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Key Points:
- This study explores thermal and chemical evolution of diapirs rising through the mantle wedge
- We use a two-phase Darcy-Stokes-energy model to investigate thermal evolution, melting, and melt segregation in such a diapir
- Melt migration in ascending diapir segregates interior from outer rim; segregation may be preserved, if the diapir leaks melt during ascent

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3
- Data Set S4
- Data Set S5
- Data Set S6

Correspondence to:
N. Zhang,
nan_zhang@pku.edu.cn

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Melt Segregation and Depletion During Ascent of Buoyant Diapirs in Subduction Zones

Nan Zhang[1,2,3], Mark D. Behn[1,4], E. Marc Parmentier[5], and Christopher Kincaid[6]

[1]Department of Geology and Geophysics, Woods Hole Oceanography Institution, Woods Hole, MA, USA, [2]Key Laboratory of Orogenic Belts and Crustal Evolution, School of Earth and Space Sciences, Peking University, Beijing, China, [3]Earth Dynamics Research Group, Department of Applied Geology, Curtin University, Perth, Western Australia, Australia, [4]Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA, USA, [5]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA, [6]School of Oceanography, University of Rhode Island, Narragansett, RI, USA

Abstract Cold, low-density diapirs arising from hydrated mantle and/or subducted sediments on the top of subducting slabs have been invoked to transport key chemical signatures to the source region of arc magmas. However, to date there have been few quantitative models to constrain melting in such diapirs. Here we use a two-phase Darcy-Stokes-energy model to investigate thermal evolution, melting, and depletion in a buoyant sediment diapir ascending through the mantle wedge. Using a simplified 2-D circular geometry, we investigate diapir evolution in three scenarios with increasing complexity. In the first two scenarios we consider instantaneous heating of a diapir by thermal diffusion with and without the effect of the latent heat of melting. Then, these simplified calculations are compared to numerical simulations that include melting, melt segregation, and the influence of depletion on the sediment solidus along pressure-temperature-time (*P-T-t*) paths appropriate for ascent through the mantle wedge. The high boundary temperature induces a rim of high porosity, into which new melts are focused and then migrate upward. The rim thus acts like an annulus melt channel, while the effect of depletion buffers additional melt production. Solid matrix flow combined with recrystallization of melt pooled near the top of the diapir can result in large gradients in depletion across the diapir. These large depletion gradients can either be preserved if the diapir leaks melt during ascent, or rehomogenized in a sealed diapir. Overall our numerical simulations predict less melt production than the simplified thermal diffusion calculations. Specifically, we show that diapirs whose ascent paths favor melting beneath the volcanic arc will undergo no more than ~40–50% total melting.

1. Introduction

As early as the 1970s, Marsh and Carmichael (1974) suggested that the spacing of arc volcanoes was related to the development of gravitational instabilities formed from a thin "ribbon" of buoyant melt pooled along the surface of the subducting slab. More recently, Hall and Kincaid (2001) invoked the rapid ascent of melt diapirs to explain U-series disequilibrium observed in many arc lavas (e.g., Ivanovich & Harmon, 1982). Other sources of buoyancy have also been proposed to drive diapirism from the descending slab. Gerya and Yuen (2003) proposed the development of "cold plumes" that originate from a layer of buoyant hydrated mantle lying just above the downgoing slab. Numerical models suggest that such cold plumes can be up to tens of kilometers in diameter, entrain significant amounts of sediment/crustal material from the slab, and dramatically influence the thermal and chemical dynamics of the mantle wedge (Castro & Gerya, 2008; Gerya & Yuen, 2003; Gorczyk et al., 2006; Marschall & Schumacher, 2012; Nielsen & Marschall, 2017; Zhu et al., 2009). Others have argued that subducted sediments may be the primary source of buoyancy, invoking a model in which sediment diapirs rise and melt as they ascend through the mantle wedge (Behn et al., 2011; Currie et al., 2007; Kelemen et al., 2003, 2003; Miller & Behn, 2012; Spencer et al., 2017). Diapiric ascent from a sedimentary layer has been used to explain both the ubiquitous presence of a "sediment signature" (enrichment in fluid-immobile elements such as Ba, Th, Be, Pb, and other light rare earth elements) in arc lavas (e.g., Elliott et al., 1997; Hawkesworth et al., 1997; Plank & Langmuir, 1993), as well as geochemical constraints that indicate this melting occurs dominantly in the mantle wedge as opposed to on the slab surface (Behn et al., 2011). However, while there is accumulating evidence that diapirs play an important role in subduction zone dynamics (Cruz-Uribe et al., 2018; Liu et al., 2015; Marschall

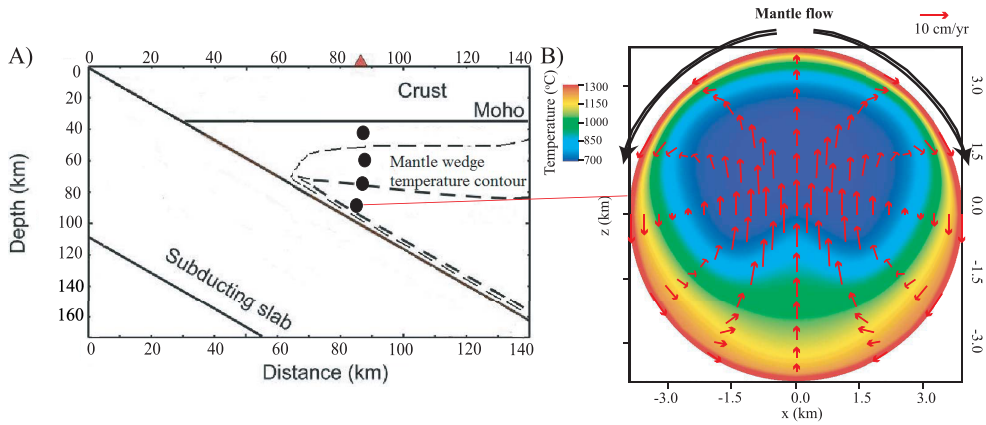

Figure 1. (a) Schematic showing the ascent of a sediment diapir through the mantle wedge and (b) solid velocity field inside an ascending diapir associated with the Stokes flow on the margins. A 3.5-km radius diapir with a density of 3,000 kg/m^3 is calculated to move upward at a velocity of 10 cm/year assuming a mantle wedge viscosity of 5×10^{18} Pa·s. Here the velocity field is used to calculate a representative internal temperature field assuming no melting.

& Schumacher, 2012; Nielsen & Marschall, 2017), there have been few quantitative modeling studies that investigate both the solid advection of buoyant material, as well as the physical process of melting, melt segregation, and depletion in these environments. Such models are necessary to better understand the depletion of ultrahigh-pressure rocks that record the residues of this melting process (Hacker et al., 2005) and the relationship between melt segregation and the observed "sediment signature" in arc lavas.

Here we focus on the physical processes of thermal evolution, melting, and melt segregation within the end-member of an ascending sediment diapir, acknowledging that the composition of diapirs in natural settings may involve more complex mixtures of sediment and hydrated crustal and mantle rocks. As a buoyant diapir rises from the cold slab top through the hot mantle wedge, the surrounding mantle will heat the diapir, promoting melting along its boundary (e.g., Ghods & Arkani-Hamed, 2002). Melt generated at the boundary will in turn segregate and migrate within this deforming matrix. The resulting melt-matrix interaction plays a key role in fractionating volatile and incompatible elements within the diapir and in turn influences its chemical evolution of the depleted residuum.

Melt migration in ascending mantle plumes has been investigated in previous studies. Ghods and Arkani-Hamed (2002) and Schmeling (2000) studied melt migration in hot plumes rising through the upper mantle. These studies modeled a plume in a continuous compacting porous media, in which the plume is driven by thermal buoyancy and deforms along its path toward the surface. Both studies found a region of high melt fraction concentrated at the top of the plume, and that the high melt fraction region ascends faster than the bulk of the plume. However, neither of these studies investigated the dynamics of a fertile, compositionally buoyant diapir that is chemically distinct from the surrounding mantle. In the closest related study, Katz and Rudge (2011) investigated energy conservation in a fertile heterogeneity ascending through the mantle and estimated the evolution of the average melt fraction within the heterogeneity. Their model predicts that thermal diffusion into a spherical heterogeneity can produce >50% melt for bodies with diameters smaller than ~1 km. However, Katz and Rudge (2011) did not explore the migration and segregation of these melts or the depletion of the residue during diapir ascent.

In this study, we investigate melt generation and migration in a cold, fertile sediment diapir (Figure 1) rising from a subducting slab and heating and convecting during ascent through the mantle wedge. Diapir geometry is simplified as a two-dimensional (2-D) circle and pressure-temperature-time (*P*-*T*-*t*) ascent paths are estimated from subduction zone thermal models. Two-phase flow simulations are used to calculate melting and depletion within the diapir. We find that melts preferentially migrate upward within an annulus channel at the margins of the diapir where conductive heating generates a melt-rich, high permeability layer. Depletion of the margins buffers additional melt production and promotes the creation of strong chemical gradients within the diapir, with a highly depleted (and more refractory) rim surrounding a less depleted and more primitive interior.

2. Model Description and Methods

2.1. Model and Mathematical Formulation

We use a numerical model to investigate the internal structure of an ascending diapir as it rises through the mantle wedge of a subduction zone. The internal melt-solid two-phase flow is calculated assuming a fixed diapir morphology, in which the diapir head is simplified as a 2-D circle. This simplification is reasonable based on previous laboratory and numerical experiments (Hall & Kincaid, 2001; Marsh, 1979; Miller & Behn, 2012), which show little deformation of the diapir head during ascent. This 2-D circle can be easily implemented with the software package we use (see section 2.5). Using this 2-D circular geometry, we model two-phase flow of the melt and matrix along pressure-temperature-time (*P*-*T*-*t*) trajectories appropriate for ascent of a diapir through an idealized mantle wedge. Limitations of our simplified geometry and avenues for future research are discussed in section 4.2.

2.2. Two-Phase Flow

Our treatment of two-phase melt migration is based on McKenzie (1984) and the subsequent reanalysis by Spiegelman et al. (2007). Mass conservation for the melt and total solid take the form

$$\frac{\partial \phi}{\partial t} + \nabla \cdot \left(\phi \vec{v}\right) = \dot{\Gamma} \tag{1}$$

$$\frac{\partial (1-\phi)}{\partial t} + \nabla \cdot \left((1-\phi)\vec{W}\right) = -\dot{\Gamma} \tag{2}$$

where ϕ is the porosity, t is the time, $\vec{v}$ and $\vec{W}$ are the melt and solid velocities, respectively, and $\dot{\Gamma}$ is the melting/crystallization rate. These mass conservation formulations neglect the change in melt density during melting (McKenzie, 1984). The force balance for melt follows Darcy's law

$$\vec{S} = \phi\left(\vec{v} - \vec{W}\right) = -\frac{K}{\mu}\left(\nabla P - \Delta\rho g \vec{e_z}\right) \tag{3}$$

where $\vec{S}$ is the Darcy flux, K is the permeability, μ is the melt viscosity, P is the effective pressure (Phipps, 1987), $\Delta\rho = \rho_s - \rho_f$ is the density difference between the solid and the melt, g is the gravitational acceleration, and $\vec{e_z}$ is the unit vector (positive upward). Permeability depends on porosity through a power law relation (von Bargen & Waff, 1986; Wark & Watson, 1998):

$$K = \frac{d^2}{C}\phi^n \tag{4}$$

where d is grain size and C is a geometrical factor. The exponent n takes on values of 1–3 (Riley & Kohlstedt, 1991; Wark et al., 2003; Wark & Watson, 1998; Zhu & Hirth, 2003). Following recent experimental studies (Miller et al., 2014), we choose $n = 3$ for the simulations shown in this study. A constant grain size of 1 cm is used in all simulations based on the average value for the mantle wedge from Wada et al. (2011).

Similar to Scott and Stevenson (1986), we approximate the difference between the melt and the solid pressures by compaction rate of the matrix $(\nabla \cdot \vec{W})$ times bulk viscosity ξ (McKenzie, 1984),

$$P_c = P_f - P_s = \xi \nabla \cdot \vec{W}, \tag{5}$$

where

$$\xi = \frac{\eta}{\phi} \tag{6}$$

and η is the shear viscosity of the solid, which is assumed to be constant in our calculations.

This implies that differences between the solid and fluid pressure drive volume changes of the solid matrix, for example, the matrix will expand if the fluid pressure exceeds the solid pressure ($P_f > P_s$). This formulation is consistent with the derivation of Scott and Stevenson (1984, 1986). In the simulations considered here, we assume that the shear viscosity (Hirth & Kohlstedt, 2004) of the mantle wedge is constant.

5. Conclusions

1. Using instability analyses we predict that the radii of sedimentary diapirs arising from sediment layers 0.2–1.1 km thick are between 0.7 and 3.7 km, and diapirs with radii between 2.4 and 3.7 km will ascend and melt within 25 km of the volcanic arc at subduction zones. Smaller diapirs will detach farther downdip on the slab surface leading to ascent paths that do not transit the mantle wedge beneath the volcanic arc.
2. Numerical two-phase flow calculations indicate that diffusive heating of a sedimentary diapir as it ascends through the hot corner of the mantle wedge will produce melts that form an annular channel of high porosity and high permeability along the margin of the diapir. As the diapir heats during ascent into the hot core of the mantle wedge, new melts are focused into this channel, migrating upward and accumulating near the top of the diapir. Melt segregation is driven primarily by the pressure difference between the high porosity channel and the low porosity interior. Such a high porosity annular melt channel leads a strong depletion gradient from the central portion of the diapir to the exterior. During ascent, depletion variations induced by the melt channel can range from 1–2% near the center, to just under ~100% near the base of the diapir. For an impermeable diapir, the depletion heterogeneity is homogenized in the final crystallization stage. Permeable diapirs would flatten due to loss of melt to the surrounding mantle, but the residue would retain an annular pattern of depletion.
3. Our numerical results indicate that most diapirs (even those that thermally equilibrate with the hot core of the mantle wedge) do not undergo complete melting and indeed have lower average melt fractions than predicted from simple scaling analyses for thermal diffusion. Diapirs whose ascent paths favor melting beneath the volcanic arc will undergo no more ~40–50% total melting. Further only 10–30% melting occurs at temperatures >1050 °C required to generate the sediment signature in arc lavas.
4. In summary, thick sediment layers generate large diapirs that ascend rapidly along relatively cool *P-T-t* paths through the mantle wedge. The resultant diapirs undergo relatively little melting and chemical fractionation during their ascent, leading to the relamination of relatively unmelted sediments at the base of the crust. By contrast, smaller diapirs that ascend more slowly along longer, hotter *P-T-t* paths will undergo more extensive melting (at higher temperatures). In this scenario, a sediment signature can be imparted to arc volcanoes through melt escaping from the diapir and transiting the mantle wedge by porous flow.

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