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Wet plume atop of the flattening slab: Insight into intraplate volcanism in East Asia

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ABSTRACT

Geophysical observations imply the intraplate volcanism in East Asia is related to dehydration of slab stagnating in the transition zone. To better understand the dynamics of such process, a thermochemical mantle convection model is constructed to simulate numerically the thermal evolution of slab and the transportation of water in the process of slab downgoing, flattening and stagnation. Equation of water transfer is included, and water effects on density and viscosity are considered. Model results indicate the warming of slab by surrounding mantle is rather slow. Water could be successfully dragged into the transition zone if the reference viscosity of the hydrous layer (with initial water of 2 wt%) is higher than 10^{17} Pa s and that of mantle is 10^{21} Pa s. Wet plumes could then originate in the flat-lying part of the slab, relatively far from the trench. Generally, the viscosity of the hydrous layer governs the initiation of wet plume, whereas the viscosity of the overlying mantle wedge controls the activity of the ascending wet plumes – they are more active in the weaker wedge. The complex fluid flow superposed by corner flow and free thermal convection influences greatly the water transport pattern in the upper mantle. Modeling results together with previous modeling infer three stages of water circulation in the big mantle wedge: 1) water is brought into the mantle transition zone by downward subducting slab under some specific thermo-rheological conditions, otherwise water is released at shallow depth near wedge tip; 2) wet plume generates from surface of the flattening slab warmed by surrounding mantle, and 3) water spreads over the big mantle wedge. Wet plume from the flattening Pacific Plate arrives at the lithospheric base and induces melting, which can explain the intraplate Cenozoic volcanoes in East Asia.

1. Introduction

1.1. Water and slab dynamics

Water in mantle minerals plays a significant role in mantle dynamics by effectively reducing the density, viscosity, and melting temperature of rocks. Many numerical experiments have been conducted focusing on water circulation and its dynamical effects on mantle dynamics. For example, some mantle convection modeling incorporated subduction of seawater and its redistribution in the whole mantle (Richard et al., 2002; Fujita and Ogawa, 2013; Nakagawa et al., 2015), and the importance of water in the global-scale mantle dynamics has been continuously revealed. Numerous numerical models of subduction have been published that addressed various aspects of geodynamic consequences of fluid and melt in subduction zone, such as occurrence of plate tectonics and the dynamical process of subduction (Mackwell et al., 1998; Regenauer-Lieb and Branlund, 2001; Stern, 2002; van Thienen et al., 2004; Gerya et al., 2008; Gerya and Meilick, 2011). Moreover, slab dehydration and its effects on volcanism, including small scale convection in the mantle wedge, thermal–chemical plume development and magmatic productivity, have attracted lots of numerical simulation too (Gerya et al., 2004; Richard and Bercovici, 2009; Richard and Iwamori, 2010; He, 2014; Sheng et al., 2016).

According to the minerals and to the pressure and temperature conditions, water can be present in different forms: as free water, as H_2O form in hydrous minerals, or as point defects in nominally anhydrous minerals NAMs). Numerical models of the water content and transportation can be divided into two categories: petrolo gical–thermo-mechanical models (Gerya et al., 2004; Gerya and Meilick, 2011; Vogt et al., 2012; Quinquis and Buiter, 2014; Wilson et al., 2014; Sheng et al., 2016) and thermochemical mantle convection models (Richard et al., 2002; Richard and Bercovici, 2009; Richard and Iwamori, 2010; Fujita and Ogawa, 2013; Nakagawa et al., 2015).

In studies of the subduction dynamics, the coupled petrologi cal–thermo-mechanical numerical models have been widely used

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(Gerya et al., 2004; Gerya and Meilick, 2011; Vogt et al., 2012; Sheng et al., 2016). They solved the momentum, continuity, and temperature equations within the framework of the two-dimensional creeping-flow approximation and considered both thermal and chemical buoyancies. For this method, water content is usually determined in wt% as a function of pressure, temperature and bulk composition (based on phase diagrams) (Arcay et al., 2005; Iwamori, 2007; Gerya and Meilick, 2011; Wada et al., 2012; Hebert and Montési, 2013; Quinquis and Buiter, 2014; Wilson et al., 2014; Sheng et al., 2016). They focused on first-order behavior of free water migration on subduction dynamics. The migration of free water in the mantle was simplified by different approximations: 1) Imposed as a vertical velocity which is not coupled to the solid-phase flow in the mantle wedge (Arcay et al., 2005); 2) Imposed as a vertical velocity added to the velocity of the solid-phase flow (Gorczyk et al., 2007; Gerya and Meilick, 2011; Sheng et al., 2016) or as a dehydration front with an imposed horizontal and vertical velocity (Gerya et al., 2004); 3) As a Darcy flow (Cagnioncle et al., 2007; Hebert and Montési, 2013; Wilson et al., 2014). Particles are usually used to track the material field (through a material identifier) and properties such as water content (e.g. Quinquis and Buiter, 2014). Effects of free water content on mantle viscosity were not taken into account (Gerya et al., 2004; Gerya and Meilick, 2011; Wilson et al., 2014; Sheng et al., 2016).

For the second method, water content is determined by solving water transport equation (Richard et al., 2002; Richard and Bercovici, 2009; Richard and Iwamori, 2010; Fujita and Ogawa, 2013; Nakagawa et al., 2015; Nakao et al., 2016; Wang et al., 2016). Water is assumed to be bounded to or captured in minerals and transported with mantle flows. Convection diffusion equation of water can be solved either by the finite-element method or the marker-and-cell method. The mantle viscosity includes the rheological effects due to water content (Richard and Bercovici, 2009; Richard and Iwamori, 2010; Nakagawa et al., 2015; Nakao et al., 2016; Wang et al., 2016)

1.2. Wet plume and intraplate volcanism

Prominent low-velocity anomalies have been revealed above the subducting slabs where active intraplate volcanoes and geothermal anomalies exist, such as the Pacific plate under the Changbaishan volcano in Northeast China, the Eurasian lithosphere under South Taiwan, the Burma microplate under the Tengchong volcano in Southwest China, and the Indian lithospheric mantle under Tibet (Lei et al., 2013). These suggest that dehydration may take place after the plates subduct into the mantle. The upper mantle above the stagnant Pacific slab under East Asia may have formed a big mantle wedge which exhibits significantly low seismic velocity (Zhao et al., 2004, 2009, 2011; Lei and Zhao, 2005; Huang and Zhao, 2006; Zhao and Ohtani, 2009; Lei et al., 2013).

Iwamori (1992) proposed that wet plumes induced by water related to the stagnant slab could explain the Cenozoic volcanism in East Asia. Deep stagnation and dehydration of the subducted Pacific slab in the mantle transition zone might result in wet upper mantle (Shieh et al., 1998; Komabayashi et al., 2004; Ohtani et al., 2004; Huang et al., 2005), and the lowering of density of the transition zone minerals by water is likely to trigger wet plumes at the top of a stagnant slab (Richard and Bercovici, 2009). Numerical models have demonstrated that tens of kilometers thick hydrous layers above the slab might carry a considerable amount of water (e.g., ~1 wt% H_2O on the average within the hydrous layer beneath the central Japan) and reach the mantle transition zone (Iwamori, 2004; Richard et al., 2006). Richard and Iwamori (2010) simulated the wet plume induced by water from the stagnant slab. Their results confirm that the presence of water is likely to produce Rayleigh-Taylor type instabilities (wet plumes) that are able to transport water up to the base of the surficial lithosphere in a relatively short time scale, and melting can happen when wet plumes reach the lithospheric base under initial conditions representative of the subducting Pacific slab under East Asia.

In this paper, a thermochemical mantle convection model is established to investigate the water transport within the big mantle wedge in the process of slab flattening. It differs from previous modeling which focused either on the formation of cold and buoyant diapirs rising from the subducting slab surface near the wedge tip at shallow depth (<150 km) associated with the 'choke-point' (Gerya and Yuen, 2003; Gerya et al., 2004) or on the wet plume from the stagnant slab (Richard and Iwamori, 2010). This modeling concerns about the thermo-rheological conditions of both the slab and wedge mantle under which the water can be successfully brought into the transition zone and discuss their effects on wet plume generation and the water transport behavior.

2. Model setup

2.1. Equations

To describe the mantle thermal convection and water transport during subduction, flattening and stagnation, we use the laws of conservation of mass, momentum, energy and water:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\nabla \cdot [-P\mathbf{I} + \eta(\nabla\mathbf{u} + (\nabla\mathbf{u})^T)] + \Delta\rho g = 0 \tag{2}$$

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \cdot (-k\nabla T) + \rho c_p \mathbf{u} \cdot \nabla T = A \tag{3}$$

$$\frac{\partial H}{\partial t} - \kappa_H \nabla^2 H + \mathbf{u} \cdot \nabla H = 0 \tag{4}$$

where $\mathbf{u}$, P, T, and H represent velocity, pressure, temperature and water content (wt%), respectively. t is time, η viscosity, g gravity acceleration, ρ density, c_p specific heat, k thermal conductivity, A radiogenic heat production, and κ_H the water diffusivity.

Water bounded to or captured in the mineral is transported with mantle flows, as expressed by the convection diffusion Eq. (4). Because the modeling focuses on the effect of water on viscosity, the rheology is assumed to be Newtonian, which is commonly made in the studies of small-scale sublithospheric convection (e.g. Hunen et al., 2003; Richard and Bercovici, 2009; Richard and Iwamori, 2010; He, 2014). Following Richard and Iwamori (2010), it assumes:

$$\eta = \eta_0 H^{-r} e^{-(E^* + PV^*)(T - T_0)} \tag{5}$$

where T_0 is the reference temperature corresponding to the reference viscosity η_0. E^* and V^* are constant proportional respectively to the activation enthalpy and volume, and r an experimentally determined parameter [$r = 1$, (Karato, 2006)].

Density is also temperature and water dependent. In Eq. (2), $\Delta\rho$ denotes a density anomaly with

$$\Delta\rho = \rho_0 \alpha \Delta T + \beta H \tag{6}$$

where α is the coefficient of thermal expansion, and β is a coefficient expressing the linear dependency of the density on water content. Since β has not been explicitly measured for wadsleyite and ringwoodite, Richard and Bercovici (2009) used a first-order approximation which was extracted from published data (Inoue et al., 1998; Angel et al., 2001). To fully account for the uncertainties, they employed a wide range for β from 1×10^{-2} to 5×10^{-2} wt%$^{-1}$, and carefully evaluated the influence of β on the dynamics. After a thorough evaluation, Richard and Iwamori