

# Non-hotspot volcano chains produced by migration of shear-driven upwelling toward the East Pacific Rise

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## ABSTRACT

While most oceanic volcanism is associated with the passive rise of hot mantle beneath the spreading axes of mid-ocean ridges (MOR), volcanism occurring off-axis reflects intraplate upper-mantle dynamics and composition, yet is poorly understood. Off the south East Pacific Rise (SEPR), volcanism along the Pukapuka, Hotu-Matua, and Sojourn ridges has been attributed to various mechanisms, but none can reconcile its spatial, temporal, and geochemical characteristics. Our three-dimensional numerical models show that asthenospheric shear can excite upwelling and decompression melting at the tip of low-viscosity fingers that are propelled eastward by vigorous sublithospheric flow. This shear-driven upwelling is able to sustain intraplate volcanism that progresses toward the MOR, spreads laterally close to the axis, and weakly continues on the opposite plate. These predictions can explain the anomalously fast eastward progression of volcanism, and its spatial distribution near the SEPR. Moreover, for a heterogeneous mantle source involving a fertile component, the predicted systematics of volcanism can explain the geochemical trend along Pukapuka and the enriched anomaly of SEPR mid-oceanic ridge basalt at 16°–20.5°S. Our study highlights the role of horizontal asthenospheric flow and mantle heterogeneity in producing linear chains of intraplate volcanism independent of a (deep-rooted) buoyancy source.

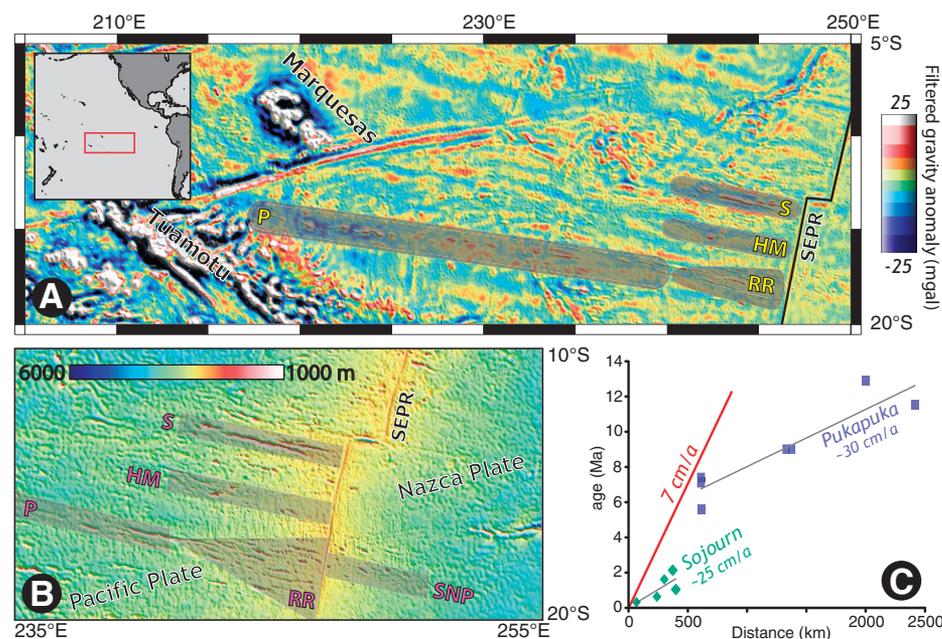
## INTRODUCTION

In the framework of the hotspot concept, intraplate volcanism is typically related to stationary melting sources. However, the geochemical fingerprints of off-axis intraplate volcanism and adjacent mid-ocean ridge (MOR) segments often indicate an influence from a distal plume and hence significant lateral displacement of the source (Vlastélic and Dosso, 2005; Yamamoto et al., 2007). While the details of horizontal flow in the asthenosphere remain to be understood, both its direction and speed may differ significantly from those of the overriding plate (Conrad and Behn, 2010; Phipps Morgan et al., 1995). In the southeast Pacific Ocean, asymmetry in both subsidence and seismic velocity across the south East Pacific Rise (SEPR) (The MELT Seismic Team, 1998) provides independent evidence for vigorous, pressure-driven eastward asthenospheric flow that opposes plate motion (Conder et al., 2002; Toomey et al., 2002). Moreover, sample ages indicate that the source of off-axis volcanism propagated eastward toward the spreading center at rates of ~20 cm/yr (Fig. 1C). This volcanism occurred predominantly on the Pacific plate, not on the opposite Nazca plate, creating a series of east-west-trending parallel volcanic ridges: the Sojourn and Hotu-Matua ridges extend ~650 km, and the Pukapuka extends >3000 km into the Rano Rahi seamount field (Fig. 1). Recent experiments suggest that the volcanism originates from the dynamics of a heterogeneous mantle (Harmon et al., 2011).

To date, none of the proposed models for the formation of the intraplate volcanism has successfully explained all of the geochemical and geophysical observations. Although lithospheric cracking, which taps abundant asthenospheric

melts, explains the morphologies of the ridges (Lynch, 1999; Sandwell et al., 1995), it is inconsistent with the underlying anomalous asthenosphere (Buck and Parmentier, 1986; Harmon et al., 2011). Dynamic models such as small-scale sublithospheric convection and viscous fingering instabilities can explain the asthenospheric anomalies and radiometric ages (Ballmer et al., 2009; Harmon et al., 2011; Weeraratne et al., 2007) (Fig. 1C); however, small-scale convection is typically not expected to occur beneath such a young plate (Ballmer et al., 2009; Buck and Parmentier, 1986), and viscous fingering alone is not expected to spawn significant melting by the slow decompression of channelized low-viscosity anomalies creeping eastward along the base of the oceanic lithosphere.

Geophysical evidence nonetheless suggests a role for channelized pressure-driven flow in the asthenosphere (Conder et al., 2002; Toomey et al., 2002; Weeraratne et al., 2007), and we hypothesize that shear-driven upwelling (SDU) within such a flow can account for all



**Figure 1.** Overview of filtered free-air gravity anomalies (A) (Harmon et al., 2011) and bathymetry in (B) the southeast Pacific Ocean. Volcano chains are shaded: S—Sojourn; HM—Hotu-Matua; P—Pukapuka; RR—Rano Rahi; SNP—seamounts on the Nazca plate juxtaposed against Rano-Rahi. SEPR—south East Pacific Rise. C: Radiometric ages along the Sojourn (Forsyth et al., 2006) and Pukapuka ridges (Sandwell et al., 1995). Age-distance relationships significantly differ from absolute Pacific plate motion (i.e., ~7 cm/yr), and indicate eastward progression of the magmatic sources at rates of ~20 cm/yr relative to the lower mantle.

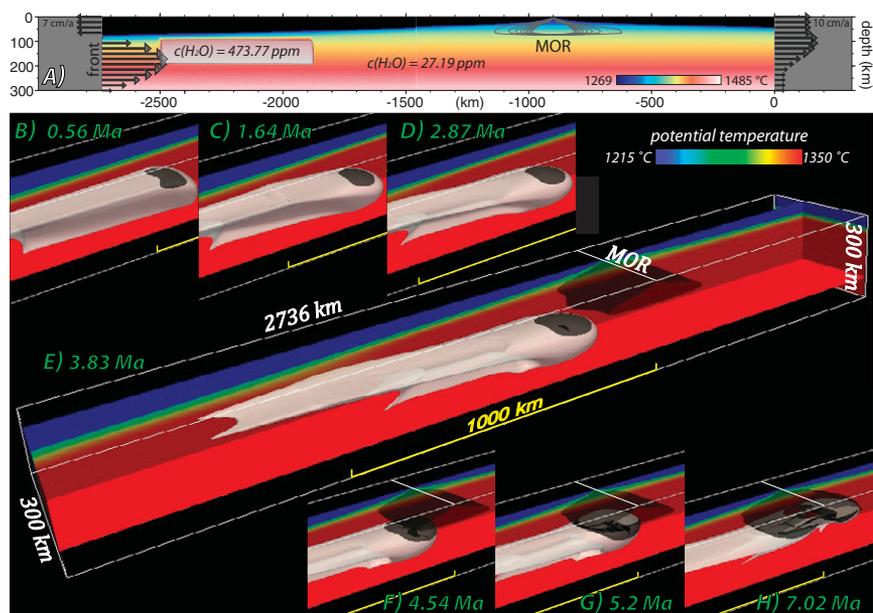
the observational constraints. SDU is a mechanism that can produce decompression melting without mantle density heterogeneity: shear and viscosity heterogeneity are sufficient to drive vertical flow (Bianco et al., 2011). In particular, asthenospheric shear (and pressure-driven flow) becomes concentrated within a low-viscosity anomaly, and this concentration is accommodated by upwellings and downwellings close to the edges of the anomaly (illustrated schematically in Fig. DR1 in the GSA Data Repository<sup>1</sup>). The induced upwelling may be indeed sufficient to sustain significant decompression melting—particularly for viscosity anomalies sustained by higher water contents or temperatures.

The South Pacific asthenosphere offers ideal conditions for SDU. The injection of chemically enriched and possibly hydrous (Karato, 2008) low-viscosity materials into the ambient mantle beneath the South Pacific Superswell is thought to induce eastward asthenospheric flow (Conrad and Behn, 2010) (Fig. DR2) that undergoes fingering instabilities to create channelized low-viscosity anomalies (Weeraratne et al., 2007). The association of the apparent cross-grain lineations in gravity and topography (Fig. 1) with seismically slow asthenosphere corroborates such lateral variability in mantle viscosity independent of an ambiguity in origin (thermal versus compositional) (Harmon et al., 2011). Together with rapid shear across the asthenosphere as imposed by westward Pacific plate motion and eastward asthenospheric flow (Conrad et al., 2011), this viscosity heterogeneity sets up the necessary conditions for SDU.

## METHODS

Here we use three-dimensional finite-element models of viscous mantle flow and decompression melting (after Ballmer et al., 2009, 2010; Table DR1 in the Data Repository) to investigate whether SDU within channelized low-viscosity fingers can explain seamount volcanism near the SEPR. The fingers are assumed to be symmetric and periodic about an axis parallel to plate motion, and propelled eastward by vigorous pressure-driven flow (cf. Fig. 2A). We explore two reference cases: case A with ambient, and case B with elevated (by 60 °C) finger temperatures (Table DR2 in the Data Repository). The initial viscosity contrast between the fingers and the ambient mantle is  $\eta_{\text{mantle}}/\eta_{\text{finger}} = 47$  in both cases, and sustained by relatively high finger water contents. As viscosity in our models depends on temperature, water, and melt content, the effective viscosity of the finger evolves over time due to the effects of thermal

<sup>1</sup>GSA Data Repository item 2013123, methods and model setup, Tables DR1–DR3, Figures DR1–DR5, and Movies DR1 and DR2, is available online at [www.geosociety.org/pubs/ft2013.htm](http://www.geosociety.org/pubs/ft2013.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



**Figure 2.** Time series of temperature and melting for case B. Colors show temperature in vertical cross sections. A: Initial and boundary conditions for case B in a vertical cross section. Shading, arrows, and gray contours denote the initial shape of the finger, side velocity boundary conditions, and mid-ocean ridge (MOR) melting rates, respectively. B–H: White and black isosurfaces are the three-dimensional shapes of the low-viscosity finger and the active melting zone, respectively. Significant melting occurs independent of the distance between the finger and the MOR, and increases with decreasing distances. Also, compare Movie DR2 in the Data Repository (see footnote 1).

diffusion and melting (melt retention, latent heat consumption, and dehydration of the residue). Lagrangian particles are used to track composition. A full description of our methods and model setup is provided in the Data Repository.

## RESULTS

Shear-driven flow dominates the dynamics of low-viscosity fingers. While initially imposed as elongate rectangular boxes, the modeled finger maintains a droplet-like shape from model time  $\sim 1.5$  m.y. onward due to toroidal shear-driven flow that acts to inflate its leading edge and deflate its trailing edge. Moreover, persistent SDU is fueled within the low-viscosity finger close to its leading edge. This upwelling can sustain low-degree decompression melting (Fig. 2; Fig. DR3). Dehydration of the residue by melting only subtly weakens SDU by increasing finger viscosities over time (cf. Fig. DR4). Comparison of cases A and A<sub>test</sub> (Fig. DR5), which are identical except for an imposed threshold in compositional rheology (that keeps  $\eta_{\text{mantle}}/\eta_{\text{finger}} = 1$ , and hence artificially shuts off SDU) in case A<sub>test</sub>, elucidates that the SDU mechanism is critical for off-axis volcanism. Additional tests show that viscosity contrasts of  $\eta_{\text{mantle}}/\eta_{\text{finger}} > \sim 20$  are required for significant off-axis SDU-fueled volcanism (Fig. DR5).

Our model predictions are consistent with the extents, volumes, and ages of the volcanic ridges close to the SEPR. Pressure-driven flow in the

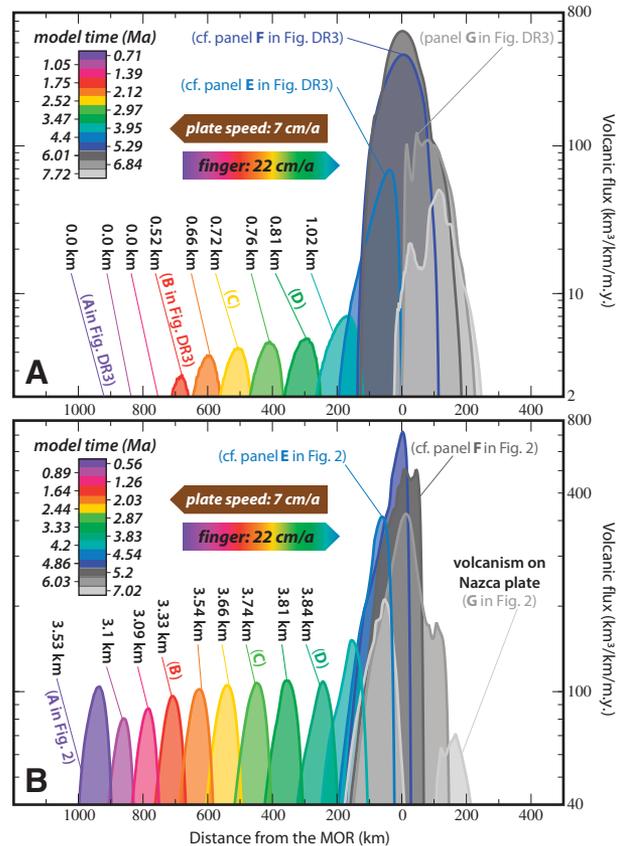
modeled asthenospheric channel gets focused within the low-viscosity finger and therefore pushes its tip eastward at rates (i.e.,  $\sim 22$  cm/yr) that are faster than those of ambient asthenospheric flow ( $< 20$  cm/yr). The implied age-distance relationship of the associated volcanism on the Pacific plate (which moves  $\sim 7$  cm/yr westward) of  $\sim 29$  cm/yr well agrees with that constrained by radiometric ages sampled along the Pukapuka and Sojourn ridges (Fig. 1C). Furthermore, ridge heights as predicted from cases A and B (Fig. 3) bracket those measured. In case A, ridge heights are between 0.5 and 1 km, but zero at distances  $\geq 750$  km from the MOR (due to degrees of SDU melting smaller than the threshold for extraction i.e.,  $< 0.5\%$ ). In case B, ridge heights are between 3 km and 4 km, and are almost independent of MOR distance. Thus, case A can account for the short extents ( $\sim 650$  km) of the Sojourn and Hotu-Matua ridges, and the warm-finger case B can reconcile the longer extent of Pukapuka. Evidence for warm material beneath Pukapuka comes from extensive melting that formed the Tuamotu plateau close to the inferred location of the Easter hotspot at 40–55 Ma (Ito et al., 1995). The Pukapuka ridge indeed projects back to the Tuamotu plateau (Fig. 1A).

The prediction of an eastward boost of SDU-derived off-axis volcanism very close to the MOR (Fig. 3) disagrees with geological constraints (White et al., 2006). This boost occurs in our models due to upward entrainment of the finger into the spreading center. However, we

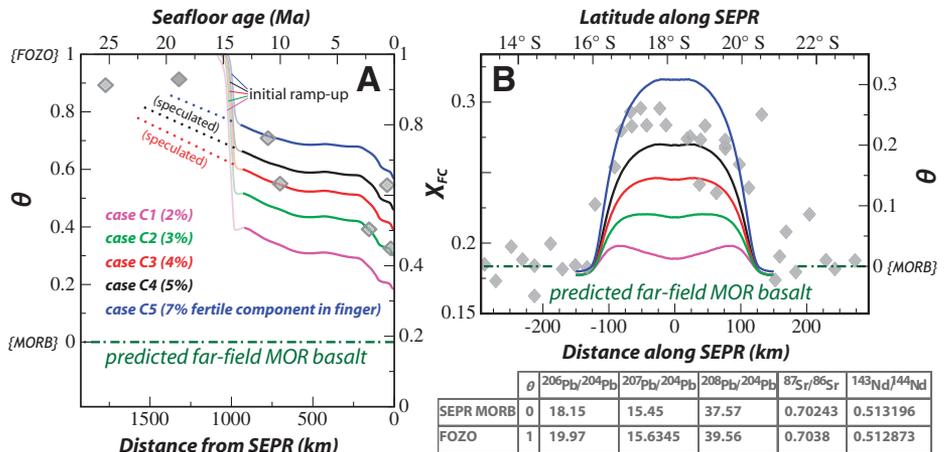
expect such additional magmas in nature to be diverted into the ridge axis due to the progressive merging of the SDU and MOR melting zones (Fig. 2; Fig. DR3) and steepening of the base of the lithosphere (Hebert and Montesi, 2010). Such a diversion indeed agrees with along-axis variations of ridge cross-sectional area (Scheirer and Macdonald, 1993).

The interaction of low-viscosity fingers with the MOR can also account for the geographical distribution of off-axis seamounts east of Pukapuka. The Pukapuka ridge *sensu strictu* terminates ~600 km west of the SEPR and splits into the triangular-shaped Rano-Rahi seamount field (Fig. 1). This field's peculiar shape may be explained by lateral spreading of the predicted finger melting zone caused by the ascent of the finger beneath increasingly thin lithosphere just before the full merger with the MOR melting zone (Figs. 2D–2G). Because SDU melting is predicted to continue after the finger crosses the ridge axis (cf. Fig. 3B), it may further account for off-axis volcanism on the Nazca plate. A short lineament of kilometer-high seamounts is indeed juxtaposed across the East Pacific Rise from the Rano-Rahi (Fig. 1B). Radiometric ages indicate that the Pukapuka source, in contrast to the Sojourn and Hotu-Matua sources, already crossed the SEPR (a few million years ago; cf. Fig. 1C). This earlier advance of the finger beneath Pukapuka, and its associated ability to spread laterally unimpeded by neighboring fingers, may be critical for seamount formation on the Nazca plate, and the triangular shape of the seamount field west of the SEPR, respectively. Further, it explains the lack of these features for the Sojourn and Hotu-Matua ridges.

For a heterogeneous mantle source, our models also predict geographic variations in the genetic origin of lavas that are consistent with geochemical trends along the Pukapuka ridge (Janney et al., 2000). In cases C1–C5, we add a small amount of a fertile component (FC; we use pyroxenite as representative, and add 2%–7% to the low-viscosity finger and 2% to the ambient mantle). Otherwise, these cases are identical to case B with a simple peridotitic source. The contribution of melts derived from this fertile component within the total erupted lavas,  $X_{FC}$ , depends on the temperature-pressure conditions in the SDU melting zone. We find that  $X_{FC}$  systematically decreases eastward as the warm and buoyant finger slowly decompresses along the base of the lithosphere. Assuming a focus-zone (FOZO)–like geochemical fingerprint (as characteristic for Tuamotu and western Pukapuka lavas) for the fertile component, this predicted decrease would imply a near-linear trend from FOZO toward SEPR mid-oceanic-ridge basalt (MORB) signatures in all isotope systems (Fig. 4A; Table DR3). Therefore, our models can provide an explanation for the observed trends in isotope geochemistry versus



**Figure 3.** Volcanic flux over space and time for case A (A), and case B (B). Volcanic flux in  $\text{km}^3/\text{m.y. per km}$  of plate (in the direction of plate motion) is shown for various snapshots (time is color coded) assuming a width of 150 km for the volcanic feeding zone. The areas under the curves are translated into a predicted volcano ridge height (numbers) assuming a slope of the continuous volcanic ridge of  $10^\circ$  and a relative motion between the plate and the shear-driven upwelling (SDU) melting zone of 29 cm/yr. Volcanic ridge heights are upper bounds as intrusive magmatism is neglected. In case A, volcanism is restricted to distances from the mid-ocean ridge (MOR) of  $<700$  km, whereas in case B, off-axis volcanism initiates immediately and is maintained at high amplitudes for ~4 m.y.



**Figure 4.** Comparison of predicted trends in  $X_{FC}$  (contribution of melts derived from the fertile component) from cases C1–C5 (lines) with geochemical signatures (diamonds). Geochemical data are projected on an axis in five-dimensional isotope space ( $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$ ,  $^{208}\text{Pb}/^{204}\text{Pb}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{143}\text{Nd}/^{144}\text{Nd}$ ) that extends from focus zone (FOZO) ( $\theta \equiv 1$ ) to a south East Pacific Rise (SEPR) mid-oceanic ridge basalt (MORB) signature ( $\theta \equiv 0$ , cf. inset table and Table DR3 [see footnote 1]). As Pukapuka lavas stretch between these two end members,  $\theta$  is a good representation of their geochemical characteristics. A:  $\theta$  of Pukapuka lavas (Janney et al., 2000), and  $X_{FC}$  for shear-driven upwelling (SDU)–derived volcanism (as integrated over model times 0–5 m.y.) versus distance from the SEPR. B:  $\theta$  of SEPR lavas (Mahoney et al., 1994), and  $X_{FC}$  for total volcanism at model time 4.6 m.y. (i.e., the arrival of the tip of the finger beneath the SEPR) versus along-axis distance. For computation of  $X_{FC}$ , lavas are integrated over feeding zone widths of 150 km (A) and 300 km (B).

relative age (i.e., seafloor age at eruption) along the Pukapuka ridge (Hall et al., 2006; Janney et al., 2000). Cases C4 and C5, in which the finger initially contains a significantly greater share of the fertile component (i.e., 5%–7%) than the

ambient mantle (2%), can moreover account for the observed geochemical enrichments of SEPR MORB near the intersection with the Pukapuka ridge at  $16^\circ$ – $20.5^\circ\text{S}$  (Fig. 4B) (Hall et al., 2006; Mahoney et al., 1994).

## DISCUSSION AND CONCLUSION

Our models show that SDU within channelized, horizontally traveling, low-viscosity material can transport enriched source materials over large horizontal distances to form non-hotspot volcano chains. In particular, we show that this process can reconcile the spatial, temporal, and geochemical aspects of volcanism off the SEPR. Partially molten east-west-trending low-viscosity fingers (Fig. DR4) are consistent with the observed electrical and seismic asymmetry, as well as with shear-wave velocity patterns as imaged in this region (Caricchi et al., 2011; Evans et al., 2005; Harmon et al., 2011; Wolfe and Solomon, 1998).

Given that >50% of Pacific seamounts were formed close to a MOR (Hillier, 2007), and particularly in regions of large asthenospheric shear (Conrad et al., 2011), we speculate that SDU plays an important role in supporting off-axis intraplate volcanism elsewhere. Intraplate volcanism in the Cretaceous (i.e., western) Pacific displays many analogies to the studied province: the Marshall and Wake Islands are multiple parallel volcano chains, each with complex (perhaps rapid) age progressions and systematic geochemical trends (Ballmer et al., 2010; Koppers et al., 2003). Moreover, they are associated with a superplume pulse that provided thermal and geochemical heterogeneity as well as with fast overriding plate motion, important ingredients for SDU. Recent examples may include the Hollister ridge, to which material has been channeled from the Louisville hotspot (Vlastélic and Dosso, 2005). Our findings further imply that SDU may contribute to volcano chains that trend from MORs to nearby hotspots such as Galápagos and Réunion (cf. Morgan, 1978).

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