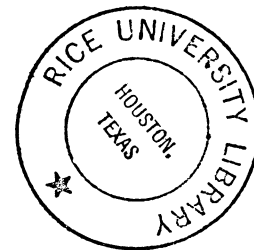


THE RICE INSTITUTE



THE THORIUM AND
URANIUM CONTENT OF THE
ENCHANTED ROCK BATHOLITH

by

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A THESIS
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INTRODUCTION

The object of this investigation is to study variations in the distribution of thorium and uranium within one granitic pluton and to relate these variations to the petrographic types and position within the pluton. For this purpose thirty-six samples were collected from the Enchanted Rock batholith in Llano and Gillespie Counties, Texas. These samples have been analysed for thorium, uranium, and potassium by radiometric methods.

PREVIOUS WORK

Comprehensive summaries on the distribution of thorium and uranium in igneous rocks have been presented by Adams, Osmond and Rogers (1959), Whitfield (1958) and Whitfield et al (1959). Whitfield investigated large-scale variations in thorium and uranium contents of granitic rocks and related these to the major petrogenesis of granitic rocks. He reached the following general conclusions:

- "1. Thorium and uranium are both controlled by the major petrogenesis of the granitic rocks to an extent heretofore not realized.
2. Uranium and thorium both increase with increasing alkalinity and acidity, and, therefore, with general petrogenetic evolution of the igneous rocks.
3. Thorium generally increases more regularly and more rapidly than uranium, thus resulting in an increase of Th/U ratio, with general petrogenetic evolution of the granitic rocks.
4. Anomalously thorium rich granites have been noted; their petrologic characteristics are very similar. Most of them are red in color, porphyritic, alkalic, and allanite bearing.
5. The increase of Th/U ratio may be explained by oxidation or complexing and subsequent loss of uranium from the magma in the stages of differentiation.
6. Plutons of different types may have characteristically high or low contents of uranium and thorium."

The increase of thorium and uranium contents of igneous rocks with increasing acidity has been reported by several authors (Billings and Keevil, 1946; Larsen Jr. and Phair, 1954; Larsen et al, 1956). Some subsilicic alkaline rocks exhibiting high concentrations of thorium and uranium indicate that the amounts present are not solely dependent on the silica content. Larsen, Jr. and Phair (1954) indicate that concentrations of thorium and uranium may be present in late-forming

rocks of many types. Larsen (1956) found a systematic variation of total uranium and leachable uranium with increasing silica and alkali content of the rocks.

The association of thorium and uranium during magmatic differentiation (Rankama and Sahama, 1950) but not during hydrothermal conditions is explained by Larsen Jr. and Phair (1954). Similarities in ionic size, charge and low concentration allow both thorium and uranium to behave similarly during crystallization. Larsen and Phair postulate that in the late magmatic cycle the 4-valent uranium is oxidized to the highly soluble 6-valent uranium with subsequent hydrothermal escape from the magma. Thorium, which has only one stable valence, is not soluble under oxidizing conditions.

Sites of radioactivity

Much of the thorium and uranium in granitic rocks appears to be associated with the major rock-forming minerals (Larsen et al, 1956). Larsen estimated that 25% of the thorium and uranium in igneous rocks is concentrated in the common accessories, as sphene, zircon, and apatite. Coppens (1951) states that between 60-70% of the alpha activity of igneous rocks is contained in all of the accessory minerals.

The large size and high ionic charge of thorium and uranium prevent them from entering the lattices of the common rock forming minerals. According to Adams, Osmond and Rogers (1959), thorium and uranium may be associated with the major rock forming minerals as liquid inclusions, fracture fillings, fixations in lattice imperfections, or by absorption on crystal surfaces. It is not known whether the intergranular radioactive material occurs as adsorbed ions or as

fine-grained minerals and secondary hydrothermal minerals.

Adams, Osmond and Rogers (1959) have summarized the available data on the thorium and uranium contents of both major and accessory minerals. Most minerals show a large variation in thorium and uranium concentrations but a correspondingly smaller spread in the Th/U ratios.

Variation of thorium and uranium contents within plutons

The ranges of concentration of thorium and uranium within individual plutons and even within rock types is commonly quite broad. The differences are commonly greater than the average differences between the various igneous rock types, as presented by Adams, Osmond and Rogers (1959). Many authors have noted peripheral concentration of radioactivity within individual plutons (see compilations by Whitfield, 1958).

Ingham and Keevil (1951) in their study of the Bourlamaque, Elzevir and Cheddar batholiths of Canada found that 6 out of 9 intrusions comprising these bodies show peripheral concentration of alpha activity. The most distinct gradations in radioactivity were found in the larger Cheddar, Elzevir and Bourlamaque batholiths. The Elzevir batholith and the related intrusions comprising the mass all featured an inner area of low radioactivity surrounded by a more radioactive border zone. In the Cheddar batholith the radioactive border zone coincided roughly with the peripheral distribution of pegmatitic granite. The masses of pegmatitic granite scattered within the interior, however, were not particularly radioactive.

The related intrusions of the Elzevir mass consisted of series from early diorite through syenite to later granites and pegmatites. Radioactivity increased with acidity through the pegmatitic stage. The most variable rocks were of intermediate acidity. Later quartz veins were impoverished in radioactivity.

Ingham and Keevil (1951) found no relationship between color, composition or texture of the pink granite of the Cheddar batholith and its radioactivity. A greater proportion of the highly radioactive rocks, however, was found in the gneissic granites.

Larsen et al (1956) found an enrichment of uranium in the border quartz diorite gneisses in the Boulder Creek batholith of Colorado. The authors considered it probable that the high uranium content of the border zone resulted from assimilation or reaction with older uraniferous rocks.

The radioactivity of the Caledonian granites of Central Tyan-Shan has been investigated by Krylov (1958). Two separate intrusions are represented in the complex. Gray porphyritic granites grading into granodiorites are the predominant rocks of the first intrusion. The granites of the second intrusion contain a 50% increase of thorium and uranium over the gray porphyritic granites with a corresponding slight increase in potassium content. Krylov found a greater variation in the radioactivity of the second phase granites and attributed it to differences in structural type, size and post-magmatic processes. It is interesting to note that aplitic and pegmatite dikes were abundant in the first intrusion but totally absent in the higher, but more variably radioactive pink granites. The distribution of radioactivity within each intrusion was not discussed.

Many plutons reportedly lack peripheral concentration of uranium. The Woodson Mountain granodiorite stock (Gottfried and Larsen, 1954) and the Milumo stock (Asayama, 1954) lack peripheral concentration of radioactivity. Keevil et al (1943) report that larger intrusions tend to have greater internal variability in radioactivity. Greater variation in uranium values with increasing size of pluton was also found by Phair (1956) in the study of the Front Range, Pre-Cambrian, "Silver Plume" granite.

Some information concerning variation of thorium and uranium contents within plutons was obtained from the investigation made by Whitfield et al (1959) on the relationships between petrology and thorium and uranium contents of some granitic rocks. The Bucks granodiorite was sampled in three localities from the contact toward the center portion. The differences reported were quite small. Three samples from the Idaho batholith showed a greater variation. One sample from the inner leucogranodiorite facies showed a low content of both thorium (5ppm) and uranium (.6ppm). The two samples from the outer granodiorite facies varied from 7.7 to 12 ppm thorium and 4.6 to .8 ppm uranium. No petrographic distinctions were noted between them.

Two samples collected from the Enchanted Rock batholith, 200 feet apart, showed no variation in thorium and uranium contents. A third sample from an aplite dike of the same locality showed thorium and uranium values half that of the main granite outcrop.

High thorium values were found in two samples collected from the Pikes Peak batholith. Both samples were collected near the contact in different parts of the batholith. The thorium content decreased inward from the contacts but was accompanied by a relatively greater decrease in uranium, resulting in increased Th/U ratios.

Two samples of the Cathedral Peak granite showed no variation in the high thorium content but almost a two fold difference in the high uranium values.

One sample collected from the border of the Marysville stock had a higher thorium and a lower uranium content than a sample from the center of the batholith.

In summarizing the variation within these intrusions, Whitfield et al (1959, p. 263) state:

".....In Bucks granodiorite and the Enchanted Rock batholith, like petrographic types are of similar thorium and uranium contents. In the Idaho batholith and probably in the Cathedral Peak and Pikes Peak granites, apparently similar petrographic types vary widely in uranium content and slightly in thorium content. In the Enchanted Rock batholith, the Marysville stock and, to a lesser extent, in the Pikes Peak granite, variations in thorium and uranium are accompanied by petrographic or textural variations."

The writers, however, do not intend to relate thorium or uranium genetically to the petrographic variation. In conclusion the writers state (p. 263):

"Some variation of thorium and uranium contents within plutons cannot be entirely attributed to, or even related to, gross petrographic variations. Thus, in comparing different types of plutons and general lithologic types, a certain amount of variation due to position within the pluton must be expected."

Correlation

Many authors have correlated radioactivity with other measurable properties of rocks. Radioactivity has been correlated with 1) silica content, 2) concentration of various accessory minerals, particularly zircon, apatite and allanite, 3) potassium content.

Increasing radioactivity with increasing silica content has been reported by several authors (Billings and Keevil, 1946; Larsen Jr. and Phair, 1954; Larsen et al, 1956). High concentrations of thorium and uranium in subsilicic alkaline rocks preclude direct correlation between silica content and thorium and uranium concentration.

Correlation between increasing amounts of accessory minerals with increasing radioactivity has been reported by Billings and Keevil (1946), Keevil et al (1943), and Soloviev (1936).

Many authors have found radioactivity to vary with potassium content (Larsen and Keevil, 1947; Larsen et al, 1956). More recently, Whitfield et al (1959) found a marked co-variation of potassium and thorium (figure 1). Uranium and Th/U ratios were highly scattered when plotted against potassium.

Whitfield et al (1959) plotted various petrographic parameters against thorium and uranium contents and Th/U ratios of some granitic rocks. Thorium and uranium both increased with increased potassium feldspar/plagioclase ratio, with thorium increasing at a greater rate than uranium. Uranium showed no relationship to the color index, but thorium decreased markedly with increasing color index. A linear relationship was found between thorium content and quartz content for thorium values under 20 ppm. Uranium and Th/U values

showed no relationship to quartz content.

The relationships found between thorium, uranium, and Th/U ratio by Whitfield (1958) are seen in figures 2-4. An increase of thorium with increasing uranium is apparent, but several anomalously high thorium rocks preclude stating the reverse. Thorium increases linearly with increasing Th/U ratio, but uranium shows no such systematic relationship. Whitfield found that thorium increased at an increasing rate with decreasing anorthite content of the plagioclase. No trend could be established between uranium and anorthite content.

Anomalously thorium-rich granites reported by Whitfield (1958) have similar petrologic characteristics. Most of them were found to be red, porphyritic, alkalic and allanite bearing. Ingham and Keevil (1951) noted that no relationship was apparent between the radioactivity of the Elzevir, Bourlamaque and Cheddar batholiths, and color, mineralogy and texture.

Radioactivity of Contact Zones

Little is known on the migration of thorium and uranium into the country rocks of invading intrusions. Ingham and Keevil (1951), in studying the radioactivity of the Elzevir, Bourlamaque and Cheddar batholiths, made several determinations on the invaded zone. They found that where granitization had occurred, the volcanic wall rocks had higher than normal activities.

Secondary concentrations of uranium have been reported by Thurlow (1956) in shear zones in the metamorphosed sediments

parallel with the contact of the Loon Lake granite intrusion, Washington. Uranium mineralization in intrusive rocks near Austin, Nevada (Thurlow, 1956) occurs in faults and fractures in both the intrusive and metamorphosed sedimentary rocks. The uranium minerals are also disseminated within roof pendants of metamorphic rocks near their contacts with the intrusive. These uranium deposits are believed to have been derived from the original magma. Migration of uranium into a contact metamorphic zone has also been observed by Krylov (1956).

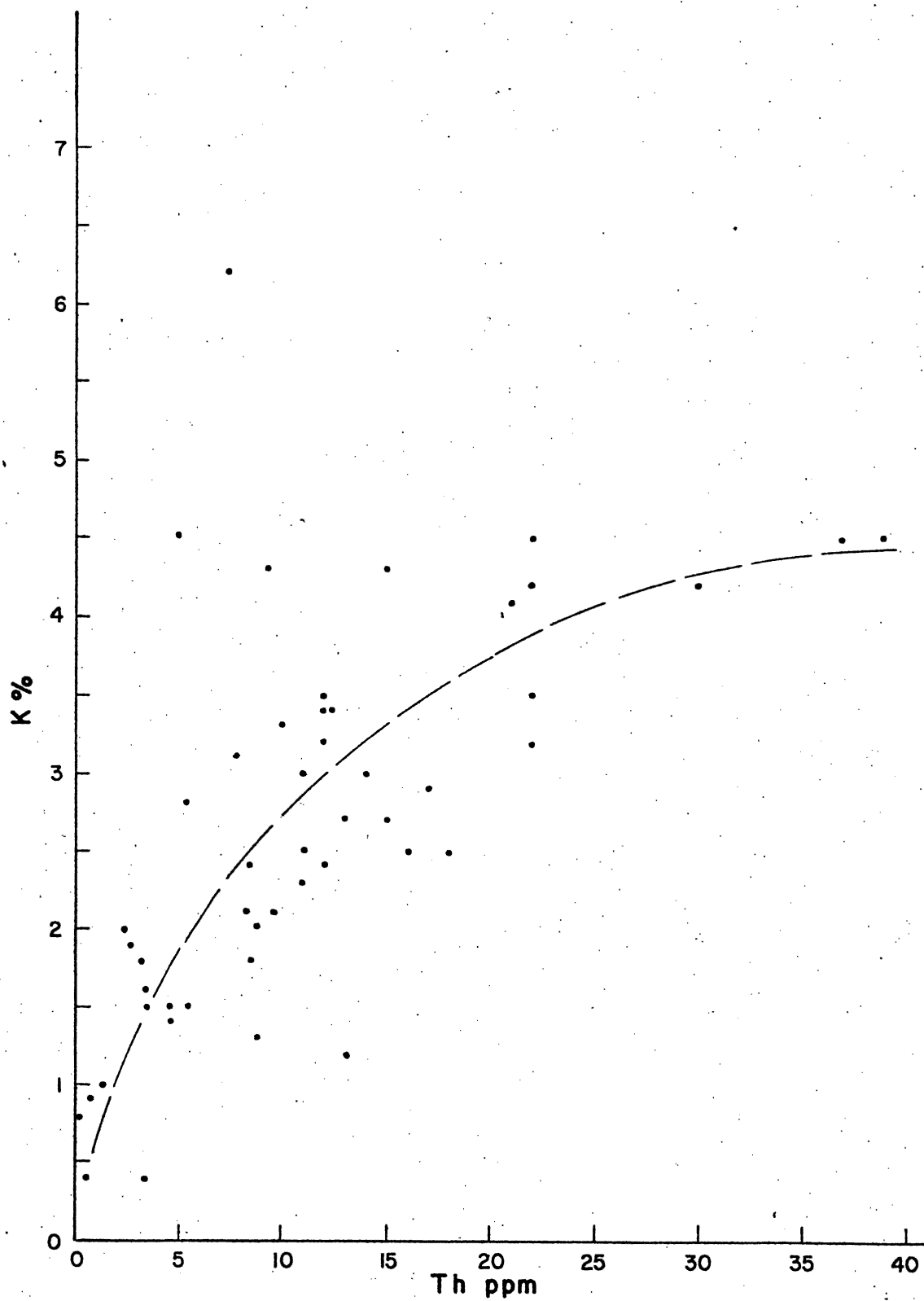


Figure 1.- Thorium content versus potassium content of granitic rocks analysed by Whitfield (1958, p. 130).

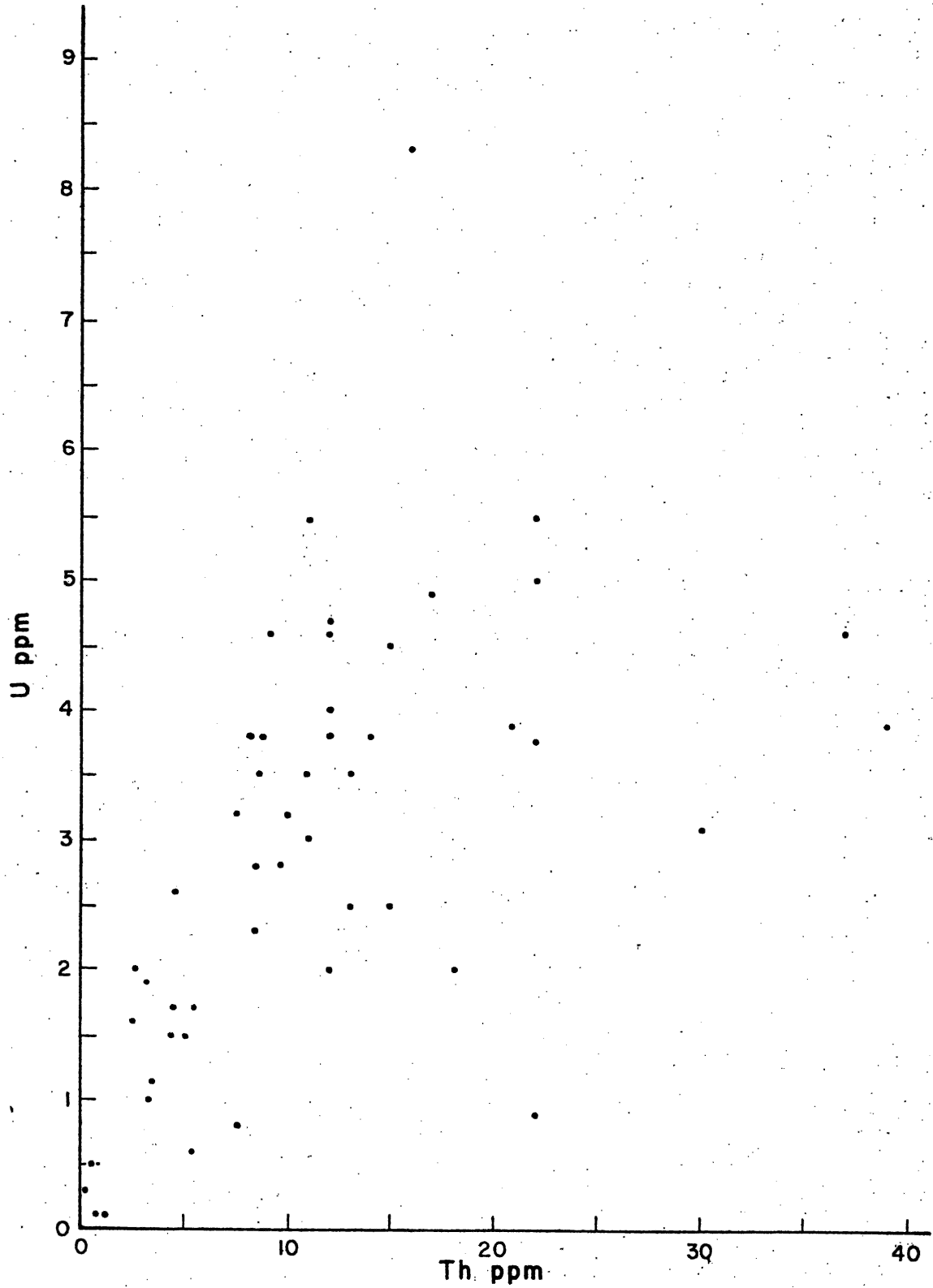


Figure 2.- Thorium content versus uranium content of granitic rocks analysed by Whitfield (1958, p. 123).

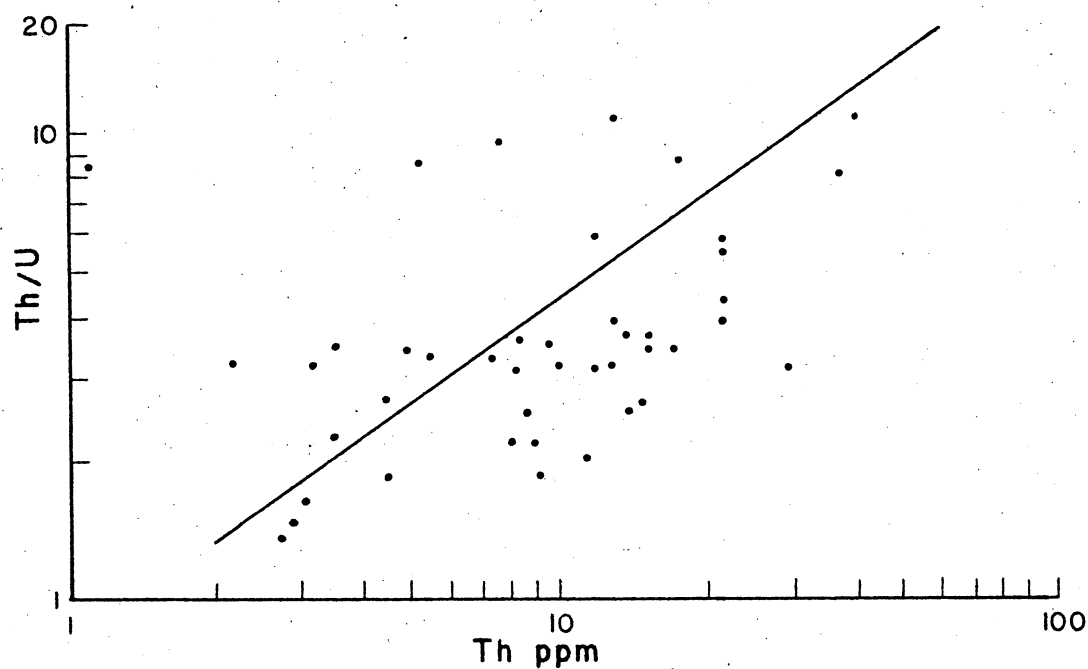


Figure 3.- Thorium content versus Th/U ratio of granitic rock analysed by Whitfield (1958, p. 124).

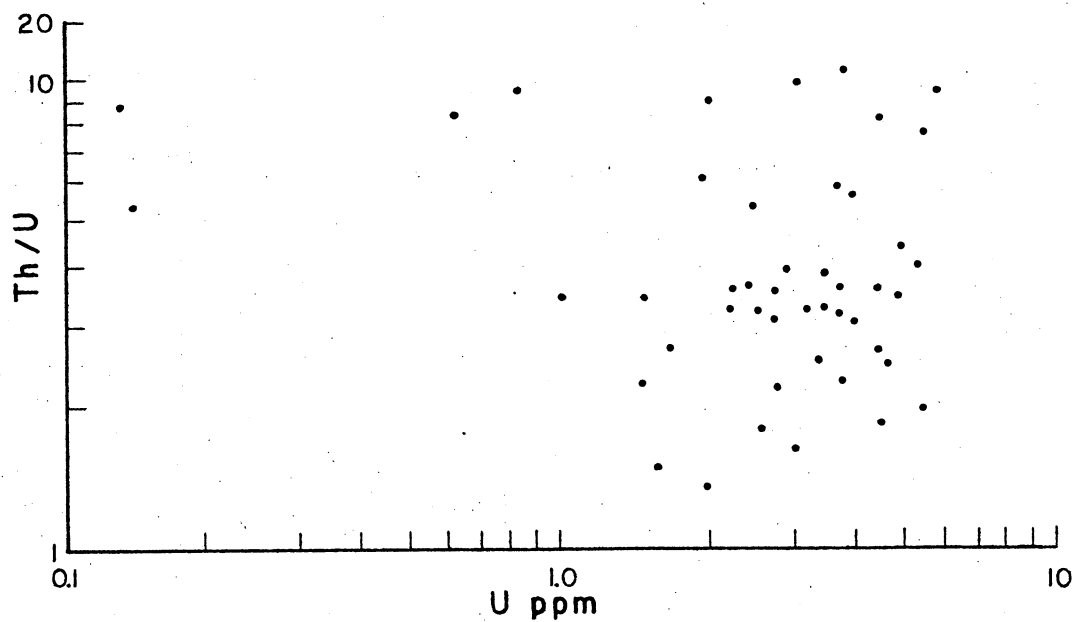


Figure 4.- Uranium content versus Th/U ratio of granitic rocks analysed by Whitfield (1958, p. 124).

PROCEDURE

The radiometric method for the quantitative determination of thorium, uranium and potassium in rock samples was used in this investigation. Gamma radiation spectral analysis for the determination of these elements has been discussed by Hurley (1956), Adams et al (1958) and Whitfield (1958). The methods described by Whitfield (1958) were used in this study.

The statistical error involved in radiometric determinations has been fully discussed by Whitfield (1958). Whitfield estimated the accuracy to be between ± 5 percent and ± 15 percent. Pliler (1959) analysed thirty shales for thorium by both radiometric and chemical means and found less than 7 percent average variation between methods. The large variations are more common in the rock samples with relatively low concentrations of thorium (less than 10 ppm). Since most of the rocks in this study contain greater than 10 ppm thorium, this author considers an upper limit of error of ± 7 percent adequate. Checks on the stability of the instrument were made by weekly re-determinations of samples previously analyzed by Whitfield (1958), Richardson (1959) and Pliler (1959). The comparisons are shown in table 1.

Table 1. - Comparison of rechecks and earlier determinations for thorium, uranium and potassium by gamma-ray spectrometry.

Sample	Th ppm	U ppm	K %
JW-SC 12-60	1. 12.2	3.3	2.3
	2. 12.4	3.9	2.5
JW-NH5-307	1. 82.5	18.6	4.1
	2. 84.6	17.5	4.5
JW-P11-141	1. 5.4	1.7	1.5
	2. 5.5	1.7	1.6
JW-P13-143	1. 8.7	3.5	2.0
	2. 9.1	3.5	2.3
JW-SC 70*	1. 4.5	.9	2.1
	2. 3.1	1.9	1.8
JW-W3-399*	1. 12.2	3.8	3.4
	2. 11.9	2.0	5.3
JW-KA6-405	1. 11.9	4.7	3.5
	2. 13.7	4.3	3.8
JW-M3-205*	1. 2.5	1.6	2.0
	2. 2.4	1.4	2.2
KR-74-1	1. 94.7	7.8	0.0
	2. 96.9	9.2	0.0
RP-WR-4	1. 13.3	1.4	2.3
	2. 12.4	1.4	2.3
RP-Grid-A-1	1. 11.5	2.6	1.9
	2. 11.7	2.8	1.9
RP-Grid J	1. 18.5	2.9	2.0
	2. 12.3	3.0	2.1

1. refers to first determination

2. refers to second determination

* rechecks made on three channels only

THE THORIUM AND URANIUM CONTENT OF THE ENCHANTED ROCK BATHOLITH

Description

The following description of the Enchanted Rock batholith has been taken in large part from Hutchinson (1956). The Enchanted Rock batholith crops out in the south-central part of the Llano uplift in Llano and Gillespie Counties, Texas. It covers an area of 110 square miles. The Enchanted Rock batholith is a pear-shaped granite-quartz monzonite-granodiorite intrusion into tightly folded Pre-Cambrian metamorphic rocks. The pluton is both concordant and discordant with the surrounding metamorphics. The northern third of the batholith is phacolithic.

Hutchinson has described five kinds of granitic rocks within the batholith: leucogranite, granite, leuco-quartz monzonite, quartz monzonite and alkalic granodiorite. Hutchinson further classed these rock types into four concentric zones. The outer zone consists of medium to coarse leucogranite and granite. The intermediate zone consists of medium to coarse granite and quartz monzonite. Coarse quartz monzonite and alkalic granodiorite make up the rocks within the intermediate-central zone. The fine- to medium-grained rocks of the core include both leuco-quartz monzonite and leucogranite. The rock zones parallel flow structures in most places. In the north and south parts of the batholith, Hutchinson found that the flow structures cross rock boundaries and are independent of them. Hutchinson states that the flow structures and the gradational nature of all rock zones suggest (p.777): "contemporaneity of development as well as emplacement of the

granite mass as a single unit".

Figure 5 is a map of the Enchanted Rock batholith, showing the rock zones as delineated by Hutchinson and the location of specimens collected for this investigation. The intrusion contains associated pegmatites, aplites, aplogranites, and quartz-enriched zones. These are indicated on the map by solid shapes. The northern, phacolithic third of the batholith was not sampled.

Contacts between all rock zones are gradational. Slight changes of color and relative proportions of minerals present are detectable over a short distance between the intermediate-central and intermediate zones. Generally the rocks consist of orange-pink to reddish orange phenocrysts of microcline in a groundmass of light gray plagioclase, clear quartz, with scattered microcline and biotite. The rocks of the outer, intermediate, and intermediate-central zones are predominantly seriate porphyritic. Hiatal porphyritic and some porphyritic texture occur in the core rocks. The groundmass texture of the batholith, exclusive of the core, is medium to coarse. The core rock has a predominantly fine- to slightly medium-grained groundmass.

Presentation of data

A total of thirty-six samples representing the Enchanted Rock batholith and its associated rocks have been analyzed for thorium, uranium and potassium by gamma-ray scintillation spectrometry. The results are presented in table 2. Modal analyses have been made on most of the thin sections and are summarized in table 3. The locations and descriptions of the samples collected are summarized in the appendix.

The collection was principally intended as a study of within-pluton variations. Some of the associated rocks within the main intrusive, and adjacent metamorphics, have been analyzed in an attempt to obtain some information on the radioactive trace element variations between them and the main granitic mass.

Of the thirty-six samples analyzed, twenty-three were collected from the five rock types described by Hutchinson (1956). The results from these rocks are presented in table 4, listed according to the zones enumerated by Hutchinson.

Large variations in thorium and uranium contents occur between samples collected within short distances. Sample MCK-32A is a fine-grained leuco-quartz monzonite grading into the medium- to coarse-grained leuco-quartz monzonite sample, MCK-32B, constituting the main mass of the outcrop. The variation in thorium and uranium contents is quite large. Sample MCK-32B has a normal content of thorium and uranium (14.6, 3.5 ppm) with a Th/U ratio of 4.7. The thorium and uranium contents of MCK-32A are abnormally high (28.3, 17.2 ppm),

Table 2. - Thorium, uranium and potassium contents of all rocks analyzed in this investigation

Sample	Th/U	Th ppm	U ppm	K %
MCK-1	11.0	18.2	1.7	4.9
MCK-2	9.2	19.1	2.1	4.7
MCK-3	13.4	20.4	1.5	4.6
MCK-4	14.3	22.8	1.6	10.1
MCK-5	11.8	23.6	2.0	2.7
MCK-6	3.3	5.7	1.8	1.7
MCK-7	3.4	5.6	1.6	1.6
MCK-8	3.5	5.5	1.6	1.6
MCK-9	3.8	7.6	2.5	2.8
MCK-10	2.7	6.7	2.5	3.2
MCK-11	4.5	16.8	3.7	4.1
MCK-12	4.3	17.5	4.1	4.3
MCK-13	3.5	17.4	5.0	4.7
MCK-14	3.6	15.7	4.3	4.3
MCK-15	2.3	21.9	9.6	4.1
MCK-16	3.8	14.6	3.8	4.5
MCK-17	2.6	14.3	5.4	4.1
MCK-18	6.5	37.6	5.8	4.5
MCK-19	5.3	41.8	7.9	4.7
MCK-20	11.7	82.8	7.1	4.6
MCK-21A	5.3	29.1	5.5	3.8
MCK-21B	15.1	38.5	2.6	4.2
MCK-22	4.1	15.4	3.7	4.1
MCK-23	5.9	16.2	2.8	4.0
MCK-24	5.2	19.2	3.7	4.3
MCK-25	5.2	16.9	3.2	5.7
MCK-26	3.3	17.5	5.4	4.4
MCK-27	2.0	4.4	2.2	8.7
MCK-28	4.1	17.3	4.3	4.8
MCK-29	4.8	11.1	2.3	3.3
MCK-30	8.3	15.9	1.9	4.9
MCK-31	6.9	20.9	3.0	4.8
MCK-32A	1.6	28.3	17.2	3.7
MCK-32B	4.7	16.6	3.5	5.1
MCK-33	2.1	9.3	4.3	2.9
MCK-34	1.5	4.8	3.3	5.4

Table 3. - Modal analyses of granitic rocks studied arranged in order of collection number

Specimen	R ¹										Quartz	Plagioclase	Potash feldspar	Biotite	Allanite	Apatite	Zircon	Monazite	Opacues	Fluorite	Sphene	Calcite	Horn-blende	Chlorite
MCK-1	1.46	42.3	23.0	33.5	1.2	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-2	1.72	27.6	25.7	44.2	2.5	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-3	0.82	21.7	40.9	33.8	3.3	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-5		17.2	60.7		22.0																			
MCK-6		46.6	31.7		17.4																			
MCK-11	1.08	30.6	30.8	33.4	5.2	?	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-12	1.17	35.4	27.9	32.7	3.9	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-13	0.81	34.2	33.5	27.3	5.0	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-14	1.42	30.8	27.2	38.7	3.2	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-15	1.06	31.9	32.9	34.7	Tr	?	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-16	0.76	40.4	32.3	23.3	3.9	?	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-17	1.47	33.8	26.6	39.3	0.3	?	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-18	1.08	58.9	19.4	20.9	0.7	?	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-19	3.00	29.9	17.1	51.2	1.8	?	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-20	1.56	33.5	24.4	38.2	3.4	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-21A	3.31	31.8	14.9	49.5	3.7	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-22	1.39	29.4	27.8	38.6	4.0	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-23	0.55	31.5	41.1	22.8	3.5	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-24	0.95	29.9	33.9	32.1	4.1	?	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-25	0.98	39.3	29.0	28.4	3.2	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-26	2.35	23.3	22.1	51.8	2.8	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-28	2.40	5.9	26.6	63.7	3.7	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-29	0.43	23.9	48.4	20.8	6.8	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-30	1.61	43.3	18.9	30.4	6.6	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-31		71.6		25.5	2.8	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-32A	0.36	34.6	47.6	17.2	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-32B	0.59	36.2	37.4	22.0	4.3	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-33	0.37	30.3	44.3	16.2	8.9	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr
MCK-34	1.16	29.1	32.8	37.9	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr	Tr

¹ R is potassium feldspar/plagioclase ratio² Tr is trace mineral

Table 4. - Thorium, uranium and potassium contents of the granitic rocks of the Enchanted Rock batholith listed according to zones.

Zone	Sample	Th/U	Thppm	Uppm	K %
Outer	MCK-1	11.0	18.2	1.7	4.9
	MCK-2	9.2	19.1	2.1	4.7
	MCK-3	13.4	20.4	1.5	4.6
	MCK-4	14.3	22.8	1.6	10.1
	MCK-18	6.5	37.6	5.8	4.5
	MCK-19	5.3	41.8	7.9	4.7
	MCK-20	11.7	82.8	7.1	4.6
	MCK-32A	1.6	28.3	17.2	3.7
	MCK-31	6.9	20.9	3.0	4.8
	MCK-32B	4.7	16.6	3.5	5.1
Inter- mediate	MCK-21A	5.3	29.1	5.5	3.8
	MCK-21B	15.1	38.5	2.6	4.2
	MCK-28	4.1	17.3	4.3	4.8
	MCK-29	4.8	11.1	2.3	3.3
	MCK-30	8.3	15.9	1.9	4.9
Inter- mediate- central Core	MCK-25	5.2	16.9	3.2	5.7
	MCK-26	3.3	17.5	5.4	4.4
	MCK-11	4.5	16.8	3.7	4.1
	MCK-12	4.3	17.5	4.1	4.3
	MCK-13	3.5	17.4	5.0	4.7
	MCK-14	3.6	15.7	4.3	4.3
	MCK-16	3.8	14.6	3.8	4.5
	MCK-22	4.1	15.4	3.7	4.1
	MCK-23	5.9	16.3	2.8	4.0
	MCK-24	5.2	19.2	3.7	4.3

with a lower Th/U ratio of 1.6. The thorium and uranium is concentrated in the finer grained rock. The uranium content increased almost five fold while thorium less than doubled its concentration. Petrographically the two rocks are also quite different. The coarse-grained material constituting the main mass of the outcrop is a leucogranite, hypidiomorphic porphyritic with rare interlocking grains. The fine- to medium-grained leuco-quartz monzonite is allotrimorphic-porphyritic, slightly seriate with abundant intergrowths between all minerals. In outcrop, the two rocks grade into each other. The quartz monzonite occurs in discontinuous lenses and patches throughout the granite.

A comparable relationship has been noted between samples MCK-15 and MCK-16. MCK-15 was sampled from a fine-grained aplite dike of leuco-quartz monzonite occurring in the porphyritic leuco-quartz monzonite of the core (MCK-16). The thorium and uranium content of the country rock is normal (14.6, 3.8 ppm) with a Th/U ratio of 3.8. The aplite dike contains 50 percent more thorium (21.9) and 250 percent more uranium (9.6) with a correspondingly lower Th/U ratio of 2.3.

The variation in radioactivity between the coarse- and fine-grained granites mentioned may have been due to the late fixation of thorium and uranium in the rock-forming minerals. Thus, they would be concentrated in the late-crystallizing portions of a given granite mass having a uniform initial concentration. For the rocks discussed above the later crystallizing rocks would be the aplite dike and fine-grained granite. The possibility that

thorium and uranium were fixed on the crystal surfaces and thus were more concentrated in the rocks of fine granularity (having more surface area) may not be discounted.

Sample MCK-29 was collected from fine- to medium-grained inclusions within the porphyritic granite of the intermediate zone. The porphyritic granite is represented by sample MCK-30. The inclusions are allotriomorphic porphyritic quartz monzonite becoming coarser grained toward the contacts with the coarse-grained granite. The thorium and uranium contents of the samples vary between 11.1 ppm to 15.9 ppm thorium and 2.3 ppm to 1.9 ppm uranium respectively for the inclusions and the porphyritic granite. Hutchinson (1956) notes on the geologic map of the batholith a gradation between porphyritic quartz monzonite and the porphyritic granite for this general locality of the intermediate zone. These inclusions may have been crystallized earlier and subsequently enclosed in the porphyritic granite. The higher concentration of thorium and uranium would then occur with the later-forming coarse-grained granite. The increase in Th/U ratio is more marked, ranging from 4.8 for the inclusions to 8.3 for the porphyritic granite.

A fine-grained quartz monzonite and a coarse-grained granodiorite were sampled from an area outside the southern part of the batholith. The fine-grained phase (MCK-34) is a pink allotriomorphic seriate quartz monzonite in abrupt contact with MCK-33, a medium- to coarse-grained granodiorite. The higher concentration of thorium and uranium in this case is present in the coarser grained granodiorite.

Three rocks of different grain size were sampled at one outcrop of the porphyritic leucogranite of the northern outer zone of the batholith. These samples showed increasing thorium content with increasing grain size. Sample MCK-18 is a porphyritic coarse-grained granite with phenocrysts of potassium feldspar averaging between 5 and 10 mm long; it contains 37.6 ppm thorium and 5.8 ppm uranium. Sample MCK-19 is coarser grained, with potassium feldspar phenocrysts averaging 15 mm, and contains 41.8 ppm thorium and 7.9 ppm uranium. The third sample, MCK-20, has coarser phenocrysts than samples MCK-18 and 19 (up to 30 mm size) but contains a greater percentage of medium-grained groundmass. The thorium content is anomalously high (82.8 ppm). The high uranium content (7.1 ppm) varies slightly from that of MCK-19 (7.9 ppm).

Variations of thorium and uranium on the hand specimen level were tested on a sample of porphyritic granite (MCK-21) from the northern intermediate zone. The analysis disclosed a thorium variation of 38.5 to 29.1 ppm and a uranium variation of 2.6 to 5.5 ppm. The thorium content is anomalously high in both subsamples and may be caused by small variations in radioactive accessory minerals.

The alkali-granodiorite of the intermediate central zone contained large phenocrysts of potassium feldspar in a uniform medium- to coarse-grained groundmass. The potassium feldspar phenocrysts ranged in size from 1.5 cm for sample MCK-26 to an average 4 cm size for sample MCK-25. This variation is unaccompanied by

change in thorium content. The uranium content varies with decreasing size of the phenocrysts from 3.2 to 5.4 ppm.

Potassium feldspar crystals were collected from a highly weathered portion of the alkalic granodiorite. The crystals are predominantly potassium feldspar with abundant perthite with inclusions of biotite, plagioclase and quartz. The sample, MCK-27, contained 4.4 ppm thorium and 2.2 ppm uranium with a Th/U ratio of 2.0. The Th/U ratio is significantly lower than the 5.2 and 3.2 values obtained from the complete rock samples from this outcrop. Assuming that the large feldspar phenocrysts were early-forming constituents of the crystallizing mass, the higher Th/U ratios appear to be associated with the late-forming constituents.

Samples MCK-4 and MCK-31 were collected from alkali- and quartz-enriched zones within the outer zone. Both minor intrusions contain a higher thorium content than the associated country rocks and a correspondingly slightly higher Th/U ratio. The quartz-enriched zone contained 20.9 ppm thorium, 3.0 ppm uranium, with a Th/U ratio of 6.9, compared to the lower thorium (16.6 ppm) and Th/U ratio (4.7) obtained from the nearby porphyritic leucogranite (MCK-32B) from the outer zone. The uranium content is slightly lower than the 3.5 ppm value of the granite. Sample MCK-4 was collected from a highly altered, sericitized aplogranite. The thorium content (22.8 ppm) is higher than that of the porphyritic leucogranite samples of this locality (MCK-1,2,3), which showed a range of 18.2 to 20.4 ppm. The uranium content (1.6 ppm) is within the range reported from the granites (1.5 to 2.1 ppm). The Th/U ratio

(14.3) of the aplogranite is higher than the range in the granites (9.2-13.4).

In summation, significant variations in thorium and uranium contents have been obtained from samples collected in close proximity to one another. These variations are usually found associated with local compositional or grain size variation. Variations are apparently independent of notable changes in the rock properties. Grain size variation unaccompanied by variation in thorium and uranium concentration has also been noted. The Th/U ratios of the associated rocks of the batholith also commonly show significant variations. When sequence of crystallization or emplacement can be reasonably established, the higher Th/U ratio appears to be associated with the later-forming rocks. This relationship has been noted between inclusions and the main granitic mass of the intermediate zone, the feldspar phenocrysts and the host rock of the intermediate-central zone, and the minor alkalic and quartz-enriched intrusions in the granite of the outer zone. The reverse relationship may exist between the aplitic dike and the host rock within the core of the batholith. The Th/U ratio decreased from 3.8 for the granite to 2.3 for the aplite dike. As mentioned previously, a significant variation in Th/U ratios occurs between the coarse- and fine-grained granites of the intermediate zone (MCK-32A, 32B). The high thorium and uranium values and low Th/U ratio occur in the fine-grained rock. The relationship between the granites is not clearly seen in outcrop. The finer grained portion accounts for a very small volume of the outcrop and may have been emplaced as dikes or by stoping.

In conclusion it may tentatively be stated that large local petrographic variations occur within the batholith and are generally associated with large variations in thorium and uranium content. The relationships are not systematic, and the writer does not mean to imply a genetic relationship between petrographic and radioactive element variations. These local variations account for the greatest ranges in concentrations found throughout the batholith. A secondary observation has been made that the later-forming constituents or rock masses tend to contain higher concentration of thorium and uranium, with a tendency toward an increased Th/U ratio.

Thorium and uranium content of the contact zone

Samples MCK-5 through MCK-10 were collected from the contact zone between the Packsaddle schist formation and the southern outer zone of the batholith. The Packsaddle schist samples (MCK-6,7) were collected 2-4 feet from the contact and are markedly uniform in thorium and uranium content, ranging between 5.7-5.6 ppm thorium and 1.8-1.6 ppm uranium. The granitized schist (MCK-5) at the contact showed a large increase in thorium content (23.6 ppm). The uranium content increased slightly to 2.0 ppm. The thorium and uranium content of the granitized schist is very close to the concentrations of outer-zone granites near the contact (MCK-1,2,3). The thorium content of these granites ranged between 18.2 ppm and 20.4 ppm. The uranium varies between 1.5 ppm and 2.1 ppm. Sample MCK-9 was collected 15 feet from the contact within the Packsaddle

schist. The schistosity is destroyed and the rock has assumed a more granular appearance compared to the neighboring schists. The analysis disclosed a large increase in potassium (2.8%) and uranium (2.5 ppm) and a slight increase in thorium (7.6 ppm) over that of the schist samples. The injection gneiss of the contact represented by sample MCK-8, with a thorium content of 5.5 ppm and uranium content of 1.6 ppm, shows nearly the same thorium and uranium concentration as that of the schists (5.7-5.6 ppm thorium; 1.8-1.6 ppm uranium). The potassium content (1.6%) is within the range of the potassium content of the schists (1.6-1.7%). The brecciated zone consists predominantly of fine-grained micaceous material with lens-like fragments of quartzitic and feldspathic material and fragments of schist. The brecciated zone narrows and disappears into the injection gneiss. This field relationship and the presence of schistose and feldspathic fragments suggests that the breccia zone consists essentially of sheared injection gneiss. The thorium content of the breccia is only slightly increased (6.7 ppm), while uranium shows a greater change (2.5 ppm). The potassium content of the breccia (3.2%) is almost a two-fold increase over that for the injection gneiss (1.6%).

The Th/U ratios of the Packsaddle schist, injection gneiss and breccia are very similar, showing a range of 2.7 to 3.5. The granitized schist further from the contact has a Th/U ratio within this range, of 3.1. These values differ markedly from the high 11.8 Th/U ratio for the granitized schist at the contact. This ratio, together with the high thorium content, is comparable to the

Th/U ratios of the nearby granites (MCK-1,2,3), ranging between 9.2 and 13.4.

The potassium content of the schist ranges between 1.7 and 1.6%. The injection gneiss has a potassium content within this range (1.6%), but the brecciated zone shows a higher value of 3.2%. This increase is accompanied by a 50% increase in uranium (2.5 ppm) and a small increase in thorium (6.7 ppm) over that of the injection gneiss and schists. The increased potassium content of the granitized schist near the contact (2.7%) is accompanied by a large increase in thorium (23.6 ppm) but only a small increase in uranium (2.0 ppm). Further from the contact the granitized schist sample contains increased potassium (2.8%) and uranium (2.5 ppm) but only a slight increase in thorium (7.6 ppm) over that of the schists.

In summation, the thorium and uranium and potassium content of the Packsaddle schist is uniform and shows no variation with distance from the contact zone for the samples analyzed. Where the schist has been granitized, an increase in both potassium and thorium contents occurs. The injection gneiss at the contact shows neither an increase in potassium, thorium nor uranium. The brecciated zone is notably enriched in both potassium and uranium, but only slightly in thorium. The thorium and uranium content of the contact granitized schist and the Th/U ratio is very close to those values obtained from the granite samples analyzed from this vicinity.

The data indicates that the thorium and uranium migrated into the metamorphic rocks along with the potassium-rich fluids.

The affected rocks, the breccia and the granitized schists, show different proportions of thorium and uranium enrichment. These data support observations made by Ingham and Keevil (1951) on the higher radioactivity of contact volcanics near the intrusives and the migration of uranium across an intrusive-metamorphic contact zone reported by Krylov (1956).

Irregular aplitic granite masses occur within the Packsaddle schist outside of the northern border of the batholith. Sample MCK-17 was collected from this locality. The analyses showed a thorium content of 14.3 ppm; uranium, 5.4 ppm; and potassium 4.1%. These values represent more than a two-fold increase of thorium, uranium and potassium over that of the Packsaddle schist samples. The Th/U ratio of the granite (2.6) is very close to the ratios recorded from the Packsaddle schist (3.4-3.3).

Results

The relationships between thorium, uranium, and Th/U ratio for the granitic rocks of the Enchanted Rock batholith are shown in figures 6, 7 and 8. The data for these diagrams is tabulated in table 4.

For values under 25 ppm thorium the trend of thorium versus Th/U ratio is linear with a low positive slope. For rocks containing greater than 25 ppm thorium, there is a broad range in Th/U ratio and no definite trend can be established. The plot of uranium versus Th/U ratio (figure 7) shows a sharp negative slope, leveling off with increasing Th/U ratio. Values for uranium above 5.5 ppm show a wide range of Th/U ratios. Figure 8 shows the relationship between thorium and uranium for these same granitic rocks. The data from samples 32A, 19 and 20 have thorium and uranium values too high to be readily plotted and have consequently been left off of the graph. The graph shows a scattering of points, with no trends indicated.

Figure 9 is a diagram of the thorium content versus the potassium content for all of the rocks analysed for this study with the exception of the feldspar crystals (MCK-27). The solid circles represent the main rocks of the batholith and were taken from table 4. The open circles include all other rocks analysed, whose data appear in table 2. A positive linear trend is apparent up to a thorium concentration of 20 ppm. Above this value there is a broad variation in both thorium and potassium content. Whitfield (1958) felt that thorium values over 20 ppm may be attributed to secondary enrichment in thorium. The samples representative of the three open circles above 20 ppm thorium were obtained from later-formed rocks:

the aplite dike, alkali-enriched zone, and the quartz-enriched zone. A fourth high thorium sample was collected from the fine-grained gradation within the intermediate zone (MCK-32A). The possible significance of this fine-grained phase has been discussed previously. The remaining high thorium data were obtained from rocks collected from two outcrops of the northern outer and intermediate zones, where all thorium values appear to be anomalously high. It may be that this portion of the intruding magma was initially higher in thorium content, and the high final thorium content was not effected by local trends in thorium concentration or by secondary enrichment. The large intra-hand specimen variation of sample MCK-21 (29-38.5 ppm thorium) may be explained by small-scale variations in thorium concentration but is more readily explained by slight differences in concentration of thorium-bearing secondary allanite. No petrographic differences are discernible in this sample, and the variation has occurred over a distance of only a few inches. Questionable allanite was found in one of the two thin sections of this rock, associated with biotite and calcite. The second thin section consisted almost entirely of one potassium feldspar crystal.

A comparison of figure 9 and the relationship found by Whitfield (1958) in figure 1, between thorium and potassium, appears in figure 10. Whitfield's data are plotted as "x"s, while the values from this investigation are shown by solid circles. It is immediately evident that the majority of rocks within this investigation have higher contents of both thorium and potassium. The trend delineated by Whitfield is shown by a dotted line. The data from this

investigation suggest that the relationship between the two components extends in a linear way through higher values of thorium and potassium than that reported by Whitfield (1958).

Diagrams 11-13 show the range of thorium, uranium, and Th/U ratios, respectively, in the peripheral zones of the batholith. The samples of quartz- and alkali-enriched zones of the outer zone are circled. The average of the values for each zone is represented by an "x". Thorium shows the broadest range of concentration in the outer zone (16.5-82.8 ppm) but is remarkably uniform in concentration within the core of the batholith (14.5-18 ppm), where it has a lower average concentration. With the exception of one high-thorium sample from the outer zone, the intermediate zone has a thorium concentration range similar to the outer zone. The intermediate-central zone is only represented by two samples which vary slightly and are within the range of thorium variation for both the intermediate zone and the homogeneous core.

The pattern of uranium variation (figure 12) for the batholith and within the zones is similar to the variation trends of thorium. The broadest ranges in concentration are found in the outer zone. The smaller variations in uranium content of the intermediate zone relative to the outer zone are more apparent than in the case of thorium. The core has a proportionately wider variation in uranium content than it had for thorium but has a concentration of values near 4 ppm uranium. The variation of uranium in the intermediate-central zone is consistent with the range of values for the intermediate zone.

Figure 13 shows the Th/U ratios for the four zones. From

the outer zone to the core, both the range and absolute values of the Th/U ratio decrease from 1.6 to 14.3 for the outer zone to 3.5 to 5.9 for the core. The intermediate zone ranges from 4.1 to 8.3 Th/U with one anomalously high value of 15.

In summation, the outer zone contains the highest values and largest variations in thorium and uranium concentrations and Th/U ratio of all of the rock zones of the batholith. The core, in contrast, is remarkably uniform. The intermediate zone shows variations between those present within the core and the outer zone; the Th/U ratios are intermediate between the core and the outer zone, but the thorium and uranium values, on the other hand, are less obviously intermediate. The thorium content of the intermediate zone rocks is decidedly higher than that of the core rock but is, for the most part, similar to the concentrations found in the outer zone. Conversely, the uranium values for the intermediate zone rocks approximate the values found within the core but are definitely lower than the concentrations obtained from the outer zone.

The variation of potassium in the rock zones is presented in figure 14. The intermediate zone shows broad variations compared to the potassium values of the core and outer zone. Exclusive of the alkali- and quartz-enriched zones, the average potassium content of the outer zones is higher than the average content of the core. Inasmuch as the core and outer zone appear to contain the extremes in thorium content (figure 11) it is interesting to compare these values with the differences in potassium content of these zones. These data are plotted on figure 15. The points are quite diffuse but nevertheless are more indicative of a positive trend than the

solid points of figure 9, which is a compilation of the data for all zones. As in figures 6 and 9, the few anomalously high thorium rocks do not follow the trend established by the majority of the samples. These high thorium samples of the outer zone (MCK-32A, 18, 19, 20) have values too high to be conveniently plotted with the remaining data.

The variation of the potash feldspar/plagioclase ratio, here designated as R, is presented for the rock zones in figure 16. The outer and intermediate zones show wide ranges in values. The core shows a greater degree of uniformity for this measureable quantity, as it did for the Th/U ratios and thorium and uranium contents, compared to the other zones. The variation in R may not be as real as it is apparent. The coarser grain sizes of the outer zones, and the greater variation in grain size for this zone, may introduce a large error in the modal analyses of these rocks.

Discussion

Whitfield (1958) found that thorium and uranium are both controlled by the major petrogenesis of the granitic rocks; that is, thorium and uranium both tend to increase with increasing acidity and alkalinity. Petrogenetic evolution might be expected to occur on a smaller scale within a large intruded and crystallizing mass such as the Enchanted Rock batholith. Assuming that the granitic magma had an initial uniform concentration of thorium and uranium, the final variations within the batholith were effected during and subsequent to emplacement and crystallization of the mass. The behavior of thorium and uranium during this process must then account for the following observations:

1. The highest thorium and uranium concentrations occur in the outer zone of the batholith; these values decrease towards the core.
2. Thorium shows a greater increase from the core to the outer zone than does uranium.
3. The Th/U ratio decreases in value and variability from the outer zone to the core.
4. The variations of thorium and uranium contents within zones are greatest for the outer zone and decrease towards the core, where both components attain the maximum uniformity within the batholith.
5. The potassium and thorium concentrations of these granitic rocks are relatively higher than the values reported by Whitfield (1958).

6. The thorium and/or uranium contents increase with increasing potassium within the metamorphic contact rocks.

According to Hutchinson (1956) the granite body represents a near vertical intrusion, emplaced as a single unit. He believes that the outer zones of the batholith crystallized first while the core material was still rising. This placed the outer zones under tension, thereby producing marginal fissures which were filled with aplites and pegmatitic material. These late intrusions are more numerous and of greater extent in the outer zone of the batholith. In accordance with Whitfield's observations these late differentiates have higher thorium and uranium contents than their associated host rocks. The thorium and uranium concentrations within the rocks of the outer zone may have been affected by their concentrations within the associated late intrusions. Furthermore the numerous fissures present within these outer zones may have facilitated the migration of thorium and uranium through deuteric solutions into the outer zone. This migration is supported by the presence of thorium-rich secondary allanite in many of the rocks. In the northern portion of the batholith the late intrusions extend into the intermediate zone. The anomalously high thorium samples of the intermediate zone here were collected within 1/4 mile of these aplogranites. This was the only portion of the intermediate zone which was sampled within any proximity of the late intrusives. Furthermore, the samples from this outcrop contained the only anomalously high thorium values in rocks sampled from the intermediate zone. The joints may have aided distribution of late differentiate fluids into the country rocks.

The field evidence presented by Hutchinson (1956) appears conclusively to support his theory that the outer zones crystallized first. However, the distribution of thorium and uranium may be explained by the crystallization sequence if the core had been the first portion to crystallize. The large ionic radii and high charge of thorium and uranium would favor the migration of these elements toward the uncrystallized portion of the magma. Thorium and uranium would thus, in a sense, become entrapped in the outer zones, where their highest concentrations occur. The wide variation in thorium and uranium concentrations found in the outer zones would then be a function of the migratory paths taken by these elements.

The increase in Th/U ratio from the core to the outer zone suggests, from Whitfield's observations, that the outer zone represents a later stage of petrogenetic evolution than does the core. If this were the case however, all rocks of the outer zone should have a characteristically high Th/U ratio. Rather, there is a wide range in Th/U ratios within both the outer and intermediate zones. Migration of thorium-rich solutions into these crystallizing rocks would not affect all rocks equally but may be controlled by the adsorptive capacity of the rock. This capacity may be related to the grain size. The finer grained rocks, having greater surface area, may tend to adsorb more thorium and uranium than their coarser grained equivalents.

The mass channeling of these solutions was probably controlled by the numerous joints and fissures developed within

the outer zones. The core, which contains very few joints, might then be expected to contain both the lowest and least variable concentrations of thorium and uranium within the batholith.

The combined higher potassium and thorium values of the Enchanted Rock batholith compared to the data reported by Whitfield (1958) suggest that thorium may linearly follow potassium in the petrogenetic evolution of the granitic rocks through concentrations higher than those reported by Whitfield.

The increase in thorium content with increasing Th/U ratios within the batholith, for values under 25 ppm, is accompanied by a decrease in the uranium content of these rocks. Whitfield (1958) attributed this to loss of uranium from the magma during petrogenetic evolution. The high thorium and uranium values which did not follow this trend relative to the Th/U ratio may be due to secondary enrichment.

The small amount of data available on the outer contact zone has suggested that intrusive effects upon the metamorphic rocks have increased potassium and thorium or uranium concentrations within these rocks.

Conclusions

The following general conclusions have been reached from this investigation:

1. The distribution of thorium and uranium within the Enchanted Rock batholith is in large part structurally controlled.
2. Abrupt textural variations are often accompanied by local variations in thorium and uranium concentrations.
3. The late differentiates of the batholith have higher concentrations of thorium and uranium than the locally associated granites.
4. Thorium and uranium have apparently migrated with the potassium for a short distance into the marginal contact zone.

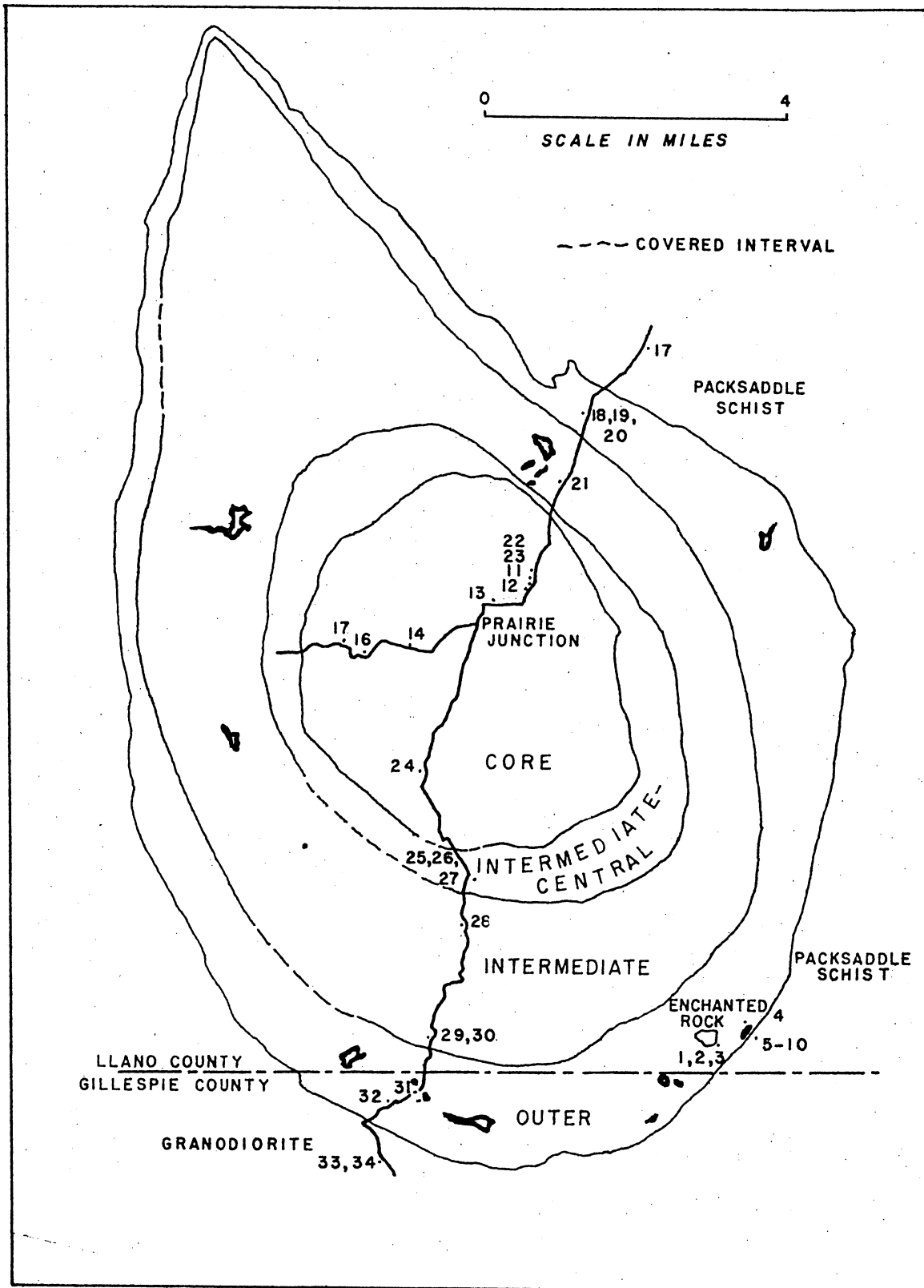


Figure 5.- Sample location map of the Enchanted Rock batholith showing the zones delineated by Hutchinson (1956) with associated late intrusions (solid shapes).

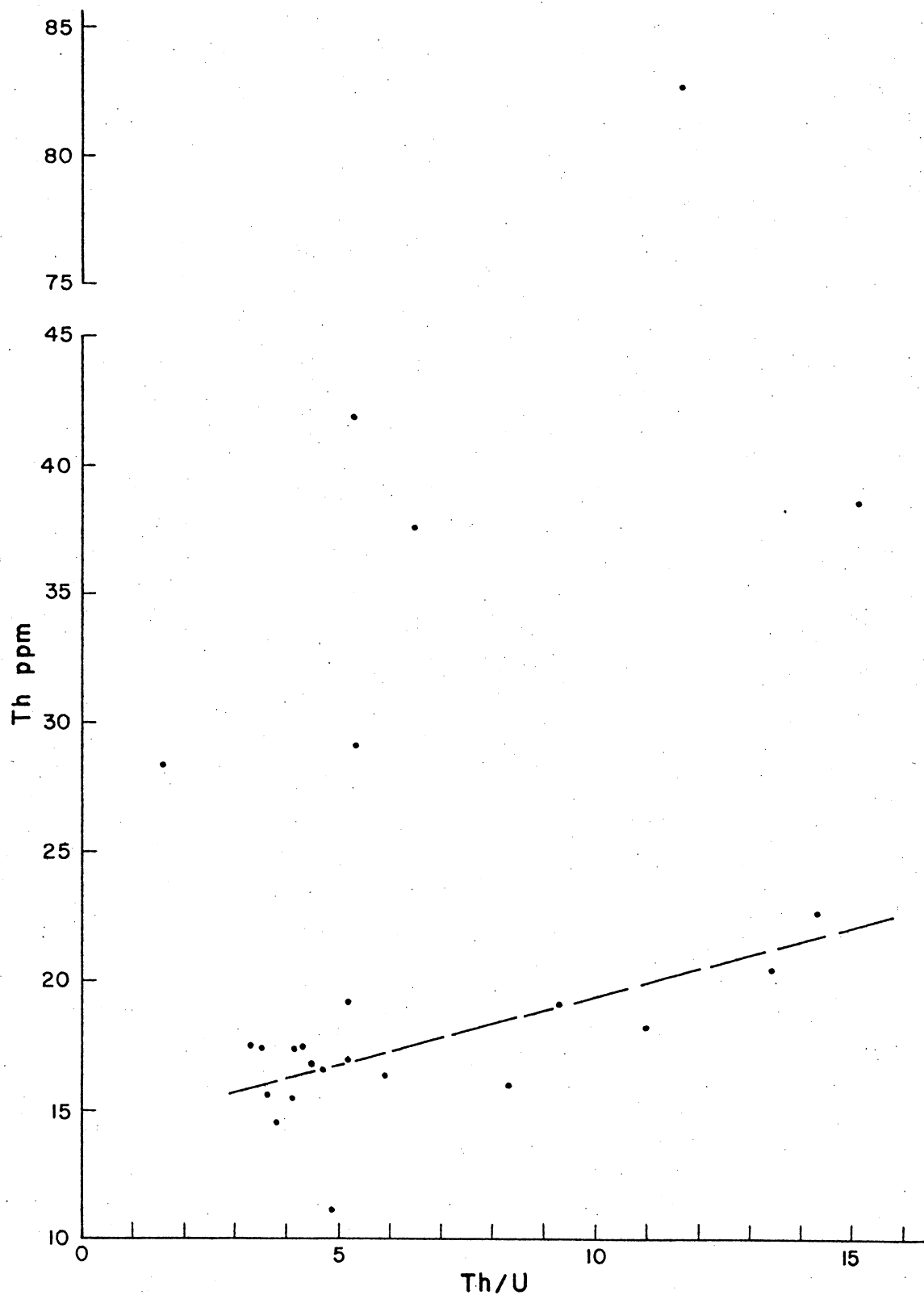


Figure 6.- Th/U ratio versus thorium content of granitic rocks analysed in this investigation. (See table 4).

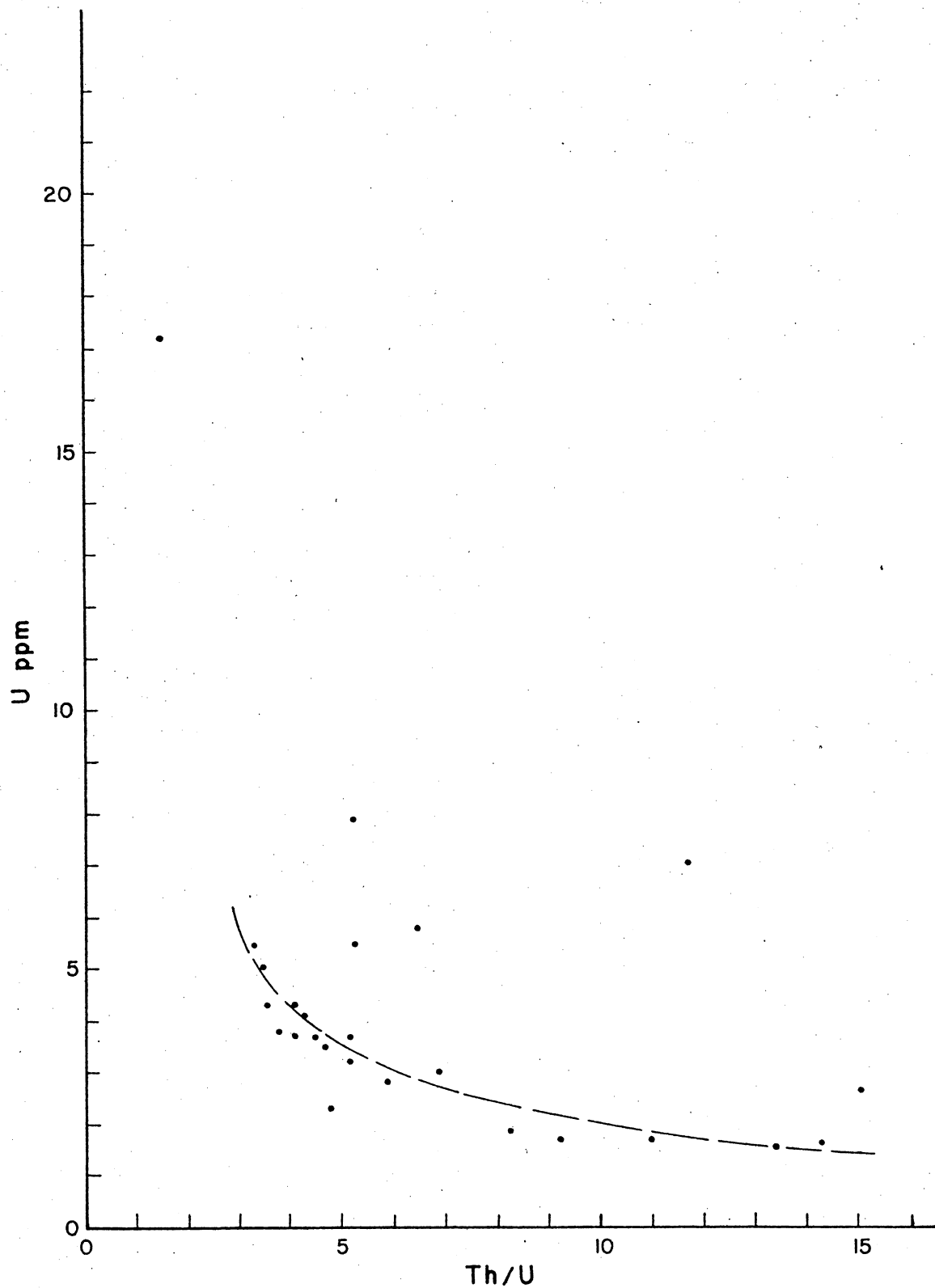


Figure 7.- Th/U ratio versus uranium content of granitic rocks studied. (See table 4).

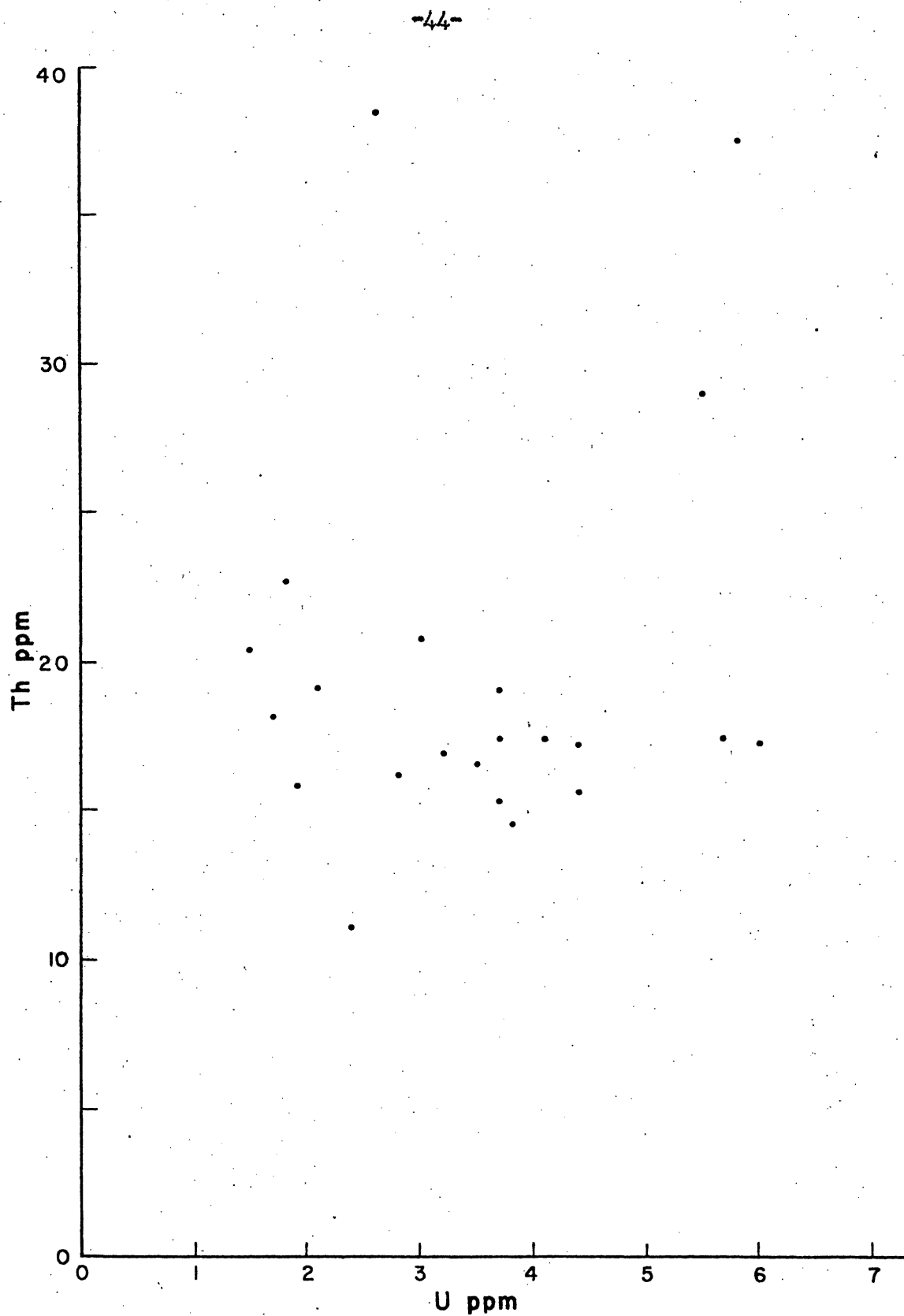


Figure 8.- Uranium content versus thorium content of granitic rocks analysed in this investigation. (See table 4).

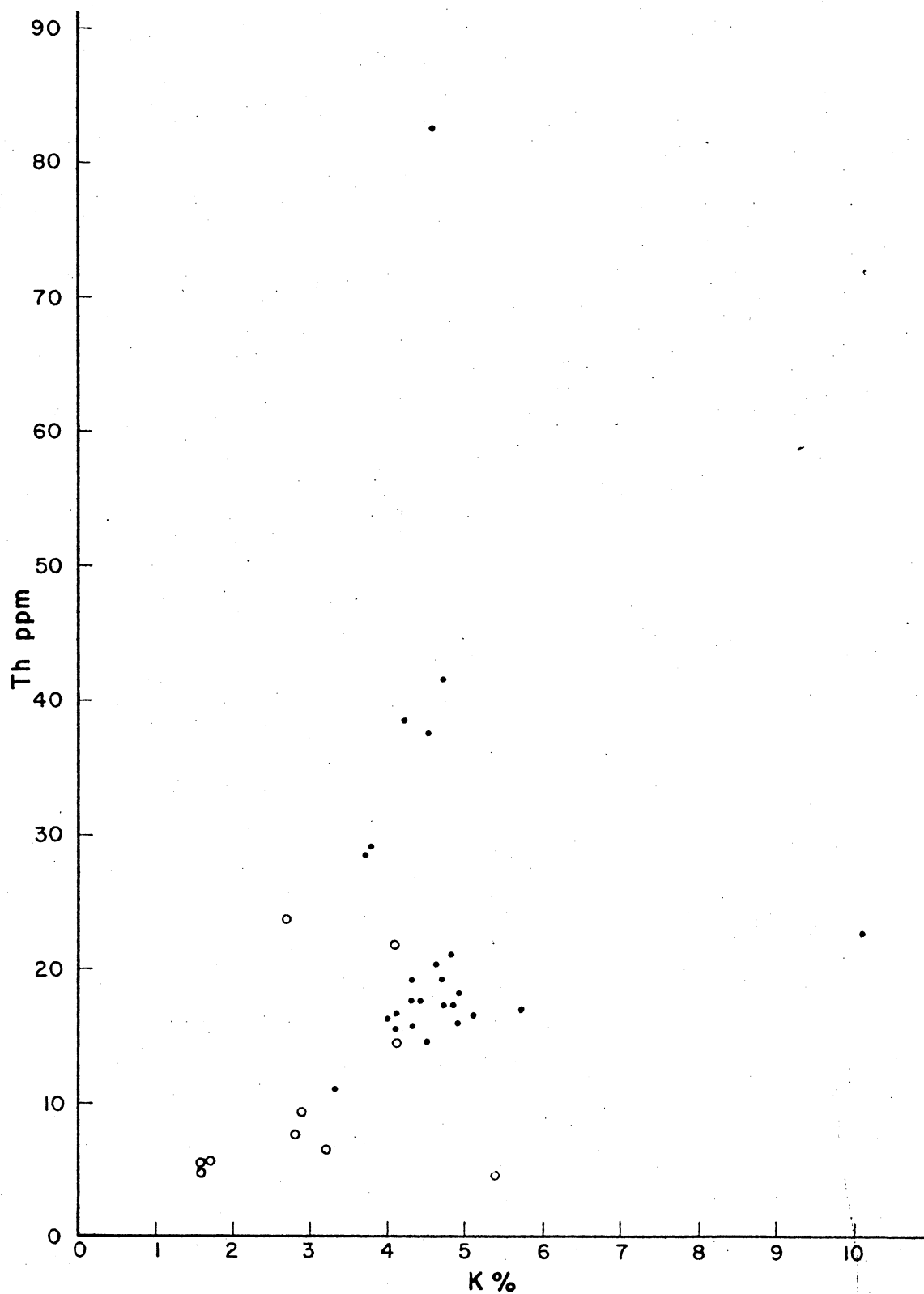


Figure 9.- Potassium content versus thorium content of rocks analysed in this investigation. Closed circles refer to granitic rocks in table 4. Open circles refer to associated rocks. (See table 2).

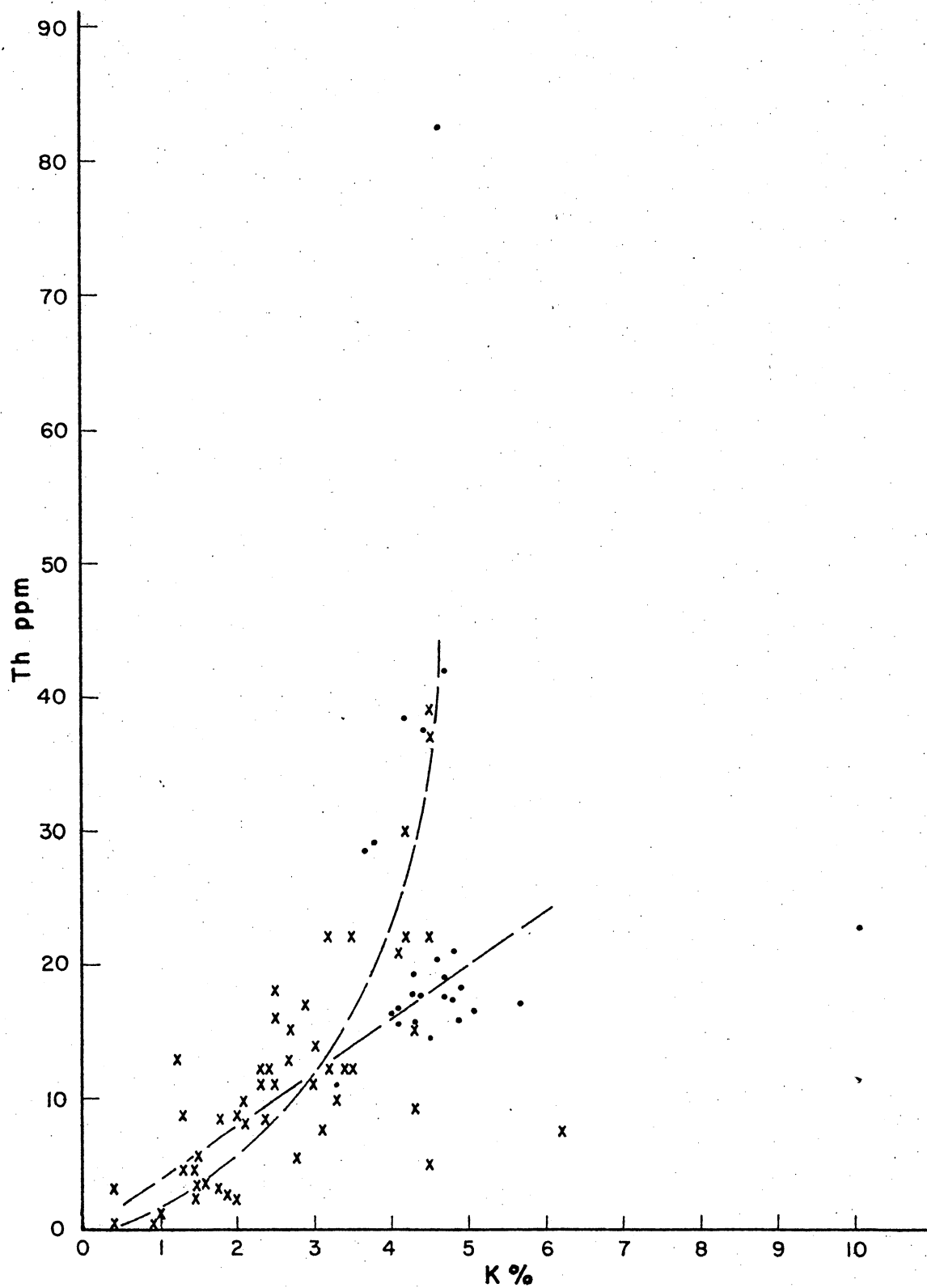


Figure 10.- Potassium content versus thorium content of granitic rocks. Closed circles represent data from this study (see table 4). Crosses represent data from figure 1.

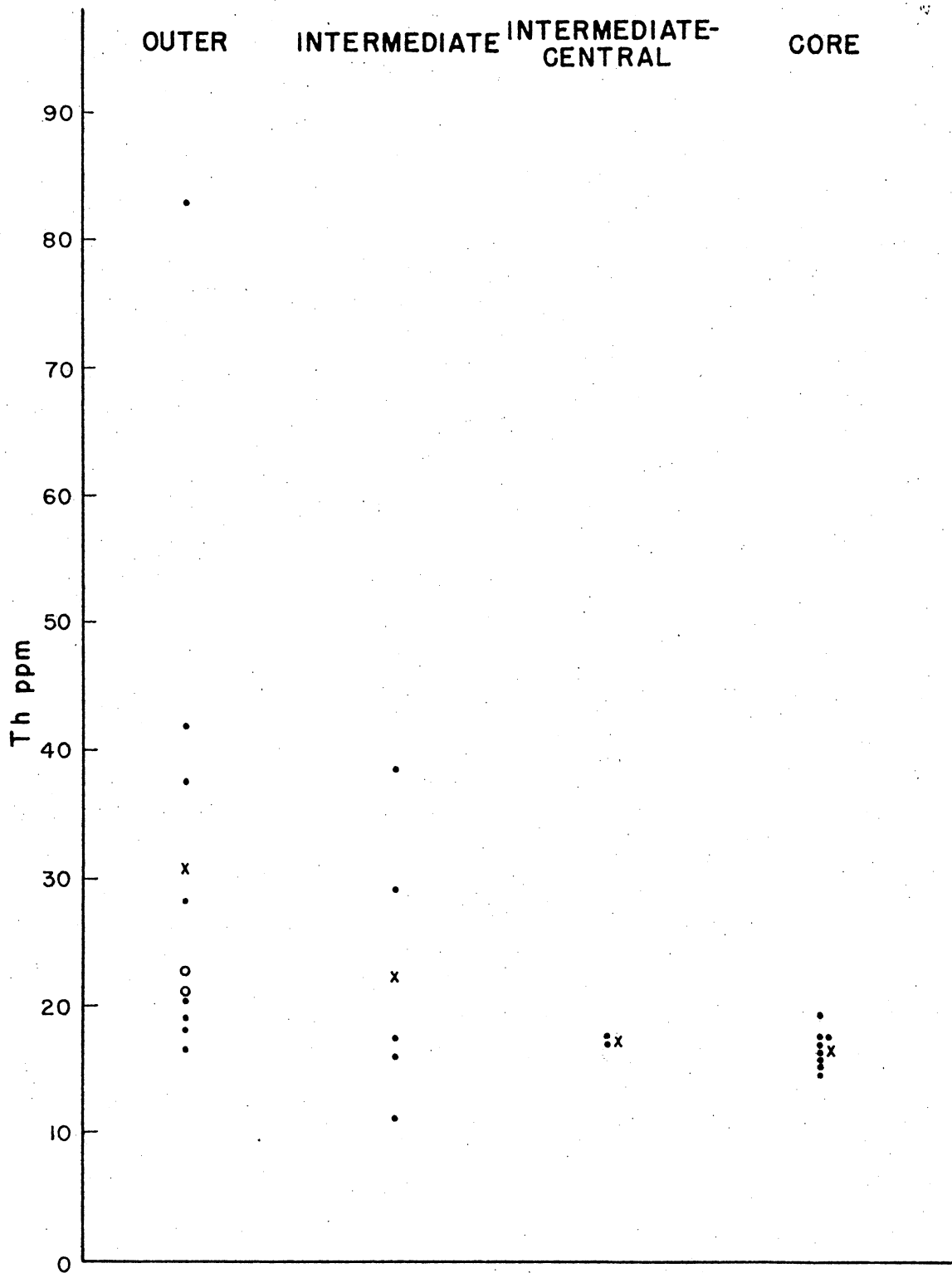


Figure 11.- Range of thorium values within and between zones of the batholith. Circled data refer to late intrusions. Crosses refer to average values. (See table 4).

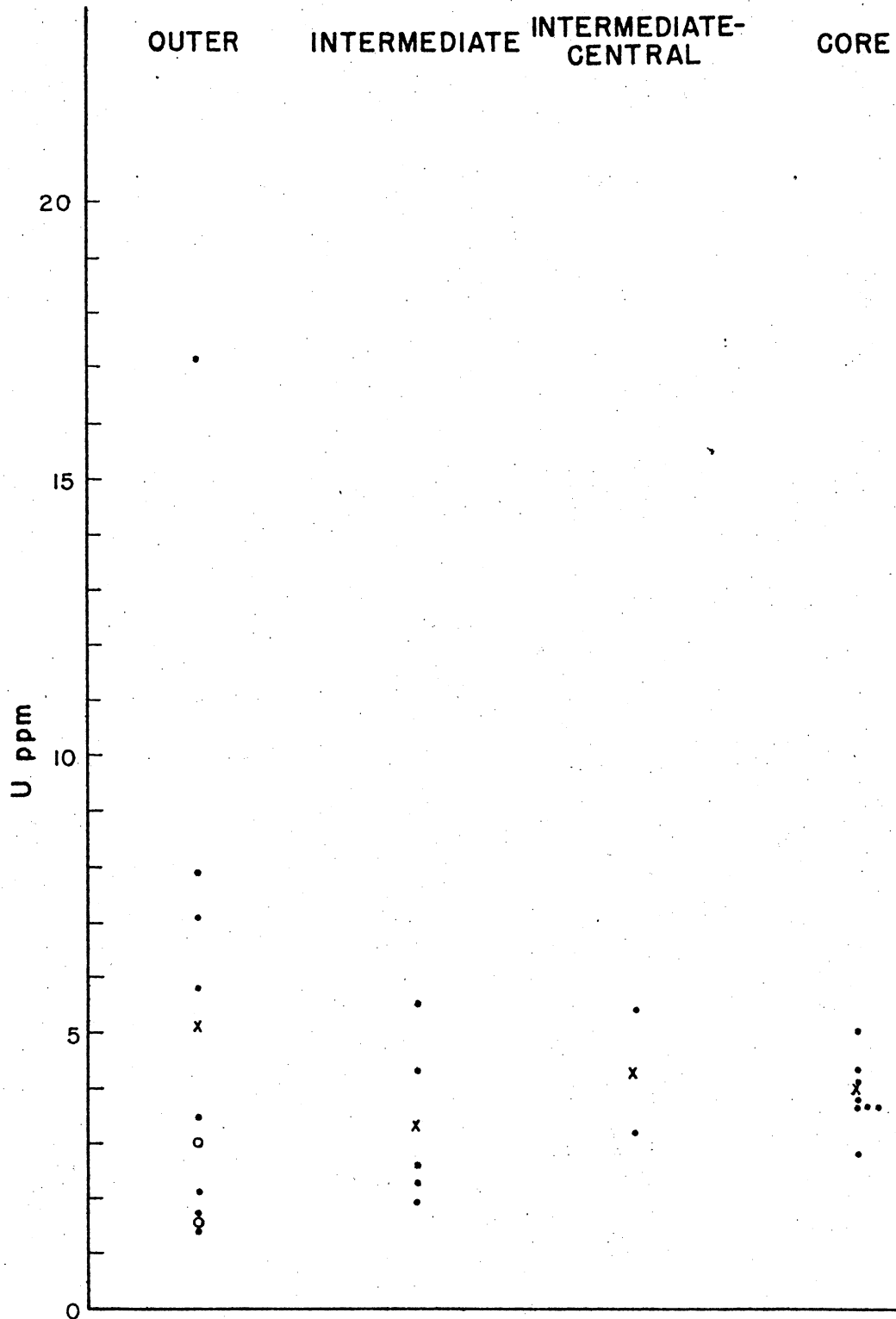


Figure 12.- Range of uranium values within and between zones of the batholith. Circled data refer to late intrusions. Crosses refer to average values. (See table 4).

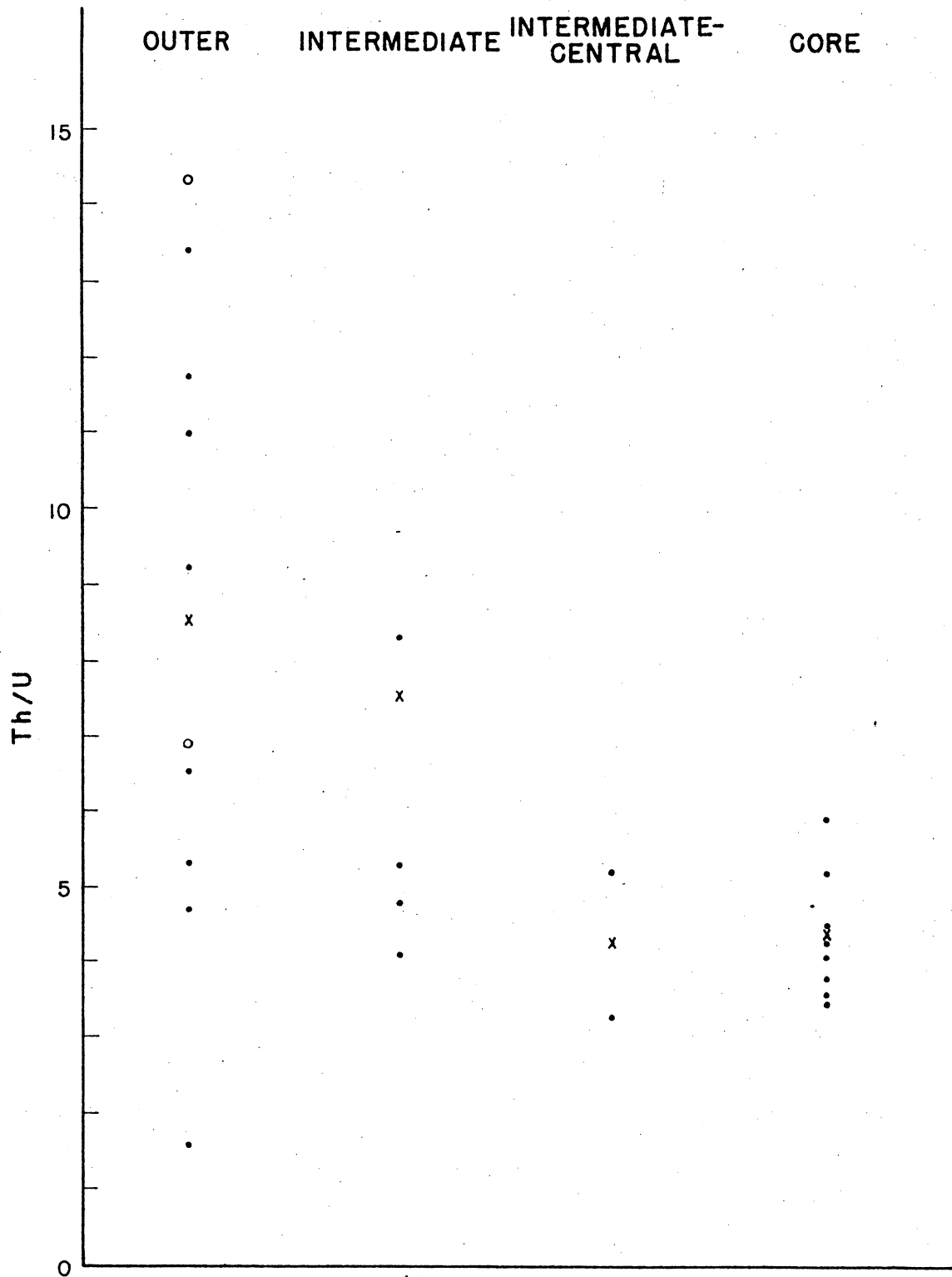


Figure 13.- Range of Th/U ratios within and between zones of the batholith. Circled data refer to late intrusions. Crosses refer to average values. (See table 4).

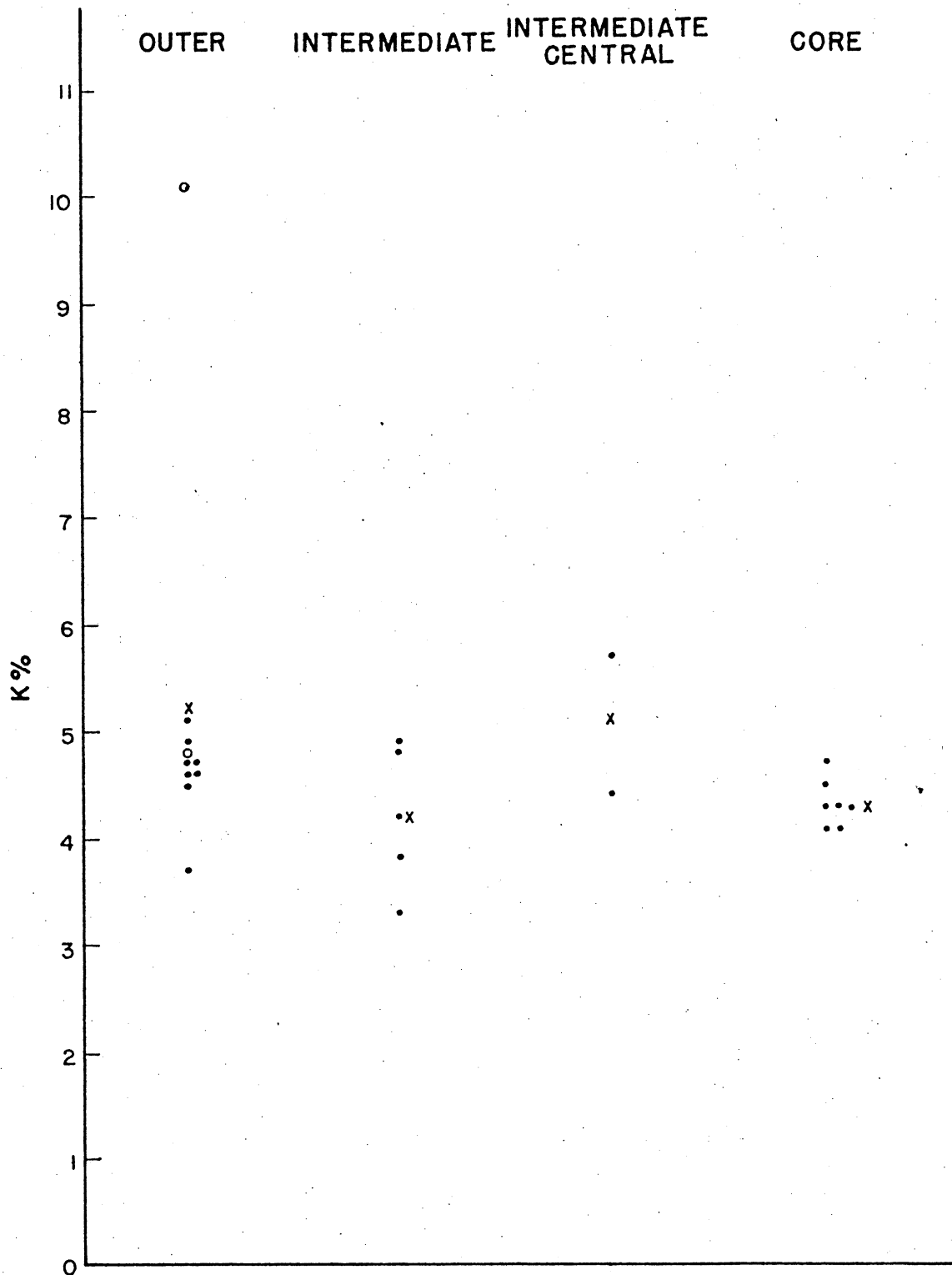


Figure 14.- Range of potassium values within and between zones of the batholith. Open circles refer to late intrusions. Crosses refer to average values. (See table 4).

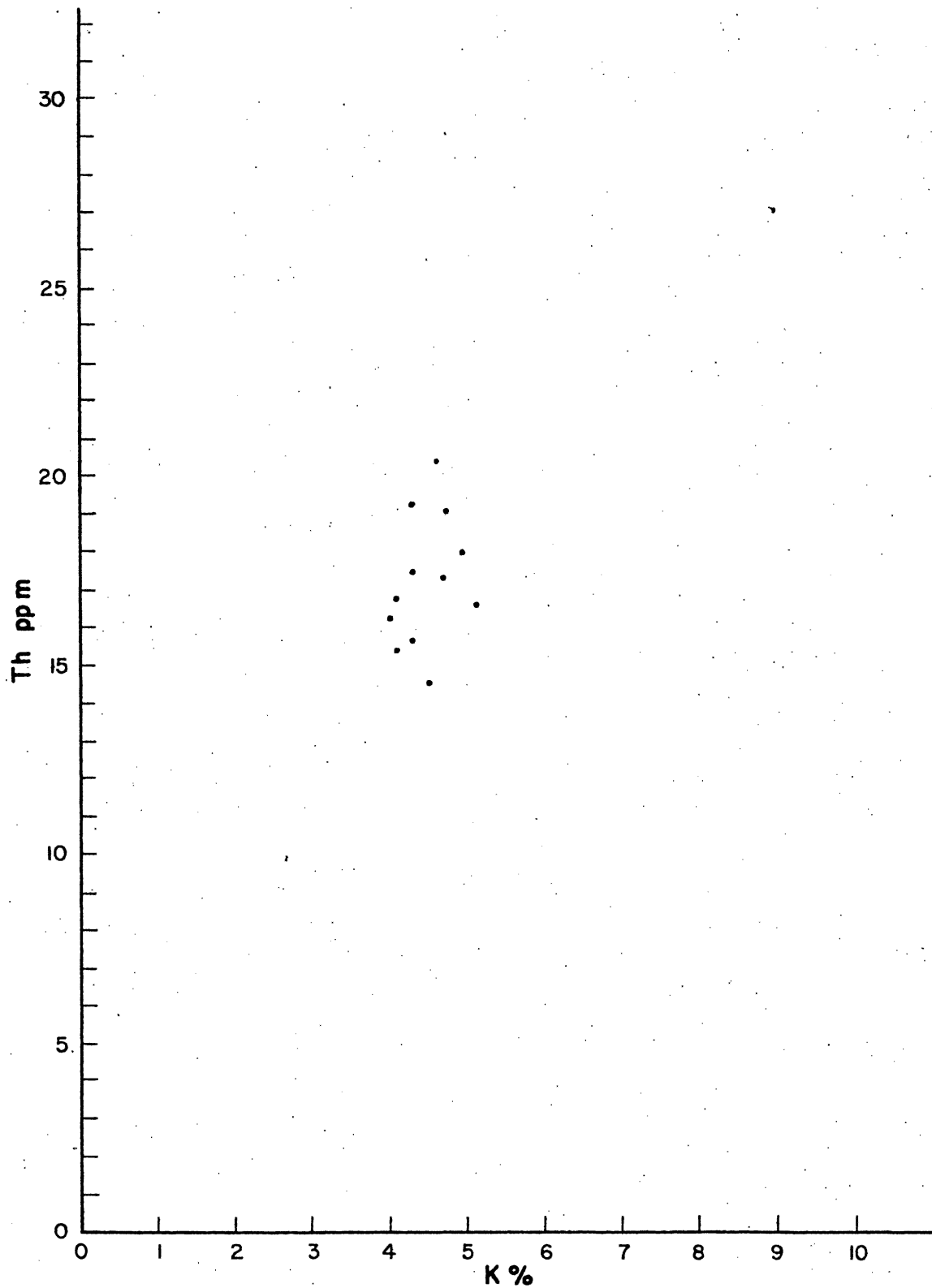


Figure 15.- Potassium content versus thorium content of granitic rocks within core and outer zone for thorium values under 25 ppm. (See table 4).

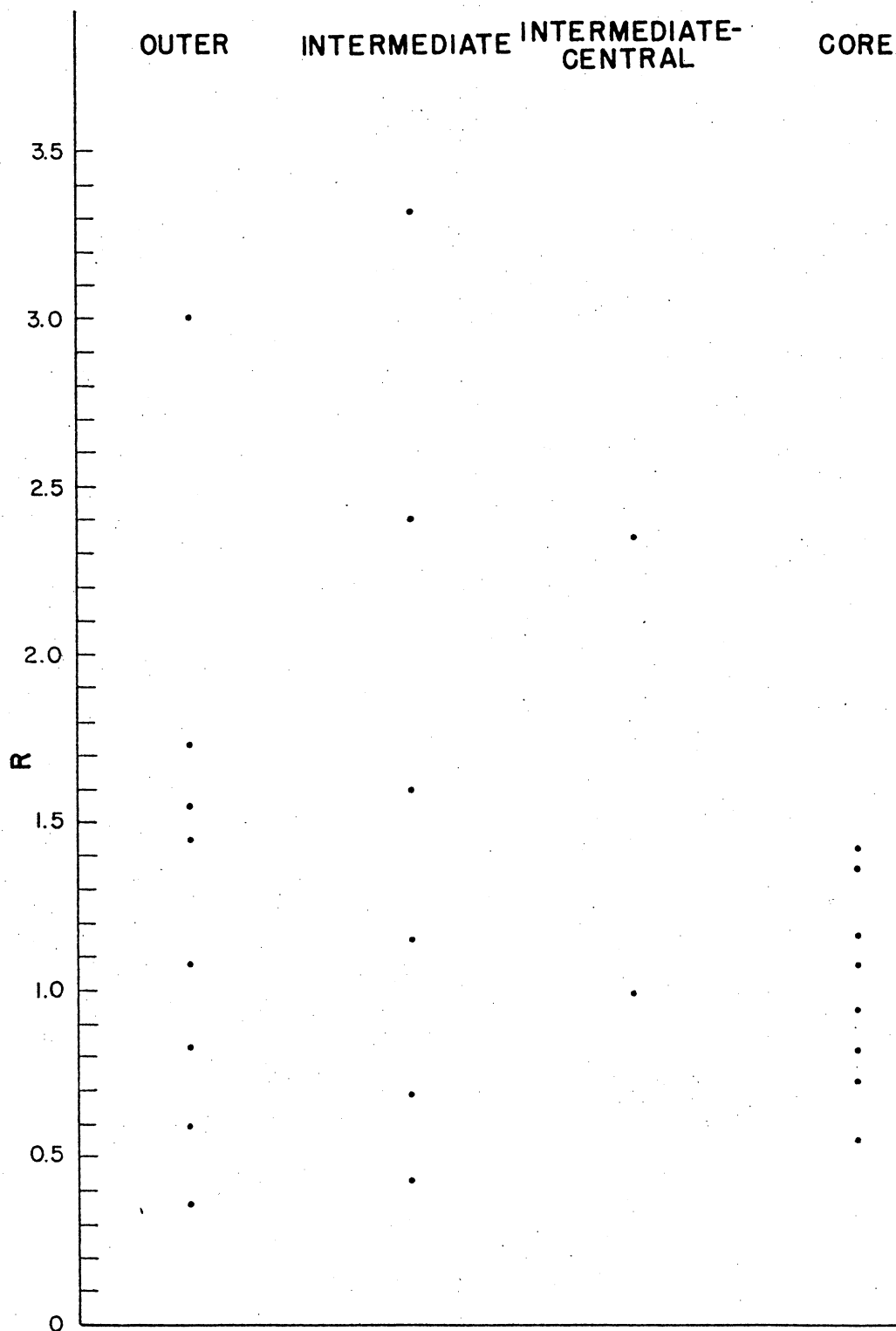


Figure 16.- Range of potash feldspar/plagioclase ratios (R) within and between zones of the batholith. (See table 3).

APPENDIX

The samples studied in this investigation are listed in order of collection number. The modal analyses of these rocks appear in table 3.

- MCK-1 Outer zone, south. This sample was collected on the south-east side of the Enchanted Rock. The texture of the rocks in this vicinity is generally uniform with differing sizes of the phenocrysts. This rock is a pink, medium- to coarse-grained, allotriomorphic-porphyritic leucogranite.
- MCK-2 Outer zone, south: 300 feet from Sandy Creek up the east side of Enchanted Rock. This rock is a pink, medium- to coarse-grained, allotriomorphic-porphyritic, slightly seriate leucogranite.
- MCK-3 Outer zone, south. This sample was collected from the southeast corner of Enchanted Rock. It is a medium- to coarse-grained, allotriomorphic-porphyritic leuco-quartz monzonite.
- MCK-4 Outer zone, south. This sample was collected from a minor intrusion at Enchanted Rock, 100 feet west of Sandy Creek. It is a dark red, coarse-grained, highly altered aplogranite consisting of microcline and altered plagioclase with minor amounts of hematitized biotite and magnetite.
- MCK-5 Packsaddle schist. This sample was collected one foot from the breccia contact in the transition zone between the schist and granite in Sandy Creek at Enchanted Rock. Feldspathic gneissic schist.

MCK-6 Packsaddle schist. Collected 1 1/2 feet from breccia contact.

Quartzitic gneissic schist.

MCK-7 Packsaddle schist. Collected 2 feet from sample MCK-6.

Fine grained quartzitic micaceous schist.

MCK-8 Packsaddle schist. This sample was collected from the transition zone. Quartzito-feldspathic injection gneiss.

MCK-9 Packsaddle schist. Collected 5 feet from contact zone.

This rock is a medium-grained, massive, biotite schist.

MCK-10 Breccia zone at contact. This sample consists of sheared Packsaddle schist with lenses of quartzitic and feldspathic material.

MCK-11 Core. This sample was collected one mile north of Prairie junction along the main north-south road across the batholith. It is a medium- to coarse-grained, hypidiomorphic-porphyritic granite.

MCK-12 Core. This sample was collected 90 feet south of sample MCK-11. This rock is a medium- to coarse-grained, hypidiomorphic-porphyritic, slightly seriate leucogranite.

MCK-13 Core. This sample was collected .8 miles north of Prairie junction from an outcrop located in a fenster of Cambrian sediments. It is a medium- to coarse-grained, hypidiomorphic-porphyritic leucogranite.

MCK-14 Core. This sample was collected one mile west of Prairie junction along an east-west subsidiary road. The rock is a medium- to coarse-grained, hypidiomorphic-porphyritic, slightly seriate leucogranite.

- MCK-15 Core. This sample was collected 2 miles west of Prairie junction from an aplite dike. The dike is 6 inches thick, fine grained, massive, with no change in grain size toward the borders. The rock is a fine-grained, allotriomorphic-granular, leuco-quartz monzonite.
- MCK-16 Core. This outcrop is located about 1/2 mile east of sample locality MCK-15 along the east-west road. The rock is medium- to coarse-grained, hypidiomorphic-porphyritic, slightly seriate leuco-quartz monzonite.
- MCK-17 Aplitic granite in the Packsaddle schist. This sample was collected 4 1/2 miles north of Prairie junction from one of the small fine-grained granitic masses occurring within the schist. The rock is a fine- to medium-grained, allotriomorphic-granular leucogranite.
- MCK-18 Outer zone, north. This sample was collected 3 1/2 miles north of Prairie junction along the main north-south road. The rock is a fine- to coarse-grained, allotriomorphic-porphyritic leucogranite. Potassium feldspar phenocrysts reach lengths of 10mm.
- MCK-19 Outer zone, north. This sample is representative of the coarser grained granite from the same outcrop as MCK-18. The rock is a medium- to coarse grained, allotriomorphic-porphyritic, slightly seriate leucogranite. The average size of the potassium feldspar phenocrysts is 15mm.
- MCK-20 Outer zone, north. This sample was collected 25 feet from MCK-18. The rock is a medium- to coarse-grained, allotriomorphic-porphyritic leucogranite. The potassium feldspar phenocrysts

are coarser than those of samples MCK-18 and 19 (up to 30mm), but there is present a larger percentage of medium-grained groundmass.

MCK-21A Intermediate zone, north. This sample was collected 2 1/2 miles north of Prairie junction. The rock is a medium- to very coarse-grained, hypidiomorphic-porphyritic granite.

MCK-21B Intermediate zone, north. This sample is the same as MCK-21A. A large rock specimen was broken into two parts in order to test small-scale variations.

MCK-22 Core. This sample was collected 1.2 miles north of Prairie junction. The rock is a fine- to coarse-grained, allotriomorphic-porphyritic, seriate through medium granularity, leucogranite.

MCK-23 Core. This sample was collected 500 feet south of MCK-22. The rock is a medium- to coarse-grained, hypidiomorphic-porphyritic, slightly seriate leuco-quartz monzonite.

MCK-24 Core. This sample was collected 2 miles south of Prairie junction along the main north-south road. The rock is a fine- to coarse-grained, hypidiomorphic-porphyritic leuco-quartz monzonite.

MCK-25 Intermediate-central zone. This sample was collected from the Rapikivi alkalic granodiorite located 4.8 miles south of Prairie junction. The rock is coarse- to very coarse-grained, hypidiomorphic porphyritic.

MCK-26 Intermediate-central zone. This sample was collected from the same outcrop as MCK-25. The rock is a medium- to coarse-grained, hypidiomorphic-porphyritic Rapikivi alkalic granodiorite.

- MCK-27 Intermediate-central zone. This sample consists of potassium feldspar crystals from the weathered Rapikivi alkalie granodiorite of locality MCK-27 and MCK-26. The feldspar crystals are subhedral to euhedral and contain numerous inclusions of biotite and plagioclase with lesser amounts of quartz.
- MCK-28 Intermediate zone, south. This sample was collected 5.3 miles south of Prairie junction. The rock is a medium- to very coarse-grained, hypidiomorphic-porphyritic, slightly seriate to coarse granularity, granite.
- MCK-29 Intermediate zone, south. This sample was collected from inclusions within the porphyritic granite of the intermediate zone, 1000 feet from the boundary with the outer zone. The inclusions are oval in outline and vary in length from 1 to 5 feet. The rock is a fine- to medium-grained, allotriomorphic-porphyritic quartz monzonite.
- MCK-30 Intermediate zone, south. This sample is representative of the country rock containing the inclusions of MCK-29. It was sampled at the same outcrop located 8 miles south of Prairie junction. The rock is a medium- to very coarse-grained, hypidiomorphic-porphyritic, slightly seriate granite.
- MCK-31 Outer zone, south. This sample was collected from the quartz-enriched zone located along the north-south road 8.7 miles south of Prairie junction. The rock is medium- to coarse-grained allotriomorphic-granular. The rock consists predominantly of quartz and potassium feldspar with a small amount of biotite. There is no plagioclase present.

MCK-32A Outer zone, south. This sample was collected 9.1 miles south of Prairie junction. It is representative of the finer grained granite occurring at this outcrop. The rock is a fine- to medium-grained, allotriomorphic-porphyritic, slightly seriate leuco-quartz monzonite.

MCK-32B Outer zone, south. This sample was collected at the same outcrop as MCK-32A. This coarser grained portion constitutes the main mass of the outcrop. The rock is a fine- to coarse-grained, hypidiomorphic-porphyritic leucogranite.

MCK-33 Outside batholith. This sample was collected 10.5 miles south of Prairie junction from the granodiorite occurring outside of the batholith. The rock is a medium- to coarse-grained, allotriomorphic-granular granodiorite.

MCK-34 Outside batholith. This sample was collected from the same locality as MCK-33. It represents a more feldspathic and finer grained phase in direct contact with the granodiorite. The rock is a fine- to medium-grained, allotriomorphic-seriate leuco-quartz monzonite.

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