

## Heat flow and flexure at subduction zones

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Received 22 August 2003; revised 17 October 2003; accepted 30 October 2003; published 5 December 2003.

[1] It is often suggested that heat flow in the incoming plate at subduction zones is lower than expected for crust of that age due to increased hydrothermal circulation from flexure (extending about 300 km seaward of the trench) and faulting (observed starting about 50–75 km seaward of the trench). Testing this suggestion using global heat flow data shows no significant difference between heat flow near the trench and the global means for the same age crust. However, on average, heat flow in the overriding plate is about 60% of that in the incoming plate. **INDEX TERMS:** 3015 Marine Geology and Geophysics: Heat flow (benthic) and hydrothermal processes; 3040 Marine Geology and Geophysics: Plate tectonics (8150, 8155, 8157, 8158); 8135 Tectonophysics: Hydrothermal systems (8424). **Citation:** Stein, C. A., Heat flow and flexure at subduction zones, *Geophys. Res. Lett.*, 30(23), 2197, doi:10.1029/2003GL018478, 2003.

### 1. Introduction

[2] Heat flow near subduction zones has been assumed to follow several general trends (Figure 1) [e.g., *Watanabe et al.*, 1977]. The highest values over the volcanic arc are presumably associated with melting processes. The lowest heat flow over the subduction complex and forearc basin is assumed to result from thermal blanketing effect by the overlying plate and accreted sediments above the subducting oceanic plate [e.g., *Langseth et al.*, 1990]. It has been speculated that heat flow seaward of the trench may be low compared to that for average crust of the same age, due to increased hydrothermal circulation resulting from flexing and normal faulting of the plate prior to subduction, but infrequently mentioned in print [e.g., *Yamano and Uyeda*, 1990; *Langseth and Silver*, 1996].

[3] If hydrothermal circulation occurs near trenches, results from other areas, especially young oceanic crust, suggest that it would produce broad low heat flow regions and a few high ones associated with upwelling [e.g., *Green et al.*, 1981]. Identifying upwelling in young crust is difficult because sediment thickness sufficient for measurements usually occurs in basement lows where heat flow is often lower than at poorly sedimented basement highs [e.g., *Becker and Von Herzen*, 1983]. However, on older and hence more thickly sedimented crust near trenches, basement highs may be more easily sampled. The amount and depth of the thermal perturbations from the flexure and faulting on the incoming plate has important implications for the seismogenic zone [e.g., *Harris and Wang*, 2002].

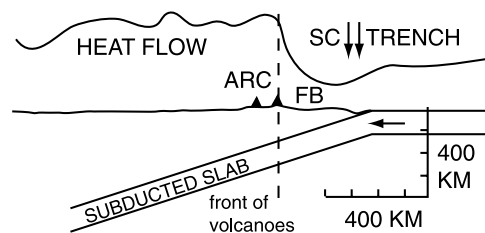
[4] The extent of the possible low heat flow should be controlled by the shape of the flexed outer bulge surface, which depends on the age of the incoming plate. Typically

uplift starts ~300 km from the trench axis [e.g., *Bodine and Watts*, 1979]. Earthquake mechanisms are consistent with flexure, indicating that the upper part of the plate (to ~20 km depth) is in tension and the lower part is in compression [e.g., *Chapple and Forsyth*, 1979; *Seno and Yamanaka*, 1996]. Normal faulting is typically observed from the trench axis to about 50–75 km seaward, often with increasing vertical displacements on faults closer to the axis, reaching a maximum displacement of ~400 m [*Masson*, 1991]. Some faults may extend ~20 km beneath the seafloor [e.g., *Ranero et al.*, 2003].

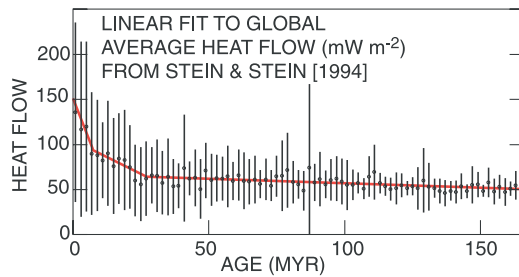
### 2. Heat Flow Data

[5] The hypothesis of low heat flow has yet to be tested because there are few detailed heat flow measurements seaward of ~10 km from the trench axis within the flexed zones [e.g., *Von Herzen et al.*, 2001]. Hence I examine ~2700 good quality measurements from global heat flow data for sites over a 500 km range from 300 km seaward of trenches to 200 km arcward of trenches, excluding island arc regions. The data are sparse: the total length of trench axes is ~51,000 km [*Bird*, 2003]. This yields, on average, about one value every 20 km of trench. Many data are concentrated in a few areas, with about half from the Juan de Fuca region. Hence rather than examine individual subduction zones, I bin all data by distance from the trench, an approach similar to the common one of examining heat flow with lithospheric age.

[6] The age of the subducting seafloor varies from ~0 Myr near Chile and northern Middle America to over 150 Myr for the Marianas. Hence, binning data by distance is unsuitable since global mean heat flow varies from ~150 mW m<sup>-2</sup> for the youngest seafloor to ~50 mW m<sup>-2</sup> for the oldest [*Stein and Stein*, 1992, 1994]. To remove the effects of the age dependence, I normalize heat flow values to measured global averages [*Stein and Stein*, 1994]. I characterize the average global heat flow ( $q$ , in mW m<sup>-2</sup>)



**Figure 1.** Heat flow variations near subduction zones. Heat flow is expected to decrease on the incoming plate approaching the trench. FB = forearc basin. SC = subduction complex. (Cross-section of the northeast Japan arc after *Uyeda* [1977].)



**Figure 2.** Measured heat flow means and standard deviations with oceanic crustal age from *Stein and Stein* [1994]. A 3-part linear fit is shown.

with age ( $t$ , in million years) by a simple 3-part linear representation:

$$q = 151 - 7.6 * t \quad t = 0 - 7.33 \text{ Myr}$$

$$q = 105 - 1.5 * t \quad t = 7.33 - 27.1 \text{ Myr}$$

$$q = 67 - 0.1 * t \quad t > 27.1 \text{ Myr}$$

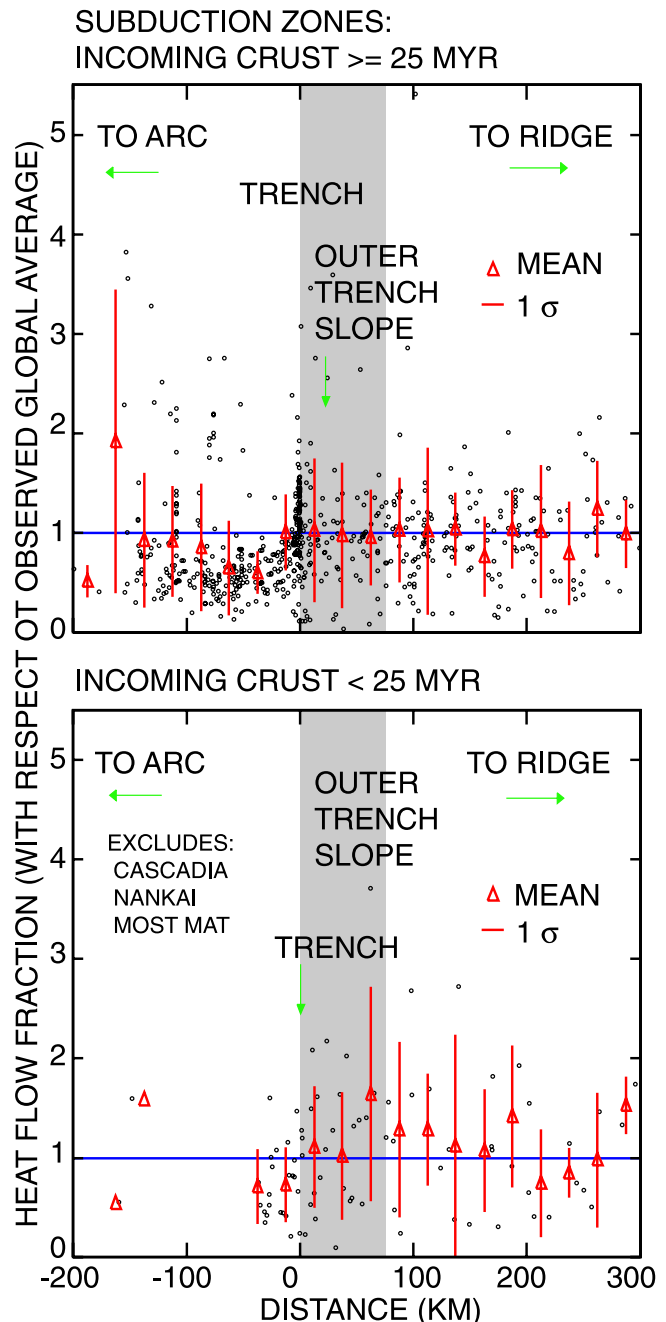
[7] This observed fit (Figure 2) is used rather than predictions from conductive cooling models because the measured heat flow for crust younger than 65 Myr is typically less than predicted due to hydrothermal circulation [e.g., *Stein et al.*, 1995]. I assume that the expected heat flow arcward of the trench is the same as for the crust entering the trench because the distance range to 200 km arcward of the trench corresponds to less than ~6 Myr age variation. This assumption should have little effect except perhaps for the youngest subducting crust.

### 3. Analysis

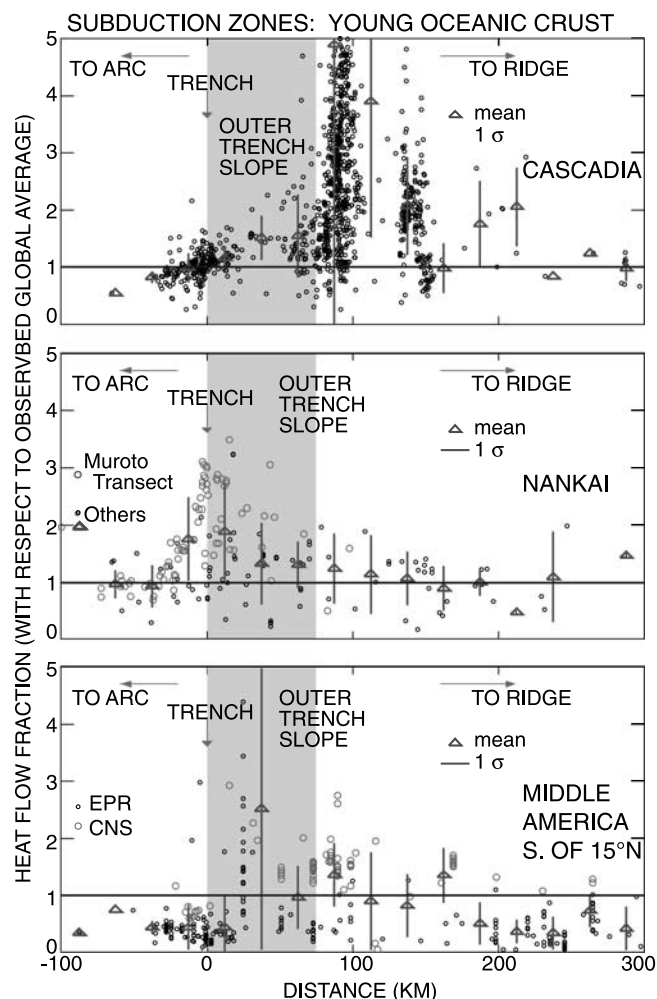
[8] Figure 3 shows the variation of the observed heat flow fraction (HFF-O), the measured value normalized by the linear fit to the observed mean heat flow for that age. These data do not support the suggestion that average heat flow decreases in the flexed incoming plate, especially in the outer trench slope, the region 0–75 km seaward of the trench axis where most faulting is observed. The scatter in these data about their means, measured by the standard deviation in the flexed region, is comparable to those for global data [*Stein and Stein*, 1994]. Data for lithosphere, older than 25 Myr (Figure 3, top) show essentially no variation in mean heat flow fraction with distance seaward of the trench. Patterns for subduction zones with young (<25 Myr) crust are more difficult to interpret (Figure 3, bottom). The sparse data (excluding relatively well-sampled regions discussed next) show a pattern similar to the older seafloor data.

[9] However, data from three subduction zones (Cascadia, Nankai, and Middle America Trench south of 15°N) with young incoming lithosphere show much greater variability over the 500 km range (Figure 4), although none have an overall lower HFF-O < 1 within the outer trench region. The Juan de Fuca plate subducting beneath Cascadia (Figure 4, top) has significantly higher heat flow than

similar-age crust (~1–8 Myr) elsewhere. Most high heat flow fractions, ~50–150 km seaward of the trench, are associated with the FlankFlux study area [e.g., *Davis et al.*, 1992]. The decrease in the HFF-O to ~1 near the trench probably results from thermal blanketing by thick sediments rather than trench slope processes. The well-sedimented Philippine plate subducting beneath Nankai has higher heat flow than typical for its ~22 Myr age [e.g., *Kinoshita and*



**Figure 3.** Heat flow fraction (HFF-O; measured with respect to observed global average for that age) with distance from the trench axis. Within the faulted outer trench slope, heat flow does not decrease. (Top) For older ( $\geq 25$  Myr) incoming crust. (Bottom) For younger (<25 Myr) incoming crust, excluding Cascadia, Nankai, and Middle America (south of 15°N) subduction zones.



**Figure 4.** Heat flow fraction (HFF-O, measured with respect to observed global average for that age) with distance from the trench axis for Cascadia (top), Nankai (middle), and Middle America south of  $\sim 15^\circ\text{N}$  (bottom) subduction zones. 223 points for Cascadia and 4 points for Middle America Trench with HFF-O > 5 are not shown.

Yamano, 1995] (Figure 4, middle). The highest values (HFF-O > 2) [Yamano *et al.*, 2000] are near ODP site 808/Leg 190 Muroto transect where a fossil spreading ridge is subducted.

[10] The  $\sim 24$  Myr Cocos plate subducting at the Middle America Trench south of about  $15^\circ\text{N}$  (Figure 4, bottom) has unusually low heat flow on East Pacific Rise (EPR)-formed crust and unusually high heat flow on Cocos-Nazca spreading center (CNS)-formed crust, extending  $\sim 700$  km seaward of the trench [Von Herzen and Uyeda, 1963; Fisher *et al.*, 2003] well beyond the flexed region. Neither the EPR-formed nor the CNS-formed sites show any overall clear decrease in HFF-O approaching the trench, but the former are more scattered. High heat flow (up to  $\sim 600$   $\text{mW m}^{-2}$ ; HFF-O > 5) occurs on a basement high  $\sim 25$  km from the trench axis [Fisher *et al.*, 2003] but 40 km away and 5 km from the axis, near the ODP Leg 170 sites, heat flow is quite low ( $\sim 10$   $\text{mW m}^{-2}$ ; HFF-O = 0.15) [Langseth and Silver, 1996]. Near here, heat flow measurements over normal

faults, in an area with  $\sim 400$  m of sediments overlying basement, show no evidence for fluid discharge [Fisher *et al.*, 2003]. This variation may reflect local hydrothermal circulation processes within the EPR crust rather than regional enhancement by the outer trench slope processes.

[11] I also examined heat flow arcward of trenches. Almost all subduction zones have data, but only a third have ten or more measurements both between 300–25 km seaward of the trench and 25–200 km arcward of the trench. Overall, the heat flow fraction on the arc side is lower ( $\sim 0.6$ ) than on the incoming plate for incoming crust older than 25 Myr (Figure 3, Top). This analysis excludes data within 25 km of the trench axis to avoid complications such as perturbations by fluid expulsion near the toe of the subduction complex. Although there is variability, individual subduction zones seem to behave similarly to the global average.

[12] The overall variation of heat flow fraction (Figure 3) may help to constrain thermal processes at those subduction zones for which there is little specific data. Expected heat flow is often not shown for subduction zone models. Predicted heat flow varies within and between both generic models [e.g., Bird *et al.*, 1975; Molnar and England, 1990; Eberle *et al.*, 2002] and those constrained by local measurements for subducted lithosphere [e.g., Hyndman and Wang, 1995; Von Herzen *et al.*, 2001; Harris and Wang, 2002]. Overall many models predict similar trends compared to the global average data.

#### 4. Discussion

[13] Although heat flow varies somewhat within and between subduction zones, mean heat flow fractions in the outer trench slope and flexed region are  $\sim 1$ , and not significantly different from typical oceanic lithosphere. Heat flow fractions within the outer trench slope for crust  $\geq 25$  Myr are slightly lower for non-accreting subduction zones compared to accreting ones [e.g., von Huene and Scholl, 1991]. However, this apparent difference results from 8 very low HFF-O values (out of 54) from 4 different non-accretionary subduction zones. These data also show no difference between ocean-ocean and ocean-continental subduction zones, and no clear trend as a function of age of the plate. Hence, they show no evidence for a decrease in heat flow associated with plate flexure and faulting or any significant alteration of the average thermal structure for the incoming plate. Given that faulting occurs and might increase permeability and thus hydrothermal circulation, why does heat flow within the outer trench slope seem unperturbed? I see two possible reasons for the non-observance of the heat flow anomaly.

[14] First, significant thermal anomalies may not be present due to a combination of factors including low amounts of heat transfer, short distances or rates of fluid flow, low driving forces, and insufficient time. Flow rates on the order of m/yr to km/yr may move significant amounts of heat and affect the outer trench slope region within 1.5 Myr, the time the plate spends in this region assuming a  $\sim 50$  mm/yr convergence rate. However, the actual time and space affected by fluid flow is probably significantly less. Fluid exchange between the basement and the water column occurs most easily for thin ( $< 50$  m) sediment cover, but most incoming seafloor has significantly more [e.g., von

Huene and Scholl, 1991]. At most subduction zones the offset from normal faulting is probably not enough to yield either bare rock or thin sediment cover to promote hydrothermal circulation.

[15] Second, there may be difficulty in distinguishing additional hydrothermal circulation from outer trench slope processes to that existing within the plate prior to flexure. The chemistry of the hydrothermal fluids, which reflects the fluid's path and history, may be useful in distinguishing these. In the outer trench slope, if crustal water advects deep in the igneous basement, the temperature estimated from the chemistry and heat flow may differ from that for shallow flow along sediment/basement interfaces typical of the crust before it flexes. Similarly, if water flow has been recently reestablished, then the water may be older than usually expected.

[16] In hindsight, it is interesting to speculate why it was thought that flexure and faulting would lower heat flow on the incoming plate near the trench. The idea seems plausible, and may have appeared consistent with data because many early heat flow studies across subduction zones were for the western Pacific, where mostly old crust is subducted. Because these studies were conducted before most old sea floor was dated from magnetic anomalies, the incoming plate's heat flow would have appeared somewhat lower than average heat flow elsewhere in the ocean basins.

[17] **Acknowledgments.** I thank A. Fisher, G. Sella, R. Von Herzen, and an anonymous reviewer for helpful comments. This research was funded by NSF grant OCE-0001941.

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