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2D and 3D numerical models on compositionally buoyant diapirs in the mantle wedge

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ABSTRACT

We present 2D and 3D numerical model calculations that focus on the physics of compositionally buoyant diapirs rising within a mantle wedge corner flow. Compositional buoyancy is assumed to arise from slab dehydration during which water-rich volatiles enter the mantle wedge and form a wet, less dense boundary layer on top of the slab. Slab dehydration is prescribed to occur in the 80–180 km deep slab interval, and the water transport is treated as a diffusion-like process. In this study, the mantle's rheology is modeled as being isoviscous for the benefit of easier-to-interpret feedbacks between water migration and buoyant viscous flow of the mantle. We use a simple subduction geometry that does not change during the numerical calculation. In a large set of 2D calculations we have identified that five different flow regimes can form, in which the position, number, and formation time of the diapirs vary as a function of four parameters: subduction angle, subduction rate, water diffusivity (mobility), and mantle viscosity. Using the same numerical method and numerical resolution we also conducted a suite of 3D calculations for 16 selected parameter combinations. Comparing the 2D and 3D results for the same model parameters reveals that the 2D models can only give limited insights into the inherently 3D problem of mantle wedge diapirism. While often correctly predicting the position and onset time of the first diapir(s), the 2D models fail to capture the dynamics of diapir ascent as well as the formation of secondary diapirs that result from boundary layer perturbations caused by previous diapirs. Of greatest importance for physically correct results is the numerical resolution in the region where diapirs nucleate, which must be high enough to accurately capture the growth of the thin wet boundary layer on top of the slab and, subsequently, the formation, morphology, and ascent of diapirs. Here 2D models can be very useful to quantify the required resolution, which we find for a 10^{19} Pa · s mantle wedge to be about 1 km node spacing for quadratic-order velocity elements.

1. Introduction

Subduction of oceanic lithosphere is associated with the formation of volcanic arcs, hence the generation of melts in the mantle wedge between the descending slab and the overriding plate. A combination of two mechanisms is potentially responsible for this melt generation (Pearce and Peate, 1995): a decrease of the mantle solidus temperature due to the presence of aqueous fluids rising from the dehydrating slab and adiabatic decompression melting of mantle rocks. There is a clear relationship between the amount of water added and the degree of volatile-induced melting (Stolper and Newman, 1994) on the one hand, and an inverse correlation between the thickness of the overriding lithosphere (acting as the upper barrier to mantle upwelling) and the amount of decompression melting on the other hand (Pearce and Peate, 1995; Plank and Langmuir, 1988). The importance of decompression melting for subduction zone volcanism is further emphasized by the similarities between melts generated at subduction zones and mid-ocean ridges (Plank and Langmuir, 1988).

Early numerical models for subduction zones (e.g. Davies and Stevenson, 1992) could not explain a significant upward motion of the mantle unless they allow for regions with positive buoyancy in the mantle wedge. Without these density anomalies the predicted flow field is similar to the analytical solution for isoviscous corner flow (Batchelor, 1967), which has been frequently used by studies focusing on the thermal evolution of subduction zones (e.g. Gutscher and Peacock, 2003; Peacock, 1991; Peacock et al., 1994) or the transport of water (e.g. Iwamori, 1998). A diagonal upward flow toward the tip of the mantle wedge is predicted by 2D numerical models that include a viscously deforming overriding plate (e.g. Eberle et al., 2002; Kelemen et al., 2003). Using a non-Newtonian rheology for the mantle rocks seems to support the development of this type of flow field (van Keken et al., 2002). More complex 2D numerical models that include different rheological units such as oceanic sediments, basaltic crust

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and dry/wet mantle rocks, phase transitions and partial melting (e.g. Gerya and Yuen, 2003; Gorczyk et al., 2006) show rotating flow fields and plume-like wet diapirs that are difficult to interpret in the context of a three-dimensional subduction zone.

Since it has been first suggested that mantle diapirism could underlie most arc volcanoes (Marsh and Carmichael, 1974) more studies have provided evidence that three-dimensional features are present inside the mantle wedge. Along-trench variations in seismic attenuation (Nakajima and Hasegawa, 2003) and seismic velocities (Zhao et al., 2009) at the Honshu subduction zone have been found to correlate with clustering of volcanic centers (Tamura et al., 2002). Honda and coworkers (e.g. Honda and Yoshida, 2005; Honda et al., 2007) suggest small-scale convection is the cause for these patterns and present 2D and 3D numerical models that have in common that they include a fixed low viscosity region within the wedge. They observe thermal instabilities resulting from conductive cooling from the top that form roll-like instabilities, so-called "Richter rolls" (Richter and Parsons, 1975), within the low-viscosity mantle wedge. These rolls have rotation axes parallel to the shallow mantle flow toward the trench. A recent 3D model by Zhu et al. (2009) predicts diapiric upwellings of various morphologies, but is very complex as it includes several mechanisms that strongly feedback into each other (e.g. different rheological units, thermodynamic phase transitions, water migration, a continuously changing subduction geometry because the trench rollback is used to approximately simulate the effects of a down-going slab). A somewhat simplified version of this model (Honda et al., 2010) predicts small-scale convection patterns if there is a small amount of chemical buoyancy (dispersed as tracer-particles) in the mantle wedge and more 2D-like flow patterns if there is a lot of chemical buoyancy.

In this study we present 2D and 3D numerical models for solid-state mantle flow and a diffusively migrating water-rich volatile phase in the mantle wedge. The subduction zone geometry is fixed during all runs, with a kinematically prescribed slab subducting at a constant angle. All model calculations are isoviscous, and we assume that dehydration of the subducting slab yields the formation of a hydrated and buoyant layer on top of the slab that has the potential to become buoyantly unstable and create diapiric upwellings. The present study may therefore be viewed as a physical study of buoyant viscous flow in the mantle wedge rather than an attempt to model the history of a specific subduction zone. We compare the predictions of 2D and 3D numerical models with identical parameters to evaluate how much intuition can be drawn from the 2D models. This comparison is of great importance since many complex models on subduction zones (e.g. Cagnioncle et al., 2007; Gerya and Yuen, 2003; Gorczyk et al., 2006; Lee and King, 2009; Syracuse et al., 2010) use two-dimensional models due to computational limitations. We will also show that a numerical resolution of at least 1–1.5 km near the slab is necessary in 2D and 3D models to obtain accurate results for this specific geodynamic problem.

2. Numerical model

2.1. Governing equations

To examine solid-state mantle flow and the advection–diffusion of a water-rich volatile phase in the mantle wedge we have formulated numerical models in two- and three-dimensional Cartesian coordinates. We describe the mantle as an incompressible, viscous fluid with infinite Prandtl number and apply the Boussinesq approximation, that is, density differences are only accounted for in the buoyancy force term. Using the index notation and Einstein summation convention, the governing equations can be written as

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial p}{\partial x_i} = \frac{\partial \tau_{ij}}{\partial x_j} - \rho g e_z \tag{2}$$

$$\tau_{ij} = \eta\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

with Eq. (1) satisfying conservation of mass by imposing incompressibility, Eq. (2) describing the force balance to ensure conservation of momentum, and Eq. (3) being the constitutive law. τ_{ij} denotes deviatoric stress tensor, η dynamic viscosity (which is constant in each experiment), u velocity, x physical coordinate, p pressure, g gravitational acceleration, ρ density and e_z the unit vector in the vertical direction. For a complete list of variables, their meaning, units, and values the reader is referred to Table 1. In our model buoyancy-driven flow is solely caused by density variations arising from the water content of the mantle rocks. The bulk density of the mantle rocks is calculated using

$$\rho(C) = (1 - C)\rho_M + C\rho_C \tag{4}$$

with ρ_M being the density of dry mantle rocks, C the volume fraction of water in the rock, and ρ_C the density of water. Note that the density of serpentinite is reasonably well approximated by this treatment. We choose to not solve for the thermal evolution within the mantle wedge to better indicate the effects of compositional buoyancy on mantle flow.

The migration of water relative to the mantle is modeled as a diffusion process in which we can vary a single easy-to-interpret diffusivity parameter. Temporal changes in the water concentration field C are calculated using an advection–diffusion equation

$$\frac{\partial C}{\partial t} = \gamma\left(\frac{\partial^2 C}{\partial x_i^2}\right) - u_i \frac{\partial C}{\partial x_i}. \tag{5}$$

Here u is the flow field of the mantle and γ the effective migration diffusivity assumed for water. Diffusivity in this context can be viewed as the mobility of volatiles in the mantle, allowing the fluid to migrate into all spatial directions without a preferred orientation. For the present study we favor the diffusion formulation over a vertical Darcy flow formulation because the latter strongly depends on mantle rock permeability, which is a poorly constrained parameter. Furthermore, we found that a purely vertical water migration scheme (superimposed on the mantle flow field) forces the instabilities to preferentially develop above the slab dehydration region. Patterns

Table 1
List of variables used in this study.

Variable	Meaning	Value, units
u	Velocity	km Myr^{-1}
p	Pressure	Pa
τ	Stress tensor	Pa
η	Dynamic viscosity	Pa · s
g	Gravitational acceleration	m s^{-2}
e_z	Unit vector in vertical direction	1
ρ	Density	kg m^{-3}
ρ_M	Dry mantle density	3300 kg m^{-3}
ρ_C	Water density	1000 kg m^{-3}
C	Volume fraction of water in mantle	1
γ	Water diffusivity	m^2 s^{-1}
t	Time	Myr
d_{BL}	Thickness of boundary layer (BL)	km
ρ_{BL}	Average density of BL	kg m^{-3}
Ra_{BL}	Local Rayleigh number of BL	1
d_C	Thickness of hypothetical water layer	km
V_S	Velocity of rising Stokes sphere	km Myr^{-1}
V_z	Vertical velocity of slab	km Myr^{-1}
R_V	Ratio between V_S and V_z	1