



Invited review article

The role of solid–solid phase transitions in mantle convection

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ABSTRACT

With changing pressure and temperature conditions, downwelling and upwelling crustal and mantle rocks experience several solid–solid phase transitions that affect the mineral physical properties owing to structural changes in the crystal lattice and to the absorption or release of latent heat. Variations in density, together with phase boundary deflections related to the non-null reaction slope, generate important buoyancy forces that add to those induced by thermal perturbations. These buoyancy forces are proportional to the density contrast between reactant and product phases, their volume fraction, the slope and the sharpness of the reaction, and affect the style of mantle convection depending on the system composition. In a homogeneous pyrolitic mantle there is little tendency for layered convection, with slabs that may stagnate in the transition zone because of the positive buoyancy caused by post-spinel and post-ilmenite reactions, and hot plumes that are accelerated by phase transformations in the 600–800 km depth range. By adding chemical and mineralogical heterogeneities as on Earth, phase transitions introduce bulk rock and volatiles filtering effects that generate a compositional gradient throughout the entire mantle, with levels that are enriched or depleted in one or more of these components.

Phase transitions often lead to mechanical softening or hardening that can be related to a different intrinsic mechanical behaviour and volatile solubility of the product phases, the heating or cooling associated with latent heat, and the transient grain size reduction in downwelling cold material. Strong variations in viscosity would enhance layered mantle convection, causing slab stagnation and plume ponding.

At low temperatures and relatively dry conditions, reactions are delayed due to the sluggish kinetics, so that non-equilibrium phase aggregates can persist metastably beyond the equilibrium phase boundary. Survival of low-density metastable olivine, Ringwoodite, pyroxene and pyrope garnet in the transition zone and uppermost lower mantle produces positive buoyancy forces that decrease the subduction velocity and may lead to slab stagnation in the transition zone. The presence of deep metastable portions is still debated, and should not be associated a-priori with a completely dry slab as field observations suggest that heterogeneously hydrated oceanic plates could contain metastable dry portions surrounded by transformed wet rocks.

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1. Introduction

Mantle convection is the main process by which excess heat is extracted from the Earth's interior. One of the most important characteristics of mantle convection is the establishment of ascending hot and descending cold currents that in an ideal viscous fluid layer will encounter no impediment to vertical flow. Seismic tomographies suggest, however, that on Earth the vertical motion of the convective currents is hampered at transition zone and mid-mantle depths, where some slabs and plumes appear to be deflected horizontally (e.g., French and Romanowicz, 2015; Fukao and Obayashi, 2013; Rickers et al., 2013). The nature of these obstacles to vertical flow is debated, although it is commonly related to important variations in the physical properties of mantle minerals (King, 2016) or to the presence of chemically distinct reservoirs (Ballmer et al., 2015).

Over the last few decades, several laboratory and theoretical studies have robustly documented that, as oceanic plates are recycled in the mantle, mafic and ultramafic rocks experience a series of solid–solid phase transformations that tend to thermodynamically re-equilibrate the system with the new pressure and temperature conditions. A reversed series of reactions is expected to occur in upwelling plumes, although with non-negligible dissimilarities due to the different plume temperature (and possibly composition) relative to cold subducting slabs. Solid–solid phase transitions are often accompanied by significant variations in the mineral physical properties such as density and viscous mechanical behaviour. As a result, these phase transformations introduce first-order thermomechanical effects in the convective mantle system that can fundamentally affect the patterns of (layered, intermittent or whole) mantle convection and, consequently, the degree of chemical mixing of the Earth's interior.

Complementing laboratory experiments, numerical simulations have provided a unique tool to explore the thermomechanical and chemical consequences of equilibrium and disequilibrium phase transitions. Several authors have critically assessed the results of both laboratory and numerical studies. For instance, phase equilibria of oceanic crustal and mantle rocks in dry or wet conditions have been reviewed by (Akaogi, 2007; Irifune and Tsuchiya, 2015; Litasov and Ohtani, 2007; Ringwood, 1991; Stixrude and Lithgow-Bertelloni, 2011). A review of numerical experiments that have evaluated the role of olivine phase transitions at transition zone depths can be found in (Christensen, 1995). More recently, (Tackley, 2012) and (Hirose et al., 2015) focused on the effects of phase transformations occurring in the deep lower mantle, while (Tackley, 2015) discussed the chemical layering induced by phase transitions in a compositionally differentiated mantle. (Kirby et al., 1996) have

summarized the effects of olivine and pyroxene disequilibrium transformations within the cold lithospheric mantle, although with particular emphasis on deep earthquakes and strain localization.

The aim of this review paper is to provide a comprehensive and updated description of solid–solid phase transformations at equilibrium and disequilibrium conditions and of their effects on mantle convection. In the first part of the review we introduce equilibrium phase transitions in mafic and ultramafic rocks that participate actively to mantle convection (in this respect, solid–solid phase transitions in the continental crust and sediments will be only marginally considered). The second part deals with disequilibrium transformations that are relevant in cold and dry lithospheric environments where metastable phases may survive beyond the equilibrium boundary due to the sluggish reaction kinetics. Here, an additional section regarding the thermokinetic modelling perspective and seismological evidence for the presence of deep metastable regions is provided. For both equilibrium and disequilibrium reactions we discuss the thermomechanical and chemical implications, together with a brief description of the numerical methods commonly employed in mantle convection simulations to account for phase transitions.

2. Equilibrium phase transitions

2.1. Phase equilibria and major solid–solid phase transitions in the oceanic crust and mantle

A widely accepted petrological model for the upper mantle that is used to explain formation by decompressional melting of a petrologically and chemically stratified oceanic plate is pyrolite (Ringwood, 1991). Oceanic plates formed at oceanic ridges with medium to high spreading rates are composed of a 6–7 km thick crust with enriched MORB composition, overlying a 5–20 km thick depleted harzburgitic layer and deeper lherzolitic/pyrolitic layers that have experienced successively smaller degrees of partial melting (Ringwood, 1982). In the following discussion we will review the phase equilibria and the most important phase transitions obtained in laboratory experiments at different mantle depths and for the different oceanic plate bulk rock compositions. We should bear in mind, however, that several discrepancies exist among experimentally determined phase boundaries, since they are affected by the experimental procedure, the kinetics of transformation, pressure standards and equations of state used for pressure calibration (with increasing depth, the predicted pressures can differ by several GPa, yielding different depths and Clapeyron slopes), difficulties in estimating the correction for measured temperatures at high pressure, and different sample composition (Ohtani and Sakai, 2008).

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