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Reply to comment by W. P. Schellart on "The thermal structure of subduction zone back arcs"

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[1] *Currie and Hyndman* [2006] documented the evidence that the majority of continental back arcs are uniformly hot with thin lithospheres over regional extents of hundreds of kilometers, even if where is no thermally significant extension. Using a number of independent observations, we showed that eight such current subduction zones have similar thermal regimes, with Moho temperatures greater than 800°C (35–40 km depth) and lithosphere thicknesses of ~60 km. The one exception, the Peru flat slab region of South America, supports our model explanation. We then presented the hypothesis that the elevated back-arc temperatures have a common mechanism: efficient transport of heat by vigorous thermal convection in hydrated, low-viscosity back-arc upper mantle.

[2] The paper was structured such that the observations indicating regionally high back-arc temperatures were separate and independent from our proposed model. The evidence for high uniform temperatures seems secure; the discussion is on the explanation. *Schellart* [2007] appears to agree that the back arcs included in our study are characterized by hot, thin lithospheres but does not agree with our interpretation of the underlying cause. His main criticisms are that (1) local tectonics, in particular extension, may account for the high temperatures in some areas, and (2) three-dimensional mantle flow and complex slab dynamics may produce elevated temperatures.

[3] We acknowledge, as stated in the original paper, that a number of site-specific processes may affect the thermal regime at each back arc. We also recognize that nearly all back-arc regions have undergone at least some past extension, as described by *Schellart* [2007]; notable exceptions are central Alaska and the northern Canadian Cordillera. The key question is whether or not this extension is the primary cause of the observed uniformly hot thermal regimes.

[4] *Schellart* [2007] argues that high surface heat flow at some back arcs is due to recent extension, including parts of the Sunda (Borneo) and Ryukyu (Korea) back arcs. We note that our compilation used a number of independent observational constraints on lithosphere temperatures, not just surface heat flow. Mantle temperatures determined using only surface heat flow data are highly uncertain, due to the point sampling and measurement uncertainties, and uncertainties in the thermal parameters used to calculate the geotherm. Other temperature constraints on upper mantle thermal structure include seismic velocities from refraction Pn and tomography, mantle xenolith thermobarometry, effective elastic thickness Te, etc. For each back arc, the upper mantle temperatures from all constraints are in good agreement and show no significant lateral variation on a regional scale. This is especially illustrated by the uniform low upper mantle seismic velocities for different back arcs [*Currie and Hyndman*, 2006, and references therein].

[5] Extension affects the thermal regime by locally decreasing lithosphere thickness and by inducing upwelling of hot underlying mantle. Modeling studies have shown that such extension should only affect lithosphere temperatures and surface heat flow within ~100 km of the extended region [*Morgan*, 1983; *Alvarez et al.*, 1984], and for continental crust, extension may actually decrease surface heat flow due to thinning of the crustal radioactive heat generation [*Waples*, 2001]. In addition, limited local extension should not significantly perturb the deep thermal region. For the back arcs in our compilation there is no evident upper mantle temperature increase in more strongly extended regions, suggesting that a more regional phenomenon is required to produce regionally elevated temperatures. We also note that extension can only occur if the lithosphere is sufficiently hot that it is weak enough to fail under available extensional stresses. A normal cool lithosphere is too strong to be deformed by plate tectonic forces [e.g., *Hyndman et al.*, 2005]. We suggest that back-arc extension is a consequence of high temperatures and associated weak lithosphere, and not the primary cause.

[6] *Schellart* [2007] also suggests a thermal role for a number of upper mantle dynamical processes, including along-margin mantle flow associated with a slab edge, slab retreat/advance, and slab break-off. We agree that each of these factors may affect the back-arc thermal regime in some locations. However, these are local phenomena. If they are thermally important, they should be evident in lateral variations in mantle seismic velocity and other deep temperature indicators. Lateral variations are not apparent in the current observational data.

[7] As stated in the original paper [*Currie and Hyndman*, 2006, paragraph 71], we do not rule out local factors in

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contributing to high back-arc temperatures at each subduction zone. Our interpretation that there may be a common primary mechanism is motivated by two key observations: (1) the uniformity of high temperatures on a regional scale within each back arc, and (2) the similarity in the thermal regime among the back arcs, each with its own tectonic history and local complexities.

[8] Our preferred explanation for the high back-arc temperatures and thin lithospheres is efficient heat transport into the back-arc region from outside the subduction zone by vigorous thermal convection in the upper mantle. This model is supported by observations of low viscosity in back arcs, 10^{19} Pa s or less [e.g., *Currie and Hyndman*, 2006, and references therein; *Freed et al.*, 2006]. Recent numerical modeling has shown that if the back-arc mantle has a low-viscosity, small-scale thermally driven convection should occur [e.g., *Honda et al.*, 2002; *Hirth and Kohlstedt*, 2003; *Honda and Yoshida*, 2005; *Arcay et al.*, 2005, 2006]. The obvious explanation for low back-arc upper mantle viscosity is hydration by water released upward from dehydration of subducting oceanic plate and entrained sediments. Both geophysical and geochemical data support back-arc upper mantles containing significant water, and laboratory studies show that the addition of water to the mantle dramatically decreases its viscosity [e.g., *Hirth and Kohlstedt*, 2003].

[9] In a region of flat slab subduction, such as Peru, there is no convecting mantle wedge and the thermal regime is cool. *Schellart* [2007] questions why there is no increase in temperature at the landward edge of the Peru flat slab region, 700 km from trench. A likely explanation is that at this distance the slab has lost most of its water through earlier dehydration [*English et al.*, 2003] and the overlying mantle is not sufficiently hydrated to induce vigorous convection. Other than regions with a flat subducting slab, we are not aware of any subduction zone with a cool back arc (i.e., thermal structure similar to a stable continental region).

[10] The geometry of back-arc mantle flow is poorly known; the thermal data only suggest vigorous convection. As noted by *Schellart* [2007], recent modeling studies have emphasized the importance of three-dimensional dynamics, but the thermal effects of these processes have not yet been quantified. An important conclusion from our work is that a simple pattern of laminar back-arc mantle flow at plate rates is insufficient to produce uniformly high back-arc temperatures on a regional scale. Subhorizontal flow will lose substantial heat as it travels, whether the flow geometry is slab-driven corner flow or along-margin flow associated with slab rollback or flow around a slab edge. To maintain regionally high back-arc temperatures, we have concluded that thermally driven, back-arc small-scale convection is required, and we look forward to the results of modeling studies and further observations that test this idea.

[11] In conclusion, *Schellart* [2007] has raised a number of points which highlight the dynamical nature of subduction zone back-arc upper mantle convection and resulting thermal regime, and the uncertainties on the interaction between a subducting plate and surrounding back-arc mantle. The recognition that back arcs have regionally uniformly hot lithosphere, as documented in our paper [*Currie and Hyndman*, 2006], is a critical constraint on subduction dynamics and one that must be addressed in future modeling studies.

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