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Constraining kinetics of metastable olivine in the
Marianas slab from seismic observations and dynamic
models

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Abstract

Transformation kinetics associated with the presence of a metastable olivine wedge in old and fast subducting slabs has been the subject of many studies in the last years. Even with improvements in kinetics models, many of the parameters are still not well constrained. In particular, there is no consensus on the blocking temperature that could inhibit the transformation from olivine to spinel.

Recently, based on anomalous later phases in the P wave coda and differential P wave slowness, a wedge of metastable olivine was detected in the Marianas subduction zone, that is approximately 25 km wide, at a depth of 590 km and is truncated at 630 km.

In this work, a thermomechanical model was used to mimic the subduction in the Marianas and try different blocking temperatures for the olivine/spinel transformation. The model includes, among other features, non-linear elasto-visco-plastic rheology based on laboratory data, phase transformations, latent heat, proper coupling between stress and thermal state of the slab and force

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balance of the system.

The results show a positive correlation between the blocking temperature, depth of the wedge and its distance from the trench (or subduction angle). We compare these results to the situation in the Marianas and suggest that a blocking temperature for the olivine/spinel transformation of approximately 725°C would be the most likely.

The volume of the wedge presents some oscillations that we relate to a run-away effect of the transformation kinetics in the mantle transition zone. Namely, the interaction between latent heat release and the advection of the isotherms due to the subduction velocity.

The inclusion of shear heating in the model was fundamental to modelling such a subduction zone. Without shear heating, the slab shows a higher level of internal stress and the necessary bending to mimic the Marianas subduction zone cannot be reached.

Keywords: Metastable Olivine, Numerical modelling, Marianas, subduction

1. Introduction

The thermal structure of a subducting slab depends on many factors, such as subduction velocity, age, and angle of subduction, among others. When the slab reaches the olivine/spinel phase boundary, the expected minimum temperature could be as low as $\sim 550^{\circ}\text{C}$ if the slab is old and subducts fast enough (Riedel and Karato, 1997).

A few decades ago, Sung and Burns (1976) noted that a very cold core in the slab at this depth could imply a metastable persistence of olivine deeper than the expected depth of about 400 km. The existence and evolution of this metastable regime of olivine was studied by many authors with different approaches (see for instance Riedel and Karato, 1997, Karato et al., 2001, and references therein). Also, its observation in nature was greatly improved in the

last years (e.g. Koper and Wiens, 2000, Vidale et al., 1991) by means of better techniques and resolution.

Despite the existent reaserch into the dynamics of the olivine/spinel transformation, the blocking temperature under which olivine cannot transform to spinel remains poorly constrained.

In particular, Kaneshima et al. (2007) observed anomalous later phases in the P wave coda and differential P wave slowness for some deep earthquakes inside the subducted Pacific Plate in Northern Marianas. This localized seismic anomaly was interpreted as a wedge of olivine (α) surrounded by ringwoodite (γ). The wedge seems to be approximately 25 km wide and extends down to a depth of 630 km. Shallower into the upper mantle, the deeper structure could be constrained by the data only down to 580 km. Above this depth, they suppose that the wedge extends continuously upwards to the upper mantle. Below this structure, the depression of the spinel/perovskite transformation boundary seems to be ~ 30 km.

In this work, we present a fully dynamic thermomechanical model, which includes proper interaction and feedback between thermal and stress state of the slab, force balance, phase transformations, shear heating and latent heat, among other processes.

We reproduce a subduction system with a similar tectonic setting as the one in the Marianas in order to be able to constrain the blocking temperature of the olivine/spinel transformation and to study the effect of the metastable olivine wedge in the system as a whole.

2. Previous studies

Rubie and Ross (1994) studied the evolution of a metastable olivine wedge on slabs and its influence on subduction dynamics by means of a transforma-

tion kinetics model coupled with a vertical kinematic subduction model. They found that, in cold slabs that subduct fast, transformation is not influenced by nucleation. Rather, it is mainly controlled by growth rate, preserving the metastability for more than 100 km below the expected 410 km phase transformation boundary.

Rubie and Ross (1994) also show the strong influence of latent heat on the kinetics of the system, which produces a runaway reaction by which the time and space needed for the transformation reduces to a few kilometres in the descending path of the slab (see Fig. 10b in Rubie, 1984). They conclude that, in order to improve the models and evaluate better the force balance of the slab, it is necessary to couple properly the thermal and dynamic mechanical models.

Riedel and Karato (1997) used a thermal analytical model from McKenzie (1969, 1970) coupled to a phase transformation kinetics model to get a strength profile of a subducting slab. They concluded that the subducting slab contains a weak region below the tip of the metastable olivine wedge. This weakness is related to the grain size reduction during the olivine-spinel transformation. In the case of a slab subducting at 10 cm/yr, they calculated that the wedge of metastable olivine could reach 593 km of depth if the slab is 85 km thick and even down to the lower mantle if its width is 100 km. An improved version of this model was presented by Karato et al. (2001) to study the strength of the subducting slab in relation to the deformation due to the interaction with the 660 km boundary.

Schmeling et al. (1999), and later Tetzlaff and Schmeling (2000), used a thermomechanical model coupled with a transformation kinetics model to study the influence of a metastable olivine wedge on subduction velocity. They used free subduction models without elasticity. Due to the initial conditions of the experiments and the lower limit on viscosity value (10^{21} Pa.s), the subduction

velocity is many times slower than that observed in the region studied in this paper. They assumed that transformation of olivine/spinel takes place between 600°C and 700°C linearly. However, they also recognized that the transformation is actually much faster than linear and that the temperatures are poorly constrained.

Their results showed that in slabs older than 70 My a metastable olivine wedge should be present. Moreover, they concluded that in slabs older than 100 My, the wedge should be smaller than 5000 km² in cross section and that the cooling half-space model is not applicable. Finally, they concluded that the thermal parameter, defined as

$$\phi = V_z \cdot A_{sl} \quad (1)$$

V_z being the vertical subduction velocity and A_{sl} the age of the slab, would be limited by the presence of a metastable olivine wedge. They claimed that the thermal parameter will not be greater than 10.000 km because the metastable olivine strongly affects the subduction dynamics, reducing the velocity of subduction (V_z) and therefore the thermal parameter (ϕ) as well. This was called “the parachute effect” by Kirby et al. (1996). However, the authors recognized that the special cases of the Marianas and Tonga do not conform to these results as the thermal parameter is much higher than this limit.

Tetzlaff and Schmeling (2009) focused on the interaction between the metastable olivine wedge and the spinel/perovskite transformation boundary. They detected three different phases in what they called “velocity-depth loops” of the wedge. During the first phase, velocity reduces due to the buoyancy of the wedge, while in the second phase, the volume of the wedge is reduced because of the slow velocity. Finally, in the third phase, velocity and wedge volume increase again due to the slab-pull. They also studied the influence of depth-

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9 dependent latent heat in comparison with a constant latent heat in the maxi-
10 mum depth reached by a metastable olivine wedge. They concluded that the
11 inclusion of depth-dependent latent heat can reduce the maximum depth of a
12 metastable olivine wedge ~ 50 km. Their model is similar to the one used in the
13 previous work (Tetzlaff and Schmeling, 2000), but there were some differences.
14 For example, they changed the blocking temperature to 650°C and improved
15 the transformation kinetics model and the latent heat release calculation.
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18 Billen (2010) studied the dynamics of slabs in mantle transition zone by cou-
19 pling a similar thermomechanical model with a transformation kinetics model
20 based on Mosenfelder et al. (2001). The results were based on free dynamic sub-
21 duction experiments where elasticity was not considered. Regarding metastable
22 olivine and the combined buoyancy of the slab due to the different phase transi-
23 tions, she concludes that for slabs of 80 My, the positive buoyancy of metastable
24 olivine is unlikely to influence the subduction velocity even in a minor way. The
25 cause is the small amount of metastable olivine in the slab, with a wedge as
26 narrow as ~ 25 km. This observation does not conform completely with the
27 results of Tetzlaff and Schmeling (2009). One possible explanation is the dif-
28 ferent parameters that these two studies used for the kinetics model, that led
29 to different growth rates. Also, in Billen (2010) the age of the slab is slightly
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45 **3. Numerical method and model setup**

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48 In this study a coupled elasto-visco-plastic thermomechanical numerical model
49 based on code SLIM-3D (Popov and Sobolev, 2008) was used to run all experi-
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53 The finite element method was used to solve the governing equations. Namely,
54 the conservation of momentum
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$$\frac{\partial \sigma_{ij}}{\partial x_j} + \rho \vec{g} = 0 \quad (2)$$

and conservation of energy

$$\rho C_p \frac{DT_P}{Dt} = \kappa \nabla^2 T_P + r \quad (3)$$

Here, σ_{ij} is the Cauchy stress tensor, ρ is density, $\vec{g}$ is gravity acceleration, C_p is heat capacity, κ is thermal conductivity, $\frac{D}{Dt}$ is the material time derivative, T_P is the potential temperature and r is the volumetric heat sources.

Adiabatic heating, which is approximated as a linear function depending on depth ($0.3^\circ C.km^{-1}$), is added to the potential temperature (T_P) and consistently included in the calculation of pressure, density and viscosity.

The effects of compressibility were coupled with the constitutive equation by means of

$$\frac{Dp}{Dt} = -K \left(\frac{\partial v_i}{\partial x_i} - \alpha \frac{DT}{Dt} \right), \quad (4)$$

where K is the bulk modulus and α is the thermal expansion. In the same way, volumetric deformations were followed by corrections in the calculation of density by means of the Murnaghan approach.

The model includes true free surface and elastic deformation. Total deviatoric strain rate ($\dot{\varepsilon}_{ij}$) is additively decomposed in an elastic, viscous and plastic term. Namely,

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{el} + \dot{\varepsilon}_{ij}^{vis} + \dot{\varepsilon}_{ij}^{pl} = \frac{\hat{\tau}_{ij}}{2G} + \frac{\tau_{ij}}{2\mu_{eff}} + \dot{\gamma} \frac{\partial Q}{\partial \tau_{ij}} \quad (5)$$

where G is the elastic shear modulus, μ_{eff} is the effective viscosity, $\hat{\tau}_{ij}$ is the objective stress rate tensor, $\dot{\gamma}$ is the plastic multiplier and Q is the plastic potential function. Numerical integration of stresses was calculated by means

of the Hughes-Winget scheme (Hughes and Winget, 1980) for the trial stresses, while a predictor-corrector procedure (Simo and Taylor, 1985) was applied to update deviatoric stresses considering plasticity.

Viscosity is stress and temperature dependent. Three different types of creep (diffusion, dislocation and Peierls) were included, following the approach of Kameyama et al. (1999).

Effective viscous strain rate was additively decomposed into these three mechanisms, namely

$$\dot{\epsilon}_{eff}^{(v)} = \dot{\epsilon}_d + \dot{\epsilon}_n + \dot{\epsilon}_p . \quad (6)$$

Strain rate due to diffusion creep was defined as

$$\dot{\epsilon}_d = B_d \tau_{II} e^{-\frac{H_d}{RT}} , \quad (7)$$

dislocation, power-law creep as

$$\dot{\epsilon}_n = B_n \tau_{II}^n e^{-\frac{H_n}{RT}} , \quad (8)$$

and Peierls creep as

$$\dot{\epsilon}_p = B_p e^{\left[-\frac{H_p}{RT} \left(1 - \frac{\tau_{II}}{\tau_p}\right)^q\right]} , \quad (9)$$

where τ_{II} is the square root of the second invariant of the deviatoric stress, R is the gas constant, B_d, B_n, B_p are creep parameters and τ_p is Peierls stress. H_d, H_n, H_p are the activation enthalpies for each creep, which are defined as

$$H_j = E_j + P.V_j \quad (10)$$

for $j \in \{d, n, p\}$ and being E the activation energy, P the pressure and V the activation volume. A yield stress of 350 MPa was also applied in transition

zone and lower mantle. In accordance with Běhounková and Čížková (2008), Conrad and Lithgow-Bertelloni (2002), Čížková et al. (2002) we obtain that higher stresses cause the slab to become too stiff to be deformed and, therefore, the evolution does not mimic what one can see in nature.

Finally, effective viscosity was calculated as

$$\mu_{eff} = \frac{\tau_{II}}{2\dot{\epsilon}_{eff}^{(v)}} . \quad (11)$$

The rheological parameters used in this set of experiments for the slab, overriding plate and upper mantle were taken from Hirth and Kohlstedt (2003) assuming dry olivine rheology for lithosphere and wet olivine rheology for the rest of the upper mantle (see Table 1). Viscosity values for the background mantle transition zone ($\sim 3 \cdot 10^{20}$ Pa.s) and shallower lower mantle ($\sim 3 \cdot 10^{21}$ Pa.s) were prescribed based on the ones calculated by Quinteros et al. (2010).

Subduction channel was considered as a well lubricated interface with weak rheology (wet quartz from Ranalli (1995)) and a low friction coefficient (0.05), which favours the development of subduction. This interface is three elements wide, defined at every time step and restricted to the contact between the two plates at a depth less than 120 km, treated similarly by Sobolev and Babeyko (2005).

Subducting slab is composed of ~ 7 km of oceanic gabbro, a layer of harzburgite-type material and a thermal layer with the same rheology as mantle down to ~ 100 km depth. According to Kaneshima et al. (2007) this is approximately the width of the slab being subducted in the Marianas. This is also in agreement with Schmeling et al. (1999)'s observation concerning the misfit of half-space cooling and real width of the slab when older than 100 Myr.

3.1. Phase transformation kinetics

Several implementations of transformation kinetics models by different authors (e.g. Tetzlaff and Schmeling, 2009, Billen, 2010) were mentioned above. Even where similar thermomechanical models were used, very different modes of evolution of the metastable olivine resulted. Tetzlaff and Schmeling (2009) claimed that one of the main reasons for this differentiation is the selection of constants used in these models. For example, they used kinetic parameters that allowed for a growth rate 5 times slower than in Mosenfelder et al. (2001).

In this model we used a simple approach concerning the transformation kinetics from olivine to spinel. A large number of markers (particles) is inserted in every element. These particles keep all the relevant information about its state during the whole simulation. The phase transformation takes place at the level of these markers and, therefore, modifies the properties of the containing element. Every timestep the state of the particles is evaluated and when a particle crosses the boundary between olivine and spinel in the phase diagram, material properties of the particle change and latent heat is released.

This transformation is instantaneous. The effects of a mixed region, in which olivine and spinel can coexist, were neglected. This decision was based on many experiments where, for different models, the rate of transformation between 10/20 and 80/90 % takes place in a small interval of depth (see for instance Riedel and Karato, 1997, Tetzlaff and Schmeling, 2009), which would occur in only a few elements in our thermomechanical model, mainly due to the effects of latent heat release, which has a strong influence on the transformation kinetics in cold subducting slabs (Rubie and Ross, 1994). Latent heat is released instantaneously and not gradually as a depth-dependent function, what could shift the maximum depth of metastable olivine ~ 50 km upwards (Tetzlaff and Schmeling, 2009).

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9 Clapeyron slope for olivine-spinel transition is considered to be +2.0 MPa/K,
10 while the one related to the combined spinel-perovskite and garnatite-perovskite
11 transformations is -1.0 MPa/K. These values are within the expected range from
12 seismological data (Fukao et al., 2009) and laboratory experiments (Litasov
13 et al., 2005, Irifune et al., 1998).

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18 Thermal expansivity was averaged based on Steinberger and Calderwood
19 (fig. 3 from 2006) for three different depths: upper mantle ($3.0 \cdot 10^{-5}/K$), tran-
20 sition zone ($2.0 \cdot 10^{-5}/K$) and the shallower lower mantle ($2.2 \cdot 10^{-5}/K$). Density
21 is increased by 6% at the olivine-spinel phase transition (Christensen, 1995) and
22 8% at the spinel-perovskite (Dziewonski and Anderson, 1981).

23 24 25 26 27 *3.2. Boundary conditions*

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30 The domain is 1700 km wide and 750 km deep. Classical Winkler foundation
31 boundary conditions (see fig. 5 in Regenauer-Lieb, 2006) were defined at the
32 bottom part of the model. The material is free to subduct through this bound-
33 ary. We chose this depth in order to exclude uncertainties associated with the
34 influence of the slab pull from the lower mantle and isolate the evolution of the
35 metastable olivine from the stress state in the lower mantle.

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40 It is known that the influence of slab pull below 750 km should be much
41 smaller if compared to slab-pull in the upper mantle and viscous resistance at the
42 670 km boundary. However, there are still many uncertainties about viscosity in
43 the lower mantle, the level of stress that could be transmitted upwards through
44 the slab and how this would affect its final configuration. For these reasons,
45 only a thin layer of lower mantle was included in our model. The influence from
46 the material below 750 km has been excluded as it is consider out of the scope
47 of this work.

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52 The slab was kinematically pushed with a constant velocity of 9 cm/yr during
53 the experiment in order to simulate the Marianas subduction. A schematic view
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of the setup can be seen in Fig. 1.

The top side of the domain is a free surface with zero stress. On the right side free slip conditions were applied, while the bottom and left side were open and material was free to move in or outside the model.

In previous works from our group we used a different approach in the boundary conditions to simulate subductions. For example, in Sobolev and Babeyko (2005) we include a proxy for the slab-pull by kinematically pulling the slab from the bottom side of the domain. This was justified because the model extended only to 400 km depth, so slab-pull force could not be considered in a self-consistent way. However, in this set of experiments the domain includes part of the lower mantle and, therefore, a big part of the slab-pull is already present in the system. Considering the final results, where we were able to reproduce appropriately the situation in the Marianas, we confirmed “a posteriori” that our approach was consistent.

The set of experiments was run with a blocking temperature ranging from 700°C to 800°C and with a sampling interval of 25°C. Almost all the experiments were run with and without shear heating in order to study the influence on the overall evolution of the system.

4. Results and discussion

The first few Myr of subduction evolution have not been taken into account as results, as they were considered to be strongly influenced by the initial conditions of the setup, such as the thermal state of the slab tip or the subduction angle. In this study, we focused on an ongoing subduction, where the tip of the slab is already subducted into the lower mantle and has little influence on the thermal and density state of the slab in mantle transition zone.

Rubie and Ross (1994) claimed that properly taking the force balance of the system into account could lead to an oscillating rate of subduction. However, it is not only the subduction velocity that could stabilize the system as a whole. In tectonic settings where the subduction velocity of big, old plates are strongly influenced by basal drag force, the volume of the metastable olivine wedge or the subduction angle could also change, thus, balancing the forces acting on the slab. Here, because of the imposition of a constant velocity of subduction, the blocking temperature and wedge volume associated with the kinetics of phase transformations will affect only the dipping angle of the slab instead of its velocity.

All of the experiments showed approximately similar evolution. Once the slab crosses the 410 km phase transition boundary, it bends due to the extra slab pull achieved in the mantle transition zone and the subduction angle becomes steeper.

The evolution of the trench is independent from the variables considered in these experiments and seems to be influenced mainly by the kinematic boundary conditions imposed, which were kept constant in every case.

After ~ 6 Ma a wedge of metastable olivine starts to form in the slab and evolves strongly influenced by the selected blocking temperature. The presence of this wedge modifies the force balance of the subduction regime and changes the stress pattern inside the slab. When the wedge reaches a deeper position in the mantle transition zone, it increases the buoyancy of the entire slab due to its lower density. The amount of metastable olivine oscillates during the simulation, affected by the thermal state of the slab.

One example of the wedge volume oscillation can be observed in Fig. 2. One can see that in a period of 3.2 Myr the wedge increases and later decreases its volume. A similar oscillation was already described by Tetzlaff and Schmeling

(2009), called “velocity-depth phase loops”. They also detected periods of oscillation in the order of 3 to 4 Myr in simulations of dynamic free subductions. In our results, the intensity of these oscillations varies with respect to the chosen blocking temperature but the periodicity ranges from 3 to 4 Myr as well.

We suggest that the main cause of the volume oscillations is the thermal runaway process that takes place once the wedge descends deep enough. At this moment, release of latent heat shifts very fast the boundary between olivine and spinel upwards. Then, the isotherms are advected downwards by the subduction and the wedge starts to grow again.

Position of the metastable wedge

In Fig. 3 the position of the metastable olivine wedge tip for different blocking temperatures along the simulations is shown. The general evolution of each experiment is plotted in a two variables space (depth of wedge and distance from trench). Every point in the plot corresponds to a moment in the evolution of the simulation. The position of the wedge in the Marianas is shown in a black bold box. One can see that the largest effect when changing the blocking temperature is that the distance from the trench increases strongly, while the maximum depth does it in a less pronounced way. This is caused by an increase in the buoyancy and stiffness of the slab. Namely, by the density deficit of the metastable olivine, the retarded release of the latent heat flow and the higher yield stress related to the olivine compared to the spinel.

The results show that the metastable olivine wedge stabilizes close to the trench at a distance ranging from 250 to 400 km. The maximum depth of the wedge ranges from ~ 430 to 670 km and the magnitude of its oscillations at given blocking temperature is 70-100 km.

There is a positive correlation between blocking temperature and depth of the wedge or its distance from the trench. Positions of the wedge for all model

runs with the same blocking temperature are outlined by black ellipses (Fig. 3). These ellipses move towards deeper positions and away from the trench when the blocking temperature increases.

The width of the metastable olivine wedge in the subducting slab in the Marianas is approximately 25 km and it extends as deep as 630 km (Kaneshima et al., 2007). The distance from the trench in the studied segment seems to be ~ 260 km. Comparing the modeling results with the present situation of the Marianas, we see that a blocking temperature of 725°C provides the best fit for the wedge's distance from the trench and its maximum depth.

Fig. 4 shows one snapshot of the slab in the mantle transition zone with our preferred blocking temperature (725°C). The geometry of the wedge conforms well with the one detected by Kaneshima et al. (see fig.1 in 2007). Here, the wedge has exactly the same width, is located at the same distance from the trench and only its maximum depth is slightly shallower than the one seen in the Marianas.

The width of the wedge is in agreement with the results described by Billen (2010). The distance between the trench and the position of the slab in the mantle transition zone also coincides with similar experiments presented by Billen (2010), who applied a yield stress of 500 MPa. When the metastable olivine reaches the maximum depth, the volume of the wedge in the cross section is $\sim 5000 \text{ km}^2$. This value conforms with the limit suggested by Schmeling et al. (1999) for slabs older than 100 My, as in this case. This volume is also similar to the values obtained by Mosenfelder et al. (2001) for a 140 My old slab that subducts at 8 cm/yr. Mosenfelder et al. (2001) tested different parameters for the kinetics model and obtained wedges of up to $\sim 4200 \text{ km}^2$, with a maximum volume between $\sim 4700 \text{ km}^2$ and $\sim 5700 \text{ km}^2$ if uncertainties are taken into account.

We estimate from our preferred model that the metastable olivine adds a bouyancy force ranging between 3 to 9×10^{12} N/m due to the change in the wedge volume. This is approximately one order of magnitude smaller than the expected values from slab-pull, what according to Billen (2010) can reach values of $\sim 50 \times 10^{12}$ N/m.

We see a strong influence on the subduction angle caused by the blocking temperature. However, for a given blocking temperature we do not see that the oscillations in the volume of the wedge cause major changes in the dynamics of the subduction system. This is in agreement with the previous work from Billen (2010), who claimed that in experiments of free dynamic subduction no variation in the subduction velocity is observed with a wedge of ~ 25 km width.

Another important factor that helps determine whether the simulation is in agreement with the situation seen in nature, is the depression of the spinel/perovskite transformation boundary. According to Kaneshima et al. (2007) it is ~ 30 km where the cold part of the slab is subducted. As can be seen in Fig. 4, this fits very well with our results.

Influence of shear heating

The stiffness of a slab is related to many factors. We applied rheological parameters commonly used in the geodynamic community (see Table 1), but considering the steep angle of subduction in the Marianas, we selected those favouring an appropriate bending of a slab. For example, Peierls creep was included following the approach of Kameyama et al. (1999). We used wet olivine for the rheology in the upper mantle, which makes the subducting angle steeper in comparison with dry olivine. We also applied a yield stress in transition zone and lower mantle, what makes the slab not too stiff, being able to deform and avoiding upwards transmission of an unrealistic amount of stress (e.g. Conrad and Lithgow-Bertelloni, 2002, Běhouňková and Čížková, 2008).

We run many of the experiments again without the inclusion of shear heating to evaluate the influence that this could have in the thermal structure of the slab. The results of these experiments are shown in Fig. 5. The largest difference with the experiments with shear heating included (Fig. 3) is a significantly smaller subduction angle. As a result, the distance from the trench for the whole range of blocking temperatures is never closer than 360 km. As such, with the present setup, not even one experiment can reproduce the subduction geometry in the Marianas case if shear heating is not taken into account.

The reason of such behaviour is that shear heating reduces the internal strength of the slab by slightly increasing the temperature. The slab then becomes less stiff and easier to bend, making the slab-pull more effective due to the smaller resistance exerted by the slab.

In Fig. 6 two examples of the temporal evolution of the maximum depth with and without shear heating for different blocking temperatures are shown. One can see that, after the system is stabilized (~ 12 Myr) the difference in depth could be as much as ~ 70 km more for the experiment with shear heating.

5. Conclusions

We have presented a set of experiments that constrain the blocking temperature of the metastable olivine in a cold slab based on comparison of the modeling results and seismic observations by Kaneshima et al. (2007) in the Marianas. Our model includes a proper feedback between thermal and stress state of the slab as well as the force balance caused by the presence of the wedge.

Our results show a positive correlation between blocking temperature, maximum depth of the metastable wedge and its distance from the trench. When compared with the present situation in the Marianas subduction zone, we can conclude from our experiments that a blocking temperature of 725°C for the

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9 olivine/spinel transformation best fits the geometry observed by Kaneshima
10 et al. (2007). Though this blocking temperature is slightly higher than pre-
11 vious estimates (e.g. 600°C and 650°C for Schmeling et al., 1999, Tetzlaff
12 and Schmeling, 2000, respectively), modeling results with significantly lower
13 or higher blocking temperatures appear to be not consistent with seismic obser-
14 vations.
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19 We confirm Tetzlaff and Schmeling (2009)’s results concerning the periodic-
20 ity of oscillations in volume of the metastable olivine wedge. We suggest that
21 these oscillations are caused by the thermal runaway process due to latent heat
22 release competing against the advection of isotherms in a subducting slab and
23 they take place even if subduction velocity is fixed.
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28 Shear heating has a strong influence on the dynamics of the slab, by slightly
29 increasing the temperature inside the slab, reducing its strength and thus, mak-
30 ing the active slab-pull more effective in slab bending.
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Material	ρ	K	G	$\log(B_d)$	E_d	V_d	$\log(B_n)$	E_n	n	V_n	$\log(B_p)$	E_p	τ_p	ϕ	c	α	C_p	k	A
Crust	2.8	550	360				-28.0	223	4.0	10				0.6	20.0	3.7	1.2	2.5	1.3
Mantle	3.3	1220	740				-15.41	480	3.5	14				0.6	20.0	3.0	1.2	3.3	
Lith.slabb	3.28	1220	740	-8.96	335	2	-16.30	535	3.5	14	11.75	540	8500	0.6	40.0	3.0	1.2	3.3	
Oc.gabbro	3.0	630	400				-25.90	485	4.7	14				0.6	40.0	2.7	1.2	2.5	0.2
Eclogite	3.43	1220	400				-25.90	485	4.7	14				0.6	40.0	2.7	1.2	2.5	0.2

Table 1: Model parameters used for the set of experiments. ρ : density, K : Bulk modulus, G : Shear modulus, B_j : Pre-exponential factor, E_j : Activation energy, V_j : Activation volume, where the subscript $j \in \{d : \text{diffusion creep}, n : \text{dislocation creep}, p : \text{Peierls creep}\}$, n : exponential constant in dislocation creep, τ_p : Peierls stress, ϕ : friction coefficient, c : cohesion strength, α : thermal expansion, C_p : heat capacity, k : heat conductivity and A : radiogenic heat production. (Mackwell et al., 1998, Kameyama et al., 1999, Hirth and Kohlstedt, 2003)

Figure 1: Schematic model setup used for the experiments. Slab velocity is kinematically prescribed to mimic the Marianas subduction zone. Inset: Example of viscosity profile, away from the subduction zone, based on the rheological parameters from Hirth and Kohlstedt (2003). Values for mantle transition zone and shallower lower mantle are taken from Quinteros et al. (2010).

Figure 2: Example of oscillating size of metastable olivine wedge. Blocking temperature is 775°C. Potential temperature is shown in color. The contour lines show the phase transformation boundaries inside the domain. One can see how the wedge changes through time in response to the overall buoyancy of the slab and the variation of subduction angle.

Figure 3: Position of the metastable olivine wedge for different blocking temperatures along the simulations. For every experiment a different blocking temperature was tested and its evolution in space was plotted with one color. Every point in the plot corresponds to a moment in the evolution of the simulation. The position of the wedge in the Marianas is shown in the black bold box. One can see that the maximum depth of the wedge increases with the blocking temperature, but also the distance from the trench increases due to the buoyancy of the slab.

Figure 4: Cross section of the slab in the mantle transition zone for a blocking temperature of 725°C. Potential temperature is shown in color. The contour lines show the phase transformation boundaries inside the domain. One can see that the size and position of the metastable olivine wedge as well as the depression of ~ 30 km at the spinel/perovskite transformation boundary are in very good agreement to the ones detected by Kaneshima et al. (2007).

Figure 5: Position of the metastable olivine wedge for different blocking temperatures when no shear heating is considered. The same scale as in Fig. 3 is used for comparison. Every blocking temperature corresponds to one experiment and is plotted in one color. Every point in the plot corresponds to a moment in the evolution of the simulation. As in the case with shear heating, maximum depth of the wedge and distance from the trench increase with the blocking temperature as the slab becomes more buoyant. The position of the wedge in the Marianas is shown in the black bold box. Comparing the results with and without shear heating one can see that in the second case the slab tends to decrease the subduction angle. New incoming segments of the slab need more time to reach the same depth, are warmer, and the metastable olivine reaches a slightly shallower depth.

Figure 6: Temporal evolution of the maximum depth of the metastable olivine wedge. Only values after stabilization of the system are shown. Lines in orange and in violet represent the experiments with and without shear heating, respectively. a) Evolution for a blocking temperature of 750°C . b) Evolution for a blocking potential temperature of 775°C . One can see that in the experiments with shear heating the maximum depth of the wedge is usually deeper than the ones without.

Figure1

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Figure2

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Figure5

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Figure6a

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Figure6b

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