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Unspiked K–Ar dating of Koolau lavas, Hawaii: Evaluation of the influence of weathering/alteration on age determinations

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ABSTRACT

In order to evaluate the influence of weathering/alteration on K–Ar dating for Hawaiian tholeiites, unspiked K–Ar ages were determined for 21 samples from four lava flows with varying degrees of weathering or alteration collected from the Makapuu Head section of Koolau volcano, Hawaii. The samples were classified based on freshness of olivine phenocrysts and the groundmass olivine, and the presence of secondary minerals in vesicles. The results indicate that the ages for samples with fresh groundmass olivine are reliable, even though olivine phenocrysts may be slightly altered (thin reaction rims) or secondary minerals may have crystallized in the vesicles. The ages for the lowermost lava flow in the Makapuu Head section and the lava flow approximately 120 m above it are 2.58 ± 0.13 and 2.36 ± 0.09 Ma, respectively. The accumulation rate of this section is calculated to be 0.04–0.11 cm/year.

We also report K–Ar ages for lava samples collected from the submarine flank of the Koolau volcano and the Nuuanu landslide blocks. The age for an early Makapuu-stage lava collected from the submarine flank of Koolau volcano is 2.5 Ma, similar to the age from the lower part of the subaerial Makapuu Head section. Another lava sample collected from the submarine flank of the Koolau volcano has an age of 3.3 Ma, older than any subaerial part of Koolau volcano. These results suggest that the onset of Koolau's shield-stage volcanism was no later than ~3.3 Ma, and the duration of the shield stage was at least 1.2 m.y.

1. Introduction

Accurate and precise determination of volcanic rock ages is essential for understanding the history of Hawaiian volcanoes and the structure of the Hawaiian plume. Unspiked K–Ar dating has proven to be very successful for determining crystallization ages for many Hawaiian lavas (e.g. Guillou et al., 1997, 2000; Ozawa et al., 2005, 2006; Sherrod et al., 2007). To obtain reliable (nonspurious) K–Ar ages, the lava samples need to meet various requirements and lack of K and Ar loss during weathering or alteration is one of the most important considerations. Therefore, for reliable K–Ar dating, it is desirable to choose fresh rock samples that have not been affected by weathering/alteration; however, such samples are generally not available among the tholeiitic lava of shields older than about 1 Ma.

In previous studies, the alteration of samples was evaluated by thin-section observations (e.g. Ozawa et al., 2005, 2006; Sano, 2006). However, the criteria for sample selection for K–Ar dating have not been examined closely. Therefore, the goals of this study are to evaluate the effects of alteration on tholeiitic lavas relevant to K–Ar dating and to establish criteria for sample selection. We measured unspiked K–Ar ages for 21 lava samples with varying degrees of weathering/alteration, collected from four flows in the Makapuu Head section of Koolau volcano, where about 200 m of tholeiitic basalt lava flows is exposed. The Makapuu Head section is an ideal for this study because its well-exposed strata have been studied in detail (Frey et al., 1994) and a reliable age was determined previously using fresh samples from one of the flows (Ozawa et al., 2005, their sample HVO2-11).

We also determined K–Ar ages for lava samples collected from the submarine flank of the Koolau volcano and the Nuuanu landslide blocks. The duration for the shield stage of Hawaiian volcanoes has been estimated to be ~0.7 Ma (Clague and Dixon, 2000). However, the age of the submarine lava erupted in the early shield stage has not yet been clearly determined. The ages of the submarine lavas in the Nuuanu landslide blocks erupted during the main shield stage of

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Koolau volcano provide important information for understanding the duration of the shield stage volcanism of Hawaiian volcanoes.

2. Geological setting and analyzed samples

2.1. Koolau volcano

Koolau volcano, on the island of Oahu, consists of shield-stage tholeiitic basalts (1.8–3.2 Ma; McDougall, 1964; Doell and Dalrymple, 1973; Laj et al., 2000; Haskins and Garcia, 2004; Ozawa et al., 2005; Herrero-Bervera et al., 2007) overlain by rejuvenated-stage alkalic basalts of the Honolulu Volcanics (0.8–0.03 Ma; Gramlich et al., 1971; Lanphere and Dalrymple, 1980; Ozawa et al., 2005). Much of the eastern half of Koolau volcano collapsed into the ocean (Fig. 1(a); Nuuanu landslide; Moore et al., 1994); consequently, the Koolau caldera is positioned on the east coast of the island. Two rift zones extend to the northwest and east–southeast from the caldera. The shield-stage lavas were divided into two parts on the basis of geochemistry: main shield stage and late-shield or Makapuu-stage (Shinozaki et al., 2002). Main shield-stage lava has been found in Nuuanu landslide blocks (Shinozaki et al., 2002) but not in the subaerial Koolau shield. Makapuu-stage lava, which is exposed in an approximately 800 m-thick section at the top of the shield (Takahashi and Nakajima, 2002), has a volume in the order of 500–1000 km^3 (Shinozaki et al., 2002), only a small part of the 34,000 km^3 that forms the Koolau volcano (Robinson and Eakins, 2006). Among the Hawaiian lavas, the Makapuu-stage lavas have the highest SiO_2 and $^{87}Sr/^{86}Sr$ ratios and the lowest $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ ratios (e.g. Stille et al., 1986, Frey et al., 1994, Tanaka et al., 2002). In contrast, the main shield-stage lavas resemble Loa- or Kea-type compositions; they are characterized by lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ ratios than those of the Makapuu-stage lavas (Tanaka et al., 2002).

2.2. Makapuu head section

The samples for evaluation of weathering/alteration for K–Ar dating studies were collected from the north side of the well-exposed and accessible Makapuu Head section investigated by Frey et al. (1994) (Figs. 1(a), (b), and 2). A schematic stratigraphic column of the section (M.O. Garcia, pers. comm.) and the sampling locations are presented in Figs. 1(b) and 2 and listed in Table 3(a). The ratio of pahoehoe to aa flows is roughly 40:60 for the entire 200-m-thick section.

In the tropical environment of Hawaii, weathering can decrease K_2O and SiO_2, and K_2O/P_2O_5 can be a good indicator of alteration (e.g. Frey et al., 1994). Frey et al. (1994) analyzed major element compositions for the Koolau shield lavas and reported that 20 of the 67 samples they analyzed had low K_2O/P_2O_5 ratios (less than 1.0). They attributed the low ratios in the Koolau shield lavas to low-temperature alteration (Fig. 3). For this study, 21 lava samples with varying degrees of alteration were collected from four flows (KOO-03, KOO-07, KOO-19, KOO-23; Fig. 2), which, for the most part, have relatively higher K_2O/P_2O_5 ratios than those of the study by Frey et al. (1994). KOO-07 is a pahoehoe flow and the others are aa flows. Since the outcrops at Makapuu Head are along the coast, the lava flows there may have been affected by seawater as well as terrestrial water.

2.3. Submarine samples

The Nuuanu landslide is one of the largest landslides on the Hawaiian Ridge. Debris extends more than 250 km out from the northeast coast of Oahu and contains giant blocks. The largest block, the Tuscaloosa Seamount is 20 by 30 km in size. The micro fossils in the mudstone collected from Tuscaloosa Seamount constrain the sediment to have been deposited between 2.5 and 3.3 Ma (Morgan et al., 2006). In order to investigate the structure of the sea floor of Koolau volcano and the Nuuanu landslide, seven dives and four dredges were conducted during the joint Japan-USA cruises, sponsored by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) in 1998 and 1999.

Oahu North-a site is a shallower part (2000–3000 m) of the northeastern flank of Oahu (Fig. 1(a)), likely undisturbed by the Nuuanu landslide (Shinozaki et al., 2002). Subaerial or shallow submarine pillow lavas and hyaloclastite erupted during the Makapuu-stage occur on this site, whereas hyaloclastites are dominant in the deeper sites. This frank, which displays a rock-type transition similar to that of the Hilina slump on the south flank of Kilauea volcano (Lipman et al., 2002), is interpreted as a typical Hawaiian volcano flank that has undergone a volcano-tectonic growth cycle (Shinozaki et al., 2002). Sample S500-8 collected from the Oahu North-a site on dive S500 is from an in-place pillow lava, while sample S500-7 is from displaced lava that is probably a locally derived from submarine Koolau.

Nuuanu blocks are landslide deposits derived from the main shield-stage of Koolau (Shinozaki et al., 2002). Dive S498 ascended the southeast wall of Tuscaloosa Seamount and non-vesicular olivine basalt (S498-4) was sampled from a rocky outcrop on the dive at the Nuuanu-2 site (Fig. 1(a)). The Nuuanu-3 site investigated on dive S499 (Fig. 1(a)), is along the southwestern slope of an unnamed hummock-shaped block and shallow submarine lava breccia (S499-6) was collected from this site. The petrological and geochemical signatures of the samples collected from the Oahu North-a site are similar to those of the subaerial Makapuu stage lavas. In contrast, the signatures of the Nuuanu landslide lavas are similar to those of Mauna Loa and Mauna Kea lavas on Hawaii (Shinozaki et al., 2002; Tanaka et al., 2002).

3. Analytical procedures

3.1. Classification for weathering/alteration of the lava samples

The lava samples collected from the Makapuu Head section were studied with the naked eye, with a hand lens and in thin sections and have been classified into seven categories based on: (1) freshness of olivine phenocrysts, (2) presence of secondary minerals in vesicles and (3) freshness of groundmass olivine. The criteria for grouping the lavas into categories based on the degree of weathering/alteration are presented in matrix form in Table 1. The presence of secondary minerals in vesicles is dependent on the development of vesicles and the chemistry of any aqueous fluid that invaded the lavas during the weathering/alteration process. Therefore the presence of secondary mineralization in vesicles is valid only for samples with vesicles, and may be supplementary criterion for the evaluation of weathering/alteration. In the six Makapuu Head samples classified in the B1 and C1 groups, there are no secondary minerals although vesicles are present. In terms of the presence of secondary minerals, one submarine sample was indeterminate because of the absence of vesicles. In previous studies, fairly fresh samples that would qualify as A1 and B1 groups in this classification were used for K–Ar dating (Ozawa et al., 2005; Sano, 2006).

3.2. Whole rock major-element analysis

Whole rock major element compositions for the Makapuu Head samples were determined to estimate the degree of alteration (Table. 2). Sample preparation techniques and analytical procedures are based on those of Goto and Tatsumi (1994, 1996). To make fused glass beads, lithium tetraborate ($Li_2B_4O_7$) was used as a flux. 0.40000 ± 0.00015 g of powdered sample and 4.00000 ± 0.00015 g of flux were weighed directly in a platinum crucible. Fusion and agitation