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# Buoyancy rather than rheology controls the thickness of the overriding mechanical lithosphere at subduction zones

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**Abstract.** The thickness of Earth's mechanical lithosphere is poorly defined. To investigate whether rheology controls the thickness of the overriding plate's mechanical lithosphere in subduction zones, the thermal structure was modelled numerically assuming a temperature dependent mantle viscosity. It was found that the overriding lithosphere was ablated such that very high temperatures reached close to the surface near the apex of the wedge corner, leading to unrealistically high heat flow. Since temperature dependent rheology clearly does not control the thickness of the mechanical lithosphere, we suggest that it is instead controlled by buoyancy. The source of buoyancy we assume is compositional, e.g. buoyant crust. Two end-member models with crustal thickness of 10 and 70 km respectively were then undertaken, these had lower heat flow. This work supports the assumption of some earlier workers (e.g. Plank and Langmuir, 1988) who equated the mechanical lithosphere with the crust of the overriding plate.

## Introduction

The thermal field of a subduction zone is important for many reasons. These include controlling:- the location of a source region of magmatism (*Davies and Stevenson*, 1992; *Furukawa*, 1993; *Tatsumi et al.*, 1983), the heat flow at the surface, the velocity and attenuation of seismic waves passing through the mantle (*Zhao and Hasegawa*, 1993), the density of the mantle and therefore also the gravitational field and dynamics, and the depth extent of seismicity (*Tichelaar and Ruff*, 1993).

The thickness of Earth's lithosphere depends on the property under consideration, e.g.: thermal, seismic, mechanical, elastic or chemical. We will define the mechanical lithosphere to be that part of the lithosphere that is effectively rigid on the time scale of interest.

The thickness of the mechanical lithosphere is important for the thermal models of subduction zones, since heat transfer must be by conduction through any rigid layer, therefore regions with thicker mechanical lithospheres will be cooler. Some workers have made the thickness of their mechanical lithosphere (*Hsui et. al.*, 1983) the thickness of the thermal lithosphere (estimated at around 100 km, *Stein and Stein*, 1992). Others have used much smaller values, e. g. 35 km (*Honda*, 1985) and 40 km (*Davies and Stevenson*, 1992). The thickness is poorly understood.

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Most of the previous kinematic thermal models of subduction, similar to the type used here, have used a constant mantle viscosity (*McKenzie*, 1969; *Hsui et. al.*, 1983; *Davies and Stevenson*, 1992). Laboratory studies of the rheology of mantle-like rocks and minerals, have revealed that, at high temperatures and pressures they deform by creep (*Ranalli*, 1995) like a viscous fluid whose viscosity is strongly dependent on temperature.

We will investigate the possibility that the temperature dependent rheology of the mantle controls the thickness of the overriding lithosphere. The concept is that the mechanical lithosphere might be thick before subduction, but is thinned quickly by thermal ablation to a lower steady-state thickness during subduction. We will model the mantle, including the lithosphere, as a temperature dependent viscous fluid and self-consistently evaluate the thickness of the mechanical lithosphere.

Previous workers who have studied the effect of using a temperature dependent viscosity in their thermal models include, *Andrews and Sleep* (1974), *Bodri and Bodri* (1978), *Hsui and Toksöz* (1979), *Honda* (1985), *Furukawa* (1993), *Kincaid and Sacks* (1997) and *Olbertz* (1997). None have focused on the question of the thickness of the mechanical lithosphere.

## The Numerical Model

The steady state thermal and velocity fields were calculated for a kinematic model of subduction using a modified version of a two dimensional finite element code developed by *King et. al.* (1990). The code solves three equations; the conservation of mass (or continuity) equation, the conservation of momentum (or Stokes) equation and the conservation of energy (or heat) equation.

The equations were solved in non-dimensional form. We assumed that the non-dimensional temperature, $T' = 0$ represented a temperature of 0 °C and $T' = 1$ a temperature of 1350 °C, i. e. $T = \Delta T T'$, where $\Delta T = 1350$ °C.

The viscosity of the mantle was assumed to be temperature dependent and to obey the following non-dimensional viscosity law:

$$\eta(T') = \eta^* \exp\left(\frac{E^*}{T'+T_o} - \frac{E^*}{1+T_o}\right) \qquad (1)$$

where $\eta^*$ is the normalised pre-exponential viscosity, $\eta(T')$ is the effective viscosity, $T'$ is the dimensionless temperature, $E^*$ is the activation energy divided by $R\Delta T$, where R is the gas constant , $\Delta T$ is the temperature scaling factor and $T_o$ is the temperature offset (0.2022). The second term in the exponential is a scaling factor on $\eta(T')$, such that $\eta(1.0) = \eta^*$.

The value of the activation energy can be varied, and this alters how sensitive the viscosity is to temperature. We assumed

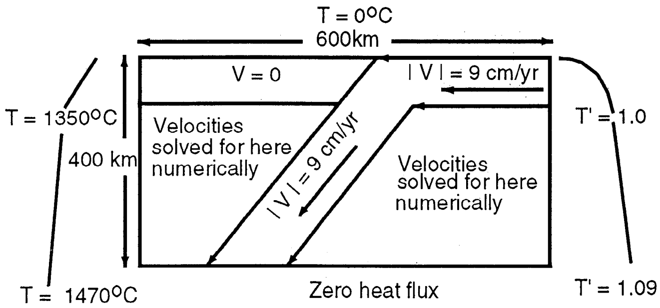


**Figure 1.** A figure showing the velocity and temperature boundary conditions applied to the models. In the models of figure 2, the v=0 condition of the overriding plate is only applied at the surface.

$E^*$=45.4, i.e. E= 510 kJ/mol, the activation energy for dry olivine, (*Goetze and Evans*, 1979), which is the main mineral of the upper mantle. Simulations were also undertaken with $E^*$ = 22.7, and the results were nearly identical to those presented here.

## Boundary and Starting Conditions

In our models we define the mechanical and thermal lithosphere separately. The thermal lithosphere was modelled via the side boundary conditions. On both sides of the model the thermal boundary layer was assumed to be 100 km thick with a base temperature of $T' = 1$. On the overriding plate side, it was assumed that vertical heat transfer was practically by conduction alone, so the boundary condition was a linear temperature gradient with depth, going linearly from $T' = 0$ at the surface to $T' = 1$ at 100 km depth. For the subducting oceanic lithosphere, the temperature profile of a 40 million-year-old lithosphere was modelled using the plate model of *Stein and Stein* (1992). Below this, on both sides of the model, an adiabatic temperature gradient of 0.4 °C/km was assumed. The boundary condition at the bottom of the model was forced to have zero heat flux.

Subduction was forced via the velocity boundary conditions by pinning the velocities in the subducting slab to the chosen convergence velocity, in this case 9 cm/year. Initially, we just pinned the top of the overriding plate to be stationary and allowed the thermal structure of the model to define the thickness of the mechanical lithosphere. The thermal and velocity boundary conditions applied to the models are illustrated in figure 1.

*Bodri and Bodri* (1978) investigated the effect of time on their temperature dependent viscosity models. In order to compare our models with theirs and to investigate how our models evolved with time, we used the following starting temperatures. The top 100 km of the model had a temperature of $T' = 0$ at the top and $T' = 1$ at its base and a linear temperature gradient to represent the thermal lithosphere. Below this, the mantle was prescribed an adiabatic temperature gradient of 0.4 °C/km. The grid was 96 elements wide by 64 elements high.

## Results

Figure 2a and 2b show the thermal field for the original model, 1 and 12 Myr after the initiation of subduction. The position of the volcanic front (assumed to be 90-160 km above the subducting slab, *Gill*, 1981) and the mechanical lithosphere (44km thick) of the subducting plate are indicated. It can be seen that ablation of the wedge corner occurs soon after subduction commences and continues until steady state is reached (approximately 12 Myr after the initiation of subduction). *Bodri and Bodri* (1978) observed a similar effect. Two models identical to our original model were run to steady state on grids of double and half the original resolution. The resulting thermal fields were almost identical to those in the original model. Only small temperature differences were noted, and only in the apex of the wedge corner close to the slab, not in the region suffering ablation.

The steady state thermal field in figure 2b reveals that, using a temperature dependent mantle viscosity focuses very high temperatures close to the surface near the trench. The velocity of the overriding plate far from the trench remains close to zero down to depths below 100 km. Approaching the trench, the thickness of this rigid layer decreases rapidly, allowing high temperatures to reach close to the surface near the trench.

To demonstrate that such high temperatures at such shallow depths are unreasonable we have evaluated the surface heat flow. The heat flow at the surface of the model was calculated by multiplying the temperature gradient at the surface by the thermal conductivity of the crust (assumed to be 2.5 W $m^{-1}$ $°C^{-1}$). The temperature gradient at the surface of the model was calculated using the temperature difference between the first and second row of nodes and the distance between them.

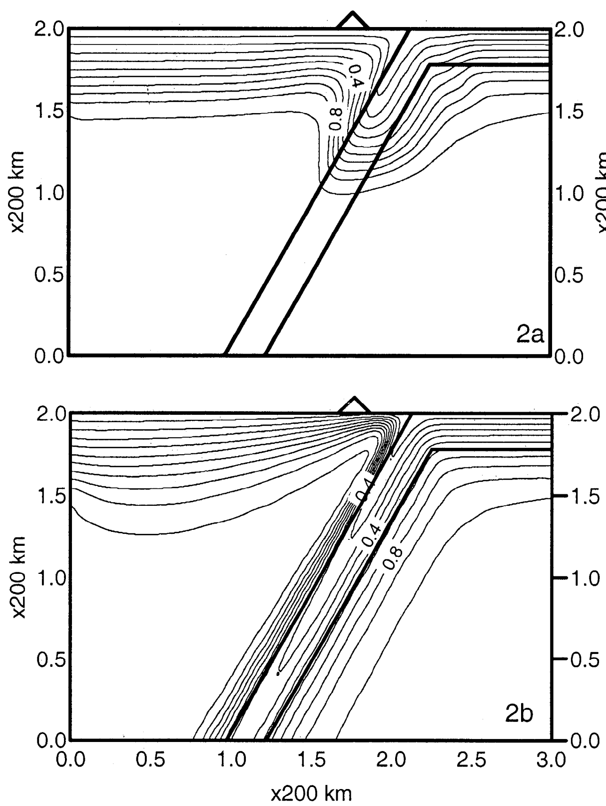


**Figure 2.** The thermal structure of the original model, (a) 1 and (b) 12 Myr after the initiation of subduction. The outline of the 40 km thick subducting slab is shown; while the probable location of the volcanic arc is represented by a small triangle at the surface. The contour lines are in non-dimensional temperature, spaced 0.1 apart. $T'=1$ was assumed to equal $1350^0C$.

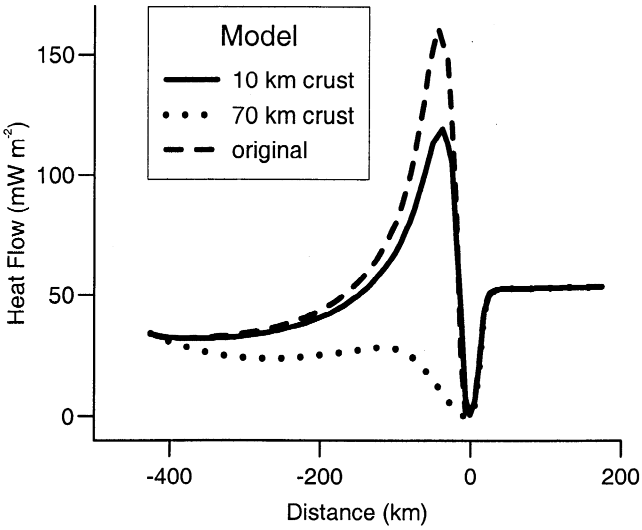


**Figure 3.** The heat flow at the surface of the original model and the 10 km and 70 km crustal thickness models.

Figure 3 shows the resulting heat flow for the steady state thermal field in figure 2. Heat flow profiles measured at subduction zones generally have a broad peak that coincides with the position of the volcanic front (*Gill*, 1981). In addition to the broad peak, spikes of high heat flow are measured in localised regions due to the effect of shallow magmatic intrusions, but such mechanisms were not included in our model. In addition our model does not include groundwater flow, erosion, and radioactivity. Therefore our modelled heat flow is a lower bound which should only be compared to the broad background level. The peak of the predicted heat flow (170 mW m$^{-2}$) is far greater than the background level observed at subduction zones and shows that this model is unreasonable.

This model has failed to give a sensible value for the thickness of the mechanical lithosphere. We therefore conclude that temperature does not control the thickness of the mechanical lithosphere of the overriding plate at subduction zones through temperature dependent viscosity. The thickness of the mechanical lithosphere could instead be related to compositionally controlled variations in rheology or buoyancy. A logical and reasonable suggestion is that the mechanical lithosphere is the crust. We have modelled two further cases; one with a 10 km rigid (stationary) upper layer on the overriding plate, and the other with a 70 km rigid layer. The thickness of these rigid layers was chosen to represent the end members of oceanic crust and thickened continental crust respectively. The thermal fields for these models, run to steady state, are shown in figures 4a and 4b respectively. The position of the volcanic front (125 ± 34 km above the surface of the subducting slab, *Gill*, 1981) and the mechanical lithosphere are indicated on each of the figures. Due to the buoyant crust the induced mantle flow cannot bring high temperatures right to the surface. Instead, high temperatures are brought up to the base of the crust. Figure 3 shows that increasing the thickness of the crust decreases the heat flow at the surface, producing more plausible background levels.

## Conclusions and discussion

The models presented here demonstrate that subduction zone mantle wedge with temperature dependent viscosity does not sensibly define the thickness of the rigid mechanical lithosphere. Our initial model, with no buoyant crust, allows unreasonably high temperatures to reach close to the surface, near the apex of the wedge corner, leading to very high heat flow. This is the result of very effective thermal ablation. We note that the isothermal, dynamic models of *Tao and O'Connell* (1992) also demonstrate viscous ablation of the overriding mantle demonstrating the ubiquity of this process. The thermal ablation results from the initial corner flow velocity field having a slight surfaceward component (along the radial line making a downward angle of ~ 25° at the wedge corner), which brings deeper mantle to shallower depths. Since the deeper mantle is hotter, and the mantle is advected sufficiently quickly such that conduction does not have time to cool it significantly, this flow locally increases the temperature. Due to the temperature dependent viscosity this region then has lower viscosity and the mantle can flow in even more easily increasing the temperature further. This leads to a strong feedback, and the process is only limited when cooling of the flow by conduction from the surface is significant. The reason why this process is more effective than the modelled erosion of lithosphere by impinging mantle plumes (*Davies*, 1994), is that the flow in this case is not a stagnation flow. The mantle flows up into the ablated region from the back arc side, and down on the trench side, driven by the entrained flow due to the subducting slab. The flow therefore never stagnates, and hence can more effectively advect heat and ablate the lithosphere.

This leads us to suggest that the thickness of the mechanical lithosphere above the mantle wedge is strongly controlled by compositional buoyancy and not rheology; and that this

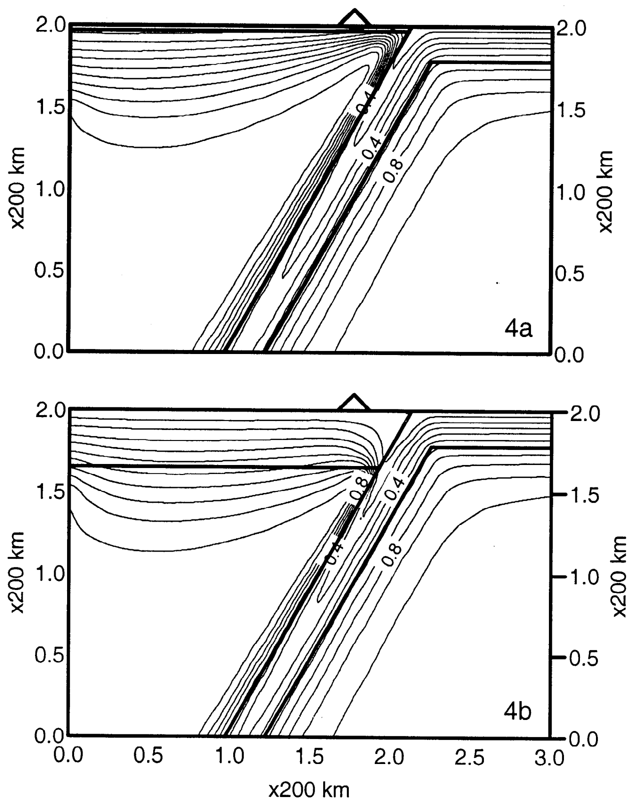


**Figure 4.** The steady state thermal field for a model with (a ) 10 km, (b) 70 km of rigid buoyant crust. The lithospheres are highlighted. The probable location of the volcanic arc is represented by a small triangle at the surface. Contour lines are in non-dimensional temperature, spaced 0.1 apart.

thickness is closely related to that of the crust of the overriding plate. This has been alluded to in a single sentence by *Honda* (1985), and was implicit, but not stated explicitly in *Furukawa* (1993). Modelling a buoyant crust reduces the broad background heat flow peak to a more realistic value, but does not affect its position, which is closer to the trench than the predicted volcanic front. It is likely that slab shape, which we have ignored here, is a major factor in determining the position of the heat flow peak. Studies involving variable slab shape with temperature dependent rheology also lead to unrealistically high heat flow for models with a mechanical lithosphere defined solely by temperature dependent viscosity (*Rowland*, 1997). It is plausible therefore, that the thickness of the mechanical lithosphere, which controls the shallow thermal structure of subduction zones, may be equivalent to the thickness of the crust.

In our models where the mechanical lithosphere is based on crustal thickness, the mechanical lithosphere was made rigid. We have therefore not demonstrated that the crust is sufficiently buoyant to resist being advected downwards by the induced flow. This is an issue for further work, but studies of advection of crust by mantle flow in a different tectonic environment (*Lenardic and Moresi*, 1999) suggest that crust will probably be stable over the lifetime of a subduction zone (<200Myr).

Our model assumes that the overriding plate has a viscous temperature dependent rheology, in reality at cold temperatures we can expect brittle failure. Due to the cold temperatures of the mega thrust, the nearby overriding plate in the model is effectively rigid and hence with the kinematic boundary conditions we mimic well the thrusting. We note that if the megathrust is hotter it will deform ductilely, and this is captured by our temperature dependent rheology.

*Plank and Langmuir* (1988) found a correlation between crustal thickness and the major element chemistry of parental magma at subduction zones. In explaining this correlation they assumed that the thickness of the crust can be equated to that of the mechanical lithosphere of the overriding plate at subduction zones. This work suggests that their assumption could be reasonable.

The thermal ablation of the overriding lithosphere suggests that it has been reasonable to assume a thin lithosphere beneath the volcanic front (*Honda*, 1985, *Davies and Stevenson*, 1992). The significance of this for subduction zone magmatism is well illustrated by *Furukawa* (1993). Such hot mantle so shallow in the mantle wedge possibly provides the buoyancy to counter the gravity signal of the subducting slab, and explain the paradox of why the gravity signature of the dense slab is not observed.

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