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Combining 2D-basin and structural modelling to constrain heat transport along the Muroto Transect, Nankai Trough, Japan

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Abstract

The Nankai Trough located southeast of Shikoku Island, Japan, exhibits a zone of exceptionally high heat flow. In the central part of the Nankai Trough the fossil spreading centre of the Shikoku Basin is subducted beneath the southwest Japan arc. We have modelled the temperature and maturation history along the Muroto Transect reaching from the tip of the thrust zone out into nearly undeformed Quaternary and Tertiary sediments seawards of Nankai Trough. We used two balanced cross-sections defining the sections before and after overthrusting as input for 2D-basin modelling. We can show that rapid burial and overthrusting during the Quaternary in combination with a heat flow history following the cooling curve of a 15 Ma old oceanic plate is not sufficient to explain measured maturity of organic material in the sediments. Several heat flow scenarios derived from theoretical concepts (Yamano et al., 2003) and previous modelling approaches (e.g. Brown et al., 2001; Spinnelli and Underwood, 2005; Steurer and Underwood, 2003) were tested. The best match between observed maturity levels, temperature and heat flow measurements is reached for a heat flow history which initially assumes the cooling of 15 Ma old oceanic lithosphere of but is reheated to 170-180 mW/m² during the phase of rapid burial in the Quaternary. This can be achieved either by assuming the onset of hydrothermal circulation in the cooling crust or by reheating caused by off-axis volcanism at about 6 Ma (Yamano et al. 2003).

1. Introduction

The Nankai Trough is a convergent plate boundary where the Philippine Sea plate is subducted beneath the Japanese Island arc forming a trench rapidly filled with thick terrigenous sediments (Fig. 1). Within these young sediments intact phospholipids, microbial “life markers”, were found to depths as great as 745 mbsf and in situ temperatures as high as 85 °C (Zink et al., 2003). The thermal and maturation evolution of organic matter is of particular interest because alteration products may serve as feed stock for the deep biosphere detected in the ODP wells 1173 and 1174 (Horsfield et al., 2006).

The middle part of the Nankai Trough is also an area with an extremely high heat flow anomaly (Yamano et al. 2003). Heat flow data have been used (Wang et al., 1995; Yamano et al., 1992; 2003) to draw conclusions on the anomalous thermal history of the crust leaving the question about cause and timing open. Spinelli and Underwood (2005) tried to constrain the thermal history by modelling temperature and diagenetic reaction processes in well 1173. A 1D-modeling approach which ignored tectonic processes was used to model the thermal and maturation history of wells ODP 808 and 1174 (Ondrak and di Primio, 2002, Horsfield et al., 2006).

The availability of an interpreted seismic line and a balanced cross-section (Fig 2) allows to construct a 2D-basin model which is used to model the thermal and maturation evolution of the Nankai Trough from the first thrust out into undeformed sediments. The combination of basin modelling and section balancing provides to treat tectonic processes correctly because it allows modelling the deposition of deeper buried and thus hotter sediments on top of cooler sediments. This is not possible if an overthrust is modelled as a rapid sedimentation event. The combination of both modelling approaches thus can improve temperature and heat flow calculations. The present study combines both modelling approaches to improve the reconstruction of the temperature evolution of the area. Vitrinite

reflectance, temperature and heat flow data will be used to constrain the modelled thermal history of the area.

2. Geological frame

The subduction boundaries of the Pacific and Philippine Sea plates form deep trenches east of the Japanese Island arc system (Moore et al., 2001a). The Nankai Trough located southeast of Shikoku Island, is the plate boundary between the Eurasian and the Philippine Sea plate where the Shikoku Basin is subducting to the northwest under the southwest Japan arc at a rate of 2-4 cm/a (Karig and Angevine, 1986; Seno et al., 1993).

The underlying oceanic lithosphere of the Shikoku Basin is closely related to the history of the proto-Izu-Bonin arc where rifting started in the Oligocene (Taylor, 1992). The spreading ridge ceased to be active at 12-15 Ma (Chamot-Rooke et al., 1987; Okino et al., 1994). Seafloor spreading in Shikoku Basin lasted until about 15 Ma by which most of the Japan Sea ocean floor had formed (Jolivet et al., 1994; Otofujii, 1996). An important aspect of the study area are the volcanic activities documented by the Kinan Seamount Chain, a line of volcanic seamounts close to the fossil spreading centre of Shikoku Basin which indicates that the area was thermally active after cessation of seafloor spreading until 7-10 Ma (Sato et al., 2002).

The sedimentary section was studied in great detail during ODP cruises 131, 191 and 196 (Hill et al., 1993; Moore et al, 2001a; Mikada et al., 2002). Sedimentation started with the deposition of middle Miocene volcanoclastic facies consisting of acidic volcanoclastics on oceanic crust (Fig. 3). Then the middle Miocene to mid-Pliocene Lower Shikoku Basin facies follows dominated by massive hemipelagites. From upper Pliocene to lower Pleistocene the Upper Shikoku Basin facies was deposited which is characterized by hemipelagites and intercalated tephra layers. The transition from hemipelagite to turbidite deposition took place

in the Pleistocene forming the Basin-to-Trench Transition facies. From Pleistocene to Holocene followed the trench-wedge facies which is subdivided into two sub-units, the outer trench-wedge facies and the axial trench-wedge facies. Massive turbidites filled the trench with terrigenous sediments derived predominantly from the central part of Japan.

3. Previous studies of the thermal regime of the Nankai Trough

Several studies have been carried out to elucidate the heat flow regime of the accretionary prism and the Nankai Trough which exhibits a zone of exceptionally high heat flow (Moore et al., 2001a; Yamano et al., 1992; 2003). Heat flow in the Nankai Trough is generally higher than 130 mW/m² but rather variable reaching values of up to 200 mW/m² (Fig. 4). Landwards of the deformation front along the accretionary prism heat flow decreases rapidly to 50 mW/m² over a very short distance of only 60 km (Yamano et al., 1992; 2003; Kinoshita and Yamano 1985).

The seafloor of the Shikoku Basin is 15-25 Ma old (Okino et al., 1994) The studied profile lies very close to the fossil spreading centre, therefore, the age of the lithosphere in the study area is approximately 15 Ma old which is also supported by biostratigraphic ages just above the basement at sites 808, 1174 and 1173 (Shipboard Scientific Party, 2001). Thermal models for the heat flow evolution of oceanic lithosphere (Parson and Sclater, 1977; Lister, 1977; Stein and Stein, 1992) give a simple relation between heat flow and age, $q=C/t^{1/2}$ where q is heat flow in mW/m², t is age of the oceanic lithosphere in Ma and C is a constant of about 500. According to this relation, expected heat flow for a crustal age of 15 Ma is 120-130 mW/m². However, the dampening effect of sedimentation on surface heat flow should further decrease surface heat flow (Langseth et al., 1980; Hutchinson, 1985; Yamano et al., 2003). Several studies have been carried out to elucidate the significantly higher heat flow in the area and study the thermal and fluid flow regime of the Nankai Trough and the adjacent accretionary prism.

Wang et al. (1995) modelled the thermal regime of the Southwest Japan subduction zone on a crustal scale. The effect of the subduction of a fossil ridge and the increasing age of the subducting age of the plate is the focus of their model. They also studied the effects of frictional heating, slab thickness, convergence velocity, and wedge growth. Their model did not account for fluid flow caused by accretion and subduction of sediments. Wang et al. (1995) can explain the observed landward decrease of surface heat flow but not the rapid decrease of heat flow within 60 km of the deformation front. Wang and Davis (2002) conclude that the subduction history of the last 15 Ma controls the thermal regime within approximately 150 km of the deformation front. Furthermore, frictional heating is not considered important for the SW Japan subduction zone but lack of precise data prevents conclusive consideration.

Yamano et al. (1992) discuss fluid flow near the décollement zone related to deformation in the protothrust zone in combination with vertical diffusive flow as a possible explanation for the heat flow anomaly in the Nankai Trough. At present however, the temperature data from ODP well 808 doesn't support fluid flow (Yamano et al., 1992). In addition, based on mass balance calculations, there is probably not enough water brought into the accretionary prism by subduction and accretion. Therefore, expulsion of hot water from dewatering sediments is not considered as the main driving force for the observed high surface heat flow (Yamano et al., 1992, 2003).

Several models studied temperature controlled clay mineral alteration processes and their effect on a Cl-anomaly observed in the Lower Shikoku Basin facies in ODP wells 808, 1174 and 1173 (Brown et al, 2001; Saffer and Bekins, 1998; Spivack et al., 2002). Within the lower Shikoku Basin facies a low-Cl zone can be observed which can be the result of pore water freshening resulting from clay mineral reactions or alternatively caused by pore water dilution due to fluid flow. However, the importance of fluid flow in comparison to diagenetic

reactions to explain observed low-Cl zone is controversial (Moore et al. 2001b). Saffer and Bekins (1998) combined a coupled flow and solute transport model with a kinetic model for smectite dehydration to study the mineral diagenetic processes with fluid flow driven transport processes in order to explain an observed low chloride concentration within the Lower Shikoku Basin facies. Saffer and Bekins (1998) concluded from their modelling study that few short periods of 80-160 ka may have occurred in the study area without evaluating its effect on temperature field. Brown et al. (2001) strongly favour thermally controlled chemical processes, i.e. smectite dehydration as the controlling mechanism for the observed low Cl-anomaly in ODP well 808, although, they don't completely rule out lateral flow as additional process. Recently, Spivack et al. (2002) published additional data supporting fluid flow as the controlling mechanism for the observed Cl-profiles along the Muroto profile, Nankai Trough. Spivack et al. (2002) postulate no continuous fluid flow but frequent flow episodes. They postulated channelled fluid flow but not only within or near the décollement zone but over most of the Upper and in particular the Lower Shikoku Basin Facies. Spivack et al. (2002) calculate an average velocity of 13 ± 5 cm/a between sites 808 and 1174 for the Lower Shikoku Basin Facies, which can be converted to a volume average flow velocity of 4.6 ± 2 cm/a. This is also considered for the space between sites 1174 and 1173 although there is no clear continuation of the observed Cl-minima between the two wells.

Brown et al. (2001), Spinelli and Underwood (2005) and Steuer and Underwood (2005) studied temperature controlled clay mineral alteration processes wells 808, 1174 and 1173. Spinelli and Underwood (2005) modelled the thermal history of ODP site 1173 using temperature data and diagenetic reaction progress as constraints. According to their model, smectite-to-illite conversion is controlled by heat flow from the underlying oceanic lithosphere alone. Their favourite models predict for the first 10 Ma a heat flow from the oceanic crust which is near typical values for conductively cooling crust. Only for the last

5 Ma a higher heat flow is necessary to explain the measured temperature and the degree of smectite-to-illite conversion observed in well 1173. They assume off-axis volcanism and hydrothermal circulation as causes for the anomalous high heat flow of the area.

Steuer and Underwood (2005) modelled the illite-smectite reaction process for different burial histories and constant heat flow of 180 mW/m². In addition, the initial clay mineral composition and fluid chemistry were varied to include these parameters controlling the reaction progress. Their model predicted correctly the degree of smectite-to-illite conversion in well 1173 but overestimated it slightly in wells 1174 and 808.

For ODP well 808 vitrinite reflectance data exists (Berner and Koch, 1993) which was used to model the thermal and maturation history of well ODP 808 and 1174 (Ondrak and di Primio, 2002; Horsfield et al., 2006). Their 1D-basin modelling approach also showed that a heat flow history derived from a standard cooling model for oceanic lithosphere cannot reproduce observed vitrinite reflectance values or the present day temperatures. A heat flow increase to 180 mW/m² during the Quaternary at the time of maximum burial was the most likely scenario to match model data and measurements.

4. Modelling the temperature history along the Muroto Transect

4.1 The conceptual model

The transient heat flow, finite element model PetroMod 2D (IES ®) was used to model the temperature and maturation along the Muroto Transect reaching from the tip of the thrust zone out into nearly undeformed Quaternary and Tertiary sediments seawards of the Nankai Trough. The compressive tectonic system of the Nankai Trough required the integration of 2D-structural and basin modelling. The model profile (Fig. 4) was constructed from an interpreted seismic line NT62-8 and a balanced cross-section of the same seismic profile (Fig. 2) (Gaedicke, 1995) using 2DMove (Midland Valley ®). Well control was provided by well

data from the ODP wells 808, 1173 and 1174. Well 808 is located in the frontal part of the imbricate thrust zone showing minor deformation. In well 808 the trench-wedge facies is duplicated by 145 m at the frontal thrust which is located in 365 m depth in well 808C (Pickering et al., 1993). Well 1174 is located in the protothrust zone representing a zone of incipient deformation and initial development of the décollement within the hemipelagic unit. Well 1173 was drilled in the undeformed sediments of the trench. The balanced cross-section represents the situation before the overthrust at the location of the first thrust in well 808. The two profiles provided the structural input for a 2D-basin model. The profile consists of five main lithostratigraphic units (Taira et al. 1992), the volcanoclastic facies, the lower Shikoku Basin facies, the upper Shikoku Basin facies, the trench-to-basin transition facies and the trench-wedge facies which was subdivided into two more sub-units, the outer trench-wedge facies and the axial trench-wedge facies since these units could be correlated with interpreted horizons of the seismic line NT62-8 and the resulting balanced cross-sections (Gaedicke, 1995). Specifically defined lithologies were used for the simulations (Tab. 1) to approximate measured values at ODP sites 808, 1174 and 1173.

4.2 Bottom heat flow

Six different heat flow scenarios were used to study different thermal histories of the area (Fig. 5). The first tested heat flow curve (Fig. 5: HF 1) is based on the age-heat flow relationship for ocean basins of Stein and Stein (1992) representing the "coldest" scenario. The second scenario (Fig. 5: HF 2) assumes a thermally young oceanic crust which started to cool only 7 Ma ago when volcanic activity at Kinan Seamount Chain ceased, which is also one of the "hot" scenarios. Alternatively, two heat flow scenarios were applied published by Spinelli and Underwood (2005) who modelled smectite-to-illite conversion in well 1173. The one scenario (Fig. 5: HF 3) assumes a relation between heat flow and age like the standard models by (e.g. Stein and Stein 1992) but postulating a certain delay in cooling: $q=C/(t+1-$

$t_1)^{1/2}$ where q is heat flow in mW/m^2 , t is age of the oceanic lithosphere in Ma, t_1 is 1.2 Ma and C is a constant of about 733. According to this relation, the expected heat flow for a crustal age of 15 Ma is 190 mW/m^2 . The alternative heat flow scenario (Fig. 5: HF 4) assumes a stepwise decrease of heat flow which increases again to 194 mW/m^2 for the last 5 Ma to account for volcanic activity and possible hydrothermal circulation in the area.

Next, a gradually decaying heat flow (Fig. 5: HF 5) was tested which is based on the age-heat flow relationship for ocean basins by Stein and Stein (1992) but increased again to 170 mW/m^2 heat flow during the Quaternary to allow for advective heat transport caused by hydrothermal convection and expulsion of fluids from the accretionary prism by expulsion. Finally, a heat flow scenario (Fig. 5: HF 6) was used which follows the age-heat flow relationship from 14-8 Ma after that heat flow increases again until the cessation of volcanic activity of the Kinan Seamount Chain at 6 Ma, thereafter, following the age-heat flow relationship again.

4.3 Modelling results

The burial histories of all wells except for well 1173 are characterized by a moderate sedimentation up to Pliocene and a very rapid burial during the Quaternary (Fig 6). Well 1173, which is located further seaward of the trench also shows an increase in sedimentation during the Quaternary but much less than in the other wells.

The gradually decaying heat flow scenario (HF 1) based on empirical formula by Stein and Stein (1992) could neither reproduce measured vitrinite reflectance data (Fig. 7, HF 1) nor measured temperature (Fig. 8, HF 1) or heat flow but produced much lower values.

The scenario assuming a 6 Ma old oceanic lithosphere (HF 2) overestimates temperatures for well 808 while it matches temperatures in well 1174 and 1173 (Fig 8, HF 2). Only the highest measured $\%R_o$ values match with the calculated $\%R_o$ values in well 808 and

1174 (Fig 7, HF 2). Therefore, heat flow scenario 2 represents the upper limit for heat flow near the deformation front.

Alternatively 2 heat flow scenarios were applied to the model, which were used by Spinelli and Underwood (2005) to model smectite-illite conversion. The first scenario (HF 3) assumes just a short delay of cooling of about 1 Ma but requires a much higher thermal constant of 733 instead of 500 as commonly used resulting in present day heat flow of about 192 mW/m². The other scenario (HF 4) assumes a stepwise decrease of heat flow with a subsequent rise of heat flow over the last 5 Ma. Both scenarios reproduce the measured temperatures in well 1173 and 1174 well but overestimate temperatures in well 808 significantly (Fig 8: HF 3 & 4). However, both heat flow scenarios overestimate organic matter maturation calculating vitrinite reflectance values which only match the highest measured values thus representing an upper limit for the heat flow scenarios (Fig 7: HF 3 & 4).

A much better match of modelled values and measured values is obtained if we assume a gradually decaying basal heat flow which follows the age-heat flow relationship for ocean basins by Stein and Stein (1992) but is increased to 170 mW/m² during the Quaternary to allow for advective heat transport caused by the onset of hydrothermal circulation in the cooling crust. Such a heat flow history (HF 5) produces a good match between calculated and vitrinite reflectance (Fig 7: HF 5) and measured temperature (Fig 8: HF 5). The match between calculated and measured near surface heat flow has also improved to the previous model. The calculated near surface heat flow in well 1173 of 169 mW/m² is again close but below the measured value of 180, while in well 1174 the calculated surface heat flow of 158 mW/m² is still below the measured heat flow of 180 mW/m². Also in well 808 the calculated surface heat flow of 143 mW/m² is still above the measured heat flow of 132 mW/m².

A similar match of modelled and measured values is obtained if we assume that volcanic activity reheated the crust in the area at about 6 Ma by off-axis volcanic activity (Yamano et al., 2003) after which cooling of the oceanic lithosphere again follows the relationship given by Stein and Stein (1992). This heat flow scenario (HF 6) results in a present day basal heat flow of about 170 mW/m². Calculated and measured maturity match very well in well 808 and 1174 (Fig 7: HF 6). Temperature data from well 808 and 1174 also match (Fig 8: HF 6). Only modelled temperatures for well 1173 are slightly lower than measured data. The calculated near surface heat flow in well 1173 of 169 mW/m² is close to but below the measured value of 180, while in well 1174 the calculated heat flow of 157 mW/m² is below the measured heat flow of 170 mW/m². The lowest calculated heat flow of 147 mW/m² occurs in well 808 but this is still above the measured heat flow of 132 mW/m².

4.4 Discussion of results

Vitrinite reflectance increases as a function of temperature and time. However, it is not possible to extract information on thermal events which occurred before the time of maximum burial unless temperature was higher than at the time of maximum burial. The Nankai Trough is characterized by a long period of relative slow burial from middle Miocene to upper Pliocene and very rapid burial in the Quaternary. Even the heat flow model with the youngest oceanic crust reached its maximum maturity not before maximum burial which occurs today. A heat flow history derived from the cooling of an oceanic lithosphere of 15 Ma age (heat flow scenario 1) is not sufficient to match the measured vitrinite profile although burial rates increased dramatically during the Quaternary in wells 808 and 1174. The existence of 6 Ma old crust (heat flow scenario 2), as introduced and considered implausible by Yamano et al. (2003) can be ruled out by the model. Heat flow scenarios 3 and 4 are considered unlikely scenarios because of the overestimation of organic matter maturation (Fig 6). However, with respect to well 1173 both scenarios achieve a slightly better match with measured

temperatures than the other heat flow scenarios. The limited smectite-to-illite conversion determined by Spinelli and Underwood (2005) and their modelling results, indicate that heat flow from the underlying crust at well 1173 was not higher than observed. A higher heat flow assuming young oceanic crust predicts a more significant degree of smectite-to-illite alteration than observed (Spinelli and Underwood, 2005). The lack of vitrinite reflectance data for well 1173 inhibits detailed comparison of the present study with the study by Spinelli and Underwood (2005).

The best match with measured data is obtained by heat flow scenario 5 and 6 which assume either an increase of heat flow during the Quaternary as a result of thermal convection (heat flow scenario 5) or the reheating of the crust caused by off-axis volcanism at about 7 Ma ago (heat flow scenario 6). Modelling results show that not only present day heat flow data require a higher than expected bottom heat flow but also organic matter maturation data. Only an increased heat flow during maximum burial (heat flow scenarios 5 & 6) can reproduce measured vitrinite reflectance values observed today (Fig. 7). Similar results were obtained by Brown et al. (2001) who modelled smectite-to-illite conversion for well 808 assuming a basinal heat flow of 180 mW/m² during times of rapid burial in the Quaternary. Steurer and Underwood (2003) also modelled smectite-to-illite conversion with a constant heat flow of 180 mW/m² which resulted in a good match for well 1173 but overestimated the degree conversion for wells 1174 and 808 which is in very good agreement with results of our study using heat flow scenarios 5 and 6.

The very rapid sedimentation in the Nankai Trough reduces surface heat flow (Yamano et al. 1992; 2003). They postulate a dampening effect of 20% assuming an average thermal conductivity of 0.98 W/m²/K for marine sediments and an average sedimentation rate of 300 m/Ma over a period of 2 Ma. Yamano et al. (2003) estimate the effect based on measurements made in the upper tenth of meters of the ocean floor where compaction and

thus thermal conductivities are low. However, compaction and thus thermal conductivity increase with depth thus reducing the dampening effect of sedimentation. The dampening effect according to Langseth et al. (1980) reduces to only about 10% if a thermal conductivity of $1.5 \text{ W/m}^2/\text{K}$ is used which is more characteristic for a depth of 200 mbsf in well 808 (Shipboard Party, 1991) and 100 mbsf in well 1174 (Moore et al. 2001a). Powell et al. (1988) even calculated a dampening effect of less than 5% for similar sedimentation rates using a diffusivity of $1.0 \cdot 10^{-7} \text{ m}^2/\text{s}$. The difference indicates the uncertainty of the estimates of the dampening effect of rapidly deposited sediments. The estimates used constant values for the rock physical properties neglecting temperature dependence and facies depending change of rock physical properties, which significantly modify heat flow distribution with depth. The present model (PetroMod® V.10 IES) calculates thermal conductivity as a function of temperature, and even more important as a function of the different lithologies, which have quite different thermal conductivities, defined in the model. In addition, the model also considers transient effects like changes in heat capacity as a function of decreasing porosity due to compaction. Therefore, surface heat flow varies along the profile and will not increase linearly with depth. In addition, this modelling approach defines heat flow at the base of the profile underneath the sediments in about 800 – 2000 mbsf and not a constant temperature at great depth. Therefore, depression of surface heat flow will be much smaller than predicted by Langseth et al. (1980) and Hutchinson (1985), because only the difference between heat flow at the base of the sediments and at the surface is considered. Our model calculates a reduction of surface heat flow of about 8% due to sedimentation at the deformation front (well 1174). The depression of surface heat flow by 14% calculated for well 808 (Fig. 9) which penetrates the first thrust is almost twice as large. The rapid thickening of the sedimentary column by thrusting has an even more significant influence on surface heat flow than sedimentation alone. Although the present model does not predict the absolute values correctly,

underthrusting of relatively cold sediments in the accretionary wedge may explain the observed rapid decrease of surface heat flow as documented by Yamano et al. (2003).

5. Conclusion

The Muroto Transect together with the ODP well 808, 1174 and 1173 provide a good data base to study an area of the Nankai Trough which is characterised by very high heat flows, and rapid sedimentation and accretion during the Quaternary. Modelling the maturity history of organic matter in wells 808 and 1174 shows that the measured vitrinite reflectance values in well 808 require a heat flow of approximately 170 mW/m². Such a heat flow is supported by studies of smectite-to-illite transformation in wells 808 and 1174 (Brown et al, 2001; Steurer and Underwood, 2003).

With respect to modelling surface heat flow the model is less precise but still well within the scatter of measured heat flow in the area (Fig. 4). The model calculates for well 808 a surface heat flow of 147 mW/m² which is about 11% higher than the calculated heat flow of 132 mW/m² (Hill et al., 1993). For well 1174 the model calculates a surface heat flow of 157 which is about 12 % less than the calculated value of 180 mW/m² (Moore et al., 2001a). For well 1173, the heat flow predicted by the model (179 mW/m²) and the calculated value (180 mW/m²) are close. Although heat flow is not exactly reproduced by the present model, it indicates that the observed rapid decrease of surface heat flow towards the accretionary wedge (Yamano et al., 2003) is the result of the young tectonic activity in the front of the wedge. Surface heat flow in well 808 which penetrates the first thrust in about 400 mbsf is reduced by 14 % while in well 1174 which is not yet affected by tectonic activity, heat flow is reduced by just 8%. This shows that the combination of cross-section balancing and basin modelling improves the accuracy of thermal modelling in compressional environments. At present, only conductive heat flow was considered in the model. Convective fluid flow still has to be considered as an additional transport mechanism in the Nankai Trough. However,

the lack of reliable temperature data from the deeper sections of the wells puts another difficulty on the interpretation of the heat flow distribution in the Nankai Trough.

Vitrinite reflectance observed in well 808 is best reproduced with a heat flow scenario which basically follows a typical $500/t^{1/2}$ curve early in the burial history and increases again towards the Quaternary (Fig. 7: HF 5 & 6), because high sedimentation rates alone are not sufficient to explain observed % R_o values. The exact mechanism cannot be deduced from the model but a combination of the documented young volcanic activity of the Kinan Seamounts and convective heat transport is considered to be the most likely mechanism. For the present model a heat flow increase to 250 mW/m² at 6 Ma with subsequent cooling along a typical heat flow curve for oceanic crust as simulated by heat flow scenario 6 is capable to model the observed maturity trend in wells 808 and 1174, and achieves a good fit with temperature measurements in all wells.

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Figure Captions

Figure 1: (a) Geologic map showing the Nankai Trough and the SW Japan forearc region with locations of the ODP sites and Muroto Transect used in this study.
(b) Generalized cross-section along the Muroto Transect, after Moore et al. (2001a), PTZ=Protothrust Zone.

Figure 2: Depth converted seismic section NT62-8 with the interpretation below and the restoration of the first thrust (Gaedicke, 1995) which provide the basis for the development of the conceptual model.

Figure 3: Schematic lithostratigraphy of well 1174, lithofacies description and ages of lithostratigraphic units defined for modelling.

Figure 4: Conceptual model of the profile along the Muroto Transect before and after the thrust has become active. Heat flow data projected on the profile show data from Yamano et al. (2003) (diamonds), Shipboard Scientific Party (2001) (squares) and model data (stars).

Figure 5: Heat flow scenarios used to model the thermal evolution of the model, see text for discussion.

Figure 6: Burial and temperature histories of ODP Leg 190 Sites 808, 1174 and 1173 using a basal heat flow scenario 4 which varies as a function of the age of the oceanic lithosphere but increases to 180 mW/m² during the Quaternary. Q = Quaternary; P = Pliocene; LM = Late Miocene; MM = Middle Miocene.

Figure 7: vitrinite reflectance-depth profile for the tested heat flow scenarios for wells a) 808 and b) 1174. Black rhombi mark calibration data measured in the wells.

Figure 8: Temperature-depth profile for the tested heat flow scenarios for wells a) 808, b) 1174 and c) 1173. Black rhombi mark calibration data measured in the wells.

Figure 9: The line shows the modelled present day heat flow distribution for well 808. The strong increase of heat flow above the thrust is the result of underthrusting colder rocks beneath warmer rocks at the first frontal thrust.

a

b

NW Line NT 62-8 (restored first thrust)

Fig. 6a

Fig. 6b

Fig. 6c

Table 1: Assigned thermal conductivities of rock matrix (at 20 and 100 °C) and initial, maximum and minimum porosity for the various facies in model

Facies	thermal conductivity W/(mK) at 20°C	thermal conductivity W/m/K at 100°C	% porosity	
			min	max
Trench-wedge				
sandstone	2.12	2.04	5	55
silt-sand	2.09	1.97	5	65
silt-shale	1.79	1.71	5	60
Trench basin transition	2.44	2.45	5	65
Upper Shikoku Basin	2.41	2.35	5	62
Lower Shikoku Basin				
shaly	2.44	2.55	5	65
silty	2.78	2.71	5	70
Acidic volcanoclastic	2.27	2.13	5	56
oceanic crust	1.80	1.81		