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# Relative impact of mantle densification and eclogitization of slabs on subduction dynamics: A numerical thermodynamic/thermokinematic investigation of metamorphic density evolution

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ABSTRACT

Understanding the relationships between density and spatio-thermal variations at convergent plate boundaries is important for deciphering the present-day dynamics and evolution of subduction zones. In particular, the interaction between densification due to mineralogical phase transitions and slab pull forces is subject to ongoing investigations. We have developed a two-dimensional subduction zone model that is based on thermodynamic equilibrium assemblage calculations and includes the effects of melting processes on the density distribution in the lithosphere. Our model calculates the “metamorphic density” of rocks as a function of pressure, temperature and chemical composition in a subduction zone down to 250 km. We have used this model to show how the hydration, dehydration, partial melting and fractionation processes of rocks all influence the metamorphic density and greatly depend on the temperature field within the subduction system. These processes are largely neglected by other approaches that reproduce the density distribution within this complex tectonic setting. Our model demonstrates that the initiation of eclogitization (i.e., when crustal rocks reach higher densities than the ambient mantle) of the slab is not the only significant process that makes the descending slab denser and generates the slab pull force. Instead, the densification of the lithospheric mantle of the sinking slab starts earlier than eclogitization and contributes significantly to slab pull in the early stages of subduction. Accordingly, the complex metamorphic structure of the slab and the mantle wedge has an important impact on the development of subduction zones.



## 1. Introduction

Subduction zones, regions where two tectonic plates converge and the denser plate sinks beneath the other, are distributed worldwide and, along with seafloor spreading, represent the core process of plate tectonics (e.g., Isacks et al., 1968; Le Pichon, 1968; Morgan, 1968). These regions are characterized by strong earthquakes and volcanic eruptions, which significantly affect human life and destroy habitats. Therefore, it is crucial to further understand this geological process. However, the limited observations at depth and differing timescales complicate investigations. Numerical simulations in combination with observed geological and measured geophysical data can make up for the lack of observations (Gerya, 2011, and references therein). Many discussions concern the mechanisms that drive this complex tectonic system and the influence of volatiles, phase transitions, melt generation and the chemical composition of the descending and overriding slabs (Billen, 2008; Grove et al., 2012; Quinteros and Sobolev, 2012; Stern, 2002). It is assumed that in the majority of cases, the primary force driving plate movement is the excess density of the descending slabs lithosphere (Davies, 1999; Forsyth and Uyeda, 1975; Vlaar and Wortel, 1976) due to the cooling of the plate surface as the oceanic plate moves away from the spreading ridge (Oxburgh and Parmentier, 1977). Consequently, the density distribution in the lithospheric slab and the change of density due to the change of pressure and temperature (*P*-*T*) conditions in subduction zones play a significant role in understanding plate dynamics. The density behavior of subducting and overriding plates has been studied using several approaches, such as the following: (a) gravimetrical measurements (e.g., Prezzi et al., 2009; Tašárová, 2007), (b) seismics/tomography (e.g., Kárason and Van der Hilst, 2002; Zhao, 2001), (c) petrologic investigations (e.g., Connolly and Kerrick, 2002; Hacker et al., 2003; Sobolev and Babeyko, 1994; Ringwood and Green, 1966) and (d) numerical

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simulations (e.g., Doin and Henry, 2001; Gerya et al., 2004; Sobolev et al., 2006; van Keken et al., 2008).

In this study, our focus is on the density evolution of subducting slabs. McKenzie (1969) first noticed the importance of mineralogical changes on the negative buoyancy force of a sinking slab during subduction, demonstrating the effect of metamorphic densification at the transformation of oceanic crust (basalt and gabbro) to eclogite. This so-called "metamorphic density" is a function of temperature, pressure and chemical composition and has a large influence on lithospheric dynamics (e.g., Duesterhoeft et al., 2012; Goffé et al., 2003; Henry et al., 1997). Modeling the density structure of the lithosphere solely by fixed physical parameters (thermal expansivity and bulk modulus) based on the fixed chemical composition of each layer is not adequate because the mineral reactions within each layer significantly influence the rock density (e.g., Afonso et al., 2005; Bousquet et al., 1997, 2005; Duesterhoeft et al., 2012; Le Pichon et al., 1997). Most thermodynamic studies of subduction zones focus on the density structure of the upper part of the mantle ($\approx$200–660 km depth). Below 200 km, the basaltic layer of a descending slab is always heavier than the lower harzburgitic layer (Ganguly et al., 2009). Bina et al. (2001) showed how phase changes in the transition zone at depths of 410–660 km are perturbed by the thermal environment and result in density anomalies that may affect the subduction rate. Similarly, the subduction rate influences the thermal structure and thus the density structure of a subduction zone because it depends on the convergence rate of the descending and overriding plates. Here, we study the upper 250 km of the lithosphere of a young (41 Ma), shallow (35 °, fast (77 km/Ma) and thus cold subduction zone (yielding a slab thermal parameter $\Phi =$ slab age $\times$ vertical descent rate $=$ 1800 km). By analyzing the density and metamorphic structure of such a subduction zone, we may gain knowledge about the major, and thus driving, metamorphic processes in the upper 250 km of the subduction zone. These processes are the breakdown of hydrous minerals and the release of fluids or the generation of partial melts. Moreover, investigating the metamorphic density structure in a 2D thermodynamic approach may provide new insights into the initiation of subduction and the exhumation process of low-temperature, high-pressure metamorphic rocks (e.g., blueschist and eclogite) that characterizes paleosubduction zones (e.g., Giunchi and Ricard, 1999; Guillot et al., 2009; Pourteau et al., 2010).

## 2. Methods

The modeling of subduction is performed by means of two different and independent approaches. In the first, a simple 2D model with a kinematically prescribed slab and a constant subduction rate (Table 1) is used. The advantage of a simple model is the limited parameter space, which allows the investigation of the "metamorphic density" in a systematic manner (Gerya, 2011). Therefore, we calculate the thermal structure down to a depth of 670 km (with a vertical resolution of 1000 m) to generate a steady-state subduction zone. In the second approach, we use a thermo-mechanical model in which the subduction rate is prescribed, but the evolution of the slab is self-consistent. This means that only the subducting velocity is imposed, but the variations in the subduction angle, bending, unbending and other related processes are coherent with the state of the system as a whole. In the calculation of the metamorphic density structure of subduction zones, the study focuses only on the upper part (0–250 km depth) because it is the part in which most mineralogical changes take place. Furthermore, it is the region of greatest seismic activity.

**Table 1**
A summary of model parameters.

| Parameter | Value |
|---|---|
| Slab dip (°) | 35 |
| Slab age (Ma) | 41 |
| Subduction velocity (cm/a) | 7.7 |
| Basal temperature of lithosphere (°C) | 1450 |
| Depth of the base of the model (km) | 670 |
| Total model length (km) | 1000 |
| Total time of evolution (Ma) | 11 |
| MORB layer thickness (km) | 7.0 |
| Bulk rock composition after | (Hofmann, 1988) |
| Serpentinite layer thickness (km) | 2.0 |
| Bulk rock composition after | (Li et al., 2004) |
| Harzburgite layer thickness (km) | 21.0 |
| Bulk rock composition after | (Ganguly et al., 2009) |
| Lherzolite layer thickness (km) | 65.0 |
| Bulk rock composition after | (Brown and Mussett, 1993) |

### 2.1. Temperature-pressure setting

We use the kinematic finite-difference heat transfer algorithm TEMSPOL (Negredo et al., 2004), an open MATLAB® code, to calculate temperature distributions in subduction zones. The thermo-kinematic model is calculated by solving the 2D heat equation, including adiabatic heating, radioactive heat generation, latent heat and frictional heating (the last two are not taken into account in our calculations). Here, the surface temperature is taken as 0 °C, and the temperature at the base of the lithosphere is 1450 °C (Jaupart and Mareschal, 2011; Stein and Stein, 1992). We modified the code to model the thermal structure of more than two layers (the oceanic crust and the mantle). The modification subdivides the 95-km-thick oceanic slab, from top to bottom, into a MORB layer (7 km thick), a serpentinite layer (2 km thick), a dry harzburgite layer (21 km thick) and a dry lherzolite layer (65 km thick). These subdivisions are implemented to evaluate the different effects of the chemical bulk composition of each layer on the slabs mineralogical changes (Ganguly et al., 2009; Ringwood and Irifune, 1988). Calculating the metamorphic density also requires the corresponding pressure of each temperature in our model, which is computed lithostatically from the thermo-kinematic model. We know that this is a valid first-order approximation, and we keep in mind that there could be certain additional tectonic over- and underpressure effects (Babeyko and Sobolev, 2008; Li et al., 2010; Petrini and Podladchikov, 2000). We checked the influence of these effects on our results by using full dynamic pressure from a thermo-mechanical model (see Supplementary Material).

A second set of pressure and temperature distributions was calculated by means of a thermo-mechanical model (see Supplementary Material). We use an enhanced 2D version of SLIM-3D, a code (Popov and Sobolev, 2008; Quinteros and Sobolev, 2013) suitable for simulating the evolution of a subducting slab in a self-consistent manner (gravity driven) in a vertical cross section through the upper mantle. The model has a true free surface, includes elastic deformation and utilizes nonlinear temperature- and stress-dependent visco-elasto-plastic rheology. The domain is 1400 km wide and 670 km deep. On the left side, the overriding plate is moved eastwards throughout the whole simulation with a velocity of 3 cm/a, while the subducting plate is pushed at 4.7 cm/a (resulting in a total subduction velocity of 7.7 cm/a). On the left side of the model, a lithostatic pressure boundary condition is applied under the overriding plate. This leaves the major part of the side open, allowing the material to enter and exit the model in a realistic way. A subduction channel is considered to be a well-lubricated interface with weak ductile rheology and a low friction coefficient, which favors the development of realistic one-sided subduction (Gerya et al., 2008; Sobolev and Babeyko, 2005).

### 2.2. Thermodynamic modeling

The metamorphic density is determined by accounting for the mineralogical changes that occur with changes in temperature and/or pressure. Therefore, we apply the Theriak/Domino software (version 01.08.2009; de Capitani and Petrakakis, 2010) to calculate the metamorphic density using the principle of minimized ("apparent") Gibbs