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Petrology and geochronology of lavas from Ka'ula Volcano: Implications for rejuvenated volcanism of the Hawaiian mantle plume

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Abstract

Marine surveying and submersible sampling of Ka'ula Volcano, located 100 km off the axis of the Hawaiian chain, revealed widespread areas of young volcanism. New $^{40}Ar/^{39}Ar$ and geochemical analyses of the olivine-phyric submarine and subaerial volcanic rocks show that Ka'ula is shrouded with 1.9–0.5 Ma alkalic basalts. The ages and chemistry of these rocks overlap with rejuvenated lavas on nearby, northern Hawaiian Island shields (Ni'ihau, Kaua'i and South Kaua'i Swell). Collectively, these rejuvenated lavas cover a vast area (~7000 km^2), much more extensive than any other area of rejuvenated volcanism worldwide. Ka'ula rejuvenated lavas range widely in alkalinity and incompatible element abundances (e.g., up to 10× P_2O_5 at a given MgO value) and ratios indicating variable degrees of melting of a heterogeneous source. Heavy REE elements in Ka'ula lavas are pinned at a mantle normalized Yb value of 10 ± 1, reflecting the presence of garnet in the source. Trace element ratios indicate the source also contained phlogopite and an Fe–Ti oxide. The new Ka'ula ages show that rejuvenated volcanism was nearly coeval from ~0.3 to 0.6 Ma along a 450 km segment of the Hawaiian Islands (from West Maui to north of Ka'ula). The ages and volumes for rejuvenated volcanism are inconsistent with all but one geodynamic melting model proposed to date. This model advocates a significant contribution of pyroxenite to rejuvenated magmas. Analyses of olivine phenocryst compositions suggest a major (33–69%) pyroxenite component in Ka'ula rejuvenated lavas, which correlates positively with radiogenic Pb isotope ratios for Ka'ula. This correlation is also observed in lavas from nearby South Kaua'i lavas, as was reported for Atlantic oceanic islands. The presence of pyroxenite in the source may have extended the duration and volume of Hawaiian rejuvenated volcanism.

Keywords: Hawaii; Basalt; Submarine; Major and trace element geochemistry; Geochronology; Olivine

1. INTRODUCTION

Mantle plumes are recognized by most geoscientists as the cause for mid-plate volcanism (e.g., Kerr, 2013). One intriguing but poorly understood aspect of mantle plumes is the resumption of volcanism hundreds of kilometers downstream from the ascending mantle plume stem

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following a hiatus in eruptive activity. This second period of volcanism is common on and around the shield volcanoes in many oceanic island groups including Samoa (Wright and White, 1987), Kerguelen (Weis et al., 1998), the Canary Islands (Hoernle and Schmincke, 1993), Madeira (Geldmacher and Hoernle, 2000), and Mauritius (Paul et al., 2005). Since its first recognition in Hawaii by Dana (1890), this second period of volcanism has been given many different names: post-erosional, rejuvenation, secondary, etc. Here we will use the common term "rejuvenation" to recognize the return of volcanism to the areas of previous shield activity. Volcanism on the flexural arch that surrounds the Hawaiian Islands is distinct because these areas are 200+ km off the axis of the hotspot trace and had no previous plume-related volcanism (e.g., Lipman et al., 1989; Frey et al., 2000). However, the major and trace element, and isotopic composition of arch lavas is very similar to rejuvenated lavas (e.g., Yang et al., 2003).

Comprehensive geochronological and magnetostratigraphy studies of other oceanic island such as Gran Canaria, an oceanic island in the Atlantic, have documented its episodic and protracted history of rejuvenated volcanism (~5 Myr; Guillou et al., 2004). Although it has been argued that Gran Canaria's long duration of rejuvenated volcanism is related to the slow movement of the African plate (1.9 cm/yr), its geologic history and rock compositions are very similar to those of Hawaiian and other oceanic islands and thus, probably share a similar origin (Carracedo et al., 1998).

Hawai'i is the archetypal example of a plume-derived hotspot having produced the Hawaiian-Emperor Chain, one of the longest linear chains in time and space on Earth (e.g., Clague and Dalrymple, 1987; Garcia et al., 2015). Recent marine expeditions to the northern Hawaiian Islands (Garcia et al., 2008; Greene et al., 2010) and numerical modeling studies (Ballmer et al., 2011, 2013, 2015; Hofmann and Farnetani, 2013) have prompted renewed interest in the what, where, when and why of rejuvenated volcanism in the Hawaiian Islands. Our 2007 expedition surveyed and sampled Ka'ula Volcano, which is located southwest of the islands of Kaua'i and Ni'ihau (Fig. 1). These surveys revealed extensive areas of rejuvenated submarine volcanism (Garcia et al., 2008). In this paper we present and interpret new compositional and geochronological data for submarine lavas lavas collected during two JASON dives on the NW and SE flanks of the volcano, and accidental volcanic blocks we collected from the tuff cone that caps the volcano.

2. GEOLOGIC SETTING AND SAMPLES

Ka'ula Island is a crescent shaped tuff cone remnant (~0.5 km^2) located ~33 km west-southwest of the island of Ni'ihau (Fig. 1), the oldest of the main Hawaiian Islands (Sherrod et al., 2007). The Ka'ula tuff cone is located on the southeast corner of a wave-cut platform that caps a separate and distinct volcanic edifice unrelated to the nearby volcanic complexes that form the islands of Ni'ihau and Kaua'i (Hinds, 1930). These three complexes form a ridge that crosscuts the trend of the Hawaiian Islands with their volcanic centers spanning ~130 km across the width of the Hawaiian plume, versus only ~50 km for the southern Hawaiian Islands (Fig. 1). The origin of the anomalous Ka'ula-Ni'ihau-Kaua'i (KNK) ridge has been related to a fracture in the underlying Cretaceous oceanic crust, possibly a splay of the Murray fracture zone (Macdonald et al., 1983). The KNK ridge is oriented roughly parallel to some of the factures and ridges in the Cretaceous oceanic crust west of the islands in the Kamehameha basin (Fig. 1). However, a synthesis map of the structure of the Cretaceous crust around the KNK ridge shows no major fractures disrupting the abyssal hill fabric or magnetic anomalies east or west of the ridge that align with its trend (e.g., Holcomb and Robinson, 2004). The absence of a structural weakness in the surrounding oceanic crust leaves open the question of the origin of this anomalous cross-trend ridge. Another cross-trend ridge with three volcanic complexes has been proposed for Moloka'i Island area, ~200 km to the south (Xu et al., 2014). No explanation has been given for its origin.

Ka'ula Volcano has been poorly studied because of its remote location (Fig. 1) and use as a bombing target by the U.S. military since World War II. The volcano was not mentioned in the recent compilation of the geology of the State of Hawai'i (Sherrod et al., 2007). The first preliminary description of Ka'ula's geology was by Palmer (1927). The petrology and age of some lithic volcanic blocks from the island (tholeiite, phonolite, alkalic basalt and basanite) were documented by Garcia et al. (1986). Eight of these samples (a tholeiite, alkalic basalt and six basanites) are included in our study. Numerous garnet pyroxenite and spinel peridotite lithic blocks are also present on the island (Garcia and Presti, 1987). Isotope (Hf, Nd, Sr, Pb) analyses of a few basanite, phonolite and pyroxenite xenoliths were presented by Bizimis et al. (2013) on samples from the Garcia et al. (1986) and Presti (1982) studies. Three of these basanites are included in our study (KA-19, -28, -34). The Ka'ula phonolites have been well documented (Garcia et al., 1986; Bizimis et al., 2013) and are not discussed in this paper.

Eighty-one new lava samples were colllected during two JASON remotely operated vehicle dives on opposite sides of the main Ka'ula edifice (Fig. 2). Dive 300 traversed a field of flat-topped cones on Ka'ula's northwest apron collecting multiple basaltic samples from six cones at depths of 3927–3125 mbsl before ascending the northwest flank of the main edifice and recovering samples from a broad terrace and nearby ridge to 2530 mbsl. Dive 304 sampled two terraces on the lower southeast flank of the Ka'ula submarine edifice starting at 3615 mbsl, then sampled a pointed cone between 2607 and 2411 mbsl (cone F) before ascending and collecting samples along a ridge (that may have been one of Ka'ula's rift zones) to 1700 mbsl (Fig. 2). Forty-four pillow basalts were collected on dive 300 and 37 during dive 304 (Table S1).

3. ANALYTICAL TECHNIQUES

The $^{40}Ar/^{39}Ar$ ages were determined in two labs. Seven submarine samples were analyzed at Oregon State University using methods described by Koopers et al. (2003) and