RHEOLOGICAL WEAKENING OF SUBDUCTED SLABS DUE TO THE PERSISTENCE OF METASTABLE OLIVINE DOWN TO 600 KM DEPTH

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1. Introduction

It has been hypothesized that deep earthquakes in subducting slabs might result from transformational faulting in cold peridodite wedges containing metastable olivine to depths of more than 600 km. The slab instability arises then from sudden failure by localized superplasticity in thin shear zones where the metastable host mineral transforms to a denser phase (Kirby *et al.*, 1991; Kirby *et al.*, 1996). One pre-supposition of this hypothesis is that the untransformed cold interior of fast subducting slabs is acting as a stress-guide for the slab down to 600 km depth. The viscosity of a cold (olivine) wedge extrapolated to low temperatures of about $\sim$850 K is indeed extremely high and no deformation seem to be possible on the geological timescale. On the other hand, seismic tomography reveals that slab bending seems to be possible in some of the western Pacific subduction zones (van der Hilst *et al.*, 1991; van der Hilst, 1995). Hence, mechanisms for the rheological weakening of subducted slabs are called for.

One mechanism that has been suggested is the weakening due to the grain-size reduction as a result of the olivine to spinel transformation (Vaughan and Coe, 1981; Rubie, 1984; Ito and Sato, 1991). The distinct possibility of a grain-size reduction accompanying this transformation was indeed indicated in several kinetic high-pressure experiments (Vaughan and Coe, 1981; Burnley *et al.*, 1991; Brearley *et al.*, 1992; Fujino and Irifune, 1992).

More recently, an attempt was made to quantify the extent of grain-size reduction under subduction conditions, based on a scaling model of nucleation and growth (Riedel and Karato, 1996). The estimate of the degree of grain-size reduction was done using available experimental data on the olivine-spinel transformation kinetics as reviewed, e.g., by (Rubie and Ross, 1994; Kirby *et al.*, 1996; Karato, 1997).

2. Thermal slab structure and transformation kinetics

Since kinetic processes depend critically on temperature, we need to know the thermal structure of subducting slabs. It depends primarily on the subduction rate and the age of the subducting oceanic lithosphere, both of which vary greatly for different subduction zones (Molnar *et al.*, 1979; Lay, 1994). Minimum predicted slab temperatures can be as low as 500 ^{o}C at the top of the in the transition zone.

A typical thermal profile of a subducting slab is shown in Fig. 1: Isotherms are advected downwards dependent on the plate thickness and subduction speed and finally lead to the formation of a metastable olivine wedge inside of a slab when the critical isotherm at $\sim$830 K crosses the equilibrium phase boundary between olivine and β-spinel at 410 km depth.

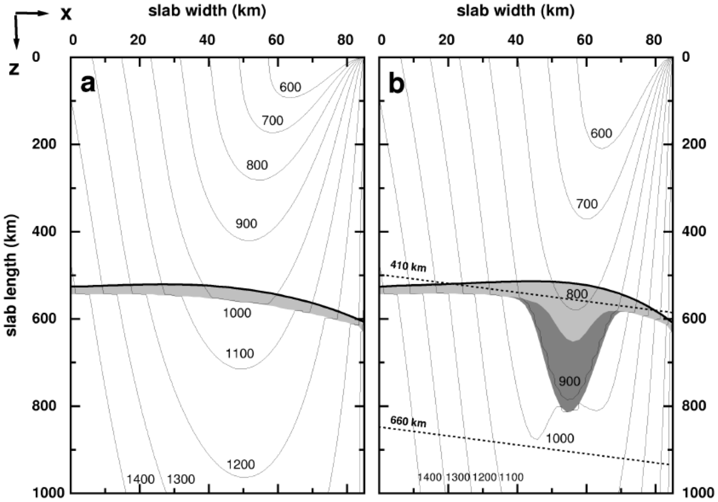

Figure 1. Thermal profiles (in K) of a slab with a thickness of 85 km according to (McKenzie, 1969): a) v_{slab} = 4 cm/yr, b) v_{slab} = 10 cm/yr. The metastability region of olivine (grey) and the region with mixed olivine-spinel aggregates (dark grey) are shown.

3. Grain-size evolution in a subducting slab

The main process that controls the grain-size of the product phase during a first-order phase transformation is competition between nucleation and growth. Briefly, grain-size is small when nucleation dominates over growth, and vice versa. Theoretical considerations show (Riedel and Karato, 1996) that the average grain-size is given approximately by the so-called *Avrami length*, either in 3D (δ_{Av}, grain size after completion of the transformation), or in 2D (δ_{Av}^{2D}, grain diameter at the formation of continuous films). These scaling parameters are defined as (Y - growth rate, I^V, I^B - homogeneous resp. grain-boundary nucleation rate)

$$\delta_{Av} = [I^V/Y]^{-1/4}, \qquad \delta_{Av}^{2D} = [I^B/Y]^{-1/3}, \tag{1}$$

In Fig. 2, we have plotted the numerically calculated spinel grain-sizes according to eq. (1) for a slab with varying thickness (60–100 km) on the basis of the thermal model shown in Fig.1. This plot indicates that under subduction zone conditions a dramatic grain-size reduction up to 4 orders in magnitude is possible when slab temperatures reach values well below 900 K, as a result of the metastable persistence of olivine in peridotite.

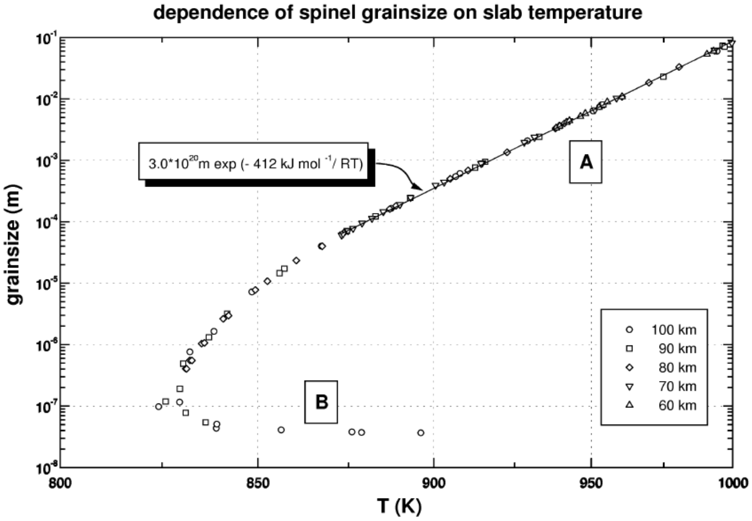

Figure 2. Dependence of spinel grain-size (logarithmic scale) on slab temperature (reciprocal scale). Above 900 K, there is an Arrhenius dependence with an apparent "activation energy" of about 412 kJ/mol (branch "A"). Within the metastable wedge, the apparent "activation energy" for spinel grain-size can be negative (branch "B").

Upon completion of the olivine-spinel transformation, spinel grain-size will be further controlled by grain-growth. The grain-growth kinetics is also very temperature sensitive: it is slow at low temperatures. Therefore, when a phase transformation occurs in a cold slab, any significant grain-size reduction will be kept for a relatively long time. Thus the cold slab interior will tend to have a weaker strength when a phase transformation affect its rheology through grain-size reduction. In Fig. 3, we illustrate the two main effects of the phase transformation, the thermal feedback due to the release of latent heat (Däßler *et al.*, 1996) and the kinetic grain-size reduction, for the case of a slab of 85 km thickness shown in Fig. 1b.

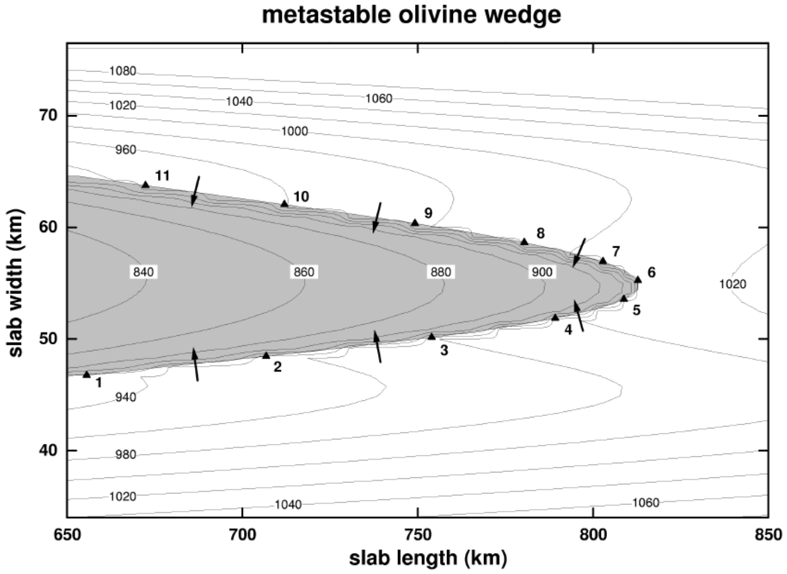

Figure 3. Spinel grain-size (given in Table 1) and temperatures (in Kelvin) along the cold olivine wedge of a fast subducting slab. Arrows indicate large thermal gradients.

TABLE 1. Spinel grain-size (in μm) at the triangle points of Fig.3

1	2	3	4	5	6	7	8	9	10	11
5.01	2.76	0.43	0.23	0.10	0.08	0.07	0.08	0.12	0.19	0.68

The formation of a continuous film of very fine-grained (sub-micron) spinel around the olivine grains in peridodite is very likely - at a certain stage of the transformation (critical volume fraction of spinel ~1% to 10%, depending on the p, T-conditions in the slab) - related to a change of the creep mechanism of the whole slab material. The dominant deformation mechanism of the cold slab core will then change from dislocation creep to diffusion creep, and deformation will occur predominantly at shear zones along the olivine grain boundaries, resulting in considerable rheological weakening of the slab interior of fast subducting slabs. Both the degree of weakening due to grain-size reduction and the extent to which the weakened state lasts depend critically on slab temperatures. Based on the well-known deformation laws for olivine (Ashby and Verrall, 1977; Goetze and Evans, 1979) and available data on spinel creep (Vaughan and Coe, 1981), we have estimated the resulting strength profile of slabs (Riedel and Karato, 1997). Taking into account the two combined effects of latent heat release and grain-size reduction, we found that

(i) the strength of slabs will have unusual temperature dependence through the temperature dependence of grain-size and that
(ii) a subducting slab has a complicated rheological structure containing a weak region near the tip of a cold slab.

Both observations contradict to the conventional picture of cold slabs that they should be mechanically stronger than their surroundings (Turcotte and Schubert, 1982; Wortel and Vlaar, 1988). The results cast some doubts on the capability of cold slabs to sustain and transmit higher stresses to greater depth.

4. Discussion

The present results provide also some insight into the possible mechanisms of deep earthquakes. Deep earthquakes are believed to occur as a result of instability of deformation in the ductile regime, and it has been argued that deep earthquake activities are related to the transformation of metastable olivine to modified or spinel phase (Green and Burnley, 1989; Kirby *et al.*, 1991). The nature of instabilities associated with the olivine-spinel transformation appears to be fundamentally different between the warm and cold branches of the kinetic phase boundary (branches “A” and “B” shown in Fig. 2). Our results suggest that instabilities will occur only when the transformation occurs in the cold branch “B”. The effects of grain-size reduction to cause softening and hence instability will be important only in the cold branch because significant grain-size reduction occurs only at relatively low temperatures.

Checking the applicability of the “standard” thermal assimilation model (Wortel, 1982; Wortel and Vlaar, 1988) for the occurence of deep earthquakes with seismological observation, Kirby (1995) found that variations of maximum intraslab earthquake depths with slab thermal maturity (the thermal parameter) are too complex for the description with this simple model. Instead, he and other authors argued (see e.g. (Bebout *et al.*, 1996)) that the metastable persistence of olivine may cause a nonlinear declination of deep earthquakes depths in dependence of the thermal parameter. Here, we partly confirm this hypothesis by plotting the location of the metastable olivine wedge in the coldest part of subducted slabs vs. the thermal parameter, Fig. 4.

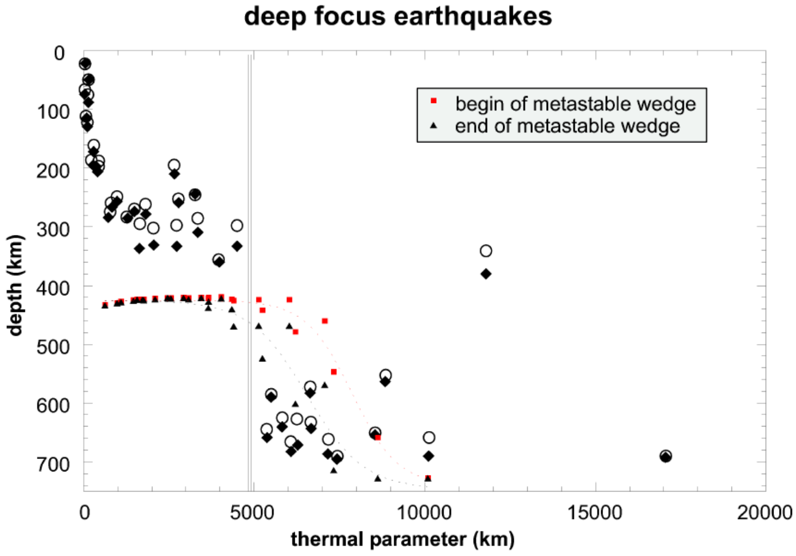

Figure 4. Depth of metastable wedge vs. slab thermal maturity for different slab thicknesses (60-100 km) and different slab velocities (4, 7, and 10 cm/yr). Also shown is the compiled data by Kirby (Kirby, 1995) of maximum (circles) and next maximum (triangles) intraslab earthquake depths. Note the reasonably good correlation of both plots.

Since there are still large uncertainties in the kinetic parameters underlying the thermo-kinetic model, the quantitative details of the size and location of the metastable olivine wedge should be taken with caution. Despite of this, there seems to be a quite reasonable correlation of the geometry of the metastability region with the depth of the deepest earthquakes in several subduction zones.

5. Acknowledgements

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