Distribution of Uranium in Rocks and Minerals of Mesozoic Batholiths in Western United States

By ESPER S. LARSEN, JR., and DAVID GOTTFRIED

INVESTIGATIONS OF WESTERN BATHOLITHS

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DISTRIBUTION OF URANIUM IN ROCKS AND MINERALS OF MESOZOIC BATHOLITHS IN WESTERN UNITED STATES

By ESPER S. LARSEN, JR., and DAVID GOTTFRIED

ABSTRACT

Fluorimetric analyses for uranium have been made on a variety of igneous rocks and minerals from the southern California, Sierra Nevada, Idaho, and Coast Range batholiths. The uranium content of nearly 200 igneous rocks, ranging from gabbro to quartz monzonite, indicates that during magmatic differentiation uranium increases from about a half a part per million in the gabbroic rocks to about four parts per million in quartz monzonites. The extreme differentiates, chiefly muscovite-quartz monzonites, show a consistent decrease in their uranium content as compared with ordinary quartz monzonites of about the same chemical composition. The uranium analyses do not fall on smooth variation curves as do the major constituents but show considerable scatter. This is especially true for the rocks ranging in composition from granodiorite to the quartz monzonites. Taking into consideration the areas underlain by the various rock types, the weighted-average uranium contents of the batholiths are as follows: southern California, 1.7 ppm; Sierra Nevada, 2.7 ppm; Idaho, 2.5 ppm; and the Coast Range, 2.7 ppm. The weighted-average uranium content of the four batholiths is approximately 2.5 ppm.

Uranium determinations on the major minerals and many of the accessory minerals of 26 igneous rocks show that in most rocks the major rock-forming minerals contain the bulk of the uranium present in the rock. In general, there is an average increase in the uranium content of a given mineral from the mafic to the siliceous rocks.

The amount of uranium soluble in acid (hot 1 + 4 HCl) was determined in six igneous rocks representing the major rock type of the southern California batholith. The percent soluble uranium ranged from 40 percent in a calcic gabbro to 83 percent in a quartz monzonite. Similar acid treatment of the major minerals of four igneous rocks shows that the bulk of the uranium contained in separated fractions of quartz, feldspar, and the mafic minerals is readily dissolved.

INTRODUCTION

This investigation on the distribution of uranium in the calc-alkalic rocks of the great Mesozoic batholiths of the western United States is one phase of a project concerned with similar studies on the major petrographic provinces of the United States. The igneous rocks of the southern California, Sierra Nevada, Idaho, and Coast Range batholiths underlie vast areas and are fairly typical of the average igneous rocks exposed in the earth's crust. Hence the data obtained on them are important for establishing the abundance of uranium in the earth's crust.

Essentially the primary objectives were to find where and in what manner the uranium is fixed in a succession of igneous differentiates formed from the crystallization of a magma. The approach adopted was to study the distribution of uranium among the various rock types of the batholiths, and the distribution of uranium among the minerals within the rocks.

Part of the data given here was discussed previously by Larsen and Phair (1954) and Larsen, Phair, Gottfried, and Smith (1956). For this report many of the earlier uranium analyses have been rechecked and additional new data are presented on the total uranium content and the acid-soluble uranium content of some of the igneous rocks and minerals. A brief summary of the uranium and thorium data on many of these rocks has been reported by Larsen 3d and Gottfried (1960).

ACKNOWLEDGMENTS

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We are grateful to E. S. Larsen 3d, Michael Fleischer, and George Phair, of the U.S. Geological Survey; and Dr. L. T. Silver, of the California Institute of Technology, for helpful suggestions during the course of this investigation.

This research was undertaken as part of the investigations concerning the distribution of uranium in igneous rocks by the U.S. Geological Survey on behalf of the Division of Research of the U.S. Atomic Energy Commission.

METHOD OF URANIUM ANALYSIS

Uranium determinations given in this report were made by the fluorimetric method described by Grimaldi, May, and Fletcher (1952), and Grimaldi and others (1954). The method based on the fluorescence of uranium in fluoride phosphors is one of the most sensitive for the determination of uranium in the low parts-per-million range.

At the present time few data are available to make comparisons between the fluorimetric method and other techniques for determining uranium in ordinary igneous rocks. Using the fluorimetric method, Adams (1955) checked to within 10 percent the uranium content of a granite on which an isotope-dilution uranium determination had been made by George Tilton. A comparison of fluorimetric uranium analyses made by chemists of the Geological Survey with other techniques for determining uranium is given for the granite G–1, and the diabase W–1 in table 1. The agreement between the different methods is satisfactory. In this report the uranium analyses, for the most part, are probably accurate to ± 10 to 15 percent for samples containing more than 1 ppm uranium. For rocks and minerals containing less than 1 ppm of uranium the error is greater—probably 20 to 50 percent.

SOUTHERN CALIFORNIA BATHOLITH

The batholith of southern California occupies the core of the Peninsular Range from the vicinity of Riverside, Calif., southeastward to the southern tip of Baja California—a distance of about 1,000 miles. The average width in the northern part is about 70 miles and somewhat less in the southern part. The main northwestern part of the batholith underlies an area of about 20,000 square miles and the entire mass probably more than 40,000 square miles. In California the batholith occupies an area of about 8,000 square miles. Field, chemical, and petrologic studies have been made by Larsen (1948) and Larsen and Draisin (1948) of an area probably fairly representative of the entire batholith.

The batholith was divided on the geologic map of the Elsinore, San Luis Rey, and Corona quadrangles into 20 map units. However, in the area mapped by Larsen (1948) nearly 90 percent of the batholith is made up of 5 major rock types. The sequence of intrusions is similar to that found in other composite batholiths. In general, the gabbros were intruded first; then the tonalites, granodiorites, quartz monzonites, and granites; and finally the muscovite-quartz monzon-

TABLE 1.—*Comparison of fluorimetric and other methods of uranium analyses*

	Average uranium (ppm)		
Method	*Granite (G–1)* [1]	*Diabase (W–1)* [2]	*Analyst*
Fluorimetric	3.5	0.5	Jesse Warr.[3]
Do	3.7	.6	Marjorie Molloy.[3]
Do	3.8	.6	Marian Schnepfe.[3]
Do	[4] 3.8	[4] .52	Ahrens and Fleischer (1960).
Gamma-ray spectrometry	3.8	.5	P. M. Hurley.[5]
Radioactivation	3.6	.53	Hamilton (1959).

[1] Granite, Westerly, R.I.
[2] Diabase, Centerville, Va.
[3] U.S. Geological Survey.
[4] Average of 46 determinations.
[5] Massachusetts Inst. Technology (written communication, 1955).

ites. Approximate percentages of the area underlain by the various rock types are as follows:

	Percent		Percent
San Marcos gabbro	7	Miscellaneous tonalites	3
Bonsall tonalite	28	Woodson Mountain granodiorite	24
Lakeview Mountain tonalite	20	Miscellaneous granodiorites	4
Green Valley tonalite	12	Quartz monzonites and granites	2

From its relations to fossiliferous rocks in northern Baja California the batholith probably is early Late Cretaceous in age. Twenty-five lead-alpha age measurements on suitable accessory minerals separated from various plutonic rocks of the batholith give a mean age of 110 ± 13 millions of years (Larsen, Gottfried, Jaffe, and Waring, 1958).

URANIUM CONTENT OF IGNEOUS ROCKS OF THE SOUTHERN CALIFORNIA BATHOLITH

SAN MARCOS GABBRO

The rocks included in the San Marcos gabbro are highly variable in composition and texture (Miller, 1937) and consists of anorthosite, calcic-gabbro, norite, and quartz-biotite norite. Norite is the most abundant rock type of this group. Uranium analyses of 12 gabbroic rocks are listed in table 2. They all contain about 0.5 ppm or less of uranium except El 230, which contains 2.6 ppm uranium. This rock is from a small body of coarse quartz-biotite norite transitional to tonalite. The average uranium content of the other 11 gabbros, after omitting this sample, is 0.3 ppm.

TABLE 2.—*Uranium content of gabbroic rocks from the southern California batholith*

Sample	Rock type and locality	Uranium (ppm)
SLR M354	Olivine norite, northeast part of San Luis Rey quadrangle	0. 56
El 303	Calcic hornblende gabbro, southeast part of Elsinore quadrangle.	. 33
SLR 218	Quartz-biotite hornblende norite, 3 miles southwest of Escondido.	. 33
SLR M229	Noritic hornblende gabbro, 1½ miles west of Fallbrook	. 22
SLR M334	Norite, 3 miles east of Vista	. 17
SLR M229A	Nodules of nodular norite, half a mile east of Vista Grande.	. 47
SLR M229B	Matrix of nodular norite, same location as M229A	. 35
SLR 360	Hornblende gabbro, San Luis Rey quadrangle	. 30
S-3	Norite, Emil Johnson quarry, northeast of Pala	. 40
G-26	Gabbro, north of Cuyumaca Reservoir	. 30
El 230	Coarse quartz-biotite norite, 5 miles west of Perris	2. 6
G-37	Hornblende hypersthene gabbro, west of Elsinore	. 25
	Average (omitting El 230)	0. 33

TONALITES

Several kinds of tonalite make up more than half of the igneous rocks of the batholith; tonalite is the average rock type of the batholith. Only three types of tonalite underlie large areas; the Bonsall tonalite, the Lakeview Mountain tonalite, and the Green Valley tonalite. All three types contain biotite and hornblende. The uranium content of 18 samples of tonalite collected from widely scattered localities is given in table 3. Some of the rocks are from small bodies and are unusual rocks. One sample, SLR 582, which contains 0.38 ppm uranium, crops out over a small area and is intermediate in composition between the San Marcos gabbro and the Green Valley tonalite. The average uranium content of the other tonalites is 1.5 ppm.

GRANODIORITES

The most abundant type of granodiorite of the batholith is a uniform light-colored coarse-grained rock called the Woodson Mountain granodiorite. In general it is massive, but near contacts with older rocks it has a banded or gneissoid structure that parallels the contact.

TABLE 3.—*Uranium content of tonalites from the southern California batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
SLR 582	Green Valley tonalite (quartz-biotite-hornblende gabbro), 1½ miles north of Vista.	0. 38
SLR 213	Green Valley tonalite, quarry 2.2 miles southwest of Escondido.	1. 6
SLR 138	Green Valley tonalite, southwest corner of San Luis Rey quandrangle.	1. 4
SLR 1016	Bonsall tonalite, eastern part of Bear Valley, Ramona quadrangle.	. 74
El 38–28	Bonsall tonalite, 2 miles west of Valverde	2. 0
Ra–3	Tonalite, near Auganga	. 62
Cor 36–57	La Sierra tonalite, quarry 0.9 mile east of Mount Hole	2. 4
El 314	Domenigoni Valley tonalite, Domenigoni Valley	. 57
El 38–134	Lakeview Mountain tonalite, quarry 3½ miles northeast of Perris.	1. 2
G–11	Tonalite, 2½ miles west of Alpine	2. 8
S–1	Lakeview Mountain tonalite, 2 miles east of Nuevo	2. 2
S–5	Tonalite, 8 miles east of Descanso Post Office	1. 6
G–3	Tonalite, 3 miles west of Mountain Center, Hemet quadrangle.	2. 2
G–49	Tonalite, 5 miles west of Coahuila	. 95
G–50	Tonalite, In-Koh-Pah gorge, east of Jacumba	. 68
G–51	Tonalite, half a mile east of Santa Ysabel	1. 6
G–54	Tonalite, 1 mile east of Oak Grove	1. 5
G–56	Tonalite, 1 mile east of Yaqui Well	1. 6
	Average (omitting SLR 582)	1. 5

The average uranium content of 35 samples of all types of granodiorites is 2.1 ppm (table 4), which is a little higher than the average for the 12 samples of the Woodson Mountain granodiorite from a single mass. This is, in part, due to the greater uranium content of a few samples of granodiorite of unusual texture and composition. The granodiorite from Banning is aplitic and the Mount Hole granodiorite, which contains 6.0 ppm of uranium, is rich in allanite.

TABLE 4.—*Uranium content of granodiorites from the southern California batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
S–10	Woodson Mountain granodiorite, 1½ miles southeast of Rainbow.	1. 8
S–17	Woodson Mountain granodiorite, Poway grade	1. 3
S–16	Woodson Mountain granodiorite, 2 miles north or Pala Guard Station.	1. 9
G–12A	Woodson Mountain granodiorite, Descanso Junction	2. 1
G–12B	Woodson Mountain granodiorite, Descanso Junction	2. 4
G–31	Woodson Mountain granodiorite (near contact), 2½ miles east of Auld.	1. 4
G–58	Woodson Mountain granodiorite, 3 miles east of Pala	2. 9
Cor–la	Woodson Mountain granodiorite, quarry 3 miles east of Corona.	3. 8
Ra–135	Woodson Mountain granodiorite, head of Poway grade	1. 5
SLR–596	Woodson Mountain granodiorite, quarry half a mile east of Rainbow.	2. 7
S–2	Woodson Mountain granodiorite, 1 mile south of Temecula.	1. 4
S–6	Woodson Mountain granodiorite, northeast of Descanso Junction.	1. 9
S–7	Woodson Mountain granodiorite, roadside spring south of Temecula.	1. 5
S–8	Woodson Mountain granodiorite, 3.2 miles south of S–7	1. 5
S–9	Woodson Mountain granodiorite, 1 mile from U.S. Highway 395 on road to Rainbow.	1. 8
S–11	Woodson Mountain granodiorite, 3 miles north of Rainbow.	1. 6
S–12	Woodson Mountain granodiorite, intersection north of Rainbow.	2. 4
S–13	Woodson Mountain granodiorite, 0.8 mile south of Riverside-San Diego County line on road to Pala.	3. 3
S–14	Woodson Mountain granodiorite, 1½ miles south of S–13	1. 6
S–15	Woodson Mountain granodiorite, 1½ miles northwest of Pala Guard Station.	1. 4
G–4	Granodiorite, 1 mile northeast of Mountain Center	1. 8
G–48	Granodiorite, Stonewall Mountain, Cuyumaca quadrangle	2. 2
G–13	Granodiorite, near La Posta ranch	2. 5
G–9	Granodiorite, east shaft of Los Angeles aqueduct southeast of Banning.	4. 2
G–5	Granodiorite (aplitic), 2 miles south of Banning	6. 0

TABLE 4.—*Uranium content of granodiorites from the southern California batholith*—Continued

Sample	*Rock type and locality*	*Uranium (ppm)*
G–10	Granodiorite (aplitic), 1 mile east of Aguanga	1. 6
G–53	Granodiorite (aplitic), 5 miles east of Aguanga	1. 1
G–52	Granodiorite (aplitic), 1 mile north of Pine Cove	1. 4
G–14	Granodiorite (aplitic), 3 miles west of Lone Oak Springs	1. 2
G–30	Granodiorite (aplitic), 5 miles southwest of Palm Springs	1. 9
Ra–106	Lake Wolford leuco granodiorite, quarry north of San Pasqual Valley.	. 8
SLR–597	Escondido Creek leuco granodiorite, Escondido Creek	1. 9
Cor 36–60	Mount Hole granodiorite, 3½ miles northeast of Corona	5. 9
Cor 2	Porphyritic granodiorite, 1 mile east of Porphyry	2. 8
El 38–126	Granodiorite, east portal of tunnel 5 miles northeast of Perris.	. 7
SLR–685	Granodiorite, upper part of Los Monos Canyon	2. 4
Average (omitting Cor 36–60)		2. 1

To test the variation of uranium content of a mapped body of rock, 12 samples of the Woodson Mountain granodiorite were collected from different parts of the mass south of Temecula (fig. 7). The data show a rather wide range in the uranium content of these rocks—1.4 to 3.3 ppm, averaging about 1.9 ppm. The rocks near the contact tend to contain slightly less uranium.

QUARTZ MONZONITES

Quartz monzonites are rare in the main part of the batholith and make up only a few percent of the igneous rocks. The uranium content of 10 samples is given in table 5. Seven samples are ordinary

TABLE 5.—*Uranium content of quartz monzonites from the southern California batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
El 38–167	Coarse quartz monzonite, Rubidoux Mountains	4. 1
El 38–265	Fine quartz monzonite, Rubidoux Mountains	5. 2
Cor. 3	Micropegmatite, 1 mile east of Corona	6. 0
SLR L 61	Leucogranite, Roblar Canyon	4. 1
El 228	Dike, 1 mile west of Good Hope mine	3. 4
G–6	Aplitic, quartz monzonite east shaft of Los Angeles Aqueduct southeast of Banning.	3. 7
G–7	Quartz monzonite, same locality as G–6	6. 6
Average		4. 6
S–4	Muscovite-quartz monzonite, north end of Rattlesnake Valley.	1. 1
RG–1	do	2. 7
G–27	do	3. 6
Average		2. 5

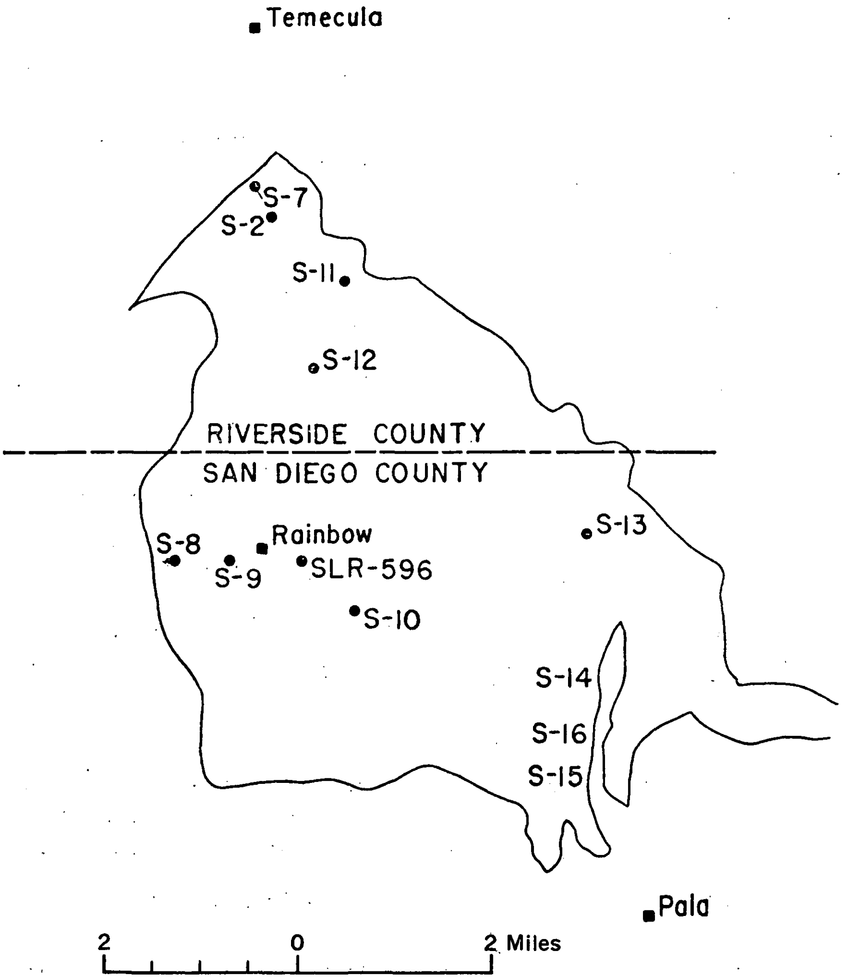

FIGURE 7.—Map showing location of samples analyzed for uranium in a stock of Woodson Mountain granodiorite in southern California

quartz monzonites and range in uranium content from 3.4 to 6.6 ppm. They average 4.6 ppm uranium. The three samples of muscovite-quartz monzonite—the Rattlesnake granite of Everhart (1951)—are coarse-grained rocks approaching the texture of pegmatite. They contain from 1.1 to 3.6 ppm of uranium and average 2.5 ppm.

IGNEOUS ROCKS OF THE DESERT AREA

The intrusive rocks in the desert ranges east of the Peninsular Range occur in small scattered bodies separated by large masses of prebatholithic rocks. Based on chemical analyses furnished in a report by Miller (1946), Larsen (1948) points out that the rocks of the desert area are lower in SiO_2 and higher in K_2O, Na_2O, and Al_2O_3

than the rocks from the western part of the batholith. The intrusive rocks are chiefly granodiorites and quartz monzonites.

The uranium content of tonalites, granodiorites, and quartz monzonites are given in table 6. Two tonalites average 1.8 ppm uranium, five granodiorites average 1.5 ppm, and nine samples of quartz monzonite average 1.7 ppm uranium. The average uranium content of each of the three rock types is nearly the same. The quartz monzonites of the desert area contain much less uranium than the quartz monzonites from the main part of the batholith.

RELATION OF URANIUM CONTENT TO CHEMICAL COMPOSITION

Chemical analyses of 35 igneous rocks, representing the major rock types and some of the more variable units, have been published by Larsen (1948). A plot of their major oxides on a variation diagram of the type proposed by Larsen (1938) gives smooth variation curves on which nearly all the points fall. The gabbroic rocks and a few other rocks of unusual composition are erratic.

Analyses for uranium of 28 of the chemically analyzed rocks are listed in table 7. They range from a gabbroic rock with about 43

TABLE 6.—*Uranium content of tonalites, granodiorites, and quartz monzonites from the desert area*

Sample	*Rock type and locality*	*Uranium (ppm)*
G–18B	Tonalite, northern Providence Mountain	1.7
G–41	Tonalite, south of Atolia	1.9
	Average	1.8
G–39a	Granodiorite, three-fourths of a mile east of Victorville	1.4
G–38	Granodiorite, Cactus Flat	1.7
G–29	Granodiorite, 6 miles northeast of Indio	1.3
G–40	Granodiorite, 4½ miles east of Victorville	1.7
G–33	Granodiorite, Mount Wilson	1.3
	Average	1.5
G–15	Quartz monzonite, Cottonwood Springs	2.6
G–17	Quartz monzonite, Joshua Tree National Monument	1.5
G–18	Quartz monzonite, Sheephole Mountains	1.1
G–19	Quartz monzonite, east of Rock Springs	1.2
G–21	Quartz monzonite, Rock Springs	1.0
G–22	Quartz monzonite, 4 miles northeast of Kelso	1.9
G–23	Quartz monzonite, 5 miles north of Cima	1.3
G–24	Quartz monzonite, Soda Lake Mountains	3.0
G–39b	Quartz monzonite, three-fourths of a mile east of Victorville.	1.3
	Average	1.7

percent SiO_2 to a granite with about 77 percent SiO_2. The rocks are listed in approximately the order of increasing SiO_2 content or position on a variation diagram. Figure 8 shows how the uranium content varies with the chemical composition of the rocks. In general, the uranium content increases from the mafic to the more siliceous rocks and ranges from less than 0.3 ppm in the gabbros to about 6.0 ppm in some of the highly siliceous rocks. This is an increase of about twentyfold. The increase is not very regular or systematic as one of the gabbroic rocks (position 0.2) contains 2.6 ppm of uranium, whereas all the other gabbroic rocks contain somewhat less than 0.5 ppm. As pointed out earlier this gabbro is an unusual rock. It is interesting to note that the same rock was found to be unusually high in alpha activity as compared to the other gabbros by Larsen and Keevil (1947). A tonalite, Ra3 (position 18.7), is low in uranium as is the Lake Wolford leucogranodiorite (position 22.7). Both rocks are erratic on a chemical-variation diagram. Sample Ra3 is low in both K_2O and FeO and high in Al_2O_3. The specimen of the Lake Wolford granodiorite is not typical of the formation (Larsen, 1948); it is low in K_2O and FeO and high in SiO_2.

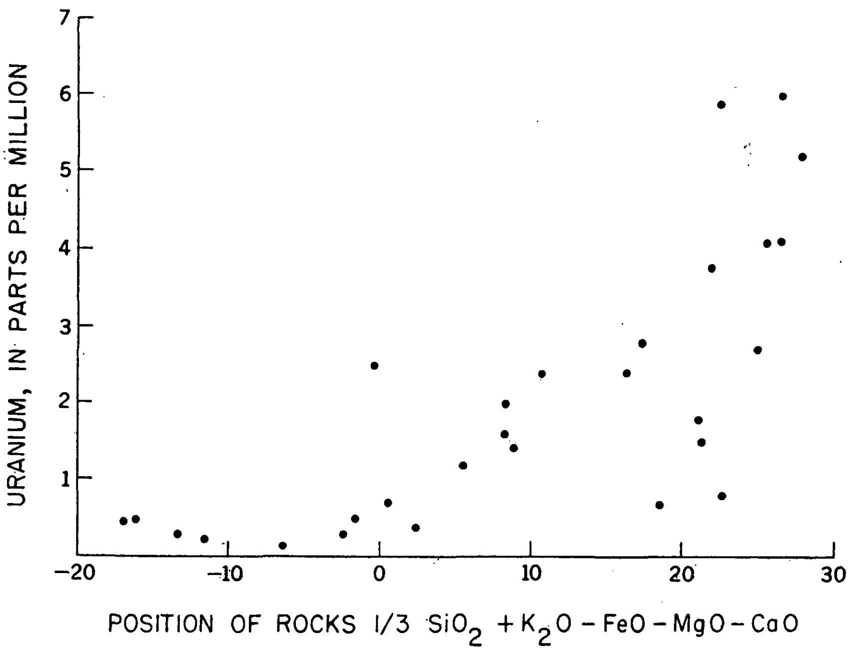

FIGURE 8.—Uranium in igneous rocks of the batholith of southern California plotted against the composition of the rocks.

TABLE 7.—*Analyzed rocks from the batholith of southern California—their SiO_2, K_2O, and U content and their position on the variation diagram*

Sample	SiO_2	K_2O	Uranium (ppm)	Position	Rock
SLR M354	42.86	0.09	0.56	−16.0	Olivine norite.
El 303	45.78	.42	.33	−17.0	Calcic hornblende gabbro.
SLR 218	47.22	.13	.33	−13.3	Quartz-biotite hornblende norite.
SLR M299	48.16	.31	.22	−11.6	Noritic hornblende gabbro.
SLR M334	52.12	.25	.17	−6.1	Norite.
SLR M229 B	54.70	1.06	.35	−2.2	Matrix of nodular norite.
SLR M229 A	56.92	.44	.47	−1.5	Nodules of nodular norite.
El 230	56.62	1.36	2.6	−.2	Quartz-biotite norite.
SLR 1016	55.14	1.36	.74	.4	Bonsall tonalite.
SLR 582	58.68	1.20	.38	2.5	Quartz-biotite hornblende gabbro.
El 38-134	59.28	1.53	1.2	5.5	Lakeview Mountain tonalite.
SLR 213	63.38	1.78	1.6	8.8	Green Valley tonalite.
SLR 138	63.70	1.92	1.4	9.0	Do.
El 36-57	60.41	1.60	2.4	10.4	La Sierra tonalite.
El 38-28	62.28	1.49	2.0	8.4	Bonsall tonalite.
SLR 685	69.26	2.34	2.4	16.5	Granodiorite of Green Valley tonalite.
Cor 2	68.56	2.80	2.8	17.2	Porphyritic granodiorite.
Ra 3	69.72	1.32	.6	18.7	Tonalite.
Ra 135	72.55	2.84	1.5	21.2	Woodson Mountain granodiorite.
Cor-1a	72.94	4.24	3.8	22.0	Do.
SLR 596	74.72	3.40	2.7	25.0	Do.
SLR 597	73.11	1.73	1.8	21.0	Escondido Creek leucogranodiorite.
Cor 36-60	72.80	3.71	5.9	22.4	Mount Hole granodiorite.
Ra 106	74.68	2.01	.8	22.7	Lake Wolford leucogranodiorite.
El 38-167	73.60	4.27	4.1	25.5	Coarse-grained quartz monzonite.
Cor 3	74.46	5.04	6.0	26.2	Micropegmatite.
El 38-265	75.38	4.95	5.2	27.7	Fine-grained quartz monzonite.
SLR L 61	76.54	4.29	4.1	26.2	Roblar leucogranite.

AVERAGE URANIUM CONTENT OF THE IGNEOUS ROCKS AND OF THE BATHOLITH

It would be possible to make a fairly accurate calculation of the uranium content of the batholith if uranium were distributed as systematically as are the major constituents in the igneous rocks. However, the amount of uranium present in the igneous rocks does not follow as simple a relation as do the major constituents.

Analyses for uranium obtained on 89 samples of igneous rocks of the batholith are summarized in table 8. In the main part of the

TABLE 8.—*Average uranium content of igneous rocks of the southern California batholith*

Rock type	Number of samples	Uranium (ppm) Range	Uranium (ppm) Average	Region
Gabbro	11	0. 17–0. 56	0. 3	Main part of batholith.
Tonalite	17	. 62–2. 8	1. 5	Do.
Granodiorite	35	. 7 –6. 0	2. 1	Do.
Quartz monzonite	7	3. 4 –6. 6	4. 6	Do.
Muscovite-quartz monzonite.	3	1. 1 –3. 6	2. 5	Do.
Tonalite	2	1. 7 –1. 9	1. 8	Desert.
Granodiorite	5	1. 3 –1. 7	1. 5	Do.
Quartz monzonite	9	1. 0 –3. 0	1. 7	Do.

batholith the average uranium content in the gabbro is 0.3 ppm; in tonalite 1.5 ppm; in granodiorite 2.1 ppm; in quartz monzonite 4.6 ppm, and decreases to 2.5 ppm in muscovite-quartz monzonites. From these data and from the estimates of the areas underlain by the various rock types (Larsen, 1948), the weighted-average uranium content of the batholith is estimated to be 1.7 ppm (table 9).

DISTRIBUTION OF URANIUM IN MINERALS OF THE ROCKS

To study the distribution of uranium within the rocks the component minerals of 16 rocks from the batholith of southern California were separated. The rocks cover a wide range in chemical composition, ranging from an olivine norite to a muscovite quartz monzonite. Concentrates of the major and accessory minerals were obtained by heavy-liquid and magnetic separations and handpicking. However, even the best monomineralic concentrates contained microscopic inclusions of an unidentifiable nature. Generally, the amount of uranium these inclusions contribute to the mineral concentrate is probably insignificant.

The abundance in weight percent, the uranium content of rock-mineral concentrate, and the amount of uranium contributed by each mineral to the uranium content of the rocks are given in tables 10, 11, 12, and 13.

TABLE 9.—*Average uranium content of the southern California batholith*

Rock type	Percent area of batholith	Average uranium content (ppm)
Gabbro	7	0. 3
Tonalite	63	1. 5
Granodiorite	28	2. 1
Quartz monzonite	2	4. 6
Weighted average		1. 7

TABLE 10.—*Uranium content of the minerals of some gabbroic rocks from the southern California batholith*

Mineral	Norite S-3			Olivine norite SLR M354			Hornblende gabbro El 303			Hornblende gabbro SLR M299			Quartz-biotite norite El 230		
	Abundance (weight percent)	U (ppm)	Weight percent of mineral × $\frac{U\ (ppm)}{100}$	Abundance (weight percent)	U (ppm)	Weight percent of mineral × $\frac{U\ (ppm)}{100}$	Abundance (weight percent)	U (ppm)	Weight percent of mineral × $\frac{U\ (ppm)}{100}$	Abundance (weight percent)	U (ppm)	Weight percent of mineral × $\frac{U\ (ppm)}{100}$	Abundance (weight percent)	U (ppm)	Weight percent of mineral × $\frac{U\ (ppm)}{100}$
Quartz													10	3.2	0.32
Plagioclase	56.0	0.88	0.49	67	0.32	0.21	47	0.44	0.21	51	0.10	0.05	52	.96	.50
Biotite	.2	.96	.002							1	4.4	0.4	16	1.8	.29
Hornblende	18.0	.17	.03	10	.26	.03	34	1.1	.37	42	.31	.13	3	1.4	.04
Augite	9.5	.37	.04				5	1.1	.05	5	6.0	.30	8	3.7	.30
Hypersthene	11.0	.36	.04	2	.01	0	6	.14	.01				9	2.0	.18
Olivine				18	<.01	0									
Apatite	.01	8.8	.001												
Sphene	.004	71	.003												
Zircon	.0005	90	0												
Opaque minerals	5.0	1.0	.05	2	.6	.01	8	.36	.03	2	.88	.02	2	.84	.02
Total uranium (by sum of minerals)			.66			.25			.67			.54			1.7
Total uranium in bulk rock (measured)			.40			.56			.33			.22			2.6

GABBROS

The data for a variety of gabbroic rocks from the San Marcos gabbro are given in table 10. Because of the low uranium content of most of these highly mafic rocks, the error in the analyses for uranium on the bulk rock and on the mafic minerals is relatively large compared to those on minerals and rocks of the later differentiates. However, the analyses probably provide a valid approximation of the amount of uranium present in each of the minerals. The accessory minerals—apatite, sphene, and zircon—were separated from only one of the gabbroic rocks (S–3). About 200 pounds of this rock was processed to obtain sufficient amounts of zircon for analysis for uranium. Most of the accessory minerals from the other gabbroic rocks were not analyzed because they were present in too small amount.

From the data given in table 10 it is clear that about 90 percent of the uranium in the gabbroic rocks is accounted for by the major minerals. The mineral with the highest uranium content is zircon, which contains 90 ppm uranium. However, the amount of zircon present is estimated to be less than 5 ppm of the rock, hence the amount of uranium contributed by the zircon to the rock is negligible. Next highest in the uranium are sphene and apatite; 71 and 8.8 ppm, respectively. Olivine and hypersthene are very low in uranium, generally containing from less than 0.01 to as much as 0.36 ppm. In one rock (El 230) hypersthene carries 2.0 ppm uranium. As pointed out earlier, this is an unusual rock chemically and it is higher in uranium than any of the ordinary gabbros. Highly calcic plagioclase and hornblende are the chief constituents of the common gabbroic rocks. Omitting sample El 230, plagioclase and hornblende average 0.44 and 0.46 ppm uranium, respectively, and carry the bulk of the uranium in these rocks.

TONALITES

The data for the minerals separated from four tonalites are given in table 11. The accessory minerals are relatievly high in uranium as compared to the major minerals. Listed in order of decreasing uranium content these are: zircon, sphene, apatite, epidote, and the opaques consisting of magnetite and ilmenite. The chief minerals contain nearly the same amount of uranium as the bulk rock, contributing from 70 to 90 percent of the uranium to the bulk rock.

GRANODIORITES

Most of the minerals from the four grandiorites listed in table 12 show an increase in their average uranium content over those from the earlier formed rocks. Monazite and xenotime appear in the more siliceous granodiorites. Muscovite or garnet, or both, are commonly present when either monazite or xenotime has been found. Xenotime

TABLE 11.—*Uranium content of the minerals of some tonalites from the southern California batholith*

Mineral	G-3			El 38-134			SLR 138			El 38-28		
	Abundance (weight percent)	U (ppm)	Weight percent of mineral X U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral X U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral X U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral X U (ppm) / 100
Quartz	24	1.5	0.36	36	0.72	0.26	24	1.3	0.31	22	0.3	0.07
Plagioclase	54	1.8	.97	53	1.9	1.0	48	.56	.27	52	2.2	1.11
Orthoclase	5	1.4	.07									
Biotite	12	3.2	.38	6	.50	.03	12	.8	.10	15	1.7	.26
Hornblende	5	3.2	.16	1	.55	.01	11	.7	.08	9	3.6	.32
Augite				2	.13	0	3	2.5	.08			
Epidote										.5	50	.25
Apatite	.07	59	.04	.01	120	.01	.01	290	.03	.02	38	.01
Sphene	.17	8.8	.02	.05	140	.07	.05	360	.18	.04	350	.14
Zircon	.02	485	.10	.02	170	.03	.02	270	.05	.01	450	.05
Opaque minerals	.3	1.8	.01	.01	.7	0	2	3.5	.07	1.0	7.0	.07
Total uranium (by sum of minerals)			2.1			1.4			1.2			2.3
Total uranium in bulk rock (measured)			2.2			1.2			1.4			2.0

TABLE 12.—*Uranium content of the minerals of some granodiorites from the southern California batholith*

Mineral	S-6			S-2			S-11			G-13		
	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100
Quartz	45	1.6	0.72	37	1.0	0.37				27	1.6	0.43
Orthoclase	10	1.3	.13	22	1.3	.29	20	1.1	.22	7	2.2	.15
Plagioclase	40	2.1	.84	37	1.9	.70	[1] 73	.8	.58	53	1.2	.64
Biotite	4	2.8	.11	2	4.0	.08	5	13.5	.68	8	1.2	.10
Hornblende	.5	28.0	.01	1	2.0	.02	1	13.0	.13	4	6.1	.24
Allanite				.04	55.0	.02	.02	330	.01			
Apatite	.003	62.0	.002	.01	370	.04				.2	35	.07
Sphene				.015	110	.02				.1	236	.24
Monazite	.012	820	.10									
Zircon	.006	1,700	.10	.008	1,070	.09				.02	860	.17
Xenotime	.001	12,700	.13									
Garnet	.18	7.5	.16									
Opaque minerals	.003	3.5	0	.3	3.2	.01	.02	1.7	0	.5	2.1	.01
Total uranium (by sum of mineral)			2.3			1.6			1.6			2.1
Total uranium in bulk rock (measured)			1.9			1.4			1.6			2.5

[1] Plagioclase and quartz.

has by far the greatest concentration of uranium (12,700 ppm) than any of the other analyzed accessory minerals. Even in the granodiorite (S–6), which contains xenotime, monazite, and zircon, the major portion of the uranium is accounted for by the major minerals. In general, quartz and the feldspar carry a little less uranium than the bulk rock. Biotite and hornblende contain more uranium than the felsic minerals in the granodiorites, but they are small in amount in these rocks.

QUARTZ MONZONITES

Minerals from three of the most siliceous rock types that occur in the batholith are listed in table 13. Each of the major minerals has a greater average uranium content than any of those from the rocks previously discussed. In two of the rocks monazite and xenotime were separated, but in only one rock was a sufficient amount of concentrate available for uranium analyses. In one of these rocks (El 38–265), thorite was noted in the zircon concentrate. The analysis for uranium was made on the zircon concentrate after acid treatment to remove the thorite. In two of the three rocks the uranium content of the zircon is considerably greater than in the zircon from the granodiorites or tonalites. However, zircon is present in smaller amounts in the quartz monzonites. Allanite is a fairly abundant accessory mineral in two of the rocks; it contains 540 ppm uranium in one rock and 400 ppm uranium in the other.

The mafic minerals have a greater uranium content than the rock itself, but they make up only a small percent of the rock. Hypersthene in the quartz monzonite (El 38–167) is rich in iron and contains 9.0 ppm uranium. In the gabbroic rocks hypersthene is low in iron and is very low in uranium content.

The total uranium in the major minerals ranges from about 75 to 90 percent of the uranium in the rock.

SIERRA NEVADA BATHOLITH

Granite rocks of the Sierra Nevada form a vast composite batholith underlying an area of about 17,000 square miles. The southern end of the Sierra Nevada batholith is about 100 miles north of the northern end of the southern California batholith. For a distance of about 400 miles the batholith trends north-northwestward. This is the same general trend as that of the southern California batholith.

The igneous rocks of the Sierra Nevada batholith have about the same range of composition as do those of the southern California batholith—from gabbro to muscovite-quartz monzonite. With regard to the average igneous rock of the batholith, Paul C. Bateman (written communication, 1955) states,

My best guess is that the average rock is hornblende-biotite granodiorite with a quartz-orthoclase-plagioclase ratio of 1–1–2. This rock would contain about 6

TABLE 13.—*Uranium content of the minerals of some quartz monzonites from the southern California batholith*

Mineral	RG-1			El 38-265			El 38-167		
	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100
Quartz	40	2.4	0.96	34	5.6	1.9	33	3.5	1.2
Orthoclase	36	1.3	.47	36	2.2	.79	32	2.6	.83
Plagioclase	16	2.3	.37	26	1.5	.39	34	2.8	.95
Biotite	1	5.2	.01	2	13	.26	2	2.2	.04
Hornblende				.5	60	.30	1	19	.19
Hypersthene							.5	9.0	.01
Muscovite	7	8.0	.56				.5	9.0	.01
Opaque minerals				.7	15	.11	.5	6.8	.03
Zircon	.002	4,600	.09	.01	4,700	.47	.01	1,080	.11
Allanite				.05	540	.27	.01	400	.04
Monazite	.004	2,500	.10	.008		.2±			
Xenotime	.003	360	.01	Tr.		.1±			
Garnet	.2	5.8	.01						
Apatite	.001	47	0						
Thorite				Tr.		.1±			
Total uranium (by sum of minerals)			2.6			4.9			3.4
Total uranium in bulkrock (measured)			2.7			5.2			3.2

percent of biotite, 4 percent of hornblende, and 2 percent of accessories. The average composition of the plagioclase would be about An_{30-35}.

URANIUM CONTENT OF IGNEOUS ROCKS OF THE SIERRA NEVADA BATHOLITH

Most of the samples analyzed for uranium are from the eastern part of the Sierra batholith from an area near Bishop, Calif., and were collected by Paul C. Bateman who is making a geologic study of the area. Other rock samples are from widely separated localities—from Shasta County in the Klamath Mountains in the northern part of the State, to Tehachapi near the southern end of the batholith.

Analyses for uranium on 48 igneous rocks from the Sierra Nevada batholith are listed according to rock type in tables 14 through 18.

GABBROS

Analyses for uranium on four gabbros are listed in table 14. The average uranium content of the four samples is 0.57 ppm, which is a little higher than that of the gabbroic rocks from southern California, which averaged 0.33 ppm uranium.

TABLE 14.—*Uranium content of gabbros from the Sierra Nevada batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
G–47	Olivine gabbro, 2.5 miles southwest of Kernville	0. 50
G–47A	Hornblende gabbro, 3 miles west of Kernville	. 75
PB–A	Hornblende gabbro, south central part of Big Pine quadrangle.	. 54
PB–9	Hornblende gabbro, eastern part of Mount Tom quadrangle.	. 50
Average		0. 57

TONALITES

Analyses for uranium on two tonalites from the southern Sierra Nevada batholith and on two tonalites from Shasta County are given in table 15. They are fairly uniform in uranium content and average

TABLE 15.—*Uranium content of tonalites from the Sierra Nevada batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
G–1	Tonalite, on road from Bakersfield to Tehachapi, near road intersection to Caliente.	1. 4
G–2	Tonalite, 8 miles southwest of sample G–1	1. 1
180–3	Tonalite, west-central part of French Gulch quadrangle, Shasta County.	1. 2
180–4	Biotite-hornblende tonalite, southeast part of French Gulch quadrangle, Shasta County.	1. 9
Average		1. 4

1.4 ppm. They are very similar in uranium content to the tonalites of southern California.

GRANODIORITES

Six samples of granodiorite analyzed for uranium are listed in table 16. The uranium content of these rocks averages 2.6 ppm as compared to 2.1 ppm for the granodiorites from southern California.

QUARTZ MONZONITES

Nearly all the samples of quartz monzonite are from the Mount Tom, Mount Goddard, and Big Pine quadrangles near Bishop, Calif. Analyses for uranium on 26 samples are given in table 17. They average 3.6 ppm uranium as compared to 4.6 ppm in the quartz monzonites from southern California.

ALBITE-QUARTZ MONZONITES AND GRANITES

The uranium contents of eight albite-bearing quartz monzonites and granites are given in table 18. Four of the albite-quartz monzonites from the Big Pine, Bishop, and Mount Tom quadrangles range in uranium content from 1.7 to 5.0 ppm, and they average 3.4 ppm. The muscovite granite and albite granites average less in uranium than the ordinary quartz monzonites. The average of the eight samples is 2.9 ppm uranium.

AVERAGE URANIUM CONTENT OF THE IGNEOUS ROCKS AND OF THE BATHOLITH

Analyses for uranium on 48 igneous rocks from the Sierra Nevada batholith are summarized in table 19. The average uranium content increases from 0.6 in the gabbroic rocks to 1.4 ppm in the tonalites, 2.6 ppm in the granodiorites, and 3.6 ppm in the quartz monzonites. In the more extreme rocks, such as the muscovite quartz monzonite and albite granites, there is a decrease in the uranium content. The

TABLE 16.—*Uranium content of granodiorites from the Sierra Nevada batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
53PB-8	Granodiorite of Gateway, junction of Avalanche Creek with Merced River, Yosemite National Park.	3.9
G-46	Granodiorite, 0.5 mile east of Isabella	2.6
6-120-3	Inconsolable granodiorite, eastern part of Mount Goddard quadrangle.	1.7
PB-7	Inconsolable granodiorite, western part of Big Pine quadrangle.	2.8
PB-6	Round Valley Peak granodiorite, northwest part of Mount Tom quadrangle.	3.0
PB-G	Granodiorite from Tungsten Hills, eastern part of Mount Tom quadrangle.	1.9
Average		2.6

TABLE 17.—*Uranium content of quartz monzonites from the Sierra Nevada batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
53 PB-10	Half Dome quartz monzonite, 1 mile west of Tenaya Lake, Yosemite National Park.	5.5
53 PB-9	Quartz monzonite of the El Capitan granite, junction of Tamarack and Cascade Creeks, Yosemite National Park.	3.2
PB-2	Tungsten Hills quartz monzonite, near Pine Creek mine, Mount Tom quadrangle.	7.5
PB-4	Tungsten Hills quartz monzonite, Bishop Creek road, northern part of Mount Goddard quadrangle.	3.5
PB-D	Tungsten Hills quartz monzonite, southeastern part of Mount Tom quadrangle.	3.1
PB-E	Tungsten Hills quartz monzonite, west-central part of Mount Tom quadrangle.	3.8
12-13-12	Tungsten Hills quartz monzonite, north part of Big Pine quadrangle.	3.5
6-155-2	Tungsten Hills quartz monzonite, western part of Big Pine quadrangle.	2.5
12-28-12	Tungsten Hills quartz monzonite, eastern part of Mount Goddard quadrangle.	2.6
6-70-14C	Tungsten Hills quartz monzonite, northern part of Mount Goddard quadrangle.	1.4
98-69-18	Tungsten Hills quartz monzonite, eastern part of Mount Tom quadrangle.	7.8
11-169-2	Tungsten Hills quartz monzonite, southern part of Big Pine quadrangle.	1.5
PB-5	Quartz monzonite of the Tinemaha granodiorite, south-central part of Big Pine quadrangle.	4.5
12-11-3	Quartz monzonite of the Tinemaha granodiorite, center of Big Pine quadrangle.	4.0
6-141-7	Quartz monzonite of the Tinemaha granodiorite, western part of Big Pine quadrangle.	3.3
6-153-6	Quartz monzonite of the Tinemaha granodiorite, west-central part of Big Pine quadrangle.	4.6
PB-10	Quartz monzonite, center of Big Pine quadrangle	3.0
11-173-12	do	2.5
PB-3	Quartz monzonite of the Lamarck granodiorite, northeast side of South Lake, Mount Goddard quadrangle.	4.5
6-7-1	Quartz monzonite of the Lamarck granodiorite, western part of Mount Tom quadrangle.	4.9
PB-B	Quartz monzonite of the Lamarck granodiorite, northwest part of Mount Goddard quadrangle.	3.1
PB-C	Quartz monzonite of the Lamarck granodiorite, northern part of Mount Goddard quadrangle.	3.6
PB-8	Wheeler Crest quartz monzonite, west-central part of Mount Tom quadrangle.	2.9
PB-F	Wheeler Crest quartz monzonite, central part of Mount Tom quadrangle.	3.1
G-44	Quartz monzonite, 9 miles west of Walker Pass	1.7
G-45	Quartz monzonite, 1 mile west of Onyx	2.6
Average		3.6

TABLE 18.—*Uranium content of albite-quartz monzonites and granites from the Sierra Nevada batholith*

Sample	Rock type and locality	Uranium (ppm)
PB-1	Orthoclase-albite quartz monzonite, western part of Big Pine quadrangle.	1.7
12-14-2	Orthoclase-albite quartz monzonite, northern part of Big Pine quadrangle.	5.0
98-19-2	Orthoclase-albite quartz monzonite, southwestern part of Bishop quadrangle.	3.0
6-10-2	Orthoclase-albite granite, western part of Mount Tom quadrangle.	3.8
G-42	Muscovite quartz monzonite, 7 miles east of Walker Pass	3.1
G-43	Granite, 3 miles east of Walker Pass	2.0
1	Albite granite, Mule Mountain stock, Redding quadrangle.	1.6
2	Albite granite, Mule Mountain stock, French Gulch quadrangle.	3.3
Average		2.9

pattern is similar in this respect to that shown for the rocks of southern California. Unfortunately, bulk chemical analyses were not available for the samples on which the analyses for uranium were made. Hence, a detailed relation between the uranium content and the chemical composition of the rocks cannot be shown. The data indicate, however, a progressive increase in uranium in the more siliceous rocks up until the extreme rock types are reached.

From the uranium analyses made on the igneous rocks from the Sierra Nevada batholith, we can make only a rough approximation of its average uranium content. Most of the rocks analyzed for uranium are from the eastern part of the batholith where quartz monzonites are the most abundant rock type. Analyses for uranium are needed on a larger number of granodiorites, the average rock type of the batholith, in order to characterize the batholith with regard to its uranium content. On the basis of the data available for the different rock types and from estimates of their relative abundances (Paul C. Bateman, oral communication), the average uranium content of the batholith is about 2.7 ppm (table 20).

TABLE 19.—*Average uranium content of igneous rocks of the Sierra Nevada batholith*

Rock type	Number of samples	Uranium (ppm)	
		Range	Average
Gabbro	4	0.50–0.75	0.6
Tonalite	4	1.1 –1.9	1.4
Granodiorite	6	1.7 –3.9	2.6
Quartz monzonite	26	1.4 –7.8	3.6
Albite-quartz monzonite and granite	8	1.6 –5.0	2.9

TABLE 20.—*Average uranium content of the Sierra Nevada batholith*

Rock type	Abundance	Average uranium content (ppm)
Gabbro	Some	0.6
Tonalite	Rare	1.4
Granodiorite	Chief rock	2.6
Quartz monzonite	Abundant	3.6
Albite-quartz monzonite and granite	Some	2.9
Estimated weighted-average uranium content		2.7

DISTRIBUTION OF URANIUM IN MINERALS OF THE ROCKS

Analyses for uranium on major and accessory mineral concentrates from six igneous rocks from the Sierra Nevada batholith are listed in table 21. These rocks range in composition from granodiorite to muscovite-quartz monzonite. Monazite and xenotime were noted in the muscovite-quartz monzonite, but were present in too small amounts for uranium analyses. Thorite was found in trace amounts in one of the quartz monzonites. The uranium content of the zircon from the quartz monzonites is variable, ranging from 710 to 4,100 ppm. Zircon from the granodiorite contains less uranium, 590 ppm. Sphene ranges from 430 to 660 ppm uranium. Epidote is fairly high in uranium, containing around 200 ppm, whereas allanite contains from 50 to 79 ppm.

The common accessory minerals listed in order of decreasing average uranium content are zircon, monazite, sphene, epidote, allanite, and the opaques. In most of these rocks the accessory minerals contribute about 10 to 30 percent to the total uranium content of the rock. However, for one of the rocks (PB-3) the data show that the bulk of the uranium is contained in the accessory minerals. This rock contained thorite and zircon of relatively high uranium content.

The felsic minerals contain less uranium than the bulk rock. They generally carry from about 1 to a little over 2 parts per million. The mafic minerals are high in uranium as compared to the rocks themselves. They appear to be highest in uranium content in the more siliceous rock, in which they are present in small amounts.

IDAHO BATHOLITH

The Idaho batholith occupies the main part of the mountains of central Idaho and underlies an area of about 16,000 square miles. A comparison of the age, chemical composition, mineral composition, and physical characteristics of this batholith with the southern California batholith has been published by Larsen and Schmidt (1958). Much of the pertinent geologic information given here is taken from that paper.

TABLE 21.—*Uranium content of the minerals of some igneous rocks from the Sierra Nevada batholith*

Mineral	Muscovite-quartz monzonite G-42			Albite-quartz monzonite PB-1			Quartz monzonite PB-2		
	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100	Abundance (weight) percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100
Quartz	30	1.4	0.42	30	2.3	0.69	29	2.3	0.67
Orthoclase	18	2.0	.36	16	1.3	.21	31	1.6	.50
Plagioclase	47	1.4	.66	48	1.1	.53	33	1.3	.43
Biotite	2	54	1.08	4	16	.64	4	16	.64
Hornblende							1	14	.14
Pyroxene									
Opaque minerals	2	7.6	.15	1	9	.09	1.5	6.9	.10
Muscovite	1	50	.50						
Apatite							.02	38	.01
Sphene				.003	660	.02	.06	430	.26
Zircon	.001		.01	.005	710	.04	.02	1,060	.21
Allanite				.02	50	.01	.01	91	.01
Monazite	.0005		.01	.005	640	.03			
Xenotime	.001		.01						
Epidote									
Garnet	.1	33	.03						
Thorite									
Total uranium (by sum of mineral)			3.2			2.3			3.0
Total uranium in bulk rock (measured)			3.1			2.0			7.5

Mineral	Granodiorite PB-7			Quartz monzonite PB-3			Quartz monzonite PB-4		
	Abundance (weight percent)	U (ppm)	$\frac{\text{Weight percent of mineral} \times \text{U (ppm)}}{100}$	Abundance (weight percent)	U (ppm)	$\frac{\text{Weight percent of mineral} \times \text{U (ppm)}}{100}$	Abundance (weight percent)	U (ppm)	$\frac{\text{Weight percent of mineral} \times \text{U (ppm)}}{100}$
Quartz	12	1.8	0.22	23	1.1	0.25	26	2.4	0.62
Orthoclase	15	.44	.07	20	.64	.13	25	.68	.17
Plagioclase	52	.80	.42	45	1.1	.50	42	1.5	.63
Biotite	7	4.4	.31	4	2.0	.08	5	10.8	.54
Hornblende	5	4.7	.24	8	2.7	.22			
Pyroxene	6	16	.96						
Opaque minerals	2	2.3	.05	.2	1.0	0	1	11.0	.11
Muscovite									
Apatite				.1	60	.06			
Sphene	.01	550	.06	.2	460	.92			
Zircon	.02	590	.12	.02	4,100	.82	.02	1,870	.37
Allanite	.01		.01	.04	79	.03	.02	78	.02
Monazite									
Xenotime									
Epidote	.1	180	.18	1	220	.22			
Garnet									
Thorite				.002		.20			
Total uranium (by sum of mineral)			2.6			3.4			2.9
Total uranium in bulk rock (measured)			2.8			4.5			3.5

The igneous rocks of the Idaho batholith are rather similar chemically to those of the southern California batholith. A comparison of the variation curves of these batholiths by Larsen and Schmidt (1958) show that the igneous rocks from Idaho are a little lower in SiO_2 and a little higher in Al_2O_3, K_2O, and MgO. Gabbro is rare in the Idaho batholith and quartz monzonite is more abundant than in the southern California batholith. The average rock type of the Idaho batholith is intermediate between a granodiorite and a quartz monzonite. The average chemical composition of the Idaho batholith given by Larsen and Schmidt (1958, p. 20) is as follows:

	Percent		*Percent*		*Percent*
SiO_2	70. 5	FeO	2. 0	Na_2O	3. 9
TiO_2	. 3	MgO	. 7	K_2O	3. 1
Al_2O_3	15. 7	CaO	3. 0		
Fe_2O_3	. 8			Total	100. 0

The individual intrusives are much larger in the Idaho batholith. Some of the larger bodies underlie areas ranging from 1,000 to 2,500 square miles. In southern California the area of the largest single intrusive mass of petrographically similar rock is about 200 square miles (Larsen, 1948).

URANIUM CONTENT OF IGNEOUS ROCKS OF THE IDAHO BATHOLITH

Nearly all the igneous rocks analyzed for uranium were collected by E. S. Larsen, Jr., and Robert G. Schmidt as part of their reconnaissance study of the Idaho batholith. They were collected while traversing the batholith along the roads, of which there are a moderate number. Relatively small areas of the batholith were more than 15 miles from a traverse. The samples of igneous rocks analyzed for uranium are believed to be fairly representative of the more important rock types of the batholith.

Analyses for uranium on 44 igneous rocks, ranging in composition from gabbro to muscovite-quartz monzonites, are given in tables 22, 23, 24, 25, and 26.

GABBROS

The uranium content of two gabbros is given in table 22. Like most of the gabbros from southern California and the Sierra Nevada

TABLE 22.—*Uranium content of gabbros from the Idaho batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
L–239	Gabbro, 1.4 miles north of Harpster	0. 24
L–240	Gabbro, 0.7 mile north of Harpster	. 82
Average		0. 53

batholiths, they contain less than 1 ppm uranium. The average uranium content of these two samples is 0.5 ppm.

TONALITES

The uranium contents of tonalites are given in table 23. Most of these rocks contain both hornblende and biotite. They average 2.0 ppm uranium which is a little higher than the tonalites from the southern California and Sierra Nevada batholiths.

ANODIORITES

Larsen and Schmidt (1958) describe two major types of granodiorite from the Idaho batholith. One type of granodiorite, exposed along the Payette River from Cascade southward to Boise, is called the Cascade type. Another large body consisting chiefly of granodiorite, but in part quartz monzonite, which underlies most of the drainage of the South and Middle Forks of the Boise River, is referred to as the Atlanta type. Analyses for uranium on some of these rocks and on several other granodiorites from other localities are given in table 24. The average uranium content of 16 samples is 2.4 ppm.

QUARTZ MONZONITES AND GRANITE

Coarse-grained quartz monzonite is the most widespread and abundant rock type in the batholith. A large mass of this rock forms the central part of the southern part of the batholith and underlies an area of more than 2,500 square miles. Eight samples of quartz monzonite from scattered localities of the batholith have been analyzed for uranium (table 25). They average 3.7 ppm. One specimen (L–201) of fine-grained granite not included in the average contains about 6.0 ppm uranium.

TABLE 23.—*Uranium content of tonalites from the Idaho batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
L–217	Fine-textured tonalite, north of Bungalow, Fourth of July Creek.	1.4
L–65	Biotite-hornblende tonalite, north of Burgdorf, 0.2 mile above Fall Creek.	1.6
L–81	Hornblende-biotite tonalite, South Fork of Payette River, 0.4 mile below Longpan.	2.3
L–227	Hornblende-biotite tonalite, northeast of Pierce, 3 miles from Barby Gulch.	1.0
L–247	Biotite-hornblende tonalite, north of McCall	3.2
L–63A	Biotite-hornblende tonalite, road up Secesh Creek to McCall.	3.3
L–231	Hornblende-biotite tonalite, 3 miles north of Greer	1.4
Average		2.0

TABLE 24.—*Uranium content of granodiorites from the Idaho batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
L–70	Cascade type, 3.5 miles above Big Eddy	3. 3
L–255	Cascade type, south of Cascade	1. 7
L–259	Cascade type, 3.9 miles south of Smiths Ferry	1. 1
L–295	Atlanta type, 3.5 miles above Atlanta	1. 2
L–293	Atlanta type, 6.5 miles east of Lake Creek	2. 4
L–288	Atlanta type, near mouth of Vaughn Creek	3. 4
L–301	Atlanta type, 2 miles west of Featherville	3. 3
L–304	Atlanta type, 1.8 miles southeast of Jumbo Creek	1. 7
L–253	Fine granodiorite, above Riggins Hot Springs	1. 4
L–112	Fine granodiorite, 0.4 mile above Yankee Fork	5. 1
L–303	Fine granodiorite, 1.3 miles east of Snake Creek	2. 5
L–111	Fine granodiorite, 1.1 miles below Marshall Creek	1. 2
L–110	Fine granodiorite, 0.6 mile above Burnt Creek	1. 9
H–55	Granodiorite, near Coeur d'Alene	2. 8
H–62	do	3. 4
H–63	do	1. 3
Average		2. 4

MUSCOVITE-QUARTZ MONZONITES

Muscovite-bearing quartz monzonites are more widespread in the Idaho batholith than in the southern California batholith. Chemical analyses of a sample of muscovite-quartz monzonite from the Cuyumaca quadrangle in southern California and of a sample from Garden Valley, Idaho, show that they are nearly identical in chemical composition (Larsen and Schmidt, 1958). Analyses for uranium on 10 samples of muscovite-quartz monzonite are listed in table 26. Regardless of their position in the batholith all but one sample contain less than 2 ppm. One sample (L–274) contains only 0.5 ppm uranium.

TABLE 25.—*Uranium content of quartz monzonites and granite from the Idaho batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
L–169	Quartz monzonite, 0.3 mile above Lolo Hot Springs	3. 4
L–71	Quartz monzonite, 0.5 mile northeast of Idaho City	4. 0
L–219	Coarse quartz monzonite, 1 mile above Bungalow	5. 0
L–211	Coarse quartz monzonite, road to Rocky Ridge	6. 0
L–74	Coarse quartz monzonite, 0.5 mile east of Idaho City	1. 9
L–207	Coarse quartz monzonite, 0.7 mile east of Indian Grave Lookout road.	4. 9
L–266	Coarse quartz monzonite, Placerville	2. 5
L–84	Porphyritic quartz monzonite, 0.1 mile above bridge over Bear Creek, north of Lowman.	2. 2
L–201	Fine-grained granite, 1.8 miles east of Indian Post Office	6. 3
Average (omitting L–201)		3. 7

These rocks are significantly lower in uranium content than the ordinary quartz monzonites from this batholith. The average uranium content of the 10 samples is 1.6 ppm.

GNEISSES AND SCHISTS

Analyses for uranium are listed in table 27 for 12 samples of porphyroblastic gneisses and schists. Typical schist with large porphyroblasts is gradational to porphyritic gneiss that resembles porphyritic tonalite. Except for one sample (L–113), which contains 13.3 ppm uranium, these rocks contain about the same amount of uranium as the igneous rocks. The average uranium content of 11 of the samples is 2.2 ppm.

RELATION OF URANIUM CONTENT TO CHEMICAL COMPOSITION

Analyses for uranium have been made on a few chemically analyzed rocks ranging in composition from tonalite to muscovite-quartz monzonite. Figure 9 shows a plot of the uranium content of 6 of the igneous rocks against their position on a variation diagram. The position of each rock is calculated from the chemical analyses published by Larsen and Schmidt (1958). The uranium content of 5 of the rocks shows a progressive increase from about 1 ppm in the quartz diorite, at about position 12, to 5 ppm in the quartz monzonite

TABLE 26.—*Uranium content of muscovite-quartz monzonites from the Idaho batholith*

Sample	*Rock type and locality*	*Uranium (ppm)*
S–15	Muscovite-quartz monzonite, 5 miles above mouth Secesh Creek.	1. 5
L–263	Porphyritic muscovite-quartz monzonite, road from Boise to Idaho City, 0.5 mile north of Thorn Creek road.	1. 8
L–209	Muscovite-quartz monzonite, northeast of Sherman Peak along Lolo Trail.	1. 7
L–274	Muscovite-quartz monzonite, 2.8 miles above Silver Creek Guard Station.	. 5
L–272	Muscovite-garnet-quartz monzonite, Silver Creek, north of Garden Valley.	1. 9
L–71	Muscovite-quartz monzonite, 5 miles northeast of Idaho City.	1. 6
S–50	Muscovite-quartz monzonite, 2.3 miles east of Lamar Creek on Idaho City-Lowman road.	1. 7
L–298	Muscovite-quartz monzonite, 5.7 miles south of Atlanta	2. 3
L–15	Muscovite-quartz monzonite, South Fork of Salmon River, 1 mile below Phoebe Creek.	1. 4
L–253	Fine muscovite-quartz monzonite, above Riggins Hot Springs, 1.7 miles above Hunter Creek.	1. 4
Average		1. 6

TABLE 27.—*Uranium content of gneisses and schists from the Idaho batholith.*

Sample	*Rock type and locality*	*Uranium (ppm)*
L 122	Porphyroblastic gneiss, Elk City to Sourdough Lookout, 0.8 mile from Red Horse Creek.	2.9
L 123	Porphyroblastic gneiss, Red Horse Creek, 2.7 miles Red River Ranger Station.	3.3
L 127	Porphyroblastic gneiss, Sourdough Lookout road, 1.5 miles below Legett Creek.	2.8
L 132	Injected gneiss, 0.6 mile west of road to Burnt Knob	2.2
L 91	Tonalite gneiss, 6.9 miles below Stanley	3.1
L 113	Porphyritic tonalite gneiss, Salmon River below Stanley, 1.3 miles above Yankee Fork.	13.3
L 153	Porphyroblastic gneiss, 1.5 miles east of Indian Creek Ranger Station, below Shoup.	2.2
L 154	Injected schist, near Shoup, above Indian Creek	1.2
L 156	Porphyroblastic gneiss, 0.5 mile west of Sheepeater Creek	3.6
L 157	Injected schist, road 0.5 mile east of Wheat Creek	.7
L 159	Injected schist, near South Bear Creek	.5
L 148	Granodiorite gneiss, above Shoup	2.0
	Average (omitting L 113)	2.2

at position 26. One sample, near position 25, contains 1.9 ppm uranium and falls considerably below the curve. This sample is a muscovite-quartz monzonite which, like the other muscovite-quartz monzonites, is low in uranium. Although based on fewer samples, the trend is similar to that shown by the rocks of the southern California batholith.

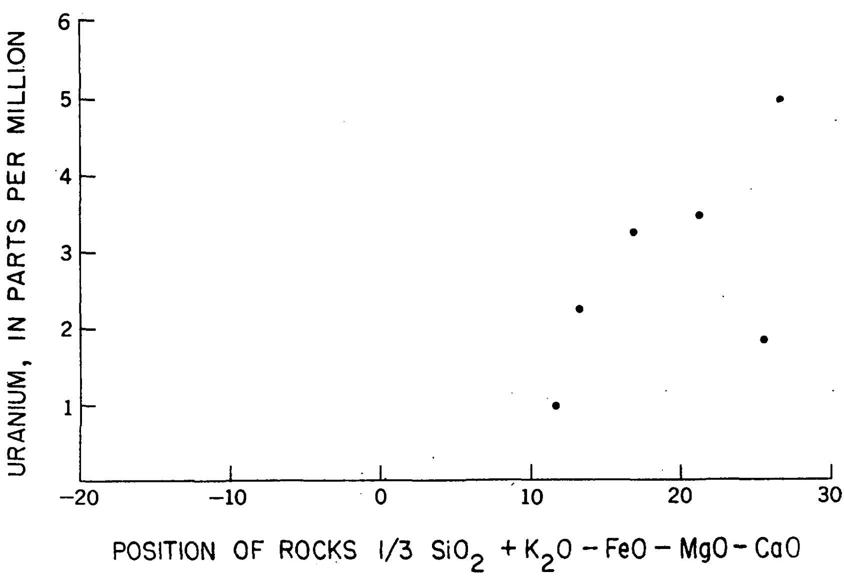

FIGURE 9.—Uranium in igneous rocks of the Idaho batholith plotted against the composition of the rocks.

TABLE 28.—*Average uranium content of igneous rocks of the Idaho batholith*

Rock type	Number of samples	Uranium (ppm) Range	Average
Gabbro	2	0.24–0.82	0.5
Tonalite	7	1.0 –3.3	2.0
Granodiorite:			
Cascade type	3	1.1 –3.3	2.0
Atlanta type	5	1.2 –3.4	2.4
Fine-textured type	5	1.2 –5.1	2.4
Near Coeur d'Alene	3	1.3 –3.4	2.5
Quartz monzonite	8	1.9 –6.0	3.7
Microgranite	1	----------	6.3
Muscovite-quartz monzonite	10	.5 –2.3	1.6

AVERAGE URANIUM CONTENT OF THE IGNEOUS ROCKS AND OF THE BATHOLITH

The uranium content of the various igneous rock types of the Idaho batholith is summarized in table 28. On the average, the uranium content increases from the gabbro to the quartz monzonites. Gabbro, a relatively rare rock in the batholith, averages 0.5 ppm, tonalite 2.0 ppm, granodiorite from 2.0 to 2.5 ppm, and quartz monzonite 3.7 ppm. The highest uranium content of any of the igneous rocks was obtained on a single specimen of microgranite. The muscovite quartz-monzonites show a sharp reversal of the trend, averaging 1.6 ppm uranium. From these data and from the areas underlain by each of the rock types, the weighted-average uranium content of the batholith is 2.5 ppm (table 29).

TABLE 29.—*Average uranium content of the Idaho batholith*

Rock type	Percent of batholith [1]	Average uranium content (ppm)
Gabbro	<1.0	0.5
Tonalite	12	2.0
Granodiorite:		
Cascade type	15	2.0
Atlanta type	16	2.4
Fine-textured type	22	2.4
Quartz monzonite	26	3.7
Microgranite	<1	6.3
Muscovite-quartz monzonite	9	1.6
Weighted average		2.5

[1] Modified from data published by Larsen and Schmidt (1958).

DISTRIBUTION OF URANIUM IN MINERALS OF THE IGNEOUS ROCKS

Mineral concentrates of the major and most of the accessory minerals were made from four igneous rocks of the Idaho batholith, a tonalite, a granodiorite, a quartz monzonite, and a muscovite-quartz monzonite. The abundance of the various minerals, their uranium content, and an estimate of the amount of uranium contributed by the minerals to the bulk rock are given in table 30.

The uranium content of each of the major minerals from the tonalite is less than the uranium found in the same minerals from the more siliceous rocks. The zircon from the tonalite contains 250 ppm uranium, which is also lower than the uranium content of zircon from the more siliceous rocks.

In the granodiorite, zircon containing 700 ppm uranium has the highest uranium content of any of the minerals in the rock. Sphene contains 170 ppm uranium, whereas apatite contains 42 ppm uranium. Allanite contains 36 ppm and has a lower uranium content than allanite from rocks of the southern California and Sierra Nevada batholiths. Additional data on allanite from these batholiths by Smith, Franck. and Sherwood (1957) have been published.

An interesting comparison can be made between the two quartz monzonites with regard to their accessory minerals and their uranium content. The muscovite-quartz monzonite that is lower in uranium content contains zircon, monazite, and xenotime. The zircon contains 2,400 ppm uranium, the monazite 1,070 ppm, and the xenotime 7,600 ppm. In the ordinary quartz monzonite that contains about 5.0 ppm uranium, only zircon and sphene were the main accessory minerals. Zircon from this rock contained 800 ppm uranium and the sphene 50 ppm. In each rock most of the uranium is accounted for by the major minerals, orthoclase, quartz, plagioclase, and the micas. In the muscovite-quartz monzonite these major minerals are lower in uranium content than those in the quartz monzonite even though the accessory minerals in the muscovite-quartz monzonite have very high concentrations of uranium.

COAST RANGE BATHOLITHS AND THEIR URANIUM CONTENT

Northwest of the Idaho batholith lie the Coast Range batholiths, chiefly in British Columbia, but extending for about 80 miles into the State of Washington. In an easterly direction they extend nearly across the State of Washington. In Canada the Nelson batholith extends north for about 170 miles and the Coast Range batholith forms the core of the Coast Ranges for 550 miles beyond the international boundary and continues in smaller bodies into Alaska to the

TABLE 30.—*Uranium content of minerals in some igneous rocks from the Idaho batholith*

Mineral	Muscovite-quartz monzonite (L272)			Coarse quartz monzonite (L219)			Granodiorite (L70)			Tonalite (L227)		
	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100	Abundance (weight percent)	U (ppm)	Weight percent of mineral × U (ppm) / 100
Orthoclase	30	.40	0.12	32	1.9	0.61	7	0.94	0.07			
Quartz	36	.80	.29	} 64	3.5	2.2 {	30	.74	.22	29	0.44	0.13
Plagioclase	27	.96	.26				53	1.3	.69	43	.52	.22
Biotite	2	2.9	.06	4	37	1.5	8	.34	.03	11	.45	.05
Hornblende										16	.34	.05
Epidote												
Muscovite	5	7.3	.36									
Garnet	.2	6.5	.01									
Opaques	.3	25	.07				1	6.7	.07			
Fluorite	.03	.49	.02									
Apatite	.01	28	.003				.06	42	.03	.03		.01
Sphene				.001	50	.001	.15	170	.25	.1		.10
Zircon	6.003	2,400	.07	.002	800	.01	.01	700	.07	.01	250	.03
Monazite	6.005	1,070	.05									
Xenotime	.001	7,630	.08									
Allanite							.02	36	.01			
Total uranium (by sum of mineral)			1.4			4.3			1.4			.59
Total uranium in bulk rock (measured)			1.9			5.0			1.9			.50

St. Elias Range. In Canada the Coast Range and Nelson batholiths underlie about 80,000 and 20,000 square miles, respectively. In the United States the intrusive masses are given separate names; collectively they occupy about 8,000 square miles.

In the State of Washington the igneous rocks of the batholiths are chiefly granodiorites with some tonalites.

The uranium content of 5 samples of tonalite and 9 samples of granodiorite are listed in tables 31 and 32, respectively. The tonalites average 1.7 ppm uranium. The granodiorites contain more uranium than the tonalities, averaging 2.9 ppm.

Too few samples have been analyzed for uranium to make more than a rough approximation of the average uranium content of these batholiths. From the data available their average uranium content is comparable to that of the Sierra Nevada and Idaho batholiths.

TABLE 31.—*Uranium content of tonalites from the Coast Range batholiths*

Sample	*Rock type and locality*	*Uranium (ppm)*
G 122	Hornblende tonalite, 2 miles south of Richter Ranch, British Columbia.	2.7
G 142	Hornblende-biotite tonalite, 3 miles north of Entiat, Wash.	1.3
G 143	Hornblende-biotite quartz diorite 1.5 miles west of Leavenworth, Wash.	2.5
G 144	Biotite tonalite, near eastern adit of Cascade tunnel, in Washington.	1.1
G 145	Biotite tonalite, 4 miles east of Skykomish, Wash	.9
Average		1.7

TABLE 32.—*Uranium content of granodiorites from the Coast Range batholiths*

Sample	*Rock type and locality*	*Uranium (ppm)*
G 112	Hornblende granodiorite, near southern end of Loon Lake, Wash.	2.7
G 115	Biotite granodiorite, 1.5 miles south of Arden, Wash	4.1
G 111	Coarse biotite-muscovite granodiorite, 1 mile southeast of Dartwood, Wash.	3.0
G 123	Porphyritic biotite granodiorite, Whiskey Mountain, Osoyoos quadrangle, Wash.	4.3
G 127	Fine-grained granodiorite, east of Oroville, along Tonasket Creek, Wash.	1.0
G 128	Coarse granodiorite, east of Oroville, along Tonasket Creek, Wash.	2.8
G 133	Biotite granodiorite, west of Nespelem, Wash	3.1
G 135	Biotite granodiorite, 1 mile southeast of Bridgeport, Wash	.5
G 137	Biotite granodiorite, 1 mile west of Pateros, Wash	5.0
Average		2.9

ACID-SOLUBLE URANIUM IN IGNEOUS ROCKS AND MINERALS FROM THE SOUTHERN CALIFORNIA BATHOLITH

Hurley (1950) has shown that as much as 90 percent of the alpha activity in igneous rocks can be removed by treating the rocks with dilute hydrochloric acid. A detailed study of acid-soluble radioactive material in igneous rocks of a wide range in composition and age has been described by Brown and Silver (1956). They found that uranium, thorium, and rare earths are highly concentrated in the dissolved fractions. The importance of acid-leaching in geochemical and petrologic studies and on age measurements has been pointed out by various workers (Tilton and others, 1955; Neuerburg, 1956; Neuerburg, Antweiler, and Bieler, 1956; Tauson, 1956; Brown and others, 1953; and Brown and Silver, 1956).

To obtain additional information on the distribution of uranium in the igneous rocks of the batholith of southern California 6 samples representing each of the major rock types were selected to determine the relation of chemical composition and uranium content to the amount of acid-soluble uranium. The samples which ranged in composition from gabbro to quartz monzonite were pulverized to less than 200-mesh and treated with 1 part of concentrated hydrochloric acid to 4 parts of water for 24 hours on a steam bath. The total uranium content before leaching, the amount of insoluble uranium, and the percent of sample and uranium dissolved are given in table 34. The percent uranium leached from the rocks ranges from 40 percent in the gabbro to 83 percent in a quartz monzonite. The uranium content of these rocks before and after acid treatment is plotted against the chemical composition of the rocks in figure 10. These experiments indicate that the amount and percentage of soluble uranium are closely related to the uranium content and compositon of the rocks.

The major minerals from a gabbro, tonalite, granodiorite, and quartz monzonite were subjected to the same acid treatment as the bulk rocks. The data for the chief minerals from the gabbro are given in table 34. Approximately two-thirds of the uranium content of the

TABLE 33.—*Acid-soluble uranium content of some igneous rocks from the southern California batholith*

Sample	*Rock type*	*Uranium (ppm)* Original	*Uranium (ppm)* Insoluble	*Percent dissolved* Bulk sample	*Percent dissolved* Uranium
El 38-265	Quartz monzonite	7.2	1.2	3.7	83
El 38-167	do	3.3	.91	4.3	72
Ra 135	Granodiorite	1.5	.72	7	52
SLR 1016	Tonalite	.74	.26	14.4	54
SLR 229	Norite	.70	.34	13.4	46
El 303	Calcic-hornblende gabbro	.43	.38	29.3	40

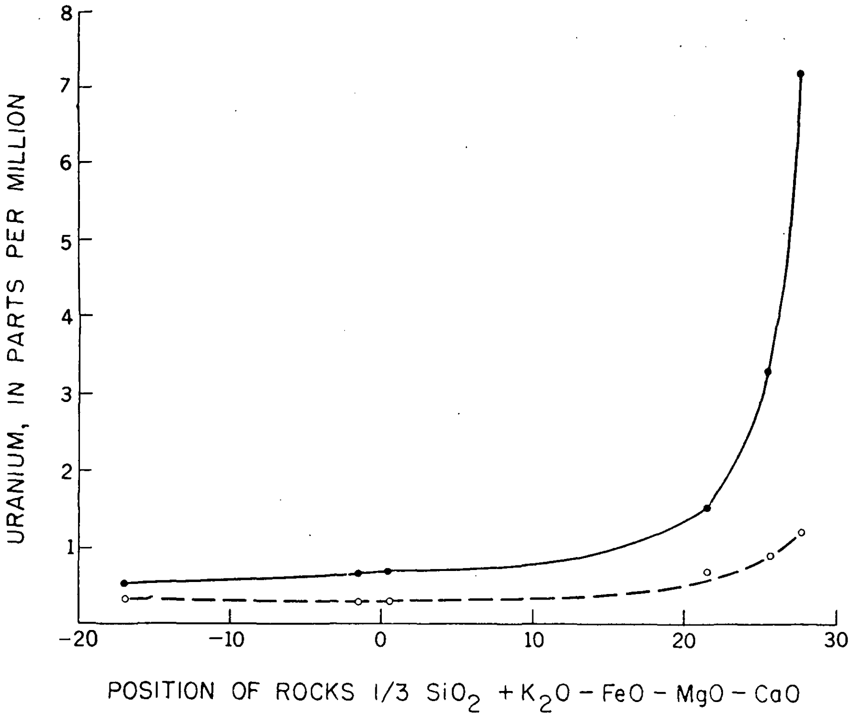

FIGURE 10.—Uranium content of some igneous rocks from the southern California batholith before and after acid treatment. Dots indicate uranium content before acid treatment; circles, uranium content after acid treatment.

hornblende and plagioclase is soluble in acid and about 20 percent of the uranium in the opaque minerals, magnetite and ilmenite, is soluble. In the tonalite the percent uranium dissolved from the major minerals ranges from 66 percent in the quartz to 85 percent in the plagioclase (table 35). The data for the major minerals from the granodiorite (table 36) and the quartz monzonite (table 37) also show that the bulk of the uranium is in an acid-soluble form. Much of the uranium in the allanite from the granodiorite and quartz monzonite is soluble in acid. The percent allanite dissolved in acid is, in part,

TABLE 34.—*Acid-soluble uranium content of minerals from a calcic-hornblende gabbro (El 303)*

Mineral	*Abundance (weight percent)*	*Uranium (ppm)*		*Percent dissolved*	
		Original	*Insoluble*	*Sample*	*Uranium*
Plagioclase	47	0. 44	0. 15	50	66
Hornblende	34	1. 1	. 37	20	67
Augite	5	1. 1	1. 2	8	0
Hypersthene	6	. 16	. 18	9	0
Opaque Minerals	8	. 36	. 28	19	22

TABLE 35.—*Acid-soluble uranium content of minerals from a tonalite (El 38–28)*

Mineral	Abundance (weight percent)	Uranium (ppm) Original	Uranium (ppm) Insoluble	Percent dissolved Sample	Percent dissolved Uranium
Plagioclase	52	2.2	0.33	9	85
Quartz	22	.3	.1	<2.0	66
Biotite	15	1.7	.40	64	76
Hornblende	9	3.6	.79	10	78

due to metamictization of some of the allanite. Other common accessory minerals that would contain acid-soluble uranium are epidote, apatite, thorite, and some varieties of sphene and zircon.

It is probable that the acid-soluble uranium associated with the major rock-forming minerals is derived from several sources, as pointed out by Larsen and Phair (1954), Neuerburg (1956), and Brown and Silver (1956). These include uranium (1) in metamict minerals, (2) as absorbed ions on crystal surfaces and fractures, (3) in acid-soluble minerals with high uranium content, and (4) as interstitial material along grain boundaries and cracks introduced by late magmatic or hydrothermal solutions.

TABLE 36.—*Acid-soluble uranium content of minerals from a granodiorite (S–11)*

Mineral	Abundance (weight percent)	Uranium (ppm) Original	Uranium (ppm) Insoluble	Percent dissolved Sample	Percent dissolved Uranium
Orthoclase	20	1.1	0.11	2	90
Plagioclase and quartz	73	.8	.2	2	78
Biotite	5	13.5	.80	58	94
Hornblende	1	13	5.4	11	58
Allanite	.02	330	120	60	64

From the data given here, the exact source of the acid-soluble uranium cannot be stated. Detailed autoradiograph and chemical studies, such as those carried out by Brown and Silver (1956), are needed on the major minerals to determine which of the possible sources contributes most of the soluble uranium.

TABLE 37.—*Acid-soluble uranium content of minerals from a quartz monzonite (El 38–265)*

Mineral	Abundance (weight percent)	Uranium (ppm) Original	Uranium (ppm) Insoluble	Percent dissolved Sample	Percent dissolved Uranium
Orthoclase	36	2.2	0.38	9	83
Plagioclase	26	1.5	.47	3	69
Quartz	34	5.6	2.0	<3	64
Biotite	2	13	1.9	66	85
Hornblende	.5	60	13	47	78
Allanite	.005	540	100	90	81

SUMMARY AND DISCUSSION

Fluorimetric analyses for uranium have been made on nearly 200 igneous rocks that probably are fairly typical of the major rock types comprising the southern California, Sierra Nevada, Idaho, and Coast Ranges batholiths. The area underlain by these batholiths in the United States is about 50,000 square miles. Variation diagrams of the uranium content of the chemically analyzed rocks show that the uranium values do not fall on as smooth curves as do the major constituents. The greatest scatter of uranium values is shown by the more siliceous rocks. However, the average uranium content in general reflects the chemical composition of the rocks—increasing with silica and potassium—to the extreme differentiates where the uranium content decreases. The averages of the uranium content of the various rock types and of the batholiths are summarized in table 38. The average uranium content is lowest in the gabbroic rocks, which contain 0.3 ppm in the southern California batholith and 0.5 ppm in the Sierra Nevada and Idaho batholiths. It increases to 4.6 ppm in the quartz monzonites of the southern California batholith and to 3.6 and 3.7 ppm in the quartz monzonites of the Sierra Nevada and Idaho batholiths, respectively, then decreases to 2.5 and 1.6 ppm in the muscovite-quartz monzonites in the southern California and Idaho batholiths. The albite-quartz monzonites of the Sierra Nevada average 2.9 ppm uranium.

The lower uranium content of the extreme differentiates cannot be attributed to any one geologic process at the present time. In addition to sampling uncertainties other possible reasons for the lower uranium content are depletion of uranium in the magma, partial loss of uranium from the magma during its final stages of crystallization, or the postcrystallization history of the rocks.

Whitfield, Rogers, and Adams (1959) have noted that thorium increases more regularly than uranium in differentiated rocks and believe that the greater thorium-to-uranium ratios in the more siliceous rocks may be, in part, due to the preferential removal of

TABLE 38.—*Average uranium content, in parts per million, of various igneous rock types and of the batholiths*

Rock type	*Southern California*	*Sierra Nevada*	*Idaho*	*Coast Ranges*
Gabbro	0.3	0.6	0.5	----------
Tonalite	1.5	1.4	2.0	1.7
Granodiorite	2.1	2.6	2.4	2.9
Quartz monzonite	4.6	3.6	3.7	----------
Muscovite-quartz monzonite	2.5	2.9	1.6	----------
Weighted average	1.7	2.7	2.5	2.7

NOTE.—Weighted-average uranium content of the batholiths is about 2.5 ppm.

uranium in the late stages of magmatic activity. Neuerburg (1956) however cautions that the total uranium content of an igneous rock does not reflect the uranium content of the magma from which it crystallized. He points out that the total uranium content of an igneous rock is the sum of the amount of uranium fixed at the time of its crystallization, and the amount of readily dissolved uranium that may have been changed after crystallization of the rock.

Six igneous rocks representing the major rock types of the batholith of southern California were studied with regard to the relation of acid-soluble uranium and total uranium to chemical composition. The data show that the amount and percent of acid-soluble uranium increases with uranium content and silica content of the rocks. The percent soluble uranium ranged from 40 percent in a calcic-gabbro to 83 percent in a quartz monzonite. The observed systematic relations strongly indicate that the readily dissolved uranium in the rocks tested is related to petrologic processes occurring during the time of their crystallization. However, studies of leachable uranium on various rock types by Neuerburg, Antweiler, and Bieler (1956) show, that with few exceptions, there is no systematic correlation between uranium content and uranium leachability and rock type.

Analyses for uranium on the major minerals and many of the accessory minerals of 26 igneous rocks indicate that with few exceptions the major minerals contain the bulk of the uranium present in the rock. Common accessory minerals such as zircon, sphene, allanite, and apatite contain significantly greater percentages of uranium than the chief minerals. However, they are generally present only in small amounts and rarely contribute more than 30 percent of the total uranium to any one rock. There is, in general, an average increase in the uranium content of a given mineral from gabbro to quartz monzonite. In the muscovite-quartz monzonites the major minerals decrease in uranium, but the accessory minerals, xenotime, monazite, and zircon contain considerably higher percentages of uranium than in any of the earlier formed rocks.

Acid treatment of the major minerals of four igneous rocks shows that most of the uranium associated with quartz, feldspar, and the major mafic minerals is readily dissolved. How this soluble uranium is held in these minerals is unknown.

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