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The effects of phase transitions and compositional layering in two-dimensional kinematic models of subduction

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ABSTRACT

Subduction zones exhibit a wide range of behaviour, from slab stagnation at the base of the transition zone, to direct sinking into the lower mantle. Numerical simulations have utilised a range of approximations to improve computational efficiency, such as limiting the phase transitions or compositional effects included in a model: the net effect of these approximations on slab dynamics remains unclear. With the goal of developing more complete, self-consistent, and less idealised simulations, we analyse the importance of various modelling choices on slab evolution: the presence of shear, adiabatic and latent heating, compositional layering and composition-dependent phase transitions. We find that slabs in models with additional heating terms (extended Boussinesq approximation) are warmer, weaker and exhibit more folding and stretching than in models without these terms (Boussinesq approximation). The presence of compositional layers and the stress-dependence of rheology acts to strengthen the slab, decreasing slab dip and leading to less folding and lateral migration of the slab. We also find that the extent of slab folding and stagnation is overestimated by modelling only the olivine phase transitions at 410 and 660 km. A more realistic subduction zone with compositional layers and all the pyrolite phase transitions exhibits almost no slab stagnation at 660 km and is instead characterised by broad, periodic, slab folding. This slab behaviour is more similar to a model with no phase changes or compositional layers. Therefore, for studies in which a complete treatment of compositional layers and phase transitions is not possible, rather than including an incomplete approximation that over-predicts folding, the large-scale deformation of slabs is best approximated by a model with no phase transitions and no layers.

1. Introduction

The motion of tectonic plates is determined by the ability of ridge push and slab pull to overcome viscous drag at the base of the plate. Of these forces, the negative buoyancy of a descending slab is the dominant driver of plate motions. The negative buoyancy of the slab depends on the thermal structure (age, rate of descent, shear heating, latent heat), compositional layering (basaltic crust and residual harzburgitic mantle) and thermal dependence of mineral phase transitions, which all contribute to anomalous slab density relative to the surrounding mantle. Tomography studies show that while some slabs appear to sink directly into the lower mantle, many subducting slabs stagnate at or near the upper-lower mantle boundary (ULMB) (e.g., Bigwaard et al., 1998; Li et al., 2008; Fukao et al., 2009). Stagnation of the slab suggest that the negative slab buoyancy is significantly reduced in some slabs due to processes related to the many mineral phase transitions occurring near this boundary, and, or the effect of higher viscous resistance in the lower mantle is amplified in some subduction zones. Alternatively or in conjunction with these other processes, variations in trench motion may act to pile-up or lay the slab down in the transition zone, focusing or spreading out the negative slab buoyancy (Griffiths et al., 1995; Guillou-Frottier et al., 1995; Christensen, 1996).

Past geodynamic studies show that slab stagnation can be caused by a strong ringwoodite to perovskite phase transition at 660 km (e.g. Christensen, 1996). However, with recent studies supporting a weaker 660 km phase transition, its importance for slab stagnation has declined, initiating new studies to identify an alternate mechanism. One such mechanism is metastable olivine and/or pyroxene, which occurs in the slab when the phase change is kinetically delayed beyond the usual pressure–temperature conditions (Kirby et al., 1996; Mosenfelder et al., 2001). Because the less dense phase continues to be present in a metastable state to higher pressures, it becomes a source of positive buoyancy within the slab at transition zone depths (Tetzlaff and Schmeling, 2000; Quinteros and Sobolev, 2012; Agrusto et al., 2014). In addition, numerical

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models of metastable olivine show that latent heat release creates a time-dependent, repeating cycle from stagnant slabs to those that sink straight into the lower mantle (Tetzlaff and Schmeling, 2009). However, there are many outstanding questions regarding the conditions under which metastable phases may be present in real slabs.

Seismic observations suggest that metastable olivine and/or enstatite may be present in some slabs, including the Japan (Jiang and Zhao, 2011) and Marianas subduction zones (Kaneshima et al., 2007). Metastable olivine was not observed in the Halmahera slab, where reflectors for all six major phase transitions were observed (Thomas and Billen, 2009). However, metastable olivine is not expected to exist in wet conditions (>300 ppm H_2O; Diedrich et al., 2009; Mosenfelder et al., 2001), and the seismic observations require that the slab be very dry (<100 wt. ppm for Japan (Kawakatsu and Yoshioka, 2011) and 150 wt. ppm for the Marianas (Kubo et al., 2009). In addition, the cold thermal conditions needed to create the kinetic delay of the phase transition are only found in fast subducting and old lithosphere (100 My), limiting which slabs may be effected by metastability (Mosenfelder et al., 2001). Finally, latent heat will counteract kinetic effects and reduce the size of a metastable olivine wedge (Tetzlaff and Schmeling, 2009; Quinteros and Sobolev, 2012). Therefore, the presence of additional phase transitions within the transition zone and their associated latent heat release may create a slab that is too warm for olivine to exist in a metastable state.

In contrast to the attention paid to special buoyancy mechanisms, such as metastable olivine, no models of subduction dynamics have addressed the importance of starting with an accurate mineralogical model (e.g., pyrolite), including compositional layers, and composition-dependent phase transitions. Several theoretical studies indicate a pyrolite mineralogy (olivine, garnet and pyroxene, and associated phase transitions) changes the internal stress and buoyancy of a subducting slab (Ricard et al., 2005; Ganguly et al., 2009). In addition, the pyrolite system for the mantle and subducting slabs is considerably better studied and well-established (see Section 1.1) compared to mineralogical constraints on proposed metastable phases.

Geodynamic studies of subduction employ inconsistent treatments of the transition zone, including either no, one, or two phase transitions, and usually only for pure olivine (e.g., Billen and Hirth, 2007; Tetzlaff and Schmeling, 2009; Čížková and Bina, 2013). Previous models that found the transition from ringwoodite to perovskite and magnesiowustite ($rw \rightarrow pv + mw$) instrumental for slab stagnation used relatively large Clapeyron slope values from seismic or thermodynamic studies (e.g. Christensen, 1996), while those with smaller experimental values derived from X-ray diffraction studies found that similar results required a significantly larger viscosity jump into the lower mantle (Torii and Yoshioka, 2007). Compared to a mantle of pure olivine, in a pyrolite mantle the olivine ($(Mg,Fe)_2SiO_4$) phase transitions at 410 km and 660 km have smaller density changes, thus requiring higher rates of trench retreat to produce slab stagnation (Nakakuki et al., 2010). Interestingly, in the absence of the $rw \rightarrow pv + mw$ phase transition, the exothermic $ol \rightarrow wd$ phase transition produces large folds in the upper mantle while the $rw \rightarrow pv + mw$ alone only produces very small folds that are nearly negligible (Běhounková and Čížková, 2008). Therefore, complete model of phase transitions, that is consistent with the best-known mineralogical constraints, is needed to properly assess how the slab deforms in the transition zone.

Similarly, the compositional layering of the slab (basaltic crust with residual harzburgitic mantle) is typically not included in subduction models. The effect of compositional layering has been considered for models focused on plateau subduction (van Hunen et al., 2004; Arrial and Billen, 2013), and some other specialised applications including decoupling and separation of the crust from the slab, slab deformation and slab stagnation (Christensen, 1997; Yoshida et al., 2012). This general lack of attention to compositional layering may be because, when at the same temperature, there is no net buoyancy anomaly due to the combined effect of the thin, eclogite (more dense) crustal layer and thicker, harzburgite (less dense) layer. However, eclogite and harzburgite each go through different phase transitions and have different mineral proportions compared to pure olivine or pyrolite. Therefore, compositional layers may also impact slab dynamics by changing the local balance of forces within slab.

In addition to the approximations or simplifications made related to material properties, past geodynamic studies of subduction have also chosen to use different approximations of the governing equations: conservation of mass, momentum and energy. The most complete form of the governing equations is the compressible, anelastic liquid approximation (ALA) including the effect of pressure on the buoyancy forces and latent heat, adiabatic heating and viscous dissipation terms in the energy equation (Leng and Zhong, 2008).

Because the effects of compressibility are not generally important in the upper mantle, the ALA from of the equations has not typically been used for subduction studies. Instead, subduction studies have used either the incompressible Boussinesq approximation (BSQ; e.g., Christensen, 1996; Billen and Hirth, 2007; Schellart et al., 2007; Quinteros et al., 2010; Lee and King, 2011) or the extended Boussinesq approximation (EBA; e.g., Ita and King, 1998; Schmeling et al., 1999; Čížková et al., 2002; Tetzlaff and Schmeling, 2009), where the latter includes latent heat, adiabatic heating and viscous dissipation terms in the energy equation. However, the adiabatic heating and viscous dissipation terms will only perfectly balance when the ALA form is used, and the lack of compressibility will effect the local stress-state in the slab associated with the phase transitions.

Past models have shown that the choice of the governing equations does effect how the slab deforms. For example, changing from BSQ to EBA, the addition of an adiabat and latent heat increases the mass flux across phase transitions (Ita and King, 1994), and can increase the effective thickness of the transition (Katsura et al., 2004). Inclusion of latent heat can increase the length of low-angle subduction by 350 km (van Hunen et al., 2001), and cause time-dependent behaviour in a metastable olivine wedge (Tetzlaff and Schmeling, 2009). To create a self-consistent buoyancy model for subduction, at a minimum modelling of phase transitions needs to include the effects of latent heat.

This study was designed with two goals: first to develop numerical models of subduction that are consistent with observational, experimental and geodynamic constraints on the mineralogy structure of the upper mantle, and second, to better understand what is known (or not known) from the existing numerical models in the literature that each incorporate different combinations of parameters for composition, phase transitions and energy equation. In working towards that goal, we chose to first use 2D kinematic subduction models with a non-Newtonian composite viscosity to systematically test the effect of including (or not): latent heat and shear heating, a compositionally-layered slab, and eight composition-dependent phase transitions. In addition, we specifically compare more complete models with more simplified models commonly found in the literature, so that the differences or similarities in behaviour between different models can be better understood.

Compared to natural systems, the main limitations in the modelling approach employed here are the use of 2D models, kinematic boundary conditions and a fixed trench. The 2D model set-up is best interpreted in terms of the slab deformation that would occur near the centre of a long subduction zone without effects of flow around the edges. A fixed trench may occur where the upper plate is