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# Plume–slab interaction: The Samoa–Tonga system

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ABSTRACT

Mantle plume behavior near subducting plates is still poorly understood and in fact varies significantly from the classical hotspot model. We investigate using 3D laboratory models how subduction-driven flow relates to the deformation and dispersal of a nearby plume. Results show slab-driven flow severely distorts plume-driven flow, entraining and passively advecting plume material despite its thermal buoyancy. Downdip sinking of the slab initially stalls vertical plume ascent while the combination of downdip and rollback sinking motions redistribute material throughout the system. As a consequence of the subduction-induced flow, surface expressions differ significantly from traditional plume expectations. Variations in slab sinking style and plume position lead to a range in head and conduit melting signatures, as well as migrating hotspots. For the Samoa–Tonga system, model predictions are consistent with proposed entrainment of plume material around the subducting plate.



## 1. Introduction

The dynamics of mantle plumes rising near spreading centers (e.g., Iceland) or mid-plate locations (e.g., Hawaii) have been well studied (e.g., Griffiths and Richards, 1989; Feighner and Richards, 1995; Kincaid et al., 1995; Ribe and Christensen, 1995). The behavior of plumes near subducting plates, however, remains poorly understood and may in fact differ from the typical expected plume surfacing patterns (Kincaid et al., 2013). Classically, plumes are expected to consist of an axisymmetric mushroom-shaped head fed by a thin vertical stem or conduit (e.g., Whitehead and Luther, 1975); the surface expressions of which serve well to explain flood basalts (or large igneous provinces, LIPs) and age-progressive volcanic chains, respectively (e.g., Morgan, 1972; Richards and Griffiths, 1989; Hill et al., 1991). Topographic swells, continuous seismic anomalies, and deep mantle geochemistry are additional plume-related signatures and agree with intuitive expectations from the classic plume model. While this provides a useful first-order description of the surface expression, it does not fully capture the complexity of the real system, in which the observable features of an individual plume are diverse (e.g., Courtillot et al., 2003) and likely to depend on many factors, including the regional tectonic setting.

Examples of hotspots in close proximity to subducting margins include Yellowstone in the Northwest U.S. and Samoa in the Southwest Pacific (Fig. 1), where past observations from each region have conflicted with the traditional view of mantle plumes. The Yellowstone controversy has been largely focused on reconciling regional volcanism with a single plume, which has generated numerous plume versus non-plume debates of the geologic origin and evolution (e.g., Hooper et al., 2007). The local LIP (Steens/Columbia River flood basalts) and eastward age-progressive hotspot track (Snake River Plain) both fit with the simple plume model, however the region's second volcanic track (High Lava Plains), which youngs opposite to plate motion to the west, has been viewed as inconsistent (e.g., Christiansen et al., 2002). In the Southwest Pacific, early studies argued the volcanic timing of the Samoan volcanic chain failed to demonstrate a clear age-progression, instead suggesting that shallower, non-plume mechanisms such as lithospheric bending and fracturing were responsible (Hawkins and Natland, 1975; Natland, 1980; Foulger and Natland, 2003).

Compared with intraplate settings and spreading centers, the plate-induced mantle flow in subduction zones is strongly three-dimensional (e.g., Kincaid and Griffiths, 2003; Kincaid and Griffiths, 2004; Schellart, 2004; Funiciello et al., 2006; Stegman et al., 2006). Plumes rising within the vicinity of sinking slabs face possible

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disruption not only from horizontal surface shear above, but additionally the poloidal and toroidal circulation cells generated by the longitudinal and rollback components of subduction e.g., Schellart (2004). Kincaid et al. (2013) recently showed that for locations similar to Yellowstone (e.g., plumes originating forward of the trench), subduction can dramatically transform actively rising plumes into features that move passively with the local flow. For the Northwest U.S. region, this suggests that models need not be strictly "plume" or "no plume" but can be a hybrid where plumes (or other thermally anomalous material) and the resulting volcanism are controlled by slab-induced flow. Similarly with Samoa, recent studies have favored a plume origin that differs from the classic model due to complex interaction with the nearby Tonga subduction zone (Hart et al., 2000; Hart et al., 2004; Koppers et al., 2008). Elevated helium isotope values observed within the northern arc and back-arc regions of the Tonga system (Poreda and Craig, 1992; Turner and Hawkesworth, 1998; Lupton et al., 2009) indicate possible entrainment of Samoan material, supporting the argument for plume–slab interaction.

This paper focuses on "Samoa-style" plume–slab interaction as a compliment to the recent "Yellowstone-style" study (Kincaid et al., 2013). We investigate the effect of subduction and rollback-induced mantle flow on nearby buoyant upwellings. Results are presented from a series of 3D laboratory experiments in which a thermally buoyant plume rises within a complex spatial and temporal varying flow field generated by a subducting slab. For Earth-like plumes, subduction drives complex circulation patterns that deform and weaken the plume, thereby severely limiting vertical heat and mass transport to the surface. Plumes that are efficiently converted to warm, passive mantle produce surface patterns that are controlled by background circulation and show very little resemblance to expected patterns from traditional schematic plume models. Results have important implications for the Samoa–Tonga system and support the suggested interaction that the Samoan plume is influenced by motion of the slab and entrained into the Lau Basin (Turner and Hawkesworth, 1998; Hart et al., 2004) (see Fig. 1).

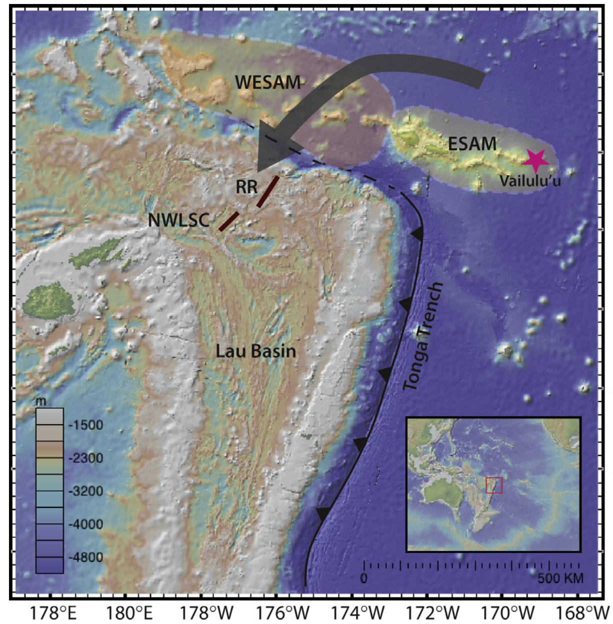


**Fig. 1.** Regional map of the Tonga subduction system and the Eastern (ESAM) and Western (WESAM) Samoan volcanic chains (modified from Jackson et al., 2010; Lytle et al., 2013). Also shown is the proposed entrainment of Samoan material by the rollback-driven mantle flow (grey arrow), Vailulu'u (present day hotspot location), the Rochambeau Rift (RR) and Northwest Lau Spreading Center (NWLSC). Basemap was created using GeoMapApp (http://www.geomapapp.org) (Ryan et al., 2009).

## 2. Laboratory methods

### 2.1. Apparatus

We examine the evolution and interaction of thermal plumes with 3D. subduction-induced flow using a kinematic laboratory model (e.g., Kincaid and Griffiths, 2003; Druken et al., 2011; Kincaid et al., 2013). The upper 2400 km of the mantle is modeled using glucose syrup in a transparent acrylic Perspex tank (100 cm long × 60 cm wide × 40 cm deep) while the subducting plate is modeled by a rigid Phenolic sheet (20 cm wide × 2.5 cm thick) (Fig. 2a). Precise sinking motions are controlled by three hydraulic pistons and are prescribed to systematically mimic the range in sinking styles observed dynamically (e.g., Kincaid and Olson, 1987; Griffiths and Turner, 1988; Griffiths and Turner, 1988; Funiciello et al., 2003; Schellart, 2004). Two pistons control downdip ($U_D$) and translational ($U_T$) motions of the slab while the third controls the dip angle with time ($\theta_t$).

To model rollback that varies along trench (e.g., Tonga), the translational motion has been modified to include an asymmetric, or 'hinging', component not previously modeled by Kincaid and Griffiths (2003, 2004). The trench is fixed to a pivot point at the tank edge (30 cm from slab centerline) with a motor to control the rate of rotation ($U_H$) as the plate retreats.

Two distinct setups are used for producing primary components of surface plate motion. An overriding plate is modeled using a thin transparent Perspex plate that migrates with trench motion. This plate couples with the underlying wedge fluid imposing a vertical shear flow under the plate. The focus of this study is on 'Samoa-style' plume–slab interaction, where the plume originates under the pre-subducted slab. To represent this mode of backside (or ocean-side) shear flow, we include a spool of mylar sheeting placed along the fluid surface behind the trench (Fig. 2b). This is done in order to mimic the surface shear produced by dynamically sinking slabs. The mylar is attached to the tip of the slab and imposes a horizontal velocity equal to the sinking rate ($U_D$).

A benefit of utilizing kinematic 3D subduction is that flows are repeatable and controllable. In similar fashion, we aim to control the location, size, and buoyant flux of our modeled plumes. We produce thermally buoyant mantle plumes by heating a pressurized reservoir of ambient glucose material that is later injected into the tank via a fixed insulated pipe. The glucose syrup used to model both the mantle and plume has a temperature dependent viscosity, described by Kincaid and Griffiths (2003) as:

$$\mu(T) = 15 \exp\left(\frac{1800}{T+93} - 12.10\right) \quad (1)$$

where $\mu$ and $T$ are dynamic viscosity (Poise) and temperature (°C). For this initial study, the ambient mantle is isothermal (20 °C) until interaction with the thermal plume. Once injected, plume material gathers until forming a semi-spherical head shape. Volume flux of the plume is held constant across all experiments while outlet position ($x_p, y_p, z_p$) and temperature ($T_p$) are varied. For visualization, the plume material is marked by neutrally buoyant (or passive) microbead tracers.

### 2.2. Scaling

Length and time scales of the flow for the kinematic models can be scaled to the mantle using the Péclet number,

$$Pe = \frac{U_D D}{\kappa} \quad (2)$$