Thermal models of the Middle America Trench at the Nicoya Peninsula, Costa Rica

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[1] We present thermal models of the 24 Ma Cocos plate subducting under the Caribbean plate at the Nicoya Peninsula, Costa Rica. Our modeling incorporates the effect of hydrothermal cooling of the seafloor and the absence of an accretionary prism. Initial geotherms of the incoming plate, representing different effective cooling depths of hydrothermal circulation, affect the thermal structure and temperatures along the main subduction thrust. Excluding the deforming prism results in a higher heat flow immediately landward of the trench than previous models and therefore significant frictional heating is not required. Conductive plate cooling over-predicts heat flow across the frontal forearc. With no or very low frictional heating, models with hydrothermal cooling to depths of 2 km under-predicts the heat flow. Comparisons with recently determined hypocenter locations indicate that the updip limit of seismicity is consistent with temperatures between 100°–150°C, but there are large along-strike variations in both the seismicity and thermal regime. *INDEX TERMS:* 3015 Marine Geology and Geophysics: Heat flow (benthic) and hydrothermal processes; 8105 Tectonophysics: Continental margins and sedimentary basins; 8130 Tectonophysics: Evolution of the Earth: Heat generation and transport. **Citation:** Harris, R. N., and K. Wang, Thermal models of the Middle America Trench at the Nicoya Peninsula, Costa Rica, *Geophys. Res. Lett.*, *29*(0), XXXX, doi:10.1029/2002GL015406, 2002.

1. Introduction

[2] Understanding the seismogenic portion of subduction thrusts is important because of its role in the production of large earthquakes and tsunamis. It is now generally acknowledged that the updip and downdip limits of the seismogenic zone are influenced or even controlled by temperature through its influence on fault frictional properties. The downdip edge of seismicity appears to be limited to either the 350°C isotherm or the presence of serpentinized mantle, while the updip limit appears to be controlled by the intersection of the 100°–150°C isotherm with the main subduction thrust [*Hyndman and Wang*, 1993; *Hyndman et al.*, 1997; *Oleskevich et al.*, 1999; *Peacock and Hyndman*, 1999]. *Moore and Saffer* [2001] reviewed thermally controlled diagenetic and low grade metamorphic reactions that may lead to a transition from velocity strengthening to velocity weakening thereby controlling the updip limit of seismicity.

[3] A primary controlling factor for the thermal regime of a subduction zone is the temperature structure of the incoming oceanic plate at the trench. Most thermal models have assumed conductive geotherms for the incoming plate. The ability of hydrothermal circulation to ventilate and cool the incoming upper oceanic crust may have an important influence on the shallow thermal regime and push the updip limit of the seismogenic zone landward. Thermal and fluid data from the Middle America Trench offshore of the Nicoya Peninsula indicate that the upper oceanic crust is significantly (~70%) colder than expected for a conductively cooling plate of this age (~20–25 Ma), due to vigorous hydrothermal circulation. The purpose of this paper is to investigate thermal models of subduction at the Middle America Trench and explore the influence that hydrothermal cooling has on the seismogenic zone of the main subduction thrust off shore and beneath the Nicoya Peninsula.

2. Regional Setting

[4] At the Nicoya Peninsula, Costa Rica, the Cocos plate is subducting beneath the Caribbean plate at the Middle America Trench (Figure 1). Subduction rates vary from 70 mm yr^{-1} off Guatemala to nearly 90 mm yr^{-1} off southern Costa Rica [*DeMets et al.*, 1999]. The incoming Cocos plate has an age of 20–25 Ma [*Barckhausen et al.*, 2001] and is covered by approximately 400 m of pelagic and hemipelagic sediment [*Kimura et al.*, 1997]. Offshore of the northern Nicoya Peninsula, oceanic crust likely originated at the East Pacific Rise (EPR), while offshore of the southern Nicoya Peninsula, oceanic crust likely originated at the Cocos-Nazca Spreading Center (CNSC). Interpretations of magnetic data [*Barckhausen et al.*, 2001] place the transition between these crustal elements near the middle of the Nicoya Peninsula. The crust from the EPR has a smooth morphology characteristic of fast spreading ridges, while the crust from the CNSC has a rough morphology characteristic of slow spreading. The transition between these crustal provinces may have important implications for fluid flow and the thermal evolution of the plate.

[5] The Nicoya Peninsula is composed of Late Jurassic to Late Cretaceous ophiolitic rocks overlain by Late Cretaceous and younger sedimentary rocks. The margin wedge is composed of two parts: relatively high seismic velocity material [*Christeson et al.*, 1999; *Ye et al.*, 1996], thought to be the

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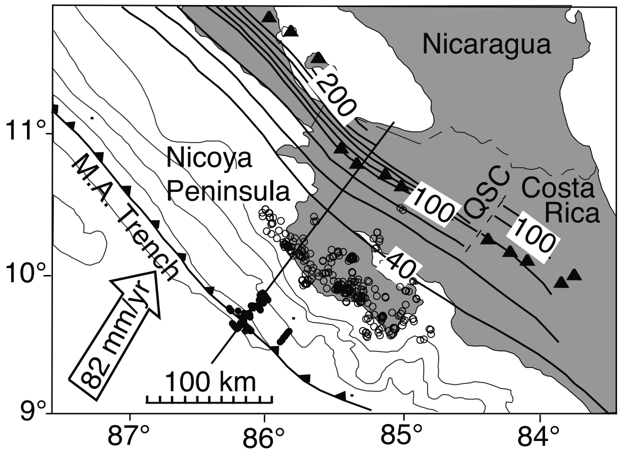

Figure 1. Regional tectonic map (modified from *Protti et al.* [1995]) showing major tectonic boundaries and geographic features around the Nicoya Peninsula. Contours to the top of the Wadati-Benioff Zone are at 20 km intervals and QSC is Quesada Sharp Contortion. Triangles show location of active volcanoes, and open circles show epicenter locations as determined from the Seismogenic Zone Experiment [*Newman et al.*, 2002]. Closed circles show location of marine heat flow data and closed triangle show location of ODP Holes with thermal measurements.

offshore extension of the ophiolitic rocks comprising the Nicoya Peninsula and, seaward, a deformed sedimentary wedge compositionally distinct from incoming sediments and similar to the sedimentary apron overlying the wedge [*Kimura et al.*, 1997]. Concentrations in ^{10}Be suggest a relatively old age for the sedimentary apron [*Valentine et al.*, 2000]. These observations indicate that the present margin is dominantly nonaccretionary [*Kimura et al.*, 1997].

3. Heat and Fluid Flow

[6] Heat flow determinations offshore the Nicoya Peninsula are generally low with significant heterogeneity. Heat flow for oceanic crust of age 20–25 Ma predicted by conductive cooling models is approximately 100 mW m^{-2} [*Stein and Stein*, 1992]. Initial regional heat flow values indicating that oceanic crust created at the EPR had lower heat flow than the observational average while crust created at the CNSC were higher than the theoretical value [*Vacquier et al.*, 1967; *von Herzen and Uyeda*, 1963] were confirmed by *Langseth and Silver* [1996] using detailed heat flow profiles. Their probe measurements, in the trench and just seaward of it, have an average heat flux of 14 mW m^{-2}. Inboard of the trench, on the sedimentary apron covering the margin wedge, heat flow increases to an average value of 28 mW m^{-2}, with the variability decreasing landward (Figure 3). New heat flow profiles designed to investigate the thermal transition between oceanic crust formed at the EPR and crust formed at the CNSC found variations in heat flow are factors of 2 to 10 over distances of a few to a few tens of kilometers in both the strike-normal and strike-parallel directions [*Fisher et al.*, 2001]. The magnitude and wavelength of these variations, suggestive of vigorous fluid flow in the upper oceanic crust, are observed over a relatively broad area.

[7] A series of Ocean Drilling Program (ODP) Holes provided the opportunity to investigate the thermal structure to depths of hundreds of meters below seafloor [*Ruppel and Kinoshita*, 2000]. The curvature in temperature-depth profiles at or near the trench axis indicates upward fluid flow through the sediments, whereas the temperature profile at a more landward mid-slope site appears conductive.

4. Thermal Models

[8] The high variability in heat flow at the Nicoya margin is challenging for thermal models designed to model the thermal regime averaged along strike. However, two-dimensional margin-normal models remain useful for investigating the effects of variations in the local thermal structure of the incoming plate. We estimate the temperature structure along the subduction thrust using the two-dimensional numerical model described by *Wang et al.* [1995] and *Peacock and Wang* [1999]. This model solves the heat conduction – advection equation using a finite element approach. Heat is transferred advectively with the subducting plate and conductively through the forearc.

[9] The model geometry is based on the seismic velocity model of *Christeson et al.* [1999] and integrated modeling of *Sallarés et al.* [1999]. Seaward of the Nicoya Peninsula, the oceanic plate has a crustal thickness of 6 km [*Ye et al.*, 1996], and deepens from 4 km at the trench to 15–16 km at the Nicoya Peninsula coastline. The dip angle of the subducting plate increases from 6° to 13° at a distance of about 30 km from the trench [*Christeson et al.*, 1999]. This dipping plate structure is represented in a 2-D finite element mesh that extends from 40 km seaward of the trench to 200 km landward. The landward boundary is placed sufficiently far from the seismogenic zone to avoid edge effects. Seaward of the trench the mesh has a horizontal surface to aid in the evaluation of the thermal structure of the incoming plate. The model is divided into five thermostratigraphic units: marine sediments, upper continental crust, lower continental crust, mantle wedge, and oceanic plate (Table 1). We use a maximum crustal thickness of 40 km for the Costa Rican Isthmus [*Sallarés et al.*, 1999]. Because the Nicoya Peninsula and Costa Rica are thought to represent an accreted oceanic plateau, we use thermophysical rock properties that are typical of thickened oceanic crust. The top and bottom boundaries of the model are fixed at temperatures of 0°C and 1400°C, respectively. Flow in the mantle wedge between the two converging plates is kinematically introduced using the analytical corner flow solution described by *Peacock and Wang* [1999]. The wedge flow results in a warm backarc, but it has little effect on the forearc thermal regime.

[10] We explore the effective cooling depth of hydrothermal circulation by varying initial geotherms within the

Table 1. Model Parameters

Unit	Thermal Conductivity W m^{-1} K^{-1}	Heat Capacity MJ K^{-1} m^{-3}	Heat Production μW m^{-3}
Crust (0–20 km)	2.7	–	1.5
Crust (20–40 km)	2.7	–	0.3
Mantle Wedge	2.9	–	0.03
Sediments	1.2	2.6	0.60
Oceanic Plate	2.9	3.3	0.03

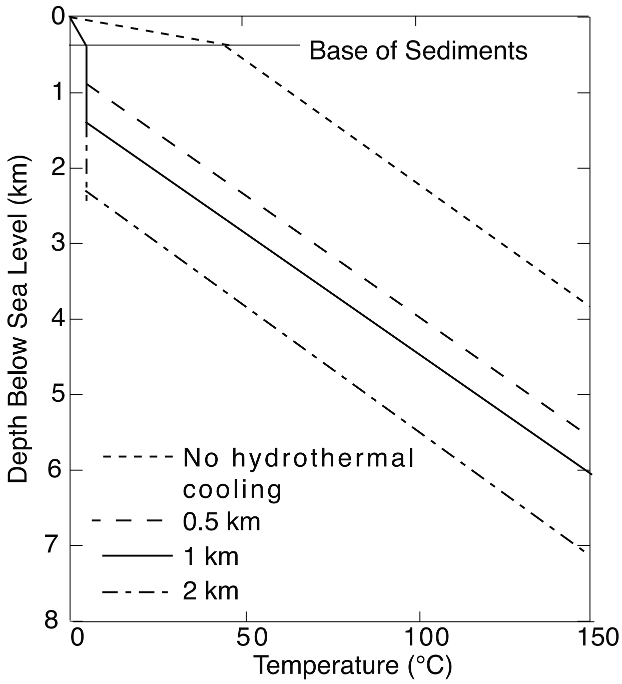

Figure 2. Geotherms of the incoming plate at the trench. The no hydrothermal cooling geotherm corresponds to a plate age of 24 Ma and constant sedimentation resulting in a final sediment thickness of 400 m. The remaining geotherms represent different effective cooling depths of hydrothermal circulation.

incoming oceanic plate at the trench. Four initial geotherms are shown in Figure 2. These geotherms correspond to half space cooling for 24 Ma oceanic crust with constant sedimentation and a series of three prescribed geotherms consisting of an upper section having a thermal gradient of 12°C/km through 400 m of marine sediments, an isothermal section of varying thickness, and a lower section based on half space cooling for 24 Ma. Following *Langseth and Silver* [1996], we assign a much reduced conductive thermal gradient in the sediments to simulate the effects of underlying crustal cooling by vigorous hydrothermal circulation. Without prior knowledge of the shape of the geotherm in the hydrothermally cooled section, we use the simplest approach of assigning a zero gradient. The three hydrothermal models consist of isothermal sections that are 0.5 km, 1 km, and 2 km thick, respectively, representing different depth extents of the vigorous hydrothermal cooling. Once the oceanic plate enters the trench, we assume that circulations stops and the initially cooled section warms up gradually as a result of heat conduction from below. Because we assume that hydrothermal circulation shuts off at the trench our results represent minimum estimates of effective cooling. As discussed above there is evidence that fluid flow in the upper oceanic crust continues after subduction, but presently have no data to constrain the landward extent of continued hydrothermal circulation.

[11] The conceptual model of a hydrothermally cooled incoming plate subducting beneath the Costa Rica margin was originally proposed by *Langseth and Silver* [1996]. Our new model differs from theirs in two aspects. First, a deforming accretionary prism was incorporated in their model by allowing the sediment column to be thickened and vertically stretched in the frontal forearc. It was later concluded that there is no modern accretionary prism, all sediment is subducted at this margin [*Kimura et al.*, 1997], and the deforming prism is excluded from our new model. Secondly, our two dimensional model calculates temperatures for the entire system and hence can be tested against seismicity and deformation models constrained by geodetic data.

5. Results

[12] Model heat flow profiles across the subduction zone resulting from these different initial geotherms are shown in Figure 3. The half space cooling geotherm shows decreasing heat flow landward of the subduction thrust as expected for downward advective heat transport by the subducting plate. Heat flow values for models with initial isothermal upper crustal sections of 0.5 and 1 km, increase landward of the trench, as hydrothermal cooling is shut off. The maximum increase near the trench depends on the depth of the initial hydrothermal cooling. For a 0.5 km cooling depth, the heat flow increases rapidly and reaches a low peak before slowly decreasing landward, but for a 1 km cooling depth, heat flow monotonically increases landward. Heat flow values for the model with an initial isothermal section of 2 km show an initial decrease due to the increased time it takes to warm up the cooled section of incoming plate. In all cases, the heat flow eventually increases near the volcanic arc region as a result of mantle wedge flow.

[13] Also plotted in Figure 3 are two cases involving frictional heating along the thrust fault, both with a 1 km initial cooling depth. One model is the heat flow profile proposed by *Langseth and Silver* [1996], with a friction coefficient $\mu = 0.85$ and a pore fluid pressure ratio, $\lambda = 0.85$; these parameters give an effective friction coefficient $\mu' = \mu(1 - \lambda) = 0.13$ and a cooling depth of 1 km. The other case is the heat flow profile predicted by the present model

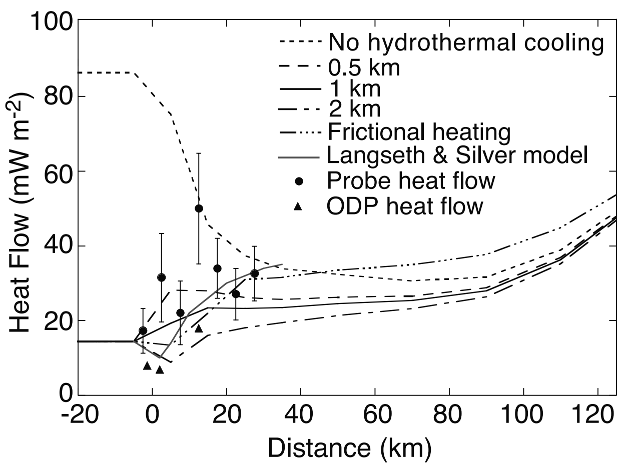

Figure 3. Model heat flow corresponding to different incoming-plate geotherms shown in Figure 2. Heat flow data, from *Langseth and Silver* [1996], are averaged in 5 km bins (circles). Bars represent standard deviations. Triangles show ODP heat flow values from *Ruppel and Kinoshita* [2000].

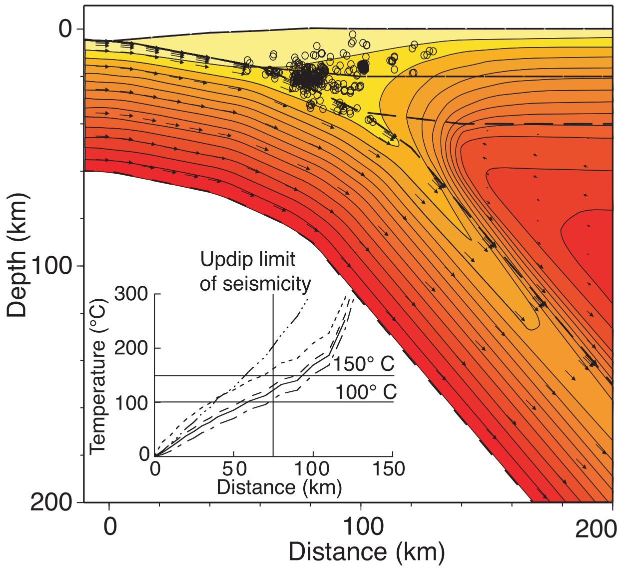

Figure 4. Thermal model of subduction beneath the Nicoya Peninsula using a plate geotherm model corresponding to an effective cooling depth of 1 km. Basal continental heat flow for the landward boundary condition is 60 mW m^{-2}. Contour interval is 100°C. Arrows show flow vectors and circles show hypocenter locations. Note approximate correspondence between updip limit of seismicity and 100°C isotherm. No frictional heating along the plate interface is included in this model. Inset, Temperature on main subduction thrust. Curves correspond to incoming plate geotherms shown in Figure 2 and heat flow patterns shown in Figure 3.

assuming a μ' of 0.05. In the model of *Langseth and Silver* [1996], vertical stretching of the sediment column, representing active accretion and thickening of sediments, caused heat flow to decrease just landward of the trench. Thermal recovery of the hydrothermally cooled section was not sufficient to offset this prism deformation effect. In order to have a model heat flow comparable to the observed values, fairly significant frictional heating was introduced. The μ and λ values used were consistent with the shape of the sediment wedge, which was assumed critically tapered [*Davis et al.*, 1983]. Given the new evidence for the lack of active accretion [*Kimura et al.*, 1997], our model does not include the effect of deformation thickening. Consequently, no significant frictional heating is required. Slight frictional heating ($\mu' = 0.05$) with a cooling depth of 1 km or no frictional heating with cooling depth 0.5 km are both allowed by the heat flow data.

[14] Although the quality of the heat flow measurements are good, the scatter in the present data make it difficult to limit the range of permissible thermal models. Results in Figure 4 represent one of a range of models allowed by the thermal data. Recently determined hypocenter locations [*Newman et al.*, 2002] from the Nicoya SIEZE experiment indicate that the updip limit of seismicity is approximately 70 km landward of the subduction thrust and shallows to the south. All of our hydrothermally perturbed geotherms produce isotherms, between 100° and 150°C, which intersect the main subduction thrust at 70 km from the trench (Figure 4, inset).

[15] The 350° C isotherm does not intersect the subduction thrust until well below the mantle wedge. Thus the downdip limit of the seismogenic zone does not appear to be thermally controlled, but instead may correspond to the intersection of the subduction thrust with the mantle wedge [*Hyndman et al.*, 1997; *Peacock and Hyndman*, 1999].

6. Conclusions

[16] We have numerically modeled the thermal regime of the Middle America Trench along a profile across the Nicoya Peninsula, Costa Rica. Accounting for the effects of hydrothermal cooling of the incoming plate and the absence of a growing accretionary prism, our models predict a landward increase in surface heat flow, in agreement with heat flow data. In all of the models hydrothermal circulation is assumed to shut off as the plate enters the trench, thus the magnitude and location of landward increasing heat flow represent maximum and minimum values, respectively. Relative to a plate undergoing simple half space cooling, a hydrothermally cooled plate results in lower temperatures on the subduction thrust and may result in the updip limit of seismicity being further landward. Thermal models of continental subduction zones which span a wide range of subduction environments indicate that the updip limit of seismicity approximately corresponds to the position where the 100°C isotherm intersects the subduction thrust [*Oleskevich et al.*, 1999]. All of our hydrothermally perturbed geotherms intersect the updip limit of seismicity, as determined from recently re-located hypocenters, between the 100° to 150°C isotherm in agreement with results elsewhere. However, because of the large scatter in heat flow data, the thermal model is not well constrained and therefore is predictive and to be tested by future observations.

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