AGE AND STRONTIUM ISOTOPIC COMPOSITION OF THE HONOLULU VOLCANIC SERIES, OAHU, HAWAII

MARVIN A. LANPHERE and G. BRENT DALRYMPLE

U.S. Geological Survey, Menlo Park, California 94025

ABSTRACT. K-Ar ages on basalts from 12 vents of the Honolulu Volcanic Series suggest that these post-erosional basalts were erupted less than about 0.6 m.y. ago. The reproducibility of argon measurements on basalts from 6 of the vents is poor, and for some samples the calculated ages are older than the younger age limit for the underlying Koolau Volcanic Series. These data indicate that at least some of the Honolulu basalts contain variable amounts of excess radiogenic 40Ar that probably was contributed to the basaltic liquid from ultramafic xenoliths.

$^{87}Sr/^{86}Sr$ ratios for 14 basalts of the Honolulu Volcanic Series and 8 basalts of the Koolau Volcanic Series have weighted mean values of 0.70332 ± 0.00004 and 0.70386 ± 0.00006, respectively. These data clearly demonstrate the heterogeneity of the mantle source regions for basalt beneath Oahu and also indicate that the time-integrated Rb/Sr ratio in the source region for basalts of the Honolulu Volcanic Series is lower (that is, indicates a less differentiated source) than in the source region for basalts of the Koolau Volcanic Series.

INTRODUCTION

The volcanic rocks of the Hawaiian Islands have been studied in considerable detail over the last 50 yrs. Early workers recognized that the rocks erupted from Hawaiian volcanoes typically followed the same general sequence (Powers, 1935, 1955; Kuno and others, 1957; Tilley and Scoon, 1961). Macdonald and Katsura (1964) classified the eruptive rocks into three groups which, in order of eruption, are: (1) a tholeiitic suite that forms the bulk (>99 percent) of the shield volcanoes, (2) an alkaline suite that forms thin caps on the shields shortly after caldera collapse, and (3) a nephelinitic suite that is erupted from satellite vents after a prolonged period of quiescence and erosion. Any individual volcano may have representatives of one, two, or all three groups. The currently active volcanoes Kilauea and Mauna Loa on the island of Hawaii have not evolved to the alkaline stage; the extinct West Molokai Volcano, Lanai Volcano, and Koolau Volcano on Oahu apparently never erupted rocks of the alkaline suite. Nephelinitic basalts occur on several of the main Hawaiian Islands but are not present on Lanai or East or West Molokai volcanoes, Haleakala Volcano on Maui, Waianae Volcano on Oahu, or any of the 5 volcanoes on Hawaii. The most extensive and carefully studied nephelinitic suite is the Honolulu Volcanic Series on Oahu.

The Honolulu Volcanic Series is an assemblage of undersaturated volcanic rocks scattered over the southeastern part of the Koolau tholeiitic shield, which forms the eastern part of the island of Oahu. The subaerial part of Koolau Volcano was constructed between about 1.8 and 2.7 m.y. ago (McDougall, 1964; Doell and Dalrymple, 1973). Magmas of the Honolulu Series were erupted from 37 vents or groups of vents (fig. 1) located by Stearns and Vaksvik (1935, 1938) and Winchell (1947). Stearns and Vaksvik (1935) were the first to recognize that these vents occur along rifts normal to the rift zone of the older Koolau shield volcano and are clustered near the ancient Koolau caldera. The order of eruption of the
Honolulu Series vents was established by Stearns and Vaksvik (1935) and modified by Winchell primarily on the basis of relations between the basalts and marine deposits and terraces; the numbering of vents on figure 1 is the order of eruption after Winchell. Stearns and Vaksvik (1935) suggested that the Honolulu Series is late Pleistocene and Holocene on the basis of relations of the volcanic rocks to ancient stands of sealevel.

The Honolulu Volcanic Series comprises a range of volcanic products including tuff cones, spatter cones, cinder cones, flows, and dikes. Although the rocks are chemically diverse, they tend to be poor in silica and rich in alkalis and include nepheline- and melilit-bearing basalt and undersaturated alkali olivine basalt (Winchell, 1947; Macdonald and Katsura, 1962, 1964; Jackson and Wright, 1970).

Jackson and Wright first recognized that the Honolulu Volcanic Series is compositionally zoned with respect to its location on the Koolau tholeiitic shield. The predominant rocks nearest to the former Koolau caldera are melilitic-nepheline basalt (fig. 1); these change outward to nepheline basalt and finally to alkalic olivine basalt at the southwest apron of the ancient Koolau shield. Xenoliths, which are common in basalts of the Honolulu Series, vary in chemical composition and mineralogy with respect to the Koolau shield, but this zoning does not coincide with compositional zoning in the host basalts (Jackson and Wright, 1970).

In their study of the Honolulu Volcanic Series and the included xenoliths, Jackson and Wright (1970) were concerned with several ques-

![Fig. 1. Map of southeastern Oahu showing location of vents of the Honolulu Volcanic Series, Honolulu rift system, and Koolau rift zone (after Jackson and Wright, 1970, fig. 1). Numbers indicate order of eruption of vents after Winchell (1947). Dashed lines indicate percent SiO₂ and separate geographic occurrence of vents of the Honolulu Series into the three major basalt types.](image-url)
tions such as depth of magma generation, processes causing compositional diversity in the basalt, genetic relations between xenoliths and host basalt, and possible mechanisms for the long time interval between eruptions of the tholeiitic and nephelinitic suites. They came to several important conclusions: (1) the xenoliths and basalts are genetically related, the xenoliths representing rock fragments of the source region from which basaltic magmas of the Koolau and Honolulu Volcanic Series were derived by fractional melting; (2) the compositional diversity of the Honolulu Series reflects heterogeneity of the upper mantle beneath Oahu; (3) magmas of the Honolulu Series were generated at greater depths than magmas of the Koolau Series; and (4) Honolulu Series volcanism may have been caused by elastic unloading as the Hawaiian Arch progressed southeastward along the island chain.

The objectives of this study were to test and document further some of the conclusions of Jackson and Wright, in particular: (1) to determine the duration of Honolulu Series volcanism and whether the vents are zoned with respect to age, (2) to test the hypothesis of mantle heterogeneity in the source region for the Honolulu Series using strontium isotopic composition, and (3) to test the hypothesis that the Honolulu and Koolau Series originated from separate source regions.

**ANALYTICAL TECHNIQUES**

K-Ar ages were measured on samples of basalt from 12 different vents of the Honolulu Volcanic Series; all samples were collected by E. D. Jackson during his comprehensive study of xenoliths in the Honolulu Volcanic Series. Rubidium and strontium concentrations and Sr-isotopic composition were measured on these 12 samples, on 2 additional samples of Honolulu Series basalt that were not suitable for K-Ar dating, and on 8 samples of basalt of the Koolau Volcanic Series. Four of these 8 samples were previously described by Jackson and Wright (1970), and the other four by Doell and Dalrymple (1973).

Thirty-five K-Ar ages were measured on the 12 basalt samples. Argon was determined on blocks of basalt that weighed from about 7 to 20 g. Argon analyses were by isotope dilution using an $^{88}$Ar tracer. Mass spectrometry was done with a 15.24-cm-radius, 60°-sector, single-collector instrument utilizing analog data acquisition. Separate aliquants of basalt were pulverized to less than 0.074 mm and used for potassium measurements. Potassium was determined by flame photometry after lithium metaborate fusion (Ingamells, 1970). K-Ar ages were calculated using the decay constants for $^{40}$K recommended by the International Union of Geological Sciences Subcommission on Geochronology (Steiger and Jäger, 1977); all older data cited in this report have been converted to these new constants.

Rubidium and strontium concentrations in the 21 basalt samples were measured by X-ray fluorescence. The isotopic composition of strontium was measured on unspiked aliquants of basalt pulverized to less than 0.074 mm. Mass spectrometry was done with an automated 30.48
cm-radius, 90°-sector, single-collector instrument utilizing a triple-filament source configuration and digital data acquisition.

PREVIOUS GEOCHRONOLOGIC STUDIES OF THE HONOLULU VOLCANIC SERIES

The first K-Ar age reported (Funkhouser, Barnes, and Naughton, 1968) for the Honolulu Volcanic Series was 0.9 ± 0.5 m.y. on the Sugar Loaf Basalt from Moiliili, Hawaii, (fig. 1, vent 37). Gramlich, Lewis, and Naughton (1971) reported K-Ar ages on 14 basalts of the Honolulu Series from 12 different vents. The ages ranged from 0.03 to 0.8 m.y. and included an age of 0.067 ± 0.003 m.y. on a sample from the Sugar Loaf Basalt different from that studied by Funkhouser, Barnes, and Naughton.

The sequence of ages measured by Gramlich and others on 10 of the vents agree with the order of eruption proposed by Winchell (1947); these ages range from 0.470 m.y. for Kalihi (fig. 1, vent 7) to 0.033 m.y. for Kaupo (fig. 1, vent 34). Two ages that do not agree with the order of eruption are 0.662 m.y. for Kaau (fig. 1, vent 16) and 0.874 m.y. for Castle (no. 21 of fig. 1). The implications of these results are discussed later below.

Stearns and Dalrymple (1978) report K-Ar ages for the Black Point Basalt (vent 26) and for an olivine basanite dike at Black Point that is considered contemporaneous with the flow. The ages of 0.48 ± 0.08 m.y. for the flow and 0.41 ± 0.04 m.y. for the dike agree within analytical uncertainty. Because of the smaller analytical uncertainty in the age of the dike, Stearns and Dalrymple consider this age the best for both dike and flow. This age is somewhat older than the age of 0.305 m.y. measured by Gramlich, Lewis, and Naughton (1971) on two samples of the Black Point Basalt.

K-Ar RESULTS

The results for 12 samples of basalt from the Honolulu Volcanic Series are given in table 1. Duplicate argon measurements were made on 6 samples; three to five argon measurements were made on the other 6 samples. The reproducibility in argon measurements is good for only 5 of the 12 samples (vents 7, 12, 17, 26, and 28, table 1). For 4 other samples (vents 11A, 20, 23, and 34) the reproducibility is poor, but the data have been pooled to yield a mean age. The reproducibility for the other 3 samples is so poor that a mean age has not even been calculated.

The generally poor reproducibility in both potassium and argon measurements on Hawaiian tholeiites is well known (Funkhouser, Barnes, and Naughton, 1968; Doell and Dalrymple, 1973; Dalrymple, Lanphere, and Jackson, 1974). However, for basalts of the Honolulu Volcanic Series, which are much richer in alkalis than Hawaiian tholeiites, the reproducibility in potassium measurements is very good (table 1). The scatter in calculated ages for basalt of the Honolulu Series is due solely to the argon measurements. For most of the measurements the 40Ar in the samples is between about 4 and 20 percent radiogenic; those measure-
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ments in which $^{40}\text{Ar}$ is less than 4 percent radiogenic have higher analytical uncertainties, but the discrepancies are still much larger than can be accounted for by these uncertainties alone (for example, vents 1, 3, and 21, table 1). We conclude that the scatter in argon measurements is an inherent characteristic of the rocks and is produced by excess radiogenic $^{40}\text{Ar}$ from xenoliths, as discussed below.

**PREVIOUS Rb/Sr DATA ON THE HONOLULU VOLCANIC SERIES**

Rb/Sr analyses of basalts of the Honolulu Volcanic Series have been reported in several previous studies (Lessing and Catanzaro, 1964; Hamilton, 1965; Powell, Faure, and Hurley, 1965; Powell and Delong,

<p>| Table 1 |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Potassium-argon ages and analytical data for basalts of the Honolulu Volcanic Series |</p>
<table>
<thead>
<tr>
<th>Field no.</th>
<th>Sample</th>
<th>K (p.mol)</th>
<th>Sr (mg/kg)</th>
<th>$^{87}\text{Sr}$/$^{86}\text{Sr}$</th>
<th>Calculated age (10^9 yr)</th>
<th>Ages reported by</th>
</tr>
</thead>
<tbody>
<tr>
<td>66 USMC-1</td>
<td>1</td>
<td>Pele Mountain</td>
<td>0.496 ± 0.0014</td>
<td>16.058</td>
<td>42.4 ± 10^{-11}</td>
<td>3.2</td>
</tr>
<tr>
<td>66 PF-1</td>
<td>4</td>
<td>Pyramid rock</td>
<td>0.392 (2)</td>
<td>6.848</td>
<td>15.168</td>
<td>7.34</td>
</tr>
<tr>
<td>69 KAL-2</td>
<td>7</td>
<td>Kailua</td>
<td>1.02 (2)</td>
<td>9.268</td>
<td>15.168</td>
<td>7.34</td>
</tr>
<tr>
<td>68 KAV-2</td>
<td>11A</td>
<td>Kaneohe Group</td>
<td>1.282 (2)</td>
<td>10.6</td>
<td>17.168</td>
<td>7.34</td>
</tr>
<tr>
<td>69 NUI-2</td>
<td>12</td>
<td>Oahu</td>
<td>1.212 (2)</td>
<td>9.268</td>
<td>15.168</td>
<td>7.34</td>
</tr>
<tr>
<td>69 KIL-1</td>
<td>17</td>
<td>Kilauea</td>
<td>1.012 (2)</td>
<td>9.268</td>
<td>15.168</td>
<td>7.34</td>
</tr>
<tr>
<td>65 AIM-1</td>
<td>20</td>
<td>Aiea</td>
<td>0.616 ± 0.0074</td>
<td>18.0</td>
<td>28.8</td>
<td>7.34</td>
</tr>
<tr>
<td>65 KAPA-11</td>
<td>21</td>
<td>Kilauea</td>
<td>0.597 (2)</td>
<td>10.6</td>
<td>17.168</td>
<td>7.34</td>
</tr>
<tr>
<td>68 TAF-3</td>
<td>23</td>
<td>Training School</td>
<td>1.256 ± 0.019 (4)</td>
<td>19.09</td>
<td>28.8</td>
<td>7.34</td>
</tr>
<tr>
<td>65 BP-1</td>
<td>26</td>
<td>Black Point</td>
<td>0.379 ± 0.020 (4)</td>
<td>15.429</td>
<td>28.8</td>
<td>7.34</td>
</tr>
<tr>
<td>68 JPB-2</td>
<td>22</td>
<td>Punchbowl</td>
<td>1.022 (2)</td>
<td>11.0</td>
<td>20.3</td>
<td>7.34</td>
</tr>
<tr>
<td>54490-3</td>
<td>31</td>
<td>Koapua</td>
<td>0.737 (2)</td>
<td>9.268</td>
<td>15.168</td>
<td>7.34</td>
</tr>
</tbody>
</table>

* Listing of vents by number and name after Winchell (1947).
† Errors are calculated standard deviations; number of measurements is in parentheses.
‡ $\lambda_0 = 5.62 \times 10^{-8}$ yr^{-1}, $\lambda' = 7.97 \times 10^{-8}$ yr^{-1}, $\lambda_B = 4.60 \times 10^{-8}$ yr^{-1}, $4\Delta K/K = 3.4 \times 10^{-4}$ mol/mo. Errors are estimated standard deviations of analytical precision (Cox and Dalrymple, 1967). Mean age of each sample was calculated by weighting each measurement by the inverse of its estimated variance.
# Samples from same vent as this study. Ages of Gramlich and others (1971) were recalculated with decay constants used in this study.
1966; Bence, 1966; O’Neil, Hedge, and Jackson, 1970). The most detailed
study was by Powell and DeLong, who also summarized the earlier
studies. All published data have been adjusted to a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of
0.7080 for the Eimer and Amend SrCO$_3$ standard except for the data of
Hamilton, who did not use this standard.

Powell and DeLong (1966) analyzed 13 basalts of the Honolulu
Series from 11 different vents; rubidium and strontium concentrations
were not given, but Rb/Sr ratios ranged from 0.006 to 0.040. The $^{87}\text{Sr}/^{86}\text{Sr}$
ratios of these samples ranged from 0.70274 to 0.70354 with a mean
value of 0.70314 and a standard deviation of 0.00006. Powell and DeLong
also analyzed 7 tholeiites of the Koolau Volcanic Series and obtained
$^{87}\text{Sr}/^{86}\text{Sr}$ ratios ranging from 0.70364 to 0.70407, with a mean value of
0.70379 and a standard deviation of 0.00006. The difference between
mean values for the Koolau and Honolulu Series is significant at the
99 percent confidence level. Powell and DeLong concluded that the Sr-
isotopic data showed that these two volcanic series were not derived
from a common parent magma, nor was the Honolulu Volcanic Series
derived from a tholeiitic parent magma. They further suggested that
the differences in Sr-isotopic composition reflected chemical and isotopic
heterogeneities in upper mantle source regions for the various magma
types.

O’Neil, Hedge, and Jackson (1970) analyzed two basalts of the Honolulu
Volcanic Series (fig. 1, vents 3 and 8) and three garnet pyroxenite
xenoliths from Salt Lake Crater (fig. 1, vent 18). The $^{87}\text{Sr}/^{86}\text{Sr}$
ratios for the basalts and xenoliths agree within analytical uncertainty, which
is compatible with a genetic relation between basalt and xenoliths, as
suggested by Jackson and Wright (1970).

O’Nions, Hamilton, and Evensen (1977) measured $^{87}\text{Sr}/^{86}\text{Sr}$
ratios on two samples of nepheline basalt from Honolulu, Oahu; their values
of 0.70350 ± 4 and 0.70351 ± 4 lie at the high end of the range of values
reported by Powell and DeLong. DePaolo and Wasserburg (1976) reported
a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70320 ± 8 for a nepheline from Oahu. Neither
O’Nions, Hamilton, and Evensen nor DePaolo and Wasserburg gave
sufficient information to identify the location of vents from which their
samples were collected.

Rb/Sr and Sr isotopic results

Analytical results for 14 basalts of the Honolulu Volcanic Series
are given in table 2; rubidium and strontium concentrations range from
6 to 36 ppm and 497 to 2026 ppm, respectively. The range in Rb/Sr
ratios is from 0.006 to 0.045. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, however, all fall within
the narrow range of 0.70298 ± 36 to 0.70347 ± 19. The weighted mean
value, in which the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for each of the 14 basalts is weighted
by the inverse of its variance, is 0.70332, with a standard deviation of
0.00005. The variation in Sr-isotopic composition is about half that
reported by Powell and DeLong (1966) for 6 of the same vents. The Sr
isotopic composition measured on each of these 6 vents in the two
studies agree within analytical uncertainty.
The two basalts analyzed by O'Neil, Hedge, and Jackson (1970) are splits of the samples used by us; the data obtained in two different laboratories agreed within the analytical uncertainty of the measurements, and the Rb/Sr ratios agree within 5 to 10 percent. For the $^{87}$Sr/$^{86}$Sr ratios, O'Neil, Hedge, and Jackson (1970) obtained a value of $0.7033 \pm 3$ for 66 PY-1 (vent 3) and a value of $0.7086 \pm 3$ for 68 KEE-1 (vent 8).

Eight tholeiites of the Koolau Volcanic Series were analyzed in order to compare the Sr–isotopic compositions of basalts of the Honolulu Volcanic Series with that of rocks from the underlying tholeitic shield (table 3). Four of these tholeiites, from the main constructional part of Koolau shield volcano, are aliquants of the samples used by Doell and Dahrymple (1973) in their K-Ar and paleomagnetic study of the Koolau Volcanic Series. The other four are aliquants of samples studied by Jackson and Wright (1970, table 1). Three of Jackson and Wright's samples are from flows that underlie tuffs and ashes of the Honolulu

<table>
<thead>
<tr>
<th>Field no.</th>
<th>Vnt.</th>
<th>Rock type</th>
<th>$Rb$ (ppm)</th>
<th>$Sr$ (ppm)</th>
<th>$Rb/Sr$</th>
<th>$Sr^{87}/Sr^{86}$</th>
<th>$Sr^{87}/Sr^{86}$</th>
<th>$Sr^{87}/Sr^{86}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 USMC-1</td>
<td>1</td>
<td>Phonolite</td>
<td>10</td>
<td>2026</td>
<td>0.006</td>
<td>0.70327 ± 0.70337</td>
<td>0.70327 ± 0.70327</td>
<td>0.70327 ± 0.70327</td>
</tr>
<tr>
<td>66 PY-1</td>
<td>3</td>
<td>Phonolite</td>
<td>21</td>
<td>1188</td>
<td>0.018</td>
<td>0.70327 ± 0.70327</td>
<td>0.70327 ± 0.70327</td>
<td>0.70327 ± 0.70327</td>
</tr>
<tr>
<td>69 KAL-2</td>
<td>7</td>
<td>Phonolite</td>
<td>23</td>
<td>1474</td>
<td>0.017</td>
<td>0.70330 ± 0.70330</td>
<td>0.70330 ± 0.70330</td>
<td>0.70330 ± 0.70330</td>
</tr>
<tr>
<td>62 KEE-1</td>
<td>8</td>
<td>Phonolite</td>
<td>23</td>
<td>676</td>
<td>0.024</td>
<td>0.70325 ± 0.70325</td>
<td>0.70325 ± 0.70325</td>
<td>0.70325 ± 0.70325</td>
</tr>
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<td>68 KAN-2</td>
<td>11A</td>
<td>Phonolite</td>
<td>12</td>
<td>1371</td>
<td>0.023</td>
<td>0.70327 ± 0.70327</td>
<td>0.70327 ± 0.70327</td>
<td>0.70327 ± 0.70327</td>
</tr>
<tr>
<td>69 NUK-1</td>
<td>12</td>
<td>Phonolite</td>
<td>32</td>
<td>1010</td>
<td>0.032</td>
<td>0.70325 ± 0.70325</td>
<td>0.70325 ± 0.70325</td>
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<tr>
<td>69 WIL-1</td>
<td>17</td>
<td>Phonolite</td>
<td>24</td>
<td>1206</td>
<td>0.020</td>
<td>0.70331 ± 0.70331</td>
<td>0.70331 ± 0.70331</td>
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<tr>
<td>65 AIN-1</td>
<td>20</td>
<td>Phonolite</td>
<td>6</td>
<td>550</td>
<td>0.017</td>
<td>0.70333 ± 0.70333</td>
<td>0.70333 ± 0.70333</td>
<td>0.70333 ± 0.70333</td>
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<tr>
<td>65 KAPPA-2</td>
<td>21</td>
<td>Phonolite</td>
<td>20</td>
<td>1060</td>
<td>0.019</td>
<td>0.70346 ± 0.70346</td>
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<td>23</td>
<td>Phonolite</td>
<td>26</td>
<td>1441</td>
<td>0.023</td>
<td>0.70309 ± 0.70309</td>
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<tr>
<td>68 FS-2</td>
<td>25</td>
<td>Phonolite</td>
<td>18</td>
<td>588</td>
<td>0.019</td>
<td>0.70304 ± 0.70304</td>
<td>0.70304 ± 0.70304</td>
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<tr>
<td>45 SP-1</td>
<td>26</td>
<td>Phonolite</td>
<td>14</td>
<td>535</td>
<td>0.045</td>
<td>0.70326 ± 0.70326</td>
<td>0.70326 ± 0.70326</td>
<td>0.70326 ± 0.70326</td>
</tr>
<tr>
<td>45 PB-2</td>
<td>28</td>
<td>Phonolite</td>
<td>17</td>
<td>1095</td>
<td>0.025</td>
<td>0.70323 ± 0.70323</td>
<td>0.70323 ± 0.70323</td>
<td>0.70323 ± 0.70323</td>
</tr>
<tr>
<td>45 KUC-1</td>
<td>34</td>
<td>Phonolite</td>
<td>6</td>
<td>497</td>
<td>0.010</td>
<td>0.70329 ± 0.70329</td>
<td>0.70329 ± 0.70329</td>
<td>0.70329 ± 0.70329</td>
</tr>
</tbody>
</table>

* Listing of vents by number and name after Winchell (1947).
† Measured $^{87}$Sr/$^{86}$Sr ratios normalized to a value of 0.1194 for the $^{87}$Sr/$^{86}$Sr ratio. normalized $^{87}$Sr/$^{86}$Sr ratios were adjusted to a value of 0.7080 for Eimer and Amend SrCO$_3$ standard.
§ Measured $^{87}$Sr/$^{86}$Sr values have been adjusted to a value of 0.7080 for Eimer and Amend SrCO$_3$ standard.
Series; the fourth sample is from a dike of the type that Macdonald (1968) called “caldera-filling basalt.” The weighted mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for the eight tholeiites is 0.70386, with a standard deviation of 0.00006.

**DISCUSSION**

*Geochronology.*—The K-Ar data (table 1) show clearly that measuring ages for basalts of the Honolulu Volcanic Series is not straightforward. Some ages obviously are greatly inconsistent with geologic relations. For example, the ages for Pau Hawai‘iloa (vent 1) and Ainoni (vent 20) are older than the lower age limit of about 1.8 m.y. for the underlying Koolau Volcanic Series. These anomalously old ages and the poor reproducibility in argon measurements indicate that the samples contain excess radiogenic $^{40}\text{Ar}$ that is heterogeneously distributed. The most likely source of this excess $^{40}\text{Ar}$ is potassium-poor xenoliths in the basalts, a conclusion that has been documented elsewhere. For example, the historic Kaupulehu flow (1800-1801) from Hualalai Volcano on Hawaii contains abundant ultramafic xenoliths. Analyses of the 1801 basalt (Dalrymple, 1969) yielded an apparent K-Ar age of 1.1 m.y. with about $1.5 \times 10^{-12}$ mol/g of excess $^{40}\text{Ar}$. The total content of radiogenic $^{40}\text{Ar}$ in basalt of the Honolulu Series (table 1) ranges from about 0.3 to $10 \times 10^{-12}$ mol/g. Thus, the apparent age of the Honolulu Volcanic Series basalts would be very strongly influenced by amounts of excess $^{40}\text{Ar}$ comparable to that found in the Kaupulehu flow.

Xenoliths have been observed in basalts from 9 of the 12 vents on which K-Ar ages were measured (Jackson and Wright, 1970). Reasonably consistent ages were measured on basalt from two vents (vents 26 and 34) where xenoliths were not observed; however, the third vent (vent 20) yielded an age of about 2 m.y., which is unacceptably old. Four vents that

<table>
<thead>
<tr>
<th>Field no.</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
<th>Rb/Sr (ppm)</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>5176-1</td>
<td>0</td>
<td>376</td>
<td>0</td>
<td>0.70380 : 26</td>
<td>Unit 66, site B of Dool and Dalrymple (1973). Top flow of Waiapu Beach section of 23 lavas.</td>
</tr>
<tr>
<td>5176-2</td>
<td>0.7</td>
<td>311</td>
<td>0.002</td>
<td>0.70407 : 12</td>
<td>Unit 76, site B of Dool and Dalrymple (1973). Bottom flow of Waiapu Beach section.</td>
</tr>
<tr>
<td>5173-1</td>
<td>0.4</td>
<td>451</td>
<td>0.001</td>
<td>0.70504 : 12</td>
<td>Unit 72, site F of Dool and Dalrymple (1973). Top flow of four lavas in Pacific Coast Aggregates quarry.</td>
</tr>
<tr>
<td>5171-1</td>
<td>1.8</td>
<td>432</td>
<td>0.004</td>
<td>0.70389 : 14</td>
<td>Unit 69, site F of Dool and Dalrymple (1973). Bottom flow in Pacific Coast Aggregates quarry.</td>
</tr>
<tr>
<td>5174-1</td>
<td>1.6</td>
<td>410</td>
<td>0.002</td>
<td>0.70336 : 9</td>
<td>Basalt flow beneath Sugar Loaf ash. See Table 1 of Jackson and Wright (1970).</td>
</tr>
<tr>
<td>5174-2</td>
<td>0.2</td>
<td>461</td>
<td>0.0006</td>
<td>0.70376 : 17</td>
<td>Basalt flow beneath Punchbowl tuff. See Table 1 of Jackson and Wright (1970).</td>
</tr>
<tr>
<td>5174-25</td>
<td>0.7</td>
<td>484</td>
<td>0.013</td>
<td>0.70412 : 22</td>
<td>Basalt flow beneath Salt Lake tuff. See Table 1 of Jackson and Wright (1970).</td>
</tr>
<tr>
<td>5174-40</td>
<td>19.9</td>
<td>483</td>
<td>0.036</td>
<td>0.70385 : 20</td>
<td>Basalt dike, H. C. &amp; O. Co. quarry. See Table 1 of Jackson and Wright (1970).</td>
</tr>
</tbody>
</table>

* See corresponding footnote in table 2.
contain xenoliths (vents 7, 12, 17, and 28) yielded consistent and reasonable ages; basalt from two of these vents (vents 17 and 28) did not contain enough xenoliths for field counts (Jackson and Wright, 1970), but the content of xenoliths in basalt from the other two (vents 7 and 12) is substantially greater. Inconsistent or unreasonably old ages were obtained on basalt from three vents (vents 1, 3, and 21) that contain abundant xenoliths, two vents (vents 11A and 23) that contain too few xenoliths to count, and one vent (vent 20) that contains no xenoliths. If, as seems likely, disaggregated or microscopic xenoliths are present in basalts that do not contain megascopic xenoliths, then ultramafic xenoliths are the probable cause of the inconsistent and unacceptable ages for basalts of the Honolulu Series. Another possibility is that excess $^{40}$Ar, either from xenoliths or from the xenolith source region, was dissolved in the basaltic melt and did not completely escape before the lavas solidified.

We measured ages on basalt from six vents for which Gramlich, Lewis, and Naughton (1971) reported K-Ar ages; for only one vent (vent 12) do the results of these two studies agree within analytical uncertainty. For the other five vents (table 1) the ages reported by Gramlich, Lewis, and Naughton are significantly younger than those determined by us. The reproducibility of ages measured by Gramlich, Lewis, and Naughton is impressive, and their results show none of the scatter seen in our data; we have no explanation for these discrepancies.

If internal consistency and reproducibility are used as criteria for evaluating the K-Ar data, then only six basalts in our study yield acceptable ages. These are:

<table>
<thead>
<tr>
<th>Vent no.</th>
<th>Vent name</th>
<th>Calculated age ($10^8$ yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Kalihi</td>
<td>0.58 ± 0.025</td>
</tr>
<tr>
<td>12</td>
<td>Luakaha</td>
<td>0.56 ± 0.06</td>
</tr>
<tr>
<td>17</td>
<td>Mauumaee</td>
<td>0.43 ± 0.04</td>
</tr>
<tr>
<td>26</td>
<td>Black Point</td>
<td>0.48 ± 0.08</td>
</tr>
<tr>
<td>28</td>
<td>Punchbowl</td>
<td>0.53 ± 0.04</td>
</tr>
<tr>
<td>34</td>
<td>Kaupo</td>
<td>0.32 ± 0.04</td>
</tr>
</tbody>
</table>

Kalihi (vent 7) is one of the older vents and Kaupo (no. 34) is one of the younger vents based on field relations, so the 6 ages agree roughly with the order of eruption (Winchell, 1947). We are reluctant to accept the age for any single vent in table 1 as accurate in view of the obvious effect of excess $^{40}$Ar in some of the basalts. The results suggest, however, that the Honolulu Volcanic Series is less than 0.6 m.y. old. If there is any systematic variation in age with location of vents of the Honolulu Volcanic Series, it is not obvious from the age data.

*Rb-Sr relations.—* The most striking feature of the strontium isotopic data obtained by us is the small but significant difference in strontium composition between the Honolulu and Koolau Volcanic Series first
pointed out by Powell and DeLong (1966), who believed that this
difference reflected chemical heterogeneities in the upper mantle source
regions of the basalts. At the time of their study, Powell and DeLong
did not have enough evidence to amplify their interpretation further,
but the classic study of Jackson and Wright (1970) has provided the
basis for additional inferences on upper mantle chemistry and volcanic
processes beneath Oahu.

Jackson and Wright made the important observation that the xenol-
liths in the Honolulu Volcanic Series as well as basalt in the vents are
compositionally zoned around the caldera of Koolau Volcano. The xenoll
ths nearest the caldera are mostly dunite with subordinate lherzolite.
Lherzolite becomes abundant at greater distances, and near the apron
of the shield, garnet pyroxenite and peridotite xenoliths are prominent.
Textural evidence suggests that these xenoliths are refractory residua of
primary mantle material from which the basalt was removed by fractional
melting (Jackson and Wright, 1970). The fact that dunite xenoliths,
considered residual after the generation of tholeiite of the Koolau Vol-
canic Series, are very abundant in basalt of the Honolulu Volcanic Series
in the caldera area led Jackson and Wright to conclude that the source
for magmas of the Honolulu Series lies below that of the tholeiitic
magmas, a conclusion that is consistent with predictions based on experi-
mental petrology (Green and Ringwood, 1967; Kushiro, 1968).

Although rocks of the Honolulu Volcanic Series are compositionally
zoned, particularly with respect to SiO₂ (fig. 1), the Sr isotopic composi-
tion of the basalts shows no obvious zoning parallel to the major-element
chemistry, as illustrated by a plot of ⁸⁷Sr/⁸⁶Sr ratio versus percent SiO₂
(fig. 2). A possible zoning occurs in strontium concentration with average
contents of 1607, 1189, and 745 ppm for basalts with less than 40, 40 to 44,
and more than 44 percent SiO₂, respectively. However, average rubidium
contents for the same SiO₂ groups are 16, 28, and 16 ppm, respectively.

![Fig. 2. Plot of ⁸⁷Sr/⁸⁶Sr versus percent SiO₂ for basalt of the Honolulu Volcanic
Series. SiO₂ data from Jackson and Wright (1970) and E. D. Jackson (unpub. data).
Numbers refer to vents in table 1.](image-url)
This absence of Sr isotopic zoning is not surprising, because elemental concentrations are strongly influenced by the composition of the source region and by the degree of partial melting that generated the basaltic liquid, whereas the Sr-isotopic composition is relatively insensitive to these factors.

In their evaluation of Sr-isotopic variations and oceanic basalt compositions, Peterman and Hedge (1971) found a positive correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and $K_2O/(K_2O + Na_2O)$, which they used as a parameter to reduce the effect of variations in $K_2O$ content that may result from fractionation during crystallization. Their sample population encompassed ocean ridge tholeiites and oceanic island basalts, including the samples of the Honolulu Volcanic Series studied by Powell and DeLong (1966). For the Honolulu Series, Peterman and Hedge used average values of 0.7031 and 0.190 for $^{87}\text{Sr}/^{86}\text{Sr}$ and $K_2O/(K_2O + Na_2O)$, respectively; the average values obtained by us for these ratios are 0.7033 and 0.213, respectively. However, as shown in figure 3, $^{87}\text{Sr}/^{86}\text{Sr}$ does not vary as a function of $K_2O/(K_2O + Na_2O)$ within basalts of the Honolulu Volcanic Series.

The strontium isotopic data obtained by us clearly demonstrate the heterogeneity of the mantle source regions for basalt beneath Oahu. Thus, the source regions from which basalts of the Koolau and Honolulu Volcanic Series were derived must have had different Rb/Sr ratios over a long period of time in order to develop the differences in $^{87}\text{Sr}/^{86}\text{Sr}$ ratio observed in the derivative basalts. The lower Rb/Sr ratio in the source region for basalts of the Honolulu Series is consistent with models of mantle evolution that require upward enrichment of rubidium in the crust and mantle throughout geologic time (Gast, 1968; Hurley, 1968; Hart and Brooks, 1970).

The isotopic composition of strontium in a basalt is a very sensitive indicator of the coupled Rb/Sr ratio and age of the source region, provided that partial melting to generate a basaltic magma is an equilib-

![Fig. 3. Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $K_2O/(K_2O + Na_2O)$ for basalt of the Honolulu Volcanic Series. $K_2O$ and Na$_2$O data from Jackson and Wright (1970) and E. D. Jackson (unpub. data). Numbers refer to vents in table 1.](image-url)
rium process, at least to the extent that isotopic fractionation of strontium does not occur. The term “age” refers to rubidium residence time in the source region, a condition that holds whether the composition of the derivative liquid is determined by the depth in the mantle at which partial melting occurs (Kushiro and Kuno, 1963) or by the depth at which magma segregates from residual refractory crystals (Green and Ringwood, 1967). On the other hand, one cannot infer the Rb/Sr ratio of the parent material from the Rb/Sr ratio of the basalt, unless one also knows the degree of partial melting, partition coefficients, and mechanism by which the magma composition was fixed.

One can speculate on the age of the source region, that is, the time when differentiation occurred to create the source region from which basaltic magmas of the Honolulu Volcanic Series were derived. The smallest Rb/Sr ratio measured on a basalt of the Honolulu Series is 0.0024 in 66 USMC-1 (table 2), a value that represents an upper limit for the Rb/Sr ratio of the source region. DePaolo and Wasserburg (1976) have suggested that unfractoned mantle has a present-day $^{87}$Sr/$^{86}$Sr ratio of about 0.7045 and a Rb/Sr ratio of about 0.029. Comparison of these values with the average $^{87}$Sr/$^{86}$Sr ratio of 0.7033 and the Rb/Sr ratio of 0.006 for basalts of the Honolulu Series gives an “age” of about 1250 m.y. for the source region. This calculation involves several questionable assumptions; for example that an unfractoned mantle reservoir exists in the Earth, that geologic processes always yield a residual mantle product of lower Rb/Sr ratio, and that the geochemical behavior of Rb-Sr and Sm-Nd are correlative. However, if we use the model of DePaolo and Wasserburg, then the calculation seems to show that the source region of the Honolulu Volcanic Series has been isolated from undepleted mantle for at least a billion years.

Jackson and Wright (1970) have argued that if fractional melting occurs as a simple one-stage process, then xenoliths representing potential parents and residua must lie on a mixing line that also includes the melt composition. Some xenoliths in basalt of the Honolulu Volcanic Series have major element chemistry that fits this model. If these conditions are met, then the strontium isotopic composition should be identical in both xenoliths and basalts. Limited data (O’Neil, Hedge, and Jackson, 1970; M. A. Lanphere, unpub. data) show that this is indeed true. The data also indicate that isotopic fractionation did not occur during fractional melting to generate the undersaturated liquids.

A positive correlation between $^{87}$Sr/$^{86}$Sr and Rb/Sr ratios for basalts from various environments has been noted in a number of studies; these data have been summarized by Brooks and others (1976). A similar correlation between Pb–isotopic composition and U/Pb ratio was shown by Tatsumo (1966), who concluded that these characteristics were inherited from the mantle source regions of the basalts and indicated that U/Pb heterogeneities have existed in the mantle for a billion years or more. The correlation between $^{87}$Sr/$^{86}$Sr and Rb/Sr for alkali basalts (including nephelinites) from oceanic islands was interpreted by Sun and
Hanson (1975) as indicating heterogeneities in the mantle source regions for about 2 b.y. The only nepheline basalts in their synthesis were from the Honolulu Volcanic Series. Brooks and others (1976) subsequently extended the evaluation of Rb/Sr systematics to include both tholeiites and alkali basalts from oceanic islands. The two basalt types occupy distinct fields on a plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus Rb/Sr, and the slope of the tholeite correlation suggests an age of about 1.6 ± 0.2 b.y. Brooks and others interpreted this correlation as a mantle isochron that dates a major differentiation event of the mantle. Tatsumoto later (1978) suggested, however, that the analogous correlation between $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ is not an isochron with age significance but an average value reflecting progressive mantle differentiation.

The $^{87}\text{Sr}/^{86}\text{Sr}$ and Rb/Sr data obtained by us are plotted in figure 4 together with the fields outlined by Brooks and others (1976) for tholeiites and alkalic basalts from oceanic islands; Brooks and others averaged data by island group in order to define these fields. Our weighted-average values for basalts do not fall within the fields outlined by Brooks and others (1976). Although our data are for only a single volcano, the Hawaiian Islands as a group do not show any correlation between $^{87}\text{Sr}/^{86}\text{Sr}$ and Rb/Sr (Brooks and others, 1976; M. A. Lanphere, G. B. Dahrymple, and D. A. Clague, unpub. data). Evidence for long-term heterogeneities in the mantle is strong, but the reason why some oceanic island groups show well-correlated Rb/Sr systematics whereas other island groups do not is unknown.

The age of the Honolulu Volcanic Series has special significance for the "hot-spot" hypothesis, first proposed by Wilson (1963a,b) to explain the origin of the Hawaiian Islands and other linear island chains.
in the Pacific Ocean. According to this hypothesis, linear volcanic island chains are formed when a crustal plate moves relative to a source of lava in the asthenosphere. A volcano that forms above the hot-spot is eventually moved away from the lava source, and a new volcano is erupted behind the first. Kohala Volcano on Hawaii was being constructed above a hot spot at approximately the same time that the Honolulu Volcanic Series was being erupted on Oahu (McDougall and Swanson, 1972); thus, basalts of the Honolulu Series have no direct relation to the Hawaiian hot spot but instead are the result of a second-order effect. Jackson and Wright (1970) suggested that melting to generate magmas of the Honolulu Series may have been caused by isostatic response to volcanic loading of the ocean crust. Whatever the mechanism, however, basalts of the Honolulu Volcanic Series are rocks derived from a chemically and isotopically different source region than the overlying zone from which tholeiites of the Koolau shield were derived.

CONCLUSIONS

Our data indicate that basalts of the Honolulu Volcanic Series are less than about 0.6 m.y. old. However, strong evidence for variable amounts of excess radiogenic 40Ar in 6 other basalts makes it difficult either to set unequivocal limits on the age of the Honolulu Volcanic Series or to accept the age data as absolutely accurate. No systematic variation in age with location of vents was detected.

Strontium isotopic compositions of basalts of the Honolulu and Koolau Volcanic Series document the heterogeneity of the source regions for basalt beneath Oahu. The isotopic data require a vertical variation in Rb/Sr ratio within the source regions. The source region for basalts of the Honolulu Volcanic Series must have had a lower Rb/Sr ratio than the source region for tholeiitic basalts of the Koolau Volcanic Series for a long time before the basaltic liquids were extracted by partial fusion and erupted.

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A major impetus for our study of the Honolulu Volcanic Series came from Dale Jackson whose infectious enthusiasm for a wide variety of geologic problems stimulated all his colleagues. We thank S. J. Kover, B. M. Myers, A. L. Atkinson, J. C. Von Essen, and L. B. Schlockers for assistance with the K-Ar measurements and A. L. Berry for assistance with the Rb-Sr measurements. We also thank R. L. Armstrong, Z. E. Peterman, H. T. Stearns, and T. L. Wright who reviewed the manuscript and suggested constructive changes.

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