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Notes

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ABSTRACT

Vigorous fluid circulation maintained in newly subducted ocean crust significantly affects subduction zone temperatures on the Nankai margin, Japan. The shallow part of the igneous ocean crust is pervasively fractured and thus highly permeable, allowing vigorous hydrothermal circulation. This circulation has been recognized as an important control on the thermal budget and evolution of ocean crust worldwide. However, existing subduction zone thermal models either do not include hydrothermal circulation in ocean crust or assume that it abruptly stops upon subduction. Here we use a conductive proxy to incorporate the thermal effects of high Nusselt number fluid circulation in subducting crust into a subduction zone thermal model. Hydrothermal circulation reduces temperatures in the seismogenic zone of the Nankai margin plate boundary fault by ~20 °C at the updip limit of seismicity and ~100 °C at the downdip limit. With improved thermal models for subduction zones that include the effects of hydrothermal circulation in subducting crust, estimates of metamorphic reaction progress and interpretations of fault zone processes on various margins may need to be revisited.

INTRODUCTION

Results of subduction zone thermal models have been used to predict metamorphic reaction progress in subducting material (Peacock, 2003), estimate temperatures in areas of seismicity (Abers et al., 2006; Hyndman et al., 1995), and examine subduction dynamics (van Keken et al., 2002). In a prime example of the application of subduction zone thermal model results, thermal limits for the updip and downdip limits of megathrust seismicity for the well-studied Nankai margin (Hyndman et al., 1995), Japan, have been exported to other margins in order to draw inferences on the potential extent of the seismogenic zone on plate boundary faults (Oleskevich et al., 1999). However, thermal models to date for the Nankai margin (Hyndman et al., 1995; Wang et al., 1995) are unable to account for large observed thermal anomalies (Yamano et al., 2003).

Hydrothermal circulation within ocean crust redistributes heat in settings ranging from mid-ocean ridges (Lister, 1972) and young ridge flanks (Becker and Davis, 2004; Davis et al., 1997; Fisher et al., 2003) to 106 Ma crust in abyssal environments (Fisher and Von Herzen, 2005). We suggest that the high permeability of the ocean crust aquifer can largely be sustained as the crust is subducted to ~10 km or even greater depths, allowing fluid circulation to redistribute heat in subducting crust. For continental crust, from the surface to the base of the brittle crust (~10 km depth), permeability decreases by more than three orders of magnitude due to chemical and mechanical sealing of fractures (Manning and Ingebritsen, 1999). Quantitative constraints on the permeability of subducting ocean crust are not yet available, but the thermal and mechanical conditions of subducting crust are more favorable for preserving permeability at depth than in continental crust. Subducting crust is typically much colder than continental crust at equivalent depth. The cooler thermal history for subducting crust minimizes the chemical sealing of fractures. Tensional stress in the upper part of a subducting plate during bending causes normal faulting (Ludwig et al., 1966) and favors the opening of fractures, countering the mechanical effects of increasing confining pressure upon subduction. In laboratory tests of continental rocks, highly fractured samples show less permeability reduction with increasing confining pressure than less fractured samples (Morrow et al., 1994). If this relationship extends to ocean crust, where extensive fracturing supports much higher permeability than in continental rocks, newly subducted crust could maintain very high permeability.

Vigorous fluid circulation allowed by persistence of high permeability within subducting crust has an observable signature in subduction zone heat flux. This fluid circulation mines heat from under the margin wedge and transports it seaward (Kummer and Spinelli, 2008). The Nankai margin (Fig. 1), with extensive heat flux data and a sediment cover of moderate thickness on the subducting plate, is a good site to examine the thermal effects of fluid circulation in an aquifer in subducting crust. The magnitude and distribution of surface heat flux anomalies resulting from hydrothermal circulation in the basement aquifer of subducting crust are modulated by the sediment distribution on the incoming plate. At margins where the sediment cover is much thicker (e.g., Cascadia; Hyndman and Wang, 1993), surface heat flux signatures of this circulation are greatly subdued. Where the sediment cover is much thinner (e.g., parts of the Middle America Trench; Fisher et al., 2003), ventilated hydrothermal circulation greatly disturbs surface heat flux, making it more difficult to discern the effects of fluid circulation in subducting crust.

NANKAI THERMAL ANOMALIES

There are two large thermal anomalies on the Nankai margin; the most prominent is a high heat flux zone in the trench (Watanabe et al., 1970; Yamano et al., 1984, 2003). Along our transect (Fig. 1), heat flux in the trench averages 198 mW/m^2 (Yamano et al., 2003), much higher than the 130 mW/m^2 predicted for conductively cooled 15 Ma crust. Including sedimentation effects, the expected heat flux in the trench is ~100 mW/m^2 (Nagihara et al., 1989; Yamano et al., 1984, 1992), exacerbating the difference between observed and predicted heat flux. The second anomaly is that heat flux decreases from ~200 mW/m^2 in the trench to ~50 mW/m^2 60 km landward of the trench (Yamano et al., 1984, 2003). In subduction zones, a landward decrease in seafloor heat flux is expected due to the cooling effects of the subducting plate and the landward thickening of the margin wedge, but the landward decrease on the Nankai margin is much steeper than can be explained by existing conductive thermal models (e.g., Wang et al., 1995). Separate from these anomalies, observed seafloor heat flux gradually decreases with distance from a fossil spreading center (Yamano et al., 2003), as would be expected given the increasing age of the crust. The distinct anomalies along the trench-perpendicular transect are present both on and off the axis of the fossil spreading center (Yamano et al., 2003).

Post-spreading volcanism and various aspects of hydrothermal circulation have been proposed to explain the high heat flux in the trench on the Nankai margin, but the mechanisms examined to date have proven unacceptable. First, very recent thermal rejuvenation by post-spreading volcanism is unlikely; the youngest volcanic rocks on the Kinan Seamount chain are 7–10 Ma (Sato et al., 2002). Second, fluid flow along the décollement is likely not sufficient to produce the broad heat flux anomaly observed (Yamano et al., 1992). Finally, the transition from open hydrothermal circulation (ventilated through exposed seamounts) to a sediment-sealed system was suggested as a means to generate a spike in heat flux in the trench (Yamano et al., 1984). Stopping the ventilation of heat from the underlying crust upon sealing with sediment can result in a rebound to higher heat flux, but model-predicted post-sealing heat flux remains below the theoretical conductive cooling values and far below the anomalously high heat flux actually observed at the trench (Nagihara et al., 1989).

Explaining the anomalously steep drop in heat flux landward of the trench is equally or more challenging. Net flow of cool water downdip into the system is unlikely given the high heat flux in the trench; flow updip from deeper in the system would lead to elevated temperatures (and elevated seafloor heat flux on the margin wedge; Wang et al., 1995). Some have speculated that rapid hydrothermal circulation in the basaltic basement may provide a suitable explanation for each anomaly individually (Hyndman et al., 1995; Yamano et al., 1992). We maintain that the two observed thermal anomalies are manifestations of a single process, i.e., hydrothermal circulation in sealed subducting crust.

NUMERICAL MODELING METHOD

We examine the thermal effects of this circulation using a simple two-dimensional (2-D) finite element model. The physical property structure, initial conditions, and boundary conditions of the model have been described previously (Hyndman et al., 1995; Wang et al., 1995). Here we note differences between the model in this study and the Wang et al. (1995) model; the most significant difference is the addition of a mechanism to redistribute heat in a shallow basement aquifer (Fig. 2). In addition, the geometry of the subduction zone is updated based on seismic reflection and refraction data (Kodaira et al., 2000). At the seaward boundary (150 km seaward of the trench), time-dependent temperatures are defined by 1D conductive lithospheric cooling beginning from uniform 1400 °C lithosphere (i.e., an active ridge) with cooling continuing for 15 m.y. and including the effects of sedimentation. We include frictional heating on the plate boundary fault with a pore pressure ratio of 0.95. All model cells are 2 km wide (Fig. 2). Aquifer cells are 600 m high; underthrust sediment cells are 250 m high.

Hydrothermal circulation in a high-permeability ocean crust aquifer occurs at high Rayleigh number (*Ra*; measure of thermal buoyancy versus viscous resistance to flow) and is nonsteady (i.e., periodic or chaotic). Studies covering small distances (≤40 km) have simulated coupled fluid and heat transport in subducting ocean crust in order to examine circulation patterns (Kummer and Spinelli, 2008). However, a different approach is required to examine the larger domain (400 km) problem. Vigorous buoyancy-driven flow is intrinsically nonsteady, and simulating its time-dependent details is not only computationally intensive, but also unnecessary for the purpose of the present study. To examine the consequence of the redistribution of heat by the vigorous circulation, it suffices to use a conductive proxy in which the very efficient advective heat transfer (high Nusselt number, *Nu*; ratio of total heat transport to heat that would be transported by conduction alone) is approximated using a high thermal conductivity (Davis et al., 1997).

The upper 600 m of basaltic basement in the modeled ocean crust is an aquifer; this thickness is consistent with previous studies of heat transport in ocean crust (Davis et al., 1997; Fisher et al., 2003). Thermal conductivity of the aquifer layer is increased by a factor of *Nu* over the actual conductivity (Davis et al., 1997). To estimate *Nu* throughout the aquifer, we first model temperatures in the system with no thermal effects of fluid circulation (i.e., no enhanced conductivity in the aquifer). Those temperatures are used to determine the heat flux into the base of the aquifer and the fluid density and viscosity throughout the aquifer. With this information, we calculate *Ra* (cast in terms of conductive heat flux, *q*, into the base of the layer; Bessler et al., 1994) for each aquifer cell for a prescribed permeability, *k*:

$$Ra = \frac{\alpha g k L^2 \rho_f q}{\mu \kappa K}, \quad (1)$$

where α is fluid thermal expansivity, *g* is gravitational acceleration, *L* is aquifer thickness, ρ_f is fluid density, μ is fluid viscosity, κ is thermal diffusivity, and *K* is thermal conductivity. As *Ra* increases, consistent with more vigorous convection, a greater proportion of heat is transported by convection (*Nu* increases). To estimate *Nu*, we use:

$$Nu = 0.08 Ra^{0.89}, \quad (2)$$

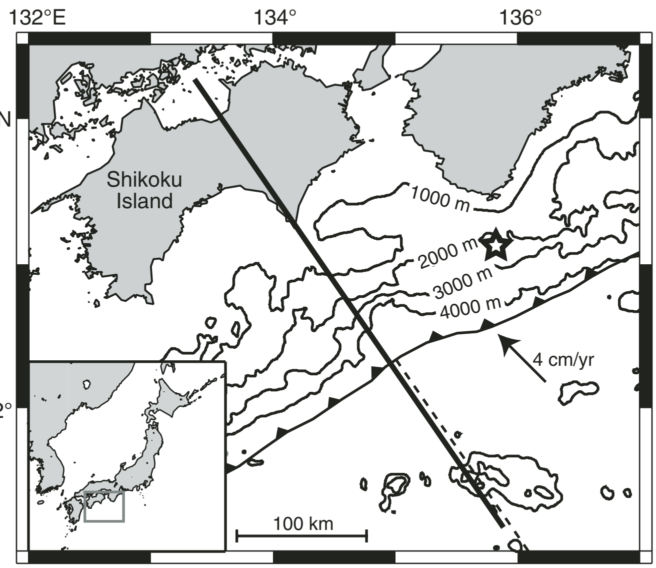

Figure 1. Locations of deformation front in Nankai Trough (barbed line) and cross section modeled (bold line), which is along the axis of a fossil spreading center (dashed line). Thin lines are bathymetry in meters. Arrow indicates convergence between Philippine Sea plate and southwest Japan. Star marks epicenter of 1946 Nankaido earthquake. Inset shows study area offshore southern Japan.

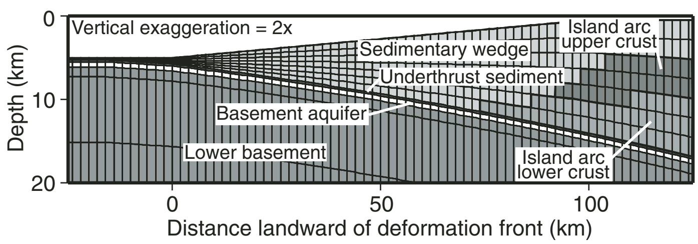

Figure 2. Portion of grid used in finite element model; model extends from 150 km seaward to 250 km landward of deformation front. The 600-m-thick aquifer at top of the subducting crust facilitates updip heat transport. The thermal effect of high Nusselt number (*Nu*) circulation in the aquifer is simulated using high thermal conductivity.

a relationship determined by comparing results from simulations with coupled fluid and heat circulation (Kummer and Spinelli, 2008) to results using a conductive proxy for the same problem. The trend of *Nu* increase with *Ra* is well known; Equation 2 yields *Nu* estimates at the upper end of the range for previously published *Nu* versus *Ra* relationships (Wang, 2004). The precise values of the constants in this equation are much less important than the overall trend for the purpose of this study. For each aquifer cell, we determine an effective thermal conductivity by multiplying *K* (the intrinsic thermal conductivity) by *Nu*; then we re-run the conductive model. The resultant temperatures and fluid properties are then used to recalculate *Ra* from Equation 1, which gives an updated *Nu* for each aquifer cell. We repeat the process until the temperatures stabilize.

RESULTS

We run a number of models with various aquifer permeability values and/or distribution and compare predicted surface heat fluxes with observations. The general characteristics of the suite of models can be represented by the four examples displayed in Figure 3. As a reference, we use a model with no fluid circulation in the oceanic crust (dashed line). In one model, *k* of the aquifer is uniformly 10^{-9} m^2, near the upper end of previous estimates for ocean crust permeability (Becker and Davis, 2004) (Fig. 3, dot-dash line). In the other two models, *k* decreases from a pre-subduction value of 10^{-9} m^2 with burial depth (Fig. 3 inset), with one following a trend parallel to that for continental rocks (Manning and Ingebritsen, 1999) reaching 3.1×10^{-13} m^2 upon 10 km of burial (thin gray line) and the other following a linear trend reaching 4.3×10^{-10} m^2 at 10 km (thick black line).

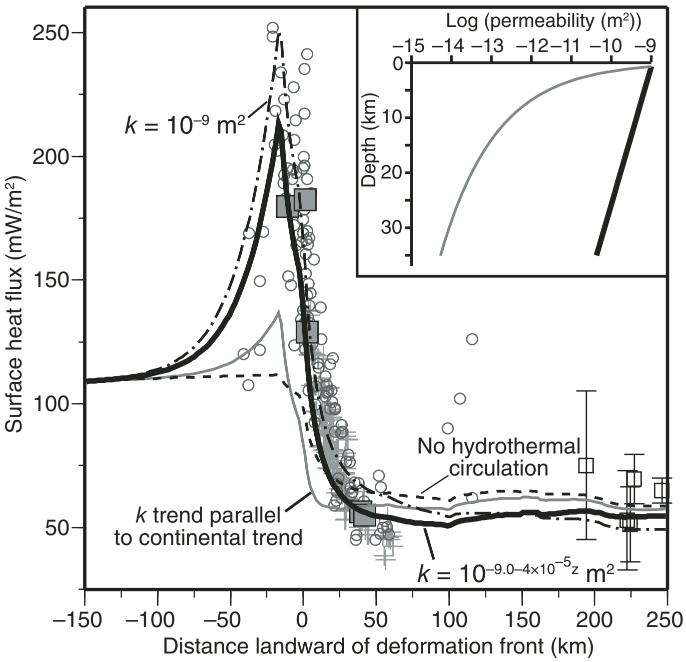

Figure 3. Measured and modeled surface heat flux along transect indicated in Figure 1. Observations are from seafloor probe measurements (circles), estimates from the depth to a gas hydrate–related bottom simulating reflector (crosses), and temperature gradients in Ocean Drilling Program (filled squares) and land boreholes (open squares). Compared to a model with no hydrothermal circulation (dashed line), simulations with enhanced lateral heat transport in a basement aquifer result in higher heat flux in trench and very steep drop in heat flux landward of trench. Results are shown with basement aquifer permeability (*k*) of 10^{-9} m^2 (dot-dash line) and for two cases with aquifer permeability decreasing with depth (inset). Thin gray line is for case with permeability trend parallel to the trend for continental rocks. In the preferred model (thick black line), the permeability decreases more gradually with depth.

As with previous models, the modeled heat flux with no hydrothermal circulation in the basement aquifer falls well below the observed values in the trench, and the drop in modeled heat flux landward of the trench is more gradual than observed. Including the effects of vigorous hydrothermal circulation in the crustal aquifer results in a higher modeled heat flux in the trench and a steep drop in heat flux landward of the trench. The observed heat flux is most consistent with high permeability prior to subduction and a gradual decrease in permeability with depth (thick line in Fig. 3), indicating that permeability is better maintained in the subducting crust than in continental rocks at depth. The preferred model reproduces three key features in the observed heat flux data: (1) high heat flux in the trench, (2) a drop to heat flux ~55 mW/m^2 in Ocean Drilling Program sites ~40 km landward of the trench, and (3) a trend toward slightly higher heat flux values at the landward end of the system. Our model in effect provides a way of constraining the formation-scale permeability of newly subducted crust from surface heat fluxes.

The redistribution of heat in the crustal aquifer that is consistent with the surface heat flux data has considerable influence on temperatures on the plate boundary fault. Comparison of previous thermal model results (Hyndman et al., 1995; Wang et al., 1995) with a well-defined distribution of coseismic slip on the plate interface for the 1944 Tonankai and 1946 Nankaido megathrust earthquakes (Sagiya and Thatcher, 1999) would indicate a seismogenic zone extending to >450 °C. In our preferred model, the inferred rupture area for the megathrust earthquakes (Sagiya and Thatcher, 1999) is between ~125 and 365 °C (Fig. 4). Enhanced heat transport in the basement aquifer reduces seismogenic zone temperatures by at least 20 °C (near the updip end) and up to ~100 °C (near the downdip end) compared to simulations with no effects of hydrothermal circulation.

CONCLUSIONS

As noted in previous studies (Hyndman and Wang, 1993), the downdip limit of the seismogenic zone appears to be controlled by a temperature of ~350 °C, consistent with the temperature range of the transition

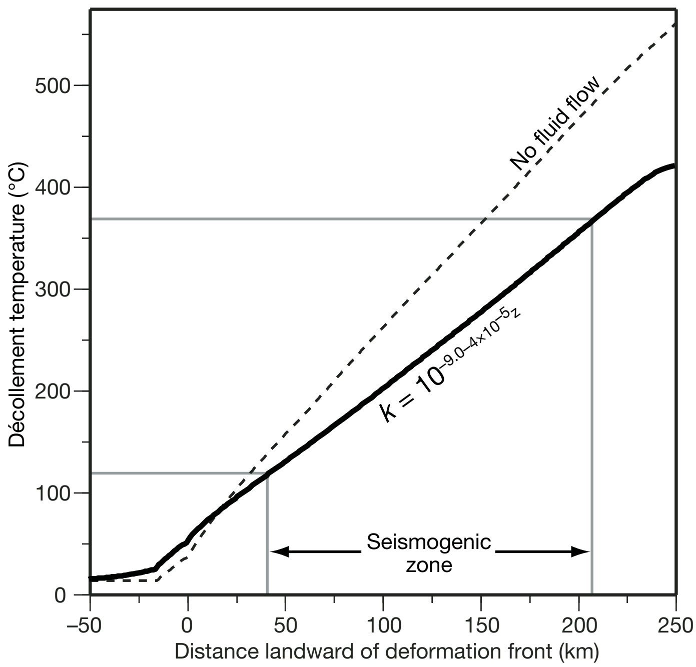

Figure 4. Modeled temperatures along the megathrust. With preferred aquifer permeability (thick solid line), seismogenic zone defined by Sagiya and Thatcher (1999) extends from ~125 to ~365 °C.

from stick-slip to stable sliding in laboratory friction experiments (Blanpied et al., 1995). The location of 350 °C on the plate interface estimated from a thermal model without the effect of fluid circulation would predict a significantly narrower seismogenic zone than does the model with this effect (Fig. 4).

The effect of fluid circulation on subduction zone temperatures in the Nankai margin is illustrative of a process that may be important at other margins. Modeled subduction zone temperatures (and the application of those temperatures for estimating diagenetic and metamorphic reaction progress) from simulations that do not account for hydrothermal circulation may need to be revisited. Differences in plate age and subduction geometry may influence the magnitude of the effects of fluid circulation on subduction zone temperatures. Margins with continuous, but thin, sediment cover on the incoming plate are favorable for having observable anomalously high surface heat flux in the trench resulting from this fluid circulation. In contrast, systems with open circulation in the incoming plate near the trench (e.g., seamounts or outcrops exposing the basement aquifer at the seafloor) should have anomalously low surface heat flux in the trench (Harris and Wang, 2002; Kummer and Spinelli, 2008). Margins of interest will need to be examined individually with heat flux data constraining thermal models that incorporate the effects of hydrothermal circulation.

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