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Host rocks and their alterations as related to uranium-bearing veins in the United States

By George W. Walker

Trace Elements Investigations Report 638

UNITED STATES DEPARTMENT OF THE INTERIOR
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Geology and Mineralogy

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George W. Walker

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FOREWORD

This paper, dealing with the different kinds of host rocks and their alterations associated with uranium-bearing veins in the United States, is a chapter of a comprehensive report entitled, "Geology of uranium-bearing vein deposits in the United States," in preparation by George W. Walker, Frank W. Osterwald, and others. The comprehensive report will include detailed information on tectonic and structural setting, kinds of host rocks, wall-rock alteration, mineralogy, physical characteristics, processes of deposition, and concepts of origin of uraniferous veins; but, because it will not be completed until sometime in the future, some chapters of the report are being transmitted as they are finished. Part of an introductory chapter to the comprehensive report entitled, "Classification and distribution of uranium-bearing veins in the United States" (Walker and Osterwald, 1956) has already been transmitted; several of the terms used herein are defined in the introductory chapter.

Data included in this chapter demonstrate that uranium-bearing veins are: 1) in rocks of nearly all textural, chemical, and mineralogic types; 2) most abundant in holocrystalline, commonly equigranular, igneous and metamorphic rocks characterized by a moderate to high silica content and by similar physical properties. Although some of the physicochemical properties of the host rocks are discussed in terms of favorability or nonfavorability for uranium deposition, the principal purpose of this chapter is to establish the petrologic environment in which uranium-bearing veins have been found. Because favorability or nonfavorability of host rocks is related complexly to the chemistry of ore solutions and to methods of uranium transport and deposition, several hypothetical processes of transport and deposition have been referred to briefly; these and other hypotheses will be outlined and discussed in greater detail in a subsequent chapter.

The compilation of data leading to this report and its preparation by a member of the Uranium Research and Resource Section, U. S. Geological Survey, was done on behalf of the Division of Raw Materials, U. S. Atomic Energy Commission. The report is based on both published and unpublished information collected principally by personnel of the U. S. Geological Survey, the U. S. Atomic Energy Commission or its predecessor organization, the Manhattan Engineer District, and to a lesser extent by staff members of other Federal or State agencies and by geologists in private industry. Information concerning foreign uranium-bearing vein deposits has been extracted almost exclusively from published reports; references to these and other data are included at appropriate places.

HOST ROCKS AND THEIR ALTERATIONS AS RELATED TO URANIUM-BEARING VEINS IN THE UNITED STATES

By George W. Walker

INTRODUCTION

Uranium-bearing vein deposits in the United States have been found in many different kinds of igneous, metamorphic, and sedimentary host rocks that range from Precambrian to late Tertiary in age. Most of these rocks have been altered adjacent to uraniferous veins but some veins are enclosed in fresh, unaltered rock. Where alteration effects are evident, several distinct zones of alteration are commonly present at a single deposit as successive sheaths around the veins and, locally, as zones approximately parallel to the ground surface profile.

Both published and unpublished information regarding the character of host rocks and their alterations has been evaluated in order to 1) present descriptive data concerning the host rocks of uranium-bearing veins, 2) establish, if possible, whether certain kinds or groups of rocks are more favorable for the occurrence of uranium in veins than other kinds of rocks, 3) determine whether the more favorable host rocks have any mineralogic, chemical, or physical characteristics in common, and 4) ascertain the nature and any unique features of wall-rock alteration accompanying the veins. No genetic relations between these host rocks and the veins that they contain are implied, although locally such relationships may exist.

The lithology, mineralogy, and chemistry of the host rocks of uraniferous veins and the wall-rock alterations associated with these veins have been studied in detail in only a very few places. Most uraniferous vein deposits have received little study; most of the enclosing-rock identifications and descriptions of wall-rock alteration were based only on field observations. Consequently, these identifications have introduced several problems of interpretation. Some of the important problems concerning the host rocks are closely bound to 1) variable petrographic nomenclature and classification, particularly as related to igneous and metamorphic rocks, and 2) the paucity of adequate petrographic descriptions and chemical analyses, and the resultant inaccuracies in naming rocks. Many of the inaccuracies are perhaps minor, as for example rocks with the physical, chemical, and mineralogic characteristics of a diorite that were hastily labeled granite or granitic rock, or monzonite, or quartz monzonite, or granodiorite on the basis of megascopic field examinations; some "igneous" host rocks, particularly those derived or altered by metasomatic processes or those in which assimilation of invaded rock is prevalent, consist of a mineral assemblage and/or chemical composition that is completely incompatible with the field names.

Because very little is known about the majority of these host rocks, beyond a superficial field name, somewhat greater emphasis has been placed in this report on data from districts or deposits in which the host rocks intimately related to uranium-bearing veins have received more petrographic study. Principal among these are deposits in the Boulder batholith, Mont., the Marysvale district, Utah, the Thomas Range, Utah, the Front Range of Colorado and the Sierra Ancha region, Gila County, Ariz.

Initially, an attempt was made to determine the frequency distribution of the different mineralogic classes of uranium-bearing veins in specific kinds of host rocks. Such correlation must be based on accurately identified rocks. However, the lack of precision in available data precludes highly refined comparisons and the establishment of valid empirical relationships for carefully defined, specific host-rock types or groups of host rocks. Nevertheless, the accumulation and review of available data on the host rocks of uranium-bearing veins lead to several generalizations regarding the influence of broadly defined groups of host rocks on uranium deposition in veins.

KINDS OF HOST ROCKS

Uranium-bearing veins are enclosed in many kinds of host rocks whose petrographic identities have been described by various authors, first, in broad terms such as "granitic," "sandstone," "acid volcanic rock," or "schist," and second, with widely varying accuracy, particularly where more specific terminology has been used. It is impossible to place many of the host rocks as described by the authors within any one of the accepted and precise petrographic classifications. To do so would entail not only considerable risk of misinterpretation, but, for rocks grossly misidentified, also would involve placing radically different rocks in the same class. For example, one of the reports that has been reviewed identifies the host rock of a uranium-bearing vein as arkose; a check of field relationships and study of several thin sections demonstrate that the host rock called arkose is an altered mafic dike. Without further study there is no way to ascertain how many of the host rocks of uranium-bearing veins are misidentified nor is there any way to determine the limits of inaccuracy. In view of the problems noted above, a generalized classification of the host rocks of uranium-bearing veins seems most useful and is commensurate with available data. Consequently, the host rocks are subdivided into igneous, sedimentary, and metamorphic rocks and, for purposes of generalization and comparison, are further subdivided herein into seven arbitrary groups which are: 1) felsic to intermediate plutonic and hypabyssal igneous rocks, including related rocks derived through metasomatic processes, 2) felsic to intermediate volcanic rocks, 3) intermediate to mafic plutonic, hypabyssal, and volcanic rocks, 4) clastic sedimentary rocks, excluding clastic limestone and dolomite, 5) carbonate rocks, 6) low-grade metamorphic rocks, and 7) intermediate-grade to high-grade metamorphic rocks. It is obvious qualitatively that within each group are rocks of diverse mineral composition and chemistry; however, few, if any, valid quantitative estimates are possible as to the limits and complexities of these diversities.

Igneous host rocks

Felsic to intermediate plutonic and hypabyssal igneous rocks

This group comprises intrusive crystalline rocks that are essentially within the range of granite through diorite or their alkali-rich equivalents. The group probably includes some crystalline rocks derived wholly or in part from metasomatism or modified by deuteric solutions and some rocks, presumably largely of magmatic origin, that contain greater or lesser amounts of assimilated material from the invaded rocks.

Included within this group are those host rocks, as named by the authors with greater or lesser accuracy, as granite, microgranite or aplite, granodiorite, quartz monzonite or monzonite, syenite, quartz diorite, diorite, alaskite, pegmatite, felsite, and those rocks identified only as "granitic." Although the rocks within this group are diverse in mineral composition and chemistry, in physical characteristics they show some uniformity in that they are holocrystalline and that most are massive and competent; they exhibit many textural variants and they may be either coarse- or fine-grained.

Most of the host rocks of this group are thought to be of Late Jurassic, Cretaceous, or early Tertiary age; some are of Precambrian age; and a few, as for example the quartz monzonite host at Marysvale, Utah, are thought to be of middle Tertiary age.

Selected chemical analyses of both host rocks and altered wall-rocks of this group are presented in table 1. Although the analyses indicate considerable variation in the content of many of the basic oxides and acid radicals, modal analyses of these rocks as compared to modal analyses of felsic to intermediate igneous host rocks from other areas indicate that considerably greater variation in chemical composition must be expected.

A few of the variations, even within a single district, can be demonstrated by available data for host rocks at Marysvale, Utah. At Marysvale, uranium minerals are localized principally in a rock identified as quartz monzonite by Callaghan (1939), but also are known to occur in microgranite as well as other kinds of rock. Several modal analyses of quartz monzonite and one of microgranite are compared below:

	1	2	3	4
Quartz	6	3.8	6.0	29.7
K-feldspar	29	48.8	44.5	59.2
Plagioclase	33	29.7	24.6	5.7
Biotite - partly as chlorite .	14	2.7	4.8	0.7
Augite	11			
Pigeonite.		12.7	16.2	
Magnetite	7			
Opaques		1.2	3.0	
Apatite		0.8		
Accessory minerals			0.2	
Calcite			0.2	
Pyrite				2.9
Fluorite				2.0
Totals	100	99.7	99.5	100.2

1. Quartz monzonite from Marysvale area; chemical analysis of specimen given in table 1, column 1. (Callaghan, Eugene, 1939)

2. "Quartz monzonite" from Sunnyside mine, Marysvale, Utah.

3. "Quartz monzonite" from wall of Freedom No. 2 vein, Marysvale, Utah.

4. Microgranite from Yellow Canary deposit, Marysvale, Utah.

Table 1.--Chemical analyses[/] of felsic to intermediate plutonic or hypabyssal intrusive host rocks of uranium-bearing veins

	Marysvale, Utah		Boulder batholith, Montana							Colorado Front Range		
	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	57.96	57.81	68.01	65.30	66.05	64.44	69.13	59.86	76.85	54.25	55.66	57.63
Al_2O_3	15.71	16.10	15.52	15.06	14.80	14.37	15.15	22.30	13.50	20.27	19.89	20.47
Fe_2O_3	3.38	3.33	0.29	8.85	1.52	(9.13	0.20	1.74	0.69	4.26	2.57	1.13
FeO	4.11	3.34	2.95	0.18	2.71	(	1.74	0.14	0.10	3.87	3.10	2.83
MgO	3.16	3.21	1.42	0.07	1.58	0.46	1.94	0.87	0.89	1.43	1.24	1.09
CaO	5.11	4.81	2.69	0.07	2.68	0.03	2.74	1.21	0.09	3.70	3.34	1.65
Na_2O	3.48	3.66	3.10	0.18	2.57	0.07	2.83	2.24	0.58	3.42	3.31	0.82
K_2O	4.08	4.66	3.24	3.16	5.00	3.61	4.49	3.80	2.66	5.55	6.18	10.26
H_2O+	1.26	0.74	0.72	5.21	0.83	1.75	0.81	7.10	3.84			
H_2O-	0.11	0.11	0.22	0.60	0.28	0.04	0.18	2.00	0.53			
TiO_2	1.05	1.15	0.48	0.47	0.52	0.40	0.48	0.64	0.68			
P_2O_5		0.42	0.10	0.23	0.13	0.00	0.08	0.10	0.04			
MnO	0.11	0.11	0.04	0.02	0.30	0.03						
CO_2	trace	0.02	0.02	0.01	0.74	0.02	0.35	0.12	0.31			
BaO		0.09	0.01	0.04	0.04	0.01						
S	0.07		0.99	0.02	n.d.	7.65	0.32	trace	0.02			
Cr_2O_3	0.02											
V_2O_5		0.01										
FeS_2		0.02										
F		0.15										
Cl		0.05										
SrO		0.07										
	99.61	99.86	99.80	99.47	99.75	102.01	100.44	102.12	100.78	96.75	95.29	95.88

[/] Includes complete and partial rock analyses

1. Quartz monzonite from east side of Marysvale Canyon at mouth of Deer Creek. Analyst: R. E. Stevens (from Callaghan, 1939).

2. Quartz monzonite from north end of Monzonite Hill. Analyst: E. H. Oslund (from Kerr, et al., 1953, table 8, p. 86).

3. Quartz monzonite from G. Washington claim, Jefferson County, Montana. Analyst: J. Theobald (from S. Rosenblum, unpublished data).

4. Argillized quartz monzonite from G. Washington claim, Jefferson County, Montana. Analysts: L. N. Tarrant and J. Theobald (from S. Rosenblum, unpublished data).

5. Quartz monzonite from Bunker Hill mine, Lewis and Clark County, Montana. Analysts: L. N. Tarrant and L. Trumbull (from S. Rosenblum, unpublished data).

6. Altered quartz monzonite from Bunker Hill mine, Lewis and Clark County, Montana. Analysts: L. N. Tarrant and L. Trumbull (from S. Rosenblum, unpublished data).

7. Quartz monzonite from W. Wilson mine, Jefferson County, Montana, (from Wright, H. D., Bieler, B. H., and Shulhof, W. P., written communication, 1953).

8. Moderately altered quartz monzonite from W. Wilson mine, Jefferson County, Montana, (from Wright, H. D., Bieler, B. H., and Shulhof, W. P., written communication, 1953).

9. Altered quartz monzonite from W. Wilson mine, Jefferson County, Montana, (from Wright, H. D., Bieler, B. H., and Shulhof, W. P., written communication, 1953).

10. Essentially fresh syenite from Caribou mine, Boulder County, Colorado, (from Wright, 1954).

11. Essentially fresh syenite from Caribou mine, Boulder County, Colorado, (from Wright, 1954).

12. Altered syenite from Caribou mine, Boulder County, Colorado, (from Wright, 1954).

These few modal analyses indicate not only that the quartz monzonite host rock is inhomogeneous, at least as related to the relative abundance of the constituent minerals, but also that the mineral composition, and undoubtedly the chemical composition, of the quartz monzonite and the microgranite are very different. Furthermore, both modal and chemical analyses indicate that the rocks from Marysvale identified as quartz monzonite are unusual and have little in common with the quartz monzonite of the Boulder batholith and probably with other host rocks identified as quartz monzonite in other parts of the western United States. According to Meschter (written communication, 1953), "A typical specimen .../of the quartz monzonite host rock at the W. Wilson mine, Jefferson County, Mont./ ...has the following approximate modal composition: plagioclase -- 50 percent, orthoclase -- 25 percent, quartz -- 15 percent, biotite -- 5 percent, and hornblende -- 2-3 percent. The accessory minerals are magnetite, apatite, sphene and zircon."

Greater variations in mineralogy and chemical composition of rocks within and among districts or deposits could be demonstrated if modal or chemical analyses or both were available for host rocks identified as porphyritic quartz monzonite at the Midnite mine, Wash. (Weis, P. L., written communication, 1956), quartz monzonite, granodiorite, and alaskite in deposits in the Boulder batholith, Mont. (Roberts and Gude, 1953; Becraft, 1956, p. 119), granodiorite and quartz diorite in Kern Canyon, Calif. (MacKevett, E. M., written communication, 1956), greisen at the Redskin mine, Park County, Colo., quartz monzonite at the Early Day claims, Nev. (Sharp and Hetland, 1954), granite pegmatite and bostonite porphyry in the Front Range of Colorado (Sims and Tooker, 1956, p. 108), and for other igneous host rocks from deposits in other parts of the country.

Felsic to intermediate volcanic rocks

The host rocks within the group defined as felsic to intermediate volcanic rocks range in composition from rhyolite through andesite and includes both alkalic and calc-alkalic varieties. These rocks occur as plugs and related near-surface, concordant and discordant intrusives, flows, flow breccias, and welded tuffs. These rocks are composed dominantly of glass or silica and silicate minerals, in various proportions, and contain many different kinds of varietal and accessory minerals. The flows, flow breccias, and intrusives are composed dominantly of crystals or of volcanic glass, which may be either altered or unaltered. The welded tuffs consist of different proportions of crystals or crystal fragments, glass or products of devitrification, and rock fragments which may be similar to or very different in composition from the matrix.

Dominant among the petrographic names, as applied by the authors and thus placed in this group, are rhyolite, dacite, latite, and andesite; some of the host rocks have been termed simply "acid volcanic rock" in available reports. Although specific mineralogic data are lacking, it seems reasonable to infer that several, if not many, mineralogic varieties of these rocks are represented. Many of these rocks, as named by the authors, are flows; some of the rocks called flows are, in fact, welded tuffs composed of different proportions of crystal and lithic fragments and glass based both on thin section study and re-examination of field relationships in the course of the present study.

For the presently known uranium-bearing veins, virtually all of the host rocks in this group are of Tertiary age, although a few may be of late Mesozoic age.

Where unaltered or only slightly altered, these rocks are, in general, hard and brittle and some are massive.

The three chemical analyses (columns 11, 12, and 13, table 2) do not indicate the range in chemical composition of the host rocks that are placed in this group, but they are the only readily available analyses of host rocks that are closely related, in space, to uranium-bearing veins. These three analyses are used herein only for purposes of comparison with the chemical composition of the other groups of host rock; they represent some of the most silicic host rocks for which analytical data are available. Significant differences in the chemical composition of host rocks within this group could assuredly be established if analyses were available for those host rocks identified as rhyolite porphyry at the Staats mine, Utah (Thurston, Staatz, and Cox, 1954, p. 18), as altered and silicified rhyolitic and latitic tuffs and flows at the Moonlight mine, Nev. (Taylor, A. O. and Powers, J. F., 1955, p. 8), as partly glassy to devitrified and altered rhyolitic dikes in the Bullion Monarch (Farmer John) mine, Marysvale district, Utah (Taylor, et al., 1951), as andesite at the Pitchblende Strike prospect, N. Mex. (Everhart, 1956), as rhyolite porphyry at the White Oaks

Table 2.--Chemical analyses[1] of several different kinds of host rocks of uranium-bearing veins

	Colorado Front Range										Thomas Range, Utah			Michigan		Sierra Ancha region, Ariz.		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
SiO_2	71.76	68.61	76.3	75.5	52.4	51.4	49.7	54.86	51.70	32.87	77.24	76.54	74.67	77.20	18.60	59.4	56.9	61.5
Al_2O_3	14.73	14.10	12.2	12.1	8.2	9.4	10.5	14.65	18.06	9.10	10.81	12.16	12.26	6.17	19.10	14.7	14.4	17.7
Fe_2O_3	1.13	2.33	.9	2.3	11.7	10.9	4.9	4.66	12.36	0.45	1.66	0.92	0.71	Total Fe 5.16	Total Fe 10.77	3.7	3.0	1.6
FeO	1.80	1.72	2.0	.68	13.9	15.0	16.8	7.99	0.16	10.57	0.27	0.37	0.27			0.35	5.8	0.54
MgO	0.59	0.64	.48	.44	2.8	3.8	2.0	3.40	1.15	5.60	0.33	0.14	0.11	0.75	2.22	1.0	0.31	0.04
CaO	2.05	2.51	1.7	.12	5.4	3.0	2.30	6.67	2.41	12.03	1.48	0.78	0.61	0.08	0.35	1.8	0.53	0.82
Na_2O	4.95	3.60	3.7	.11	0.10	0.09	0.09	3.28	2.46	0.21	2.59	3.50	3.31			0.18	0.55	0.92
K_2O	2.02	1.15	1.1	4.6	0.49	1.8	0.31	0.79	3.30	7.13	4.12	4.97	5.05			12.4	11.6	14.1
H_2O+	0.33	1.22	.83	1.6	0.74	0.87	1.4	1.35	3.74	0.23	0.37	0.11	2.24			0.77	0.72	0.72
H_2O-	0.03	1.71						0.30	1.93	0.15	0.49	0.05	0.13					
TiO_2	0.27	0.54	.22	.16	0.32	0.52	0.38	1.41	1.72	0.81	0.20	0.09	0.14			0.86	0.72	1.0
P_2O_5	0.04	0.11	.06	.06	0.70	0.59	8.0	0.05	0.25	0.36	0.06	0.02	0.01			0.11	0.10	0.12
MnO	0.06	0.14	.02	.01	3.5	3.2	0.52	0.31	0.28	0.29	0.02	0.05	0.05			0.02	0.03	0.00
CO_2	0.54	1.49	.20	.05	0.25	0.13	3.5	0.22	0.17	20.58	0.13	0.16	0.01			2.5	0.56	< 0.05
S								0.02	0.01					2.65	5.45	2.7	3.7	1.1
Cl											0.01		0.10					
F				.61							0.04	0.32	0.26					
C														6.96	29.11			
	100.30	99.87	99.7	98.3	100.5	100.7	100.4	99.96	99.70	100.38	99.82	100.18	99.93	--	--	100.5	98.9	100.2

[1] Includes complete, partial, and rapid rock analyses

1. Biotite-quartz-plagioclase gneiss from Essex mine, Gilpin County, Colorado. Analyst: L. N. Tarrant (from Tooker, E. W., written communication, 1956).

2. Altered biotite-quartz-plagioclase gneiss from Essex mine, Gilpin County, Colorado. Analyst: L. N. Tarrant (from Tooker, E. W., written communication, 1956).

3. Least altered quartz monzonite gneiss from East Calhoun mine, Gilpin County, Colorado. Analysts: P. L. D. Elmore, K. E. White, S. D. Botts (from Tooker, E. W., unpublished data).

4. Most altered quartz monzonite gneiss from East Calhoun mine, Gilpin County, Colorado. Analysts: P. L. D. Elmore, K. E. White, S. D. Botts (from Tooker, E. W., unpublished data).

5. Garnet-quartz rock from Fall River area, Clear Creek County, Colorado. Analysts: H. F. Phillip, P. L. D. Elmore, P. W. Scott, K. E. White (from Hawley, C. C. and Moore, F. B., unpublished data).

6. Garnet-quartz rock from Fall River area, Clear Creek County, Colorado. Analysts: H. F. Phillip, P. L. D. Elmore, P. W. Scott, K. E. White (from Hawley, C. C. and Moore, F. B., unpublished data).

7. "Altered" garnet-quartz rock from Fall River area, Clear Creek County, Colorado. Analysts: H. F. Phillip, P. L. D. Elmore, P. W. Scott, K. E. White (from Hawley, C. C. and Moore, F. B., unpublished data).

8. Hornblende gneiss from Union Pacific prospect, Jefferson County, Colorado. Analyst: L. M. Kehl (from Adams and Stugard, 1956).

9. Altered hornblende gneiss from Union Pacific prospect, Jefferson County, Colorado. Analyst: L. M. Kehl (from Adams and Stugard, 1956).

10. Breccia reef material from Union Pacific prospect, Jefferson County, Colorado. Analyst: L. M. Kehl (from Adams and Stugard, 1956).

11. Porphyritic rhyolite from the Thomas Range, Juab County, Utah. Analyst: E. Tomasi (from Staatz, M. H., unpublished data).

12. Rhyolite flow from the Thomas Range, Juab County, Utah. Analyst: L. M. Kehl (from Staatz, M. H., unpublished data).

13. Glassy base of rhyolite flow from Thomas Range, Juab County, Utah. Analyst: E. Tomasi (from Staatz, M. H., unpublished data).

14. Black slate from the Sherwood mine, Iron County, Michigan (from L. P. Barrett, 1953, p. 11).

15. Black slate from the Sherwood mine, Iron County, Michigan (from L. P. Barrett, 1953, p. 11).

16. Siltstone from Dripping Spring quartzite, Gila County, Arizona. Analysts: P. L. D. Elmore, Katrine E. White, Samuel D. Botts (from Granger, H. C. and Raup, R. B., Jr., unpublished data).

17. Hornfels from Dripping Spring quartzite, Gila County, Arizona. Analysts: P. L. D. Elmore, Katrine E. White, Samuel D. Botts (from Granger, H. C. and Raup, R. B., Jr., unpublished data).

18. Recrystallized hornfels from Dripping Spring quartzite, Gila County, Arizona. Analysts: P. L. D. Elmore, Katrine E. White, Samuel D. Botts (from Granger, H. C. and Raup, R. B., Jr., unpublished data).

mine, Ariz. (Raup, R. B., Jr., written communication, 1953), and as rhyolite, quartz porphyry, and rhyolite breccias at Majuba Hill, Nev. (Trites and Thurston, in preparation).

Intermediate to mafic plutonic, hypabyssal, and volcanic rocks

Both primary and secondary uranium minerals have been found in veins enclosed in a group of rocks defined herein as "Intermediate to mafic plutonic, hypabyssal, and volcanic rocks." Host rocks of this group have been identified principally as sills and dikes of diabase or locally lamprophyre, as sills, dikes, and flows of basalt, and, in a few places, as "intrusive" masses of hornblende-rich rock which apparently are altered, in part, to minerals of the serpentine group. These rocks are the host for uranium-bearing veins in about 30 different places or deposits within the United States and a very much larger number of uranium-bearing vein deposits, though enclosed in other kinds of rock, are closely related in space to mafic igneous rocks, both within the United States and elsewhere. Examples of uraniferous vein deposits in rocks of this group are known in the White Signal district, N. Mex., (Granger and Bauer, 1956, p. 334, 343, 345) at the Escondida claims and the Linda Lee prospect, Pima County, Ariz., and at the Lowary claims and Two Chuckers claims, Nev. (Twitchell, C. L., written communication, 1955).

Detailed data bearing on the mineralogic or chemical composition of these rocks in places where they represent the host for concentrations of uranium minerals in veins are lacking. However, judging from the petrographic names that have been applied to these host rocks, they probably are composed almost exclusively of calcic plagioclase and ferromagnesian minerals; locally, some contain noteworthy amounts of simple oxides of iron and titanium. Most of the rocks of this group have been identified as either of Precambrian or Tertiary age.

Sedimentary host rocks

Clastic sedimentary rocks

This group of host rocks includes all varieties of both marine and non-marine, clastic sedimentary rocks; this group excludes all carbonate sedimentary rocks. Because detailed data are lacking in regard to the differences in texture and in mineralogic and chemical composition among host rocks of this group, no further subdivision of clastic sedimentary rocks is possible.

Data in available literature indicate that most of the uraniferous veins in clastic sedimentary rocks are either in quartzitic or feldspathic sandstone or in tuffaceous strata which, in some places, are composed "exclusively" of pyroclastic debris. A smaller number of uranium-bearing vein deposits have been found in rocks described as conglomerate, shale, siltstone, and coal.

The field names that have been applied to rocks of this group are indicative of considerable inhomogeneity. Some of the rocks are phosphatic, or carbonaceous, or calcareous, whereas others are characterized by an abundance of silica, iron oxides, or alumina; not uncommonly the phosphate, carbonate -- largely as calcite --, and silica occur as cement.

Most, if not all, of the rocks of this group contain some of either non-expandable lattice or expandable lattice (montmorillinite, beidellite, nontronite, etc.) clay minerals. The expandable lattice clay minerals, commonly derived by devitrification of vitric ash, are particularly prevalent in the tuffs and tuffaceous sedimentary rocks; in places, these rocks also are enriched in phosphate. Organic carbon is characteristic of most of these rocks, occurring in some in only trace amounts and in a few host rocks as a major constituent. Rocks of this group are inhomogeneous in texture, in degree and kind of cementation, and in competence.

Some of the different lithologies and ages of host rocks of this group are exemplified by the Los Ochos mine, Colo., in sandstone of the Morrison formation of Jurassic age (Derzay, 1956); by the Pallaoro (or Morrison) deposit, Colo., in the Dakota sandstone of Cretaceous age; by veins in siltstone of the Deadwood formation of Cambrian age in South Dakota (Vickers, 1953); the Ridenour mine, Ariz. (Miller, 1954), in the top sandy member of the Supai formation of Permian age; by the Orphan mine, Ariz., in Coconino sandstone (Permian) and possibly Supai (Permian) formation; by veins cutting a sheared, partly silicified coal bed in the Upper Cretaceous Laramie formation at the Leyden Coal mine, Colo. (McKeown, F. A. and Gude, A. J., 3rd., written communication, 1951); by several deposits in fault gouge and brecciated sandstone and arkose of Rico (Permian), Cutler (Permian), and Chinle (Triassic) formations in the Moab-Inter-river area, Utah (Hinrichs, E. N., written communication, 1954); and by numerous uraniferous vein deposits enclosed in tuffaceous sedimentary rocks of Tertiary age in southeastern Oregon, western Nevada, southeastern California, and central Wyoming.

Carbonate rocks

Sedimentary rocks composed dominantly of either calcium or magnesium carbonate minerals or both are the host for uranium-bearing veins in several widely distributed deposits in the western United States; most of the deposits are fissure fillings although replacement, probably by uranium minerals and certainly by closely associated base-metal sulfide minerals and by uraniferous fluorite, is locally prevalent. Most of these host rocks have been described in reports simply as limestone or dolomite, although several textural, chemical, and mineralogic varieties are represented. Some are clastic carbonate rocks, as for example clastic dolomite in the Thomas Range (Staatz and Osterwald, in preparation) whereas others are chemical precipitates.

Some of these host rocks are nearly pure calcite or dolomite and some contain greater or lesser amounts of silica commonly in the form of chert; others are argillaceous or arenaceous carbonate rocks. In some places these host rocks have been modified, by diagenetic processes, to form silicified or dolomitized limestone.

In general, data in available reports are not specific as to the kind or detailed characteristics of the carbonate host rocks nor, as far as known to the author, are any chemical analyses or any detailed petrographic descriptions available except for dolomitic host rocks of Silurian age in the Thomas Range, Utah. According to Staatz and Osterwald (in preparation), the uranium-bearing fluorite pipes and veins of the Thomas Range district are enclosed largely in clastic dolomite locally characterized by minor to moderate amounts of chert as blebs and discontinuous layers along the bedding; in general, the lime content is about 30 percent and the magnesia content about 20 percent.

Several of the better known uraniferous vein deposits enclosed in rocks of this group are: the Green Monster mine, Clark County, Nev., in which kasolite and dumontite are concentrated in the oxidized parts of a lead-zinc ore body in brecciated Bullion dolomite of Carboniferous age; deposits at Bisbee, Ariz., in which uraninite is present in sulfide ores enclosed in carbonate rocks of Paleozoic age (Bain, 1952); and the Blue Bird mine, Lincoln County, Nev., where uranium minerals are concentrated in a breccia of silicified limestone and quartzite (Sharp and Myerson, written communication, 1956). Other deposits are known in cherty parts of the Madison limestone (Mississippian) in Carbon County, Mont., in silicified limestone of the Kaibab formation (Permian) adjacent to the Hurricane fault in Washington County, Utah, in Furnace limestone (Paleozoic) in San Bernardino County, Calif., (Walker, Lovering, and Stephens, 1956, p. 23), and in other Paleozoic limestone or dolomite elsewhere.

Metamorphic host rocks

Low-grade metamorphic rocks

The group, low-grade metamorphic rocks includes those host rocks transitional in character between obviously metamorphic rocks on one hand, and obviously unmetamorphosed rocks on the other hand. In general, host rocks placed in this group, regardless of the rock names used by various authors, are probably correlative with Turner's (1948) "greenschist" facies, on the basis either of the broad geologic environment of their occurrence, or of further re-examination in the course of the present study. This group serves to set apart from the igneous and sedimentary rock groups those host rocks wherein slight to moderate recrystallization has occurred.

Arbitrarily, host rocks of Precambrian age, to which sedimentary rock names such as siltstone, shale, and quartzite have been applied by various authors, are placed herein; this has been done on the basis that most, if not all, Precambrian rocks are at least slightly recrystallized. Again arbitrarily, included herein are host rocks not necessarily in a recognized metamorphic terrain but described as quartzite, slate, phyllite, argillite, hornfels and those identified only as metasedimentary and metavolcanic rocks. The mineralogy and chemical composition of host rocks placed in this group are diverse; many are highly siliceous, whereas others contain large to moderate amounts of clay minerals, carbonate minerals, graphite, iron sulfide or hydrated iron oxides, lime silicate minerals, or other constituents. In general, host rocks in this group are highly indurated and are hard and brittle.

Partial or "complete" chemical analyses of a few of the host rocks of this group are included in table 2 (columns 16, 17, and 18) principally for comparative purposes with other kinds of host rocks. The analyses of the three samples of host rock from the Dripping Spring quartzite, collected by H. C. Granger in the Sierra Ancha region, Gila County, Ariz., are representative of the formation in those places where it contains concentrations of uranium minerals, according to Granger (oral communication, 1956). Based on available analytical data, these are some of the most potassic host rocks of uranium-bearing veins. Only a few analyses are available for host rocks of uraniferous veins characterized by a relatively high carbon content. The two analyses presented in table 2 (columns 14 and 15), both of which contain carbon, are indicative, though probably not representative, of the composition of black slate host rocks of late Huronian age in northern Michigan; locally, these rocks are highly ferruginous near concentrations of uranium minerals.

Several of the different kinds of uraniferous vein host rocks of this group, in addition to those for which analyses are available, are exemplified by the quartzitic members of the Belt Series in the Coeur d'Alene district, Idaho, and at the Garm Lamoreaux deposits, Lemhi County, Idaho (Armstrong, F. C. and Weis, P. L., written communication, 1954), the metasedimentary rocks -- including quartzite, phyllite, silicified limestone and hornfels -- of Paleozoic age in the Reese River mining district, Lander County, Nev., (Sharp and Hetland, 1954), and the highly siliceous, Red Creek quartzite of Precambrian age at the Yellow Canary claims, Daggett County, Utah (Wilmarth, 1953).

Intermediate-grade and high-grade metamorphic rocks

Metamorphic rocks, including amphibolite, skarn, and many mineralogic varieties of schist and gneiss, constitute the host for a large number of uranium-bearing veins principally in the Front Range and adjoining areas of Colorado and in more widely distributed areas in Arizona, California, Nevada, New Mexico, New York, North Carolina, Washington, and Wyoming. These completely recrystallized host rocks are the products of both dynamic and thermal metamorphism and, locally, of metasomatic processes. Virtually all of the rocks have been designated as of Precambrian age, though some probably are metamorphosed Paleozoic or younger rocks.

The mineralogy of several of the host rocks identified as schist is not given in the reports that describe them. Because such mineralogic data are lacking, all rocks, designated as schist by the various authors, arbitrarily have been included in this group; some of these rocks may be the products of low-grade metamorphism and, consequently, would be correlative with Niggli's (1924) "epizone" or Turner's (1948) "greenschist" or "epidote-amphibolite" facies.

Although available data permit the establishment of some qualitative differences in host rocks of this group, data on quantitative chemical and mineralogic differences are scarce or lacking. Virtually all of the diversities in mineralogy and chemical composition exemplified by the host rocks heretofore described, by groups, also are known in this group. In addition, several host rocks in this group, particularly skarn, are enriched in certain elements, or contain large to moderate amounts of minerals that are present in much smaller amounts in other host-rock groups. A few of the minerals that apparently are more abundant in host rocks of this group are chlorite, biotite, muscovite or sericite, several varieties of amphibole, molybdenite in molybdenite-graphite schist, tourmaline, lime silicate minerals of different compositions, and metamorphic aluminum silicate minerals. These rocks are holocrystalline, exhibit many textural variants and, in general, are either foliated or banded or are massive.

Several chemical analyses of these host rocks are presented in table 2, columns 1-10; all of these analyses are of samples collected from uraniferous **vein** deposits located within the Front Range of Colorado. Considerable variation in the content of basic oxides and acid radicals is indicated by these few analyses, even within this limited geographic area, and greater variations are predictable on the basis of the petrographic names that have been applied to high-grade metamorphic host rocks both in the Front Range and elsewhere.

Uranium in veins has been reported in garnet-quartz rock in the Fall River area, Clear Creek County, Colo. (Hawley and Moore, 1955, p. 1675), in a carbonate-potash feldspar breccia reef cutting hornblende gneiss at the Union Pacific prospect, Jefferson County, Colo. (Adams and Stugard, 1956), in altered biotite-quartz-plagioclase gneiss and amphibolite in deposits on Nigger Hill, Gilpin County, Colo. (Sims, Osterwald, and Tooker, 1955, p. 5), in lime silicate rock, tourmaline gneiss, and other metamorphic rock types in deposits near Ralston Creek, Jefferson County, Colo., in quartz-garnet-hornblende-magnetite gneiss (locally magnetite-rich) in deposits near Critchell, Colo., in skarn at the Copper King mine, Colo. (Sims, Phair, and Moench, in preparation), in molybdenite-graphite schist at the Little Man mine, Carbon County, Wyo. (Adams, J. W., oral communication, 1956), in quartz diorite gneiss in the Black Hawk district, N. Mex., (Gillerman and Whitebread, 1956), in schist and gneiss in Avery County, N. C., and in many other kinds of metamorphic host rocks elsewhere.

Some aspects of the petrologic environment of uranium-bearing veins

The foregoing summary descriptions of the host rocks of uranium-bearing veins provide some data on the character of the petrologic environment in which uraniferous veins have been found in the United States. These data demonstrate some of the quantitative and more largely qualitative differences in chemical and mineralogic composition of the host rocks; the chemical and mineralogic composition of these rocks are extremely diverse and, even within a single district, many different kinds of rock constitute the host for concentrations of uranium minerals in veins. The physical characteristics of the host rocks also are diverse particularly as regards their texture, structure or lack of structure, and their competence or lack of competence under stress. Further, the data establish that uranium-bearing veins have been found in rocks of nearly all geologic ages but are most common in rocks of Precambrian, late Mesozoic, or Tertiary age.

Although these data establish that the petrologic environment of uranium-bearing veins is extremely diverse, in terms of the physical, chemical, and mineralogic character of the host rocks as we now see them, the nature of the petrologic environment at time of uranium deposition is very obscure. The physical, chemical, and mineralogic character of many of these rocks has been changed either before, contemporaneous with, or after uranium deposition and not uncommonly these changes are localized or best exemplified in or adjacent to the shear zones containing the veins. Many of these host rocks have been subjected to metasomatism, deuteric alterations, or metamorphism either before, contemporaneous with, or after the introduction of uranium, and many have been altered by either ore solutions or other solutions. Cataclasis has affected the rocks in some deposits to form pseudotachylyte, mylonite, fault gouge, or breccia, any one of which may be critical in establishing the physical characteristics of the environment of uraniferous veins. Furthermore, the petrologic environment of uranium deposition may be characterized in part or entirely, in some deposits, by the nature of metallic or non-metallic minerals that have been deposited in the vein prior to the introduction of uranium. Thus, although presently available data indicate considerable diversity in the petrologic environment of uranium-bearing veins in the United States, the physical, chemical, and mineralogic character of the environment at time of uranium deposition remains essentially unknown.

FREQUENCY DISTRIBUTION OF VEINS BY KINDS OF HOST ROCKS

A critical review was made of the frequency distribution of uraniferous veins in host rocks, using the specific rock names quoted in reports and several different groupings of these rocks, to determine which specific kinds or groups of rocks are the more favorable environments for uranium-bearing veins and, further, to determine whether these more favorable rocks have particular physical and chemical characteristics in common. This critical review of the available data indicated 1) that the descriptions of host rocks were sufficient only to indicate in a generalized manner the true nature of host rocks and 2) that any comparisons between a large number of the vein deposits in the United States and their host rocks could only be based on the general characteristics of these rocks. The arbitrary classification of host rocks into the seven groups heretofore described is adequate to segregate the loosely used rock names into geologically meaningful groups, and is considered the presently most useful in revealing any relationships between veins and host rocks. Further, the classification does permit relatively easy determination of the group in which to place a host rock, whether that rock has been precisely identified or, as in most places, has been given a general name such as "granitic."

The frequency distribution of 435 deposits which are estimated to represent about 80 percent of the known uraniferous veins in the United States is shown in table 3 in five mineralogic classes of uraniferous veins and in the seven host-rock groups. Inspection of the percent frequency distribution by host-rock type and by mineralogic class immediately indicates that 1) the host rocks for about one-third of the deposits are felsic to intermediate plutonic or hypabyssal intrusive rocks, 2) the host for one-half of the deposits are igneous rocks, and 3) the mineralogic class for about one-half of the deposits is "uranium minerals dominant," that is, containing tetravalent- or hexavalent-uranium minerals, with or without small amounts of hydrated iron oxides or sulfide minerals of which pyrite and marcasite are most common. However, the percentage

Table 3.--Approximate frequency distribution (in percent) of known uranium-bearing veins in the United States, by mineralogic class, according to host rock type.✓

Rock group	Mineralogic class of uraniferous veins					Totals by rock group
	Uranium minerals with fluorite gangue abundant or common	Uranium minerals subordinate to base-metal sulfide minerals	Uranium minerals "dominant"	Magnetite or other iron-oxide minerals dominant	Thorium or rare earths minerals dominant	
1. Felsic to intermediate plutonic or hypabyssal intrusive rocks including alkalic and calcic-alkalic varieties	3.4	11.7	14.0	0.7	1.8	31.6
2. Felsic to intermediate volcanic rocks including alkalic and calcic-alkalic near surface intrusive, extrusive, and pyroclastic varieties	3.0	2.1	8.7	---	---	13.8
3. Intermediate to mafic plutonic, hypabyssal, near surface intrusive and extrusive rocks	---	1.8	3.4	0.2 (1 deposit)	---	5.4
4. Clastic sedimentary rocks	0.2 (1 deposit)	3.2	9.4	---	0.2 (1 deposit)	13.0
5. Carbonate rocks	2.5	3.9	4.6	---	---	11.0
6. Slightly recrystallized sedimentary and igneous rocks including principally metasedimentary and metavolcanic varieties	0.7	2.3	4.4	0.2 (1 deposit)	0.2 (1 deposit)	7.8
7. Low-grade and high-grade metamorphic rocks including principally silicic to subsilicic varieties of gneiss and schist	1.4	9.7	4.6	0.7	0.9	17.3
Totals	11.2	34.7	49.1	1.8	3.1	99.9

✓ Percentage figures are based on 435 observations figures, as shown on table 3, must be evaluated and the favorability or nonfavorability of groups of host rocks must be judged with considerable caution. The percentage figures are influenced to different, but quantitatively unknown, degrees by: 1) the relative abundance of outcrops of a particular kind of rock within mining districts or geographically limited areas that have been intensely prospected -- particularly the Front Range mineral belt, Thomas Range, Boulder batholith area, White Signal district, Marysvale district, and Sierra Ancha region -- in contrast to those districts that have been examined in less detail, 2) the interpretation necessary in classifying some of the different host rocks according to the seven groups, and 3) the difficulty in establishing what constitutes a single uraniferous vein deposit, particularly in those mines or prospects characterized by several veins or ore shoots enclosed in different kinds of host rock. Furthermore, the frequency distribution of uraniferous veins in the seven different groups of host rock may be dependent, in part or entirely, on the relative abundance of a particular host rock within selected parts of the earths crust or to its outcrop distribution; no valid figures are readily available to solve this problem.

The percentage figures representing totals by rock group (table 3) may conceivably reflect the relative abundance of the different kinds of rocks that crop out in 1) those districts characterized by many known uranium-bearing veins, 2) those parts of the western United States that have been more intensely prospected than others, 3) the western United States, or 4) those parts of the United States that have been systematically prospected. If these percentage figures are correlative --

or nearly so -- with the outcrop distribution in any of these four categories, the relationship between uraniferous veins and the enclosing host rocks could be fortuitous and, as a result, the percentage figures would not indicate favorability of one host-rock group in relation to other groups.

The foregoing review of the different kinds of rocks that constitute the host for uranium-bearing vein deposits in the United States has shown that 1) such veins are in rocks of nearly all textural, chemical, and mineralogic types, and 2) they are most abundant in holocrystalline, igneous and metamorphic rocks characterized by a moderate to high silica content; these rocks have diverse chemical compositions but have similar physical characteristics in regard to deformation under stress.

Possible influence of host-rock composition in localizing uraniferous veins

Available data are inadequate to demonstrate any widely applicable relationship between the presence or relative abundance of any element or suite of elements in the rocks and concentration of uranium minerals in veins. No specific chemical interaction between the host rocks and ore solutions can be demonstrated for all deposits; however, in a few places the data suggest a specific relationship.

Within some districts -- or deposits -- characterized by several different kinds of rock, the chemical and mineralogic composition of certain rocks appears to aid in the deposition of uranium in individual veins. In the Central City district, Gilpin County, Colo., metatorbernite has replaced some of the constituent minerals of altered biotite-quartz-plagioclase gneiss and altered amphibolite wall rocks in the supergene zone; it is absent in other rock types (Sims and Tooker, 1955, p. 1680; Sims, Osterwald, and Tooker, 1955, p. 17-18). Hawley and Moore (1955, p. 1675), suggested a chemical control of uranium deposition in the Fall River area, Clear Creek County, Colo. The veins, in which the uranium occurs, cut several different kinds of Precambrian metamorphic and granitic rock, but uranium was deposited only where the veins intersect garnet-quartz rock. Some pitchblende deposits in Golden Gate Canyon, Jefferson County, Colo., exhibit a similar type of chemical control. According to Adams and Stugard (1956, p. 113), ..."The veins occupy extensive faults considered to be of Laramide (earliest Tertiary) age and normally contain pitchblende only where they cut hornblende gneiss." Although a chemical control of uranium deposition is suggested for all of these deposits, many nearby uranium-bearing veins in the Colorado Front Range occur in an assemblage of host rocks that are noticeably different in mineralogy and chemical composition from those mentioned above. Uraniferous veins in amphibolite, quartz monzonite gneiss of several different compositions, biotite-quartz-plagioclase gneiss, sillimanite-biotite-quartz gneiss, granite pegmatite, granite gneiss, and several varieties of schist, have been reported in the Central City district and all within a few miles of each other. A somewhat parallel situation has been noted in the Goldfields region of Saskatchewan, Canada, where, although uranium was deposited in several quite different kinds of rock, the preferred host rocks were mafic gneiss, chlorite schist, amphibolite, diabase, and granites "...where they /the granites/ are crushed and contain carbonate and chlorite" (Robinson, 1955, p. 49 and table 1). The preferential localization of uranium in calcium- or iron-rich wall rocks has been demonstrated for deposits in these and other areas; however, the variable character of the host rocks of the great majority of deposits in the United States would seem to preclude any such chemical relationship.

The generally accepted hypothesis is that uranium is transported as the uranyl ion in sulfate or carbonate solutions that may be either acid or alkaline. McKelvey, Everhart, and Garrels (1956, p. 43) have postulated that "Precipitation of primary uranium minerals in veins may be caused solely by a reduction in the amounts of sulfate or carbonate in solution by whatever cause, by a decrease in temperature or pressure or both, or by chemical interaction with the host rock. Either pressure or chemical interaction with the host rock may result in $(U^{+6}O_2)^{+2}$ reduction, which seems to be the factor of major importance in the precipitation of uranium minerals in hydrothermal and many other types of deposits." Although there is little question that most host rocks contain reducing agents of one kind or another, positive criteria are lacking as to whether any of these reducing agents aided the precipitation of primary uranium minerals in any one deposit.

Many uranium-bearing vein deposits in the United States show no clear-cut relation between ore deposition and the chemical composition of wall rock possibly owing to 1) lack of adequate data, 2) inert chemical properties of ore solutions with respect to the altered or unaltered host rocks, or 3) marked differences in the nature of chemical interaction between ore solutions and host rocks from one deposit to another.

Possible influence of physical properties of host rocks in localizing uranium

The most significant generalization that can be made about the influence of host rocks in localizing uranium is that a majority of uraniferous veins are enclosed in rocks that are dominantly silica and silicate minerals, of which igneous and metamorphic, coarse- to medium-grained, holocrystalline rocks are most abundant. These rocks, although their mineralogic and chemical compositions differ between wide limits, do have certain physical properties in common, particularly their competence under stress. Silicate rocks lack any important plastic flow phenomena under near-surface conditions of pressure and temperature and are more apt to rupture under stress than other kinds of rock (Robertson, 1955). Conceivably this tendency to rupture and the detailed characteristics of the resultant fractures and fragmentation possibly affecting the adsorptive properties of the host rock, may affect the apparent preferential deposition of uranium. Presumably, for uranium to be adsorbed on crushed wall-rock or crushed pre-uranium vein filling and deposited directly as a tetravalent-uranium mineral, the following conditions should be met. The uranium should be carried in the ore solution in the reduced state, most likely as a colloidal sol, or as the uranyl ion which is converted to a colloid composed of 4-valent uranium at or near the site of deposition. Although this is in contrast to the summary statements concerning transportation and deposition of uranium by McKelvey, Everhart, and Garrels (1956, p. 43), such a mechanism could explain many of the textural characteristics of pitchblende and the texture and distribution of some sooty pitchblende.

WALL-ROCK ALTERATION

Although few detailed and comprehensive studies have been made of the wall-rock alteration adjoining uranium-bearing veins, the results of these few studies, in combination with voluminous field data, indicate that such alteration is analogous in nearly all ways to the alteration haloes that enclose other kinds of vein deposits. Because of these similarities, the results of recent studies and summaries on the character of wall-rock alterations and the processes involved in their formation by Lovering, et al., (1949), Lovering (1950), Sales and Meyers (1948), Kerr (1955), Schwartz (1955), White (1955), and others, have a direct bearing on the wall-rock alteration associated with uranium-bearing vein deposits. This section of the report will adhere, in so far as practical, to these similarities and will discuss any apparent or real quantitative or qualitative differences.

Most alteration haloes are mineralogically zoned as a result of decreasing alteration intensities from the vein outward with boundaries between different zones being either sharp or gradational. For purposes of generalization in this report, three principal zones are delineated -- namely, a sericitic zone closest to the vein, an argillic zone, and a chloritic zone furthest from the vein (fig. 1).

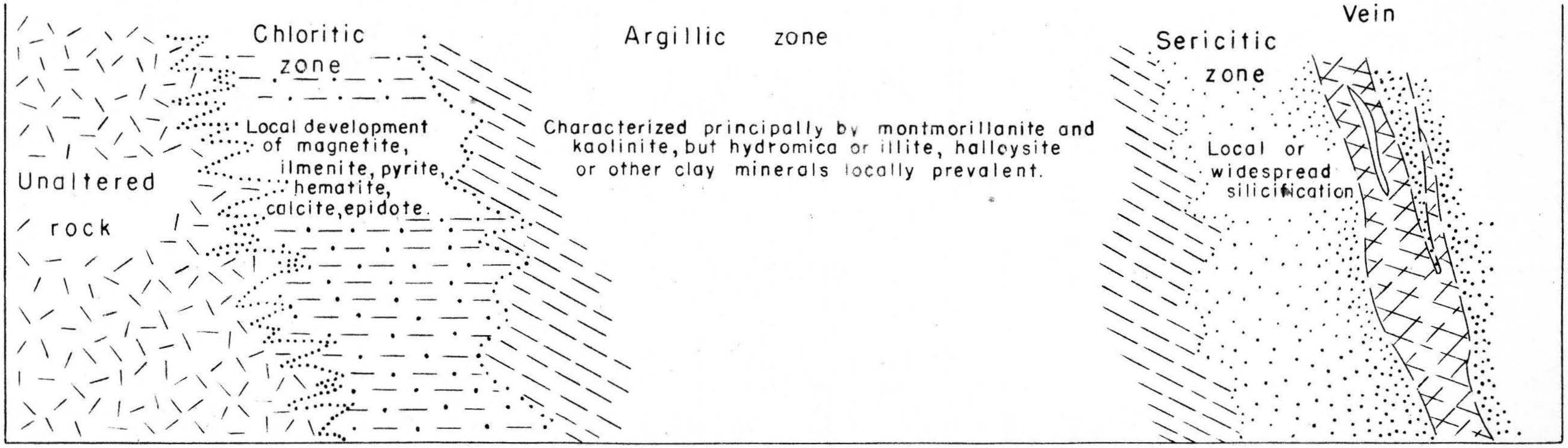

FIGURE I.- COMPOSITE SKETCH DIAGRAM SHOWING GENERAL MINERALOGIC FEATURES OF WALL-ROCK ALTERATION ZONES ADJOINING URANIUM-BEARING VEINS.

Some physical aspects of alteration

Although some uranium-bearing veins are enclosed in unaltered rocks, most exhibit some megascopic evidence of wall-rock modification or reconstitution adjacent to the vein. In most places, the mineralogic and chemical alteration of the wall rock is manifest by readily observable physical changes in color, texture, and competence. Bleaching and softening of the rocks is most common, largely as a result of the transformation of original silicate minerals into a more or less porous, incoherent, fine-grained mass of light-colored alteration products of which the most abundant are sericite and minerals of the kaolinite or montmorillonite groups. Some veins show wall-rock alteration as envelopes faintly to intensely stained red, yellow, or brown largely by iron oxide minerals, or grayish-green or green, in part through the development of secondary silicate minerals containing ferrous iron; some alteration envelopes are hard, resistant silicified zones, that are different shades of gray, green, red, yellow, brown, or white. Though some alteration sheaths are rather uniform in their appearance, many show considerable heterogeneity of coloring material, alteration textures, porosity, and competence. The heterogeneous character of these alteration haloes has resulted largely from 1) differences in the composition and relative stability of host rocks, 2) probable local differences in chemistry of altering solutions, and 3) differences resulting from several periods and kinds of alteration. Many alteration haloes contain different zones representing different types and intensities of alteration; locally, this zonation is megascopically distinct.

In some deposits, the alteration zones are closely related spatially to concentrations of uranium and associated minerals, but elsewhere alteration is much more widely distributed than the ore and gangue minerals. Locally, the alterations form a sheath of rather uniform thickness adjacent to veins or fractures, particularly where the host rocks are physically and mineralogically uniform. Where the host rocks are diverse or where fracturing is intense and widespread, the alteration haloes are commonly quite irregular in shape. The alteration haloes -- or the different zones within a halo -- range from a fraction of an inch to several tens of feet in thickness.

Some mineralogic aspects of alteration

The alterations most frequently referred to in the literature as associated with uranium-bearing veins are those in which the wall rocks have been silicified, argillized, sericitized, chloritized, pyritized, or hematitized; most common reference is made to argillic alteration, Less common reference is made to several other alterations including albitization or feldspathization, tourmalinization, dolomitization, propylitization, and carbonatization. An accurate analysis of the geologic significance of these less common alterations is complicated by both 1) lack of data on spatial and paragenetic relations of several of these alterations to uranium and associated minerals, even though they are known to occur in the same deposit and 2) presence of many of the minerals characterizing these alterations, particularly secondary feldspars, chlorite, epidote, and zoisite derived through propylitization, and secondary carbonate minerals, as constituents of alteration haloes that are dominated by sericitized, argillized, or chloritized rocks. The assemblage of alteration minerals that has been reported includes not only all of those specifically characterizing the different alteration zones but also several other minerals derived wholly or in part from constituent minerals of the host rocks. Included are magnetite, ilmenite, hydrated iron oxides, hydromica or illite, alunite, opal, chalcedony, and biotite.

In those places where wall-rock alterations associated with uranium-bearing veins have been studied in detail, the alterations have been shown to exhibit similarities in mineralogy and in the distribution of alteration products. Wright (1954), in reporting on the alteration halo at the Caribou mine, Boulder County, Colo., states "... The major features of the pattern -- relative stability of the primary mineral groups in zones of different alteration intensity, the alteration minerals developed, sequence of formation of the alteration products, and progressive chemical changes with increasing intensity of alteration -- conform rather closely to a general pattern that has emerged from hydrothermal alteration studies in many districts ..." His statement applies with equal cogency to alteration haloes accompanying many uranium-bearing veins.

The major mineralogic features of the wall-rock alteration pattern, as shown diagramatically in figure 1, can be generalized into three principal zones characterized most commonly by the presence or dominance of sericite, by different kinds of clay minerals, and by chlorite in the altered host rock. This generalized alteration pattern is based largely on the results of studies at the Caribou mine (Wright, 1954; Moore, Cavender, and Kaiser, in preparation), of base-metal sulfide veins that locally contain uranium in the Central City-Idaho Springs area, Gilpin and Clear Creek Counties, Colo. (Tooker, 1955; Tooker, in press; Sims, Osterwald, and Tooker, 1955, p. 15-16), of uraniferous veins in the Boulder batholith, Mont. (Meschter, D. Y., written communication, 1953; Wright and Bieler, 1953; Wright, et al., 1954; Roberts and Gude, 1953, p. 148-149; Becraft, 1956, p. 120; Rosenblum, Sam, unpublished data), and at Marysvale, Utah (Taylor, et al., 1951; Kerr, et al., 1952 and 1953; Kerr, 1956); many other alteration haloes associated with uraniferous veins, though described in considerably less detail, apparently also conform to a part or all of this alteration pattern. The haloes in some deposits exhibit zones of sericitized, argillized, and chloritized rock, whereas in other deposits one or another of these zones of alteration are absent in the halo.

The sericitic zone, closest to the vein, is characterized principally by sericite and fine-grained quartz but may contain considerable kaolinite and pyrite and, locally, some disseminated base-metal sulfide minerals. Characteristically, the quartz-sericite ratio increases veinward and, locally, an innermost siliceous part of the sericite zone is gradational into the adjacent vein; consequently, detailed descriptions of several alteration haloes have delineated a siliceous subzone immediately adjacent to the veins. Furthermore, Rosenblum (unpublished data) has found local concentrations of tourmalinized rock in the silicified part of the sericite zone adjacent to veins in the Boulder batholith, Trites and Thurston (in preparation) report tourmalinized rock associated with sericitized and silicified rhyolite porphyry at Majuba Hill, Nev., and Wright (1954, p. 138) reports abnormal amounts of calcite in the sericite zone at the Caribou mine.

The argillic or intermediate zone is characterized principally by minerals of the montmorillonite or kaolinite groups although other clay minerals or hydromica (illite?) are locally prevalent; most commonly the kaolinite - montmorillonite ratio increases toward the vein but some minor reversals in this pattern have been noted. Several detailed descriptions of alteration haloes have indicated a subdivision of the argillic zone into montmorillonite-rich and kaolinite-rich zones or subzones.

The chlorite, or outermost, zone of alteration is characterized principally by chlorite, derived largely from ferromagnesian minerals in the host rock, and by the incipient alteration of plagioclase to montmorillonite, kaolinite, and sericite. Several other alteration products are common and locally may be more abundant than chlorite; dominant among these are magnetite, ilmenite, biotite, epidote, calcite, and either hematite or pyrite.

All of the alterations described by various authors differ in minor details from the composite and idealized alteration pattern, composed of chloritic, argillic, and sericitic alteration zones, shown in figure 1. These minor differences are: 1) the absence of one or more of the three alteration zones in some deposits, 2) the distinction by several geologists of additional alteration zones (or subzones) in a few deposits, or 3) variations from one deposit to another in the presence or relative abundance of certain alteration minerals within comparable zones. Many of these differences are the result of original compositional differences in the enclosing rocks, whereas other differences are more largely attributable to alteration intensities and to the physical and chemical characteristics of the altering solutions.

Characteristically, the chloritic zone of alteration is lacking or only weakly developed around deposits enclosed in host rocks with only minor amounts of ferromagnesian minerals, as for example at Majuba Hill in rhyolite porphyry (Trites and Thurston, in preparation), at the Moonlight mine, Nev., in acid volcanic rocks (Taylor and Powers, 1955), associated with uranium deposits in siltstone and hornfels of the Dripping Spring quartzite in Gila County, Ariz. (Granger and Raup, in preparation), at several deposits in the Colorado Front Range enclosed in felsic crystalline rocks (Sims, P. K., oral communication, 1956) and probably at the Los Ochos mine, Colo., in the Morrison formation (Derzay, 1956). Lacking a typical chloritic zone, these deposits are characterized principally by argillized, sericitized, and commonly silicified rocks. The alterations accompanying many uraniferous vein deposits in felsic igneous rocks and in some feldspathic sedimentary and metasedimentary rocks have been identified, in the field, as argillic or kaolinitic; presumably most have formed at lower alteration intensities than alteration haloes characterized by sericitic zones.

Where the host rocks contain greater amounts of ferromagnesian minerals or, locally, where altering or ore solutions introduced iron and possibly other ions, the chloritic zone is commonly developed. Within the chloritic zone of alteration, several different iron minerals are commonly present, including several iron silicate minerals as well as magnetite, pyrite, and hematite. Because hematite -- or hematitic alteration -- has received considerable attention by uranium geologists throughout the world and because this alteration may conceivably be more commonly associated with uranium-bearing veins than with other veins, it will be discussed further.

Hematitic alteration

Hematite in and adjacent to uranium-bearing veins in many different parts of the world has led to the generally accepted concept that hematitic alteration is perhaps a widely applicable and diagnostic feature of uranium mineralization in veins. This general concept has been cited by Everhart and Wright (1953, p. 94), who state: "One of the most persistent features of pitchblende deposits is accompanying hematitic alteration of vein matter and wall rock." Nininger (1954, p. 27-28), in describing the morphology and occurrence of pitchblende, has given further recognition to this concept as follows:

> "The presence of hematite (a red iron oxide mineral) extending from the pitchblende a few inches to a few feet into the wall rock is the most characteristic feature [of alteration]. The formation of hematite has occurred in all of the major pitchblende vein deposits and in many of the deposits of minor importance."

Although the spatial association of uranium minerals and hematite in many uraniferous vein deposits throughout the world cannot be denied, it is by no means universal and, within the United States, Everhart (1956, table 2) has demonstrated that this association is not particularly common. Consequently, the pertinent data bearing on this concept have been reviewed.

No clear-cut distinction is made in the following pages between 1) hematite in the vein -- which may constitute either a hypogene vein mineral, a product of supergene alteration, or a product of radiation-induced oxidation (Adams, Gude, and Beroni, 1953, p. 16; Lovering, 1956, p. 192) and 2) hematite in the wall-rocks which presumably is derived wholly or in part as a product of hydrothermal alteration, because, for many deposits, data are lacking to make such a distinction.

Red, hematitic alteration or iron-stained chert or jasper in association with concentrations of uranium minerals in veins has been noted in most, but not all, of the deposits in the Goldfields region of Saskatchewan, Canada (Lang, 1952; Robinson, 1955), at the Eldorado mine, N.W.T., Canada (Lang, 1952, p. 53; Murphy, 1946), in several deposits in the Montreal River district, Ont. (Lang, 1952; Wright, 1951), at both Joachimsthal and Johanngeorgenstadt, Czechoslovakia (Everhart and Wright, 1953), in deposits in Cornwall, Great Britain (Davidson, 1956, p. 205), in some, but not all, of the vein deposits in Portugal (Cavaca, Rogério, 1956, p. 184) and in France (Geffroy and Sarcia, 1954), at the President Perón deposit, Argentina (Belluco, 1956, p. 87), and at Radium Hill (Sprigg, 1954; Whittle, 1954, p. 139), Mount Painter (Stillwell and Edwards, 1954, p. 95), and Rum Jungle (Fisher and Sullivan, 1954) in Australia. Other uraniferous vein deposits of lesser importance characterized by hematitic alteration could be listed. Within the United States, hematite is a not uncommon associate of uranium minerals in and adjacent to a number of vein deposits although at most deposits the pervasive stain or coloration of wall rocks characteristic of several of the foreign vein deposits is absent. Hematite -- or iron-stained jasper -- has been noted in greater or lesser quantities at the Sunshine mine, Idaho (Kerr and Robinson, 1953, p. 506-507), at Marysvale, Utah (Taylor, et al., 1951; Kerr, 1956, p. 634; Walker and Osterwald, 1956, p. 125), at the Red Bluff mine, Ariz. (Everhart, 1956), the Caribou mine, Colo. (Wright, 1954, p. 136), the Union Pacific prospect and the Buckman adit, Colo. (Adams and Stugard, 1956), at the Prince mine, N. Mex. (Walker and Osterwald, 1956), at Bisbee, Ariz. (Bain, 1952, p. 20) and in several other vein deposits elsewhere.

The presence of hematite in these deposits, irrespective of any stated or inferred genetic or environmental relationship, has led to the general concept heretofore mentioned. Concerning uranium-bearing vein deposits in the United States, the statement that ..."Hypogene red hematite zones adjacent to veins are very common" ... (Staffs of the U. S. Geological Survey and the U. S. Atomic Energy Commission, 1956, p. 212) presumably has resulted largely from observed spatial associations of hematite and uranium minerals in domestic deposits, but may be based, in part, on conditioned thinking because of this association in several of the very large deposits in other parts of the world.

In contrast to those uraniferous vein deposits that are characterized by the presence of hematite, there are a larger number of deposits which, according to available data, probably contain little or no hematite. Neither Thoreau and du Trieu (1933) nor Derriks and Vaes (1956) mention the presence of hematite at Shinkolobwe, the largest known uraniferous vein deposit in the world, although Derriks and Vaes (op. cit., fig. 6) do delineate several units of rose and lilac breccia; the identity of the coloring material is not given. Hematite appears to be lacking in the vein deposits at Tyuya Muyun, Turkistan, in some of the deposits of Portugal, in several of the deposits in the Goldfields region, Saskatchewan, Canada, and in the Mary Kathleen uranium deposit, Australia (Matheson and Searl, 1956). The deposits in the vicinity of Spokane, Wash., and Kern Canyon, Calif., many of the deposits in acid volcanic rocks in Oregon, Nevada, and California, those in the Boulder batholith, Mont., deposits in the Cochetopa district, Colo., the lower parts of the vein deposits at Marysvale, Utah, and most of the deposits in the Front Range of Colorado and the Dripping Spring quartzite, Ariz., which collectively represent a very large part of all the known uraniferous vein deposits in the United States, do not contain abnormal amounts of hypogene hematite either in the vein or as hematitic alteration of the adjoining wall rocks.

Although there is little doubt that hematite and uranium occur together in a large number of vein deposits throughout the world, the geologic significance of this association is still obscure. Hematite, which forms either by hypogene or supergene processes, is a ubiquitous and locally abundant mineral in the earths crust irrespective of the presence or absence of uranium minerals; consequently it is difficult to establish 1) what is an "abnormal" amount of hematite, particularly in consideration of the trace amounts of hematite necessary to give the characteristic red coloration, either in a uraniferous vein deposit or elsewhere, 2) what is the ratio of hypogene hematite to supergene hematite in those uraniferous vein deposits characterized by this association, 3) what percentage of the hematite in these deposits results from radiation-induced oxidation of ferrous iron, 4) what, if any, genetic association exists between uranium and hematite, 5) in what percentage of different places is this association fortuitous, and conversely in what places does this association represent a favorable, iron-rich environment for the precipitation of uranium minerals, and 6) what percentage of non-uraniferous ore deposits contain hematite. None of these questions can be answered with complete satisfaction, and some of the available data bearing on the problem are conflicting. It is interesting to note, however, that magnetite and hematite are abundant in many pyrometasomatic deposits (Knopf, 1933, p. 538) and are important constituents of many hydrothermal deposits (McLaughlin, 1933, p. 558) which are not known to contain uranium.

It is generally accepted that some and perhaps most of the hematite in and adjacent to uraniferous vein deposits is hypogene and is closely related, though not necessarily contemporaneous, with uranium deposition. A mechanism whereby primary uranium minerals can be deposited simultaneously with the formation of hematite is based on ferrous iron, presumably in the wall rocks, acting as a reducing agent for uranyl ions carried in solution. Gruner (1952, p. 16) co-precipitated pitchblende and hematite under controlled conditions in the laboratory, and McKelvey, Everhart, and Garrels (1956,

p. 43-44) have postulated that the "widespread" association of iron oxides with pitchblende in vein deposits may be explained by the following reaction:

$$3H_2O + 2Fe^{+2} + (U^{+6}O_2)^{+2} \rightarrow Fe_2O_3 + U^{+4}O_2 + 6H^+$$

In some deposits the spatial association and the apparent simultaneous deposition of uranium and hematite would seem to bear out the efficacy of this oxidation-reduction reaction; in other deposits the hematite appears to have formed either prior to or after pitchblende deposition through oxidation of iron-bearing minerals of the wall rocks. Whittle (1954, p. 66) and Webb and Whittle (1954, p. 121) have presented evidence indicating that the uranium was introduced after the formation of hematite and, locally, replaces it in several of the Australian deposits. A brief description of the red alteration in the Goldfields district by K. R. Dawson (in Lang, 1952, p. 27) includes the following:

> "The width of the altered zone does not appear to bear any consistent relationship to occurrences of pitchblende. In the Martin Lake workings, the alteration was effective for the same uniform width along barren fractures as along radioactive veins. At the Ace, it bears a closer relationship to the St. Louis fault than to the occurrence of pitchblende, as though the alteration preceded the pitchblende mineralization. The veins in that mine occur in shatter zones within the zones of strong red alteration, unaccompanied by any additional alteration. I do not believe a general rule regarding the width of the alteration relative to the occurrence of pitchblende will be found to apply to the camp as a whole.
>
> "It is also noteworthy that there are numerous zones of 'red alteration' in the area around Goldfields, which are megascopically identical with those carrying pitchblende but which are barren." ...

As a result of detailed paragenetic studies of the ores from the Eldorado mine, Canada, Kidd and Haycock (1935) have found that hematite was formed later than the pitchblende and earlier than several carbonate gangue minerals and many of the base-metal sulfide minerals. This paragenetic relationship between hematite and pitchblende tends to substantiate an impression held by the author that the distribution of hematite is not correlative, in detail, with the distribution of pitchblende; the impression is based both on personal observation of the Eldorado mine in 1954 and more largely on discussions with Mr. L. T. Jory, then Chief Geologist at Eldorado. Furthermore, according to Jory (oral communication), argillic alteration is the most dominant alteration on all veins and appears to be closely associated with uranium mineralization.

Hematite, in the President Péron deposit, Argentina, apparently was derived as a result of supergene alteration of magnetite, pyrite, or other iron-bearing minerals. According to Belluco (1956, p. 87) ..."The hematite, as a product of alteration, partly colors the oxidized zone of the veins red"...

Adams and Stugard (1956), in studying the Union Pacific prospect, have hypothesized that ferrous iron released by alteration of hornblende in the wall rocks was partly oxidized to hematite and uranium was simultaneously reduced and deposited as pitchblende in the vein; in the nearby Buckman adit, hematite replaces quartz and sulfides and veins the pitchblende. Both hypogene crystalline and supergene hematite are present in the Prince deposit, N. Mex.; some evidence indicates contemporaneous precipitation of uranium and the hypogene? hematite (Walker and Osterwald, 1956). At Marysvale, a thin alteration zone marked by trace amounts of hematite around some ore bodies -- and incidentally peripheral to zones of fracturing -- occurs principally in the hypogene? zone; but at places, it persists in the zone of supergene alteration. The distribution of other kinds of alteration at Marysvale, upon which the hematite zone is impressed, suggests that most of the alteration may be related to near-surface oxidation of pyrite; if so, the hematite at Marysvale is, most likely, also supergene. Hematite, both in the vein and as intense wall-rock staining, is prevalent in several of the deposits in the United States characterized principally by thorium and rare earths minerals and lesser amounts of uranium. According to J. W. Adams (oral communication, 1956) some, and perhaps most, of the hematite in these deposits has resulted from the near-surface oxidation of pyrite.

The general concept that hematite in veins or hematitic alteration of adjoining wall-rocks is a widely applicable and diagnostic feature of uranium mineralization in veins is neither proved nor disproved by a critical review of the pertinent data. Like other kinds of alteration, hematitic alteration or iron-stained chert or jasper locally serve as useful guides to permeable structures that may or may not be mineralized with uranium.

CONCLUSIONS

Although much of the published and unpublished data regarding the host rocks of uranium-bearing veins in the United States are of questionable accuracy, these data, in combination with some precise data, field and office review, and selected thin-section study, do permit several broad generalizations regarding the petrologic environment of uraniferous veins.

In general the host rock environment of uranium-bearing veins in the United States is diverse; the age and the mineralogic and chemical composition of the rocks in which such veins are known to occur are especially diverse. In physical characteristics the host rocks also are dissimilar; however, three-quarters of the known uranium-bearing vein deposits are enclosed in igneous and metamorphic rocks that lack any important plastic-flow phenomena under near-surface conditions of pressure and temperature and are more apt to rupture under stress than other kinds of rock. The considerable differences in mineralogic and chemical composition of the host rocks, as we now see them, indicate that the environment of uranium deposition probably was equally diverse; however, because many of the host rocks have been modified, reconstituted, or mineralized either before, during, or after the introduction of the uranium the true nature of the depositional environment remains essentially unknown.

In general, uranium-bearing veins are enclosed in alteration haloes that show no significant differences from the alteration haloes that enclose other kinds of vein deposits.

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