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How old is Kīlauea Volcano (Hawai'i)? Insights from $^{40}Ar/^{39}Ar$ dating of the 1.7-km-deep SOH-1 core

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ABSTRACT

Reliable estimates for lava accumulation rates are essential for interpreting magma fluxes to intraplate volcanoes and inferring the thermal and compositional structure of mantle plumes. Kīlauea Volcano's (Hawai'i) 1.7-km-deep SOH-1 scientific drill hole provides an opportunity to assess the lava accumulation rate and duration of the early shield stage for Hawaiian volcanoes. New $^{40}Ar/^{39}Ar$ ages were determined for four SOH-1 tholeiitic samples. Combining these results with two previous $^{40}Ar/^{39}Ar$ ages and the age of the drill-site surface flow, and correcting sample depth to remove intervening dikes, yields a good correlation (R^2 = 0.97) for a 4.4 m/k.y. accumulation rate, which may have increased to 5.9 m/k.y. during the last 50 k.y. These rates contrast with a predicted 40% decrease during the last 200 k.y. from a simple shield volcano growth model. Mauna Loa, a massive shield volcano that buttresses the north flank of Kīlauea, may have contributed to this nearly constant lava accumulation rate. Extending the correlation to the base of the SOH-1 core indicates that Kīlauea's tholeiitic volcanism probably started by 240 ka. Assuming an ~400 k.y. duration for the preshield stage, Kīlauea is much older than some previous estimates (ca. 600 ka versus 150–275 ka) and has been vigorously erupting tholeiitic lavas for at least the past 200 k.y. During this period, it has been competing with Mauna Loa for the higher-temperature output of the Hawaiian mantle plume, which is contrary to previous models. New models that assess the magmatic output and thermal history of the Hawaiian mantle plume need to consider a steep increase in magma supply during the transition from preshield to shield stages to explain the near-constant lava accumulation rate during early shield growth.

INTRODUCTION

Quantifying the lava accumulation rate for a volcano is essential to determine its growth rate, volume, and lifespan. Reliable estimates of these parameters are essential for interpreting the thermal and geochemical structure of mantle plumes (e.g., DePaolo and Stolper, 1996). The Island of Hawai'i has two volcanoes in the shield stage of volcanism (Kīlauea and Mauna Loa), two dormant ones in the post-shield stage (Hualālai and Mauna Kea), and another south of the island (Lō'ihi; Fig. 1) emerging from the preshield stage. Fundamental disagreements persist regarding the lifespan of a Hawaiia volcano (0.6–1.5 m.y.; Moore and Clague, 1992; Garcia et al., 2006). A longer lifespan (>1000 k.y.) would indicate that at least some new Hawaiian volcanoes formed directly on Cretaceous seafloor or the distal flanks of an older adjacent volcano (DePaolo and Stolper, 1996), which would influence their structural development, eruptive behavior, and volume estimates. Shorter lifespans such as that proposed for Kīlauea (150–275 ka; Holcomb et al., 2000; Lipman and Calvert, 2013) would position it high on the submarine flanks of Mauna Loa at the time it formed and result in smaller volumes.

Hawaiian volcanoes are massive (thicknesses up to 9 km and volumes >10 × 10^6 km^3; Lipman and Calvert, 2013), sink rapidly (2.6 mm/yr; Ludwig et al., 1991), and have limited subaerial vertical exposures (usually <500 m), making it impossible to establish a complete history for any volcano from surface exposures. A composite approach is needed to interpolate well-dated stratigraphic sequences from their various stages of growth (Fig. 1). Continuously cored, scientific drill holes provide a means to penetrate deep into these massive volcanoes and average out their episodic pulses of eruptive activity to gain a more reliable indication of their average lava accumulation rate and lifespan. The middle to late stages of growth of Mauna Kea (Fig. 1) are well documented by the ~3.0 drill core of the Hawaiian Scientific Drilling Project (HSDP; e.g., Sharp and Renne, 2005).

A key missing component to our understanding of the evolution of Hawaiian volcanoes is a well-dated stratigraphic sequence from the early stages of shield growth. Kīlauea, the youngest subaerial Hawaiian volcano, has accumulated less lava than older Hawaiian volcanoes, making it the best choice for documenting early shield volcanism. Age estimates for Kīlauea's inception range widely (150 to >600 ka; e.g., DePaolo and Stolper, 1996; Holcomb et al., 2000). The age for the start of Kīlauea's shield volcanism (when tholeiitic magma starts erupting regularly) is also controversial (>350 ka versus <100 ka). The older age is based on an unspiked K-Ar date for a tholeiitic basalt (351 ± 12 ka) recovered at 1550 m depth from the SOH-1 drill hole (Scientific Observation Hole; Quane et al., 2000). Younger ages are based on the overlapping relationships of lavas from several volcanoes on the Island of Hawai'i (Holcomb et al., 2000) and $^{40}Ar/^{39}Ar$ ages for transitional and alkalic rocks (138 ± 115 to 280 ± 20 ka) collected on the submarine flanks of Kīlauea (Calvert and Lanphere, 2006; Fig. 1).

The high rate of recovery (88%) of relatively unaltered rocks in the ~1684-m-deep SOH-1 drill core (Quane et al., 2000) provides a superb opportunity to fill a major gap in our understanding of Hawaiian volcanoes (Fig. 1 inset). Previous attempts to date this core and other Hawaiian tholeiitic lavas using K-Ar (conventional and unspiked) or $^{40}Ar/^{39}Ar$ methods have been problematic because of the low K content (typically <0.5 wt%) and glassy texture of the rocks and their susceptibility to K loss during tropical weathering. A new generation of multi-collector mass spectrometers for $^{40}Ar/^{39}Ar$ geochronology offers improved precision, higher mass resolution, and a dramatic reduction in the required sample size. Here we present four new $^{40}Ar/^{39}Ar$ ages obtained using a multi-collector instrument for SOH-1 samples to show that Kīlauea's shield stage volcanism has been ongoing for at least 200 k.y. Kīlauea's overall age is probably ca. 600 ka, if the duration of preshield stage of Hawaiian volcanism is ~400 k.y. (Garcia et al., 2006).

GEOLOGY BACKGROUND ON SOH-1 DRILL CORE

The SOH-1 core was drilled ~2 km north of Kīlauea's east rift zone at 19.483°N and

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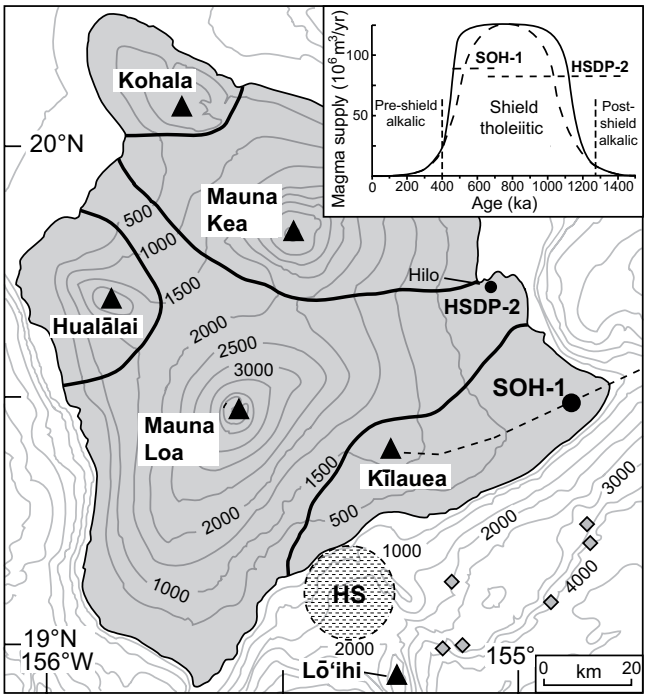

Figure 1. Topographic map of Island of Hawai'i (gray area) showing its five main volcanoes (Kīlauea, Mauna Loa, Hualālai, Mauna Kea, and Kohala) and submarine Lō'ihi. Summits are shown by triangles. Gray diamonds show locations of submarine alkalic samples of Calvert and Lanphere (2006). Approximate location of Hawaiian hotspot (HS) is shown by large circle with dashed outline south of island. Contour interval is 500 m. Inset: Schematic models for magma supply rate (10^6 m³/yr) variation during life of a Hawaiian volcano (dashed, after Garcia et al., 2006; solid, proposed revision). Age span for Hawaii Scientific Observation Hole Program SOH-1 (Table 1) and Hawaiian Scientific Drilling Project (HSDP) scientific drill holes (Sharp and Renne, 2005) are shown by horizontal dashed lines.

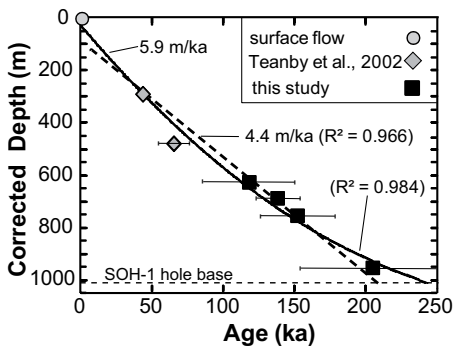

Figure 2. Radioisotopic ages for Hawaii Scientific Observation Hole Program SOH-1 samples plotted versus corrected depth (after excluding intervening dikes). Ages include surface flow at SOH-1 drill site (200–400 yr; Moore and Trusdell, 1991), reliable $^{40}Ar/^{39}Ar$ ages from Teanby et al. (2002), and $^{40}Ar/^{36}Ar$ ages from this study (Table 1). Lines are for best fit (short dashed, $R^2 = 0.966$) and second-order polynomial line (curved solid line, $R^2 = 0.984$) for the seven ages.

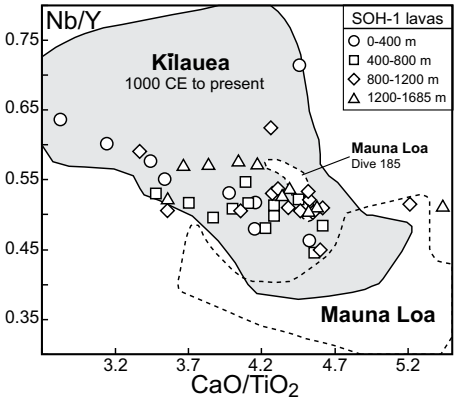

Figure 3. Plot of CaO/TiO_2 versus Nb/Y for Kīlauea, Mauna Loa, and Hawaii Scientific Observation Hole Program SOH-1 samples based on X-ray fluorescence data all analyzed at the University of Massachusetts (USA). SOH-1 samples are subdivided by depth (400 m increments uncorrected for dikes), and no systematic change in these ratios toward Mauna Loa compositions occurs with depth, although there is overlap for rocks from Kīlauea and anomalous submarine lavas collected on *PISCES V* submersible dive 185. Field for Kīlauea is from Greene et al. (2013, and references therein); those for Mauna Loa are from Rhodes and Vollinger (2004, and references therein).

154.90°W (Fig. 1) to evaluate the area's geothermal potential (Quane et al., 2000). Subaerial lava flows (~45% of the core) extend to ~600 m below sea level and are underlain by glassy, mostly fragmental submarine rocks (15% of the core; see Fig. DR1 in the GSA Data Repository[1]). Dikes (~40% of the core) cut both units, especially the lower fragmental section (Garcia et al., 2007). The drill site is covered by a young prehistoric flow (200–400 yr; Moore and Trusdell, 1991).

Two previous geochronological studies examined SOH-1 rocks. The unspiked K-Ar technique was used to analyze 14 rocks from a wide range of depths (234–1550 m; Quane et al., 2000). Three samples were successfully duplicated and gave ages that increased with depth. The $^{40}Ar/^{39}Ar$ method was employed by Teanby et al. (2002) to analyze 14 subaerial samples (including six previously analyzed by Quane et al. [2000]). Only two of these samples were considered by Teanby et al. (2002) to provide reliable ages (Fig. 2). The poor success rate for these two studies (five of 22 different SOH-1 samples) attests to the difficulty of extracting reliable ages from young, Hawaiian tholeiitic rocks. Given the importance of the SOH-1 drill core for determining the magmatic history of Kīlauea, we reexamined selected new samples using improved $^{40}Ar/^{39}Ar$ analytical methods.

METHODS

Incremental heating experiments were performed on ~20 mg aliquots of phenocryst-free groundmass from six SOH-1 samples with a 60W CO_2 laser and a Nu Instruments Noblesse multi-collector mass spectrometer at the University of Wisconsin–Madison following the procedures of Jicha et al. (2016). Procedural blanks averaged 6000 counts per second (cps) for ^{40}Ar and ~22 cps for ^{36}Ar, corresponding to ~3%–4% of the ^{40}Ar and ^{36}Ar signals per heating step. Samples were analyzed at least twice to assess reproducibility and reduce age uncertainty. New ages are reported relative to the 1.1864 Ma Alder Creek sanidine standard (Jicha et al., 2016). Additional information on the multi-collector instrument, its calibration, and data evaluation are given in the Data Repository, and in Table DR1 therein.

Four SOH-1 samples were selected based on their holocrystalline texture, absence of secondary minerals in thin section, moderate K_2O content (0.26–0.49 wt%), low to moderate loss-on-ignition (LOI) values (<0.6 wt.%), and K_2O/P_2O_5 values (K/P) between 1.5 and 2.1, which are typical of unaltered Kīlauea lavas. These samples are considered unaltered and unaffected by hydrothermal alteration. None of samples from the lower part of the SOH-1 (>1150 m) have both lower LOI values (<0.6 wt%) and magmatic K/P values. The two freshest samples from the lower part of the hole were included in our study (1374 and 1457 m; Fig. DR1; Table DR2).

RESULTS

Fifty (50) SOH-1 samples were analyzed (Table DR2) by X-ray fluorescence for major and trace elements. Compositions are typical of historical Kīlauea lavas with no change toward Mauna Loa compositions with depth (Fig. 3). Ten SOH-1 samples analyzed (from 166 to 1606 m deep in the core) have $^{206}Pb/^{204}Pb$ (18.48–18.59), $^{87}Sr/^{86}Sr$ (0.70354–0.70360), and ε_{Nd} (+6.3 to +6.6) values that lie within the compositional fields of Kīlauea lavas (e.g., Marske et

[1]GSA Data Repository item 2017020, Figure DR1 (graphic log), Figure DR2 (age spectra and isochrons), Table DR1 (Ar-Ar dating methods), Table DR2 (XRF major element analyses of SOH-1 drill core), and Table DR3 (complete $^{40}Ar/^{39}Ar$ results for SOH-1 samples), is available online at www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

al., 2007; J.P. Marske, unpublished data) and are distinct from shield-stage Mauna Loa lavas (e.g., Weis et al., 2011). Thus, the entire ~1.7-km-deep SOH-1 drill hole was erupted from Kīlauea.

Four of the six analyzed SOH-1 samples gave statistically acceptable $^{40}Ar/^{39}Ar$ plateau ages with isochron intercepts within error of the atmospheric $^{40}Ar/^{36}Ar$ value (Table 1; Table DR3; Fig. DR2). Plateau model ages are preferred as there is very little (0.1%–3.9%) radiogenic ^{40}Ar in these samples and thus insufficient spread in $^{40}Ar/^{39}Ar$ ratios to give precise isochron ages. Two unsuccessful samples (1103 and 1457) had large ^{36}Ar signals, which did not allow sufficient radiogenic Ar to be resolved from the trapped atmospheric component and resulted in near-zero or negative ages. SOH-1 samples 711, 772, 871, and 1374 give plateau ages of 118 ± 32 ka, 138 ± 15 ka, 152 ± 25 ka and 205 ± 48 ka, respectively (Table 1). The progressive increase in age with depth for these four samples and the two reliable ages from Teanby et al. (2002) is the first basic test for reliability of the geochronological results.

TABLE 1. SUMMARY OF $^{40}Ar/^{39}Ar$ EXPERIMENTS ON HAWAIIAN SCIENTIFIC OBSERVATION HOLE SOH-1 SAMPLES

Depth (m)	K/Ca total	Total fusion age (ka ± 2σ)	$^{40}Ar/^{36}Ar_{initial}$ (± 2σ)	Isochron age (ka ± 2σ)	N	^{39}Ar (%)	MSWD	Plateau age (ka ± 2σ)
711	0.12	162 ± 43	299.0 ± 3.4	71 ± 190	19 of 22	82.1	0.60	110 ± 46
	0.07	53 ± 73	294.6 ± 5.6	400 ± 420	11 of 13	90.2	0.57	125 ± 74
	0.10	130 ± 61	300.1 ± 5.8	–10 ± 180	14 of 14	100.0	0.53	129 ± 62
		Combined isochron:	298.4 ± 2.5	130 ± 120			Weighted mean:	**118 ± 32**
772	0.26	54 ± 26	293.0 ± 6.9	260 ± 210	7 of 14	66.1	0.73	144 ± 19
	0.17	21 ± 43	297.1 ± 6.4	160 ± 340	7 of 11	64.2	0.61	127 ± 27
		Combined isochron:	295.9 ± 4.6	190 ± 120			Weighted mean:	**138 ± 15**
871	0.04	147 ± 37	299.4 ± 2.2	130 ± 220	11 of 12	92.7	0.66	162 ± 40
	0.04	61 ± 35	297.9 ± 5.6	200 ± 1500	6 of 9	71.6	0.60	144 ± 34
		Combined isochron:	299.4 ± 1.8	126 ± 84			Weighted mean:	**152 ± 25**
1374	0.04	101 ± 86	300.3 ± 5.5	91 ± 190	9 of 17	70.7	0.48	229 ± 82
	0.05	194 ± 64	298.9 ± 3.0	170 ± 580	12 of 12	100.0	0.27	192 ± 61
		Combined isochron:	299.5 ± 2.4	140 ± 380			Weighted mean:	**205 ± 48**

Note: Ages calculated relative to 1.1864 Ma for the Alder Creek sanidine standard (Jicha et al., 2016). Atmospheric $^{40}Ar/^{36}Ar$ = 298.56 ± 0.31. See Table DR3 (see text footnote 1) for complete data, constants used, etc. Weighted mean age in **bold** is preferred. MSWD—mean square of weighted deviates.

DISCUSSION

Lava Accumulation Rates for Hawaiian Shield Volcanoes

Magmatic flux rates for the Hawaiian mantle plume are highly variable on all scales. The average rate has increased more than five-fold during the last 7 m.y., reaching a high of 11 m^3/s during the last 1 m.y. for Mauna Loa (Wessel, 2016). Superimposed on this long-term increase are fluctuations of more than an order of magnitude on centennial time scales (e.g., Poland et al., 2012) that correlate with geochemical variations related to source heterogeneity and the degree of partial melting (e.g., Pietruszka and Garcia, 1999). Even more dramatic oscillations in Kīlauea's magma flux occurred during prehistoric times with alternating, multiple century-long cycles of explosive followed by effusive activity (Swanson et al., 2014). These short-term changes in magma flux rates obfuscate attempts to assess the lava accumulation rates on Hawaiian volcanoes. The core from the SOH-1 drill hole averages out the decades- to centuries-long variations in magma flux, providing a more reliable estimate of the lava accumulation rate during Kīlauea's early shield stage.

Dikes were excluded from the SOH-1 section to obtain the true section lava thickness using the detailed core stratigraphy of Garcia et al. (2007). The combined SOH-1 geochronology results (seven samples; four new $^{40}Ar/^{39}Ar$ ages [Table 1], two $^{40}Ar/^{39}Ar$ ages interpreted as reliable by Teanby et al. [2002], and the surface flow) indicate a remarkably consistent rate of lava accumulation along Kīlauea's lower east rift zone (~4.4 m/k.y., R^2 = 0.97; Fig. 2). The overall consistency of this rate is striking compared to the 50× fluctuations observed for Kīlauea's last 2.5 k.y. of activity (Swanson et al., 2014). A second-order polynomial fit to the SOH-1 ages gives a slightly better correlation (R^2 = 0.984; Fig. 2) and indicates that the age of the volcanics at the bottom of the SOH-1 drill hole (at 1006 m depth, corrected for dike thickness) may be ca. 240 ka. The polynomial curve suggests a slightly higher rate of lava accumulation for the last 50 k.y. (~5.9 m/k.y.).

The SOH-1 average lava accumulation rate (4.4 m/k.y.) is lower than predicted for the summit of Kīlauea (12–15 m/k.y.; DePaolo and Stolper, 1996), which is consistent with the distal location of SOH-1 drill site ~40 km from the volcano's summit. The nearly constant lava accumulation rate at the SOH-1 site conflicts with the radial growth model prediction of a decrease by 40% over the last 200 k.y. (DePaolo and Stolper, 1996). The difference between observed and predicted lava accumulation rates is partly a consequence of Kīlauea's growth being impeded by Mauna Loa volcano (Fig. 1), causing lava to accumulate faster along and south of Kīlauea's rift zones. However, average SOH-1 flow thickness is only ~3 m compared to ~7 m for Mauna Loa lavas in the HSDP-2 drill hole (Garcia et al. 2007). Another factor affecting the SOH-1 lava accumulation rate is Kīlauea's strongly asymmetrical growth leading to much of its magma supply going to the east rift zone (Fig. 1).

Estimates of lava accumulation rates for neighboring Mauna Loa vary dramatically with age and location. The older (>470 ka) submarine southwest rift zone had a rate of 25 m/k.y., whereas the younger rift section (270–59 ka) had a much lower rate (1 m/k.y.) (Jicha et al., 2012). The subaerial lava accumulation rate over the last 100 k.y. at the HSDP site ~25 km from Mauna Loa's east rift zone on the volcano's lower slope (Fig. 1) was estimated at 2–3 m/k.y. (Lipman and Moore, 1996; Sharp et al., 1996). This moderate rate is consistent with the observation that the Mauna Loa sank isostatically at a slightly faster rate (~2.6 m/k.y.) than it grew. However, Mauna Loa has undergone a recent resurgence during the last ~180 yr (~5 m/k.y.). During the same period, Kīlauea had a remarkably high overall subaerial accumulation rate (24 m/k.y.), which is twice the rate predicted for its summit (DePaolo and Stolper, 1996) and symptomatic of the problem of using short-term observations to infer lava accumulation rates.

Mauna Kea's lava accumulation rate was estimated at 8.6 m/k.y. based on $^{40}Ar/^{39}Ar$ ages from the 3-km-deep HSDP-2 drill hole (Sharp and Renne, 2005). This rate represents the middle to late shield stage when the rate of volcanism should have been declining (Fig. 1, inset). The Mauna Kea rate is twice the SOH-1 rate, which is surprising given the location of the HSDP site 15 km from the volcano's poorly developed east rift zone (Fig. 1) and Mauna Kea's moderate size compared to other Hawaiian volcanoes (Lipman and Calvert, 2013). In contrast, the SOH-1 site is 2 km from the axis of Kīlauea's east rift zone where eruptions are more frequent (Fig. 1) and the lava accumulation rate should have been higher during the early shield stage (e.g., DePaolo and Stolper, 1996). The higher rate for Mauna Kea may be a consequence of coeval growth of two shield volcanoes on the southern flank of Mauna Kea (Hualālai and Mauna Loa) and another in the late shield stage to the north (Kohala; Fig. 1) forcing lava to accumulate mainly on Mauna Kea's east and west flanks.

How Old Is Kīlauea?

Proposed values for Kīlauea's age range widely: ca. 600 ka (DePaolo and Stolper, 1996) to ca. 150 ka (Holcomb et al., 2000). The older inception age was based on the assumption that individual Hawaiian volcanoes are active for

~1000 k.y. and that Kīlauea is ~60% through its lifespan. If a Hawaiian volcano's lifespan is ~1500 k.y., as inferred from recent studies (Garcia et al., 2006; Lipman and Calvert, 2013), then Kīlauea might be as old as 900 ka and its lava accumulation would not be decreasing as predicted from assuming a shorter lifespan. Younger inception ages (150–275 ka) reflect models for the overlapping growth of volcanoes on the Island of Hawaii (Holcomb et al., 2000) and $^{40}Ar/^{39}Ar$ ages for basaltic alkalic lavas collected on Kīlauea's submarine flanks (Fig. 1). Hawaiian volcanoes are not known to erupt alkalic basalts during their shield stage. Thus, it was assumed that these submarine rocks represent Kīlauea's preshield stage. This led Lipman and Calvert (2013) to propose dramatic reductions in Kīlauea's inception age (from ca. 600 to ca. 275 ka), duration of tholeiitic volcanism (from >350 to <100 k.y.), volume (from 31.6 to 11×10^3 km^3), and magma supply rate. These submarine rocks are more compositionally diverse and, in some cases, more alkaline than any known lavas from the Island of Hawaii (Lipman and Calvert, 2013) and have $^{206}Pb/^{204}Pb$ isotope ratios much higher and lower than subaerial Kīlauea lavas (Hanyu et al., 2010). These features suggest a magma source distinct from that of Kīlauea and raise questions concerning the parentage of the submarine lavas.

Kīlauea's overall age is a composite of its shield and preshield stages of volcanism (Fig. 1). The new SOH-1 ages, which undoubtedly represent a Kīlauea source (Fig. 3), establish the start of its shield stage at no later than ca. 200 ka. If the model for the duration of Lō'ihi's preshield stage is adopted (~400 k.y.; Garcia et al., 2006), the age of Kīlauea is probably ca. 600 ka. This is consistent with a previous estimate by DePaolo and Stolper (1996). Our new $^{40}Ar/^{39}Ar$ ages indicate that:

(1) Kīlauea is much older than some previous estimates (150–275 ka) and has been vigorously producing tholeiitic magmas for at least the last 200 k.y.

(2) Kīlauea and Mauna Loa were both tapping the higher-temperature output of the Hawaiian mantle plume to produce tholeiitic magma. This provides a minimum estimate of ~40 km for the diameter of the plume's core (assuming plate velocity of 10 cm/yr).

(3) Models for the magmatic output and thermal history of the Hawaiian plume should consider a sharper increase in magma supply during the transition from the preshield to shield stages (Fig. 1) to explain the near-constant lava accumulation rate during the early shield stage.

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