Physics of the Earth and Planetary Interiors 178 (2010) 162–175

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Shear-driven upwelling induced by lateral viscosity variations and asthenospheric shear: A mechanism for intraplate volcanism

Clinton P. Conrad[a,*], Benjun Wu[b], Eugene I. Smith[c], Todd A. Bianco[a], Ashley Tibbetts[c]

[a] Department of Geology and Geophysics, SOEST, University of Hawaii, Honolulu HI 96822, United States
[b] Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore MD 21218, United States
[c] Department of Geoscience, University of Nevada at Las Vegas, Las Vegas NV 89154, United States

ARTICLE INFO

Article history:
Received 24 March 2009
Received in revised form 6 October 2009
Accepted 6 October 2009

Keywords:
Intraplate volcanism
Asthenospheric upwelling
Upper Mantle Flow
Plate motions
Viscous shear
Viscosity heterogeneity
Melting instability

ABSTRACT

Volcanism occurring away from ridges and subduction zones does not have an obvious plate tectonic explanation, but instead must arise from sub-lithospheric processes that generate upwelling flow and decompression melting. Several convective processes, such as mantle plumes, convective instability, edge-driven convection, and Richter rolls, produce upwelling via the action of gravity on density heterogeneities in the mantle. Here we investigate an alternative mechanism, the shear-driven upwelling (SDU), which instead generates upwelling solely through the action of asthenospheric shear flow on viscosity heterogeneity. Using a numerical flow model, we examine the effect of viscosity heterogeneity on viscous shear flow induced within an asthenospheric layer. We demonstrate that for certain geometries and viscosity ratios, circulatory flow develops within a "cavity" or "step" embedded into the lithospheric base, or within a low-viscosity "pocket" embedded within the asthenospheric layer. For asthenosphere shearing at 5 cm/yr, we estimate that SDU can produce upwelling rates of up to ∼0.2 cm/yr within a continental rift, ∼0.5 cm/yr along the vertical edge of a craton, or ∼1.0 cm/yr within a "pocket" of low-viscosity asthenosphere. In the last case, the pocket must feature an aspect ratio of more than 5, occupy ∼20–60% of the asthenosphere's thickness, and be at least 100 times less viscous than the surrounding asthenosphere. Such viscosity heterogeneity may be associated with thermal, chemical, melting, volatile, or grain-size anomalies, and is consistent with tomographic constraints on asthenospheric variability. We estimate that SDU may generate up to 2.5 km/Myr of melt that is potentially eruptible as surface volcanism; this is faster than eruption rates observed at some locations of continental basaltic volcanism. We conclude that SDU could provide an explanation for intraplate volcanism occurring above rapidly shearing asthenosphere, for example in the Basin and Range region of North America.

1. Introduction

Most of the volcanism around the globe occurs at subduction zones and mid-ocean ridges, and is well-explained by the theory of plate tectonics. Volcanism that occurs away from plate boundaries, however, is less easily explained, but has often been attributed to hot plumes that rise from deep within the mantle (Morgan, 1971). Such plumes are a natural consequence of mantle convection and provide an explanation for the numerous linear chains of volcanoes around the globe (e.g., Richards et al., 1989). Recently, however, the plume explanation for intraplate volcanism has been challenged (e.g., Foulger and Natland, 2003), and alternative explanations such as lithospheric cracking have been proposed (e.g., Anderson, 2000). Recent studies have suggested that relatively few (less than 10) volcanic chains are caused by deep mantle plumes (e.g. Courtillot et al., 2003), out of upwards of 30–40 hotspot tracks that have previously been attributed to plumes (e.g., Sleep, 1990; Steinberger, 2000). Thus, regardless of whether the major hotspots (e.g., Iceland, Hawaii, Louisville) are plume-generated, an alternative explanation is needed to explain intraplate volcanism not fed by plumes.

Furthermore, several other intraplate volcanic features, such as seamounts that pervade the Pacific basin (Hillier and Watts, 2007), are not associated with classic hotspot tracks (Clouard and Bonneville, 2001). Instead most Pacific seamounts were emplaced during the Cretaceous along with the large Pacific oceanic plateaus (Wessel, 1997). More recently, the southwestern US has become dotted by mid-Miocene to contemporary basaltic volcanic fields, such as the Death Valley-Lunar Crater belt, the Saint George volcanic Field, and the Jemez lineament. These features do not resemble plume-induced volcanism in terms of their temporal and spatial patterns (Smith et al., 2002; Smith and Keenan, 2005), associated uplift (Parsons et al., 1994), or volumetric output (Bradshaw et al., 1993; Hawkesworth et al., 1995). Other examples of non-plume intraplate volcanism, such as in the Harrat Ash Shaam field

* Corresponding author. Tel.: +1 808 956 6649; fax: +1 808 956 5154.
E-mail address: clintc@hawaii.edu (C.P. Conrad).

0031-9201/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.pepi.2009.10.001

in the Middle East (e.g., Shaw et al., 2003), and the Changbai volcano in Northeast Asia (Lei and Zhao, 2005), have been noted in several locations around the world.

Without a source of excess heat coming from the deep mantle, most alternative explanations for intraplate volcanism invoke some source of regional asthenospheric upwelling that induces decompression melting. This melting may be augmented by "melting instabilities" that involve positive feedback between decompression melting and the subsequent upwelling caused by the presence of this melt (Raddick et al., 2002; Hernlund et al., 2008a,b). This feedback can result in an episode of volcanism above asthenosphere near its melting temperature. Thus, the search for a non-plume source of intraplate volcanism generally involves a search for mechanisms that can initiate upwelling flow within fertile asthenosphere that is already near its solidus. Several upwelling mechanisms have been proposed. First, the presence of extension generates passive upwelling flow (e.g., McKenzie and Bickle, 1988), but this flow should be extremely slow unless it becomes localized in some way. In addition, numerical models show that melting instabilities may be inhibited or delayed by the presence of active lithospheric extension (Hernlund et al., 2008b). Alternatively, the temperature differential between the lithosphere and asthenosphere sets up an inverted density structure that can lead to persistent steady-state thermal convection in the asthenosphere (e.g., Haxby and Weissel, 1986; van Hunen and Zhong, 2006; Ballmer et al., 2007) or occasional "drips" of dense lithosphere sinking into the upper mantle (e.g., Le Pourhiet et al., 2006). Both convection and "dripping" involve asthenospheric upwelling that can lead to volcanism, and may be enhanced by viscosity heterogeneity or lithospheric deformation (e.g., Conrad, 2000). Finally, small-scale convection in the asthenosphere may be enhanced near the edges of cratons or other sharp gradients in lithospheric thickness because the associated lateral temperature gradients can produce an "edge-driven" convective circulation in the asthenosphere (e.g., King and Anderson, 1998) that can lead to volcanism (King and Ritsema, 2000).

The density inversion between the lithosphere and asthenosphere is not the only energy source that can drive small-scale asthenospheric circulation and upwelling. For example, the asthenosphere accommodates up to a few cm/yr of relative motion between the lithospheric plates and the convecting mantle via a shearing deformation that can be detected by observations of seismic anisotropy (e.g., Silver and Holt, 2002; Conrad et al., 2007). When asthenospheric shear occurs simultaneously with small-scale convection, the density heterogeneity produced by convection becomes elongated into roll-like circulatory structures known as "Richter Rolls" (e.g., Richter and Parsons, 1975; Korenaga and Jordan, 2003). Less well-studied, however, is the response of a shear flow to viscosity heterogeneity, either within the asthenospheric layer (e.g., associated with thermal or chemical heterogeneities or pockets of melt) or associated with lateral variations in lithospheric thickness (e.g., near a ridge or a cratonic "edge"). In some engineering applications, for example, the presence of a shear flow beneath an open fluid-filled "cavity" can produce circulatory flow within the cavity at low Reynolds numbers (e.g., Shen and Floryan, 1985; Pakdel et al., 1997; Shankar and Deshpande, 2000). Applied to the asthenosphere, this "shear-driven cavity flow" may produce a type of upwelling that is not associated with any convective process. Instead, the driver for this type of upwelling is the relative motion between the plates and mantle; upwelling flow is excited in this case by viscosity heterogeneity, rather than density heterogeneity (e.g., Fig. 1). In this study,

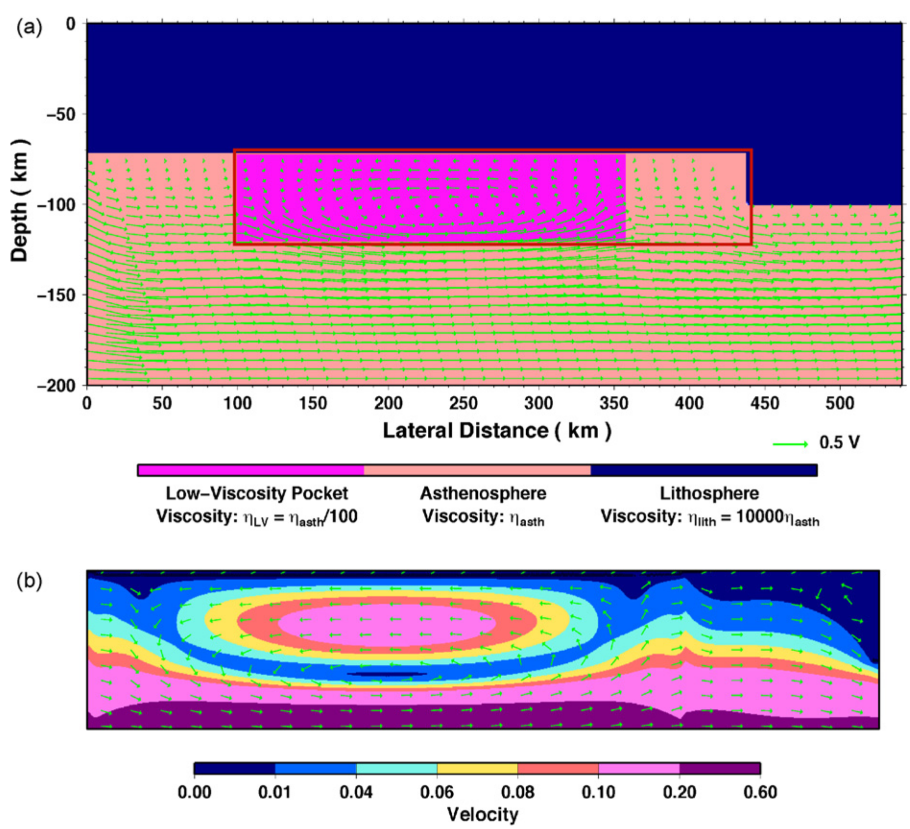

Fig. 1. Viscous flow calculation showing the effect of both a low viscosity "pocket" and a lithospheric step on asthenospheric shear flow. In (a), arrows indicate velocity direction and magnitude (note scale arrow showing 0.5 *V*, where *V* is the magnitude of the velocity imposed on the asthenospheric base at 200 km), while colors indicate viscosity variations. A detailed view of the red-outlined box in (a) is shown in (b), where arrows indicate velocity direction and colors indicate magnitude of velocity. In (a) and (b), amplitudes of velocity are given as a fraction of the velocity that drives the shear flow at the base of the asthenosphere.