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Formation of the Cameroon Volcanic Line by lithospheric basal erosion: Insight from mantle seismic anisotropy

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ABSTRACT

The formation mechanism of intraplate volcanism such as that along the Cameroon Volcanic Line (CVL) is one of the controversial problems in global tectonics. Models proposed by previous studies include reactivation of ancient suture zones, lithospheric thinning by mantle plumes, and edge-driven mantle convection. To provide additional constraints on the models for the formation of the CVL, we measured shear-wave splitting parameters at 36 stations in the vicinity of the CVL using a robust procedure involving automatic batch processing and manual screening to reliably assess and objectively rank shear-wave splitting parameters (fast polarization directions and splitting times). The resulting 432 pairs of splitting parameters show a systematic spatial variation. Most of the measurements with ray-piercing points (at 200 km depth) beneath the CVL show a fast direction that is parallel to the volcanic line, while the fast directions along the coastline are parallel to the continental margin. The observations can best be interpreted using a model that involves a channel flow at the bottom of the lithosphere originated from the NE-ward movement of the asthenosphere relative to the African plate. We hypothesize that progressive thinning of the lithosphere through basal erosion by the flow leads to decompression melting and is responsible for the formation of the CVL. The model is consistent with the lack of age progression of the volcanoes in the CVL, can explain the formation of both the continental and oceanic sections of the CVL, and is supported by previous geophysical observations and geodynamic modeling results.

1. Introduction

Most of the Earth's magmatism is associated with dehydration of minerals in subducting slabs and with decompression melting along mid-ocean ridges, and thus can be well-explained by the theory of plate tectonics (e.g., Turcotte and Oxburgh, 1978; Courtillot et al., 2003). The formation mechanism for intraplate magmatism, on the other hand, remains enigmatic. Various models have been proposed to explain intraplate magmatism, including those involving mantle plumes (Morgan, 1972; Courtillot et al., 2003), tensional cracking in the lithosphere (Turcotte and Oxburgh, 1978; Anderson, 2000), and edge-driven convection (EDC) (King and Anderson, 1998).

The African plate is ideal for studying intraplate magmatism. It contains several intraplate volcanic segments or centers that are remote from the African plate boundaries (Fig. 1). One of such segments is the NE–SW oriented Cameroon Volcanic Line (CVL), which consists of a continental and an oceanic section. The CVL intercepts with the Atlantic coastline at the joint point between the E–W and N–S segments of the coastline (Fig. 2).

Many studies proposed that the CVL was the result of the NE-ward movement of the African plate over a mantle plume that is currently beneath St. Helena (e.g., Morgan, 1983) (Fig. 1). This model predicts that the age of the volcanoes decreases toward the SW. Such an age progression, however, is not observed (e.g., Fitton and Dunlop, 1985). Additionally, $^3He/^4He$ ratios measured along the CVL are lower than those observed at typical hotspots such as Loihi and Iceland (Aka et al., 2004), probably suggesting an upper-mantle origin of the magmatism. Other studies concluded that the CVL was due to decompression melting beneath re-activated shear zones on the African continent (e.g., Fairhead, 1988). This model, while can explain the lack of age progression, cannot satisfactorily explain the existence of the oceanic section of the CVL. The third group of studies advocated edge-driven convection as the major cause of the CVL (King and Ritsema, 2000; Koch et al., 2012; Milelli et al., 2012). This model suggests that the upwelling flow thins the lithosphere and creates a line of volcanoes parallel to the boundary between two areas with contrasting lithospheric thickness. In the study area, the northern edge of the Congo craton is a potential locale for the EDC to occur and thus

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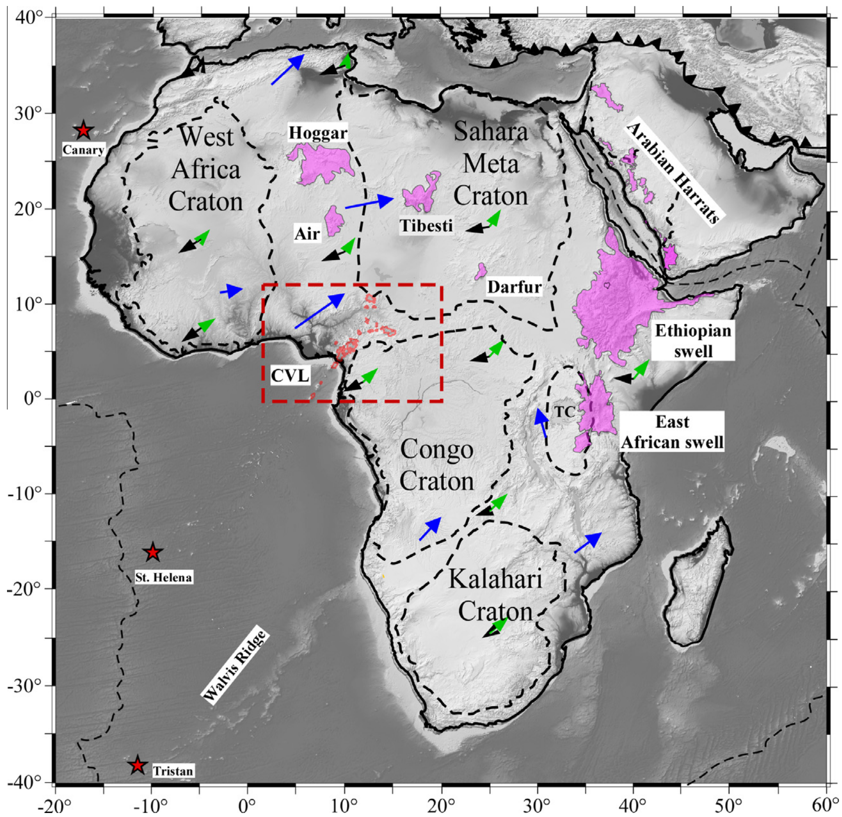

Fig. 1. Topographic relief map of Africa showing major intraplate volcanic centers and cratons (Turcotte and Oxburgh, 1978; Abdelsalam et al., 2011). CVL, Cameroon Volcanic Line. TC, Tanzania Craton. The area inside the red dashed rectangle is shown in Figs. 2 and 3. The green arrows represent absolute plate motion (APM) vectors calculated using the GMHRF model (Doubrovine et al., 2012), and the black arrows show APM vectors determined by the HS3-NUVEL1A model (Gripp and Gordon, 2002). The blue arrows indicate the horizontal component of mantle flow predicted at 250 km depth (Forte et al., 2010). Red stars represent the locations of the Atlantic mantle plumes (Doubrovine et al., 2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

could be responsible for the formation of the continental section of the CVL (Fig. 3). However, this model cannot explain the orientation of the oceanic section of the CVL, because the anticipated strike of the zone of thinned oceanic lithosphere should be parallel to the coastline, while the actual CVL has a NE–SW strike. In addition, as described below, neither the plume nor the EDC model is supported by shear-wave splitting (SWS) measurements.

Splitting analysis of P-to-S converted phases at the core-mantle boundary on the receiver side, including the PKS, SKKS, and SKS (hereinafter collectively referred to as XKS) phases, is considered to be one of the most effective tools in measuring seismic anisotropy, which is mostly caused by deformational processes in the mantle (see Silver, 1996; Savage, 1999, and Fouch and Rondenay, 2006 for reviews). Numerous XKS splitting studies demonstrated that the spatial distribution of the two splitting parameters Φ, which is the polarization direction of the faster wave, and δt, the splitting time between the faster and slower waves, are crucial to understand mantle circulation patterns. The fast direction reflects the mantle deformation direction, while the splitting time quantifies the magnitude of the mantle deformation (Conrad and Behn, 2010; Kreemer, 2009).

The coefficient of anisotropy is defined as $(V_{fast} - V_{slow})/V_{mean}$ where V_{fast} and V_{slow} are the fast and slow shear-wave velocities, respectively and V_{mean} is the mean velocity (Birch, 1960; Wolfe and Solomon, 1998). The global average of the splitting time observed using teleseismic XKS waves is 1.0 s, which corresponds to a thickness of about 100 km for a 4% anisotropy (Silver, 1996). Olivine lattice-preferred orientations (LPO) likely forms as a result of dislocation creep deformation, leading to a macroscopic anisotropy in the upper mantle (e.g., McKenzie, 1979; Ribe, 1989; Fouch and Rondenay, 2006; Conrad et al., 2007). Numerical modeling and experimental mineral physics studies indicate that under uniaxial compression, the olivine *a*-axis rotates to be orthogonal to the maximum compressional strain direction. Under pure shear, it becomes perpendicular to the shortening direction; and under progressive simple shear, it aligns parallel to the flow direction (Ribe and Yu, 1991; Chastel et al., 1993; Zhang and Karato, 1995; Savage, 1999; Liu, 2009). Therefore, the fast direction may reveal the flow direction in the asthenosphere as observed in ocean basins, continental rifts, and passive margins (Wolfe and Solomon, 1998; Gao et al., 1994, 1997, 2008, 2010; Refayee et al., 2013).

In the lithosphere, Φ is primarily parallel to the trend of past tectonic events, as revealed at numerous locales (McNamara et al., 1994; Liu et al., 1995; Silver, 1996; Barruol and Hoffmann, 1999; Fouch and Rondenay, 2006; Li and Chen, 2006; Liu, 2009). In addition, vertical magmatic dikes in the lithosphere can result in XKS splitting with a fast direction parallel to the main strike direction of the dikes (Gao et al., 1997, 2010). This mechanism was suggested to explain rift-parallel fast directions detected in active continental rifts such as the Baikal rift zone (Gao et al., 1997), the East African rift system (Gao et al., 1997, 2010; Kendall et al., 2005), and failed rifts such as the southern Oklahoma aulacogen (Gao et al., 2008).

2. Geophysical background

The CVL is an ~1600 km elongated Y-shaped feature of Cenozoic volcanoes (e.g., Fitton, 1987; Aka et al., 2004; Tokam et al., 2010; Reusch et al., 2010; Milelli et al., 2012) (Fig. 3). It is