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# Slow changes in lava chemistry at Kamaʻehuakanaloa linked to sluggish mantle upwelling on the margin of the Hawaiian plume

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## ABSTRACT

**Temporal variations in lava chemistry at active submarine volcanoes are difficult to decipher due to the challenges of dating their eruptions. Here, we use high-precision measurements of $^{226}$Ra-$^{230}$Th disequilibria in basalts from Kamaʻehuakanaloa (formerly Lōʻihi) to estimate model ages for recent eruptions of this submarine Hawaiian pre-shield volcano. The ages range from ca. 0 to 2300 yr (excluding two much older samples) with at least five eruptions in the past ∼150 yr. Two snapshots of the magmatic evolution of Kamaʻehuakanaloa (or "Kamaʻehu") are revealed. First, a long-term transition from alkalic to tholeiitic volcanism was nearly complete by ca. 2 ka. Second, a systematic short-term fluctuation in ratios of incompatible elements (e.g., Th/Yb) for summit lavas occurred on a time scale of ∼1200 yr. This is much longer than the ∼200-yr-long historical cycle in lava chemistry at the neighboring subaerial volcano, Kīlauea. The slower pace of the variation in lava chemistry at Kamaʻehu is most likely controlled by sluggish mantle upwelling on the margin of the Hawaiian plume.**

## INTRODUCTION

Deciphering the temporal variations in lava chemistry at submarine volcanoes is a challenging endeavor. Their eruptive chronology is typically limited to historical time scales based on detailed fieldwork (e.g., Chadwick et al., 1991; Soule et al., 2007) and dating with the short-lived $^{210}$Po-$^{210}$Pb isotopic system (e.g., Rubin et al., 1994). Observations of active submarine eruptions are rare (e.g., Fox et al., 2001; Embley et al., 2014).

Kamaʻehuakanaloa (formerly Lōʻihi) is a submarine pre-shield Hawaiian volcano that is located ∼35 km south of the Island of Hawaiʻi (Fig. 1). Kamaʻehuakanaloa (or "Kamaʻehu") is last known to have erupted in 1996 based on an intense seismic swarm, crater formation ("Pele's Pit"), and $^{210}$Po-$^{210}$Pb dating (Garcia et al., 1998; Rubin et al., 2005). Little is known about the magmatic evolution of Kamaʻehu despite its importance to our understanding of the inception of Hawaiian volcanoes (e.g., Garcia et al., 2006; Clague et al., 2019) and the nature of compositional heterogeneity in Earth's deep mantle (e.g., Kurz et al., 1983; Abouchami et al., 2005; Weis et al., 2020).

Kamaʻehu has experienced recent eruptions of compositionally diverse alkalic and tholeiitic basalts (e.g., Moore et al., 1982; Frey and Clague, 1983; Garcia et al., 1993). Radiometric dating (other than the 1996 sample) is limited to a few alkalic basalts from a 500 m section of the dissected east flank, which records a transition from dominantly alkalic to tholeiitic volcanism starting at ca. 40 ka (Garcia et al., 1995; Guillou et al., 1997). The duration of this transition is unknown. Younger tholeiitic basalts from the wall of the East Pit at the volcano's summit (Garcia et al., 1993, 2006) display a systematic fluctuation in ratios of incompatible elements (e.g., La/Yb). However, a lack of age information precludes a detailed time-series investigation of lava chemistry at Kamaʻehu analogous to those for its frequently active subaerial neighbors, Kīlauea (e.g., Pietruszka and Garcia, 1999) and Mauna Loa (e.g., Rhodes and Hart, 1995). Here, we use high-precision measurements of $^{226}$Ra-$^{230}$Th disequilibria (Pietruszka et al., 2002) in Kamaʻehu basalts to estimate model ages for recent eruptions of this volcano and reveal its magmatic evolution. Our method is analogous to previous studies that used $^{226}$Ra decay (∼1600 yr half-life) to date eruptions of Pacific mid-ocean-ridge basalts (e.g., Rubin and Macdougall, 1990; Volpe and Goldstein, 1993; Cooper et al., 2003).

## SAMPLING AND METHODS

Glassy lava samples ($n = 16$) collected by submersible from the summit platform and South Rift Zone of Kamaʻehu (Fig. 1) were analyzed for $^{226}$Ra-$^{230}$Th disequilibria, $^{87}Sr/^{86}Sr$, and trace element abundances by isotope dilution mass spectrometry (see the Supplemental Material[1] for sample information, methods, and data). The ages of the samples are unknown except for sample P286-1F, which erupted in early 1996 (Garcia et al., 1998; Rubin et al., 2005). This sample was collected near Pisces Peak, currently the shallowest area on Kamaʻehu (Garcia et al., 1998, 2006). Samples from two locations can be placed in stratigraphic context with P286-1F (Garcia et al., 1993, 1998): (1) sample 1802-22 from the rim of the West Pit near Pisces Peak, which was collected in the late 1980s near the future location of the 1996 sample, and (2) the progressively older 1801 series of samples from the wall of the East Pit, excluding a talus sample (1801-1) from the crater floor.

## RESULTS

The Kamaʻehu samples are tholeiitic ($n = 12$) to mildly alkalic ($n = 4$) basalts (Fig. 2A). The alkalic index (AI) of the alkalic basalts ranges from +0.18 to +1.3, where AI > 0 divides alkalic from tholeiitic lavas. Young Hawaiian post-shield lavas (Fig. 1) span higher AI values from +1.3 to +1.7 at Hualālai and +2.5 to +3.6 at Haleakalā. Ratios of trace elements that are more versus less incompatible

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[1]Supplemental Material. Sample information, methods, data, and supplemental videos. Please visit https://doi.org/10.1130/GEOL.S.23060699 to access the supplemental material, and contact editing@geosociety.org with any questions.

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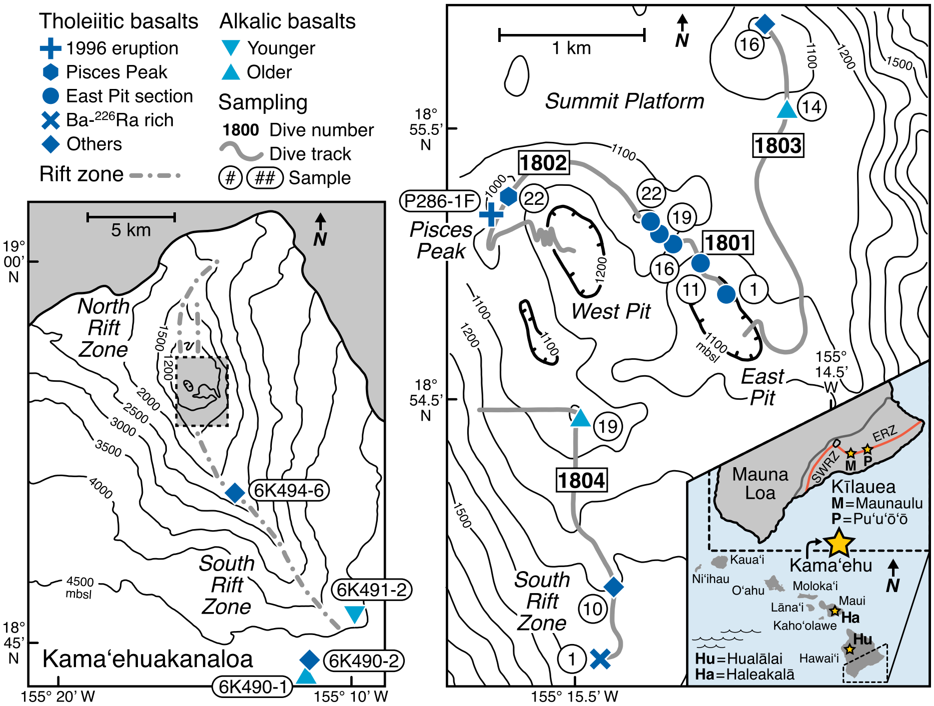


**Figure 1. Bathymetric maps of Kamaʻehuakanaloa ("Kamaʻehu"), Hawaiʻi, with sample locations, modified from Garcia et al. (1993). The location of the map on the right is shown by the dashed box in the map on the left (mbsl—meters below sea level).**

during partial melting of the mantle, such as Nd/Sm versus Th/Yb, are correlated in the Kamaʻehu basalts (Fig. 2B). These ratios tend to be higher in the alkalic basalts, but sample 6K491-2 (AI = + 0.18) is similar to the tholeiitic basalts; the tholeiitic Kamaʻehu basalts (and 6K491-2) are similar to historical Kīlauea lavas.

The $^{230}$Th-$^{238}$U disequilibria of young Hawaiian lavas correlate broadly with ratios of incompatible trace elements, such as Nd/Sm (Sims et al., 1999) or Th/Yb (Fig. 2C). In detail, Kamaʻehu basalts are not consistent with this trend for two reasons (Fig. 2D). First, at Kamaʻehu, the amount of excess $^{230}$Th in the alkalic basalts (~7.7% ± 1.4%) is only slightly larger than in the tholeiitic basalts (~6.8% ± 1.2%). The $^{230}$Th-$^{238}$U disequilibria of these samples do not correlate with Th/Yb, which varies by a factor of ~2 (Fig. 2B). Second, the tholeiitic Kamaʻehu basalts have a significantly larger amount of excess $^{230}$Th than Kīlauea lavas (~2.1% ± 1.0%), despite their nearly identical Th/Yb ratios (Fig. 2D).

Young Hawaiian lavas of known age display a bimodal distribution of $^{226}$Ra-$^{230}$Th disequilibria (Fig. 2E) (Sims et al., 1999), with a larger amount of excess $^{226}$Ra in the alkalic lavas from Hualālai and Haleakalā (~28% ± 10%) compared to the tholeiitic basalts from Kīlauea (~13% ± 1%). Tholeiitic basalts that erupted from Kamaʻehu in early to mid-1996 (Garcia et al., 1998; Rubin et al., 2005) have $^{226}$Ra-$^{230}$Th disequilibria similar to those of Kīlauea lavas, including sample P286-1F with ~12.6% excess $^{226}$Ra and two other samples with ~11%–12% excess $^{226}$Ra (Rubin et al., 2005). Older Kamaʻehu basalts display a large range in ($^{226}$Ra/$^{230}$Th) from 1.141 to 1.015 (Fig. 2F) at nearly constant ($^{230}$Th/$^{238}$U) (parentheses indicate activity ratios); only sample 1804-1 has a larger amount of excess $^{226}$Ra than P286-1F.

## DISCUSSION

The large range in $^{226}$Ra-$^{230}$Th disequilibria at Kamaʻehu is likely dominated by post-eruptive $^{226}$Ra decay. Alternative explanations, such as magma residence time in the crust or large changes in the ($^{226}$Ra/$^{230}$Th) ratio of the parental magma, are unlikely. At Kīlauea, for example, the duration of magma storage within the volcano's plumbing system (<20 yr; Pietruszka et al., 2018) is insignificant relative to the half-life of $^{226}$Ra. The magma residence time at Kamaʻehu is unknown. However, there is no correlation between ($^{226}$Ra/$^{230}$Th) and MgO content (Fig. 2G), as might be expected over the ~9 k.y. of magmatic differentiation and storage required to reach radioactive equilibrium from ~12%–14% excess $^{226}$Ra. Similarly, there is no correlation between ($^{226}$Ra/$^{230}$Th) and Ba/Th (Fig. 2H), a potential analog for $^{226}$Ra-$^{230}$Th disequilibria and tracer of parental magma composition. Accordingly, we use the ($^{226}$Ra/$^{230}$Th) ratio of each sample to model the time elapsed since its eruption (see the Supplemental Material).

The $^{226}$Ra model age calculations require (1) an estimate for the initial ($^{226}$Ra/$^{230}$Th) ratio, (2) a short and/or constant residence time of magma in the crust prior to eruption, and (3) a constant duration of melt transport from the mantle to the crust. We use two scenarios for the initial ($^{226}$Ra/$^{230}$Th) ratio. Ages are calculated from the decay equation (e.g., Rubin and Macdougall, 1990):

$$[(^{226}\text{Ra}/^{230}\text{Th})_t - 1] = [(^{226}\text{Ra}/^{230}\text{Th})_0 - 1] \times e^{-\lambda_{226\text{Ra}} t}, \quad (1)$$

where ($^{226}$Ra/$^{230}$Th)$_0$ is the initial activity ratio upon eruption, ($^{226}$Ra/$^{230}$Th)$_t$ is the activity ratio at the time (*t*) of analysis (i.e., the model age, $T_{Ra}$, relative to the year 2000), and $\lambda_{226Ra}$ is the decay constant.

For scenario 1 (Fig. 2H), we assume that the initial ($^{226}$Ra/$^{230}$Th) ratio for all of the Kamaʻehu basalts was identical to that of sample P286-1F from the 1996 eruption (~12.6% excess $^{226}$Ra). Evidence in support of this assumption is that (1) only one other Kamaʻehu sample (1804-1) has a larger amount of excess $^{226}$Ra (~14.1%) and (2) the average ($^{226}$Ra/$^{230}$Th) ratio of historical Kīlauea lavas erupted over ~80 yr (~12.9% excess $^{226}$Ra) is relatively constant (±1.3%) and similar to that of P286-1F. A constant, Kīlauea-like initial ($^{226}$Ra/$^{230}$Th) ratio for both the alkalic and tholeiitic Kamaʻehu basalts is supported by (1) their relatively low Th/Yb ratios and small $^{230}$Th-$^{238}$U disequilibria compared to Hualālai and Haleakalā alkalic basalts (Fig. 2C) and (2) their nearly constant $^{230}$Th-$^{238}$U disequilibria (Fig. 2D). Scenario 1 results in $T_{Ra}$ values for Kamaʻehu lavas (other than P286-1F) of ca. 8–2400 yr with one sample (1803-14) at ca. 5400 yr and another (1803-16) at >9000 yr.

For scenario 2, we assume a linear relationship between the initial ($^{226}$Ra/$^{230}$Th) and Ba/Th ratios of Kamaʻehu basalts based on the observation that sample 1804-1 has a higher ($^{226}$Ra/$^{230}$Th) and Ba/Th ratio than P286-1F. The origin of this signature is unknown, but it might be related to interaction between melt and plagioclase-rich crustal cumulates (e.g., Saal and Van Orman, 2004; Saal et al., 2007). The line that connects these samples on Figure 2H may be used to estimate the initial ($^{226}$Ra/$^{230}$Th) ratios. Scenario 2 results in $T_{Ra}$ values for Kamaʻehu lavas that are similar to those of scenario 1 within ~17–260 yr (excluding zero-age or indeterminate samples). Hereafter, we use the average $T_{Ra}$ values, assuming a zero age for indeterminate samples 1804-1 in scenario 1 and 6K494-6 in scenario 2, which have ($^{226}$Ra/$^{230}$Th) ratios that are higher than the assumed initial values.

The $T_{Ra}$ values, interpreted as eruption ages, are consistent with the geological observations (see below), including photos (Fig. 3) and videos (see Supplemental Material). A range of $T_{Ra}$ values for each sample based on the analytical uncertainty of the ($^{226}$Ra/$^{230}$Th) ratios (±0.3%) is reported in the Supplemental Material. Additional uncertainties related to the model assumptions are difficult to quantify. The difference in the amount of excess $^{226}$Ra between samples

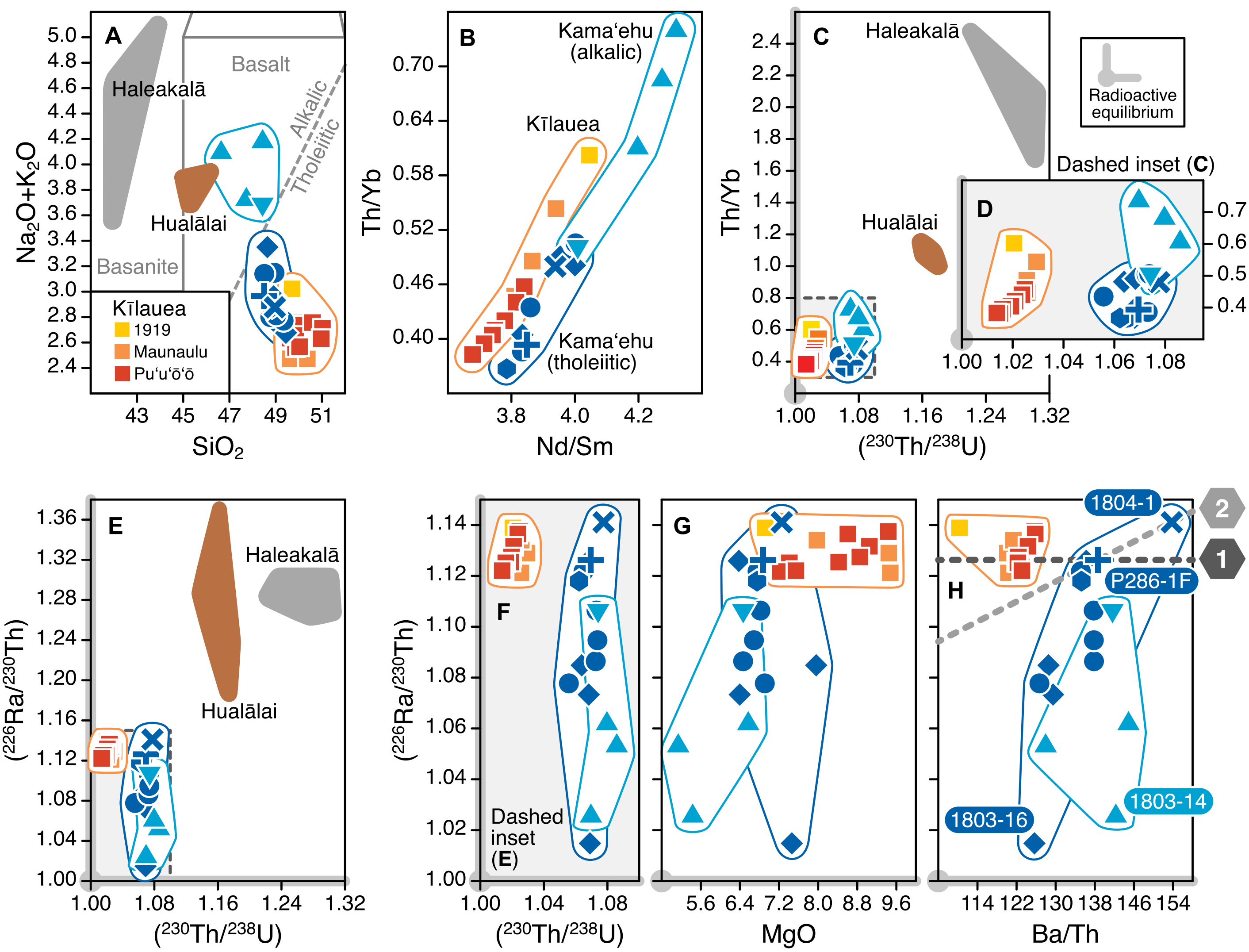


**Figure 2. Compositional variations of Kamaʻehu lavas compared to young basalts from other Hawaiian volcanoes (locations and symbol explanations are on Figure 1). Parentheses indicate activity ratios. Gray bars on axes indicate radioactive equilibrium. Plots D and F expand dashed insets in C and E, respectively. Data sources: Hualālai and Haleakalā, Sims et al. (1999); Kīlauea, Supplemental Material (see text footnote 1). Two model scenarios used for calculation of eruption ages are illustrated by dashed lines in H. Analytical errors are smaller than size of symbols.**

1804-1 and P286-1F (~1.5%) is similar to the total range observed at Kīlauea (~1.8%). By analogy, we infer that any differences in the initial ($^{226}$Ra/$^{230}$Th) ratios of Kamaʻehu basalts due to variable $^{226}$Ra decay during melt transport and storage are likely to be <2%. A ± 1% variation translates to errors of ±300 yr at $T_{Ra}$ = 600 yr and ±600–800 yr at $T_{Ra}$ = 2500 yr. Errors of this magnitude (or larger) would tend to destroy the systematic age-depth relationship and temporal variations in lava chemistry shown on Figure 4 and thus are unlikely.

The four in situ 1801 samples from the East Pit and sample 1802-22 (Pisces Peak) display a systematic age-depth relationship, with $T_{Ra}$ values from ca. 1200 yr for sample 1801-11 to ca. 58 yr for sample 1801-22 (Fig. 4A). A deeper talus sample from the floor of the East Pit (1801-1) gave a young eruption age of ca. 450 yr and likely fell from higher in the stratigraphic section. Sample 1801-22, collected from a shallow (987 meters below sea level [mbsl]) outcrop of pillow lavas with well-preserved flow textures and minor sediment, gave the second-youngest eruption age (excluding sample P286-1F). Sample 1802-22 (998 mbsl), collected near Pisces Peak, was regarded as younger than sample 1801-22 by Garcia et al. (1998). The $T_{Ra}$ value of sample 1802-22 (ca. 150 yr) lies within the uncertainty of sample 1801-22. The two oldest samples are from the eastern summit platform. Sample 1803-14 (ca. 5400 yr) was collected from a massive pillow lava that lacked most of the original flow textures. Sample 1803-16 ($T_{Ra}$ >8800 yr) was collected from a small outcrop of lava within a sediment-covered pavement; radiocarbon ages of foraminifera from nearby volcaniclastic sediments range up to ca. 5900 yr (Clague, 2009).

A young (ca. 0 yr) eruption age for sample 1804-1 (upper South Rift Zone) is consistent with the well-preserved flow textures of this nearly sediment-free outcrop of pillow lavas. Two other samples from the 1804 dive gave older eruption ages. The younger South Rift Zone sample (1804-10, ca. 970 yr) was collected from lava spatter covered with minor sediment. The older sample (1804-19, ca. 2300 yr) was collected on the summit platform from a brecciated pillow lava flow in an area of active hydrothermal venting (Karl et al., 1988) that collapsed in 1996 to form Pele's Pit (Garcia et al., 1998, 2006). Samples 6K490-1 (ca. 2300 yr), 6K490-2 (ca. 1400 yr), and 6K491-2 (ca. 510 yr) were collected from variably sediment-covered pillow lava flows on the lower South Rift Zone. Sample 6K494-6 (ca. 4 yr) from the middle South Rift Zone was collected from a glassy sheet lava flow with minor sediment. See the Supplemental Material for videos of the outcrops for the 6K samples not shown on Figure 3.

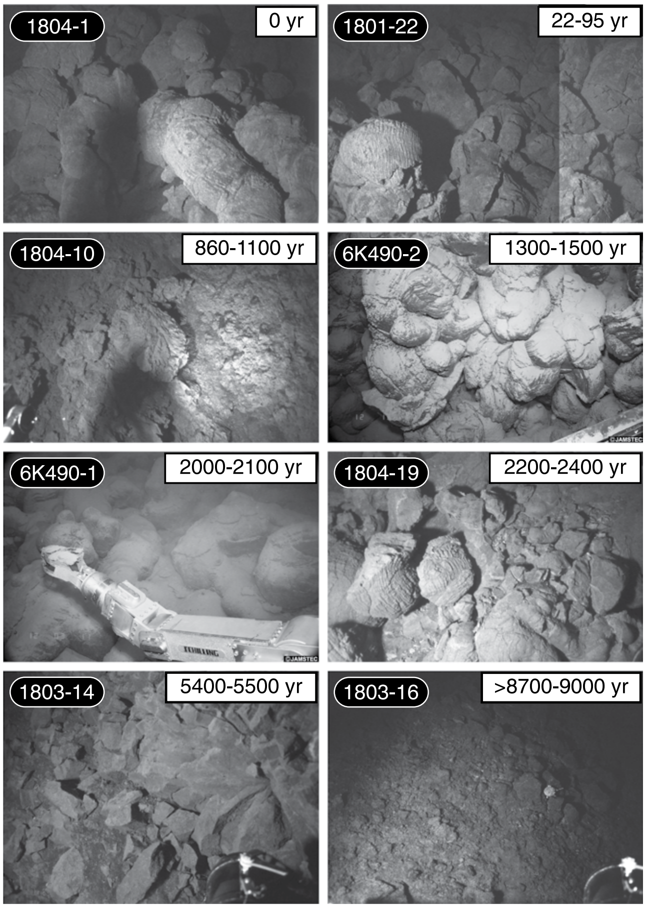


**Figure 3. Photographs of sample locations from the *Alvin* (1800 series) or *Shinkai* (6K series) submersibles with the range in average model eruption ages ($T_{Ra}$). Each image is ~2–5 m wide.**

## BROADER IMPLICATIONS

The $T_{Ra}$ values reveal that Kamaʻehu has erupted frequently on a time scale of decades to centuries, with at least five eruptions in the past ~150 yr. The four alkalic basalts decrease in AI (Fig. 4B) and Th/Yb (Fig. 4D) from ca. 5400 to 510 yr; only one mildly alkalic basalt (sample 6K491-2) erupted within the past ~1400 yr. The relatively old ages for the alkalic basalts are insensitive to their assumed initial ($^{226}Ra/^{230}Th$) ratios. For example, a ~15%–19% range of initial $^{226}Ra$ excess for the alkalic basalts from Kamaʻehu—calculated from the ($^{230}Th/^{238}U$) ratio of each sample relative to hypothetical trends between average lavas from Kīlauea and Hualālai or Haleakalā (Fig. 2E)—translates to slightly older ages of ca. 6400 to 1200 yr. In either case, the long-term transition from alkalic to tholeiitic volcanism at Kamaʻehu (Garcia et al., 1995) was nearly complete by ca. 2 ka. Tholeiitic Kamaʻehu basalts from the summit platform display a systematic short-term fluctuation in Th/Yb (Fig. 4C), confirming the stratigraphic trends noted by Garcia et al. (1993, 2006). The time scale of this fluctuation is ~1200 yr, which is much longer (factor of ~6) than the ~200-yr-long historical cycle in lava chemistry at Kīlauea (Pietruszka and Garcia, 1999). Together, these observations provide the first detailed snapshot of a submarine volcano's temporal magmatic evolution over decades to centuries.

As in Iceland (Kokfelt et al., 2003), the $^{230}Th$-$^{238}U$ disequilibria of Hawaiian lavas are controlled by variations in the rate of mantle upwelling, which is thought to decrease exponentially from the central axis (as high as ~1000 cm/yr beneath Kīlauea) to the margin of the plume (e.g., Hauri et al., 1994; Sims et al., 1999; Pietruszka et al., 2001). The upwelling rate beneath Kamaʻehu is estimated from $^{230}Th$-$^{238}U$ disequilibria to be only ~5–6 cm/yr (Pietruszka et al., 2011). At this rate, the mantle would rise insignificantly (<300 m) over ~5000 yr. Thus, the variations in Th/Yb at Kamaʻehu are most likely related to changes in the pathway of melt transport from the mantle on a time scale of centuries (Fig. 4C) to millennia (Fig. 4D) and the delivery of these compositionally distinct magma batches to the volcano. This idea of melt deliveries from different mantle sources (superimposed on the melting variations that control Th/Yb) is supported by a temporal decrease in $^{87}Sr/^{86}Sr$ for the alkalic basalts (Fig. 4F) that continued without interruption for the tholeiitic basalts from the volcano's summit platform (Fig. 4E). A similar melt-transport process is inferred to occur at Kīlauea over just years to decades (Pietruszka et al., 2006). The slower pace of the temporal variations in lava chemistry at Kamaʻehu (both for Th/Yb and $^{87}Sr/^{86}Sr$) is therefore most likely controlled by sluggish mantle upwelling and a proportionally low rate of melt production beneath this pre-shield Hawaiian volcano. Our results independently confirm the idea—previously based only on $^{230}Th$-$^{238}U$ disequilibria (Pietruszka et al., 2011)—that Kamaʻehu taps slowly upwelling mantle on the margin of the Hawaiian plume.


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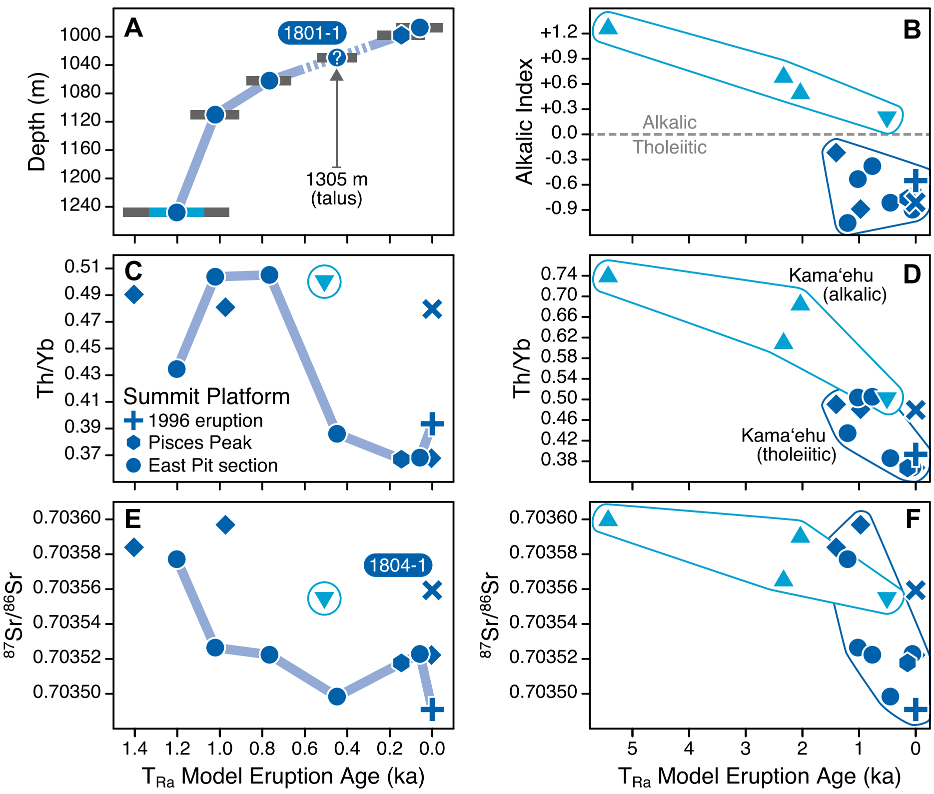


**Figure 4. Plots of model eruption ages ($T_{Ra}$) for Kama‘ehu basalts. See Figure 1 for symbol explanations. (A) Age-depth relationship for samples from summit platform and Pisces Peak. Blue bars show range in average $T_{Ra}$ values for the two model scenarios from Figure 2 (if larger than symbol size); gray bars show total range. (B–F) Temporal variations in lava chemistry at Kama‘ehu. Heavy blue lines connect samples from summit platform. Analytical errors are smaller than size of symbols.**


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