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Mantle plumes in the vicinity of subduction zones

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ABSTRACT

We present three-dimensional deep-mantle laboratory models of a compositional plume within the vicinity of a buoyancy-driven subducting plate with a fixed trailing edge. We modelled front plumes (in the mantle wedge), rear plumes (beneath the subducting plate) and side plumes with slab/plume systems of buoyancy flux ratio spanning a range from 2 to 100 that overlaps the ratios in nature of 0.2–100. This study shows that 1) rising side and front plumes can be dragged over thousands of kilometres into the mantle wedge, 2) flattening of rear plumes in the trench-normal direction can be initiated 700 km away from the trench, and a plume material layer of lesser density and viscosity can ultimately almost entirely underlay a retreating slab after slab/plume impact, 3) while side and rear plumes are not tilted until they reach ∼600 km depth, front plumes can be tilted at increasing depths as their plume buoyancy is lessened, and rise at a slower rate when subjected to a slab-induced downwelling, 4) rear plumes whose buoyancy flux is close to that of a slab, can retard subduction until the slab is 600 km long, and 5) slab–plume interaction can lead to a diversity of spatial plume material distributions into the mantle wedge. We discuss natural slab/plume systems of the Cascadia/Bowie–Cobb, and Nazca/San Felix–Juan Fernandez systems on the basis of our experiments and each geodynamic context and assess the influence of slab downwelling at depths for the starting plumes of Java, Coral Sea and East Solomon. Overall, this study shows how slab/plume interactions can result in a variety of geological, geophysical and geochemical signatures.

1. Introduction

In the theory of plate tectonics, subduction zones and mantle plumes (hotspots) are described as two distinctive elements of mantle convection. Subduction carries cool oceanic lithosphere downward and plumes carry hot mantle from the deep interior toward the surface (Schubert et al., 2001). Hotspots have preferentially been located near divergent plate boundaries, and excluded from regions near convergent plate boundaries (e.g. Weinstein and Olson, 1989). However today's observations based mostly on tomographic studies suggest the presence of plumes in the vicinity of subduction zones (e.g. Obrebski et al., 2010). Such spatial proximity could have important geodynamic implications such as flattening of subduction (Dalziel et al., 2000), plume deflection, widespread magmatism (Geist and Richards, 1993), rapid switches in tectonic modes, modified crustal growth (Wyman et al., 2002) and the formation of mineral deposits such as gold (Wyman et al., 1999).

Proposed examples of modern slab/plume interaction include the Cascadia subduction zone and the Yellowstone hotspot (Murphy et al., 1998; Smith et al., 2009), the Tonga subduction zone and the Samoa hotspot (Smith et al., 2001), and the Kamchatka subduction zone segment and the Kamchatka plume (Gorbatov et al., 2001). In the last 60 Myr, 29% and 17% of the commonly recognised mantle plumes have been within 1000 km and 500 km, respectively, of a subduction zone (Fletcher and Wyman, 2015). In the more distant geologic past, proposed examples include the interaction of the South Greenland and central Scandinavia subduction zones with a plume located between Baltica and Greenland at ∼1284–1234 Ma (Söderlund et al., 2006), interaction of the retreating Gondwanan margin and the plume responsible for the Jurassic Karroo–Ferrar flood basalts (Dalziel et al., 2000), and the Mesoproterozoic plume-modified orogenesis in eastern Precambrian Australia (Betts et al., 2009).

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Until recently, the different models that have been envisaged to explain the geological and geophysical observations have mostly been conceptual. For example, we know that mantle plumes can be deflected by mantle flow (Kerr and Mériaux, 2004) but the conditions under which a subducting plate captures a plume remain unknown. The influence of a mantle plume on a slab is not well known either. Such questions critically demand to be tested by dynamic models as they have clear importance in a number of geological environments.

Recently, Morishige et al. (2010) implemented two-dimensional numerical simulations of a hot anomaly adjacent to a cold kinematically-driven downgoing slab to test the origin of a low velocity anomaly under the subducting Pacific plate. Similarly, Lee and Lim (2014) used a two-dimensional model of a cold kinematically-driven downgoing slab with a short-term temperature anomaly into the mantle wedge to assess slab melting, and the occurrence of the Abukuma adakite in northeastern Japan. Using three-dimensional numerical simulations, Betts et al. (2012, 2015) modelled the behaviour of subducting plates encountering a plume head prescribed, either at the base of the subducting plate or at the base of the overriding plate, by a volume of lesser density and viscosity. These studies quantified the manner in which a plume head could modify trench and slab geometry. Besides those numerical investigations, a small number of laboratory models have been presented. Kincaid et al. (2013) and Druken et al. (2014) carried out experiments with a rigid and kinematically driven subducting plate in interaction with a thermal plume to model the bifurcation of the Yellowstone plume and the entrainment of the Samoan plume in the Lau basin, respectively. Mériaux et al. (2015a, 2015b) presented three-dimensional upper-mantle laboratory models of the Gibraltar subduction zone and Canary plume, and the Manila subduction zone and Hainan plume. These recent quantitative studies have been significant steps forward in the understanding of slab/plume interaction, but they were all case studies. Here we present the first generic study of such interaction, as the stage for more systematic studies to come given the complexity of the interaction.

In this paper, we report deep mantle laboratory analog experiments of a compositional plume within the vicinity of a buoyancy-driven slab with a fixed trailing plate. We present a set of 21 experiments, in which we vary the slab/plume buoyancy flux ratio over a range of 2–100 overlapping that of nature, and the initial plume source relative to a fixed trailing-edge slab. Our experiments highlight the conditions under which the slab-induced poloidal and toroidal flows affect the plume dynamics and vice-versa. Natural cases of plumes in the vicinity of a subduction zone are finally discussed.

2. Analogue modelling

We used a Perspex tank 1 m long, 0.62 m wide and 0.60 m deep that was filled with glucose syrup, a Newtonian fluid, up to $H = 0.45$ m. A plate of thickness $d = 0.015$ m, width $W = 0.20$ m, and length $L = 0.50$ or 0.60 m made of high-viscosity linear-viscous silicone (Wacker Silicone) mixed with fine iron powder was used to model an oceanic plate. The glucose syrup density was $\rho_a = 1413$ kg/m^3, and its viscosity μ_a varied within the range 74–119 Pa s due to temperature variations. The plate density of 1513 kg/m^3 was larger than that of the glucose by $\Delta\rho_s = 100$ kg/m^3. The plate dynamic shear viscosity μ_s of 64,000 Pa s was substantially larger than the glucose syrup viscosity μ_a as the ratio $\gamma = \mu_s/\mu_a$ was within the range 538–865. The plate was fixed along its trailing edge to one of the lateral walls. Subduction of the plate was initiated by downward bending a length of its free edge l_{top} equivalent to 3 cm as measured from the top by an angle θ_0. Black neutrally buoyant spheres to be used as slab-induced flow tracers were spread at the top surface. A compositional plume was introduced at the base of the tank through a nozzle. The plume fluid was made of glucose syrup diluted with water resulting in a plume density less than that of the glucose syrup by $\Delta\rho_p = 40$ kg/m^3, and a viscosity $\mu_p = 5$ Pa s. The buoyant fluid was supplied by a pressure vessel and was dyed to make the plume clearly visible. In each experiment, we maintained a constant input volume flux Q. Fig. 1 shows the laboratory setup and the different initial plume positions. Photos were taken every 10 s simultaneously from two sides, and from the top.

Lengths of the model were scaled so that 1 cm represents 50 km in nature. The time was scaled by the time a slab element takes to sink through the model depth H at the velocity scale $\hat{U} = \Delta\rho_s g d^2/\mu_a = \gamma\Delta\rho_s g d^2/\mu_s$, resulting in

$$\frac{t^{Nature}}{t^{Model}} = \frac{H^{Nature}}{\hat{U}^{Nature}} \times \frac{\hat{U}^{Model}}{H^{Model}} = \left(\frac{H^{Nature}}{H^{Model}}\right)\left(\frac{(\gamma\Delta\rho_s g d^2/\mu_s)^{Model}}{(\Delta\rho_s g d^2/\mu_a)^{Nature}}\right), \tag{1}$$

where g is the gravitational acceleration. Hence one second typically represents about 7 kyr, using a model γ, a mantle depth H and mantle viscosity μ_a of 640, 2000 km and 10^{20} Pa s, respectively. The presented models are deep mantle models and no stratification of the mantle is considered. We defined the slab buoyancy flux B_s by

$$B_s/g = \Delta\rho_s U W d, \tag{2}$$

where U is the slab steady sinking rate, while the plume buoyancy flux B_p is given by

$$B_p/g = \Delta\rho_p Q, \tag{3}$$

(see also Appendix S1). In experiments 4–21, as well as the plume relative position to the slab, we varied the buoyancy flux ratio B_s/B_p.

3. Results

We present experiments that include different initial positions of the plume relative to the slab and different buoyancy flux ratios B_s/B_p. We catalogued the relative plume positions into three classes: the front, rear and side plume positions, respectively (see Table 1 and Fig. 1). The plume was initiated at a time $t_p^i = 20$ s after subduction of the plate had been initiated, except for experiments 13, 15, 16 and 18, for which the plume was started at $t_p^i = 610, 330, 700,$ and 250 s, respectively, after subduction initiation.

In all experiments, slabs first steepened with time (up to ∼90° for the bottom half of the slab, and then steadily sunk and retreated while attaining a dip angle of ∼50° (e.g. Figs. 2–4). Slabs were also seen to curl along their lateral edges in response to the drag of the surrounding mantle, producing a top-view curvature that is concave towards the mantle wedge. Finally, as the slab tip approached the bottom of the tank, slab rollback and slab sinking decelerated. This subduction process induces a flow in the mantle that can be decomposed into slab-induced toroidal and slab-induced poloidal components (see Strak and Schellart, 2014 for stereoscopic Particle Image Velocimetry of slab-induced 3-D mantle flow). These two components vary in space and time as the slab lengthens. In particular, the slab-induced flow is characterised by the two poloidal circulations in the mantle wedge and sub-slab domain, and the two toroidal cells around the lateral slab edges (see Fig. 1). In our experiments, the extent of the slab-induced poloidal and toroidal circulation at the surface were estimated as a function of slab length using the neutrally buoyant tracers that had been seeded at the surface (Appendix S2.1).