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URANIUM AND THORIUM IN SELECTED SUITES OF IGNEOUS ROCKS*

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ABSTRACT. The uranium and thorium contents of 199 igneous rocks from a variety of petrographic provinces is here summarized. Data are given for the Mesozoic calc-alkalic batholiths of the western United States; volcanic and hypabyssal rocks of the tholeiitic magma type from Hawaii and Virginia; and effusive calc-alkalic, alkalic, and subsilic-alkalic rocks from the western United States and Hawaii.

The batholithic rocks show an increase of both uranium and thorium from gabbro to quartz-monzonite and granite. The more extreme differentiates, chiefly muscovite-quartz monzonites, contain considerably less uranium and thorium than the quartz monzonites and granites, although the Th/U ratios are nearly the same. The volcanic and hypabyssal rocks in general show a similar increase in both thorium and uranium toward the more felsic members. The alkalic basalts of the Honolulu volcanic series show an anomalous decrease in uranium and thorium toward the right on a variation diagram.

The Th/U ratios remain fairly constant from the mafic to the felsic members of each series here studied; each series also has a more or less characteristic Th/U ratio, ranging from 2½ to 5. The scatter of thorium contents, uranium contents, and Th/U ratios is larger with increasing complexity of magmatic differentiation. The batholithic rocks have the greatest scatter, and have a significantly lower Th/U ratio in the gabbros than in the more felsic members.

Our data show no increasing loss of uranium relative to thorium from the magma during the later stages of crystallization.

INTRODUCTION

New data on the uranium and thorium contents of 199 rock samples from selected suites of intrusive and extrusive igneous rocks are here summarized. We have chosen suites of comagmatic rocks from nine regions which have been or are being studied geologically in some detail. and for all but one of which conventional rock analyses were available. Data are presented on suites of igneous rocks from the Mesozoic batholiths of the western United States: the southern California, Sierra Nevada. and Idaho batholiths. For comparison with these immense batholiths. data are also given on suites of volcanic or hypabyssal rocks from the Hawaiian Islands; Medicine Lake Highlands of California; Valles Mountains of New Mexico; Bearpaw Mountains of Montana; and the diabase-granophyre complex near Fairfax, Virginia. These suites of rocks represent petrographic provinces of widely different chemical composition and include calc-alkalic. tholeiitic, and subsilicic-alkalic magma types. All these rocks are of Mesozoic or younger age and show evidence of only minor post-magmatic alteration; the data on uranium and thorium are probably representative of the original rocks after complete solidification.

In recent years considerable data have been published on the uranium content of igneous rocks (Larsen, Jr., Phair, Gottfried, and Smith, 1956; Larsen, Jr., Gottfried, and Molloy, 1958; Adams, 1955; Whitfield and others, 1959). Data on thorium are much more scarce and little has appeared on the thorium-uranium relationships in comagmatic suites (Larsen, Jr., and Phair, 1954). Adams, Osmond, and Rogers (1959) have published an up-to-date and comprehensive review of the geochemistry of uranium and thorium which contains a comprehensive bibliography.

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Adams and his colleagues have effectively applied gamma ray spectrometry to the systematic determination of thorium in ordinary rocks. In our studies, thorium has been determined by the chemical method by Levine and Grimaldi (1958) with gratifying results. The method yields results reproducible to ± 10 percent in the range above 1 ppm (part per million) thorium; the reproducibility drops off rapidly below 1 ppm to about ± 50 percent at 0.5 ppm and ± 100 percent at 0.2 ppm (the limit of determination). We have few data regarding the accuracy of the method; satisfactory agreement with gamma ray spectrometry (Adams and others, 1958) and neutron activation methods (Hamilton, 1959) has been obtained on a few samples. Uranium has been determined by the fluorimetric method of Grimaldi and others (1952) adapted to lower concentrations of uranium. The method yields results reproducible and probably accurate to ± 10 percent down to 1 ppm uranium, with increase in uncertainty to ± 100 percent at 0.1 ppm.

ACKNOWLEDGMENTS

We are grateful to Prof. Esper S. Larsen, Jr. who initiated these studies on uranium and continued to provide helpful advice and guidance during much of our work. We should mention particularly the enthusiastic and careful work of the U. S. Geological Survey chemists who contributed the analytical data for this report; the thorium analyses were made by Lillie B. Jenkins and Esma Campbell; most of the uranium analyses were made by Alice Caemmerer and Roosevelt Moore, and the remainder by Marion Schnepfe, Marjorie Molloy and others. Several geologists cooperated by supplying many of the rocks studied and data concerning them; they are acknowledged individually below. The variation diagrams used in this paper are patterned after those proposed by Larsen, Jr. (1938).

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BATHOLITHIC ROCKS

Suites of igneous rocks from three large batholithic bodies, southern California, Sierra Nevada, and Idaho, have been analyzed for their thorium and uranium content. These batholiths are of calc-alkalic rocks ranging from gabbro to granite in composition. They are essentially contemporaneous in age —early Late Cretaceous according to a large number of lead-alpha age determinations (Larsen, Jr., Gottfried, Jaffe, and Waring, 1958). Larsen, Jr. and Schmidt (1958) have compared the southern California and Idaho batholiths and showed them to yield nearly identical chemical variation diagrams; the Sierra Nevada batholith is believed to be similar.

Southern California batholith

This batholith has been studied petrologically in great detail by Esper S. Larsen, Jr. (1948), and an extensive collection of the analyzed or petrographically studied specimens has been provided by him. Additional collections have been made by Gottfried. Twenty analyzed rock samples, ranging from gabbro to granite, have been further analyzed for uranium and thorium; uranium and thorium values are shown in figure 1 and the Th/U ratios in figure 10. The

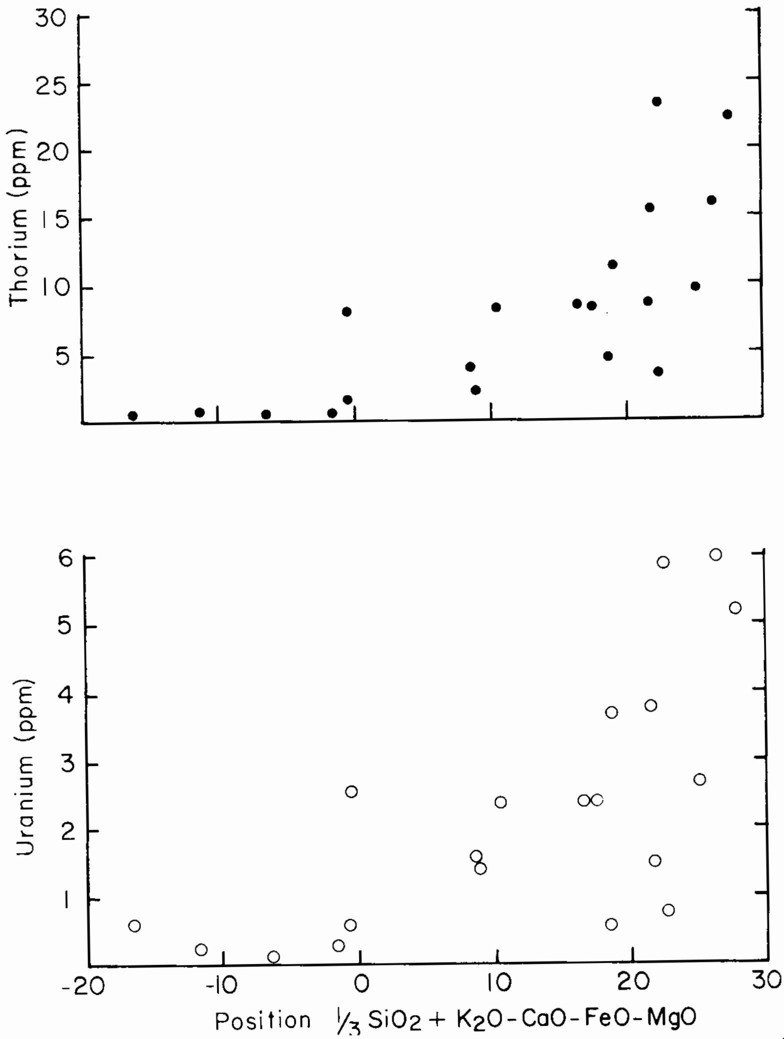

Fig. 1. Variation diagrams showing distribution of uranium and thorium in analyzed rocks of the southern California batholith.

usual relations are shown. Both uranium and thorium are quite low at the mafic end (uranium only a few tenths part per million and thorium less than one part per million in gabbro) and trend strongly upward toward the felsic end (uranium as much as 6 ppm and thorium as much as 23 ppm in the granites). The scatter of both thorium and uranium is large toward the felsic end. However, in most of those rocks in which uranium is relatively high, thorium is relatively high; when uranium is low, thorium is low. Thus the Th/U ratios show less dispersion; the mean Th/U ratio of the analyzed rocks is 3.8 and the dispersion of the individual values lie within twice or one-half of this value.

Thorium and uranium have been determined on 26 additional rock samples (studied only petrographically) and these values, together with the data on the analyzed samples mentioned above, are summarized by rock type in table 1. The wide scatter in both thorium and uranium values in each rock

TABLE 1

Thorium, uranium, and Th/U ratios in igneous rocks from the southern California, Sierra Nevada, and Idaho batholiths

Southern California

Rock types	Number of samples	Uranium (ppm) Range	Uranium (ppm) Avg.	Thorium (ppm) Range	Thorium (ppm) Avg.	Th/U Range	Th/U Avg.[1]
Gabbro	7	0.17-0.40	0.3	0.2-0.9	0.6	0.7-4.7	2.4
Tonalite	12	0.6-2.8	1.3	1.4-8.2	4.1	0.9-7.5	3.3
Granodiorite	24	1.1-4.2	2.0	3.1-15.2	7.8	2.2-6.5	4.2
Quartz monzonite and granite	2	5.2-5.3	5.2	16.0-22.2	19.1	3.0-4.3	3.7
Muscovite-quartz monzonite	1		1.0		5.5		5.5

Idaho

Rock types	Number of samples	Uranium (ppm) Range	Uranium (ppm) Avg.	Thorium (ppm) Range	Thorium (ppm) Avg.	Th/U Range	Th/U Avg.[1]
Gabbro	2	0.24-0.82	0.53	0.86-1.2	1.0	0.4-1.5	1.0
Tonalite	5	1.0-3.3	1.9	5.4-18.5	11.3	5.2-6.8	5.8
Granodiorite	12	1.1-5.1	2.4	5.4-23.2	10.3	1.6-7.1	4.8
Quartz monzonite and granite	5	2.2-6.3	4.4	14.3-22.0	17.8	2.9-8.2	4.7
Muscovite-quartz monzonite	5	0.5-1.9	1.5	4.9-7.9	6.5	4.7-5.8	5.3

Sierra Nevada

Rock types	Number of samples	Uranium (ppm) Range	Uranium (ppm) Avg.	Thorium (ppm) Range	Thorium (ppm) Avg.	Th/U Range	Th/U Avg.[1]
Granodiorite	2	5.2-5.2	5.2	14.3-24.0	19.2	2.8-4.7	3.8
Quartz monzonite and granite	5	2.3-7.2	4.3	7.6-36.0	18.7	3.3-5.0	4.2
Albite-quartz monzonite	1		2.0		9.4		4.8

[1]These data are the averages of individual Th/U ratios, not the ratio of the average thorium and uranium contents.

type is apparent, but the average thorium and uranium values (the arithmetic means) increase regularly from gabbro toward granite. The Th/U ratios show a somewhat greater dispersion for each rock type than for the analyzed rocks alone, perhaps owing to the inclusion of more erratic and uncommon rock types. Considering the batholith as a whole, the gabbros have a slightly lower Th/U ratio than the later differentiates; within the uncertainties of the averages, the rocks between tonalite and granite have much the same average Th/U ratio—between 3½ and 4.

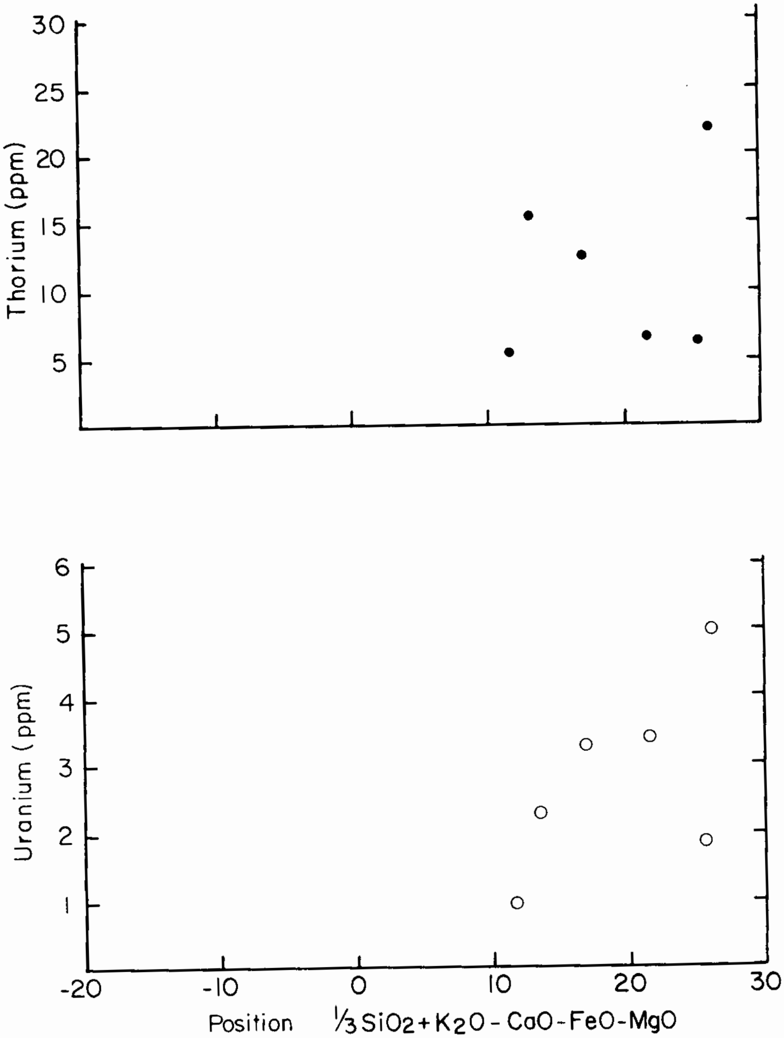

Fig. 2. Variation diagrams showing distribution of uranium and thorium in analyzed rocks of the Idaho batholith.

Idaho batholith

The Idaho batholith has been studied petrologically in broad reconnaissance by Larsen, Jr., and Schmidt (1958), and their collections of samples have been made available for this study. Only six analyzed rock samples, all of relatively felsic types, were available for uranium and thorium determinations; these data are shown on variation diagrams in figure 2. The wide scatter of both thorium and uranium values is quite similar to that shown for the equivalent analyzed rocks from the southern California batholith (fig. 1) and the Sierra Nevada batholith (fig. 3, see below). Table 1 presents the range and average thorium and uranium values for 29 rocks tabulated by rock type. The range of uranium values and the average uranium content for each rock type are very nearly the same (considering the relative uncertainties introduced by small numbers of samples and the analytical uncertainties below 1 ppm uranium) as those for the southern California batholith. The thorium values for gabbro and for quartz monzonite and granite are nearly the same as for comparable rocks from southern California, but the thorium contents of the tonalites and granodiorites are significantly greater. The Th/U ratios of the gabbros are low and comparable to those of the southern California rocks (fig. 10), but the Th/U ratios of the tonalites and more silicic rocks are significantly higher —the mean Th/U ratio ranging roughly between 4½ and 5½. Nearly all the samples have a Th/U ratio between twice and one-half the tabulated averages.

Sierra Nevada batholith

Eight analyzed samples from the eastern part of the Sierra Nevada batholith, in the Bishop area, were supplied by Paul Bateman, of the U. S. Geological Survey. These samples are of quite limited petrographic type, ranging from granodiorite to albite-quartz monzonite. The thorium and uranium contents of each are plotted on variation diagrams in figure 3. They show no relation of thorium or uranium to rock composition, but rather show a wide dispersion of both thorium and uranium, even greater than that of similar rocks from the southern California and Idaho batholiths. The ranges and average values of uranium and thorium, and of the Th/U ratios are tabulated for comparison in table 1. The range of Th/U ratios is quite small and the average values are near those of similar rocks in the southern California batholith.

Late differentiates

A few samples of rather extreme petrographic composition, and believed to be quite late in the intrusive history of the batholiths, have been analyzed for uranium and thorium. The analytical data are shown in table 1 for a single sample of muscovite-quartz-monzonite from the southern California batholith; five similar samples from the Idaho batholith; and a single sample from the Sierra Nevada batholith. They are markedly lower in both uranium and thorium than the more typical quartz-monzonites and granites. Paradoxically, the relatively rare accessory minerals monazite, xenotime, and highly radioactive zircon are commonly found in these muscovite-bearing rocks. The five muscovite-quartz monzonites from the Idaho batholith are particularly convincing in their low contents of both elements. The Th/U ratios, however, are not sig-

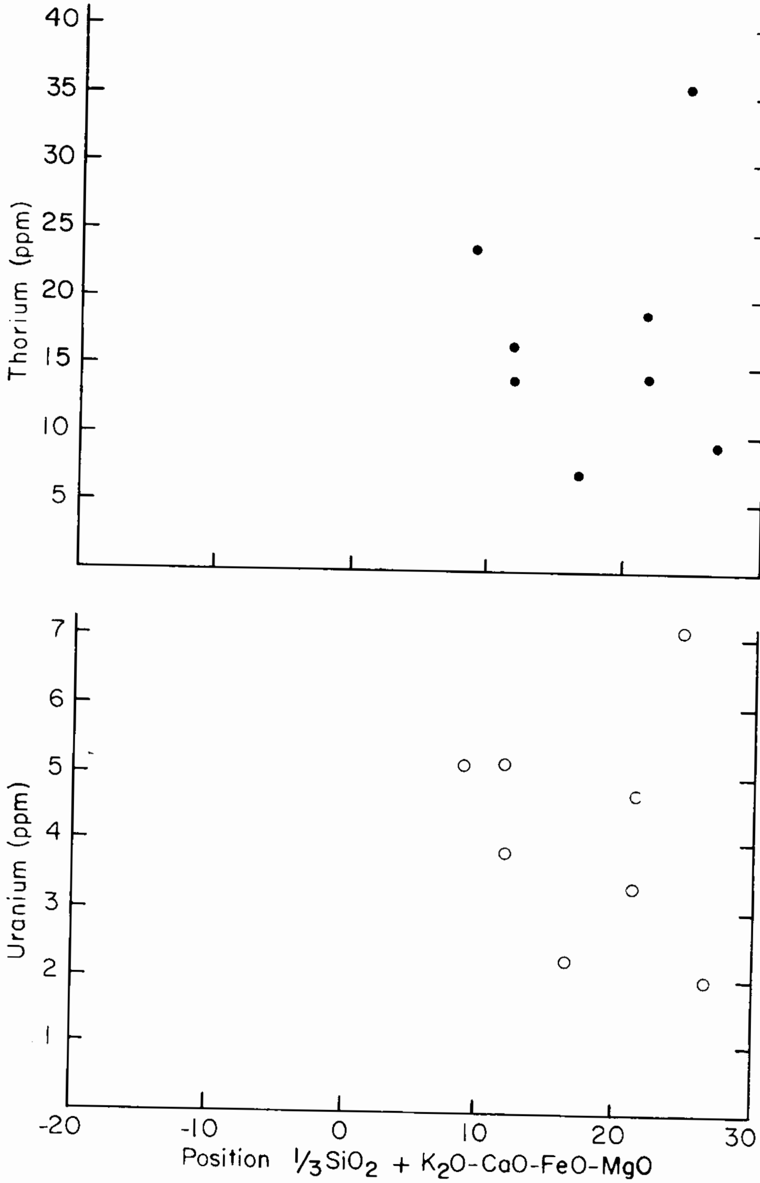

Fig. 3. Variation diagrams showing distribution of uranium and thorium in analyzed rocks of the Sierra Nevada batholith, California.

nificantly different from the more common rocks of these batholiths. Clearly neither uranium nor thorium has been selectively removed, but both uranium and thorium have been depleted in or lost from these "residual" magmas in constant proportions. We have no ready explanation for this.

VOLCANIC AND HYPABYSSAL ROCKS

Hawaiian Islands

Uranium and thorium were determined on 35 samples of volcanic rocks believed to be fairly representative of the major rock types of the Hawaiian Islands. Olivine basalts are the predominant rock type and according to Macdonald (1949) they represent the parent magma of the Hawaiian petrographic province. Powers (1955) points out that the olivine basalts of the older primitive shields are rarely silica deficient. He suggests that the name "olivine basalt" not be applied to the magma as it suggests a magma undersaturated with silica.

The undersaturated rocks that are present occur in considerably smaller amounts than the ordinary Hawaiian basalts and were formed during the declining stages of activity at some of the volcanoes.

Tilley (1950) showed that the basalts of the primitive shields from the Hawaiian Islands are very similar chemically to great basaltic provinces on the continents, such as the Triassic basalts from New Jersey, the Karoo dolerites, and the Deccan basalts of India.

All the samples which we have analyzed for uranium and thorium were made available by Howard Powers of the U. S. Geological Survey. These include samples studied by him and by other workers. A chemical rock analysis is available for each of the samples. The uranium and thorium values are summarized in table 2. Basalts from the Koolau volcanic series of Oahu studied by Wentworth and Winchell (1947) contain larger amounts of silica than most

TABLE 2

Uranium and thorium contents of volcanic rocks from the Hawaiian Islands

Location	No. of samples	Uranium Range	Uranium Avg.	Thorium Range	Thorium Avg.	Th/U Range	Th/U Avg.[1]
		Basalts of primitive stage of eruption					
Koolau volcanic series, Oahu	7	0.27-0.54	0.32	0.53-1.2	0.79	1.8-4.5	2.6
Mauna Loa, Hawaii	7	.21-0.28	.25	.63-0.98	.80	2.3-4.1	3.2
Kilauea, Hawaii	9	.28-0.41	.35	.84-1.4	1.1	2.6-3.5	3.1
		Volcanics of declining stage of eruption					
Andesite, Mauna Kea, Hawaii	1		1.3		3.6		2.8
Oligoclase andesite, Kohala	1		1.2		5.3		4.3
Olivine basalt, Kohala	1		.49		1.3		2.7
Olivine basalt, Hualalai, Hawaii	1		.41		1.4		3.4
Picrite basalt, Haleakala, Maui	1		.45		2.0		4.3
Alkalic basalts, Honolulu volcanic series, Oahu	7	0.58-3.2	1.8	2.5-10.4	5.4	2.6-4.7	3.1

[1] These data are the averages of individual Th/U ratios, not the ratio of the average Th and U contents.

Hawaiian basalts. They average about 0.3 ppm uranium, 0.8 ppm thorium, and have an average Th/U ratio of 2.6.

The samples from Mauna Loa and Kilauea are mostly olivine basalts. The uranium and thorium contents of the samples from Mauna Loa are exceedingly uniform. They average 0.25 ppm uranium and 0.8 ppm thorium. The Th/U ratio is 3.2. The samples from Kilauea also show marked uniformity in their uranium and thorium contents and have nearly the same average uranium and thorium contents as the samples from Mauna Loa. The average Th/U ratio for the Kilauea samples is 3.1.

The samples of the lavas erupted during the late, declining stage of volcanic activity form a thin veneer over the earlier extrusives. The volume of the late-stage volcanics is insignificant as compared to the volume of the earlier formed basalts. The basalts of the Honolulu volcanic series overlie the basalts

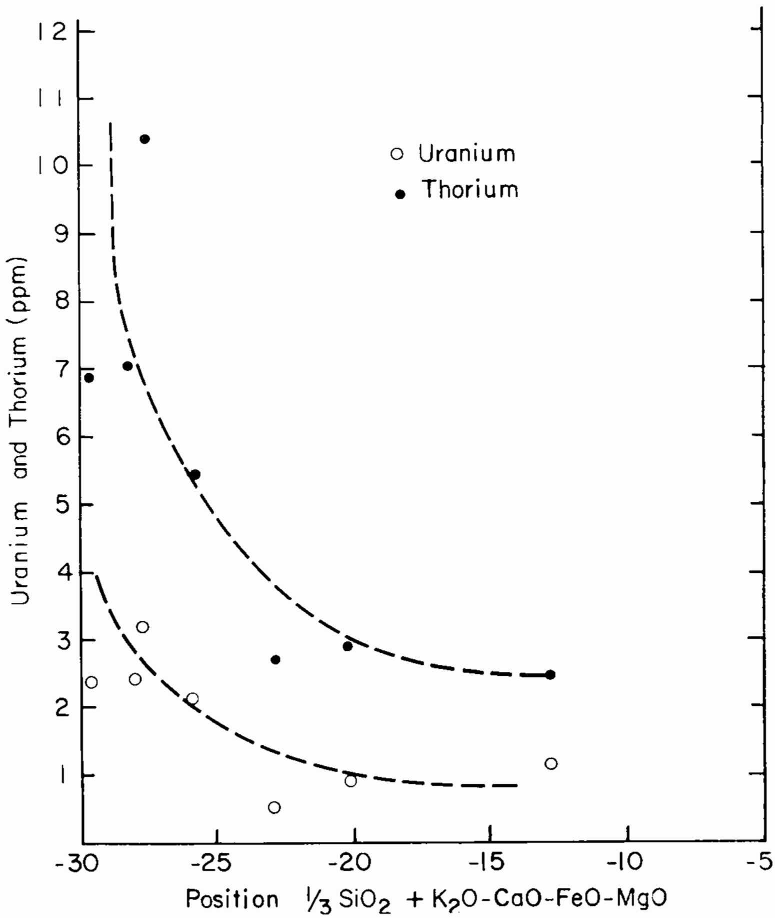

Fig. 4. Variation diagram showing distribution of uranium and thorium in analyzed rocks of the Honolulu volcanic series, Oahu, Hawaii.

of the Koolau volcanic series on the island of Oahu and are separated from them by a long erosion interval. They are low in silica (36-45 percent) with a relatively high alkali content. Petrographic studies show them to be nepheline basalt, nepheline basanite, and nepheline-melilite basalt (Winchell, 1947). The uranium and thorium values of seven samples from this series are plotted on a variation diagram on figure 4. Unlike any of the other variation curves showing the relation of uranium and thorium to chemical composition, the curves for the rocks of the Honolulu series show a decrease of uranium and thorium towards the right side of the diagram. Their average uranium (1.8 ppm) and thorium content (5.4 ppm) is higher than for any other series of volcanics from the Hawaiian Islands. However, the average Th/U ratio 3.1 is very similar to the average for the Mauna Loa and Kilauea samples (fig. 10).

Uranium and thorium determinations have been made on five samples from "late" eruptions. The two andesites contain more uranium and thorium than any of the olivine basalts. The three "late" basalts from Kohala and Hualalai on Hawaii, and Haleakala on Maui, contain a little more than 0.4 ppm uranium and 1.6 ppm thorium, which are a little higher than the average contents of the ordinary basalts. The average Th/U ratios of the two andesites is 3.5 and of the olivine basalts 3.6. More samples from these late eruptions are needed, however, before any firm conclusions can be drawn.

Fairfax County, Virginia

Twenty samples of igneous rocks from the diabase-granophyre sequence were analyzed for uranium and thorium contents. Because of lack of chemical data, the rocks are grouped in three categories based on petrographic data (E. C. T. Chao, U. S. Geological Survey, oral communication, 1958); (1) typical diabase, which consists essentially of monoclinic pyroxene and labradorite; (2) an intermediate phase containing amphibole, less calcic plagioclase, and small amounts of quartz; and (3) granophyric rocks consisting of albitic plagioclase, amphibole, and quartz.

The uranium and thorium determinations are summarized in table 3. Uranium and thorium show nearly a fivefold enrichment in the granophyric rocks over the typical diabase. The average Th/U ratios are approximately the same for each of the rock types.

TABLE 3

Uranium and thorium content of diabase-granophyre rocks[1] from Fairfax, Virginia

Rock type	No. of Samples	Uranium Range	Uranium Average	Thorium Range	Thorium Average	Th/U[2]
Typical diabase	11	0.2-0.7	0.5	0.8-3.1	2.1	4.3
Intermediate phase	5	0.8-2.0	1.4	2.6-8.5	5.4	3.9
Granophyric	4	1.9-3.3	2.5	8.2-13.1	9.6	4.0

[1] Samples supplied by E. C. T. Chao, U. S. Geological Survey.

[2] These data are the averages of individual Th/U ratios; not the ratio of the average uranium and average thorium contents.

Medicine Lake Highland, California

The Medicine Lake Highland is located approximately in the center of the Modoc Lava Bed quadrangle. The lavas which make up the Highland represent a well-differentiated series from basalt to rhyolite. The eight samples analyzed for uranium and thorium for this report are parts of the same material studied

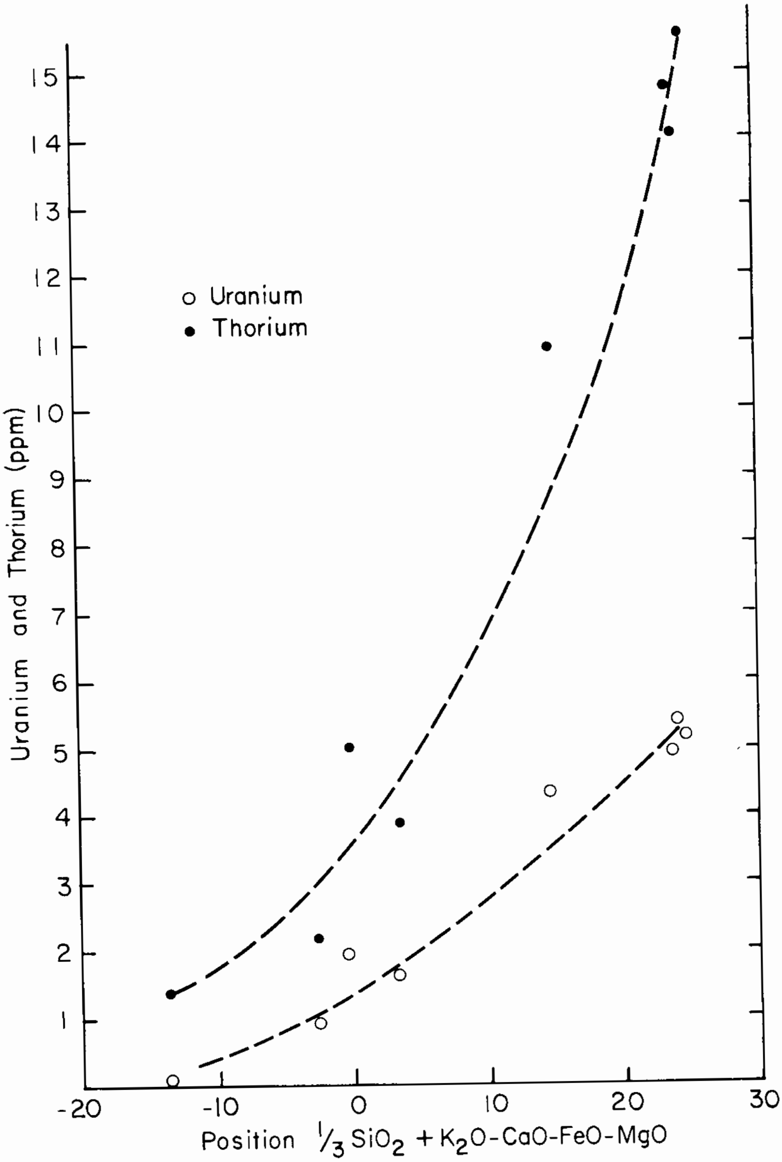

Fig. 5. Variation diagram showing the distribution of uranium and thorium in analyzed rocks of the Medicine Lake Highland, Calif.

by Anderson (1941), and were supplied by William Quaide of the Department of Geology, University of California (Berkeley). Conventional rock analyses are available for each specimen; the relation between chemical composition and uranium and thorium contents is shown in figure 5, and the Th/U ratios in figure 10. Both uranium and thorium are present in greater amounts in the more siliceous rocks than in the mafic rocks. One sample of basalt is extremely low in uranium, containing about 0.1 ppm (based on replicate analyses), and having a Th/U ratio of 14. The Th/U ratios in the two other basalts are 2.2 and 2.5. The rhyolites have Th/U ratios of 2.7 to 3.0. Except for one basalt with the Th/U ratio of 14, there seems to be a small increase in the Th/U ratios from basalts to rhyolites.

Lassen Volcanic National Park, California

The volcanic rocks from Lassen Volcanic National Park range from basalt to dacite. Compared with the volcanic rocks from the Medicine Lake Highland, which is regarded as a calc-alkalic series, the Lassen volcanic rocks are regarded as a calcic suite. Adams (1955) has reported uranium determinations and alpha activity on 39 samples from this area. He found that uranium increases with K_2O and that the relative alpha activity to uranium ratio is constant, indicating a constant Th/U ratio. Uranium and thorium determinations on 9 samples of volcanic rocks studies by Williams (1932) are plotted on a variation diagram on figure 6. These samples were supplied by William Quaide of the Department of Geology, University of California (Berkeley). There is a

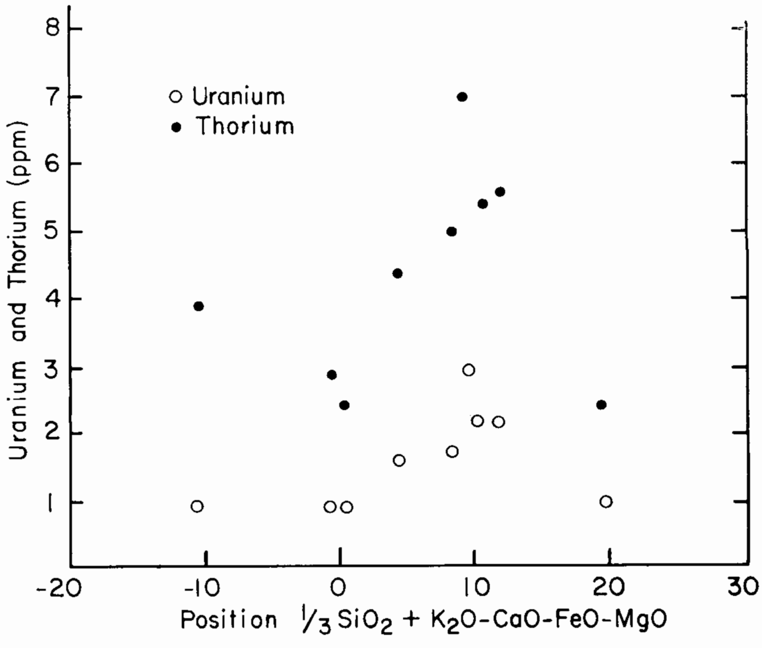

Fig. 6. Variation diagram showing the distribution of uranium and thorium in analyzed rocks of the Lassen Volcanic National Park, Calif.

clear trend toward increasing uranium and thorium in the more siliceous rocks except for one sample of dacite which is low in both uranium and thorium. This sample of dacite, the most siliceous rock of the suite analyzed for uranium and thorium, contains only 1.0 ppm uranium and 2.4 ppm thorium.

Too few samples have been analyzed by us to show any definite correlation of Th/U ratios with rock type. However, the available data indicate a small decrease in the Th/U ratios from basalt to dacite (fig. 10). The two basalts

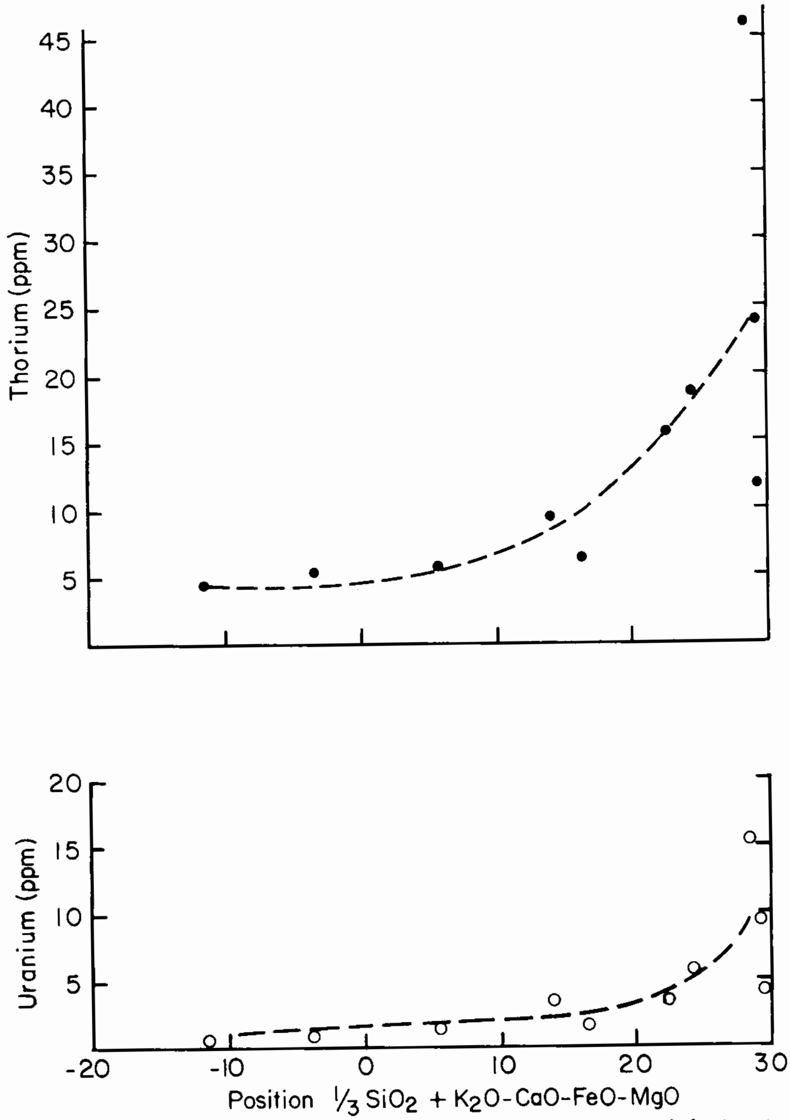

Fig. 7. Variation diagrams showing the distribution of uranium and thorium in analyzed rocks of the Valles Mountains, N. Mex.

have Th/U ratios of 4.0 and 3.0; the average Th/U ratio of five andesites is 2.7; and in the two dacites the Th/U ratio is 2.7 and 2.4.

Valles Mountains, New Mexico

A suite of 10 samples from the Valles Mountains consisting of basalt, andesite, dacite, rhyodacite, and rhyolite were analyzed for uranium and thorium. The samples and chemical analyses for each sample were provided by Robert L. Smith and Roy Bailey (U. S. Geological Survey). This suite of volcanic rocks is somewhat more alkalic than the Lassen and Medicine Lake Highland volcanic rocks. The data (fig. 7) show a fairly systematic increase of

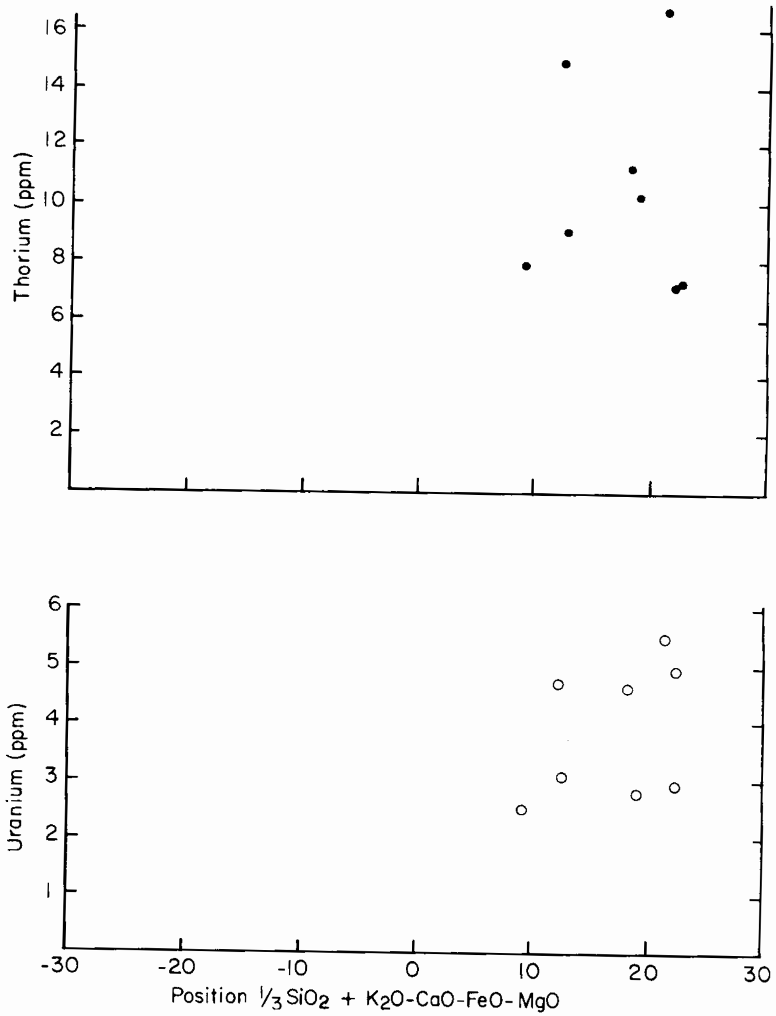

Fig. 8. Variation diagrams showing the distribution of uranium and thorium in analyzed silicic rocks of the Bearpaw Mountains, Mont.

uranium and thorium from the mafic to the siliceous rocks. The basalts contain about 1.0 ppm uranium and about 5.0 ppm thorium. The rhyolites range from 4 to about 15 ppm uranium and from 12 to 46 ppm thorium. The increase in uranium and thorium from basalts to rhyolites is greater than for any of the other volcanic provinces discussed in this report.

The Th/U ratios (fig. 10) show no systematic change with composition. The average Th/U ratios are as follows: basalt, 5.5; andesite, 3.3; dacite, 2.6; rhyodacite, 4.1; and rhyolite, 3.0.

Bearpaw Mountains, Montana

Thirty-four samples of extrusive and intrusive igneous rocks from the Bearpaw Mountains were analyzed for uranium and thorium. Eight of the samples are different types of latitic rocks from a silicic series, and 26 samples are rocks of a subsilicic-alkalic series which are predominantly mafic phono-

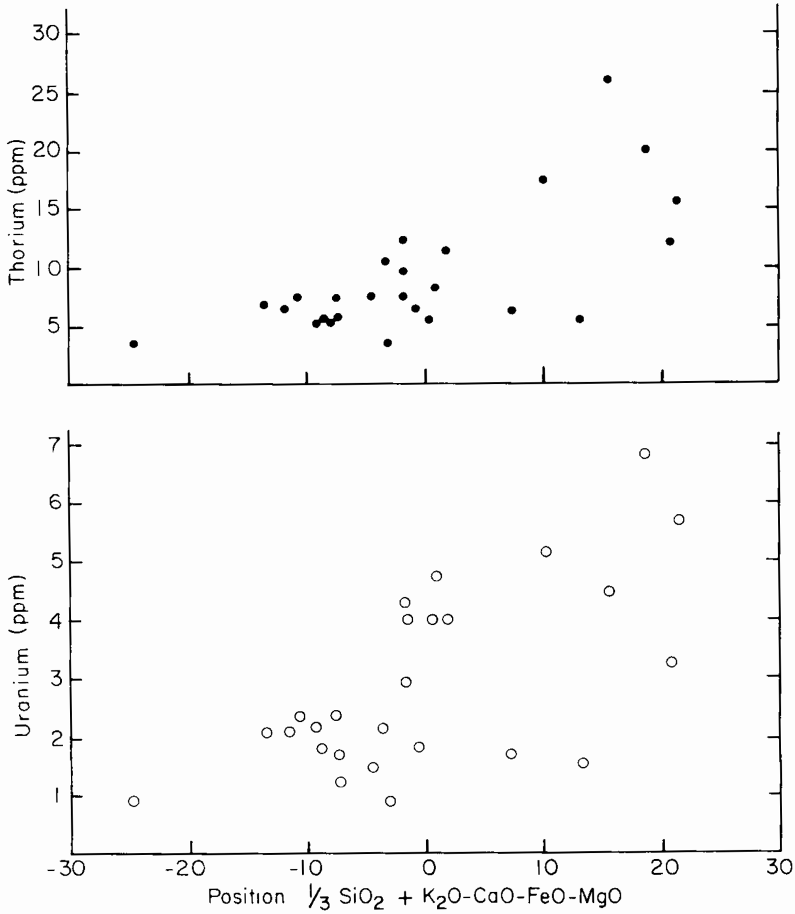

Fig. 9. Variation diagrams showing the distribution of uranium and thorium in analyzed subsilicic-alkalic rocks of the Bearpaw Mountains, Mont.

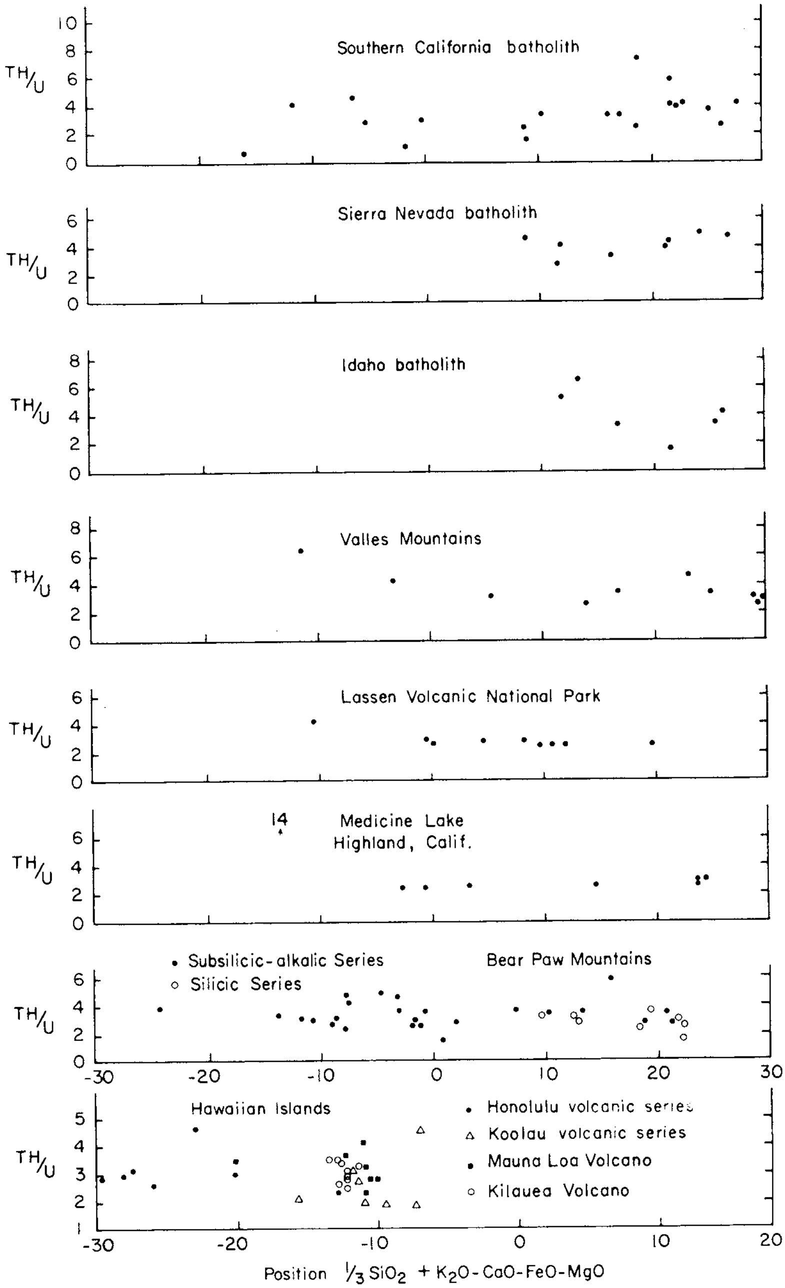

Fig. 10. Variation diagrams showing the distribution of thorium-uranium ratios in analyzed rocks from eight of the igneous provinces considered in this report. Note that the horizontal and vertical scales of the bottom diagram (Hawaiian Islands) are different from the others.

lites and shonkinites. The samples and chemical analyses were made available to us by W. T. Pecora and Robert G. Schmidt, U. S. Geological Survey. The latitic rocks average 3.9 and 10.6 ppm uranium and thorium respectively, and have an average Th/U ratio of 2.8. The uranium and thorium data for these samples are plotted on figure 8 and the Th/U ratios on figure 10.

Figure 9 shows the distribution of uranium and thorium in 26 rocks of the subsilicic-alkalic series. The most mafic rock is a biotite pyroxenite which contains a little less than 1 ppm uranium and 3.9 ppm thorium. The shonkinites and phonolites average 2.4 and 7.2 ppm of uranium and thorium respectively. The syenites, which lie on the right side of the variation diagram, average 4.1 and 14.3 ppm uranium and thorium. The Th/U ratio of each of the rocks is plotted in figure 10. The average Th/U ratio for the biotite pyroxenite is 4.1· the shonkinites and phonolites, 3.3; and the syenites 3.6.

DISCUSSION AND CONCLUSIONS

1. In the calc-alkalic and subsilicic-alkalic series of rocks we have studied, there is the usual increase in both uranium and thorium from the mafic to the felsic types. The scatter of both uranium and thorium values from "average" curves for each series is greater the more complex the history of differentiation of the magma producing the rocks. The batholithic rocks show an increasing dispersion of these elements toward the felsic end, whereas several of the volcanic series yield "average" curves from which analyzed values deviate very little.

The Honolulu volcanic series, a series of undersaturated basalts very low in SiO_2 and relatively high in alkalies, shows an unusual and strong reversal of the trend of both uranium and thorium in a variation diagram. Uranium and thorium decrease markedly and uniformly toward the right on a variation diagram (fig. 4), although they do not vary systematically with K_2O.

2. Several of the igneous provinces or subprovinces studied have more or less characteristic variation curves for both uranium and thorium. Provinces having relatively greater alkali contents but normal silica contents (such as the Valles Mountains) contain more of both thorium and uranium, on the average.

3. The Th/U ratios in the igneous rock series considered here are rather uniform for each series, although each series has a more or less characteristic ratio ranging approximately from 2½ to 5. In the simpler volcanic series, the ratios are fairly constant from basalts to rhyolites. In the volcanic series believed to have a more complicated pattern of differentiation, the Th/U ratios show somewhat more dispersion, but the average Th/U ratios are still relatively constant, within the limits of sample variations and analytical errors, regardless of stage of differentiation. In the batholithic rocks, the gabbros are significantly low in thorium relative to uranium, yielding low Th/U ratios. From the tonalites to the granites, the mean Th/U ratio of each rock type is essentially constant. This is true even of the late, more extreme differentiates, which are relatively low in both thorium and uranium, but show quite "normal" Th/U ratios.

Our data are in conflict with those of Whitfield and others (1959). They report an aparent increase in thorium relative to uranium during petrogenetic evolution (Whitfield and others, 1959, p. 264). Except in the gabbros of the batholithic rocks, we find no systematic variation of thorium relative to uranium; rather, the two elements, on the average, remain in remarkably constant proportions for each province. However, there are clear provincial differences; for example, the tonalites to granites of the southern California batholith have a mean Th/U ratio near 4, whereas similar rocks of the Idaho batholith yield a ratio near 5.

In late-stage differentiates which are associated in space and in time with vein deposits of pitchblende, Phair (1952) found that both thorium and uranium are greatly enriched, but that thorium is more enriched than uranium, the Th/U ratios averaging about 7½. He believes that, for these rocks, the relative enrichment of thorium was the result of a loss of some uranium from the late differentiates because of oxidation of uranium and its consequent increased solubility. From their studies of scattered samples (and not of petrogenetic suites), Whitfield and others (1959) have drawn the more far-reaching conclusion that increasing Th/U ratios during petrogenetic evolution of granitic rocks are the general rule, and that oxidation of uranium and its increased solubility is the usual mechanism for this relative enrichment of thorium. Our data, however, show no evidence of such systematic loss of uranium from the magma (or increase of thorium in the rocks) during the later stages of differentiation of the igneous provinces reported on here. We are unable to accept the suggested mechanism to explain the relatively greater abundance of uranium in the gabbros of the batholiths although we have no other explanation to offer.

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