf.

Based on the temperature data only, we cannot exclude the possibility that slow diffusive upward fluid flow exists. The WSTP data at Site 808 can be explained reasonably well even if there is a constant and uniform flow at a rate of 1 to 2×10^{-10} m/s, which gives surface heat flow of 130–140 mW/m^2. However, this rate is high enough to produce a significant effect on the chemical profiles of interstitial water, and such a flow was not detected by geochemical studies [12].

On the other hand, the heat flow of 125–130 mW/m^2 at Site 808 is appreciably higher than that expected from cooling of the subducting plate, considering the sedimentation effect. It is difficult to evaluate the effect of the frontal thrust quantitatively as we do not know the time and rate of the movement. But the high heat flow cannot be a result of thrusting, because the layers above the thrust, where the most of the WSTP measurements were made, must have been cooled by displacement. Therefore some heat source is required below 350 mbsf to explain the observed heat flow.

Localized flow of hot fluid might supply some heat. The temperature logs down to 800 mbsf are relatively smooth and give no evidence of localized fluid flow (Fig. 6). The décollement at about 960 mbsf is a candidate for the zone where concentrated fluid flow occurs. We could not make temperature measurements across the décollement, but interstitial water chemistry studies showed no evidence for present-day fluid movement along it [12], although anomalies in several constituents were detected there [44]. No chemical anomaly suggesting active fluid flow was found at the frontal thrust either.

4.3. Regime of fluid flow

A possible pattern of pore fluid movement discussed above is schematically summarized in Fig. 8. The surface heat flow distribution suggests the existence of significant lateral fluid flow possibly along the décollement and some kind of conduit beneath the trough floor. Hydrothermal circulation in the oceanic crust sealed beneath the sediment cover may play an important role in lateral heat transport. Thrust faults in the accretionary prism are also thought to be fluid flow paths. Diffuse upward flow should also occur both inside the prism and beneath the trough floor.

At ODP Site 808, however, no clear evidence for fluid flow was obtained by geothermal and geochemical studies. A possible solution for this discrepancy is that the fluid movement is intermittent and localized. If this is the case, currently active flow channels may not be encountered by drilling at a single site. In the Barbados accretionary complex, fluid flow is supposed to be transient, as flow velocities estimated from the observed thermal anomalies are too high for the steady state [6,7,8].

In the above discussion, fluid flow is assumed to be vertical or perpendicular to the strike of the prism. However, lateral flow parallel to the strike may exist. The variation in BSR heat flow along the strike might result from such lateral fluid flow.

5. Conclusions

Local and regional surface heat flow anomalies were observed in the western Nankai Trough area. They may indicate that warm fluid is flowing along some channels as part of expulsion of pore water from the accretionary prism and/or that heat is being laterally transported by hydrothermal circulation in the basement. The heat flow on the floor of the trough at about 135°E ranges from 100 to 200 mW/m^2, with many values significantly higher than expected from the crustal age of the subducting Shikoku Basin. One explanation for this regional high heat flow is fluid flow along the décollement zone. The large scatter in the observed heat flow may be attributed to local upward flow rising from the décollement or ongoing thermal redistribution by circulation in the underlying crust. In particular, heat flow of 170–200 mW/m^2 measured near the deformation front probably results from flow along an underlying conduit related to deformation in the protothrust zone. Expulsion by diffusive upward flow should also occur, but is not demonstrated by the present geothermal data. Information on the diffusive flow may be provided by temperature measurements in deep drill holes and surface probe measurements in the area where gas hydrate BSRs are observed.

In contrast, no direct evidence for pore fluid movement was obtained at ODP Site 808, which is located at the toe of the accretionary prism. The temperatures measured down to 350 mbsf, just below the frontal thrust, are consistent with conductive heat flow of 125–130 mW/m^2. The high heat flow value itself suggests that additional heat flux is supplied somewhere below 350 mbsf, but geochemical studies of pore water showed that there is no active fluid movement along the décollement. If fluid flow in the Nankai accretionary prism is localized and transient, it would be possible that the flow cannot be detected at Site 808.

Another important problem is that the amount of water brought into the prism is not enough to explain the high heat flow on the trough floor. A similar deficiency of pore fluid was pointed out in the Barbados, Cascadia and eastern Nankai subduction zones [43]. It is necessary to find a source of the excess fluid or a thermal model that does not require as much fluid as the previous models.

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