Earth and Planetary Science Letters 454 (2016) 178–191

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Effects of water transportation on subduction dynamics: Roles of viscosity and density reduction

Atsushi Nakao[a,b,*], Hikaru Iwamori[a,b], Tomoeki Nakakuki[c]

[a] Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, 152-8550, Japan
[b] Department of Solid Earth Geochemistry, Japan Agency for Marine–Earth Science and Technology, 2-15 Natsushima-cho, Yokosuka, Kanagawa 237-0061, Japan
[c] Department of Earth and Planetary Systems Science, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8526, Japan

ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 12 July 2016
Accepted 9 August 2016
Available online 21 September 2016
Editor: B. Buffett

Keywords:
water transportation
free convection
subduction dynamics
plate velocity
stagnant slab
trench migration

ABSTRACT

The effects of water on subduction dynamics, e.g., plate migration rate, slab geometry, stress field, and back-arc spreading, are investigated by using a 2-D self-consistent model for lithosphere subduction and whole mantle convection. We solve water transportation coupled with hydrous mineral phase changes. Mantle flows and water transportation are interactive through constitutive and state equations for hydrous rocks. Our model has successfully reproduced the water distribution in a mantle wedge and along the slab with sufficient resolution comparable to that of previous models that focus on the mantle wedge structure. As a result, low density owing to hydration reduces subduction rates, back-arc spreading, and slab stagnation on the phase boundary at 660-km depth, whereas low viscosity owing to hydration enhances rapid subduction, trench migration, and slab stagnation. We attribute these results to mechanisms that cause the hydrous buoyancy of subducting plates to reduce the slab pull force and the accompanying tensile stress on overlying lithosphere. In addition, hydrous weakening diminishes the mechanical coupling of the subducted slab with the wedge mantle and overriding lithosphere. Thus, water is capable of generating two opposite situations in the stress field of the overlying lithosphere and the subduction rate. Water is therefore expected to be an important mechanism for generating broad styles of the subduction structure and kinematics, as observed in actual subduction zones such as Tonga and Mariana. Such observed variation in the subduction mode can be caused by variation in buoyancy corresponding to the water content from relatively dry to several thousands of parts per million for the wedge mantle and slab surface, whereas the extremely buoyant case does not appear to occur in nature. Water in the mantle is thus key to better understand the whole-mantle-scale slab dynamics as well as island arc volcanic processes.

1. Introduction

It is widely accepted that the Earth's mantle contains water in several tens to several hundreds of parts per million according to electrical conductivity measurements of hydrous minerals and electromagnetic observations (Karato, 2011). Water in rocks causes subduction initiation (Van der Lee et al., 2008), low viscosity of the asthenosphere (Karato and Jung, 1998), magmatism in volcanic arcs (Iwamori, 1998), fault zones (Wannamaker et al., 2009), and deeper earthquakes (Yamasaki and Seno, 2003). Experimental studies have quantified the viscosity and the density of hydrous rocks, both of which are much smaller than those of dry rocks (e.g., Hirth and Kohlstedt, 2003; Inoue et al., 1998). The introduction of constitutive and state equations of hydrous rocks to fluid mechanical simulations enables assessment of the effects of water on mantle dynamics such as thinning of the overlying lithosphere (Arcay et al., 2005), growth of an accretion wedge and back-arc spreading owing to weak hydrous rocks and melts (Gerya and Meilick, 2011), and rapid water transportation by "wet plumes" of buoyant hydrous rocks above stagnant slabs (Richard and Iwamori, 2010).

These previous numerical studies have provided invaluable insight into the role of water in subduction zones by highlighting the individual physical and chemical influences of water on the wedge mantle and the overriding plate. Because of the limitation of the model domains, the influences of water on subduction dynamics including plate motions have been scarcely debated. Numerical and laboratory simulations of free convection show re-

---

[*] Corresponding author at: Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo, 152-8550, Japan.
E-mail addresses: a.nakao@geo.titech.ac.jp, atsushi.nakao@gmail.com (A. Nakao).

http://dx.doi.org/10.1016/j.epsl.2016.08.016

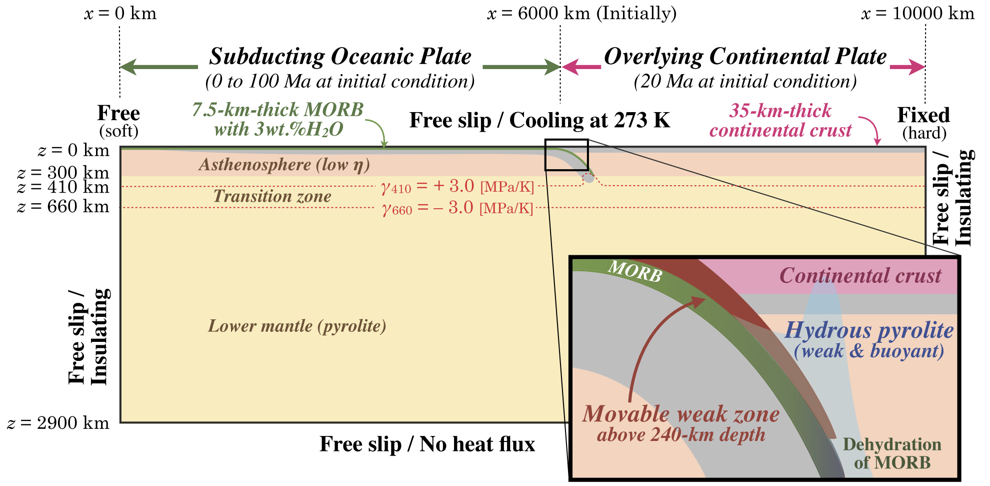

Fig. 1. Schematic diagram of the 2-D convection model. Details are described in Section 2.1.

markable acceleration/deceleration of subducting slabs associated with phase transition (e.g., Nakakuki and Mura, 2013; Schellart, 2008). In addition, seafloor age distribution analysis has revealed that the generation rates of oceanic plates have varied during the past 100 Myr (Conrad and Lithgow-Bertelloni, 2007), indicating inconstant subduction velocities in nature. However, it is still challenging to combine water transportation with a whole-mantle scale model because fine resolution is required to simulate water transportation and to apply actual rheology near the subduction zone.

This study seeks to determine the effects of water transportation on the behavior of the sinking and overlying plates integrated into the whole mantle convection. We focus on the velocity of the plates, slab deformation, the stress field of the overlying plate, and back-arc spreading by constructing a numerical model with the following characteristics: (1) free convection of whole-mantle scale without imposing velocity boundary conditions (e.g., Tagawa et al., 2007; Nakakuki and Mura, 2013), (2) phase diagrams of hydrous peridotite and hydrous basalt (Iwamori, 2007) to introduce hydration and dehydration reactions, and (3) properties of hydrous rocks formularized in constitutive and state equations. Introducing (3) makes (1) and (2) interactive. Regarding (3), we apply Arrhenius-type rheology functions for wet crystals determined experimentally (e.g., Hirth and Kohlstedt, 2003; Korenaga and Karato, 2008) and density reduction proportional to its water content (e.g., Richard and Iwamori, 2010; Horiuchi and Iwamori, 2016), both of which have been often simplified or not considered in previous studies (e.g., Rüpke et al., 2004; Arcay et al., 2005; Gerya and Meilick, 2011). Through these effects of hydration on rock properties, our simulation will demonstrate that water is not just a passive tracer in mantle flows but is an important factor in the changes of mantle flows and slab behavior.

2. Numerical settings and basic equations

2.1. Design of 2-D model and initial conditions

The 2-D domain of our model (Fig. 1) is 10,000 km in width × 2,900 km in length and includes phase boundaries at 410-km and 660-km depths, of which the effects on temperature and density are quantified in the energy conservation equation (Section 2.3) and the state equation (Section 2.5). Free slip conditions are imposed along top, bottom, and side boundaries so that the plate migration rates are controlled by the balance between the buoyancy and viscous resistance. This enables us to evaluate the effects of water on these rates. Surface temperature is constant at 273 K; therefore, as an oceanic plate migrates toward the right, the plate becomes thick as a result of cooling. Otherwise, no heat flux from the core to the mantle is assumed. In addition, insulating conditions are imposed along the side boundaries. The initial temperature of the lithosphere is determined from a cooling half-space model. The initial age of the oceanic plate is 0 Ma at the mid-ocean ridge and 100 Ma at the trench, and the initial age of the continental plate is 20 Ma. A thin, movable, and deformable weak zone dipping 27° mimicking a plate boundary is initially placed at a location 6,000 km from the left boundary. This segment has low yield strength (Section 2.4) and is transported by mantle flows (Section 2.6). Accordingly, the thickness and the angle of the weak zone change with the passage of time without synthetic forces. Although the segment extends along the slab, it does not reflect the mantle rheology below 240-km depth. Moreover, a 7.5-km-thick slab of mid-ocean ridge basalt (MORB) and a 35-km-thick slab of continental crust are placed along the surface, both of which are transported by convection.

The model domain is much larger than that of previous 2-D models (Arcay et al., 2005; Gerya and Meilick, 2011; Horiuchi and Iwamori, 2016). In order to derive fine solution around the subduction zones without consuming extensive computation time, we used a dual grid system developed by Tagawa et al. (2007), which includes a variable grid for equation of motion (Section 2.2) and a uniform grid for heat and marker transportation (Sections 2.3 and 2.6).

2.2. Mass and momentum conservation

All symbols used in the following equations are listed in Table 1.

We assume the mantle to be a 2-D incompressible, highly viscous fluid, the motion of which can be described as

$$\left(\frac{\partial^2}{\partial x^2}-\frac{\partial^2}{\partial z^2}\right)\left[\eta\left(\frac{\partial^2\psi}{\partial x^2}-\frac{\partial^2\psi}{\partial z^2}\right)\right]+4\frac{\partial^2}{\partial x\partial z}\left(\eta\frac{\partial^2\psi}{\partial x\partial z}\right)=\frac{\partial\rho}{\partial x}g, \tag{1}$$

where stream function ψ is defined by

$$\boldsymbol{v}=(u,w)\equiv\left(\frac{\partial\psi}{\partial z},-\frac{\partial\psi}{\partial x}\right). \tag{2}$$

Because we introduce water-dependent viscosity η and density ρ (Sections 2.4 and 2.5), the motion of mantle rocks is affected by hydration–dehydration reactions.