Geophysical Research Abstracts
Vol. 14, EGU2012-1950-5, 2012
EGU General Assembly 2012

Off-axis volcanism as fueled by shear-driven upwelling near the East Pacific Rise

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The study of off-axis volcanism provides an opportunity to understand the make-up and dynamics of the upper mantle beneath mid-ocean ridges (MOR). Close to the East Pacific Rise (EPR), active magmatism propagated towards the spreading center to create a series of parallel volcanic ridges on the Pacific Plate (of length ∼3500 km for the Pukapuka, and ∼500 km for the Sojourn, and Hotu-Matua ridges). Propagation of this volcanism at ∼20 cm/a, as well as asymmetry in a variety of geophysical observables across the EPR, indicates strong lateral eastward return flow in the asthenosphere that is driven by upwelling beneath the South Pacific Superswell[1]. Although this pattern of large-scale mantle flow can account for the propagation of intraplate melting towards the EPR, it does not explain decompression melting itself.

Volcanism off the EPR has been attributed to various mechanisms, but each of them has trouble in reconciling its entire characteristics. First, lithospheric cracking is inconsistent with its occurrence in the lows of the apparent gravity lineations[2]. Second, small-scale convection is not expected to develop beneath nascent and young oceanic lithosphere. Third, return flow that is channelized into viscous fingers is likely insufficient to sustain significant volumes of volcanism.

We hypothesize that shear-driven upwelling (SDU) supports off-axis volcanism. SDU is a mechanism for mantle decompression that does not require lateral density heterogeneity. For example, vertical flow emerges at the edges of viscosity anomalies if the asthenosphere is sheared horizontally[3]. These two ingredients are present in the SE Pacific, where (1) shear across the asthenosphere is inferred to be greatest worldwide[3], and (2) lateral variability in mantle viscosity is indicated by gravity and seismic anomalies[2]. Channelized return flow from the South Pacific thermal anomaly may initially provide this variability in viscosity.

Here we show that SDU can account for the observed patterns, volumes, and geochemical trends of off-axis volcanism near the EPR. We explore a series of three-dimensional numerical models in which low-viscosity fingers propagate towards, and interact with, the MOR melting zone. We find that SDU is critical for generating significant off-axis volcanism, and that channelized return flow alone is indeed insufficient. If viscosity heterogeneity is caused by mineral hydration ("damp fingers"), our predictions for volcanism caused by SDU well agree with the lengths and volumes of the Sojourn and Hotu-Matua ridges. For fingers that are both anomalously damp and warm, SDU models predict the length of the Pukapuka ridge, its volume, breakup into a triangular-shaped seamount field close to the EPR, and the occurrence of a short seamount chain on the opposite Nazca Plate. Moreover, geochemical trends along the Pukapuka, and along the EPR are best explained by SDU in fingers that comprise a small share of pyroxenite, and the resulting spatial variability in magma origin. Finally, our models imply that asymmetric melting beneath the EPR is transient, and coincides with the arrival of the fingers. Our results shed new light on the origin of intraplate volcanism, and suggest chemical heterogeneity in the source of MOR basalts on various length scales.

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