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The Nicoya convergent margin–a region of exceptionally low heat flow

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Abstract. Over 100 measurements of seafloor heat flow reveal that the accretionary complex adjacent to the Nicoya Peninsula is characterized by remarkably low heat flow; values over the accretionary prism average 28 mW/m^2, and values in the trench and the ocean crust seaward of the trench average 14 mW/m^2. We attribute the low heat flow to effective hydrothermal cooling of the upper crust on the subducting plate and suggest that extensional faults created by flexure of the lithosphere enhance hydrothermal circulation. Thermal models show that subduction of low temperature crust combined with significant frictional heating at the decollement can explain the low and uniform heat flow. Disparity between heat flow values observed on the lower trench slope with model results suggests upward advection of heat by porewater flux through broadly distributed conduits.

Introduction

Over 100 high-quality heat flow measurements were made as part of a multidiscipinary campaign, to define heat and fluid flow in the accretionary complex on the Pacific margin of Costa Rica seaward of the Nicoya peninsula.

Heat flow measurements were made with the Woods Hole Oceanographic Institution (WHOI) digital, heat flow instrument (Von Herzen et al., 1989). The WHOI instrument is a multipenetration device that measures a 5-point vertical temperature profile in the seafloor sediment to a depth of about 4 meters, and makes in situ measurements of thermal conductivity of the sediment at each thermistor location using the continuous line source method. The deep submersible ALVIN is equipped with a one meter temperature probe, which was used to make measurements on the lower slope and in active vents.

Results

We made 12 measurements on a fault-bounded bench seaward of the trench (Figure 1 & 2), which yielded anomalously low and uniform values of heat flow ($\bar{q}$ = 12.3, s.d.=2.2). (All heat flow values are in units of mW/m^2). Nineteen measurements made in the trench floor at depths greater than 4300 m yielded an average of 17.4, s.d.= 2.4 indicating a slight increase in heat flow in the vicinity of the deformation front. A line of measurements was made along the toe of the accretionary prism as close to the deformation front as possible to detect thermal evidence of fluid venting (Figure 2). Five of these penetrations were made on the toe of the prism, and they yielded consistently higher values than measurements in the trench floor ($\bar{q}$ = 28.7, s.d.= 6.5).

Sediments on the seafloor between the out of sequence thrusts and the deformation front are surprisingly hard. Attempts to penetrate the lower slope sediments frequently resulted in either the probe falling over or penetrating only a meter or two. This left a gap in the data and prevented us from making detailed measurements over the most dynamic part of the accretionary prism, the outer wedge (Figure 3).

Higher on the slope we made lines of measurements roughly parallel to bathymetric contours. Four lines of measurements were made at distances of about 9, 17, 24 and 28 km upslope from the deformation front. Seven to fifteen measurements were made on each line to obtain a statistically significant mean and provide an indication of local variability. The means of these lines indicate that heat flow and variability of the means are low (28.5 ± 3); however, variability of individual measurements along some of the lines is large (Table 1 and Figure 3).

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Discussion

Cold oceanic crust in the Middle America Trench

The remarkably low heat flow measured seaward of the deformation front is within a large area of low heat flow in the Guatemala Basin that was defined in the 1960's by Von Herzen and Uyeda (1963) and Vacquier et al, (1967). Comparison of the mean heat flow of 14 mW/m^2, which we measured, with the 100 mW/m^2 expected over 20 Ma old oceanic crust being subducted at the Nicoyan margin (Klitgord and Mammerickx, 1982) implies that over 85% of the heat from the lithosphere is "lost" before it reaches the seafloor. The only demonstrated way to cool the oceanic crust to this degree is by a "seawater heat exchanger" mechanism. That is, cold seawater enters the upper crust at basement exposures and flows horizontally absorbing heat before exiting (Langseth et al., 1992).

However, there are serious difficulties in appealing to this mechanism to explain low heat flow in the trench off the Nicoya Peninsula. The existing seismic reflection data in the area shows a smooth, low-relief basement that is covered by a 400 m layer of sediment and no local basement outcrops. However, the effectiveness of the seawater heat exchanger mechanism may be enhanced by the normal faults that are formed by flexure of the lithosphere as it enters the trench. Fracturing produced by faulting may significantly increase the large scale permeability of the upper crust, which would allow freer flow of seawater between basement exposures, even though they are separated by large distances. The faults may extend through the brittle upper crust, and provide deep-reaching conduits for seawater flow which will enhance cooling because the efficiency of the seawater heat exchanger increases with thickness. The observation that the lowest

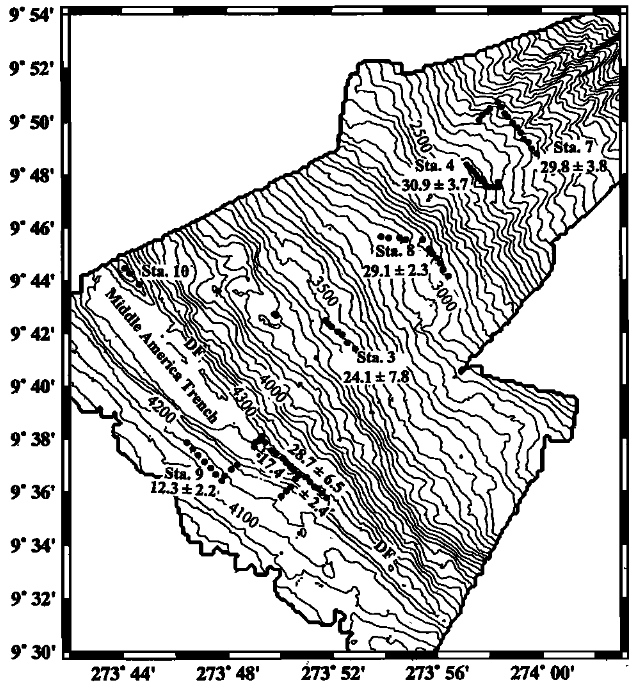

Figure 1. Location of heat flow measurements. Means and std. dev. are shown next to groups of measurements defined in Table 1. DF marks the deformation front. Contour interval = 50 m.

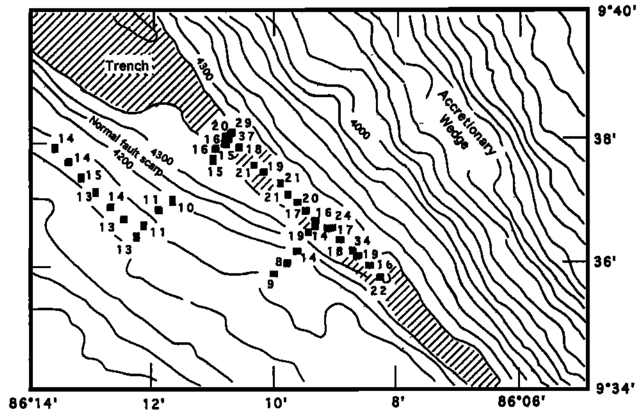

Figure 2 . Heat flow values in the trench and along the deformation front.

heat flow in the study area was measured over a fault scarp seaward of the trench (Fig. 2) lends support to the hypothesis that the faults play a role in cooling the igneous basement.

It is interesting to note that the profile of heat flow variation over the subduction complex on the Peru margin (Yamano and Uyeda, 1990) shares many similar features with the profile over the Costa Rica margin. Extremely low heat flow was observed in the trench seaward of the deformation front, but heat flow increases abruptly on the landward side. Values on the upper slope show an increase landward in the outer 50 km that reach a relatively uniform level between 40 and 50 mW/m^2. Yamano and Uyeda (1990) suggest that the extremely low heat flow in the trench may be due to enhancement of hydrothermal circulation as a result of normal faulting on the outer ridge.

Thermal models of the accretionary prism

To examine the overall heat balance of the accretionary prism we used a modeling concept developed by Ferguson et al. (1993). It is a one dimensional model that follows a column of prism material as it moves ever deeper in the prism (Figure 4). The effects of frictional heating at the decollement, changing dimensions of the column due to deformation, radiogenic and strain heat within the prism, compaction of the sediment and variations in properties as it progresses deeper into the prism are all included in the simulation. Although the model accounts for the expulsion of porewater due to compaction, it does not include the effects of heat advected by porewater flow.

Cooling of the oceanic crust prior to subduction, implied by the extremely low heat flow in the trench, is incorporated into the model by assuming an initial temperature vs. depth profile that is calculated by extrapolating the seafloor heat flow, (14 mW/m^2) to the bottom of the hydrothermally cooled zone (Figure 4). The depth to the bottom of the cooled layer is treated as a variable in the study. Below the hydrothermally cooled layer the initial temperature is calculated assuming that the lithosphere has been conductively cooling as a half-space into the zone of hydrothermal circulation for the past 20 Ma.

Frictional heat generated by shearing at the decollement is simulated by equating it to the work done against friction. That is: $Q_{decollement} = \sigma_e \cdot \Delta V$, where ΔV is the rate of shearing, and σ_e is the effective stress, estimated by $\mu_B(1-\lambda_B)\bar{\rho}gh$, where μ_B is the coefficient of friction at the decollement, λ_B is the ratio of pore fluid pressure to pressure due to the lithostatic overburden at the decollement and $\bar{\rho}gh$ is the weight of the column. The contribution of frictional heat was found to be significant; thus, λ_B is also treated as a variable in the study.

The mechanical model of Davis et al. (1983) relates the taper angle of an accretionary prism to the basal traction and internal mechanical properties. Our simulations assume that the coefficient of friction at the decollement is 0.85, and the coefficient of friction within the prism is adjusted to satisfy the taper angle formula for an assumed λ_B. The excess pore pressure ratio within the prism is set equal to λ_B. The relatively large taper angle at Costa Rica (10.7°) requires significant traction at the decollement which requires λ_B be less than 0.86 for a μ_B of 0.85.

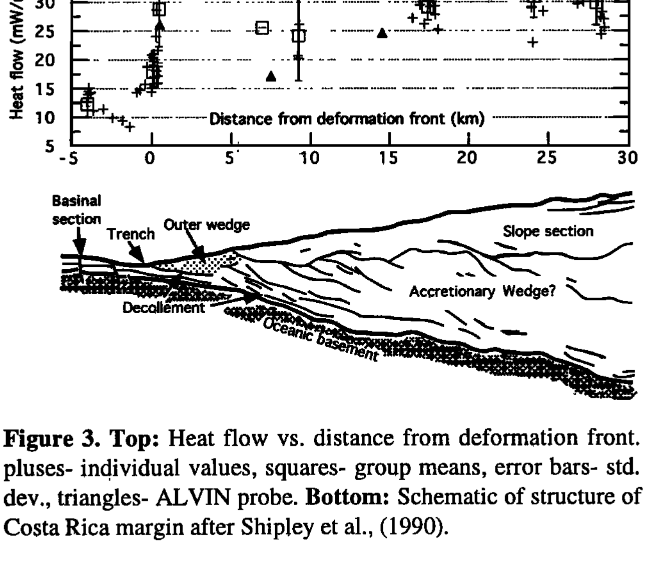

Figure 3. Top: Heat flow vs. distance from deformation front. pluses- individual values, squares- group means, error bars- std. dev., triangles- ALVIN probe. Bottom: Schematic of structure of Costa Rica margin after Shipley et al., (1990).

Table 1: Mean heat flow for groups of stations vs. distance from deformation front (landward +).

Station #	Distance (km)	Number	Heat flow mW/m^2	Std. Dev. mW/m^2
Stas. 1, 2 & 9	-4.11	12	12.3	2.2
Stas. 1, 2 & 5	-0.10	21	17.4	2.4
Stas. 1, 2 & 5	+0.10	5	28.7	6.5
Sta. 3	9.04	6	24.1	7.8
Sta. 4	23.92	10	30.9	3.7
Sta. 7	27.81	12	29.8	3.8
Sta. 8	17.26	11	29.1	2.3
Sta. 10	6.81	3	31.0	-

Modeling results

The cases presented in this study are referenced to a model that gives a reasonable fit to the data between 10 and 30 km landward of the deformation front (Table 2). All of the models that include a hydrothermally cooled layer at the top of the igneous crust predict a sharp decrease in the seafloor heat flow in the outer 2-3 km of the prism (Figure 5). The initial decrease predicted by the model is due to rapid thickening of sediment as it enters the prism. Farther upslope the heat flow increases due to reheating of the hydrothermally cooled zone after subduction and frictional heating at the decollement. The thickness of the cooled layer determines the rate of recovery and, therefore, the level of heat flow (Figure 5B).

The heat flow values for distances greater than 10 km landward of the deformation front are fitted reasonably well by a $\lambda_B \cong 0.85$, (close to the maximum allowed), and a basement that has been cooled to a depth of 1000 m. (Figure 5A). Values of $\lambda_B \leq 0.8$ lead to heat flows that reach 40 mW/m^2 or higher 30 km from the toe, which is not consistent with our data.

Comparison of the model results with data on the upper slope suggests that a hydrothermally cooled layer that is about 1 km thick best explains the level of heat flow between 10 and 30 km. Note that thinner layers predict higher heat flow than is observed even for the maximum permissible excess pore pressure, i.e. $\lambda_B = 0.86$. This implies that the upper km of oceanic crust seaward of the Nicoyan Peninsula is permeable enough to allow hydrothermal circulation to 1000 m. This indirect evidence for a thick hydrothermally cooled layer in the upper igneous crust lends support to the hypothesis that large scale permeability there has been increased and the permeable zone deepened by normal faulting on the outer ridge.

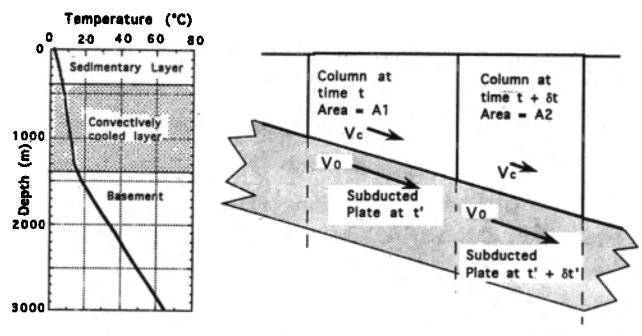

Figure 4. Modeling concept. **Left:** Initial temperature profile for crust that is cooled to 1 km. **Right:** Column of material at two successive times, δt = 5000a . Change in area due to water loss, $A_2 / A_1 = (1 - \bar{\phi}_1)/(1 - \bar{\phi}_2)$, $\bar{\phi}_1$ and $\bar{\phi}_2$ are mean porosities of the column at t and t + δt. Shearing at decollement is accounted for by incrementing time in the slab $\delta t'$ by $\delta t^* V_C/V_O$.

Evidence for pore water flow

Seismic reflection data over the outer wedge show that the decollement is very shallow at the toe of the prism. Seismic data also show a bright reflector with reversed polarity marking the decollement, which suggests that excess pore pressures exist at the base of the prism (Shipley et al., 1990). These results led to speculation that there may be significant venting of pore water at the deformation front. However, heat flow measurements along the deformation front revealed no large local anomalies, which would be expected if there were active fluid venting Furthermore, ALVIN dives to the trench and toe of the prism found no evidence for vents (Kahn et al., this volume).

The lack of a strong thermal signal associated with pore fluid flow may be attributed in some degree to low temperatures in the section that is being subducted. Model calculations indicate that material below the outer wedge is only a few degrees above bottom water temperature; therefore, if the sources of the water are shallow, the flow of pore water will carry relatively little heat toward the surface. This suggests that water flowing through the outer wedge does not come from sources deep in the prism. A similar conclusion was reached by Zuleger et al., (this volume) based on profiles of pore water chemistry.

Despite the lack of evidence for strong localized venting near the deformation front, there are two lines of evidence that support the existence of a broadly distributed flow of porewater through the surface of the outer 10 km of the prism. 1) ALVIN dives discovered several widely distributed low temperature vents in the vicinity of the out-of-sequence thrusts (Kahn et al., this volume). 2) Model simulations, which do not include heat transport by pore fluid flow, predict a decrease in heat flow over the outer 2-3 km of the prism (Fig. 5), whereas observations near the deformation front show an abrupt increase in heat flow. This increase could be explained by advection of heat by pore water flow.

Wang et al., (1993) have studied the thermal effects of pore fluid expulsion and sediment thickening in a prism being built by frontal accretion using 2-D models. Their study indicates that the diffusive expulsion of pore fluids, i.e. intergranular flow, advects a significant amount of heat upward, which counteracts the re-

Table 2. "Reference model"

	Density ($kg\text{-}m^{-3}$)	Heat Capacity ($J\text{-}kg^{-1}\text{-}°C^{-1}$)	Conductivity ($W\text{-}m^{-1}\text{-}°C^{-1}$)
Seawater	1030	4184	0.60
Sediment grains	2700	1100	3.10
Convect. zone	2900	1100	1.80
Lower crust	3300	1100	3.10

Heat flow in trench = 14 mW/m^2
Temperature at base of lithosphere = 1300 °C
Convergence rate = .09 m/a
Prism taper angle: upper (α) = 4.3°, lower (β) = 6.4
Decollement depth at deformation front = 400 m
Age of subducting lithosphere = 20 Ma
Basal coefficient of friction = 0.85,
Internal coefficient of friction = 0.89
Porosity vs. depth $\phi(z) = 0.1 + 0.6 \exp(-z / 1100)$

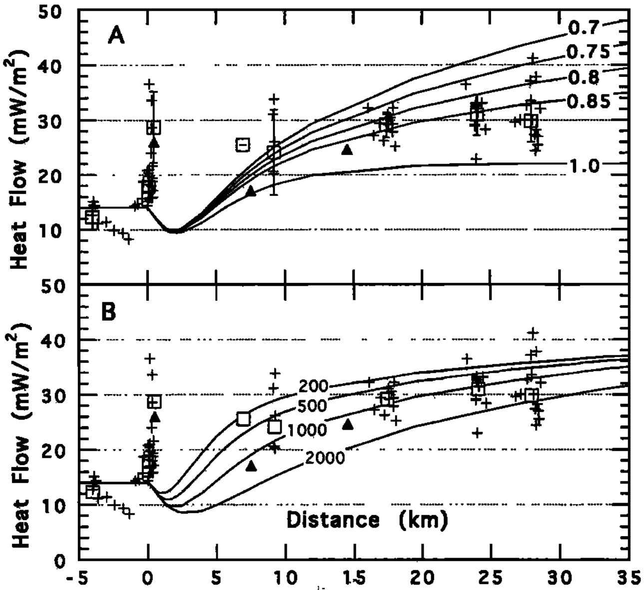

Figure 5. Predicted heat flow and data vs. distance for **A.** five values of λ_B (thickness of cooled zone = 1000 m). **B.** four thicknesses of hydrothermally cooled zone (λ_B = 0.85). Table 2 gives other model properties..

duction in heat flow due to thickening. The calculated rates of diffusive expulsion are on the order of 1 mm/a in the vicinity of the toe of the prism and advect very little heat and consequently should have only a small effect. A more vigorous flow than that predicted by the 2-D models of Wang et al. (1993) is required by the observed abrupt increase in heat flow as the deformation front is crossed. Enhanced flow might occur along many small distributed conduits such as fractures, but this flow is apparently not vigorous enough or focused enough to produce large localized heat flow anomalies or discernible seafloor vents.

Conclusions

We attribute the anomalously low heat flow over the convergent margin adjacent to the Nicoya Peninsula to unusually effective hydrothermal cooling of the upper crust of the subducting plate. We further suggest that the suite of newly-formed faults, created by flexure of the lithosphere as it enters the subduction zone, increases the efficiency of hydrothermal cooling. Models of the thermal regime of the prism that include subduction of a low temperature crust and frictional heating at the decollement can explain the anomalously low heat flow (≈28 mW/m^2) observed over the prism landward of the zone of out-of sequence thrust faults. Disparity between the relatively high heat flow over the outer wedge and that predicted by models suggests upward advection of heat by fluids flowing through broadly distributed conduits.

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