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Unspiked K–Ar dating of the Honolulu rejuvenated and Ko‘olau shield volcanism on O‘ahu, Hawai‘i

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Abstract

Many mantle plume volcanoes undergo rejuvenated volcanism after a period of construction and erosion of their shield. The cause of this renewed volcanism has been enigmatic and various models have been proposed. However, the lack of geochronological data has hindered evaluation of these models. Unspiked K–Ar ages on groundmass in 41 samples from 32 vents of Honolulu Volcanics and eight samples of underlying Ko‘olau Volcanics were determined in order to reveal the temporal distribution of rejuvenated vents and the length of the hiatus between the end of shield and start of rejuvenated volcanism. The new geochronological results show that Ko‘olau shield volcanism ended at 2.1 Ma and that rejuvenated volcanism started at 0.8 Ma, resulting in a 1.3 million year hiatus in volcanic activity. Two distinct pulses were found for Honolulu volcanism at 0.80–0.35 and ~0.1 Ma. During the first pulse, the eruption frequency increased with time and there was no spatial pattern in vent distribution, although three vents along a NNE–SSW trend produced similar compositions and may have been coeval. Volcanism apparently waned from 0.35–0.12 Ma, with only one eruption. The second pulse occurred along two rifts that trend N–S and NE–SW. Although the ages for the 10 dated flows are indistinguishable at around 0.1 Ma, lavas from the two rifts have distinct compositions: weakly alkalic vs. melilite nephelinite. The first, more widely distributed pulse of volcanism is probably related to secondary melting downstream from the Hawaiian plume stem, which may be related to lithospheric thinning. The second pulse, focused along two rifts, may be related to decompressional melting as the shield passed over the flexural arch.

Keywords: Hawaii; hotspot; mantle plume; rejuvenated volcanism; unspiked K–Ar dating

1. Introduction

Rejuvenated volcanism is common on many oceanic island chains (e.g., Hawai‘i, Samoa, Canary) but its origin remains controversial. It occurs after a hiatus in hotspot-related volcanism, normally produc-

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ing MgO-rich, alkaline to strongly alkaline lavas [1,2]. The high MgO content (>10%) of these lavas [3] and the high forsterite content of their olivines (86–89%) indicates that these magmas are relatively primitive and were erupted shortly after their formation [4]. The gap between the end of shield and start of rejuvenated volcanism provides a critical constraint for models attempting to explain rejuvenated volcanism and to understand plume dynamics [5]. The length of volcanic quiescence prior to rejuvenation was thought to range from virtually zero to several million years with no coherent pattern in the size of the gap along the Hawaiian island chain [6]. Thus, models for rejuvenated volcanism range from conductive heating of the lithosphere [7], with little or no age gap to convective mantle plume upwelling [5], to decompression melting due to lithospheric flexure [6,8], which requires a gap of several million years. However, ages for the end of shield and start of rejuvenated volcanism are poorly known for most of Hawaiian volcanoes, although new geochronological studies are changing our understanding of the duration of this gap. For example, ages of rejuvenated lavas on West Maui volcano were considered to be indistinguishable from those of underlying post-shield lavas [9]. New unspiked K–Ar age determinations in our laboratory revealed an age gap of about 0.6 m.y. between the post-shield and rejuvenated West Maui lavas [10]. In contrast, another new study found no gap longer than 0.16 m.y. nor change in composition for the volcanism on adjacent Haleakalā volcano and it was concluded that this volcano has not yet entered the rejuvenation stage [11].

The Honolulu Volcanics (HV) on the island of O‘ahu are the classic example of Hawaiian rejuvenated volcanism, with Diamond Head Crater as the outstanding landform. They were erupted from about 40 monogenetic vents on Ko‘olau shield volcano (Fig. 1) producing some extensive flows compared to the four small West Maui eruptive complexes. Although the HV is the best studied rejuvenated sequence in Hawaiian islands, with several petrological and geochemical studies [3,8,12,13], their ages were not well constrained despite several attempts [14–20]. An eruptive sequence for Honolulu vents was proposed based on sea level stands [14,15],

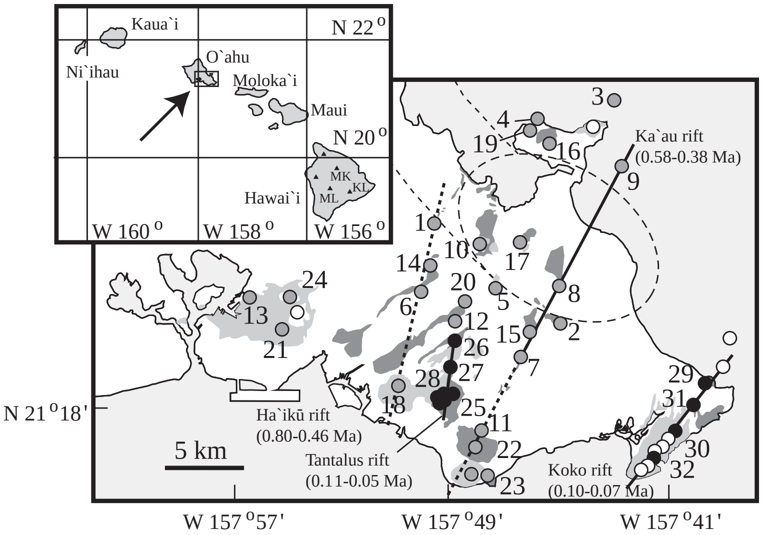

Fig. 1. Location of vents, flows and tephra from Honolulu eruptions. Dark grey—lava, light grey—pyroclastics, grey circles—vents older than 0.24 Ma; black circles—vents younger than 0.12 Ma; open circles—unknown. Broken line and dashed ovoid indicate approximate position of the north rift zone and caldera of Ko‘olau shield, respectively (based on maps of Stearns and Vaksvik [14] and Walker [48]). Dated vents in age order are: 1. Ha‘ikū, 2. Maunawili, 3. Moku Manu, 4. Pyramid Rock, 5. Pali, 6. Kamanaiki, 7. Ka‘au, 8. Training School, 9. Mōkōlea, 10. Kāne‘ohe, 11. Mau‘umae, 12. Luakaha, 13. Makalapa, 14. Kalihi, 15. ‘Ainoni, 16. Pu‘u Hawai‘iloa, 17. Castle, 18. Punchbowl, 19. Pali Kilo, 20. Makuku, 21. ‘Ākulikuli, 22. Kaimukī, 23. Black Point, 24. ‘Āliamanu, 25. Mānoa, 26. Tantalus, 27. Mō‘ili‘ili, 28. Rocky Hill, 29. Kaupō, 30. Koko, 31. Kalama, 32. Hanauma. Insert map shows the location of the study area on O‘ahu among the main Hawaiian Islands. Triangles—summit of volcanoes on the island of Hawai‘i; MK—Mauna Kea; ML—Mauna Loa; KL—Kīlauea.

which have been dated in a few cases (e.g., Szabo [16]). Unfortunately, several vents and their products are not located near the coast and do not overlap those that are near coast (Fig. 1), so the inferred ages for these vents are problematic. An alternative approach is to date the lavas or juvenile clasts from Honolulu eruptions using radioisotopic techniques. Four studies using conventional K–Ar methods on whole rocks reported a total of 26 ages from 18 vents, ranging from 33 ka to 2.0 Ma [17–20]. Some of the ages from these laboratories are significantly different for the same flow (e.g., 0.32 [20] vs. 0.03 [18] Ma for the Kaupō flow), and a few are anomalously old (e.g., 2.0 Ma), or were not reproducible. Lanphere and Dalrymple [20] concluded that extraneous argon, derived from the mantle xenoliths that are abundant in some of these lava flows, caused these problems.

K–Ar ages of Koʻolau volcanics (KV) were determined in two previous studies. McDougall [21] reported ages of 2.2–2.6 Ma from five samples collected from scattered locations, all from upper stratigraphic levels of the volcano. Doell and Dalrymple [22] reported ages of 1.8–2.6 Ma for 14 samples from 10 flows. McDougall's ages are reproducible in multiple analyses but some of the Doell and Dalrymple's ages were not reproducible and/or are stratigraphically inconsistent, especially for samples with low K_2O contents. Since they are typically highly vesicular (>20 vol.%), Hawaiian shield lavas are susceptible to K loss during low-temperature alteration. K loss can be inferred from the rock's K_2O/P_2O_5, which is typically 1.5–2.0 in unaltered Hawaiian tholeiites [23]. Frey et al. [24] reported that many of the Koʻolau lavas have K_2O/P_2O_5 ratios less than 1.0 and suggested K loss by low-temperature alteration. Although K_2O/P_2O_5 ratios for samples dated by Doell and Dalrympel are unknown, some of them have K_2O content as low as 0.1 wt.%, strongly suggesting K loss. McDougall's samples have relatively high K content and hence are likely to retain original chemical composition. Good agreement in multiple analyses of McDougall's suggests extraneous argon contamination is unlikely and hence McDougall's ages of 2.2–2.6 Ma are considered to be more reliable. Three lavas from a 630-m deep drill hole into Koʻolau volcano (KSDP) yielded $^{40}Ar/^{39}Ar$ plateau ages of 2.8–2.9 Ma. These core samples are stratigraphically deeper than the deepest subaerial surface exposure [25].

In order to clarify the temporal distribution of the Honolulu vents and determine the length of hiatus between end of shield and the start of rejuvenated volcanism, we dated 41 samples from 32 Honolulu vents and eight samples from the upper stratigraphic levels of KV in several areas by unspiked K–Ar dating method. All of the KV samples used in dating had $K_2O/P_2O_5>1.3$. The unspiked method is the preferred method for dating samples with high atmospheric contamination [26]. Mass fractionation correction procedure was applied in order to obtain accurate ages [27]. With this procedure, the initial $^{40}Ar/^{36}Ar$ is calculated from present $^{38}Ar/^{36}Ar$ assuming mass-dependent isotopic fractionation during rock formation. Since mass-dependent isotopic fractionation is observed in historical lavas in Hawaiʻi [28], this correction is essential for accurate dating especially when samples have high atmospheric contamination. Although K–Ar method cannot check existence of extraneous argon or argon loss during weathering, using fresh groundmass samples can reduce the probability of such problems.

2. Analytical procedures

About 80–100 g of rock was crushed using a stainless steel pestle and then sieved to 250–500 μm. Thin sections were checked for all of the dated samples, and most of them showed only a minor alteration in olivines. Crushed samples were cleaned with deionized water and acetone in ultra-sonic bath. Phenocrysts and xenoliths were carefully removed using a Frantz isodynamic separator to minimize extraneous ^{40}Ar. Analyses of historical lavas on the island of Hawaiʻi showed that extraneous ^{40}Ar contamination can be avoided successfully by using only groundmass material [28]. We analyzed argon isotope ratios using a VG Isotech© VG3600 mass spectrometer operated in the static mode, connected to extraction and purification lines made by Ayumi, Japan [29]. Each argon analysis used 0.75–7.48 g of sample depending on the amount of gas contained in each sample. Sensitivity of the mass spectrometer was determined by analyzing known amount of the air standard and was generally around 1.2×10^7 V/cm^3

Table 1
K–Ar dating results for the Honolulu Volcanics

Vent name	Sample name	Location		(g)	K_2O (wt.%)	^{40}Ar/^{36}Ar	^{38}Ar/^{36}Ar	^{40}Ar/^{36}Ar initial[a]	^{40}Ar[a] (10^{-8} cm^3 STP/g)	^{40}Ar[a] (%)	Age (Ma)
		Lat. (N)	Long. (W)								
Koko Rift											
Hanauma	HV02-8	21°16′24″	157°41′34″	5.99	1.06	306.1±0.8	0.1870±0.0015	295.9±4.9	0.23±0.11	3.3	0.07±0.03
Kalama	Kalama	21°17′37″	157°40′01″	6.01	0.84	302.1±0.7	0.1867±0.0015	294.9±4.9	0.21±0.14	2.4	0.08±0.05
	HV02-6	21°17′57″	157°39′52″	3.01	1.03	300.1±1.0	0.1873±0.0015	296.8±4.9	0.20±0.30	1.1	0.06±0.09
Koko	HV02-7	21°16′45″	157°41′18″	6.01	1.03	307.8±0.5	0.1854±0.0016	290.9±5.2	0.32±0.10	5.5	0.10±0.03
Kaupō	Kaupo	21°18′56″	157°39′52″	6.06	0.82	298.4±0.9	0.1850±0.00151	289.6±4.9	0.26±0.15	2.9	0.10±0.06
Tantalus Rift											
Rocky Hill	Rocky Hill	21°18′20″	157°49′17″	1.50	1.81	304.3±0.9	0.1885±0.0015	300.4±5.0	0.34±0.43	1.3	0.06±0.07
"	RHP	21°18′12″	157°49′53″	1.50	1.65	302.5±1.8	0.1885±0.0016	300.2±5.1	0.24±0.55	0.8	0.04±0.10
Mō‘ili‘ili	MQ3	21°17′55″	157°49′10″	3.01	1.29	304.4±1.2	0.1877±0.0015	297.8±4.9	0.36±0.28	2.2	0.09±0.07
"	HV02-17	21°17′54″	157°49′04″	2.28	1.52	300.7±1.3	0.1870±0.0016	295.7±5.1	0.42±0.44	1.7	0.09±0.09
Tantalus	PF-2	21°20′38″	157°48′50″	1.50	1.71	296.6±0.9	0.1865±0.0015	294.3±4.9	0.45±0.96	0.8	0.08±0.17
"	HV02-19	21°20′05″	157°48′50″	3.01	1.38	306.2±1.5	0.1871±0.0015	296.0±4.9	0.49±0.25	3.3	0.11±0.06
Mānoa	HV03-2	21°18′37″	157°48′56″	0.75	1.80	299.7±1.0	0.1871±0.0011	296.2±3.7	1.18±1.28	1.2	0.20±0.22
"	"			0.75	1.80	299.0±0.6	0.1877±0.0008	297.9±2.6	0.39±0.94	0.4	0.07±0.16
										w.m.	0.11±0.13
Ka‘au Rift											
Training School	HV02-1	21°23′29″	157°44′57″	3.01	1.40	332.7±1.7	0.1893±0.0015	302.8±5.0	2.64±0.46	9.0	0.58±0.10
Mōkōlea	MKL	21°26′04″	157°43′22″	1.52	1.33	325.8±1.3	0.1867±0.0015	294.9±4.9	2.47±0.41	9.5	0.58±0.09
Ka‘au	KAS	21°19′40″	157°46′39″	1.50	1.34	319.2±1.5	0.1863±0.0015	293.7±4.9	2.52±0.50	8.0	0.58±0.12
Other vents											
‘Āliamanu	OH-9	21°21′43″	157°54′32″	3.00	1.33	329.6±2.2	0.1875±0.0015	297.4±4.9	1.07±0.18	9.7	0.25±0.04
Black point	BP-F1	21°15′35″	157°47′41″	6.02	1.01	344.7±0.9	0.1871±0.0015	296.1±4.9	1.29±0.13	14.1	0.40±0.04

"	"			6.02	1.01	342.3±2.2	0.1872±0.0015	296.3±4.9	1.25±0.14	13.4	0.38±0.05
										w.m.	0.39±0.03
"	BP-D2	21°15′34″	157°47′53	6.01	0.99	334.9±1.0	0.1867±0.0015	295.0±4.9	1.15±0.14	11.9	0.36±0.05
"	"			6.00	0.99	334.6±2.4	0.1876±0.0015	297.7±4.9	1.06±0.15	11.0	0.33±0.05
										w.m.	0.35±0.03
Kaimukī	HV02-15	21°17′08″	157°48′32″	4.50	0.56	311.5±1.8	0.1861±0.0016	293.1±5.2	0.69±0.21	5.9	0.38±0.11
‘Ākulikuli	OH-8	21°21′03″	157°55′00″	1.50	1.63	320.3±2.4	0.1846±0.0016	288.4±5.4	2.07±0.38	10.0	0.39±0.07
Makuku	Makuku	21°20′32″	157°50′55″	6.04	1.04	354.0±1.0	0.1853±0.0015	290.7±4.9	1.32±0.11	17.6	0.40±0.03
Pali Kilo	HV02-13	21°27′35″	157°46′16″	6.01	0.97	346.5±1.6	0.1864±0.0015	294.0±5.0	1.25±0.12	15.1	0.40±0.04
Punchbowl	PB-SG	21°19′14″	157°50′58″	6.00	1.25	350.6±1.1	0.1872±0.0015	296.3±4.9	1.56±0.15	15.5	0.39±0.04
"	X-208	21°18′41″	157°51′12″	4.50	1.14	358.1±2.2	0.1867±0.0015	294.9±4.9	1.58±0.13	17.6	0.43±0.04
Castle	HV02-2	21°24′00″	157°46′09″	4.51	0.80	337.1±1.3	0.1876±0.0015	297.7±4.9	1.07±0.14	11.7	0.41±0.05
‘Ainoni	’Ainoni	21°21′14″	157°45′40″	6.02	1.07	368.4±0.8	0.1854±0.0015	291.0±4.9	1.53±0.10	21.0	0.44±0.03
Pu‘u Hawai‘iloa	PUH-B	21°27′28″	157°45′42″	3.76	0.98	320.7±1.3	0.1869±0.0015	295.6±4.9	1.34±0.27	7.8	0.42±0.09
" "	HV02-14	21°27′33″	157°45′31″	1.52	1.13	311.1±1.4	0.1867±0.0015	295.0±4.9	1.63±0.52	5.2	0.45±0.14
Kalihi	KOK	21°20′33″	157°52′39″	3.01	1.01	334.6±1.6	0.1884±0.0016	299.9±5.2	1.50±0.23	10.4	0.46±0.07
Makalapa	OH-6	21°21′50″	157°55′54″	3.00	1.01	342.8±2.8	0.1868±0.0015	295.1±5.9	1.54±0.21	13.9	0.47±0.06
Luakaha	NuuanuKH	21°19′30″	157°51′34″	6.01	1.07	368.0±1.1	0.1863±0.0015	293.8±4.9	1.63±0.11	20.2	0.47±0.03
Mau‘umae	HV02-16	21°17′20″	157°48′05″	6.81	1.04	354.6±0.9	0.1843±0.0015	287.6±4.9	1.63±0.12	18.9	0.48±0.04
Kāne‘ohe	HV02-20	21°23′51″	157°47′46″	3.02	0.90	333.7±2.0	0.1865±0.0020	294.1±6.5	1.44±0.25	11.8	0.50±0.09
Kamanaiki	HV03-1	21°21′36″	157°50′26″	7.48	1.22	468.9±1.9	0.1841±0.0015	287.0±4.9	2.31±0.07	38.8	0.59±0.02
Pyramid Rock	HV02-12	21°27′56″	157°46′00″	4.51	0.92	330.2±2.0	0.1860±0.0015	292.9±4.9	2.03±0.28	11.3	0.68±0.10
Moku Manu	MKMN	21°28′22″	157°43′28″	1.51	1.30	339.5±1.7	0.1868±0.0015	295.1±4.9	2.93±0.34	13.1	0.70±0.08
Pali	HV02-4B	21°22′27″	157°47′29″	4.52	1.23	382.0±1.1	0.1867±0.0015	295.0±4.9	2.39±0.14	22.8	0.60±0.04
"	HV02-4A	21°22′27″	157°47′29″	4.53	0.84	354.7±0.8	0.1854±0.0015	290.8±4.9	1.73±0.14	18.0	0.64±0.05
Maunawili	MNW	21°21′14″	157°45′40″	4.50	1.35	408.1±1.7	0.1865±0.0020	294.2±6.7	3.38±0.21	27.9	0.78±0.05
"	HV02-5	21°21′14″	157°45′40″	6.76	0.99	465.5±1.1	0.1863±0.0015	293.6±4.9	2.52±0.08	36.9	0.79±0.03
Ha‘ikū	HV02-3	21°25′51″	157°48′27″	3.01	1.25	356.9±2.2	0.1871±0.0016	296.1±5.3	3.22±0.30	17.0	0.80±0.08

Errors are given in 2σ.

w.m.: weighted mean ages. Weighting by inverse variance.

[a] ^{40}Ar/^{36}Ar initial: initial ^{40}Ar/^{36}Ar calculated from ^{38}Ar/^{36}Ar assuming mass fractionation.

STP. Mass discrimination in the mass spectrometer was corrected assuming $^{40}Ar/^{36}Ar$ and $^{38}Ar/^{36}Ar$ of the air standard to be 295.5 and 0.1869, respectively. Air standard was analyzed every two to three samples each day and hot blank was measured every five to ten samples. SORI93 biotite [30] was used for calibration of the air standard. Blank level was less than 1.7×10^{-8} cm^3 STP for mass 40. Blank correction was made only when isotopic composition of the blank was significantly different from the air standard. No peak drift was observed during analyses. Errors for ^{40}Ar, $^{40}Ar/^{36}Ar$ and $^{38}Ar/^{36}Ar$ were estimated from multiple analyses of the air standard, and were 2.0%, 0.2–0.4% and 0.4–0.8%, respectively. For measurement of potassium content, a flame emission spectrometer Asahi Rika FP-33D was used in a peak integration mode with a lithium internal standard [31]. Analytical error for potassium measurement is 2%, estimated from standard deviation of multiple analyses of standard JB3 and JA2 [32]. Decay constants for electron capture and â. decay are 0.581×10^{-10}/year and 4.962×10^{-10}/year, respectively [33]. All of the analyses were carried out at Kyoto University geochronological laboratory. Analytical results for standard samples Bern4B, Bern4M and FC3 biotite at this laboratory were 17.1±0.6, 17.6±0.6 and 28.5±0.4 Ma (all of three are inverse variance weighted mean ages for two analyses) respectively, and are consistent with reference values (Bern4B: 17.3±0.4, Bern4M: 18.6±0.8 [34] and 27.9±0.7 Ma [35]).

3. Results

3.1. Honolulu

Most of the samples in this study were collected from the massive interior of lava flows. The exceptions include two near-surface (<100 m) dikes, samples BP-D2 and X-208, and two juvenile lava bombs from tuff deposits, samples OH-8 and OH-9. We were unable to collect datable samples from some Honolulu vents that produced only finer grained tephra (e.g., Diamond Head). Duplicate analyses of argon isotopic ratios for samples BP-F1, BP-D2 and HV03-2 replicated well within analytical errors (Table 1). Thus, weighted mean ages of these analyses are used hereafter. We analyzed two samples each from the Maunawili, Pali, Pu‘u Hawai‘iloa, Kalama, Tantalus and Mō‘ili‘ili flows, a flow and dike from the Black Point and Punchbowl vents, and two of the four Rocky Hill vents on the Punahou and Mid-Pacific school campuses. All of the seven pairs of ages agree within 2σ error (Table 1). Consistent results for each pair of the samples imply that extraneous argon was effectively removed from these samples and did not compromise the ages obtained. Two samples collected from Tantalus (PF-2 and HV02-19) yielded concordant ages of 0.08±0.17 and 0.11±0.06 Ma, respectively. Their ages uncorrected for mass fractionation are 0.04±0.03 and 0.12±0.02 Ma, respectively, and are clearly inconsistent. The results for the Tantalus samples imply that correction for mass fractionation is necessary for samples with high atmospheric contamination.

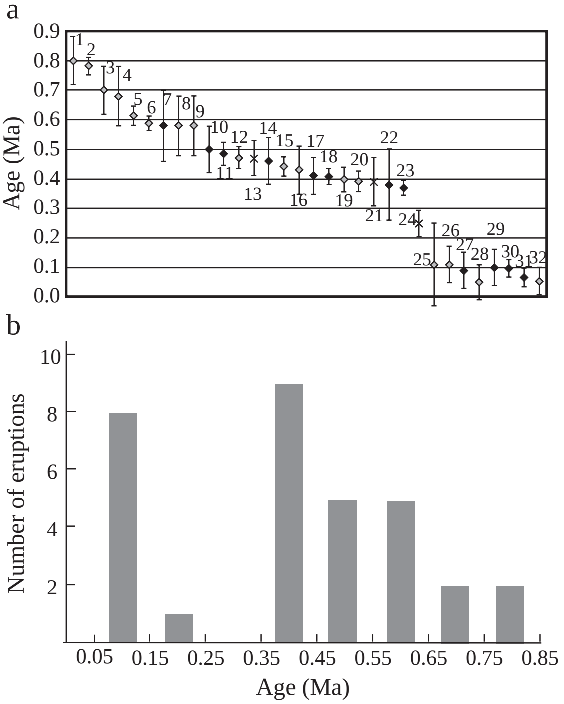

Fig. 2. (a) Unspiked K–Ar ages for Honolulu Volcanics. Symbols: Diamonds, lavas; crosses, juvenile bombs. Black diamonds are for vents with normal polarity [36] and grey diamonds are for those with unknown polarity. Only the weighted mean age is shown for samples with duplicate analyses. (b) Histogram of new K–Ar ages with number of dated eruptions per 100,000 years. Note the two distinct peaks of volcanism at about 0.4 and 0.1 Ma.

The 41 new ages for samples from 32 Honolulu vents range from 0.80±0.08 to 0.04±0.10 Ma (Fig. 2a; Table 1). This age range and many of the individual ages are generally consistent with some of the previously reported K–Ar ages (when the anomalously old samples are excluded) and with results from a new paleomagnetic polarity study of 17 HV lava flows, which found normal polarity (<0.78 Ma; Fig. 2a) for all samples [36]. The oldest of our dated flows, Haʻikū, was not included in the magnetic polarity study. However, the new ages are inconsistent with the eruption sequence inferred from sea stands except for the younger samples from Koko and Tantalus rifts [14,15]. The age of Diamond Head, the classic example of rejuvenated volcanism, can be constrained from stratigraphic relationships with newly dated flows. Diamond Head's tuff overlies the Mauʻumae lava flow (dated at 0.48±0.04 Ma) and is partly covered by Kaimukī and Black Point lava flows [15] (0.38±0.11 and 0.37±0.02 Ma). Hence, the age of Diamond Head is constrained to be 0.52 to 0.35 Ma.

3.2. *Koʻolau*

Unspiked K–Ar ages for eight KV samples range 2.39±0.09–3.19±0.24 Ma (Table 2). Samples ET-2 and W-11 were taken from drill core obtained at Wheeler Air Force Base in central Oʻahu. Their depths are about 55 and 90 m, respectively. Laj et al. [37] obtained unspiked K–Ar ages of 2.11±0.03 and 2.10±0.04 Ma for two samples from deeper in this core (~125 and ~165 m). Our results are 2.41±0.26 and 2.40±0.44 Ma for ET-2 and W-11, respectively. Although the age of W-11 overlaps with those obtained by Laj et al. [37] within analytical errors, the age of ET-2 is younger than those of Laj et al. [37] slightly beyond analytical errors. Whether our ages are overestimation or those of Laj et al. [37] are underestimation, the age of this core can be as young as 2.1 Ma.

Four KV samples are from Kamehame Ridge near Makapuʻu Point and were previously described by Frey et al. [24]. The ages for the three lavas are consistent with their stratigraphic order (3.19±0.24, 3.10±0.22, and 3.06±0.20 Ma) and a dike that cuts this section, KOO55, has a younger age (2.42±0.11 Ma). Sample HV02-11, from nearby Makapuʻu Point, gave a younger age than the Kamehame Ridge samples, 2.39±0.11 Ma, which is inconsistent with the previously inferred stratigraphy [24]. Also, ages >2.9 Ma for surface lavas seem too old compared to the KSDP core samples, which are thought to be from deeper within Koʻolau volcano [25]. Re-examination of the Kamehame lavas revealed that they contain cryptocrystalline groundmass, which may have retained extraneous argon and yielded older ages. In contrast, the dike sample (KOO-55) has a holocrystalline matrix. Thus, the new KV ages that we consider most reliable are ~2.4–2.6 Ma. Combining our results with the most reliable previous ages, we estimate the end of Koʻolau volcanism at ~2.1 Ma.

Table 2
K–Ar dating results for the Koʻolau Volcanics

Area	Sample name	(g)	K_2O (wt.%)	$^{40}Ar/^{36}Ar$	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$ initial[a]	$^{40}Ar^a$ (10^{-8} cm^3 STP/g)	$^{40}Ar^a$ (%)	K_2O/P_2O_5	Age (Ma)
Wheeler AFB	ET-2	1.50	0.62	342.0±1.4	0.1857±0.0015	291.9±5.0	4.80±0.50	14.7	2.17	2.41±0.26
"	W-11	0.95	0.62	309.8±0.7	0.1860±0.0011	292.9±3.4	5.15±1.09	5.5	1.85	2.56±0.54
		0.75	0.62	310.1±1.2	0.1871±0.0015	296.2±4.9	4.17±1.53	4.5		2.07±0.76
									w.m.	2.40±0.44
Kamanaiki	HV02-18A	1.50	0.39	326.6±1.7	0.1854±0.0015	291.0±4.9	3.26±0.47	10.9	1.31	2.57±0.38
Kamehame	KOO55	4.50	0.68	480.8±1.9	0.1858±0.0017	292.1±5.5	5.30±0.18	39.2	2.03	2.42±0.11
"	KOO49	1.50	0.67	368.0±1.5	0.1844±0.0015	288.0±4.9	6.59±0.42	21.7	1.64	3.06±0.22
"	KOO53	3.00	0.36	372.7±1.5	0.1845±0.0018	288.3±5.8	3.55±0.25	22.7	1.37	3.10±0.24
"	KOO51	2.25	0.56	356.7±1.4	0.1845±0.0015	288.2±4.9	5.77±0.43	19.2	1.66	3.19±0.25
Makapuʻu	HV02-11	4.52	0.61	463.3±2.5	0.1870±0.0015	295.9±5.1	4.72±0.17	36.1	2.17	2.39±0.12

Errors are given in 2σ.

w.m.: weighted mean ages. Weighting by inverse variance.

[a] $^{40}Ar/^{36}Ar$ initial: initial $^{40}Ar/^{36}Ar$ calculated from $^{38}Ar/^{36}Ar$ assuming mass fractionation.

4. Discussion

4.1. Age gap in Hawaiian volcanism

The duration of the gap between shield and rejuvenated volcanism has major implications for our understanding of plume dynamics. The gap between shield and rejuvenated volcanism for O‘ahu is about 1.3 m.y. This is substantially longer than shorter gap reported for Kaua‘i (~0.25 m.y.) [38], another Hawaiian island with extensive rejuvenated volcanism. However, this narrow age gap in Kaua’i volcanism is based on a single conventional K–Ar date for an alkalic basalt. There is ~1.1 m.y. between this sample and the next oldest age for a Kaua‘i rejuvenated lava [38]. If the older sample is actually part of the postshield stage, which is consistent with its composition, the gap for Kaua‘i is 1.1 m.y. This is comparable to the hiatus of O‘ahu, but both gaps are smaller than the reported 2.0 m.y. gap for Ni‘ihau, an older shield volcano located adjacent to Kaua‘i (Fig. 3). In contrast, the gaps for the two younger Hawaiian volcanoes with only small volumes of rejuvenated lavas are somewhat shorter (0.8 and 0.6 m.y.; Fig. 3). Two important points can be made from current information. There is no consistent duration for the gap between the end of shield volcanism and the start of rejuvenated volcanism for the Hawaiian Islands. Likewise, the duration of the gap does not consistently increase or decrease away from Kīlauea (Fig. 3). Second, rejuvenated volcanism was simultaneous active at ~0.5 Ma from Maui to Ni‘ihau, a distance of about 400 km.

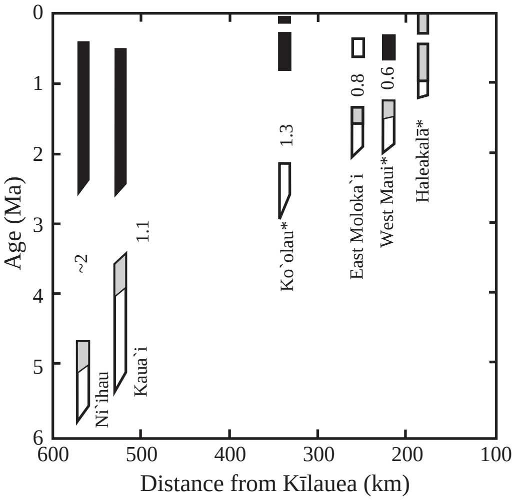

Fig. 3. Age ranges for shield (white), postshield (grey) and rejuvenated (black) stages for volcanoes plotted against distance from Kīlauea volcano. Duration of gaps in volcanism listed in millions of years. Volcanoes with asterisks are those redated after 2000. Modified after Clague and Dalrymple [6], and Tagami et al. [10].

4.2. Honolulu rejuvenated volcanism

The new unspiked K–Ar ages allow us to delineate the history of Honolulu rejuvenated volcanism. The most striking feature is the evidence for two pulses of rejuvenated volcanism (0.80–0.25 with a peak at 0.4 Ma and <0.12 Ma; Fig. 2b). During the first pulse, the frequency of dated eruptions gradually increased from two per 100,000 years to nine per 100,000 years at around 0.4 Ma. Previous workers [14,15] had aligned many of these vents into numerous rifts (up to 10), despite their geochemical differences. The orientation of these hypothetical vents are not parallel to structures in the Pacific Plate. Rather, they are roughly perpendicular to the direction of the Hawaiian islands. Ages for the three vents along the so-called Ha’ikū rift range from 0.46 to 0.80 Ma (Table 1) for lavas that range in composition from nephelinite to melilite nephelinite [3]. Ages for the six dated vents along the Ka‘au rift range from 0.38 to 0.58 Ma (Table 1) for lavas that range in composition from alkali olivine basalt to melilite nephelinite [3]. However, three of the vents (Mōkōlea, Ka‘au and Training School) have the same age (0.58 Ma; Table 1) and composition (melilite nephelinite; [3]). Perhaps these vents were part of an eruptive sequence that formed a 13 km-long rift (Fig. 1). Eruptive activity markedly waned from 0.34 to 0.12 Ma, with only one dated eruption (‘Āliamanu, 0.25±0.04 Ma).

Volcanism surged again with numerous eruptions along two, north and northwest trending rifts (Fig. 1). Ages within the second pulse (0.11–0.04 Ma) are indistinguishable within analytical errors (Table 1), although the lavas from these two rifts, Koko and Tantalus, are geochemically distinct (alkalic

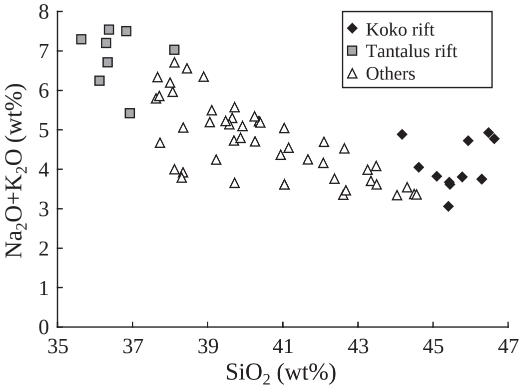

Fig. 4. Total alkalis vs. silica diagram for Honolulu Volcanics. Samples older than 0.24 Ma have intermediate compositions, whereas those younger than 0.12 Ma define the two SiO_2 end-members. Lava compositions from Clague and Frey [3].

basalts vs. melilite nephelinites [3]) and are end-members for HV (Fig. 4). The five dated vents along the Tantalus rift, including the Mānoa vent, which is commonly ignored on lists of Honolulu vents [3], gave ages of 0.04–0.11 Ma. All of these vents produced melilite nephelinite composition volcanics [3] (Garcia, unpublished data) and were probably part of the same eruptive sequence. Three other vents were thought to be part of the Tantalus rift (Kāne‘ohe, Makuku and Luakaha) [15]. Samples from two of these vents were analyzed and gave much older ages (0.47 and 0.50 Ma; Table 1), clearly predating the rest of the volcanism along the Tantalus rift.

Lavas from four of the seven major vents along the Koko rift yielded ages of 0.07–0.10 Ma (Table 1). These lavas all have weakly alkalic compositions (Fig. 4) and have been interpreted by all previous studies as part of the same eruptive sequence (e.g., [14,15]). The relative age of volcanism for the Koko and Tantalus rifts cannot be determined from our new ages or from field relationships because the deposits from these vents do not overlap. Three $^{40}Ar/^{39}Ar$ ages of 0.14±0.10, 0.14±0.06 and 0.06±0.05 Ma were obtained from submarine extention of this rift in recent study [39]. They are also indistinguishable within analytical errors from our results, consistent with the suggestion of coeval eruptions along the rift [14,15].

4.3. *Origin of Honolulu volcanism*

Numerous mechanisms have been proposed to explain mantle plume-related rejuvenated volcanism. These mechanisms include: decompressional melting following a giant landslide [40], lithospheric melting by conductive heating [7], convective mantle upwelling 300–500 km downstream of plume center [5], eustatic sea level change [41], and decompressional melting from uplift of the volcano as it passes over flexural arch created by rapid loading of the lithosphere over the mantle plume [7,8]. Since there is no evidence of a major Ko‘olau landslide within the last 1 Ma [42], this is an unlikely cause for either pulse of volcanism. Conductive heating of lower lithosphere does not explain a 1.3 m.y. gap in volcanism (Fig. 3). Numerical modelling by Ribe and Christensen [5] predicts that convective mantle upwelling may create alkalic melts 300–500 km downstream of the vertical mantle plume stem. At 0.8 Ma, when Honolulu volcanism started, the plume stem was about 300 km away from southeastern O‘ahu, under the active Mauna Kea volcano. Thus, the timing predicted for secondary plume melting zone coincides with onset of Honolulu volcanism. A new study by Li et al. [43] revealed that thickness of the lithosphere decreases from 100–110 km beneath the island of Hawai’i to 50–60 km beneath the island of Kaua‘i. This lithospheric thinning may be related to the secondary melting zone.

There appears to be no consistent correlation between the numerous Pleistocene sea level changes and Honolulu volcanism. However, the second pulse of volcanism did occur following the most recent high stand of the sea (~0.114 Ma; Szabo et al. [16]). In detail, the sea level record for O‘ahu is out of phase with the global marine record. Sea level rose 6000 years earlier and fell 5000 years later on O‘ahu [16] and the height of the change was up to 4.5 m greater than observed in tectonically stable areas [44]. This departure from the marine record led to the proposal that lithospheric flexure related to the subsidence over the Hawaiian plume caused uplift of O‘ahu [44,45]. If the radius of the flexural arch is ~300 km [46] and the center of the arch is between Mauna Kea and Mauna Loa, the arch should have been uplifting southeastern O‘ahu at 0.05–0.15 Ma, consistent with the age of the second pulse of Honolulu volcanism. The north to northeast trend of Tantalus and Koko rifts of the second pulse is nearly parallel to that of the flexural arch, which is consistent with a stress field created by the arch as the Pacific plate drifts northwestward. Vents for the North Arch volcanic field north of Oʻahu also lie along and parallel to the crest of the Hawaiian Arch [47].

5. Conclusions

K–Ar dating of Koʻolau Volcanics and Honolulu Volcanics from the island of Oʻahu has led to the following interpretations: (1) Koʻolau volcanism ended at ~2.1 Ma; (2) Honolulu volcanism started at ~0.80 Ma and consisted of two pulses at 0.80–0.35 Ma and ~0.1 Ma; (3) Many of the vents along three of the previously identified HV rifts have different ages (and compositions), and therefore are unrelated. However, three of the Kaʻau rift vents have similar ages and compositions, and maybe coeval. Vents along Koko and Tantalus rifts produced lavas with indistinguishable ages (~0.1 Ma). (4) The most plausible mechanism for the first pulse of Honolulu volcanism is secondary melting downstream of the mantle plume stem, which may be related to lithospheric thinning under Oʻahu. (5) The second pulse of Honolulu volcanism follows flexural uplift of the island of Oʻahu and the most recent high stand of sea level. The trends of Tantalus and Koko rifts are nearly parallel to the trend of the flexural arch under the island, as are fissures that produced the North Arch volcanic field, which is consistent with a stress field created by the Hawaiian flexural arch.

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References

[1] J.H. Natland, The progression of volcanism in the Samoan linear volcanic chain, Am. J. Sci. 280A (1980) 709–735.

[2] H.U. Schmincke, M. Sumita, Volcanic evolution of Gran Canaria reconstructed from apron sediments: synthesis of VICAP project drilling, Proc. of the Ocean Drilling Program, Scientific Results, vol. 157, 1998, pp. 443–469.

[3] D.A. Clague, F.A. Frey, Petrology and trace element geochemistry of the Honolulu Volcanics, Oahu: implications for the oceanic mantle below Hawaii, J. Petrol. 23 (1982) 447–504.

[4] S. Maaloe, D. James, P. Smedley, S. Peterson, L.B. Garmann, The Koloa volcanic suite of Kauai, Hawaii, J. Petrol. 33 (1992) 1–24.

[5] N.M. Ribe, U.R. Christensen, The dynamical origin of Hawaiian volcanism, Earth Planet. Sci. Lett. 171 (1999) 517–531.

[6] D.A. Clague, G.B. Dalrymple, The Hawaiian-Emperor volcanic chain, in: R.W. Decker, T.L. Wright, P.H. Stauffer (Eds.), Volcanism in Hawaii, Vol. 1, USGS Professional Paper 1350, USGS, Reston, 1987, pp. 5–54.

[7] P. Gurriet, A thermal model for the origin of post-erosional alkalic lava, Hawaii, Earth Planet. Sci. Lett. 82 (1987) 153–158.

[8] E.D. Jackson, T.L. Wright, Xenoliths in the Honolulu volcanic series, Hawaii, J. Petrol. 11 (1970) 405–430.

[9] J.J. Naughton, G.A. Macdonald, V.A. Greenberg, Some additional potassium–argon ages of Hawaiian rocks: the Maui volcanic complex of Molokai, Maui, Lanai and Kahoolawe, J. Volcanol. Geotherm. Res. 7 (1980) 339–355.

[10] T. Tagami, Y. Nishimitsu, D.R. Sherrod, Rejuvenated-stage volcanism after 0.6-m.y. quiescence at West Maui volcano, Hawaii: new evidence from K–Ar ages and chemistry of Lahaina Volcanics, J. Volcanol. Geotherm. Res. 120 (2003) 207–214.

[11] D.R. Sherrod, Y. Nishimitsu, T. Tagami, New K–Ar ages and the geologic evidence against rejuvenated-stage volcanism at Haleakala, East Maui, a postshield-stage volcano of the Hawaiian island chain, Geol. Soc. Amer. Bull. 115 (2003) 683–694.

[12] J.C. Lassiter, E.H. Hauri, P.W. Reiners, M.O. Garcia, Generation of Hawaiian post-erosional lavas by melting of a mixed lherzolite/pyroxenite source, Earth Planet. Sci. Lett. 178 (2000) 269–284.

[13] H.-J. Yang, F.A. Frey, D.A. Clague, Constraints on the source components of lavas forming the Hawaiian North Arch and Honolulu volcanics, J. Petrol. 44 (2003) 603–627.

[14] H.T. Stearns, K.N. Vaksvik, Geology and ground-water resources of the island of Oahu, Hawaii, Bull. Hawaii Div. Hydrogr. 1 (1935) 1–479.

[15] H. Winchell, Honolulu Series, Oahu, Hawaii, Geol. Soc. Amer. Bull. 58 (1947) 1–48.

[16] B.J. Szabo, K.R. Ludwig, D.R. Muhs, K.R. Simmons, Thorium-230 ages of corals and duration of the last interglacial sea-level high stand on Oahu, Hawaii, Science 266 (1994) 93–96.

[17] J.G. Funkhouser, I.L. Barnes, J.J. Naughton, The determination of a series of ages of Hawaiian volcanoes by the potassium–argon method, Pac. Sci. 22 (1968) 369 – 372.

[18] J.W. Gramlich, V.A. Lewis, J.J. Naughton, Potassium–argon dating of Holocene basalts of the Honolulu Volcanic Series, Geol. Soc. Amer. Bull. 82 (1971) 1399 – 1404.

[19] H.T. Stearns, G.B. Dalrymple, The K–Ar age of the Black Point dike on Oahu, Hawaii, and its relation to the Yarmouth interglaciation, B.P., Bishop Mus. Occas. Pap. 24 (1978) 307 – 313.

[20] M.A. Lanphere, G.B. Dalrymple, Age and strontium isotopic composition of the Honolulu volcanic series, Oahu, Hawaii, Am. J. Sci. 280A (1980) 736 – 751.

[21] I. McDougall, Potassium–argon ages from lavas of the Hawaiian Islands, Geol. Soc. Amer. Bull. 75 (1964) 107 – 128.

[22] R.R. Doell, G.B. Dalrymple, Potassium–argon ages and paleomagnetism of the Waianae and Koolau volcanic series, Oahu, Hawaii, Geol. Soc. Amer. Bull. 84 (1973) 1217 – 1242.

[23] T.L. Wright, Chemistry of Kilauea and Mauna Loa Lava in Space and Time, USGS, Washington, 1971, 40 pp.

[24] F.A. Frey, M.O. Garcia, M.F. Roden, Geochemical characteristics of Koolau Volcano: implications of intershield geochemical differences among Hawaiian volcanoes, Geochim. Cosmochim. Acta 58 (1994) 1441 – 1462.

[25] E.H. Haskins, M.O. Garcia, Scientific drilling reveals geochemical heterogeneity within the Ko'olau shield, Hawai'i, Contrib. Mineral. Petrol. 147 (2004) 162 – 188.

[26] A. Matsumoto, K. Uto, K. Shibata, K–Ar dating by peak comparison method—New technique applicable to rocks younger than 0.5 Ma-, Bull. Geol. Surv. Jpn. 40 (1989) 565 – 579.

[27] A. Matsumoto, T. Kobayashi, K–Ar age determination of late Quaternary volcanic rocks using the “mass fractionation correction procedure”: application to the Younger Ontake Volcano, central Japan, Chem. Geol. 125 (1995) 123 – 135.

[28] A. Ozawa, T. Tagami, H. Kamata, Argon isotopic composition of historical lavas of Hawaii, Abstracts of the 13th annual V.M. Goldschmidt conference, 2003, p. 369.

[29] M. Sudo, T. Tagami, K. Sato, N. Hasebe, S. Nishimura, Calibration of a new Ar analytical system for the K–Ar dating method and analytical results of K–Ar age known samples, Mem. Fac. Sci., Kyoto Univ., Ser. Geol. Mineral. 58 (1996) 21 – 40.

[30] M. Sudo, K. Uto, K. Anno, O. Ishizuka, S. Uchiumi, SORI93 biotite: a new mineral standard for K–Ar dating, Geochem. J. 32 (1998) 49 – 58.

[31] A. Matsumoto, Improvement for determination of potassium in K–Ar dating, Bull. Geol. Surv. Jpn. 40 (1989) 65 – 70 (in Japanese with English abstract).

[32] S. Terashima, N. Imai, S. Itoh, A. Ando, N. Mita, 1993 compilation of analytical data for major elements in seventeen GSJ geochemical reference samples, “Igneous rock series”, Bull. Geol. Surv. Jpn. 45 (1994) 305 – 313.

[33] R.H. Steiger, E. Jager, Subcomission on geochronology: convention on the use of decay constants in geo- and cosmochronology, Earth Planet. Sci. Lett. 36 (1977) 359 – 362.

[34] M. Flisch, Potassium–argon analysis, in: G.S. Odin (Ed.), Numerical Dating in Stratigraphy, Wiley, Chichester, 1982, pp. 151 – 158.

[35] T.A. Steven, H.H. Mehnert, J.D. Obradovich, Age of volcanic activity in the San Juan Mountains, Colorado, U.S. Geol. Survey. Prof. Paper 575-D, D47-D55.

[36] E. Herrero-Bervera, J.-P. Valet, Paleomagnetic secular variation of the Honolulu Volcanic Series (33–700 ka), Oahu (Hawaii), Phys. Earth Planet. Inter. 133 (2002) 83 – 97.

[37] C. Laj, N. Szeremeta, C. Kissel, H. Guillou, Geomagnetic paleointensities at Hawaii between 3.9 and 2.1 Ma: preliminary results, Earth Planet. Sci. Lett. 179 (2000) 191 – 204.

[38] D.A. Clague, G.B. Dalrymple, Age and petrology of alkalic postshield and rejuvenated-stage lava from Kauai, Hawaii, Contrib. Mineral. Petrol. 99 (1988) 202 – 218.

[39] D.A. Clague, J.B. Paduan, W.C. McIntosh, B.L. Cousens, A.S. Davis, J.R. Reynolds, A submarine perspective of the Honolulu Volcanics, Oahu, J. Volcanol. Geotherm. Res. (in press).

[40] J.C. Carracedo, Growth, structure, instability and collapse of Canarian volcanoes and comparisons with Hawaiian volcanoes, J. Volcanol. Geotherm. Res. 94 (1999) 1 – 19.

[41] M. Nakada, H. Yokose, Ice age as a trigger of active Quaternary volcanism and tectonism, Tectonophysics 212 (1992) 321 – 329.

[42] M.O. Garcia, S.B. Sherman, G.F. Moore, G. Acton, R. Goll, I. Popova-Goll and J. Natland, Frequent landslides from Koolau Volcano: results from ODP Site 1223, J. Volcanol. Geotherm. Res. (in press).

[43] X. Li, R. Kind, X. Yuan, I. Wolbern, W. Hanka, Rejuvenation of the lithosphere by the Hawaiian plume, Nature 427 (2004) 827 – 829.

[44] D.R. Muhs, B.J. Szabo, New uranium-series ages of the Waimanalo Limestone, Oahu, Hawaii: implications for sea level curing the last interglacial period, Mar. Geol. 118 (1994) 315 – 326.

[45] R.W. Grigg, A.T. Jones, Uplift caused by lithospheric flexure in the Hawaiian Archipelago as revealed by elevated coral deposits, Mar. Geol. 141 (1997) 11 – 25.

[46] A.B. Watts, U.S. ten Brink, Crustal structure, flexure, and subsidence history of the Hawaiian Islands, J. Geophys. Res. 94 (1989) 10473 – 10500.

[47] D.A. Clague, K. Uto, K. Satake, A.S. Davis, Eruption style and flow emplacement in the submarine North Arch volcanic field, Hawaii, in: E. Takahashi, P.W. Lipman, M.O. Garcia, J. Naka, S. Aramaki (Eds.), Hawaiian Volcanoes; Deep Underwater Perspectives, Geophysical Monograph, vol. 128, American Geophysical Union, Washington, DC, 2002, pp. 65 – 84.

[48] G.P.L. Walker, Koolau dike complex, Oahu: intensity and origin of a sheeted-dike complex high in a Hawaiian volcanic edifice, Geology 14 (1986) 310 – 313.