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Subduction-triggered magmatic pulses: A new class of plumes?

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A B S T R A C T

A variety of atypical plume-like structures and focused upwellings that are not rooted in the lower mantle have recently been discussed, and seismological imaging has shown ubiquitous small-scale convection in the uppermost mantle in regions such as the Mediterranean region, the western US, and around the western Pacific. We argue that the three-dimensional return flow and slab fragmentation associated with complex oceanic subduction trajectories within the upper mantle can generate focused upwellings and that these may play a significant role in regional tectonics. The testable surface expressions of this process are the outside-arc alkaline volcanism, topographic swell, and low-velocity seismic anomalies associated with partial melt. Using three-dimensional, simplified numerical subduction models, we show that focused upwellings can be generated both ahead of the slab in the back-arc region (though ~five times further inward from the trench than arc-volcanism) and around the lateral edges of the slab (in the order of 100 km away from slab edges). Vertical mass transport, and by inference the associated decompression melting, in these regions appears strongly correlated with the interplay between relative trench motion and subduction velocities. The upward flux of material from the depths is expected to be most pronounced during the first phase of slab descent into the upper mantle or during slab fragmentation. We discuss representative case histories from the Pacific and the Mediterranean where we find possible evidence for such slab-related volcanism.

1. Introduction

A variety of thermal plumes, including splash (Davies and Bunge, 2006), baby (e.g., Wilson and Downes, 2006) and edge (King and Ritsema, 2000) plumes, have been recently described as focused vertical upwellings that are not directly rooted in the lower mantle, as would be predicted by the original hotspot model (Courtillot et al., 2003; Morgan, 1971). Moreover, high-resolution seismological images have shown a large amount of apparent small-scale convective heterogeneities in the uppermost mantle of margins such as the western US (e.g., Sigloch et al., 2008; West et al., 2009) and the Mediterranean (Faccenna and Becker, 2010). Small scale mantle flow could explain, for example, the velocity distribution beneath the Rio Grande Rift (van Wijk et al., 2008), the uplift and magmatism of the Colorado plateau (Roy et al., 2009) and extension beneath the Great basin (West et al., 2009). Subcontinental small-scale convection may be also excited by sharp temperature gradients at a craton's edge, where decompression melting may cause volcanism (King and Anderson, 1995). Here, we suggest an indirect connection to slab return flow, which may interact with a hydrated layer in the transition zone (Leahy and Bercovici, 2007) to facilitate localized upwellings.

In several regions, there is evidence for volcanism that is spatially and temporally connected to subduction zones but not associated with mantle wedge melting. Related magmas show ocean island basalt (OIB)-type signatures developing from volcanoes located either far off the arc, ahead of the trench, or at slab edges. Relationships between subduction and anomalous volcanism, though already postulated to explain regional cases of intraplate magmatic activity (Changbai volcano, East Asia: Zhao et al., 2009; New Hebrides-North Fiji: Lagabrielle et al., 1997; Mediterranean-European: Goes et al., 1999; Piromallo et al., 2008; Lustrino and Wilson, 2007), have never been framed and modeled in a subduction-related convecting system.

The purpose of this work is to illustrate that subduction within the upper mantle could generate focused, sub-lithospheric, non-thermal mantle upwellings. The surface expressions of these small-scale convective features are outside-arc alkaline volcanism, positive non-isostatic topography and melting zones seismically recorded in the mantle as low-velocity anomalies. We show that focused upwellings are likely generated around the slab (at the lateral edges or ahead of the back-arc region) and are most pronounced during the first phase of subduction into the upper mantle, or after the occurrence of slab

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fragmentation. We first illustrate the process by presenting the results of simplified three-dimensional (3D) convection models and, afterward, we discuss several natural case studies that satisfactorily illustrate the proposed mechanism.

2. Mantle circulation during subduction

The downwelling of cold lithospheric material into the mantle triggers return flow, which has been extensively investigated in the context of the subduction wedge, the uppermost region confined between the slab and the overriding plate. Convection models have evaluated the overall flow produced by a single slab. For example, Garfunkel et al. (1986) modeled such circulation by means of two-dimensional (2D) Cartesian calculations evaluating how the 660-km viscosity jump and trench rollback can influence streamlines. The 2D cylindrical models by Zhong and Gurnis (1995) confirmed the close dependence of trench migration and mantle return flow patterns for a self-consistently subducting lithosphere with a fault. Enns et al. (2005) analyzed the influence of slab strength, thickness and side boundary conditions on 2D mantle circulation. Some of the first 3D subduction models were performed experimentally by Buttles and Olson (1998) and Kincaid and Griffith (2003), both of whom prescribed the velocity of a rigid subducting plate by investigating the pattern of deformation induced in the surrounding mantle. The feedback between subduction and the induced 3D mantle circulation has been quantified by means of laboratory models (Faccenna et al., 2001; Funiciello et al., 2003, 2004). These experimental results were later confirmed by the laboratory work of Schellart (2004) and by the numerical work of Stegman et al. (2006) and Di Giuseppe et al. (2008). Piromallo et al. (2006) and Funiciello et al. (2006) provided further detailed analysis of mantle flow during subduction and, in particular, studied the toroidal/poloidial partitioning as a function of slab strength.

Here, we explore the time-dependent evolution of subduction-induced mantle circulation adopting a 3D self-consistent (i.e., no motions are prescribed) setup. These models are not meant to match any specific subduction zone, but allow us to illustrate features whose dynamic relevance for volcanism ahead of the arc and regional tectonics appear to have not been fully recognized previously.

We approximate subduction dynamics by solving for incompressible Stokes flow in the infinite Prandtl number regime. We use the finite element code CitcomCU (e.g., Moresi and Solomatov, 1995; Zhong et al., 1998) as modified from the CIG (geodynamics.org) version and compute the time-dependent flow solutions for a cold slab sinking into the mantle, which is approximated by a visco-plastic material with temperature-dependent viscosity. Our model setup is fairly standard and is inspired by previous subduction models (e.g., Christensen, 1996; Enns et al., 2005; Stegman et al., 2006), but we neglect complexities such as the buoyancy effect of phase transitions.

The computational domain is meant to represent the upper mantle and has dimensions of 3960 km length (x), 1320 km width (y), and 1320 km depth (z) (non-dimensional aspect-ratio: $3\times1\times1$). The mechanical boundary conditions are free slip. We use 288 elements with uniform spacing in x, 96 elements subdividing the y direction and 96 elements for z, 80 of which define the upper mantle. The element refinement reflects our focus on the upper mantle and has been chosen for computational convenience. The modeling details can depend on the numerical implementation of near-surface yielding (Schmeling et al., 2007), but we have found the general system behavior to be robust with respect to mesh resolution.

Our initial condition for the non-dimensional temperature T includes an isolated oceanic plate that is fixed at the "ridge" location of $x=0$. This is implemented by prescribing a half-space cooling profile that applies $0<y<0.5$, corresponding to the zero age at $x=0$, and an equivalent ($T=0.9$) lithospheric thickness of ~150 km at $x=0$. At the old leading edge of the plate, we also prescribe a slight initial dip to facilitate the initiation of subduction, though this is not critical (cf. Tetzlaff and Schmeling, 2000). All other mantle temperatures are initially set to unity, the surface is kept at $T=0$, and the bottom boundary is zero heat flux (we only consider non-adiabatic processes, consistent with the incompressible framework). Defined by a non-dimensional reference viscosity of $\eta=1$, we use a Rayleigh number of 5.7×10^6, with the typical non-dimensionalization scheme and definitions (e.g., Zhong et al., 1998). The effective viscosity, η, within the fluid is given by a joint rheology

$$\eta = \eta_p\eta_T / \left(\eta_p + \eta_T\right) \quad (1)$$

where the regular, fluid-creeping viscosity η_T has a simplified temperature dependence as

$$\eta_T = \eta_T^0 \exp\left(E(T_0-T)\right) \quad (2)$$

using $E=6.21$ and $T_0=1$ for an equivalent viscosity contrast of 500 between the slab and mantle, for consistency with earlier such models. The constant prefactor η_T^0 is set to unity in the upper mantle and to 100 in the lower mantle to represent the probable increase in viscosity due to the phase change at 660 km (e.g., Hager and Clayton, 1989).

The pseudo-plastic "viscosity" η_p is computed from a constant yield stress at $\sigma_y=10^5$ and the second (shear) strain-rate invariant

$$\varepsilon_{II} \ as \ \eta_p = \sigma_y / (2\varepsilon_{II}) \quad (3)$$

If the yield stress is taken to be depth dependent, this approximation to plasticity is sometimes called "Byerlee" plasticity in reference to the stress-limiting effect of brittle faulting in the cold lithosphere (e.g., the discussion in Enns et al., 2005). For simplified subduction models with free-slip surface boundary conditions, yielding facilitates the formation of a properly detached slab, as opposed to a Rayleigh–Taylor instability-like drip (e.g., Enns et al., 2005). In our models, the parameter choices lead to substantial viscosity reduction in the trench region close to the surface and the formation of angular weak zones, and they eventually led to the complete detachment of the oceanic plate. However, none of these rheological details matter for the general flow patterns discussed below as long as a relatively stronger and denser slab is able to sink into the mantle. We tested various other setups, including purely compositionally driven slabs (Enns et al., 2005), a range of different choices for the yield stress, a free "ridge" location at $x=0$, and additional weak zones ("transform faults") on the sides of the slab. The dynamic behavior of all of these models was qualitatively similar to what we discuss here.

Figure 1 shows snapshots of the slab sinking into the mantle. The subduction velocity, v_s, (i.e., $|v_s|$ equal to $|v_t|$ in the fixed ridge setup) progressively increases during the development of subduction into the upper mantle (cf. Becker et al., 1999; Fig. 1a–b). Afterward, v_s decreases once the slab reaches the upper–lower mantle discontinuity and temporarily ponds at the viscosity contrast (cf. Funiciello et al., 2003). Subsequently, the subduction process is taken up by trench rollback. As discussed by Funiciello et al. (2004), the pattern of mantle circulation is strongly variable during the three aforementioned evolutionary stages. To better describe the subduction-induced mantle flow, it is instructive to perform decomposition into the toroidal and poloidal components (e.g., Tackley, 2000; Fig. 2). The poloidal component is associated with vertical mass transport, whereas the toroidal corresponds to vortex-like stirring and rigid-body rotation. The balance between these two components is representative of the vertical descent of the slab and the lateral translation of the trench. Toroidal motion is then mostly excited during the retrograde motion of the slab because the mantle material placed beneath the slab flows laterally from the sides of the slab and produces vortex-like structures.