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 $^{40}\text{Ar}/^{39}\text{Ar}$ and geochemical analyses of the olivine-phyric submarine and subaerial volcanic rocks show that Ka'ula is shrouded with 1.9 to 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 ($\sim 7000 \text{ km}^2$), 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 $10\times \text{P}_2\text{O}_5$ 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.

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 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., 2015a). 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 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 ($\sim 0.5 \text{ km}^2$) located $\sim 33 \text{ km}$ 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 $\sim 130 \text{ km}$ across the width of the Hawaiian plume, versus only $\sim 50 \text{ km}$ 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 fractures 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, $\sim 200 \text{ km}$ to the south (Xu et al., 2014). No explanation was 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 this 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 this 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 collected 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 to 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 A.1).

3. ANALYTICAL TECHNIQUES

The $^{40}\text{Ar}/^{39}\text{Ar}$ ages were determined in two labs. Seven submarine samples were analyzed at Oregon State University using methods described by Koppers et al. (2003) and Duncan and Keller (2004). These samples maximize the geographic coverage, have higher K_2O contents (0.49-1.43 wt.%), and are the freshest (based on petrography and lower loss-on-ignition, LOI; <0.95 wt.%) for the submarine suite. Holocrystalline matrix material from the interior of the pillow basalts was finely

crushed (<1 mm) with a tungsten-carbide (WC) coated hydraulic press, ultrasonically cleaned in Millipore water and dried for 24 hours at 40°C. Dried crushed rock was sieved to 250 to 350 μm . Phenocrysts were removed from the sieved split using a Frantz magnetic barrier separator and/or heavy liquids. Groundmass separates were hand picked under a binocular microscope to avoid grains with secondary alteration. Two subaerial samples (KA-14 and -31) were prepared using the same handling methods and analyzed at the University of Wisconsin at Madison using procedures described in Jicha et al. (2012).

Microprobe analyses were made of glass and olivine in Ka'ula samples using the University of Hawai'i five-spectrometer, JEOL HyperProbe. Glasses were analyzed from all glass-bearing submarine samples (31 from dive 300 and 23 from dive 304). Major element and S analyses of glass were obtained with a 15 kV accelerating voltage, 10 nA beam current and a 10 mm diameter beam. The reported analyses are an average of 10 spot analyses per sample. Accuracy and precision are estimated at <1% for major elements and 2–5% for minor elements (<1 wt.%) based on repeat analyses of a Hawaiian glass standard (A99) and Juan de Fuca glass (VG-2) from the Smithsonian collection (e.g., Jarosewich et al., 1979). Olivine was analysed using higher precision methods; 20 kV, 200 nA and longer counting times (Si, Mg, Ni, Ca, 115 s on peak, 90 s total on background for each element; Mn, 75 s on peak, 60 s on background; Fe, 30 s on peak, 30 s on background). Larger crystals were used for Fe, Mn (LIFH) and Ca (PETH) to obtain higher count rates. The standards used in calibration were San Carlos olivine USNM 111312/444 (SiO_2 , MgO, FeO; Jarosewich et al., 1980), synthetic Mn-olivine (MnO; Shannon et al., 1991), UCLA Diopside (CaO), and synthetic Ni-olivine (Ito, 1975). Raw X-ray intensities were converted into weight percent via ZAF correction methods (Armstrong, 1988). Two sigma errors are <0.03 wt.% for SiO_2 , MgO and FeO and <0.01 wt.% for CaO, MnO and NiO based on 10 replicate analyses of the San Carlos olivine standard.

A subset of volcanic rock samples was analyzed by XRF (25 from dive 300 and 30 from dive 304) to provide geographic and rock type (based on petrography glass analyses) coverage. Samples were coarsely crushed (1-8 mm) with a tungsten-

carbide (WC) coated hydraulic press, ultrasonically cleaned in Millipore water, dried for 24 hours at 40°C, and hand-picked to remove fragments with signs of alteration. This procedure ensured that only the freshest parts of each sample were analyzed. The efficiency of this process is reflected by the relatively low loss-on-ignition (LOI) values (for methods, see Rhodes, 1996) for most samples (<1.0 wt. %). The clean rock fragments were split into two aliquots; one for XRF and the other for ICP-MS analyses. Samples for XRF analysis were powdered using WC-lined mills, and analyzed for major and trace elements at the University of Massachusetts (for analytical procedures and precision see Rhodes and Vollinger, 2004).

Twenty of the freshest (i.e., low LOI) submarine samples (ten from each dive) and two accidental blocks from the island (tholeiite KA-14 and basanite KA-31) were selected for trace element analyses by HR-ICP-MS on a Thermo Finnigan Element2 at the Pacific Centre for Isotopic and Geochemical Research (PCIGR) at the University of British Columbia. Samples were powdered in an agate mill, digested in concentrated sub-boiled HF and HNO₃ for 48 h, and then redigested in 6N sub-boiled HCl for 24h. Once dried, they were redissolved in concentrated HNO₃, dried down again and diluted 5000 times using a 10 ppb In, 1% HNO₃ solution. For a detailed description of the trace element analysis procedures, see Carpentier *et al.* (2013) and Schudel *et al.* (2015).

4. RESULTS

4.1. ⁴⁰Ar/³⁹Ar Dating

Previous age determinations of Ka'ula lavas were performed using conventional K-Ar methods on two phonolites and an alkalic basalt collected from the tuff cone (Garcia *et al.*, 1986). The phonolites yielded whole-rock ages of 4.01 ± 0.09 and 4.22 ± 0.25 Ma. A biotite separate from the 4.2 Ma phonolite yielded an age of 3.98 ± 0.70 Ma. The strongly evolved alkalic composition and intermediate age of the phonolites were interpreted as representing Ka'ula's post-shield stage of volcanism (Garcia *et al.*, 1986). The alkalic basalt gave an age of 1.8 ± 0.2 Ma, which was thought to reflect Ka'ula's rejuvenated stage of volcanism based on the age and compositional

similarities to rejuvenated lavas from nearby Ni‘ihau and Kaua‘i islands (Garcia et al., 1986).

New work on seven Ka‘ula submarine alkali basalts yielded plateau ages of 0.55 to 1.95 Ma with all plateaus having a high percentage of ^{39}Ar released (88-100%, most >96%), low MSWD values (0.02 and 0.15, most <0.10) and $^{40}\text{Ar}/^{36}\text{Ar}$ intercepts overlapping the atmospheric value (Tables 1 and A.2). Thus, the plateau ages are used here as the preferred ages for the Ka‘ula lavas (Table 1). The ages for four dive 304 samples decrease along the uphill dive traverse from 1.24 to 0.55 Ma. The oldest age for a submarine sample (300-10, 1.95 ± 0.19 Ma) was from a cone with the most sediment cover based on dive observations and sidescan sonar images. Samples from two other cones with less sediment cover were collected on dive 300; they gave younger ages (0.81 ± 0.56 and 0.92 ± 0.57 Ma). The basanite accidental block from the island (KA-31) gave a plateau age of 0.663 ± 0.085 Ma (Tables 1 and A.3).

The range of ages for alkalic Ka‘ula rocks (0.55-1.95 Ma) overlaps with the K-Ar ages for rejuvenated lavas from Ni‘ihau (0.35-2.68 Ma; Sherrod et al., 2007), Kaua‘i (0.15-2.52 Ma; Garcia et al., 2010), West Ka‘ena (0.36-1.47 Ma; Greene et al., 2010) and South Kaua‘i Swell areas (0.1-1.9 Ma; Garcia et al., 2015b). The similar ages (Fig. 3) and compositions (alkalic basalt to foidite) between the lavas from these nearby centers strongly suggest that the Ka‘ula lavas are from a rejuvenated stage of volcanism.

A tholeiitic block (KA-14) from the island yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ plateau age of 6.24 ± 0.08 Ma (Tables 1 and A.3). This age, the oldest from the Hawaiian Islands with an error of less than 1 Myr (Sherrod et al., 2007), and its tholeiitic composition (Garcia et al., 1986) are indicative that the sample is from Ka‘ula’s shield stage (Fig. 3).

4.2. Petrography

The suite of submarine Ka‘ula rocks share many common petrographic features: most have an unaltered glassy or cryptocrystalline matrix, are weakly vesicular (<5 vol.%; Table A.4) and olivine phyric (>5 vol.% total olivine phenocrysts, >0.5 mm wide, and microphenocrysts, 0.1-0.5 mm wide) with a median value of 8 vol.%

(Tables A.4). About a third of the samples are picritic with 10-18 vol.% olivine (Table A.4). Many of the dive 304 samples also contain rare (<2 vol.%) microphenocrysts of plagioclase. Plagioclase is less abundant in samples from dive 300 (20% of samples vs. 35% in dive 304 samples, although sample 300-10 contains ~4 vol.% plagioclase; Table A.4). A few samples (collected on the shallower, <2700 m, flanks of the submarine edifice) have clinopyroxene microphenocrysts. Typically, samples with clinopyroxene microphenocrysts lack plagioclase microphenocrysts. The uncommon occurrence of clinopyroxene in Ka'ula samples is striking compared to rejuvenated lavas from Honolulu (Winchell, 1947) but is similar to the weakly alkaline lavas from Kaua'i (Garcia et al., 2010). Minor alteration is evident in a few Ka'ula samples (thin rim of palagonite rim on glass, 1-2 mm thick and/or clay lining some vesicles) under typically a thin (<1 to 3 mm) Mn coating.

The basaltic blocks from Ka'ula Island range widely in mineralogy. Olivine is ubiquitous; most of the samples contain 6-11 vol.% total olivine, whereas the tholeiite (KA-14) and an alkaline basalt (KA-29) have <2 vol.% olivine and plagioclase microphenocrysts, which are absent in the other samples. These non-plagioclase bearing samples contain clinopyroxene as phenocrysts, microphenocrysts and/or xenocrysts (e.g., sample KA-15 has abundant cpx xenocrysts, 17 vol.%; Table A.4). All of the volcanic blocks are moderately to strongly vesicular (19-70 vol.%) except sample KA-34 (7 vol.%; Table A.4). Zeolites (mainly phillipsite and natrolite) are present in the vesicles of the blocks) and rare calcite was found in sample KA-34 but is absent in all other samples.

4.3. Olivine Chemistry

Olivine core compositions were determined for six submarine (dive 304) and four subaerial basalts from Ka'ula Volcano. These samples were chosen to span a wide range in composition and for the presence of fresh olivine phenocrysts; all are from the rejuvenation stage. Olivine from these basalts show a broad range in forsterite content (Fo; 82.0-91.0; Table 2). The subaerial samples KA-19, -31 and -34 contain olivine with the highest Fo values (89-91%). These crystals have low CaO contents (0.02-0.09 wt.%; Table 2) but are euhedral. Such low CaO values are generally

considered to be indicative of mantle-derived olivine (e.g., Søager et al., 2015). In backscatter images, these crystals are strongly zoned with a round Mg-rich core. These subaerial lavas also contain anhedral olivine with low CaO contents, which we consider to be xenocrysts. Thus, the low CaO olivines are also probably xenocrysts that were mantle derived and subsequently overgrown with moderate forsterite olivine (Fo 85-88). The olivine with moderate CaO contents span a wider Fo range for the subaerial samples than the submarine samples (3-7% vs. 1-3%; except sample 304-23; Fig. 4). Most of the olivine in four of the submarine samples plot within the equilibrium field (Fig. 4) suggesting these basalts are representative of magmatic compositions (e.g., did not accumulate olivine phenocrysts or antecrysts). Olivine that plots above the equilibrium field (Fig. 4) from the submarine and subaerial samples are probably either xenocrysts (low CaO) or antecrysts.

4.4. Glass Chemistry

Pillow rim glasses were analyzed for major elements and S in 54 Ka'ula submarine lavas (not all samples had glass). The glasses all have weakly alkalic basalt compositions with moderate contents of SiO₂ (45.6-48.0 wt.%) and total alkalis (3.2-4.7 wt.%; Table 3). The glasses range in MgO content from 6.0 to 8.4 wt.% and have a wide range in K₂O (0.35 to 1.04 wt.%; Fig. 5). Glasses from the dives on opposite sides of Ka'ula are somewhat chemically distinct (e.g., distinct trends on MgO vs. K₂O and Al₂O₃ plots; Fig. 5). Dive 304 glasses have higher K₂O and Al₂O₃ than those from dive 300 (Fig. 5), and also higher Na₂O and P₂O₅ (Table 3). Divergent CaO/Al₂O₃ trends with decreasing MgO are present for dive 304 glasses (Fig. 5). Glasses on the increasing CaO/Al₂O₃ trend have higher CaO contents than those on the decreasing trend at similar MgO contents (12.8-13.0 wt.% vs. ≤12.1 wt.%; Table 3). The glasses from the decreasing trend are from the shallowest areas sampled (Table 3). Ka'ula glasses have higher K₂O and CaO/Al₂O₃ at a given MgO compared to submarine glasses from rejuvenated lavas of nearby Ni'ihau (Fig. 5) indicating distinct parental magma compositions for the two volcanic regions. These chemical differences may allow the distribution of the lavas from

these two adjacent and overlapping volcanic fields on the north sides of Ka'ula and Ni'ihau islands (Fig. 2) to be better delineated in future sampling.

The sulfur content of Ka'ula submarine glasses ranges from 0.10 to 0.19 wt.% (Table 3). All of the glasses collected at depths >2500 m contain ≥ 0.140 wt.% S, indicating they were probably undegassed (Fig. 5). These glasses are also weakly vesicular (≤ 4 vol.%; Table A.2). More vesicular samples (>10 vol.%) typically had no glass or have lower S contents (0.10-0.12 wt.% S; Table 3). These lower S glasses were collected on dive 304 from shallower water depths, <2400 m, along the southeast ridge. Two positive trends are evident in the S vs. depth data for dive 304 glasses; one for ridge samples and the other for cone F (Fig. 5). No correlation was found for S with FeO content (which has been observed in some suites of mid-ocean ridge glasses; e.g., Mathez, 1976), although S content generally increases with decreasing MgO for dive 300 glasses (Table 3). Ni'ihau submarine glasses have similar to somewhat lower S contents (0.06-0.19 wt.%; Dixon et al., 2008) than Ka'ula glasses (median values, 0.12 vs. 0.15 wt.%, respectively). The lower value for some Ni'ihau glasses probably reflects their somewhat shallower water depth of collection (~1000 m; Dixon et al., 2008).

4.5. Whole-rock Major Elements

Sixty-four Ka'ula samples were analyzed by XRF for major elements; eight from the island, 25 from dive 300 and 31 from dive 304 (Table 4). All of these Ka'ula volcanic rocks are alkalic except a tholeiitic volcanic lithic block from the island, sample KA-14 (Fig. 6). SiO₂ contents for the alkalic rocks range from 40.9 to 47.8 wt.% and total alkalis from 2.9 to 5.4 wt.% making the Ka'ula lavas foiditic to weakly alkalic basalts (Fig. 6). The volcanic blocks from the island show the greatest variation in SiO₂ and total alkalis (Fig. 6). Samples from dive 300 are somewhat less alkali-rich than those from dive 304 (Table 4). The alkalic compositions and the ages of the dated samples (0.55 to 1.95 Ma; Table 1) are typical of Hawaiian rejuvenated volcanism in the northern Hawaiian Islands (Figs. 3 and 6).

The MgO contents for Ka'ula lavas vary from 6.2 to 13.4 wt.% with a positive but scattered correlation with total olivine content (Table A.4). The median MgO content

is relatively high (~11 wt.%), which is typical for Hawaiian rejuvenated lavas (e.g., Winchell, 1947). The P₂O₅ content of Ka'ula rocks at the same MgO is remarkably variable (0.2-1.1 wt.%; Fig. 7). Many of the samples from both dives show a relatively tight, increasing trend for P₂O₅ with decreasing MgO. The volcanic blocks from the island show the widest variability in P₂O₅ at a given MgO content (Fig. 7). A wide range in CaO/Al₂O₃ values is also seen for Ka'ula rocks with no apparent decrease at lower MgO values (<7 wt.%; Fig. 7). This suggests that neither plagioclase nor clinopyroxene fractionation was significant in the more evolved Ka'ula rocks, which is consistent with scarcity of these minerals in Ka'ula rocks (Table A.4). There is a wide range in CaO/Al₂O₃ and P₂O₅ at higher MgO values (≥10 wt.%; Fig. 7) indicating a diversity in parental magma compositions.

Ka'ula samples generally have higher total alkali, and lower SiO₂ contents and higher P₂O₅ at a given MgO compared to rejuvenated submarine lavas from nearby Ni'ihau (Figs. 6 and 7). However, the Ka'ula rocks overlap in composition with rejuvenated lavas from the Honolulu series and Kaua'i (not shown), although these other two groups extend to lower SiO₂ (36 wt.%) and higher P₂O₅ (1.5 wt.%; Clague and Frey, 1982; Garcia et al., 2010) than Ka'ula lavas.

4.6. Trace Elements

4.6.1. XRF Results

Trace elements were analyzed by XRF for the same 64 Ka'ula samples analyzed for major elements (Table 4). Alteration is known to play an important role in modifying the composition of Hawaiian basalts (Frey and Rhodes, 1993). Thus, the effects of alteration on the abundance of these elements need to be identified before attempting to evaluate possible magmatic causes for trace element variations. The abundance of Rb and K are highly susceptible to modification in subaerial Hawaiian lavas, which leads to high and variable K/Rb values (e.g., Feigenson, 1984; Frey and Rhodes, 1993). The K/Rb ratio in Ka'ula lavas is nearly constant ($R^2 = 0.93$ for all samples; Fig. 8), which is remarkable given the wide variations in major element contents (Figs. 5, 6 and 7). If the island samples are excluded because of the presence of secondary minerals (Table A.4), the R^2 for K/Rb improves to 0.95. One

of the island samples, KA-19, has extremely high Sr content (6400 ppm; Fig. 9). This sample is highly vesicular (~70 vol.%) with abundant zeolites. Zeolites in volcanic rocks can contain substantial Sr (e.g., Cappelletti et al., 2011). The composition of the vesicle-filling minerals in sample KA-19 by energy dispersive analysis (EDS). Some but not all of the zeolites in this sample have 0.7-3.3 wt.% SrO (Table A.5; Fig. A.1). These zeolites also contain up to 2 wt.% BaO, although the BaO and SrO contents are not well correlated (Table A.5). Backscatter imagery revealed a high atomic number mineral in a few vesicles and irregular voids (Fig. A.1). EDS scans showed the mineral is Sr- and S-rich (celestite; Fig. A.1), which has not been reported previously in Hawaiian basalts. Celestite in volcanic rocks is typically found in hydrothermal veins (e.g., Deer et al., 2013). This presence of celestite at Ka'ula is probably related to hydrothermal activity in the shallow volcanic edifice under the island. Alteration is not the likely cause of elevated Sr (>1100 ppm) in five submarine samples (300-38, 304-20 to 23; Fig. 9; Table 4). These samples also have at least triple the abundance of incompatible elements compared to the other submarine samples (Table 4), are strongly vesicular (18-40 vol.%; Table A.4) compared to other submarine Ka'ula samples (median of 0.7 vol.%) and only weakly altered with no apparent secondary minerals. Thus, their high incompatible element content is a primary feature, as observed in other Hawaiian rejuvenated lavas (e.g., Clague and Frey, 1982; Yang et al., 2003; Dixon et al., 2008; Garcia et al., 2010).

Abundances of compatible trace elements Ni and Cr are relatively high in Ka'ula rejuvenated volcanic rocks (median values of 262 and 452 ppm, respectively) reflecting the comparatively high median MgO content of these rocks (~11 wt.%; Table 4). Elements that are typically highly incompatible in alkaline basalts (Rb, Nb and Ba) have wide ranges (5 to 7x variation) at a given MgO value (Table 4). Samples from dives 300 and 304 show multiple, coherent trends for Nb (Fig. 9) and other incompatible elements (Table 4) as observed for major elements (Figs. 5 and 7). The well defined trends for major and trace elements, and wide range in Nb concentrations at 10 wt.% MgO (Fig. 8) indicate Ka'ula rejuvenated lavas had a diversity of parental magma compositions. Honolulu rejuvenated lavas also show the same highly incompatible element variability, which was attributed to 5x range in

partial melting of a homogeneous source (Clague and Frey, 1982). Subsequent studies of Os Sr and Pb isotopes in the Honolulu lavas have shown the source to be somewhat heterogeneous (e.g., Lassiter et al., 2000; Yang et al., 2003; Fekiacova et al., 2007).

A plot of Zr/Y vs. Nb/Y (Fitton, 2007) is useful for discriminating lavas from the various stages of Hawaiian volcanism including alkaline rocks from the post-shield vs. rejuvenated stages (Yang et al., 2003). Ka'ula alkaline rocks plot near the upper limit of the Icelandic OIB field and within but near the base of the field for Hawaiian rejuvenated lavas (Fig. 8). The Ka'ula tholeiite (KA-14) plots in the Hawaiian shield lava field (Fig. 8). These stage designations support the interpretations presented above based on age and other geochemical results for these Ka'ula samples.

4.6.2. ICP-MS Results

Twenty-two of the 64 samples analyzed by XRF were analyzed by HR-ICP-MS for trace element concentrations (Table 5). The 22 samples were selected to span the geochemical variation observed in the XRF results, cover a wide area of the volcano and for their low level of alteration based on petrography and LOI values (Tables S4 and 4). Reference materials USFGS, BHVO-2 and Kil93 were also analysed and the values obtained are within 2σ error of recommended values (Table 5). Duplicates and replicate measurements show excellent agreement, with relative standard deviations (RSD) less than 3% for most elements. Procedural blank values for the rare earth elements (REE) and most other elements are in the ppt range, and are considered negligible in comparison to the sample concentrations, which are in the ppm range. Values obtained for incompatible elements (e.g., Rb, Ba Nb, Zr and Sr) that were analyzed by both XRF and ICP-MS methods are in excellent agreement ($R^2 > 0.985$).

Values of Sc are relatively high (median value 28.7 ppm) in Ka'ula submarine lavas but unlike the other normally compatible elements in basalts (Cr and Ni), they increase somewhat with decreasing MgO (Tables 4 and 5). These results confirm petrographic observations that clinopyroxene fractionation ($D_{Sc} = \sim 2.5$; Norman et al., 2005) did not play an important role in the magmatic history of the Ka'ula rocks.

Likewise, the absence of a Eu anomaly in Ka'ula lavas (Fig. 10) is consistent with other geochemical and petrographic evidence that plagioclase did not significantly affect the composition of these lavas.

The REE patterns for all Ka'ula volcanic rocks are remarkably similar including the tholeiite, KA-14, even when plotted on a linear rather than log scale (Fig. 10). Nearly all of the REE patterns are pinned at the same chondrite-normalized, heavy REE values (e.g., $Yb_n = 10 \pm 1$; Fig. 10) and fan out broadly in light REE (Fig. 10, Table 5). Two samples (300-10 and -38) have somewhat higher heavy REE values ($Yb_n = 18$) and steeper light to middle REE patterns (Fig. 10; Table 4). The wide variation in light REE concentrations for Ka'ula lavas (chondrite normalized values, La_n from 38 to 261; Fig. 10) is much greater than observed for rejuvenated lavas from nearby Ni'ihau (33-71, median 50; Dixon et al., 2008). The La_n range for Ka'ula lavas is comparable to that observed for Kaua'i rejuvenated lavas, although Ka'ula rocks extend to lower values (Kaua'i, $La_n = 105-291$; Garcia et al., 2010). No crossing REE patterns were found for Ka'ula alkalic lavas, unlike patterns for other suites of Hawaiian rejuvenated lavas (e.g., Ni'ihau, Kaua'i and Honolulu; Yang et al., 2003; Garcia et al., 2010; Cousins and Clague, 2015) and those from Mauritius in the Indian Ocean (Moore et al., 2011). Another major distinction between Ka'ula and Mauritius lavas is the lack of variation in heavy REEs for Ka'ula rocks.

Other incompatible elements range greatly in Ka'ula rejuvenated rocks (e.g., Pb - 0.5 to 60 ppm; Table 5). The two samples with the highest Pb concentrations (58 and 60 ppm) are the ones with higher REE (300-10 and -38). Two other Ka'ula rocks also have Pb values >7 ppm (Table 5), which is higher than any other Hawaiian Island rejuvenated lavas (Ni'ihau, 0.5-1.6 ppm, Dixon et al., 2008; Kaua'i, 1.2-3.5, Cousins and Clague, 2015; Honolulu, 1.3-6.9, Yang et al., 2003). The two samples with the highest Pb and REE concentrations are also enriched in other incompatible elements (e.g., Th, U, Li) as well as Cd, Zn, Sb, W, Bi, Mo and Y (Table 5). As noted above, these rocks are unaltered or only weakly altered (minor iddingsite with no other secondary minerals). Thus, the high incompatible element content of some Ka'ula samples is probably a source feature.

On a primitive mantle normalized diagram, Ka'ula alkalic rocks have positive anomalies for Ba and Sr, and negative anomalies for Cs, Rb, Th, U, Pb, Zr and Hf (Fig. 11, plotted on a linear scale), which yields high Ba/Th and Sr/Nd and low Zr/Sm ratios. Unusually wide ranges are observed for some elements on this diagram (Ba, Pb, light REE and Sr) creating crossing patterns (Fig. 12). Similar patterns are found for rejuvenated lavas from Honolulu, Kaua'i and Ni'ihau (e.g., Yang et al., 2003; Dixon et al., 2008; Garcia et al., 2010; Cousens and Clague, 2015) as well as those from Mauritius (Moore et al., 2011). The wide variations in Pb and Sr concentrations in Mauritius lavas has been attributed to the mobility of these elements in groundwater (Moore et al., 2011). This explanation is not valid for the submarine lavas collected from uneroded flanks of Ka'ula. Thus variations in Pb and Sr concentrations at Ka'ula and other oceanic islands may be a primary feature of some rejuvenated lavas.

5. DISCUSSION

5.1. Source Mineralogy and Heterogeneity

High-pressure melting experiments on dry peridotite have been unable to produce reasonable parent melt compositions for ocean island alkaline basalts (e.g., Walter, 1998). One possible way to produce alkaline melts from a peridotite source is with the presence of a hydrous phase (phlogopite or amphibole) (e.g., Pilet et al., 2008). Key elements for identifying the presence and type of a hydrous phase are Rb, Ba and K. Partition coefficient (K_D) values for these elements in an alkaline basalt are distinctly higher for phlogopite 2.5-3.7 compared to amphibole (0.2-0.6; LaTourrette et al., 1995). Generally, these elements are mobile during even low temperature alteration in subaerial Hawaiian lavas leading to high and variable K/Rb values (e.g., Feigenson, 1984; Frey and Rhodes, 1993). However, Ka'ula lavas, especially the submarine suite, show nearly constant K/Rb and Nb/Ba ratios ($R^2 = 0.93$ and 0.96 , respectively, for all samples; Fig. 8). Thus, abundances of these elements as well as other less mobile incompatible elements are useful for determining the source mineralogy and heterogeneity for Ka'ula lavas.

The source for Ka'ula lavas probably contained residual phlogopite and Ti-oxide. Ratios of K/Ce, Rb/La and Ba/La show a factor of 2-3 variation and broad negative correlations ($R^2 = \sim 0.6$) when plotted against a highly incompatible element (Nb), especially for the dive 300 samples (Fig. 12 and Table 5). These features are consistent with the control of residual phlogopite for Ka'ula lavas (e.g., LaTourrette et al., 1995; Class and Goldstein, 1997). Amphibole in the source would not have sufficient leverage on K, Rb and Ba to counteract the effects of very low K_D for these elements in other source minerals (olivine and pyroxene; e.g., Yang et al., 2003). Also, amphibole is unlikely to be present in the Hawaiian mantle plume given its shallow stability for an oceanic geotherm (<3 GPa; Foley, 1991) compared to the probable depth of the Hawaiian mantle plume (>3 GPa; e.g., Hofmann and Farentani, 2013). Ka'ula lavas show depletions in Zr and Hf on a mantle-normalized diagram (Fig. 11), a positive trend of Zr/Hf vs. Nb (i.e., high ratios at low degrees of partial melting; Fig. 12) and relatively low TiO₂ contents compared to most alkaline oceanic island lavas (~ 1 wt.% lower at the same SiO₂ and 2 wt.% lower than melts produced from amphibole-bearing peridotite; Pilet et al., 2008). Honolulu lavas show similar major and trace element characteristics, which were interpreted to indicate residual Ti-oxide in their source during melting (Yang et al., 2003).

Residual garnet in the source for the Ka'ula rocks is indicated by the nearly complete lack of variation in heavy REE concentration despite the wide range in the LREE (Fig. 10; e.g., Lanphere and Frey, 1987). The presence of garnet in the mantle source for Hawaiian rejuvenated lavas is also likely the cause of the correlation of Tb/Yb vs. Th and low Sc values (e.g., Clague et al., 2016). Ka'ula lavas show a good correlation of Tb/Yb vs. Th ($R^2 = 0.88$; Fig. 13) except for two samples (300-10, -38) with anomalously high heavy REE and other highly incompatible elements (Table 5; Fig. 11). These samples must have been derived from a distinct source. Most Honolulu rejuvenated lavas also have a good correlation for Tb/Yb vs. Th, which was interpreted to indicate the presence of garnet in their source (Yang et al., 2003). Compared to Honolulu lavas, Ka'ula samples have overlapping but generally lower Tb/Yb values (0.31-0.65 vs. 0.5-1.35) and Th contents (0.6-6.2 vs. 1.9-12.0; Table 3; Yang et al., 2003). The variation in Th content of Honolulu lavas was interpreted to

reflect varying degrees of partial melting (Clague and Frey, 1982; Yang et al., 2003). Thus, the lower Tb/Yb values in Ka'ula lavas probably reflects a higher degree of melting in these rocks compared to those from Honolulu.

Ka'ula lavas show a wide range in abundances of incompatible elements at constant MgO content (up to 10x for P_2O_5 and Th; Fig. 7; Tables 3 and 5). Honolulu rejuvenated lavas also have large variations in highly incompatible elements, which were attributed to variations in the degree of melting of a homogeneous source (e.g., Clague and Frey, 1982). Ka'ula lavas undoubtedly experienced variable degrees of partial melting based on the variations in their alkalinity index (total alkalis – $(SiO_2 \cdot 0.37 - 14.43)$; Rhodes and Vollinger, 2004) of 0.1 to 4.2 (see also Fig. 6) and the 5x variation in ratios of highly over moderately compatible elements (e.g., La/Yb; Fig. 12). Ka'ula rejuvenated lavas were probably also derived from a heterogeneous source based on the large range in ratios of highly incompatible elements (e.g., 4x for Ba/Th; Fig. 13). This is consistent with recent studies of Honolulu lavas that showed these lavas are heterogeneous, especially for Os and to a lesser extent for Pb and Sr isotopes (e.g., Lassiter et al., 2000; Yang et al., 2003; Fekiacova et al., 2007).

Two dominant source components are evident for Ka'ula submarine lavas based on the correlation of highly incompatible trace element ratios (e.g., $R^2 = 0.69$ for Ba/Th vs. Nb/La for all samples and 0.91 for the 10 dive 300 lavas; Fig. 13). The good positive correlation for dive 300 samples (which includes the two with anomalously high heavy REE and other highly incompatible elements on most plots; Figs. 8, 12 and 13) is indicative of a partial melting trend (e.g., Dixon et al., 2008). In contrast, submarine rejuvenated lavas from Ni'ihau show a negative correlation on the Ba/Th vs. Nb/La plot (Fig. 13), which was interpreted to reflect the addition of up to 0.2 % carbonatite melt to a peridotite source (Dixon et al., 2008). Presence of even minor amounts of carbonatite in peridotitic source would enhance the generation of alkaline melts (e.g., Dasgupta and Hirshmann, 2007). However, the lack of a negative trend on this plot for Ka'ula lavas and all other Hawaiian rejuvenated lavas (Yang et al., 2003; Garcia et al., 2010; 2015b; Greene et al., 2010)

except those from Niʻihau (Dixon et al., 2008) requires an alternative explanation for the enrichment of trace elements in rejuvenated vs. shield lavas.

Metasomatism has been invoked to explain the dichotomy of high concentrations of strongly incompatible elements but depleted ratios of Nd and Sr isotopes in Hawaiian rejuvenated lavas (e.g., Roden et al., 1984; Class and Goldstein, 1997; Yang et al., 2003). Recycled oceanic crust is commonly utilized as a source component for producing alkaline magmas (e.g., Hofmann, 1997). One mechanism for metasomatism is veining of amphibole of the upper mantle, which has been observed in some peridotite massifs (Pilet et al., 2008). Amphibole-bearing xenoliths and even hornblende have been recovered as accidental blocks from Salt Lake Crater within the Honolulu Volcanics (Sen et al., 1996). The reaction of melts derived from amphibole-rich veins with surrounding lherzolite can explain observed compositional trends for some oceanic island suites of nephelinite to alkali olivine basalts (Pilet et al., 2008). However, Kaʻula rejuvenated lavas are too poor in TiO_2 (1.2-2.8 wt.%, increasing with alkalinity; Table 3) compared to the liquids produced from the amphibole-peridotite melting experiments (3.5-5.5 wt.%; Pilet et al., 2008). Thus, an alternative metasomatic component is needed. As discussed below, the additional component that may be responsible for the extended duration and high volume of rejuvenated volcanism in the northern Hawaiian Islands is pyroxenite.

5.2. Implications of Ages and Aerial Extent for Origin of Hawaiian Rejuvenated Volcanism

The mechanism responsible for generating rejuvenated volcanism remains controversial (e.g., Hofmann and Farentani, 2013). Several models have been proposed for rejuvenated volcanism, including upwelling away from the rising stem of the plume (Ribe and Christensen, 1999; Hofmann and Farnetani, 2013) and flexure-induced decompressional melting related to loading or trench bending (Bianco et al., 2005; Konter and Jackson, 2012). Any viable model must explain the apparent decrease in the time gap between the end of the shield volcanism and the onset of rejuvenation (0.6-2 Myr; Ozawa et al., 2005) with distance towards Kīlauea, the long duration of rejuvenated volcanism on some shield volcanoes (1-2.65 Myr; Fig. 3) and

the large volumes of rejuvenated lavas on at least some shields (e.g., 58 km³; Kaua'i; Garcia et al., 2010). There are insufficient stratigraphic data for most areas of rejuvenated volcanism in Hawaii (and elsewhere around the world) to estimate the volumes of lavas erupted, especially in submarine areas. Combining our new and previous seafloor surveying with submersible observations and sampling reveals that vast areas around the northern Hawaiian Islands are covered by rejuvenated lavas. These areas are highly reflective in sidescan sonar images (Holcomb and Robinson, 2004; Garcia et al., 2008) and have yielded young lavas (Table 1; Sherrod et al., 2007; Cousens and Clague, 2015). We estimate that rejuvenation stage lavas cover an area of ~2400 km² around Ka'ula, and ~4400 km² on and around the island of Ni'ihau based on sidescan imagery for both areas (e.g., Holcomb and Robinson, 2004; Garcia et al., 2008), and sampling and geochronology (Greene et al., 2010; Ito et al., 2013; Garcia et al., 2015b; Cousens and Clague, 2015). This is much greater than the area of rejuvenated lava estimated for Savai'i Volcano in the Samoan Islands (~1700 km²), which was previously considered to have the most extensive deposits of rejuvenated lavas (Konter and Jackson, 2012). The large volume of rejuvenated volcanism on Savaii has been attributed to flexural bending in the nearby Tonga trench (Natland, 1980; Konter and Jackson, 2012). Although flexural uplift from the rapid loading of the lithosphere may contribute to Hawaiian rejuvenated volcanism (e.g., Bianco et al., 2005), it alone is unable to explain the large volumes of rejuvenated lavas in the northern Hawaiian Islands (e.g., on Kauai; Garcia et al., 2010).

Radiometric ages of Hawaiian rejuvenated lavas allow the presence and duration of the eruptive hiatus between shield and rejuvenated stages of volcanism to be determined, and to establish the frequency and duration of rejuvenated volcanism (e.g., Gran Canaria, Guillou et al., 2004; Mauritius, Moore et al., 2011). A good geochronological dataset for Hawaiian rejuvenated lavas is now available (Table 1; Ozawa et al., 2005; Greene et al., 2010; Garcia et al., 2010; 2015b). Some surprising features emerge from the recent ages for Hawaiian rejuvenated volcanism that challenge existing models for rejuvenated volcanism. All five of the northern Hawaiian shield volcanoes have undergone long-lived (>1 Myr) rejuvenated

volcanism (Fig. 3). In contrast, only three of seven extinct southern Hawaiian shields (O'ahu to Maui) have experienced rejuvenated volcanism and where present, it was short-lived and produced very small volumes in two areas (East Moloka'i and West Maui; Sherrod et al., 2007). Paradoxically, these southern shields have not as of yet had any rejuvenated volcanism within the last 300 ka (Sherrod et al., 2007), whereas two northern Hawaiian shields (South Kaua'i Swell and Kaua'i) have had more recent volcanism (0.08 and 0.15 Ma; Fig. 3). Other northern shields (Ka'ula and Ni'ihau) may have had more recent submarine volcanism (based on the lack of sediment cover in side-scan sonar imagery; Garcia et al., 2008) but have not been sampled sufficiently to confirm this suggestion. Rejuvenated volcanism on Ko'olau volcano (O'ahu) was more widespread than the other southern shields but much less than on the northern Hawaiian shields, producing ~40 vents over the last ~0.7 Myr including many that are less than 0.1 Ma (Ozawa et al., 2005). Given the episodic nature of rejuvenated volcanism (Ozawa et al., 2005; Garcia et al., 2010), it is possible that more volcanism will occur in the future on the other northern Hawaiian shields.

The observed 0.6-2.0 Myr hiatus between shield and rejuvenated volcanic stages (Fig. 3) implies that the underlying shield volcano was transported 60–200 km (assuming recent Pacific plate motion of 100 km/Myr; Garcia et al., 1987; Wessel and Kroenke, 2007) away from the location where the last shield-building eruptions occurred. On the island of Hawai'i, post-shield eruptions have occurred recently up to 50 km from the vertical mantle plume stem under the island (Sherrod et al., 2007). New ages show that rejuvenated volcanism initiated at widely varying distances away from the plume stem (110-250 km). Other key geochronological observations are: 1) the long distance (500-570 km) from the most recent rejuvenated volcanism on Ka'ula, Ni'ihau and Kaua'i to the locus of maximum loading on the island of Hawaii; and 2) the nearly coeval occurrence from ~0.3 to 0.6 Ma of rejuvenated volcanism along a 450 km segment of the Hawaiian Islands (West Maui to north of Ni'ihau). These geochronological observations are inconsistent with predictions of the flexural uplift melting model (Bianco et al., 2005), the secondary melting model (Ribe and Christensen, 1999) and the "underbelly" model (Hofmann and Farnetani,

2013), which all fail to explain the down axis extent of volcanism in the northern Hawaiian Islands. The geodynamic model of Ballmer et al. (2011, 2013) simulates the rise of a hot Hawaiian plume containing both peridotite and pyroxenite, and its interaction with small scale convection cells in the 90+ Myr-old oceanic lithosphere under the Hawaiian Islands. This model predicts volcanism will extend up to 520 km downstream of the plume stem. The presence of pyroxenite and small scale convection cells results in an extended duration (up to 520 km downstream of the plume stem) and high volumes of rejuvenated volcanism. Is there evidence for pyroxenite in the source of rejuvenated lavas from Ka'ula and on other Hawaiian shields?

5.3. Source Lithology of Hawaiian Rejuvenated Lavas

Pyroxenite has been inferred to represent a significant source lithology for Hawaiian rejuvenated lavas based on the relatively high $^{187}\text{Os}/^{188}\text{Os}$ isotope values reported for some rejuvenated lavas from Kaua'i and O'ahu (Lassiter et al., 2000) and the olivine chemistry in South Kaua'i Swell lavas (Garcia et al., 2015b). The use of olivine composition to determine the presence of pyroxenite in the source was pioneered by Sobolev et al. (2005). The method assumes that quartz-normative melts are generated by partial melting of eclogite from recycled subducted ocean crust, which react with peridotite to form olivine-free pyroxenite. Pyroxenite-derived melts should be enriched in Ni and depleted in Mn, compared to melts generated by peridotite (Sobolev et al., 2005; 2007). Thus, the Ni and Mn contents of olivine can be used to determine the original proportions of the contributing parental lithologies for basalts (pyroxenite vs. peridotite; Sobolev et al., 2005, 2007; Gurenko et al., 2009, 2010). The weight fraction of pyroxenite-derived melt (X_{px}) in Ka'ula lavas was inferred using the equation of Gurenko et al. (2010),

$$X_{\text{px}} = 6.705\text{E}^{-04} \times (\text{Ni}/\text{FeO}/\text{MgO}) - 1.332\text{E}^{-02} \times (\text{Mn}/\text{FeO}) + 1.5215, \quad (1)$$

where elemental concentrations of Ni and Mn are given in ppm, and FeO and MgO, in wt.%.

Considerable debate has arisen questioning whether high Ni and Fe/Mn in olivine reflect a major pyroxenite contribution (>50%) in the source for Hawaiian basalts

(e.g., Herzberg, 2011; Putirka et al., 2011; Rhodes et al., 2012). The high Ni content and Fe/Mn in olivine from Hawaiian tholeiitic lavas can be attributed to high temperatures of melt formation and the difference in temperature between melt segregation and olivine crystallization (e.g., Putirka et al., 2011; Matzen et al., 2013). Elegant experimental work demonstrated that the partition coefficient for Ni in olivine is strongly temperature dependent (Matzen et al., 2013). Thus, when a deep partial melt of a peridotitic mantle source is brought to low pressure and cooled, the early Mg-rich olivines will be Ni-rich. The high Fe/Mn in Hawaiian olivine has also been explained as an outer core signature (Humayun et al. 2004), although partial melts of an olivine-free source, eclogite or a secondary garnet pyroxenite, would also have elevated Fe/Mn (Huang et al., 2007). Another issue is the assumed Ni content of the source: is it low (1900 ppm) as proposed by Sobolev et al. (2005) or higher (2300 ppm), as found by Rhodes et al. (2012) for the mean of literature values for mantle peridotite? If higher source values are correct, the Ni content of Hawaiian olivine does not require an olivine-free source (Rhodes et al., 2012). High precision studies of Fe/Mn in Hawaiian shield lavas indicate a possible role for pyroxenite in their source but much less than proposed based on olivine composition (10-20% vs. >50%; Huang et al., 2007; Sobolev et al. 2005; 2007). The studies noted above advocate for peridotite as the primary source for Hawaiian shield lavas but the results of these studies do not preclude a significant role for pyroxenite. It should be noted that none of these studies examined rejuvenated lavas, which is the focus of this study.

Euhedral olivine phenocrysts (10-12/sample) were analyzed for major and minor elements using high precision methods (see methods section above for details) from 10 lavas (six submarine and four island accidental blocks) that span the compositional range for Ka'ula lavas (Table 2). The median value of the weight fraction of pyroxenite component (X_{px}) in the melts for these Ka'ula rejuvenated basalts ranges from 33-69%, with the island lavas having consistent median values (50.4-54.5%; Table 2). There is no apparent correlation of X_{px} with alkalinity, although there is a broad negative correlation of X_{px} with Al_2O_3/CaO for the six submarine lavas ($R^2 = 0.58$) but not if the island samples are included (Table 2).

Negative correlations were found for high precision Mn concentrations with total alkali content and $\text{Al}_2\text{O}_3/\text{CaO}$ in tholeiitic lavas from Hawaiian volcanoes Ko'olau and Kīlauea (Huang et al., 2007). Ka'ula lavas show a broad positive correlation for Xpx with the radiogenic Pb isotope ratios ($R^2 = 0.66$; Fig. 14). The correlation remains about the same with the addition of three rejuvenated lavas from nearby South Kaua'i Swell (SKS) volcano ($R^2 = 0.64$; Fig. 14). If the few shield lavas from SKS and Kauai that we have high precision olivine results and Pb isotopes are included, the correlation improves somewhat ($R^2 = 0.76$; Fig. 14). Thus, there is an apparent significant contribution (>30%) of pyroxenite to magmas from at least some of the northern Hawaiian Island lavas and this component has a distinct Pb isotope signature. A good correlation was found for Mn concentration vs. radiogenic Pb in some Hawaiian shield basalts (Huang et al., 2007). Thus, the source for Hawaiian basalts (rejuvenated and shield lavas) apparently contains variable Mn, which may be a good indicator of its heterogeneity in lithology. The percentage of pyroxenite in the source for these lavas is much less than indicated by the Xpx component in the melts for Ka'ula lavas (33-69%) because melting in the Hawaiian mantle plume would preferentially tap the mafic component, if it is present as a separate lithology (see discussion by Herzberg, 2011). For SKS lavas, the Xpx in olivine was 68-88%, although only 13-15% mafic crust was estimated for their source based on trace elements (Garcia et al., 2015b).

Studies of some Atlantic oceanic island lavas also found correlations in the Xpx values with Pb, Sr and Nd isotope ratios from shield and rejuvenation volcanic stages (e.g., $R^2 = 0.52$ to 0.62 for Madeira lavas; Gurenko et al., 2013). The correlation of Xpx vs. Pb isotope ratios in Madeira lavas has a positive trend as observed for Ka'ula and South Kaua'i Swell lavas. In the Madeira lavas, the Xpx to Pb isotope ratio correlation was attributed to recycled oceanic crust (Gurenko et al., 2010; 2013). High radiogenic Pb isotope values are a characteristic feature of the Loa source component in Hawaiian lavas, which is thought to be derived from a large low-shear-velocity province in the deep mantle to the west of Hawai'i (e.g., Weis et al., 2011) and is probably a recycled crustal component.

6. CONCLUSIONS

Marine surveying and rock sampling (mostly with the JASON ROV) was undertaken of Ka'ula Volcano, located 100 km off the axis of the Hawaiian chain. This westernmost volcano within the main Hawaiian Islands has long been neglected because of its remote and mostly submarine location. Geochemical studies were made on Ka'ula's submarine and subaerial rocks using a wide range of methods. The new results show:

1. Ka'ula Volcano is the oldest of the main Hawaiian Islands based on a $^{40}\text{Ar}/^{39}\text{Ar}$ age on a tholeiitic accidental block (6.2 Ma) collected from the young cone that forms Ka'ula Island. The island is surrounded and capped by young volcanic lavas (1.9 to 0.5 Ma) based on eight new $^{40}\text{Ar}/^{39}\text{Ar}$ ages.

2. The lavas from Ka'ula are mostly olivine-phyric with some containing plagioclase and rarely, clinopyroxene. Compositions of these lavas range widely, from foiditic to weakly alkalic basalt, with one tholeiitic accidental block recovered.

3. The ages and chemistry of Ka'ula alkaline rocks overlap with rejuvenated lavas from nearby, northern Hawaiian Island shields (Ni'ihau, Kaua'i and South Kaua'i Swell). Rejuvenated lavas on and around these northern Hawaiian Islands cover a vast area ($\sim 7000 \text{ km}^2$), which is much more extensive than any other area of rejuvenated volcanism worldwide.

4. Ka'ula rejuvenated lavas range widely in abundances and ratios of incompatible element abundances (e.g., up to 10x for P_2O_5 and Th at similar degrees of fractionation, 6x variation in La/Yb, and 2-3x variation in ratios of highly incompatible elements) indicating variable degrees of melting of a heterogeneous source. Heavy REE elements in Ka'ula lavas are pinned at mantle normalized Yb value of 10 ± 1 , indicating garnet in the source. The source for Ka'ula lavas probably also contained phlogopite and Fe-Ti oxides based on wide ranges and decreasing ratios vs. Nb for K/Ce, Rb/La and Ba/La (phlogopite) and positive trend for Zr/Hf (Fe-Ti oxide).

5. 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 (West Maui to north of Ka'ula). These features are inconsistent with most models for rejuvenated volcanism except a geodynamic melting model, which advocates a significant

contribution of pyroxenite to rejuvenated magmas. Olivine phenocryst compositions in Ka'ula rejuvenated lavas indicate a major (33-69%) pyroxenite component in the melts for these lavas. Radiogenic Pb isotope ratios correlate positively with the percent pyroxenite melt component for Ka'ula and nearby South Kaua'i lavas, as was reported for some Atlantic oceanic islands. These results provide strong evidence that pyroxenite is an important source component for northern Hawaiian Island and other oceanic island volcanoes. The presence of pyroxenite in the source may have extended the duration and volume of Hawaiian rejuvenated volcanism.

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Figure captions.

Figure 1. Regional bathymetry of the Hawaiian Islands illuminated from the NE. The data are from the Global Multi-Resolution Topography synthesis (<http://www.marine-geo.org/portals/gmrt/>) version GMRT v3. White box outlines the study area (Fig. 2).

Figure 2. Multibeam bathymetry map (50 meter gridding) of the study area colored and illuminated from the NW (<http://www.soest.hawaii.edu/hmrg/multibeam/>) Sample locations (red circles) are shown along the tracks of JASON ROV dives 300 and 304. The first and last samples of each dive are numbered as is cone F from dive 304.

Figure 3. Age (Ma) vs. distance (in km) from Kīlauea for lavas from the main Hawaiian Islands with rejuvenated lavas. Bars show the range of age dates for the three stages of Hawaiian volcanism: Shield (yellow), post-shield (brown) and rejuvenation (red). The gray bars for Ka'ūla, SKS and W. Ka'ena are assumed sampling gaps between dated samples. Note the variable duration in the gap between post-shield and rejuvenated volcanism along the Hawaiian Islands (0.6-2.2 Myr). The large age gap for the submarine rejuvenated volcanoes (W. Ka'ena, SKS and Ka'ūla) may be related to incomplete sampling. Ages are from: West Maui (Tagami et al., 2003), East Moloka'i and Ni'ihau (Sherrod et al., 2007), Ko'olau (Ozawa et al., 2005), W. Ka'ena (Greene et al., 2010), SKS (Garcia et al., 2015b), Kaua'i (McDougall, 1979; Garcia et al., 2010) and Ka'ūla (Table 1).

Figure 4. Whole rock Mg# [$100 \times (\text{Mg}/\text{Mg} + \text{Fe}^{2+})$] vs. forsterite content % for selected Ka'ūla olivine with Pb isotope analyses (Weis et al., in review). Individual high precision olivine analyses are shown by a triangle for phenocrysts from dive 304 samples or as an "x" for xenocrysts. The xenocrysts (only in the island samples; KA prefix) are mostly euhedral but have low (<0.1 wt.% CaO) indicative of mantle origin. The two lines labeled $K_d = 0.32$ and 0.36 bound the field for equilibrium compositions based on the experimental work of Matzen et al. (2011) for Hawaiian compositions. Four samples plot in or near the equilibrium field including some of the higher Mg# rocks. Olivine that plot above the field may have crystallized early in the magma's history and not have fractionated (so-called delayed fractionation; Maaloe et al.,

1988) or are antecrysts. Data are from Table 2. Two sigma error bars are within the size of the symbol.

Figure 5. MgO plots of Ka'ula pillow rim glass composition from dive 300 (red symbols) and 304 (orange symbols) vs. K_2O and CaO/Al_2O_3 , and depth of collection (in m) vs. S content. All values are in wt.%. Note the wide range in K_2O for Ka'ula glasses with those from dive 304 having distinctly higher values at a given MgO. All Ka'ula glasses have higher K_2O at a given value than those from Ni'ihau. Ratios of CaO/Al_2O_3 in Ka'ula glasses from dive 304 span a wider range than those from dive 300. The dive 304 glasses show two distinct CaO/Al_2O_3 trends with decreasing MgO; one decreasing and the other increasing. Glasses from Ka'ula rocks are higher in CaO/Al_2O_3 than those from Ni'ihau at MgO values >6.7 wt.%. S contents are generally high in Ka'ula glasses (≥ 0.14 wt.%) except those collected in water depths <2300 m along a ridge on the south flank of Ka'ula. The ridge glasses decrease in S with decreasing water depth but are ≥ 0.10 wt.%. Glasses from Cone F show a similar decreasing trend, although their S values are greater. Data for Ka'ula from Table 3 and for Ni'ihau, from Cousens and Clague (2015). Two sigma error bars are within the size of the symbol.

Figure 6. Total alkalis ($Na_2O + K_2O$) vs. SiO_2 for Ka'ula lavas (all values in wt.%). All but one of the Ka'ula lavas are alkalic, except a lithic block sample (KA-14) from the island. The Ka'ula lavas form two groups: 1. alkalic basalts, which are all submarine lavas [pale blue field just above the Macdonald and Katsura (1964) alkalic-tholeiitic dividing line] and 2. basanites, which include both submarine lavas and subaerial lithic blocks (pink field with white circles in the red diamonds). Ka'ula lavas have generally higher total alkalis than Ni'ihau samples (green triangles) and overlapping but somewhat higher SiO_2 than Honolulu lavas (yellow circles). Data for Ka'ula from Table 4, for Ni'ihau from Cousens and Clague (2015), and Honolulu from Clague and Frey (1982). Two sigma error bars are within the size of the symbol.

Figure 7. MgO variation diagrams for P_2O_5 and CaO/Al_2O_3 (all values in wt.%) in Ka'ula lavas subdivided into dives 300 and 304, and the island suite. The wide variation in CaO/Al_2O_3 at MgO contents >10 wt.% MgO indicate diverse parental

magma compositions. Generally coherent, nearly flat trends are observed for each dive suite and those from Ni'ihau. The factor of 10 range in P_2O_5 for Ka'ula lavas at $MgO > 10$ wt.% is remarkable. The P_2O_5 contents of Ni'ihau glasses overlap those of most Ka'ula lavas. Data for Ka'ula from Table 4 and for Ni'ihau from Cousens and Clague (2015). Two sigma error bars are within the size of the symbol.

Figure 8. Plots of some highly incompatible trace elements (K vs. Rb and Ba vs. Nb in ppm) and Nb/Y vs. Zr/Y (Fitton plot) in Ka'ula lavas based on XRF data (Table 4). Note the good correlation ($R^2 = 0.93$ and 0.96) on the element-element plots for all data including the island samples (yellow symbols) indicating these potentially mobile elements were not significantly affected by alteration. On the Fitton plot, the two diagonal lines bounding Iceland data (Fitton, 2007). Most of the Ka'ula rejuvenated lavas plot in or near the field for Hawaiian rejuvenated lavas and the tholeiitic sample KA-14 plots in Hawaiian shield field. Fields from Greene et al. (2010). Ka'ula data from Table 4. Two sigma error bars are within the size of the symbol.

Figure 9. MgO (in wt.%) variation diagram for Nb and Sr (in ppm) in Ka'ula lavas. Note the wide ranges in both elements at a given MgO . Both elements show coherent, multiple trends with decreasing MgO for the submarine lavas. Island sample KA-19 has anomalously high Sr content (6400 ppm), which is related the presence of secondary minerals in vesicles (Fig. A1). Two sigma error bars are within the size of the symbol.

Figure 10. Rare earth element (REE in ppm) diagram (ICP-MS data) for Ka'ula volcanic rocks. REE values normalized to chondrite values (Sun and McDonough, 1989). The vertical axis is linear rather than the traditional log scale to better show small-scale features and the overall data quality. There is a $>6x$ variation in light REE but nearly constant HREE values ($La_n = 10 \pm 1$) for all but two samples that have very high LREE contents. Note the absence of crossing patterns including for the tholeiite sample KA-14, which may indicate compositionally similar sources. Rejuvenated lavas from other Hawaiian islands show crossing patterns (e.g., Honolulu; Yang et al., 2003; Kauai, Garcia et al., 2010). Thus, the fanning of REE

patterns probably reflect varying degrees of partial melting for Ka'ula lavas. The nearly constant HREE abundances are probably related to garnet in the source for these lavas (e.g., Lanphere and Frey, 1987). Individual symbols are labelled with sample number and SiO₂ content in parentheses. Samples with lower SiO₂ (<45 wt.%) have higher REE values. Data are from Table 5. Two sigma error bars are within the size of the symbol.

Figure 11. Mantle normalized diagram for Ka'ula samples using primitive mantle values from McDonough and Sun (1995). The vertical axis is linear rather than the traditional log scale to better show small-scale features and the overall data quality. Note the wide ranges in highly incompatible element values (Cs to Sr). Values for Pb show extreme variations with both positive and negative anomalies. Patterns do not cross for most samples except the most enriched samples, especially 300-38 (and 300-10, not shown). Data are from Table 5. Individual symbols are labelled with sample number except the tholeiite KA-14 (Th). Two sigma error bars are within the size of the symbol.

Figure 12. Nb variation diagrams for trace element ratios La/Yb, Zr/Hf, K/Ce and Ba/La for Ka'ula lavas. The tholeiitic sample (KA-14) and the three samples with high Nb contents (KA-31, 300-10 and 300-38) are labelled. The ratios of K/Ce and Ba/La generally decrease with increasing Nb ($R^2 = 0.6$), which is indicative of phlogopite in the source (e.g., LaTourrette et al., 1995). Ratios of Zr/Hf increase with increasing Nb, which is a sign of a Fe-Ti oxide in the source (Yang et al., 2003). Two sigma error bars are within the size of the symbol. Data are from Table 5 with all values in ppm.

Figure 13. Plots Th vs. Tb/Yb and Ba/Th vs. Nb/La for Ka'ula lavas. The good correlation ($R^2 = 0.88$) of Tb/Yb vs. Th (except for the two samples with anomalous Pb contents (300-10 and 300-38) supports the interpretation that garnet is in the source for Ka'ula lavas, as observed for Honolulu lavas (e.g., Yang et al., 2003). The generally positive trend for Ba/Th vs. Nb/La (including the two anomalous samples 300-10 and -38 and the tholeiite KA-14) indicate two dominant source components for Ka'ula lavas. In contrast, Ni'ihau lavas show a negative trend for these ratios,

which was interpreted to reflect minor carbonatite in the source (0.2 %; Dixon et al., 2008). Data for Ka'ula are from Table 5 and for Ni'ihau, from Cousens and Clague (2015). Two sigma error bars are within the size of the symbol. All values are in ppm.

Figure 14. Pyroxenite melt contribution (% Xpx, using the equation of Gurenko et al., 2010; see text for details) based on high precision olivine analyses vs. radiogenic Pb ($^{208}\text{Pb}/^{206}\text{Pb}$, Pb*) isotopes for Ka'ula lavas. Plotted points are mean pyroxenite values (for at least 10 analyses/sample) for the five Ka'ula samples from dive 304 with Pb isotopes analyses (Weis et al., in review). A good correlation was found Xpx and Pb* ($R^2 = 0.66$) for Ka'ula samples. Other points are for samples from nearby South Kauai Swell volcano (SKS) lavas (rejuvenated lavas, darker gray diamonds; shield lavas, lighter gray diamonds; data Garcia et al., 2015b) and Kaua'i shield lavas (blue circles; Garcia et al., 2010).

Appendix Figure A.1. Scanning electron and electron backscattered images, and energy dispersive (EDS) spectrums for vesicle-filling minerals in Ka'ula sample KA-19, with high Sr content (6400 ppm). a) Scanning electron image of zeolite (Zeo) filling a vesicle. Broad gray areas are olivine (Ol). Two analyses were made of this zeolite (appendix Table 5); the EDS spectrum for point 1 is shown in panel c. b). Scanning electron image of celestite (Ces) in two adjacent vesicles. An analysis was made at point 1 (appendix Table 5). c) Energy dispersive spectrum (electron volts vs. intensity) for point 1 in panel a clipped at 130 counts to allow expanded scale to highlight the L-lines for Sr in the zeolite; d). Energy dispersive spectrum for the celestite shown in panel b (point 1). Spectrum shows the strong peaks for Sr and S, and minor peaks for K, Ba and Fe. e) Electron backscattered image of celestite in vesicle (approximately same view as in panel b), which appears lighter gray from the high average atomic number of celestite. Scale bars in microns are given in the lower right corners of panels a, b and e. Analyses of several zeolites and the celestite shown in panel e are given in appendix Table 5.

Table 1. Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ data for Kaula samples

Sample #	K/Ca total	$^{40}\text{Ar}/^{36}\text{Ar}_i \pm 2\sigma$	Isochron	N	MSWD	^{39}Ar %	Plateau
			Age (Ma) $\pm 2\sigma$				Age (Ma) $\pm 2\sigma$
<i>Submarine lavas^a</i>							
304-33	0.07	295.7 ± 1.8	0.542 ± 0.091	7 of 10	0.04	93.1	0.546 ± 0.081
304-26	0.13	295.4 ± 2.4	0.670 ± 0.548	9 of 9	0.10	100.0	0.652 ± 0.215
304-23	0.05	295.3 ± 2.4	0.800 ± 1.105	9 of 9	0.02	100.0	0.718 ± 0.498
300-36	0.05	296.2 ± 2.9	0.456 ± 1.272	9 of 9	0.05	100.0	0.807 ± 0.568
300-2	0.06	295.4 ± 3.2	0.973 ± 1.652	9 of 10	0.03	87.6	0.924 ± 0.569
304-10	0.11	295.5 ± 1.5	1.241 ± 0.098	12 of 12	0.03	100.0	1.241 ± 0.077
300-10	0.05	296.1 ± 2.1	1.848 ± 0.382	9 of 11	0.15	96.2	1.948 ± 0.190
<i>Island volcanic blocks^b</i>							
KA-31	0.37	297.0 ± 3.2	0.577 ± 0.179	10 of 10	0.78	100.0	0.663 ± 0.085
KA-14	0.07	293.7 ± 16.9	6.25 ± 0.13	6 of 12	0.61	59.9	6.242 ± 0.078

^a Ages for submarine lavas determined at Oregon State University and are calculated relative to

^b Ages for island lavas determined at the University of Wisconsin-Madison and are calculated

For complete data, see online Tables A.1 and A.2.

Table 2. High precision microprobe analyses of olivine cores from submarine and subaerial Kaula rejuvenation stage basalts

Submarine	SiO2	FeO	MnO	MgO	NiO	CaO	Sum	Fo	Xpx	Subaerial	SiO2	FeO	MnO	MgO	NiO	CaO	Sum	Fo	Xpx
304-05	39.85	14.05	0.217	44.94	0.207	0.289	99.54	85.1	0.35	KA-19 ph	39.88	13.64	0.175	45.390	0.216	0.211	99.51	85.6	0.53
Mg# 66.8	39.92	13.56	0.205	45.58	0.235	0.269	99.77	85.7	0.43	Mg# 66.7	40.03	13.27	0.170	45.645	0.238	0.197	99.55	86.0	0.56
	39.74	13.44	0.194	45.65	0.232	0.283	99.54	85.8	0.49		40.12	12.56	0.159	46.431	0.252	0.186	99.71	86.8	0.57
	39.89	12.96	0.179	46.08	0.258	0.238	99.60	86.4	0.57		40.43	10.94	0.143	47.637	0.300	0.198	99.64	88.6	0.53
	39.94	12.59	0.174	46.41	0.300	0.232	99.64	86.8	0.63	KA-19 x	40.90	9.44	0.139	49.362	0.367	0.047	100.26	90.3	0.37
304-13	39.76	13.56	0.204	45.32	0.247	0.274	99.35	85.6	0.46		41.12	9.09	0.133	49.828	0.369	0.031	100.57	90.7	0.36
Mg# 68.8	40.09	12.90	0.184	46.08	0.264	0.250	99.76	86.4	0.54		40.91	8.72	0.128	49.670	0.373	0.043	99.85	91.0	0.35
	39.86	13.13	0.193	45.71	0.253	0.264	99.41	86.1	0.48		40.91	9.49	0.138	49.160	0.378	0.028	100.10	90.2	0.40
	40.18	11.22	0.156	47.19	0.336	0.243	99.31	88.2	0.62		41.09	8.73	0.128	49.824	0.370	0.028	100.18	91.0	0.34
	40.07	11.66	0.162	46.87	0.330	0.242	99.33	87.7	0.64	KA-28 ph	39.80	15.52	0.194	44.054	0.164	0.198	99.94	83.5	0.53
304-23	40.60	10.02	0.143	48.85	0.367	0.035	99.99	89.7	0.55	Mg# 61.2	40.15	13.70	0.166	45.705	0.258	0.160	100.14	85.6	0.67
Mg# 65.2	39.92	13.52	0.176	45.94	0.220	0.192	99.96	85.8	0.61		39.91	14.18	0.173	45.223	0.245	0.160	99.90	85.0	0.66
	39.92	12.14	0.159	46.74	0.306	0.205	99.46	87.3	0.70		40.24	13.41	0.175	45.843	0.293	0.143	100.11	85.9	0.62
	40.15	12.09	0.158	46.79	0.301	0.204	99.69	87.3	0.69		40.41	12.49	0.163	46.536	0.258	0.207	100.07	86.9	0.54
	40.20	12.92	0.165	46.49	0.304	0.201	100.28	86.5	0.76		40.47	12.37	0.162	46.808	0.272	0.205	100.29	87.1	0.54
300-18	39.53	13.43	0.187	45.99	0.282	0.270	99.68	85.9	0.63		40.56	11.84	0.154	47.196	0.275	0.157	100.17	87.7	0.54
Mg# 58.6	39.80	13.32	0.183	46.36	0.292	0.250	100.19	86.1	0.66		40.69	11.30	0.149	47.617	0.301	0.192	100.25	88.3	0.53
	39.88	13.08	0.179	46.42	0.303	0.246	100.09	86.3	0.68	KA-31 ph	40.13	14.00	0.177	45.534	0.201	0.180	100.23	85.3	0.54
	39.80	12.94	0.176	46.49	0.307	0.243	99.94	86.5	0.68	Mg# 66.5	40.36	13.55	0.171	45.902	0.217	0.184	100.39	85.8	0.55
	39.91	12.85	0.173	46.62	0.314	0.245	100.11	86.6	0.71		40.36	12.97	0.163	46.321	0.236	0.187	100.23	86.4	0.56
304-17	39.17	16.32	0.266	43.47	0.147	0.330	99.70	82.6	0.21		40.57	12.56	0.161	46.681	0.254	0.193	100.42	86.9	0.55
Mg# 59.8	39.15	16.20	0.263	43.55	0.155	0.323	99.64	82.7	0.23		40.58	12.45	0.163	46.741	0.253	0.198	100.38	87.0	0.52
	39.21	16.07	0.243	44.07	0.165	0.260	100.01	83.0	0.36		40.77	11.49	0.151	47.464	0.277	0.196	100.35	88.0	0.51
	39.25	15.95	0.239	44.09	0.175	0.260	99.96	83.1	0.40	KA-31 x	40.28	12.01	0.149	46.786	0.276	0.088	99.59	87.4	0.61
	39.51	15.67	0.240	44.19	0.200	0.263	100.06	83.4	0.41		40.97	10.40	0.151	48.671	0.364	0.045	100.60	89.3	0.43
304-38	39.66	14.82	0.221	44.71	0.249	0.264	99.92	84.3	0.53		41.32	9.48	0.134	49.487	0.354	0.043	100.82	90.3	0.42
Mg# 66.8	40.15	13.68	0.190	45.78	0.228	0.252	100.28	85.6	0.54	KA-34 ph	39.71	15.60	0.184	44.075	0.110	0.202	99.87	83.4	0.50
	39.80	14.37	0.207	45.30	0.258	0.261	100.19	84.9	0.58	Mg# 64.0	39.82	13.91	0.172	45.245	0.186	0.187	99.53	85.3	0.54
	39.88	14.15	0.201	45.52	0.270	0.244	100.24	85.1	0.61		40.24	12.47	0.161	46.511	0.263	0.191	99.83	86.9	0.56
	39.89	13.90	0.195	45.44	0.279	0.241	99.93	85.3	0.64		40.38	11.26	0.155	47.475	0.269	0.169	99.71	88.3	0.43
	39.89	13.81	0.191	45.53	0.272	0.240	99.92	85.4	0.64		40.69	10.76	0.147	48.044	0.281	0.098	100.02	88.8	0.44
San Carlos (	40.79	9.54	0.139	49.36	0.364	0.069	100.26			KA-34 x	40.37	10.89	0.147	47.539	0.295	0.185	99.43	88.6	0.48
1 std dev	0.02	0.02	0.003	0.03	0.003	0.001					41.13	9.59	0.138	49.025	0.351	0.045	100.27	90.1	0.40
given	40.82	9.55	0.140	49.42	0.370	0.078	100.38				40.87	8.87	0.131	49.391	0.354	0.046	99.67	90.8	0.33

San Carlos given values: SiO2, MgO, FeO - Jarosewich et al. (1979); MnO and NiO - Sobolev et al., 2007; CaO - De Hoog et al. (2010)

Table 3. Microprobe analyses of Kaula pillow rim glasses

Sample	Geology	Depth	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	S	total
300-01	Cone A	3750	47.12	1.80	15.86	11.02	0.17	6.84	12.06	3.16	0.53	0.29	0.171	99.01
300-02	Cone A	3756	47.23	1.86	15.69	11.16	0.18	6.71	12.07	3.18	0.55	0.28	0.176	99.08
300-03	Cone A	3808	47.18	1.91	15.78	11.05	0.18	6.74	12.06	3.24	0.54	0.29	0.169	99.13
300-04	Cone A	3927	47.74	1.59	15.77	11.01	0.16	7.58	11.79	3.02	0.47	0.24	0.156	99.51
300-05	Cone B	3879	46.67	1.46	15.82	11.56	0.19	8.41	11.87	2.88	0.35	0.21	0.155	99.57
300-06	Cone B	3800	46.14	1.47	15.69	11.57	0.19	8.43	11.91	3.00	0.39	0.22	0.157	99.17
300-07	Cone C	3798	46.82	1.66	15.60	11.91	0.19	7.05	12.11	3.03	0.36	0.21	0.162	99.10
300-08	Cone C	3717	46.80	1.65	15.64	11.74	0.17	7.36	12.03	3.00	0.35	0.23	0.156	99.12
300-11	Cone C	3608	47.53	1.62	15.81	11.48	0.20	7.22	11.97	2.95	0.38	0.25	0.163	99.58
300-18	Cone D	3643	46.22	1.39	16.26	11.47	0.19	7.60	12.39	2.93	0.40	0.21	0.144	99.19
300-19	Cone D	3481	46.24	1.39	16.18	11.39	0.18	7.57	12.39	2.97	0.41	0.22	0.150	99.09
300-20	Cone D	3481	46.18	1.47	16.17	11.50	0.17	7.65	12.37	2.99	0.40	0.23	0.151	99.27
300-21	Cone D	3495	46.41	1.41	16.34	11.50	0.19	7.57	12.36	2.91	0.42	0.23	0.155	99.50
300-22	Cone D	3511	46.47	1.42	16.34	11.39	0.16	7.56	12.40	2.95	0.42	0.23	0.154	99.49
300-23	Cone D	3521	46.56	1.48	16.31	11.49	0.17	7.35	12.50	2.91	0.41	0.24	0.153	99.58
300-24	Cone D	3552	46.28	1.29	16.40	11.42	0.19	7.67	12.58	2.87	0.39	0.23	0.145	99.45
300-26	Cone E	3301	46.16	1.34	16.50	11.37	0.19	7.89	12.22	3.00	0.38	0.25	0.147	99.45
300-27	Cone E	3388	46.15	1.36	16.65	11.45	0.18	7.62	12.33	3.04	0.42	0.25	0.155	99.61
300-28		3360	47.06	1.96	15.96	11.17	0.20	5.99	11.57	3.66	1.04	0.40	0.164	99.15
300-29	Cone F	3283	46.02	1.45	16.27	11.49	0.18	7.19	12.51	3.20	0.46	0.29	0.179	99.24
300-30	Cone G	3496	47.28	1.57	16.11	11.31	0.17	7.01	12.19	3.10	0.44	0.22	0.168	99.57
300-31	Cone G	3489	47.04	1.45	16.09	11.29	0.19	7.51	12.01	3.02	0.42	0.21	0.157	99.40
300-32	Cone G	3378	47.50	1.44	16.06	11.04	0.21	7.38	11.94	3.01	0.38	0.24	0.150	99.37
300-33	Cone G	3369	47.47	1.37	16.15	11.21	0.18	7.57	11.91	2.96	0.36	0.22	0.149	99.54
300-34	Cone G	3359	47.76	1.48	16.00	11.12	0.18	7.38	11.96	2.99	0.37	0.24	0.154	99.62
300-35	Cone H	3315	47.61	1.41	16.01	11.18	0.18	7.64	11.87	2.94	0.37	0.21	0.149	99.59
300-36	Cone H	3282	47.99	1.54	15.90	11.13	0.19	7.07	12.01	3.09	0.39	0.21	0.164	99.68
300-37	Cone H	3125	47.88	1.49	15.94	11.25	0.18	7.14	11.97	3.11	0.39	0.25	0.149	99.76
300-40	Cone I	3090	45.98	1.87	16.17	11.59	0.18	6.89	12.26	3.20	0.53	0.33	0.172	99.17
300-41	Cone I	3038	45.66	1.91	16.10	11.61	0.19	6.20	12.44	3.29	0.57	0.34	0.167	98.48
300-42	Cone I	2886	46.11	1.83	16.19	11.57	0.17	6.97	12.23	3.20	0.53	0.33	0.162	99.28
304-02	Ledge A	3615	46.33	1.66	16.52	10.89	0.20	6.75	12.30	3.39	0.72	0.31	0.141	99.20
304-05	Bench B	3513	46.10	1.58	16.47	11.16	0.17	7.20	12.18	3.35	0.71	0.31	0.140	99.36
304-06	Bench B	3513	46.13	1.61	16.45	11.10	0.17	6.98	12.21	3.36	0.72	0.33	0.147	99.23
304-07	Ledge C	3474	46.15	1.61	16.42	11.03	0.16	6.98	12.23	3.35	0.70	0.31	0.151	99.10
304-08	Ledge C	3433	46.45	1.65	16.48	10.95	0.18	6.95	12.20	3.35	0.72	0.32	0.148	99.39
304-09	Ledge C	3350	47.80	1.62	16.36	11.06	0.17	6.48	11.60	3.67	0.93	0.36	0.171	100.21
304-10	Ledge C	3312	47.61	1.68	16.06	11.34	0.17	6.26	11.53	3.75	0.90	0.37	0.189	99.86
304-11	Ledge C	3210	45.81	1.54	16.51	11.21	0.19	6.99	12.84	3.28	0.60	0.35	0.160	99.47
304-12	Ledge C	3195	45.64	1.59	16.59	11.01	0.17	7.11	12.94	3.24	0.63	0.36	0.154	99.43
304-13	Ledge C	3161	45.62	1.61	16.44	11.13	0.17	6.95	12.99	3.23	0.61	0.38	0.149	99.27
304-14	Ledge D	3110	45.81	1.48	16.66	11.12	0.20	7.13	12.78	3.27	0.58	0.32	0.154	99.50
304-15	Ledge D	3085	45.62	1.78	16.11	11.63	0.19	6.55	13.03	3.47	0.70	0.43	0.191	99.68
304-16	Ledge D	3063	45.60	1.71	16.07	11.53	0.19	6.69	12.99	3.44	0.68	0.42	0.190	99.52
304-19	Cone E	2854	47.33	1.64	16.33	11.20	0.20	6.32	11.31	3.75	0.91	0.39	0.178	99.56
304-24		2644	46.71	1.73	16.21	11.19	0.18	6.35	11.95	3.49	0.85	0.35	0.141	99.15
304-25	Cone F	2579	47.37	1.97	16.10	11.21	0.16	6.16	11.55	3.62	1.04	0.37	0.172	99.74
304-26	Cone F	2477	47.42	1.97	15.98	11.16	0.18	6.05	11.56	3.66	1.04	0.40	0.165	99.59
304-29	Cone F	2385	47.35	2.03	16.00	11.09	0.17	6.01	11.54	3.66	1.04	0.39	0.162	99.44
304-30	Cone F	2354	47.41	1.97	15.99	11.06	0.18	5.99	11.53	3.64	1.04	0.42	0.161	99.39
304-31	Rift	2358	47.07	1.74	16.33	11.08	0.18	6.45	12.05	3.50	0.79	0.34	0.124	99.66
304-33	Rift	2346	47.66	1.68	16.79	11.22	0.16	6.57	11.99	3.18	0.88	0.32	0.121	100.57
304-36	Rift	2064	47.07	1.64	16.54	11.06	0.16	6.47	11.98	3.47	0.78	0.35	0.119	99.64
304-38	Rift	1710	47.10	1.67	16.32	11.28	0.18	6.46	12.12	3.47	0.75	0.34	0.103	99.79

Table 4. XRF analyses of Kaula volcanics.

Sample	Geology	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ *	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total	LOI	A. I
KA-14	lithic	48.41	1.62	15.36	13.67	0.12	5.49	11.69	2.43	0.46	0.45	99.69	1.25	-0.59
KA-29	lithic	47.05	2.15	14.84	11.50	0.16	8.68	10.05	3.73	1.04	0.63	99.82	1.16	1.79
KA-15	lithic	42.18	2.73	11.53	14.32	0.22	13.38	10.44	3.31	1.16	0.70	99.95	0.42	3.29
KA-17	lithic	41.49	2.62	11.94	14.23	0.25	12.41	11.41	3.35	1.22	1.13	100.04	1.78	3.65
KA-19	lithic	42.79	2.73	12.12	13.97	0.20	12.71	11.53	1.75	1.27	0.69	99.76	2.82	1.62
KA-28	lithic	42.42	2.83	12.55	14.60	0.22	10.44	10.67	3.75	1.49	0.74	99.72	0.65	3.98
KA-31	lithic	40.97	2.83	12.03	14.20	0.23	12.83	10.85	3.74	1.23	0.86	99.77	0.53	4.24
KA-34	lithic	40.89	2.83	11.91	14.74	0.33	11.87	12.62	2.52	1.35	0.87	99.92	2.13	3.17
Dive 300														
300-02	Cone A	47.34	1.784	16.02	12.12	0.18	6.70	11.81	3.04	0.623	0.292	99.91	-0.22	0.58
300-04	Cone A	46.79	1.458	14.41	12.29	0.20	10.33	10.59	2.91	0.450	0.232	99.66	-0.21	0.48
300-05	Cone B	45.75	1.272	14.42	12.78	0.20	11.45	10.57	2.74	0.328	0.180	99.69	-0.57	0.57
300-06		45.85	1.334	14.58	12.76	0.21	10.99	10.79	2.76	0.376	0.209	99.86	-0.47	0.60
300-07	Cone C	46.60	1.443	14.51	13.07	0.19	10.05	10.76	2.61	0.441	0.210	99.88	0.16	0.24
300-08	Cone C	46.73	1.461	14.56	13.19	0.20	9.83	10.86	2.71	0.441	0.212	100.19	0.21	0.29
300-10	Cone C	46.89	1.676	15.76	13.27	0.53	6.19	11.86	2.83	0.561	0.267	99.83	0.92	0.47
300-15	Cone C	47.13	1.151	17.57	10.36	0.16	6.55	14.02	2.77	0.349	0.155	100.22	1.77	0.11
300-18	Cone D	46.13	1.270	14.89	12.95	0.22	10.42	11.02	2.39	0.544	0.200	100.03	0.30	0.30
300-20	Cone D	45.99	1.289	15.16	12.74	0.20	10.37	11.13	2.66	0.403	0.204	100.15	-0.22	0.48
300-23	Cone D	45.98	1.245	14.34	13.07	0.22	11.45	10.60	2.51	0.608	0.194	100.22	0.42	0.54
300-26	Cone E	45.43	1.214	14.94	12.62	0.20	11.01	10.87	2.67	0.372	0.206	99.53	-0.40	0.66
300-27		45.50	1.190	14.99	12.64	0.20	11.00	10.91	2.78	0.387	0.229	99.83	-0.32	0.76
300-29	Cone F	45.92	1.337	15.68	12.62	0.20	9.10	11.62	2.91	0.499	0.269	100.16	0.11	0.85
300-30	Cone G	46.49	1.309	14.70	12.60	0.20	10.54	10.74	2.82	0.462	0.191	100.05	-0.05	0.51
300-32	Cone G	46.31	1.240	14.09	12.43	0.19	11.75	10.24	2.79	0.336	0.194	99.57	-0.44	0.42
300-34	Cone G	46.53	1.280	14.26	12.52	0.19	11.25	10.39	2.76	0.346	0.200	99.73	-0.46	0.32
300-36	Cone H	46.84	1.288	14.43	12.55	0.21	10.75	10.46	2.51	0.490	0.207	99.74	0.11	0.10
300-38	Cone I	44.08	2.166	13.27	14.08	0.73	10.33	8.75	3.89	1.398	0.796	99.49	1.75	3.41
300-41	Cone I	45.16	1.573	14.17	13.16	0.21	11.47	10.53	2.67	0.663	0.296	99.90	0.39	1.05
300-42	Cone I	45.31	1.605	14.39	13.07	0.21	11.04	10.70	2.72	0.539	0.288	99.87	-0.12	0.92
300-44	Ridge	46.34	1.843	13.40	12.03	0.18	11.39	10.40	2.74	0.912	0.459	99.69	0.65	0.94
300-46	Ridge	46.32	1.855	13.28	12.20	0.18	11.58	10.38	2.94	0.889	0.467	100.09	0.36	1.12
300-47	Ridge	46.30	1.805	12.76	12.18	0.24	12.62	10.16	2.89	0.959	0.460	100.37	0.89	1.15
300-48	Ridge	46.34	1.842	13.14	12.31	0.22	11.45	10.29	2.91	0.974	0.465	99.94	0.65	1.17
Dive 304														
304-01	Ledge A	44.56	1.769	13.97	13.86	0.27	12.26	10.15	2.48	0.611	0.262	100.19	0.38	1.03
304-04	Bench B	45.08	1.487	14.56	13.06	0.69	10.91	10.55	3.03	0.662	0.302	100.33	0.91	1.44
304-05	Bench B	45.61	1.420	14.60	12.55	0.20	11.46	10.60	2.94	0.674	0.281	100.34	0.46	1.17
304-06	Ledge C	45.91	1.417	14.77	12.16	0.17	10.81	11.02	2.73	0.867	0.287	100.14	1.23	1.04
304-07	Ledge C	46.01	1.448	14.95	12.32	0.19	10.32	10.90	2.70	0.880	0.293	100.01	0.97	0.99
304-08	Ledge C	46.24	1.480	15.22	12.52	0.19	9.41	11.15	2.84	0.886	0.299	100.24	0.89	1.05
304-09	Ledge C	47.47	1.555	15.68	11.93	0.19	7.91	10.95	3.35	1.031	0.337	100.40	0.50	1.25
304-10	Ledge C	47.77	1.565	16.38	11.93	0.20	6.15	11.32	3.40	1.004	0.351	100.07	0.72	1.16
304-11	Ledge C	45.30	1.285	14.76	12.38	0.20	11.77	10.96	2.79	0.644	0.297	100.39	0.46	1.10
304-13	Ledge C	45.04	1.316	14.39	12.45	0.20	12.45	10.89	2.71	0.593	0.305	100.34	0.31	1.07
304-15	Ledge D	45.63	1.639	16.35	12.28	0.25	6.78	12.63	3.38	0.728	0.423	100.09	0.38	1.65
304-16	Ledge D	45.62	1.640	16.23	12.36	0.21	6.75	12.60	3.32	0.765	0.422	99.92	0.42	1.64
304-17	Cone E	47.28	1.473	15.82	12.21	0.18	8.26	10.69	3.13	0.818	0.336	100.20	0.66	0.88
304-18	Cone E	47.16	1.467	15.77	12.09	0.19	7.76	10.95	3.20	0.872	0.340	99.80	1.06	1.05
304-19	Cone E	47.16	1.506	15.90	12.26	0.26	7.49	10.75	3.39	0.949	0.350	100.02	0.56	1.32
304-21	Cone E	41.63	2.588	12.69	13.82	0.22	11.56	11.29	3.89	1.461	0.768	99.92	0.27	4.38
304-22	Cone E	41.77	2.547	12.30	13.94	0.25	12.14	11.18	3.72	1.411	0.738	100.00	0.32	4.11
304-23	Cone E	41.76	2.590	12.67	13.65	0.22	11.63	11.41	3.86	1.429	0.770	99.99	0.45	4.27

304-24		45.57	1.389	13.94	12.89	0.22	12.26	9.82	2.89	0.852	0.289	100.12	0.37	1.31
304-25	Cone F	46.75	1.746	15.28	12.18	0.18	8.70	10.62	3.22	1.140	0.351	100.17	0.54	1.49
304-26	Cone F	46.65	1.727	15.19	12.33	0.19	8.74	10.54	3.31	1.130	0.346	100.15	0.51	1.61
304-30	Cone F	46.62	1.706	15.12	12.75	0.19	8.72	10.44	3.16	1.180	0.342	100.23	0.69	1.52
304-32	Rift	46.06	1.459	14.81	12.84	0.20	10.18	10.62	3.04	0.796	0.307	100.31	0.62	1.22
304-33	Rift	46.68	1.543	15.64	11.89	0.18	8.85	11.16	3.08	0.842	0.317	100.18	0.53	1.08
304-34	Rift	46.02	1.421	14.60	12.25	0.19	11.22	10.57	2.85	0.717	0.296	100.13	0.25	0.97
304-35	Rift	45.73	1.435	14.38	12.63	0.21	11.10	10.29	2.83	0.772	0.298	99.68	0.10	1.11
304-36	Rift	45.91	1.420	14.35	12.61	0.21	11.40	10.20	2.91	0.778	0.296	100.08	0.29	1.13
304-37	Rift	45.82	1.429	14.77	12.58	0.20	10.48	10.65	2.87	0.716	0.300	99.82	0.36	1.06
304-38	Rift	45.53	1.401	14.11	13.11	0.29	11.96	10.20	2.78	0.660	0.297	100.34	0.29	1.02
BHVO-2		49.84	2.73	13.55	12.23	0.18	7.12	11.35	2.04	0.51	0.27	99.83	--	--
1 Std. Dev.		0.05	0.01	0.05	0.02	0.00	0.07	0.03	0.26	0.00	0.00	0.25	--	--

*All iron analyzed as Fe2O3; LOI- loss-on-ignition; BHVO-2 standard averages based on 21 analyses for major elements and four for trace elements

Table 4. XRF analyses of Kaula volcanics (continued)

Sample	Ba	Rb	Sr	Y	Zr	Nb	Ga	Ba	La	Ce	Zn	Ni	Cr	V	Th	Pb
KA-14	169	4.8	330	15	95	14.3		169	10	22	94	145	470	325	1	1
KA-29	513	21.3	938	21	136	31.6	18	513	nd	nd	110	455	493	230	nd	nd
KA-15	663	28.1	1247	20	143	52.8	16	663	nd	nd	108	429	457	290	nd	nd
KA-17	947	19.6	2380	24	180	55.2	15	947	nd	nd	115	295	412	279	nd	nd
KA-19	494	20.7	6404	18	106	40.2	16	494	nd	nd	106	311	428	286	nd	nd
KA-28	825	33.0	1969	21	215	55.7	18	825	nd	nd	126	228	277	270	nd	nd
KA-31	757	29.9	1376	22	161	48.9	18	757	nd	nd	118	360	477	293	nd	nd
KA-34	860	24.9	2274	21	151	51.4	15	860	nd	nd	114	294	366	281	nd	nd
Dive 300																
300-02	262	12.4	513	20.3	86	19.9	19	262	14	32	102	91	176	248	2	2
300-04	192	10.3	400	17.9	70	15.9	16	192	10	26	99	242	421	213	1	2
300-05	143	6.0	356	17.2	61	10.4	16	143	10	24	97	289	543	231	1	1
300-06	183	7.2	414	17.8	66	12.0	16	183	11	31	98	254	505	241	2	3
300-07	138	6.5	362	18.1	63	11.5	17	138	7	23	110	254	539	231	1	1
300-08	147	7.5	365	18.5	64	11.6	17	147	8	23	112	245	541	236	1	2
300-10	203	7.8	434	24.9	85	14.1	19	203	22	78	139	118	196	272	2	30
300-15	178	7.6	474	14.4	44	7.6	18	178	9	20	73	185	609	196	1	1
300-18	151	9.9	333	17.4	66	12.1	16	151	5	21	95	275	539	234	1	2
300-20	145	7.0	335	17.4	68	12.7	16	145	8	21	93	238	490	234	1	1
300-23	148	10.9	324	17.2	66	11.8	16	148	7	23	95	325	600	227	1	3
300-26	157	7.4	353	17.6	59	12.4	15	157	10	24	90	265	440	223	1	2
300-27	180	7.4	394	18.0	58	12.5	15	180	10	24	92	260	447	228	1	1
300-29	216	9.2	461	18.5	63	14.8	16	216	13	28	92	186	320	237	2	1
300-30	167	9.2	340	17.0	66	13.1	16	167	9	21	99	262	499	221	1	1
300-32	149	6.6	354	17.0	58	11.7	16	149	8	23	97	321	573	215	2	1
300-34	155	7.2	367	17.3	60	12.0	16	155	8	25	97	276	537	218	2	2
300-36	168	7.8	392	17.7	60	12.1	16	168	11	26	100	285	556	214	1	2
300-38	648	32.2	1107	28.3	205	49.4	16	648	56	141	142	326	350	221	6	43
300-41	243	11.2	490	17.7	77	16.9	16	243	13	30	100	287	469	229	1	1
300-42	223	10.6	480	17.7	77	16.8	16	223	12	32	99	268	444	228	1	1
300-44	405	15.9	628	19.7	132	30.3	16	405	23	55	111	266	539	194	2	3
300-46	427	17.5	622	21.1	133	30.7	16	427	26	58	115	233	502	201	3	2
300-47	440	14.2	643	20.1	129	29.4	16	440	29	68	110	269	516	190	3	8
300-48	406	18.3	639	20.7	136	30.9	16	406	28	63	112	244	517	200	3	6
Dive 304																
304-01	220	9.8	446	18.1	75	15.9	15	220	13	40	103	326	508	226	2	9
304-04	316	13.5	494	22.6	98	20.1	16	316	28	95	114	294	476	244	3	38
304-05	260	12.5	472	17.7	82	19.1	16	260	15	32	100	263	491	222	2	1
304-06	290	14.8	506	17.6	83	19.1	17	290	17	32	97	242	470	217	2	2
304-07	295	13.9	508	18.0	85	19.8	17	295	16	35	97	210	447	226	1	2
304-08	299	15.2	517	18.5	87	19.9	17	299	16	34	99	195	430	230	2	1
304-09	327	20.2	560	19.3	104	23.4	18	327	17	42	100	138	349	227	2	2
304-10	362	20.7	602	20.4	105	23.0	18	362	18	44	100	72	162	237	2	2
304-11	238	10.8	484	17.1	75	16.8	15	238	14	30	92	308	530	222	2	2
304-13	243	10.3	491	17.1	75	17.5	15	243	13	32	94	340	570	221	2	1
304-15	327	13.5	659	20.9	91	22.7	17	327	19	48	96	90	146	263	2	5
304-16	329	14.4	657	20.5	90	22.8	17	329	20	44	93	85	143	262	2	2
304-17	327	13.3	581	19.1	99	21.7	18	327	17	40	100	116	289	227	2	2
304-18	335	17.0	599	19.0	99	21.5	18	335	20	43	99	113	271	219	1	2
304-19	343	18.1	600	20.1	103	22.2	18	343	21	45	105	106	243	232	2	5
304-21	705	32.5	1210	21.7	169	50.4	17	705	39	85	116	264	345	259	5	4
304-22	646	31.5	1154	21.9	169	48.5	16	646	39	89	116	261	352	262	5	7

304-23	688	31.0	1204	22.0	167	50.0	17	688	41	86	113	267	369	256	5	5
304-24	278	17.4	451	17.0	79	19.3	16	278	14	30	99	319	574	215	2	3
304-25	361	21.3	544	18.4	94	23.0	18	361	17	39	99	158	374	234	2	2
304-26	353	23.8	542	18.4	93	22.9	18	353	15	40	98	159	360	232	2	1
304-30	353	24.7	540	18.2	93	22.4	18	353	16	39	96	155	348	228	2	2
304-32	304	14.9	476	18.4	82	20.1	17	304	15	34	106	233	405	232	2	1
304-33	335	16.3	502	18.7	87	21.1	18	335	15	34	101	188	367	236	1	1
304-34	287	13.7	464	17.8	81	19.8	17	287	14	35	98	269	474	227	2	2
304-35	282	15.2	462	17.8	83	19.9	17	282	15	36	102	270	503	224	2	2
304-36	279	15.5	460	17.6	81	19.7	16	279	14	33	101	277	529	223	2	2
304-37	265	13.5	461	19.0	82	19.8	16	265	13	32	110	234	446	233	1	2
304-38	265	13.7	441	18.7	84	19.5	16	265	15	41	110	309	525	232	2	9
BHVO-2	127	8.5	386	24.5	176	18.1	21	127	13	35	111	113	288	279	1.8	1.8
1 Std. Dev	4	0.6	47	0.2	2.3	0.2	1	4	2	2	0.7	0.7	3.8	4	1	1

nd- not determined

Table 5. HR-ICP-MS analyses of Kaula volcanics (continued)

Sample	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y	Pb	Th
KA-14	170	13.0	29.3	3.75	16.7	4.11	1.53	4.50	0.71	4.01	0.77	2.10	0.28	1.78	0.24	20.9	1.24	1.01
KA-31	765	47.8	101.8	12.1	50.6	9.57	3.09	8.06	1.05	5.25	0.89	2.27	0.28	1.63	0.23	25.5	3.75	4.88
Dive 300																		
300-02	260	17.1	33.0	4.15	18.7	4.26	1.58	4.53	0.66	3.91	0.76	2.05	0.29	1.67	0.24	20.4	1.08	1.47
300-05	140	11.1	22.4	2.88	12.9	3.05	1.16	3.39	0.52	3.27	0.62	1.73	0.25	1.49	0.23	16.8	0.72	0.85
300-10	212	29.6	93.7	7.49	34.0	7.78	2.33	7.76	1.20	7.04	1.35	3.41	0.46	2.97	0.44	27.8	59.9	3.56
300-20	153	9.2	20.0	2.72	12.1	3.00	1.04	3.15	0.52	3.38	0.65	1.81	0.24	1.61	0.22	17.4	0.51	0.64
duplicate	158	9.1	20.2	2.57	11.9	2.94	1.08	3.61	0.51	3.27	0.67	1.83	0.25	1.50	0.24	17.2	0.61	0.64
replicate	158	8.6	20.0	2.54	11.9	2.92	1.09	3.24	0.49	3.26	0.63	1.85	0.24	1.58	0.24	17.1	0.50	0.64
300-29	224	15.1	30.2	3.59	15.5	3.45	1.24	3.76	0.54	3.41	0.71	1.84	0.26	1.72	0.26	18.5	0.83	1.23
300-30	173	10.8	22.2	2.73	12.4	3.02	1.08	3.46	0.49	3.18	0.63	1.82	0.25	1.44	0.23	16.9	0.68	0.90
300-38	641	61.9	144.9	13.8	58.9	11.2	3.22	9.75	1.29	7.58	1.36	3.66	0.47	3.06	0.42	29.6	58.2	6.21
300-41	241	16.4	34.9	4.23	18.0	3.96	1.36	4.05	0.54	3.62	0.71	2.02	0.27	1.58	0.24	18.2	2.76	1.34
300-47	381	31.4	64.9	7.21	31.0	6.35	1.94	5.89	0.81	4.51	0.81	2.27	0.27	1.63	0.24	21.3	14.3	2.46
300-48	400	30.4	63.0	7.09	30.6	6.15	2.11	5.89	0.80	4.23	0.81	2.21	0.27	1.68	0.22	20.8	6.40	2.41
Dive 304																		
304-01	208	15.2	34.9	3.99	17.9	4.01	1.35	4.17	0.60	3.61	0.70	1.98	0.26	1.88	0.27	18.1	6.28	1.30
304-05	260	17.3	33.8	4.18	17.7	3.78	1.30	3.89	0.59	3.58	0.66	1.77	0.24	1.58	0.23	17.7	0.95	1.29
304-10	351	23.1	44.5	5.35	22.1	4.50	1.54	4.85	0.70	4.32	0.82	2.29	0.29	1.82	0.25	20.1	1.12	1.68
304-13	257	17.1	32.3	4.04	17.5	3.67	1.26	3.70	0.57	3.35	0.65	1.85	0.25	1.56	0.23	17.3	0.85	1.40
304-15	338	24.8	47.4	5.57	23.8	4.89	1.60	5.09	0.70	4.21	0.78	2.19	0.29	1.86	0.26	20.9	3.89	2.02
duplicate	332	23.4	45.8	5.46	23.7	4.92	1.67	4.67	0.67	4.32	0.78	2.21	0.28	1.82	0.26	20.6	4.04	1.92
replicate	343	23.7	48.0	5.50	23.7	4.84	1.68	5.20	0.72	4.12	0.78	2.14	0.28	1.81	0.26	20.4	3.80	1.86
304-17	317	21.6	42.7	5.19	21.1	4.22	1.47	4.28	0.61	3.75	0.71	2.05	0.27	1.69	0.23	19.5	1.01	1.51
304-22	650	45.4	89.0	10.3	42.9	7.98	2.58	7.48	0.94	4.99	0.85	2.01	0.29	1.67	0.23	23.1	4.95	4.58
304-26	352	21.3	41.0	4.98	20.7	4.19	1.48	4.26	0.60	3.74	0.69	1.89	0.25	1.64	0.23	19.3	0.95	1.40
304-35	285	17.4	34.1	4.16	17.9	3.79	1.34	3.56	0.59	3.49	0.69	1.69	0.28	1.58	0.22	17.6	1.65	1.30
304-38	268	17.6	38.1	4.20	18.6	3.98	1.37	4.24	0.62	3.84	0.75	1.96	0.28	1.77	0.25	18.6	8.03	1.39

Table 5. HR-ICP-MS analyses of Kaula volcanics (see text for methods used)

Sample	Li	Nb	Mo	Cd	Sn	Sb	Cs	Hf	Ta	W	Bi	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr	Zr
KA-14	5.54	15.1	0.75	0.67	0.65	0.31	0.07	2.32	0.72	1.15	0.01	349	358	38	111	85.4	83.2	21.4	5.6	382	93.4
KA-31	7.81	54.2	3.48	0.42	1.10	0.05	0.49	3.64	2.56	1.48	0.02	311	453	67	310	76.5	96.6	17.0	32.0	1371	161
Dive 300																					
300-02	4.72	18.6	1.12	0.18	0.62	0.02	0.29	2.07	0.90	0.32	0.01	305	169	40	87	79.2	82.9	18.2	12.2	501	81.8
300-05	4.19	9.1	1.08	0.14	0.49	0.02	0.08	1.50	0.48	0.19	0.01	273	529	58	286	85.5	77.5	15.7	6.1	371	56.5
300-10	7.19	14.3	8.35	0.33	0.57	0.59	0.23	2.27	0.69	1.52	0.60	336	185	155	138	96.2	127	17.4	7.5	446	97.8
300-20	4.08	12.2	0.63	0.15	0.57	0.02	0.12	1.59	0.61	0.25	0.01	292	480	55	234	91.0	79.1	15.9	7.2	349	63.6
duplicate	4.11	11.6	0.62	0.15	0.59	0.03	0.13	1.62	0.60	0.22	0.01	296	479	55	233	91.8	77.2	15.7	7.4	361	63.6
replicate	4.10	12.1	0.64	0.16	0.60	0.02	0.12	1.61	0.60	0.22	0.01	305	497	55	234	93.0	79.6	15.9	7.5	360	63.6
300-29	4.76	14.1	1.19	0.16	0.54	0.03	0.23	1.50	0.64	0.38	0.01	292	288	50	171	89.2	75.4	16.0	9.2	448	59.8
300-30	4.40	11.9	0.81	0.15	0.51	0.02	0.19	1.61	0.59	0.28	0.01	268	478	54	249	86.2	82.3	16.1	9.1	356	62.8
300-38	8.04	46.0	13.0	0.41	1.25	1.01	0.56	4.13	2.49	2.62	0.69	270	351	188	349	84.4	124	15.5	31.5	1108	208
300-41	3.78	16.8	1.40	0.16	0.64	0.06	0.30	1.81	0.83	0.39	0.03	285	427	64	275	71.9	82.8	15.5	11.2	483	75.4
300-47	4.00	28.2	3.14	0.20	0.92	0.22	0.35	2.78	1.40	0.70	0.16	237	521	90	307	52.8	92.4	14.9	13.6	620	123
300-48	4.57	29.1	1.97	0.18	1.00	0.17	0.65	2.95	1.50	0.52	0.07	250	478	63	240	54.4	89.7	15.7	18.1	634	128
Dive 304																					
304-01	3.39	14.0	0.89	0.17	0.55	0.06	0.26	1.75	0.68	0.15	0.04	301	487	72	322	64.6	88.7	14.9	10.1	430	70.7
304-05	4.50	17.3	0.93	0.16	0.48	0.03	0.19	1.80	0.84	0.19	0.00	281	465	55	250	72.5	89.9	15.5	12.8	472	76.6
304-10	5.76	21.7	1.17	0.20	0.52	0.02	0.80	2.29	1.15	0.36	0.01	297	161	39	66	60.0	87.9	18.1	20.5	594	99.9
304-13	5.77	16.8	1.10	0.21	0.50	0.04	0.18	1.67	0.78	0.34	0.01	284	532	59	309	75.0	79.9	14.7	10.5	489	71.6
304-15	5.97	21.8	1.95	0.21	0.52	0.04	0.23	1.94	0.98	0.55	0.04	341	142	50	87	86.7	85.1	17.2	14.0	663	87.8
duplicate	5.68	21.6	1.90	0.21	0.34	0.03	0.23	1.96	0.99	0.54	0.04	329	139	49	85	82.7	76.5	16.8	13.7	646	85.7
replicate	5.52	21.6	1.91	0.20	0.49	0.05	0.23	1.96	1.01	0.55	0.04	333	140	49	85	84.3	78.0	16.7	13.7	654	85.1
304-17	6.89	20.7	1.00	0.17	0.67	0.04	0.25	2.07	1.06	0.24	0.01	290	278	45	116	54.4	85.8	17.2	13.3	572	94.0
304-22	7.26	43.0	3.61	0.25	1.15	0.07	0.43	3.60	2.42	1.09	0.04	327	363	63	260	57.2	96.9	15.9	31.2	1164	161
304-26	4.30	21.6	1.31	0.17	0.66	0.02	0.46	2.13	1.14	0.33	0.01	297	345	47	160	63.5	86.8	17.6	23.6	539	90.6
304-35	4.55	18.6	0.99	0.17	0.59	0.07	0.29	1.85	0.97	0.30	0.02	276	475	59	269	68.0	82.3	15.7	15.4	451	75.9
304-38	5.42	18.0	1.65	0.20	0.57	0.14	0.22	1.88	0.92	0.41	0.08	280	521	78	305	60.6	87.9	15.1	13.6	428	77.7

Duplicate (dup) refers to independent sample processing; replicate (rep) refers to repeated measurement of the same solution on the MC-ICP-MS. Kil-93 is a Kīlauea tholeiite, similar to BHVO-1, and has been described by Eggins et al. (1997).

Figure 1. Garcia et al.

Figure 2. Garcia et al.

Figure 3. Garcia et al.

Figure 4. Garcia et al.

Figure 5. Garcia et al.

Figure 6. Garcia et al.

Figure 7. Garcia et al.

Figure 8. Garcia et al.

Figure 9. Garcia et al

Figure 10. Garcia et al.

Figure 11. Garcia et al.

Figure 12. Garcia et al.

Figure 13. Garcia et al.

Figure 14. Garcia et al.

Appendix Fig. 1. Garcia et al.

Appendix Table 1. Rock descriptions for Kaula Island, and Jason dives 300 and 304 samples

Sample #	Locality	Rock Type	Lat (°N)	Long (°W)	Depth (m)	Sample	Size (x,y,z) (cm)	Weight (kgs)	Glass (mm)	Mn coating (mm)	Alteration
KA-14	Island	basalt	21.652	160.542	+110	block	11, 8, 6	0.5	-	-	moderate
KA-15	Island	basalt	21.652	160.542	+105	block	10, 6, 5	0.8	-	-	weak
KA-17	Island	basalt	21.652	160.542	+95	block	11, 7, 6	0.9	-	-	weak
KA-19	Island	basalt	21.652	160.542	+88	block	9, 8, 5	0.8	-	-	weak
KA-28	Island	basalt	21.652	160.542	+103	block	8, 7, 6	0.7	-	-	weak
KA-29	Island	basalt	21.653	160.543	+82	block	10, 12, 7	1.1	-	-	weak
KA-31	Island	basalt	21.654	160.544	+103	block	14, 10, 8	1.2	-	-	weak
KA-34	Island	basalt	21.655	160.545	+97	block	13, 11, 7	1.1	-	-	weak
Dive 300											
300-01	cone A	basalt	21.843	160.810	3750	pillow toe	15, 7, 6	0.6	6.5	<1	weak
300-02	cone A	basalt	21.848	160.805	3756	pillow	13, 12, 12	3.2	1-6	<1	weak
300-03	cone A	basalt	21.849	160.803	3808	pillow toe	21, 9, 7		5-15	<1	weak
300-04	cone A	basalt	21.853	160.799	3927	pillow	12, 9, 8	1.9	10-15	<1	weak
300-05	terrace	basalt	21.858	160.795	3879	pillow toe	11, 5, 4	0.3	1-4	1.5	weak
300-06	cone B	basalt	21.856	160.781	3800	pillow toe	13, 7, 6	0.5	10-35	4	weak
300-07	cone B	basalt	21.855	160.780	3798	pillow toe	28, 16, 5	2.2	1-2	7	variable
300-08	cone B	basalt	21.855	160.778	3717	pillow toe	18, 11, 9	3.6	5-10	4-7	weak
300-10	cone B	basalt	21.852	160.769	3613	slab	17, 16, 4	1.5	0	<1-6	weak
300-11	cone B	basalt	21.852	160.768	3608	sheet flow	12, 8, 3	0.5	15	4	weak
300-13	cone B	basalt	21.851	160.765	3578	slab	17, 11, 3	0.7	0	<1	weak
300-14	cone B	basalt	21.851	160.765	3557	slab	16, 12, 9	3.7	0	<1	weak
300-15	cone B	basalt	21.848	160.762	3565	slab	23, 21, 15	12	0	5	moderate
300-18	cone C	basalt	21.841	160.762	3643	pillow toe	50, 17, 15	11.7	1-2	<2	weak
300-19	cone C	basalt	21.837	160.760	3502	pillow toe	14, 12, 4	1.5	1-10	1.5	weak
300-20	cone C	basalt	21.837	160.760	3481	pillow toe	17, 11, 7	1.5	10	2-4	weak
300-21	cone C	basalt	21.835	160.756	3495	pillow toe	8, 7, 6	0.5	5-11	<1-3	weak
300-22	cone C	basalt	21.834	160.755	3511	pillow toe	12, 6, 6	0.7	20	2.5	weak
300-23	cone C	basalt	21.834	160.752	3521	pillow toe	33, 14, 13	6.7	1-3	1-2	weak
300-24	cone C	basalt	21.834	160.746	3552	pillow toe	5, 5, 3	0.2	4	2	weak
300-25	cone D	basalt	21.834	160.742	3442	block	16, 12, 10	3.1	0	0-1	weak
300-26	cone D	basalt	21.834	160.741	3301	pillow	16, 13, 10	4.7	7-30	2	weak
300-27	cone E	basalt	21.829	160.733	3388	pillow toe	15, 9, 7	1.4	8-11	<1	weak
300-28	cone E	basalt	21.828	160.733	3360	block	11, 9, 8	1	0	<1-1	weak
300-29	cone E	basalt	21.826	160.730	3283	pillow toe	9, 7, 5	0.5	11	1-1.5	weak
300-30	terrace	basalt	21.840	160.719	3496	pillow toe	15, 7, 6	1	7	1	weak
300-31	terrace	basalt	21.840	160.718	3489	pillow toe	8, 8, 7	0.8	1-5	1	weak
300-32	terrace	basalt	21.844	160.713	3378	pillow toe	12, 5, 4	0.5	8-12	1-2	weak
300-33	terrace	basalt	21.841	160.707	3369	pillow toe	13, 10, 6	1.2	11	<1-2	weak
300-34	terrace	basalt	21.840	160.706	3359	pillow toe	11, 7, 4	0.5	3-8	<1	weak
300-35	cone F	basalt	21.838	160.702	3315	block	15, 14, 4	8	1-4	<1	weak
300-36	cone F	basalt	21.837	160.700	3282	pillow toe	20, 11, 8	2.5	8	1-2	weak
300-37	cone F	basalt	21.836	160.696	3125	pillow toe	33, 17, 16	9.5	5-8	1-2	weak
300-38	terrace	olivine basalt	21.824	160.682	3073	block	31, 26, 17	8.9	0	2-3	weak
300-39	terrace	basalt	21.824	160.682	3082	slab	28, 25, 17	13.5	0	0-15	weak
300-40	terrace	basalt	21.823	160.680	3090	slab	10, 4, 2	0.6	1-3	3	weak
300-41	terrace	basalt	21.822	160.679	3038	pillow toe	28, 8, 7	3.2	8	1	weak
300-42	terrace	basalt	21.820	160.676	2886	pillow toe	19, 10, 8,	1.8	6-10	<1	weak
300-44	ridge	basalt	21.820	160.661	2752	pillow talu	25, 26, 13	14.5	0	2	weak
300-45	ridge	basalt	21.820	160.660	2692	block	29, 25, 15	9.5	0	2-4	weak
300-46	ridge	basalt	21.820	160.660	2654	block	32, 22, 16	13.2	0	~7	moderate

300-47	ridge	basalt	21.821	160.659	2585	block	25, 14, 13	10	0	4-5	weak
300-48	ridge	basalt	21.821	160.658	2558	block	26, 19, 15	9.5	0	6	weak
300-49	ridge	basalt	21.821	160.658	2537	block	15, 13, 11	2.6	0	1-6	weak
Dive 304											
304-01	terrace	basalt	21.523	160.433	3615	pillow	8, 6, 4	0.3	0	1-2	weak
304-02	terrace	picritic basalt	21.523	160.433	3615	pillow toe	22, 8, 6	3.0	0-3	0-2	weak
304-03	terrace	plag basalt	21.522	160.432	3582	pillow	21, 17, 8	4.8	0	<1	weak
304-04	bench	olivine basalt	21.527	160.429	3513	pillow	7, 6, 4	0.4	0	<2	weak
304-05	bench	plag basalt	21.527	160.429	3513	pillow	21, 14, 9	6.3	2-9	<1-2	weak
304-06	ledge	olivine basalt	21.529	160.428	3504	pillow	16, 11, 9	2.2	1-2	<1-2	weak
304-07	ledge	basalt	21.529	160.428	3474	pillow	20, 14, 12	3.7	1-2	0-1	weak
304-08	ledge	basalt	21.530	160.428	3433	pillow	25, 12, 8	3.0	<1	1-2	weak
304-09	ledge	basalt	21.531	160.427	3350	pillow	9, 7, 6	0.6	0-1	0-1	weak
304-10	ledge	basalt	21.531	160.427	3312	pillow	15, 13, 10	3.0	0	2-4	weak
304-11	ledge	picritic basalt	21.532	160.426	3210	pillow toe	20, 9, 8	3.2	1-2	-	weak
304-12	ledge	olivine basalt	21.533	160.426	3195	pillow toe	9, 5, 5	0.4	6-8	2-3	weak
304-13	ledge	olivine basalt	21.534	160.426	3161	pillow toe	15, 8, 7	0.9	10	1-3	weak
304-14	slope	olivine basalt	21.536	160.428	3110	pillow toe	11, 7, 7	0.9	1-2	2-4	weak
304-15	slope	basalt	21.537	160.429	3085	pillow toe	16, 11, 10	2.0	1-3	1-2	weak
304-16	slope	basalt	21.540	160.430	3063	pillow toe	23, 13, 13	4.8	1-2	1	weak
304-17	slope	olivine basalt	21.557	160.440	2982	pillow	15, 11, 10	2.5	0	1-2	weak
304-19	slope	basalt	21.559	160.441	2854	pillow	30, 19, 16	13.0	3-8	<1-2	weak
304-20	cone	vesicular basalt	21.563	160.444	2607	pillow	18, 12, 15	3.5	<1	<1	weak
304-21	cone	vesicular basalt	21.565	160.446	2469	pillow	8, 6, 5	0.4	0	<1-1	weak
304-22	cone	vesicular basalt	21.565	160.446	2437	pillow	12, 11, 5	1.0	0	<1-1	weak
304-23	cone	vesicular basalt	21.566	160.447	2411	pillow	18, 15, 12	5.0	3	1	weak
304-24	lower rift	picritic basalt	21.566	160.456	2644	pillow	22, 12, 9	7.0	3	1	weak
304-25	lower rift	olivine basalt	21.566	160.459	2579	pillow	25, 23, 8	11.0	1-2	<1	weak
304-26	lower rift	olivine basalt	21.567	160.460	2477	pillow	13, 11, 10	1.5	1-3	<1	weak
304-27	lower rift	olivine basalt	21.583	160.460	2477	pillow	6, 3, 2	0.2	1	<1-1	weak
304-28	lower rift	basalt	21.566	160.462	2385	drapery	10, 7, 6	0.4	10	<1	weak
304-29	lower rift	basalt	21.583	160.495	2385	drapery	12, 6, 5	0.4	10	1-2	weak
304-30	lower rift	olivine basalt	21.566	160.462	2354	pillow	24, 18, 17	10.8	<1	1-2	weak
304-31	upper rift	basalt	21.576	160.464	2358	pillow	48, 36, 20	28.0	0	2-4	moderate
304-32	upper rift	vesicular basalt	21.576	160.465	2346	pillow	20, 18, 16	6.2	<1	1	weak
304-33	upper rift	vesicular basalt	21.576	160.467	2252	pillow	22, 18, 15	10.3	<1	<1	weak
304-34	upper rift	ves olivine basalt	21.577	160.468	2150	pillow	20, 22, 16	10.0	1-3	1-2	moderate
304-35	upper rift	ves olivine basalt	21.576	160.469	2113	pillow	15, 14, 13	2.5	<1	1-2	weak
304-36	upper rift	ves olivine basalt	21.577	160.469	2064	pillow	21, 21, 10	7.3	1-3	1	weak
304-37	upper rift	vesicular basalt	21.577	160.473	1920	pillow	33, 23, 8	6.8	2	<1	weak
304-38	upper rift	vesicular basalt	21.577	160.476	1710	pillow	16, 12, 12	3.5	1	<1	weak

Table S2. Complete $^{40}\text{Ar}/^{39}\text{Ar}$ results from Oregon State University: Ages relative to 28.03 Ma for the Fish Canyon biotite standard

Sample: 300-02		J-value:		0.00183		± 0.0000053		(1σ)		D/amu:		1.00493		± 0.00060		(1σ)							
Material: groundmass																							
File	Temp. (°C)	⁴⁰ Ar (moles)	⁴⁰ Ar (Volts)	± 1σ ₄₀ (Volts)	³⁹ Ar (Volts)	±1σ ₃₉ (Volts)	³⁸ Ar (Volts)	± 1σ ₃₈ (Volts)	³⁷ Ar (Volts)	± 1σ ₃₇ (Volts)	³⁶ Ar (Volts)	± 1σ ₃₆ (Volts)	% ⁴⁰ Ar *	⁴⁰ Ar*/ ³⁹ Ar _K	± 1σ	Age (Ma)	± 2σ (Ma)	K/Ca	Included in wtd. mean				
09C1841	400	1.539E-18	13.37480	0.01148	0.05597	0.00016	0.01182	0.00007	0.01785	0.00001	0.04533	0.00014	1.72	4.1371	0.9286	####	± 6.08	0.406					
09C1842	500	7.590E-19	6.59511	0.00886	0.05469	0.00014	0.00696	0.00001	0.03169	0.00004	0.02268	0.00007	0.24	0.2876	0.4820	0.95 ± 3.18	0.223		✓				
09C1850	600	3.038E-19	2.96924	0.00193	0.05052	0.00013	0.00390	0.00002	0.05167	0.00005	0.01024	0.00002	0.46	0.2696	0.1913	0.89 ± 1.26	0.118		✓				
09C1851	700	1.895E-19	1.85244	0.00970	0.03942	0.00006	0.00268	0.00001	0.04722	0.00016	0.00638	0.00004	0.84	0.3986	0.3862	1.31 ± 2.54	0.100		✓				
09C1852	800	1.574E-19	1.53824	0.00275	0.04223	0.00009	0.00262	0.00001	0.04996	0.00010	0.00531	0.00004	0.72	0.2657	0.2842	0.88 ± 1.87	0.102		✓				
09C1854	900	2.354E-19	2.30422	0.00140	0.06811	0.00005	0.00434	0.00002	0.11819	0.00032	0.00800	0.00004	0.81	0.2762	0.1994	0.91 ± 1.31	0.069		✓				
09C1855	1000	1.589E-19	1.55387	0.00138	0.03929	0.00007	0.00273	0.00002	0.09935	0.00020	0.00541	0.00002	0.81	0.3243	0.2051	1.07 ± 1.35	0.047		✓				
09C1856	1125	3.725E-19	3.64495	0.00248	0.07560	0.00006	0.00579	0.00002	0.24024	0.00069	0.01275	0.00006	0.47	0.2278	0.2749	0.75 ± 1.81	0.038		✓				
09C1858	1250	2.779E-19	2.71644	0.00459	0.05226	0.00016	0.00404	0.00002	0.21759	0.00057	0.00954	0.00004	0.44	0.2328	0.2677	0.77 ± 1.76	0.029		✓				
09C1859	1400	1.030E-19	1.00704	0.00276	0.01951	0.00007	0.00151	0.00002	0.09274	0.00038	0.00354	0.00002	0.50	0.2618	0.3350	0.86 ± 2.21	0.025		✓				
															weighted mean age (9 of 10):					0.92 ± 0.57			
Sample: 300-10		J-value:		0.00185		##### (1σ)		D/amu:		1.00493		± 0.00060		(1σ)									
Material: groundmass																							
File	Temp. (°C)	⁴⁰ Ar (moles)	⁴⁰ Ar (Volts)	± 1σ ₄₀ (Volts)	³⁹ Ar (Volts)	±1σ ₃₉ (Volts)	³⁸ Ar (Volts)	± 1σ ₃₈ (Volts)	³⁷ Ar (Volts)	± 1σ ₃₇ (Volts)	³⁶ Ar (Volts)	± 1σ ₃₆ (Volts)	% ⁴⁰ Ar* ¹⁰	Ar*/ ³⁹ Ar _i	± 1σ	Age (Ma)	± 2σ (Ma)	K/Ca	Included in wtd. mean				
09C1838	400	1.853E-19	1.81040	0.01327	0.03351	0.00008	0.00261	0.00001	0.00958	0.00004	0.00618	0.00002	1.20	0.6518	0.4420	2.17 ± 2.94	0.454		✓				
09C1839	500	1.995E-19	1.94881	0.00089	0.06719	0.00013	0.00395	0.00002	0.02437	0.00009	0.00660	0.00001	2.18	0.6346	0.0816	2.11 ± 0.54	0.357		✓				
09C1873	600	1.545E-19	1.50995	0.00186	0.10629	0.00012	0.00498	0.00002	0.07134	0.00013	0.00506	0.00001	4.17	0.5957	0.0516	1.98 ± 0.34	0.175		✓				
09C1875	700	7.995E-20	0.78106	0.00104	0.08953	0.00018	0.00341	0.00002	0.15423	0.00030	0.00266	0.00002	6.67	0.5874	0.0603	1.96 ± 0.40	0.068		✓				
09C1876	800	5.907E-20	0.57697	0.00105	0.06263	0.00012	0.00210	0.00002	0.17567	0.00031	0.00204	0.00001	5.85	0.5456	0.0526	1.82 ± 0.35	0.042		✓				
09C1877	900	4.441E-20	0.43369	0.00092	0.03039	0.00004	0.00109	0.00001	0.08444	0.00015	0.00152	0.00001	3.71	0.5355	0.1442	1.78 ± 0.96	0.042		✓				
09C1878	1000	1.532E-19	1.49676	0.00248	0.04673	0.00009	0.00244	0.00001	0.11738	0.00033	0.00519	0.00004	1.73	0.5608	0.2794	1.87 ± 1.86	0.047		✓				
09C1880	1100	1.695E-19	1.65699	0.00219	0.04299	0.00005	0.00241	0.00002	0.15399	0.00043	0.00579	0.00003	1.30	0.5094	0.2546	1.70 ± 1.70	0.033		✓				
09C1881	1200	1.715E-19	1.67623	0.00246	0.04654	0.00008	0.00249	0.00001	0.25556	0.00048	0.00593	0.00005	1.74	0.6383	0.3571	2.13 ± 2.38	0.021		✓				
09C1882	1300	4.938E-20	0.48243	0.00081	0.01536	0.00003	0.00074	0.00001	0.12147	0.00034	0.00168	0.00001	5.98	1.9244	0.1786	6.40 ± 1.19	0.015						
09C1883	1400	1.696E-20	0.16553	0.00030	0.00565	0.00002	0.00027	0.00001	0.04777	0.00008	0.00058	0.00001	6.07	1.8269	0.4321	6.08 ± 2.87	0.014						
															weighted mean age (9 of 11):					1.94 ± 0.19			
Sample: 300-36		J-value:		0.00178		##### (1σ)		D/amu:		1.00493		± 0.00060		(1σ)									
Material: groundmass																							
File	Temp. (°C)	⁴⁰ Ar (moles)	⁴⁰ Ar (Volts)	± 1σ ₄₀ (Volts)	³⁹ Ar (Volts)	±1σ ₃₉ (Volts)	³⁸ Ar (Volts)	± 1σ ₃₈ (Volts)	³⁷ Ar (Volts)	± 1σ ₃₇ (Volts)	³⁶ Ar (Volts)	± 1σ ₃₆ (Volts)	% ⁴⁰ Ar* ¹⁰	Ar*/ ³⁹ Ar _i	± 1σ	Age (Ma)	± 2σ (Ma)	K/Ca	Included in wtd. mean				
09C1913	400	4.031E-19	3.92687	0.00857	0.02639	0.00006	0.00396	0.00002	0.00653	0.00001	0.01352	0.00005	0.28	0.4209	0.7699	1.35 ± 4.94	0.369		✓				
09C1914	500	3.254E-19	3.17012	0.00380	0.04214	0.00010	0.00412	0.00002	0.01360	0.00007	0.01089	0.00006	0.59	0.4440	0.4734	1.43 ± 3.04	0.282		✓				
09C1915	600	2.626E-19	2.55850	0.00311	0.06662	0.00010	0.00430	0.00002	0.04457	0.00009	0.00882	0.00004	0.69	0.2649	0.2026	0.85 ± 1.30	0.136		✓				
09C1941	600	1.127E-19	1.09800	0.00158	0.04357	0.00016	0.00214	0.00002	0.05815	0.00009	0.00383	0.00004	0.68	0.1737	0.2752	0.56 ± 1.77	0.066		✓				
09C1942	800	9.696E-20	0.94447	0.00302	0.03673	0.00009	0.00170	0.00002	0.07134	0.00007	0.00332	0.00003	0.69	0.1802	0.2436	0.58 ± 1.57	0.045		✓				
09C1943	950	1.001E-19	0.97538	0.00200	0.03548	0.00006	0.00179	0.00001	0.06923	0.00031	0.00342	0.00004	0.89	0.2486	0.3426	0.80 ± 2.20	0.045		✓				

09C1944	1100	3.654E-19	3.55878	0.00411	0.07529	0.00006	0.00531	0.00003	0.18218	0.00094	0.01245	0.00004	0.52	0.2511	0.2043	0.81 ± 1.31	0.036	✓
09C1946	1250	3.569E-19	3.47464	0.00231	0.06259	0.00004	0.00494	0.00002	0.22730	0.00036	0.01223	0.00003	0.45	0.2566	0.1936	0.82 ± 1.24	0.024	✓
09C1947	1400	7.908E-20	0.76958	0.00018	0.01400	0.00004	0.00106	0.00001	0.06189	0.00008	0.00272	0.00001	0.52	0.2936	0.3159	0.94 ± 2.03	0.020	✓

weighted mean age (9 of 9): 0.80 ± 0.56

Sample: 304-10 J-value: 0.00187 ##### (1σ) D/amu: 1.00493 ± 0.00060 (1σ)
Material: groundmass

File	Temp. (°C)	⁴⁰ Ar (moles)	⁴⁰ Ar (Volts)	± 1σ ₄₀ (Volts)	³⁹ Ar (Volts)	± 1σ ₃₉ (Volts)	³⁸ Ar (Volts)	± 1σ ₃₈ (Volts)	³⁷ Ar (Volts)	± 1σ ₃₇ (Volts)	³⁶ Ar (Volts)	± 1σ ₃₆ (Volts)	% ⁴⁰ Ar* ¹⁰ Ar*/ ³⁹ Ar _i	± 1σ	Age (Ma)	± 2σ (Ma)	K/Ca	Included in wtd. mean
09C1835	400	1.121E-18	10.96115	0.01004	0.04125	0.00013	0.00863	0.00003	0.01028	0.00004	0.03780	0.00010	0.09	0.2452	0.9713	0.83 ± 6.55	0.521	✓
09C1836	500	3.804E-19	3.71620	0.00319	0.06759	0.00006	0.00509	0.00002	0.01493	0.00003	0.01274	0.00006	0.76	0.4184	0.3028	1.41 ± 2.04	0.588	✓
09C1861	600	2.557E-19	2.49980	0.00356	0.14374	0.00013	0.00676	0.00002	0.05770	0.00027	0.00850	0.00002	2.08	0.3630	0.0630	1.22 ± 0.43	0.294	✓
09C1862	700	9.410E-20	0.92002	0.00181	0.17668	0.00037	0.00504	0.00002	0.14713	0.00029	0.00309	0.00001	7.04	0.3688	0.0247	1.24 ± 0.17	0.142	✓
09C1863	800	4.974E-20	0.48616	0.00037	0.16272	0.00035	0.00333	0.00001	0.17567	0.00027	0.00164	0.00001	12.17	0.3663	0.0275	1.24 ± 0.19	0.109	✓
09C1865	875	1.918E-20	0.18752	0.00041	0.07586	0.00012	0.00140	0.00001	0.07338	0.00045	0.00062	0.00001	14.48	0.3608	0.0339	1.22 ± 0.23	0.122	✓
09C1866	950	1.793E-20	0.17512	0.00045	0.07207	0.00019	0.00137	0.00001	0.06071	0.00018	0.00057	0.00000	14.97	0.3665	0.0188	1.24 ± 0.13	0.140	✓
09C1867	1025	1.902E-20	0.18577	0.00041	0.05752	0.00012	0.00134	0.00001	0.06655	0.00018	0.00063	0.00001	10.85	0.3533	0.0397	1.19 ± 0.27	0.102	✓
09C1868	1100	2.489E-20	0.24310	0.00039	0.04083	0.00014	0.00118	0.00001	0.09116	0.00032	0.00087	0.00001	6.44	0.3878	0.1018	1.31 ± 0.69	0.053	✓
09C1870	1200	2.018E-20	0.19699	0.00030	0.02909	0.00009	0.00081	0.00001	0.11488	0.00025	0.00075	0.00001	5.24	0.3604	0.1098	1.22 ± 0.74	0.030	✓
09C1871	1300	1.095E-20	0.10677	0.00019	0.01454	0.00004	0.00039	0.00001	0.08452	0.00016	0.00043	0.00001	5.01	0.3753	0.1377	1.27 ± 0.93	0.020	✓
09C1872	1400	4.994E-21	#####	#####	#####	#####	#####	#####	0.035801	0.000092	0.000193	0.000007	3.27	#####	#####	0.93 ± 2.32	0.019	✓

weighted mean age (12 of 12): 1.23 ± 0.08

Sample: 304-23 J-value: 0.0018 ##### (1σ) D/amu: 1.00493 ± 0.00060 (1σ)
Material: groundmass

File	Temp. (°C)	⁴⁰ Ar (moles)	⁴⁰ Ar (Volts)	± 1σ ₄₀ (Volts)	³⁹ Ar (Volts)	± 1σ ₃₉ (Volts)	³⁸ Ar (Volts)	± 1σ ₃₈ (Volts)	³⁷ Ar (Volts)	± 1σ ₃₇ (Volts)	³⁶ Ar (Volts)	± 1σ ₃₆ (Volts)	% ⁴⁰ Ar* ¹⁰ Ar*/ ³⁹ Ar _i	± 1σ	Age (Ma)	± 2σ (Ma)	K/Ca	Included in wtd. mean
09C1844	400	5.880E-19	5.10686	0.00990	0.06307	0.00011	0.00515	0.00003	0.01858	0.00003	0.01754	0.00007	0.24	0.1975	0.3984	0.64 ± 2.59	0.439	✓
09C1845	500	2.902E-19	2.51680	0.00169	0.06199	0.00017	0.00355	0.00001	0.03128	0.00005	0.00862	0.00004	0.47	0.1929	0.2001	0.63 ± 1.30	0.256	✓
09C1885	600	1.839E-19	1.79718	0.00449	0.08044	0.00020	0.00341	0.00002	0.12241	0.00055	0.00625	0.00003	1.05	0.2369	0.1215	0.77 ± 0.79	0.077	✓
09C1886	700	9.982E-20	0.97529	0.00249	0.04460	0.00004	0.00173	0.00001	0.12776	0.00043	0.00346	0.00004	0.71	0.1580	0.2781	0.51 ± 1.81	0.041	✓
09C1887	800	1.167E-19	1.14008	0.00273	0.03433	0.00011	0.00164	0.00001	0.08899	0.00020	0.00399	0.00002	0.76	0.2547	0.1760	0.83 ± 1.14	0.045	✓
09C1888	900	1.943E-19	1.89795	0.00460	0.03098	0.00012	0.00223	0.00002	0.07392	0.00020	0.00660	0.00006	0.29	0.1825	0.5865	0.59 ± 3.81	0.049	✓
09C1890	1050	5.272E-19	5.15083	0.00667	0.07379	0.00025	0.00571	0.00004	0.25689	0.00099	0.01798	0.00005	0.22	0.1577	0.2671	0.51 ± 1.74	0.033	✓
09C1892	1200	5.078E-19	4.96449	0.00284	0.06251	0.00019	0.00520	0.00001	0.32632	0.00071	0.01740	0.00009	0.33	0.2670	0.4891	0.87 ± 3.18	0.022	✓
09C1893	1400	7.079E-20	0.69193	0.00145	0.01267	0.00009	0.00080	0.00001	0.08817	0.00047	0.00246	0.00001	0.40	0.2247	0.3765	0.73 ± 2.45	0.016	✓

weighted mean age (9 of 9): 0.71 ± 0.50

Sample: 304-26 J-value: 0.00189 ##### (1σ) D/amu: 1.00493 ± 0.00060 (1σ)
Material: groundmass

File	Temp. (°C)	⁴⁰ Ar (moles)	⁴⁰ Ar (Volts)	± 1σ ₄₀ (Volts)	³⁹ Ar (Volts)	± 1σ ₃₉ (Volts)	³⁸ Ar (Volts)	± 1σ ₃₈ (Volts)	³⁷ Ar (Volts)	± 1σ ₃₇ (Volts)	³⁶ Ar (Volts)	± 1σ ₃₆ (Volts)	% ⁴⁰ Ar* ¹⁰ Ar*/ ³⁹ Ar _i	± 1σ	Age (Ma)	± 2σ (Ma)	K/Ca	Included in wtd. mean
09C1823	400	1.147E-19	1.12086	0.00097	0.00496	0.00002	0.00086	0.00001	0.00088	0.00001	0.00386	0.00002	0.04	0.0936	1.4256	0.32 ± 9.73	0.732	✓
09C1824	500	3.348E-19	3.27319	0.00560	0.09331	0.00021	0.00572	0.00001	0.01916	0.00003	0.01125	0.00002	0.50	0.1773	0.1137	0.60 ± 0.78	0.635	✓
09C1825	600	2.729E-19	2.66876	0.00072	0.18217	0.00027	0.00883	0.00002	0.08057	0.00016	0.00916	0.00002	1.28	0.1887	0.0483	0.64 ± 0.33	0.295	✓
09C1827	700	2.046E-19	1.99927	0.00232	0.13799	0.00015	0.00601	0.00003	0.12628	0.00014	0.00692	0.00004	1.31	0.1914	0.0880	0.65 ± 0.60	0.142	✓
09C1828	800	3.831E-19	3.74390	0.01307	0.15467	0.00030	0.00747	0.00003	0.10854	0.00026	0.01291	0.00004	0.82	0.1993	0.1302	0.68 ± 0.89	0.185	✓
09C1829	900	3.777E-19	3.69034	0.00403	0.16168	0.00013	0.00801	0.00002	0.10158	0.00037	0.01274	0.00002	0.65	0.1489	0.0745	0.51 ± 0.51	0.207	✓
09C1831	1050	7.191E-19	7.02753	0.01578	0.30821	0.00013	0.01565	0.00004	0.35468	0.00120	0.02429	0.00013	1.11	0.2556	0.1475	0.87 ± 1.01	0.113	✓
09C1832	1200	3.586E-19	3.50449	0.00676	0.15822	0.00018	0.00794	0.00002	0.32736	0.00046	0.01225	0.00006	1.05	0.2355	0.1294	0.80 ± 0.88	0.063	✓
09C1833	1400	1.013E-19	0.99003	0.00284	0.04061	0.00008	0.00200	0.00001	0.16549	0.00027	0.00352	0.00002	1.03	0.2550	0.1676	0.87 ± 1.14	0.032	✓
weighted mean age (9 of 9):															0.65 ± 0.21			

Sample: 304-33 J-value: 0.00171 ##### (1σ) D/amu: 1.00473 ± 0.00060 (1σ)
Material: groundmass

File	Temp. (°C)	⁴⁰ Ar (moles)	⁴⁰ Ar (Volts)	± 1σ ₄₀ (Volts)	³⁹ Ar (Volts)	± 1σ ₃₉ (Volts)	³⁸ Ar (Volts)	± 1σ ₃₈ (Volts)	³⁷ Ar (Volts)	± 1σ ₃₇ (Volts)	³⁶ Ar (Volts)	± 1σ ₃₆ (Volts)	% ⁴⁰ Ar* ¹⁰ Ar*/ ³⁹ Ar _i	± 1σ	Age (Ma)	± 2σ (Ma)	K/Ca	Included in wtd. mean
09C1926	400	3.132E-19	3.05111	0.00769	0.00369	0.00004	0.00215	0.00002	0.00064	0.00001	0.01051	0.00005	0.08	0.6509	4.7739	2.01 #####	0.514	✓
09C1927	500	2.626E-19	2.55828	0.00086	0.07015	0.00007	0.00515	0.00003	0.01525	0.00002	0.00879	0.00002	0.52	0.1918	0.1294	0.59 ± 0.80	0.412	✓
09C1928	600	4.870E-20	0.47408	0.00073	0.18248	0.00043	0.00711	0.00003	0.13404	0.00021	0.00169	0.00002	7.09	0.1856	0.0263	0.57 ± 0.16	0.122	✓
09C1931	700	1.759E-20	0.17111	0.00034	0.12353	0.00023	0.00365	0.00001	0.16207	0.00102	0.00072	0.00001	12.30	0.1720	0.0184	0.53 ± 0.11	0.068	✓
09C1932	800	1.601E-20	0.15578	0.00018	0.06789	0.00024	0.00184	0.00001	0.07104	0.00011	0.00058	0.00001	7.40	0.1712	0.0318	0.53 ± 0.20	0.085	✓
09C1933	900	1.098E-20	0.10672	0.00070	0.03299	0.00006	0.00106	0.00001	0.03216	0.00021	0.00038	0.00001	5.64	0.1841	0.0650	0.57 ± 0.40	0.091	✓
09C1935	1025	1.039E-20	0.10091	0.00033	0.03352	0.00011	0.00122	0.00002	0.06396	0.00020	0.00041	0.00001	5.60	0.1708	0.0869	0.53 ± 0.54	0.046	✓
09C1936	1150	7.389E-21	0.07174	0.00013	0.02078	0.00011	0.00077	0.00001	0.08295	0.00019	0.00031	0.00001	17.68	0.6235	0.0868	1.92 ± 0.53	0.022	
09C1937	1275	4.449E-21	0.04306	0.00013	0.01134	0.00005	0.00040	0.00000	0.06424	0.00008	0.00020	0.00001	16.15	0.6314	0.2172	1.95 ± 1.34	0.015	
09C1939	1400	4.412E-21	0.04288	0.00020	0.00630	0.00002	0.00023	0.00001	0.05232	0.00023	0.00020	0.00001	9.27	0.6527	0.3208	2.01 ± 1.98	0.010	
weighted mean age (7 of 10):															0.54 ± 0.08			

The values in this table represent blank corrected values that have not been corrected for mass discrimination or decay of ³⁷Ar and ³⁹Ar.

Atmospheric argon ratios		
⁴⁰ Ar/ ³⁶ Ar	295.5	± 0.5
³⁸ Ar/ ³⁶ Ar	0.1869	± 0.0003

Decay constants	
λ _{40Ar TOTAL}	5.543 x 10 ⁻¹⁰ a ⁻¹
³⁹ Ar	2.58 x 10 ⁻³ a ⁻¹
³⁷ Ar	8.23 x 10 ⁻⁴ h ⁻¹

Interfering isotope production ratios	
(⁴⁰ Ar/ ³⁹ Ar) _K	0.00101
(³⁸ Ar/ ³⁹ Ar) _K	0.01138
(³⁹ Ar/ ³⁷ Ar) _{Ca}	0.000673
(³⁸ Ar/ ³⁷ Ar) _{Ca}	0.000139
(³⁶ Ar/ ³⁷ Ar) _{Ca}	0.000264

Table S3. Complete $^{40}\text{Ar}/^{39}\text{Ar}$ results from the University of Wisconsin-Madison; Ages relative to 28.201 Ma for the Fish Canyon sanidine standard

Sample: KA-14
Material groundmass
J-value: 0.00178 $\pm$ 0.0000007 (1 σ) D/amu: 1.01236 $\pm$ 0.00121 (1 σ)

File		⁴⁰ Ar	⁴⁰ Ar	± 1σ ₄₀	³⁹ Ar	± 1σ ₃₉	³⁸ Ar	± 1σ ₃₈	³⁷ Ar	± 1σ ₃₇	³⁶ Ar	± 1σ ₃₆	% ⁴⁰ Ar*	⁴⁰ Ar*/ ³⁹ Ar _K	± 1σ	Age (Ma)	± 2σ (Ma)	K/Ca	Included in wtd. mean
		(°C)	(moles)	(Volts)	(Volts)	(Volts)	(Volts)	(Volts)	(Volts)	(Volts)	(Volts)	(Volts)	(Volts)						
CB7855	660	2.424E-16	0.04108	0.00020	0.01000	0.00006	0.00017	0.00003	0.05050	0.00169	0.00014	0.00001	11.87	0.489564	0.2975	1.59 ± 1.94	0.085		
CB7856	710	7.391E-16	0.12522	0.00025	0.04778	0.00011	0.00065	0.00003	0.25563	0.00807	0.00040	0.00001	22.55	0.593122	0.0652	1.93 ± 0.42	0.080		
CB7857	750	7.916E-16	0.13412	0.00022	0.07319	0.00013	0.00094	0.00003	0.44512	0.01380	0.00041	0.00001	36.12	0.664797	0.0444	2.16 ± 0.29	0.070		
CB7858	785	1.063E-15	0.18015	0.00023	0.09708	0.00017	0.00122	0.00004	0.64930	0.02020	0.00041	0.00001	61.40	1.144734	0.0357	3.72 ± 0.23	0.064		
CB7859	820	1.576E-15	0.26699	0.00031	0.13169	0.00021	0.00172	0.00006	0.88456	0.02731	0.00046	0.00001	75.17	1.531129	0.0294	4.98 ± 0.19	0.064		
CB7860	855	1.649E-15	0.27946	0.00023	0.12903	0.00023	0.00155	0.00003	0.82300	0.02547	0.00038	0.00001	82.50	1.794737	0.0287	5.83 ± 0.19	0.067		
CB7861	895	1.765E-15	0.29908	0.00031	0.13718	0.00022	0.00164	0.00005	0.81316	0.02515	0.00034	0.00001	87.90	1.924327	0.0275	6.25 ± 0.18	0.072	✓	
CB7862	955	2.254E-15	0.38195	0.00036	0.16799	0.00029	0.00202	0.00006	0.84528	0.02622	0.00042	0.00001	84.48	1.927536	0.0230	6.26 ± 0.15	0.085	✓	
CB7863	1030	2.599E-15	0.44042	0.00039	0.18357	0.00029	0.00227	0.00005	0.80032	0.02473	0.00051	0.00001	80.25	1.931227	0.0206	6.27 ± 0.13	0.098	✓	
CB7864	1115	2.279E-15	0.38617	0.00037	0.13364	0.00024	0.00183	0.00007	0.73271	0.02284	0.00065	0.00001	64.89	1.882186	0.0293	6.12 ± 0.19	0.078	✓	
CB7865	1190	1.869E-15	0.31675	0.00041	0.06791	0.00014	0.00102	0.00004	1.54829	0.04784	0.00104	0.00002	40.87	1.936767	0.0906	6.29 ± 0.59	0.019	✓	
CB7866	1250	1.442E-15	0.24426	0.00032	0.04302	0.00009	0.00074	0.00004	3.88307	0.11998	0.00156	0.00002	36.08	2.185400	0.2712	7.10 ± 1.76	0.004	✓	
weighted mean age (6 of 12):																6.24 ± 0.08			

Sample: KA-31
Material groundmass
J-value: 0.0013 $\pm$ 0.0000009 (1 σ) D/amu: 1.01064 $\pm$ 0.00172 (1 σ)

File	Temp. ($^{\circ}\text{C}$)	^{40}Ar (moles)	^{40}Ar (Volts)	$\pm 1\sigma_{40}$ (Volts)	^{39}Ar (Volts)	$\pm 1\sigma_{39}$ (Volts)	^{38}Ar (Volts)	$\pm 1\sigma_{38}$ (Volts)	^{37}Ar (Volts)	$\pm 1\sigma_{37}$ (Volts)	^{36}Ar (Volts)	$\pm 1\sigma_{36}$ (Volts)	% $^{40}\text{Ar}^*$	$^{40}\text{Ar}^*/^{39}\text{Ar}_K$	$\pm 1\sigma$	Age (Ma)	$\pm 2\sigma$ (Ma)	K/Ca	Included in wtd. mean
CB8618	675	1.972E-14	3.34161	0.00206	0.22202	0.00042	0.00795	0.00008	0.12697	0.00424	0.01105	0.00008	2.54	0.382771	0.1048	0.912 $\pm$ 0.499	0.752		✓
CB8619	720	2.356E-14	3.99207	0.00129	0.38371	0.00072	0.01148	0.00007	0.21608	0.00698	0.01325	0.00009	2.37	0.247037	0.0739	0.589 $\pm$ 0.352	0.763		✓
CB8620	760	1.962E-14	3.32442	0.00138	0.46351	0.00087	0.01140	0.00007	0.25009	0.00813	0.01078	0.00008	4.78	0.342781	0.0501	0.817 $\pm$ 0.239	0.797		✓
CB8621	805	1.666E-14	2.82273	0.00165	0.49136	0.00092	0.01149	0.00007	0.28541	0.00926	0.00914	0.00006	5.06	0.291015	0.0400	0.693 $\pm$ 0.190	0.740		✓
CB8622	850	1.149E-14	1.94730	0.00135	0.36530	0.00070	0.00917	0.00009	0.24078	0.00787	0.00637	0.00005	4.37	0.232816	0.0383	0.555 $\pm$ 0.183	0.652		✓
CB8623	915	8.597E-15	1.45670	0.00079	0.28131	0.00054	0.00695	0.00010	0.25600	0.00829	0.00476	0.00004	4.91	0.254226	0.0388	0.606 $\pm$ 0.185	0.472		✓
CB8624	1000	1.352E-14	2.28995	0.00092	0.27749	0.00051	0.00749	0.00008	0.39877	0.01290	0.00760	0.00005	3.32	0.273943	0.0602	0.653 $\pm$ 0.287	0.299		✓
CB8625	1100	9.729E-14	16.48470	0.00487	0.74968	0.00148	0.03140	0.00025	2.25281	0.07354	0.05550	0.00038	1.59	0.349826	0.1556	0.834 $\pm$ 0.741	0.143		✓
CB8626	1225	1.256E-13	21.28738	0.00889	1.84120	0.00337	0.06202	0.00057	34.80505	1.11511	0.07876	0.00054	3.47	0.406992	0.1023	0.970 $\pm$ 0.487	0.022		✓
CB8627	1300	2.072E-14	3.51000	0.00113	0.18841	0.00036	0.00362	0.00003	0.12475	0.00457	0.01179	0.00008	1.01	0.187760	0.1313	0.447 $\pm$ 0.626	0.649		✓
weighted mean age (10 of 10):																0.663 $\pm$ 0.085			

The values in this table represent blank, discrimination, and decay (^{37}Ar and ^{39}Ar) corrected values.

Atmospheric argon ratios			Decay constants	
$^{40}\text{Ar}/^{36}\text{Ar}$	295.5	$\pm$ 0.5	Steiger & Jager (197)	$\lambda_{40\text{Ar}}$ (0.580 $\pm$ 0.014) $\times 10^{-10}$ Min et al. (2000)
$^{38}\text{Ar}/^{36}\text{Ar}$	0.1869	$\pm$ 0.0003	$\lambda_{\text{B-}}$	(4.884 $\pm$ 0.099) $\times 10^{-10}$ Min et al. (2000)
			^{39}Ar	(2.58 $\pm$ 0.03) $\times 10^{-3}$ a $^{-1}$ Stoenner et al. (1965)
			^{37}Ar	(8.23 $\pm$ 0.042) $\times 10^{-4}$ h $^{-1}$ Stoenner et al. (1965)
Interfering isotope production ratios				
$(^{40}\text{Ar}/^{39}\text{Ar})_K$	(5.4 $\pm$ 1.4) $\times 10^{-4}$	Jicha & Brown (201)	^{36}Cl	(2.303 $\pm$ 0.046) $\times 10^{-6}$ a $^{-1}$
$(^{38}\text{Ar}/^{39}\text{Ar})_K$	(1.210 $\pm$ 0.002) $\times 10^{-2}$	Jicha & Brown (2014)		
$(^{39}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$	(6.95 $\pm$ 0.09) $\times 10^{-4}$	Renne et al. (2013)		
$(^{38}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$	(1.96 $\pm$ 0.08) $\times 10^{-5}$	Renne et al. (2013)		
$(^{36}\text{Ar}/^{37}\text{Ar})_{\text{Ca}}$	(2.65 $\pm$ 0.022) $\times 10^{-4}$	Renne et al. (2013)		

Table S4. Modes of Ka'ula lavas based on 300 counts minus vesicles

Sample	MgO	Olivine		Plagioclase		Cpx		Matrix Ves		Xeno
	wr wt%	ph	mph	ph	mph	ph	mph			px
Island										
KA-14	5.49	0.6	1.2	-	4.0	-	-	94.2	36.7	-
KA-15	13.38	1.3	9.3	-	-	-	2.3	70.1	35.7	17.0
KA-17	12.41	0.0	6.3	-	-	-	3.0	90.6	19.3	<0.1
KA-19	12.71	1.0	5.3	-	-	-	1.0	92.6	70.3	<0.1
KA-28	10.44	0.0	9.6	-	-	-	<0.1	90.3	21.7	-
KA-29	8.68	0.9	0.6	1.2	1.8	-	-	95.5	24.2	-
KA-31	12.83	3.3	7.3	-	-	-	<0.1	86.6	58.3	1.6
KA-34	11.87	0.6	7.3	-	-	0.6	0.3	84.3	7.3	2.3
Dive 300										
300-02	6.7	-	1.0	-	1.6	-	-	97.3	1.3	-
300-04	10.33	0.6	6.0	-	-	-	-	93.3	0.1	-
300-07	10.05	0.6	11.6	-	<0.1	-	-	87.6	1.3	-
300-08	9.83	2.0	9.3	-	-	-	-	88.6	1.6	-
300-10	6.19	-	0.3	-	4.3	-	0.3	95.0	1.0	-
300-14	-	0.0	2.3	-	-	-	-	97.6	0.6	-
300-18	10.42	5.0	11.6	-	-	-	-	83.3	4.3	-
300-19	-	2.3	2.6	-	0.6	0.0	0.0	94.3	0.1	-
300-23	11.45	6.3	4.3	-	-	-	-	89.3	0.1	-
300-26	11.01	-	7.3	-	-	-	-	92.6	0.1	-
300-30	10.45	1.0	7.3	-	-	-	1.3	90.3	1.6	-
300-36	10.75	1.6	6.6	-	0.6	-	-	91.0	0.1	-
300-38	10.33	0.6	7.3	-	-	-	-	92.0	30.0	-
300-41	11.47	2.3	8.3	-	-	-	-	89.3	0.1	-
300-44	11.39	1.3	7.0	-	-	-	1.3	90.0	48.7	-
300-46	11.58	1.0	4.3	-	-	-	-	94.6	0.1	-
300-47	12.62	3.3	6.3	-	0.3	0.0	1.0	89.0	0.1	-
300-48	11.45	0.0	9.3	-	-	-	1.3	89.3	40.3	-
Dive 304										
304-01	12.26	4.3	10.0	-	<0.1	-	-	86.0	14.0	-
304-03	-	0.3	6.7	-	<0.1	-	-	93.0	0.3	-
304-04	10.90	2.3	4.7	-	-	-	-	93.0	1.6	-
304-05	11.46	1.0	5.0	-	-	-	-	94.0	0.7	-
304-06	10.81	4.0	5.7	-	0.3	-	-	90.0	2.3	-
304-07	10.32	3.3	5.7	0.7	0.7	-	-	89.7	3.2	-
304-08	9.32	2.0	4.0	-	0.3	-	-	93.7	1.0	-
304-09	7.91	3.0	4.3	-	0.3	-	-	92.3	0.7	-
304-10	6.15	0.0	1.0	-	1.3	-	-	97.7	0.3	-
304-11	11.77	4.7	5.7	-	0.7	-	-	89.0	0.7	-
304-12	-	6.7	5.3	-	1.7	-	-	86.3	0.7	-
304-13	12.45	3.7	8.7	-	1.0	-	-	86.7	0.1	-
304-14	-	8.0	6.7	-	1.3	-	-	84.0	0.1	-
304-15	6.78	-	0.3	-	1.3	-	-	98.3	0.1	-
304-16	6.75	-	1.0	-	1.0	-	-	98.0	0.1	-
304-17	8.26	2.7	2.7	-	1.3	-	-	93.3	0.1	-

304-18	7.76	0.3	8.3	-	0.0	1.0	3.0	82.7	38.9	-
304-19	7.49	2.7	1.7	-	1.0	0.0	0.0	94.7	0.3	-
304-20	11.46	2.7	8.7	-	0.0	1.0	3.7	79.0	17.8	-
304-21	11.56	1.0	3.3	-	0.0	0.0	0.7	84.7	24.1	-
304-22	12.14	0.3	7.7	-	0.0	5.3	2.3	77.3	40.5	-
304-23	11.63	1.7	8.0	-	0.0	3.6	2.0	84.7	37.6	-
304-24	12.26	9.7	8.3	-	<0.1	-	-	82.0	0.0	-
304-25	8.70	6.0	2.7	-	1.0	-	-	90.4	0.7	-
304-26	8.74	4.0	3.3	-	0.7	-	-	92.0	0.3	-
304-27	-	5.3	4.3	0.7	2.3	-	-	87.3	0.1	-
304-28	-	2.7	2.0	-	1.3	-	-	94.0	0.3	-
304-29	-	2.0	4.0	-	0.3	-	-	93.7	0.3	-
304-30	8.72	1.3	1.7	0.3	0.7	-	-	96.0	2.9	-
304-32	10.18	9.7	3.3	-	<0.1	-	-	87.0	23.5	-
304-33	8.85	7.3	2.3	-	0.0	-	-	90.3	18.3	-
304-34	11.22	4.0	9.3	-	<0.1	-	-	86.7	11.8	-
304-35	11.10	5.0	10.7	-	<0.1	-	-	84.3	22.7	-
304-36	11.40	9.3	4.0	-	0.0	-	-	86.7	13.0	-
304-37	10.48	2.7	5.3	-	<0.1	-	-	92.0	29.1	-
304-38	11.96	4.0	6.7	-	<0.1	-	-	89.3	17.4	-

Ves- vesicularity; ph- phenocrysts; mph- microphenocrysts; wr- whole rock; Cpx- clinopyroxene; Xeno px- xenocrystic pyroxene

Table A.5. Energy dispersive analysis of secondary minerals in sample KA-19

	Zeolites						Celestite
SiO ₂	38	53.2	55.1	55.6	55.4	53.0	
Al ₂ O ₃	18.1	22.7	25.7	26.4	26.5	25.8	
FeO	nd	nd	0.1	0.4	0.3	0.2	0.5
SrO	nd	nd	0.7	1.6	2.3	3.3	56.0
BaO	nd	nd	nd	2.0	0.5	nd	2.0
CaO	nd	nd	1.6	1.9	2.3	2.4	
Na ₂ O	5.1	2.6	4.8	4.3	3.7	4.0	
K ₂ O	38.8	21.5	12.0	7.8	9.0	11.3	
SO ₃	nd	nd	nd	nd	nd	nd	41.5
nd- not detected; all analyses recalculated dry to 100.0 wt%							