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Uranium in Precambrian Granitic Rocks of the St. Francois Mountains, Southeastern Missouri, with Comments on Uranium Resource Potential

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Abstract

Red granites of the St. Francois Mountains are highly radioactive and contain 4 to 34 parts per million (ppm) uranium. The most radioactive is the Graniteville Granite which contains an average of 16.9 ppm U and 42.6 ppm Th. The Butler Hill and Breadtray Granites also contain anomalous amounts, averaging 6.2 and 5.6 ppm U and 23.5 and 20.5 ppm Th respectively. Other Precambrian granitic rocks have normal concentrations of U and Th. Fission track "maps" indicate that high concentrations of uranium are associated with magnetite in the red granites; this uranium is presumed to be readily leachable by hydrothermal or supergene solutions.

No uranium minerals or ore grade concentrations of uranium were observed in or near the granites, but there are conceptual reasons for the possible existence of uranium deposits in intragranitic veins and onlapping Cambrian-Ordovician sedimentary rocks. Although the red granites constitute a good potential source of uranium, there is not much evidence for uranium having been mobilized. Identification of features such as lamprophyre dikes and "episyenite" alteration, or sedimentary rocks containing reductants, would be of value for exploration and would permit more favorable resource appraisal.

Introduction

Precambrian granitic rocks of the Western United States were analyzed by Malan (1972) and some units from the St. Francois Mountains were found to contain above average amounts of uranium. In May of 1976, the author investigated field relations of the granitic rocks and collected samples for further petrologic and chemical studies. The present work, combined with that of Malan (1972), suggests that the uranium resource potential of Precambrian and lower Paleozoic rocks in southeastern Missouri is greater than previously reported.

This resource study approaches the problem from a genetic perspective. No uranium minerals or ore-grade concentrations of uranium were observed, but there are several conceptual reasons for the existence of possible economic deposits of uranium. Relatively well known types of deposits in other parts of the world are used for comparison and resource estimation. This approach cannot yield quantitative estimates in this application, but effectively points out geologic features that need to be documented for further resource analysis or exploration.

Methods.--Field observations were made over a 6-day period in May 1976 and measurements made with broad band gamma scintillator and 4 channel Geometrics 400 A gamma spectrometer with 3x3 inch (7.6x7.6 cm) NaI crystal[1]. Channels of particular interest were eTH (^{208}Tl): peak 2.62 mev, window width 400 kev; eU (^{214}Bi): peak 1.76 mev, window width 200 kev. Counts were collected for 120 seconds. Cosmic background was determined on a wooden dock over water. Stripping functions were determined from samples analyzed by gamma spectrometry by Carl Bunker. Precision and acuracy have not been rigorously established but are probably about ±5 percent (2σ).

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[1]Use of brand names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

Petrographic studies were made of all samples submitted for chemical analysis to describe lithology and to check for alteration. Uranium distribution was determined through the use of fission track "maps" prepared by A. J. Bartel. A muscovite detector with very low uranium content was placed next to uncovered thin sections and induced fissions of ^{235}U produced in a reactor. Induced fission tracks were developed by etching for 15 seconds in 48 percent HF.

Geologic Setting

Precambrian igneous rocks[2] of the St. Francois Mountains (fig. 1) are part of the Midcontinent craton that has been unusually stable since the Precambrian. The igneous complex consists of acidic volcanic rocks and epizonal granitic intrusions. According to the most reliable isotopic dating methods, U-Pb ages of zircon, most of the igneous rocks crystallized about 1500±30 m.y. ago (Bickford, 1976; Bickford and Mose, 1975). Exceptions are the Munger Granite Porphyry (1400 m.y.) and younger (pre-Upper Cambrian) basaltic dikes. The oldest rocks are silicic ash-fall tuffs, air-fall tuffs, and flows of the Taum Sauk Mountain caldera whose aggregate thickness is greater than 6 km (Anderson, 1970; Berry, 1970; 1976). Intrusive into this volcanic pile was a suite of compositionally similar granitic rocks of the St. Francois Mountains batholith (Robertson, 1965; Tolman and Robertson, 1969; Kisvarsanyi, 1972). Geologic mapping by Tolman and Robertson (1969) outlined two suites of granites, the Musco and Bevos Groups, that were interpreted to represent different stages of intrusion. However, more detailed studies by G. Kisvarsanyi (1973) utilizing drill core indicate that the Slabtown and Stono Granites of the Musco Group are better interpreted to be marginal facies transitional with the Bevos Group.

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[2]Stratigraphic nomenclature used in this report is that of Robertson and Tolman (1969), which has been used by the Missouri Geological Survey since 1960.

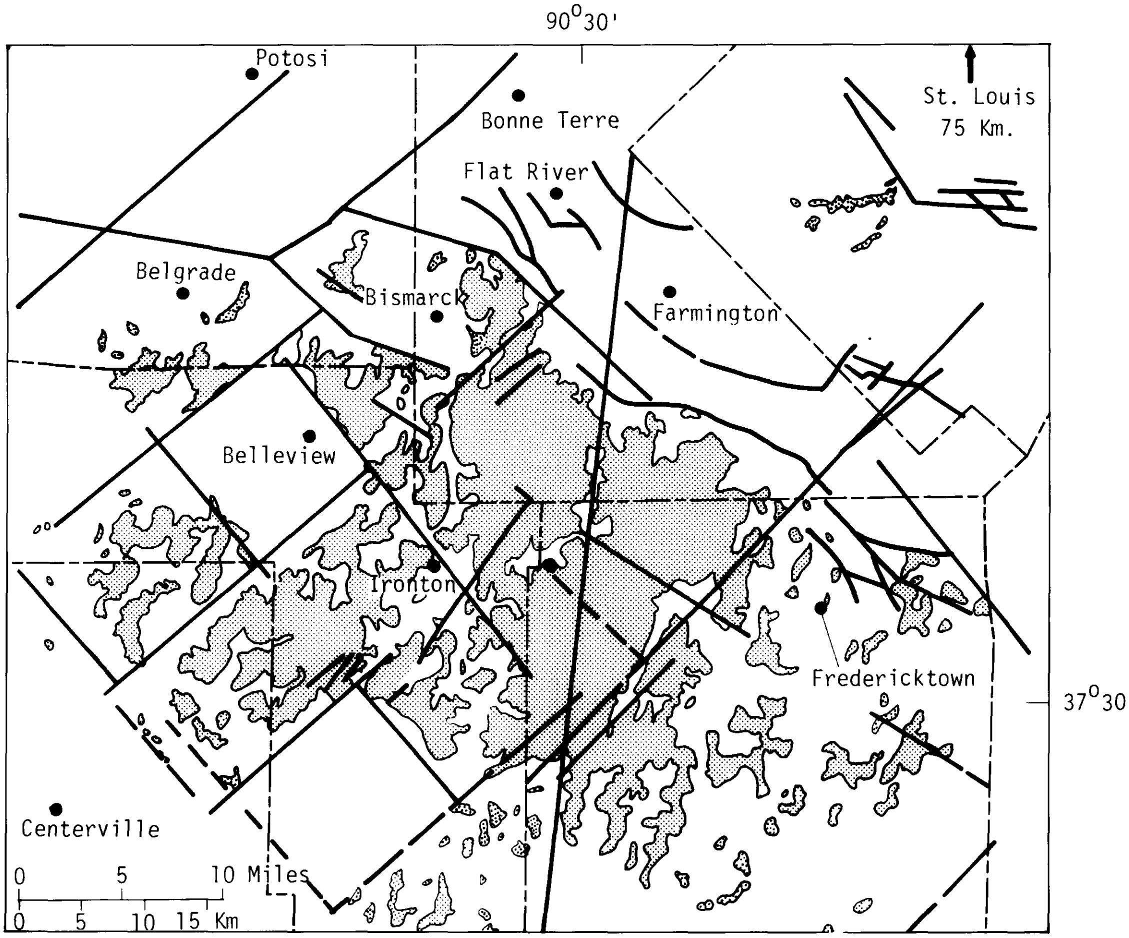


Fig. 1-- Map showing outcropping Precambrian rocks (stippled) and lineaments and mapped faults (heavy lines) in southeastern Missouri (after Kisvarsanyi and Kisvarsanyi, 1976B).

Isotopic studies (Bickford and Mose, 1975; Wenner and Taylor, 1977) indicate a period of hydrothermal activity that reset Rb-Sr ages at about 1300-1400 m.y.

Unconformably overlying the Precambrian igneous rocks are about 425 to 850 m of flatlying Upper Cambrian-Ordovician sedimentary rocks. The Upper Cambrian Lamotte Sandstone, consisting of conglomeratic arkose, sandstone, and redbrown shale, fills irregular depressions in the Precambrian surface. Overlying Upper Cambrian and Ordovician rocks are predominatly dolomite, some of which are important hosts for lead-zinc deposits. The sedimentary rocks have potential importance as host rocks for uranium deposits but only brief examinations have been made by the author.

Petrography of Granitic Rocks

Descriptions of the structure, petrography, and chemistry of intrusive rocks of the St. Francois batholith are available in several publications (e.g., Tolman and Robertson, 1969, Kisvarsanyi; 1972) and in several unpublished theses (Kisvarsanyi, 1976). The following is a summary of the major petrologic features that may pertain to uranium geochemistry. Nine units, eight of which were defined by Tolman and Robertson (1969), were examined and sampled. Of these, four are very similar in appearance and composition (Kisvarsanyi, 1972)--the Butler Hill, Breadtray, and Graniteville Granites, and the granite near Bismarck. These are very red to pink granites, with medium to medium-coarse grain size (1 to 10 mm), and contain very sparse mafic minerals. All have been quarried for dimension stone. Compositionally, these are very silicic, alkalic rocks that are true granites (table 1; see Kisvarsanyi, 1972 for more specific classifications). The peraluminous nature of the granites is expressed mineralogically by their lack of amphibole and by the presence of primary muscovite in the Graniteville. Most of the iron in these rocks is present as magnetite; biotite content is generally less than 2 volume percent. The Breadtray Granite and the granite

Table 1.--Summary of some petrochemical features of Precambrian granitic rocks.

(All data from Kisvarsanyi, 1972, p. 78-85. Normative minerals are from C.I.P.W. norms. Negative entry for corundum is equivalent to normative wollastonite)

	Modal	Normative		Minerals	
	Quartz	Corundum	Anorthite	Femics	Fluorite
Breadtray Granite (N=4)	36.0-39.2	0.41-2.0	0.56-1.39	1.7-3.7	0.23-0.55
Butler Hill Granite (N=5)	44.2-39.5	-.12-1.4	2.88-4.4	2.7-5.4	0 - .31
Graniteville Granite (N=3)	35.1-39.8	-1.18-1.3	0 -2.5	1.2-3.0	0 - .78
Knob Lick Granite (N=2)	19.8-30.7	-.23-3.2	7.5-13.3	9.0-10.4	0 - .16
Silvermine Granite (N=3)	25.3-26.8	.92-2.1	5.0- 7.5	5.3- 6.7	0 - .16
Stono Granite (N=1)	25.0	.70	3.3	8.6	.31
Slabtown Granite (N=5)	22.0-33.8	-.81- .92	1.6-4.2	4.3- 5.5	0
Brown Mountain Rhyolite Porphyry (N=1)	---	1.1	0	3.3	0

near Bismarck have well developed granophyric texture. Fluorite in amounts up to about 1 volume percent is common in these rocks, particularly in the Graniteville and Breadtray granites where it occurs dispersed through the matrix or in miarolitic cavities and veinlets.

The Slabtown, Stono, Silvermine, and Knob Lick Granites and Brown Mountain Rhyolite Porphyry are lithologically different from the previously described red granites: they are finer grained, generally porphyritic, and light gray to light brown in color. The Knob Lick, Stono, and Silvermine Granites contain green amphibole as well as biotite, whereas the Slabtown Granite and Brown Mountain Granite Porphyry contain only biotite. The Knob Lick, Stono, Silvermine, and Slabtown units contain much more plagioclase than the red granites, and are properly called quartz monzonite, or in places granodiorite. The Brown Mountain Rhyolite Porphyry is silicic-alkalic, similar in composition to the red granites.

The red granites, of chief interest here, have compositions and mineralogy typical of S-type granites as defined by Chappel and White (1974). S-type granitic rocks are interpreted to be derived by partial melting of sedimentary rocks, in contrast to I-type derived from igneous rocks. Chemical fractionation of sedimentary rocks results in the S-type granitic rocks being rich in aluminum, potassium, and silica relative to sodium, calcium, magnesium, and iron. By the S- and I-type classification, the hornblende-bearing Knob Lick, Stono, and Silvermine Granites would probably be I-type (or perhaps contaminated S-type) granites. Most uranium-rich granitic rocks are S-type, including the uranium-rich two-mica granites of France (e.g., Barbier and Ranchin, 1969).

Several mineralogical and textural features of the red granites indicate crystallization under volatile-rich conditions at high oxygen fugacity. The common miarolitic cavities and granophyric textures suggest that the magma became saturated in water and other volatiles during crystallization. Fluorite in miaroles and in the rock matrix is a record of high fluoride content. The fluorine also would stabilize muscovite and permit its crystallization at pressures of less than the 2 kilobars required for muscovite without fluorine, hence the muscovite is not incompatible with epizonal emplacement. The crystallization of iron in the minerals magnetite and hematite (presumably deuteric) rather than biotite or amphibole as in many granitic rocks probably reflects high oxygen fugacity. The high oxygen fugacity is a probable consequence of loss of hydrogen from the magma/fluid system following saturation with water (Czamanske and Wones, 1973). These chemical (F, O, H_2O) and pressure conditions seem favorable for separation of a uranium-rich post-magmatic hydrothermal fluid.

Uranium and Thorium in Granitic Rocks

Uranium and thorium contents of granitic rocks were determined by delayed neutron activation analysis and by use of a gamma spectrometer. Data for chemical determinations are in table 2. Field gamma spectrometric determinations are in table 3. The gamma spectrometer and broad band gamma scintillation counter were used to assess uniformity of radioelement distribution. Unless otherwise noted, determinations in tables 2 and 3 are typical fresh to very fresh rocks. Because many of the samples of rock are from relatively unfractured quarry sites, these data characterize uncommonly fresh rocks.

The chemical and radiometric data for uranium and thorium (tables 2 and 3) indicate that the Graniteville, Butler Hill, and Breadtray Granites contain more uranium than the mean of 4.7 ppm for Precambrian granites in the Western United States (Malan, 1972). The Graniteville Granite contains more thorium than the mean (37.8) of Precambrian granites, but all others contain considerably less. The very low thorium contents of the Knob Lick, Silvermine, Stono, and Slabtown Granites and the Brown Mountain Rhyolite Porphyry are particularly notable. The data from this study confirm the findings of Malan (1972) on samples of plutonic and volcanic rocks supplied by

Table 2.--Uranium and thorium content of some granitic rocks from St. Francois Mountains

(Analyses by delayed neutron activation, H. T. Millard, analyst)

Sample No.	Rock Unit	U (ppm)	Th (ppm)	Th/U
1	Graniteville	19.6	46.0	2.35
2	Breadtray	8.29	23.3	2.81
3	Brown Mountain	3.61	10.2	2.83
4	Breadtray	2.29	5.73	2.51
6	Knob Lick	3.31	8.54	2.58
7	Butler Hill	7.55	23.4	3.10
8	Slabtown	3.33	8.77	2.63
9	Graniteville	11.6	39.5	3.41
10	Graniteville	7.41	25.7	3.48
11	Graniteville	9.99	35.33	3.54
12	Graniteville	9.43	38.93	4.13
13	Graniteville	23.9	47.4	1.98
14	Graniteville	20.6	54.7	2.66
15	Graniteville	34.4	54.0	1.57
16	Graniteville	18.2	37.1	2.04
17	Bismark	4.81	16.0	3.32
18	Bismark	3.90	13.8	3.56
19	Stono	2.85	7.77	2.73
21	Stono	2.97	8.70	2.93
22	Breadtray	6.31	17.0	2.69

Table 2.--Uranium and thorium content of some granitic rocks from St. Francois Mountains--continued

Sample No.	Rock Unit	U (ppm)	Th (ppm)	Th/U
23	Breadtray	5.68	24.8	4.36
27	Butler Hill	5.65	24.9	4.40
29	Butler Hill	5.06	20.2	4.00
30	Breadtray	6.24	24.3	3.90
31	Breadtray	4.89	22.6	4.63
32	Breadtray	5.82	26.1	4.49
33	Silvermine[1]	2.64	11.3	4.27
34	Silvermine[1]	1.78	16.2	9.13
35	Silvermine, tan	2.12	5.60	2.64
37	Butler Hill	6.19	25.0	4.04
38	Butler Hill	5.34	23.2	4.33
39	Knob Lick	2.51	8.37	3.34
40	Butler Hill	7.54	24.6	3.26
41	Knob Lick	4.56	9.41	2.06
42	Graniteville	14.7	47.5	3.23

Statistics

No. of Samples	Unit	Uranium (ppm)		Thorium (ppm)	
		mean	std. dev.	mean	std. dev.
10	Graniteville	16.9	8.2	42.6	9.0
7	Breadtray	5.65	1.8	20.5	7.2
6	Butler Hill	6.19	1.0	23.5	1.8

Table 2.--Uranium and thorium content of some granitic rocks from St. Francois Mountains--continued

Statistics--continued

No. of Samples	Unit	Uranium (ppm) mean	Uranium (ppm) std. dev.	Thorium (ppm) mean	Thorium (ppm) std. dev.
2	Bismark	4.36	0.6	14.9	1.5
3	Knob Lick	3.46	1.0	8.76	0.6
1	Slabtown	3.33	---	8.77	---
2	Stono	2.91	0.1	8.24	0.6
3	Silvermine	2.19	0.4	6.33	2.5
1	Brown Mountain	3.61	---	10.2	---

[1]"Blue granite", feldspar completely replaced by sericite.

Table 3.--Field Gamma Spectrometric analyses for Uranium and Thorium, St. Francois Mountains

(Units: Bb, Breadtray granite; Bbi, Bismark granite; Bg, Graniteville granite; Bh, Butler Hill granite; Bk, Knob Lick granite; Bs, Silvermine granite; Mst, Stono granite.
Location: Code explained in Appendix 1.)

Number	Unit	Location		eU (ppm)	e Th (ppm)	Comments
G1-----	Bg	34-3E:	15ada	8	45	Outcrop, Elephant Rocks State Park.
G2-----	Bg	--do--		8	42	Do.
G3-----	Bg	--do--		8	39	Outcrop.
G4-----	Bg	--do--		10	40	Do.
G5-----	Bg	--do--		7	39	Do.
G6-----	Bg	--do--		9	38	Do.
G7-----	Bg	--do--		9	38	Do.
G8-----	Bg	--do--		9	46	Do.
G9 ----	Bg	--do--		8	36	Do.
G10----	Bg	34-3E:	14bbc	9	42	Quarry bench.
G11----	Bg	34-3E:	14bbc	9	35	Quarry bench.
G12----	Bg	34-3E:	14bcb	7	32	Do.
G13----	Bg	34-3E:	15aad	6	31	Do.
G14----	Bg	--do--		6	34	Do.
G15----	Bg	--do--		9	39	Do.
G16----	Bg	--do--		11	42	Do.
G17----	Bg	--do--		11	39	Do.
G17a---	Bg	34-3E:	22dab	13	32	Do.

Table 3.--Field Gamma Spectrometric analyses for Uranium and Thorium, St. Francois Mountains--continued

Number	Unit	Location	eU (ppm)	e Th (ppm)	Comments
G18-----	Bg	--do--	12	30	Quarry Bench.
G19-----	Bg	--do--	13	34	Do.
G20-----	Bg	34-3E: 22dab	12	30	Quarry, sample 10.
G21-----	Bg	34-3E: 22dba	9	22	Outcrop above quarry.
G22-----	Bg	--do--	12	33	Quarry, sample 12.
G24-----	Bg	34-3E: 10add	16	42	Quarry, sample 14.
G25-----	Bg	--do--	16	41	Do.
G26-----	Bg	--do--	18	53	Do.
G27-----	Bg	--do--	18	47	Quarry, sample 15.
G28-----	Bg	--do--	19	45	Quarry, pegmatite pod.
G29-----	Bbi	36-4E: 20cb	3	13	Quarry.
G30-----	Bbi	--do--	3	13	Do.
G31-----	Bbi	--do--	3	13	Do.
G32-----	Mst	35-4E: 24ccd	2	7	Outcrop.
G33-----	Mst	--do--	2	7	Do.
G34-----	Mst	--do--	2	7	Do.
G35-----	Bb	35-4E: 36cdb	4	16	Roadcut.
G36-----	Bb	--do--	4	15	Do.
G37-----	Bb	35-4E: 36cda	4	17	Roadcut, near sample 22.
G38-----	Bb	--do--	3	16	Do.
G39-----	Bb	--do--	4	15	Do.

Table 3.--Field Gamma Spectrometric analyses for Uranium and Thorium, St. Francois Mountains--continued

Number Unit	Location	eU (ppm)	e Th (ppm)	Comments
G40-----Bb	34-5E: 6dcb	5	18	Outcrop, near sample 23.
G41-----Bb	--do--	5	17	Do.
G42-----Bb	34-5E: 32dcc	1	6	Outcrop.
G42N----Bb	34-5E: 32aab	4	16	Do.
G43-----Bh	35-5E: 36bb	4	19	Roadcut, near sample 27.
G44-----Bh	--do--	4	21	Do.
G45-----Bh	35-5E: 36ca	4	21	Outcrop.
G46-----Bh	35-5E: 35da	4	18	Do.
G47-----Bh	34-5E: 4da	4	16	Roadcut, sample 29.
G48-----Bh	--do--	4	15	Do.
G49-----Bb	35-5E: 32cbb	5	14	Outcrop.
G50-----Bb	35-5E: 29abb	5	15	Outcrop, sample 31.
G51-----Bb	--do--	4	18	Do.
G52-----Bb	--do--	5	14	Do.
G53-----Bb	--do--	6	14	Do.
G54-----Bb	35-4E: 24aac	5	15	Outcrop, sample 32.
G55-----Bb	--do--	5	13	Do.
G56-----Bb	35-4E: 36acd	6	15	Quarry, sample 2.
G57-----Bb	--do--	8	18	Do.
G58-----Bb	--do--	8	17	Do.
G59-----Bb	--do--	7	18	Do.

Table 3.--Field Gamma Spectrometric analyses for Uranium and Thorium, St. Francois Mountains--continued

Number Unit	Location	eU (ppm)	e Th (ppm)	Comments
G60-----Bb	35-4E: 36acd	6	16	Outcrop at quarry.
G61-----Bb	--do--	6	16	Do.
G62-----Bb	--do--	6	17	Do.
G63-----Bs	33-5E: 12dd	2	6	Outcrop.
G64-----Bs	--do--	1	6	Do.
G65-----Bs	--do--	1	5	Do.
G66-----Bs	33-5E: 13ab	1	5	Do.
G67-----Bs	33-5E: 12dc	1	7	Do.
G68-----Bs	33-5E: 12cd	1	6	Outcrop, near sample 35.
G69-----Bh	33-5E: 1ac	4	19	Outcrop, weathered near sample 37.
G70-----Bh	34-5E: 35ba	4	21	Outcrop.
G71-----Bh	34-5E: 25aa	3	14	Outcrop, near sample 38.
G72-----Bh	34-6E: 5cb	4	18	Outcrop.
G73-----Bh	--do--	5	23	Do, aplite dike.
G74-----Bh	--do--	5	20	Outcrop.
G75-----Bh	--do--	4	18	Do.
G76-----Bk	34-6E: 9bc	1	7	Do.
G77-----Bk	--do--	1	7	Do.
G78-----Bk	--do--	1	7	Do, weathered.
G79-----Bk	34-6E: 9bb	1	6	Outcrop next to quarry.

Table 3.--Field Gamma Spectrometric analyses for Uranium and Thorium, St. Francois Mountains--continued

Number	Unit	Location	eU (ppm)	e Th (ppm)	Comments
G80-----	Bk	36-6E: 9bb	2	9	Quarry.
G81-----	Bg	34-3E: 11cdb	5	35	Outcrop above quarry.
G82-----	Bg	--do--	13	58	Quarry bench, 5 m below unconformity.
G83-----	Bg	--do--	11	52	Do.
G84-----	Bg	--do--	11	45	Do.
G85-----	Bg	--do--	13	56	Do, repeat no. 82.
G86-----	Bg	--do--	10	42	Do, 3 m below unconformity.

A. W. Berry.

The Graniteville Granite is very rich in uranium, approximately four times richer than most granitic rocks (Nishimori and others, 1977). The eastern zone of samples in sections 10 and 11 (see appendix 1 for locations) contain an average of 21.9 ppm U and 47.8 ppm Th (table 2), which is extremely high. Among the samples analyzed, only sample 15 selected for its aplitic texture and higher radioactivity, is atypical of large areas of the granite. None are known to be enriched in primary or secondary uranium minerals.

The radioactivity of the granitic rocks is very uniform over large areas. This conclusion is based on broad band scintillometer readings and spectrometer measurements (table 3). I observed only a few anomalously high radioactivities, (such as G-26, and G-27, table 3). In several quarries it was possible to obtain vertical profiles from various benches that satisfied quite well 2π geometry requirements. These measurements suggest leaching of about 3 to 5 ppm U (about 30 percent) from the Graniteville Granite and about 2 ppm (about 25 percent) from the Breadtray Granite in the 5 to 10 m interval below the surface. The leaching could have occurred in the Precambrian-Cambrian or in recent times. The magnitude of this leaching has resource implications that will be considered later.

Petrography of Uranium in Granitic Rocks

Distribution of uranium in rocks can be effectively established through the use of induced fission track "maps" in which fission of ^{235}U induced in a reactor is recorded in a muscovite detector placed next to an uncovered thin section. The fission tracks, which appear as fine dark lines when etched, record the location and approximate quantity of uranium in the rock. Quantitative analysis is possible but was not attempted here. Qualitative studies were made on 23 fission track map preparations that included all of the rock types analyzed (table 2) except Brown Mountain Rhyolite Porphyry.

Several mineralogical associations of uranium are demonstrated by the fission track maps. In all the rocks studied there was a very strong coincidence of fission tracks with magnetite grains (fig. 2). High density of fission tracks, that appear dark in transmitted light (fig. 2), produces a pattern that essentially is an exact copy of the magnetite crystals. In several examples the tracks form an outline around magnetite crystals. It is not possible to determine optically if there is a uranium mineral present. From the track patterns and density, I interpret that the uranium concentraion is higher than several hundred parts per million and that the uranium must be present either in the magnetite lattice or as a mineral with the appearance of magnetite--which would logically be uraninite--that is very fine grained (less than 5 micrometers). Microprobe studies may help resolve this problem. However, it is very clear that there is a strong uranium-magnetite association. Judging from track density and distrubution across thin sections, it is evident a large amount of the uranium in these granitic rocks is associated with magnetite. Magnetite separated from sample 42 contains 51 ppm uranium by chemical analysis (F. N. Ward, written commun., 1977).

Zircon crystals are represented by dense fission tracks as might be expected. Track density is comparable to that associated with magnetite. At the neutron flux used, the track density is too great to resolve individual tracks, hence no reliable estimates of uranium content can be made. Because zircon is not very abundant in these rocks, only a small part (5 percent?) of the total rock uranium can be held in zircon.

Biotite crystals produce moderate density of fission tracks (fig. 2a, 2b). Uranium seems to be uniformly distributed through the biotite. Biotite probably contains about 10 percent of the total rock uranium in those rocks containing fresh biotite. Very commonly biotite is replaced by chlorite, and the chlorite contains much less uranium than biotite.

Figure 2.--Photographs of fission track maps showing the distribution of uranium in granitic rock samples.

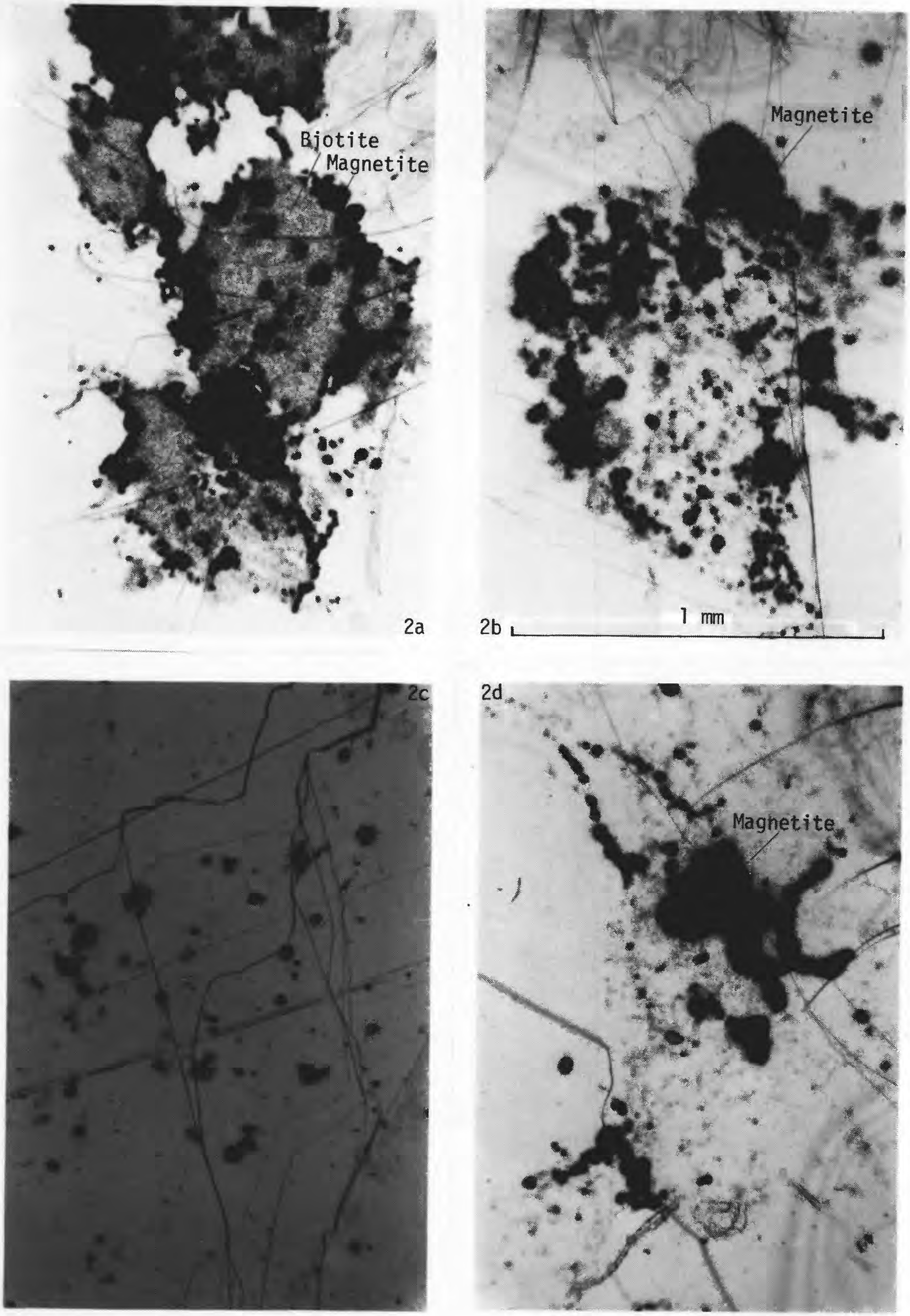
Figure 2A--Sample 14, Graniteville Granite. Dark areas are produced by high track density coincident with magnetite; gray areas have moderate track density and coincide with biotite.

Figue 2B--Sample 27, Butler Hill Granite. Black areas with high track density correlate with magnetite and gray areas correlate with portions of biotite.

Figure 2C--Sample 15, aplitic textured sample of Graniteville granite. Dark spots correlate with magnetite disseminated through the rock.

Figure 2D--Sample 13, Graniteville Granite. Dark areas coincide with magnetite.

Scale on all photos is the same and length of bar is equal to 1 mm.


Biotite
Magnetite
2a
Magnetite
2b
1 mm
2c
2d
Magnetite

Other primary silicate minerals (amphibole, plagioclase, K-feldspar, muscovite) contain very small amounts of uranium and produce only small numbers of fission tracks. These minerals must contain less than about 1 ppm uranium.

Fluorite in the red granites produces characteristic track patterns as shown in figure 3b. It is evident that the fluorite per se contains only moderate amounts of uranium, but reddish iron oxides within the fluorite produce dense tracks. The total contribution of uranium in fluorite, including iron oxides within fluorite, to total rock uranium in the red granites probably is less than 5 percent.

Red iron oxides, which will be termed hematite hereafter, in feldspars and on grain boundaries--the source of red coloration in the granites--generally contain minor amounts of uranium. In portions of a few samples high track densitites correlate with secondary hematite; in these locations the uranium seems to have migrated and been localized by the hematite.

Approximately one fourth of the fission track maps display textures which I interpret to indicate movement and redeposition of uranium. Track patterns that have thin linear form coincident with cracks and grain boundaries (fig. 3c) or are associated with minerals having textures indicative of recrystallization of replacement (fig. 3d) are intepreted to reflect redeposited uranium. Tracks that outline magnetite crystals, rather than being uniformly distributed over the crystal, also probably record mobilized uranium. Most track patterns mimic textures of igneous minerals, hence probably reflect the distribution of primary or magmatic uranium. However, many track patterns seem to reflect epigenetic redistribution of uanium. The interpretation that uranium has moved within many granite samples has implications to the possibility that uranium deposits formed in or near these rocks.

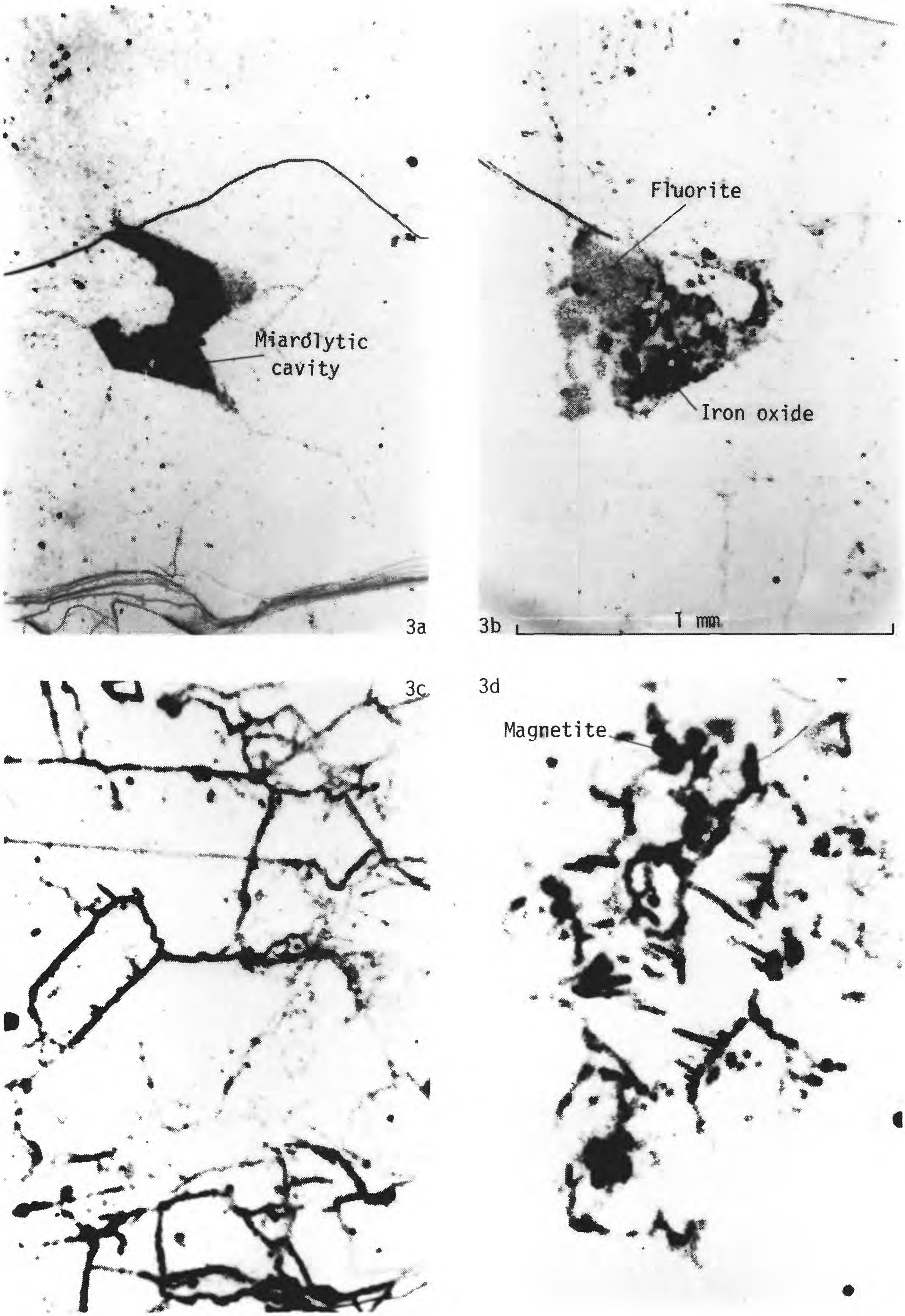
Figure 3.--Photographs of fission track maps showing the distribution of uranium in samples of granitic rocks. Scale in all photos is the same; the bar scale is 1 mm long.

Figure 3A--Sample 42, Graniteville Granite. The dark area coincides with a miarolytic cavity.

Figure 3B--Sample 42, Graniteville Granite. The central area coincides with fluorite, which produces moderate track density (gray). The dark spots coincide with iron oxide grains occluded within the fluorite.

Figure 3C--Sample 12, Graniteville Granite. Dark areas coincide with crystal boundaries, some of which contain hematite. This pattern suggests redistribution of uranium into cracks and crystal boundaries.

Figure 3D--Sample 10, Graniteville Granite. The dark round and rod shapes coincide with magnetite. This pattern might be produced by redistribution of uranium as magnetite recrystallized.


Miarolytic
cavity
3a
3b
1 mm
Fluorite
Iron oxide
3c
3d
Magnetite

Uranium Resource Potential

Missouri has generally been considered to have very low uranium resource potential (e.g., Butler, 1967, Southern Interstate Nuclear Board, 1969). Only Pennsylvanian black shales had been noted to have resource potential, and those rocks grade 0.01 to 0.001 percent uranium. My observations, supplementing those of Malan (1972), point out the possibility of uranium resources associated with Precambrian granitic rocks. The major resource and exploration questions remain: what types of deposits should be considered and where might they occur? Let us consider four types of uranium deposits: (1) "porphyry"-type deposits; (2) intragranitic veins; (3) accumulations near the unconformity; and (4) accumulations in onlapping lower Paleozoic sedimentary rocks.

The term "porphyry"-uranium deposit has been applied by Armstrong (1974) to low grade, large tonnage deposits in granitic rocks that have engineering aspects comparable to the porphyry copper deposits. The type example is the large deposit at Rössing, Namibia (South West Africa). The Rössing deposit is in migmatitic granitic rocks (Berning and others, 1976; Nishimori and others, 1977) that formed at depths much greater than the granites in the St. Francois Mountains. Because the Missouri granites are epizonal in character, they do not seem capable of forming "porphyry"-uranium deposits.

Another possible uranium resource environment is that of intragranitic veins similar to those in the Massif Central of France (Gangloff, 1970; Moreau, 1977). If such veins were to occur they can be expected to have simple mineralogy (chiefly pitchblende, chalcedony, pyrite, marcasite, and fluorite) with minor base metal content. The vein deposits probably would be relatively small; vertical extent about 100 to 300 m and uranium content roughly 1 to 10 million pounds (0.5 to 4.5 million kg). The lineaments described by Kisvarsanyi and Kisvarsanyi (1976A, 1976B, fig. 1), that generally bound exposed Precambrian rocks, but in many places cross them, could be the sites of faults or shears suitable to intragranitic veins. The French deposits are characteristically associated with episyenite (desilicified and alkali metasomatized granite) and lamprophyre dikes; I am not aware of these features in the St. Francois Mountains but they could be sought in exploration. A comparison of the tectonics and geochemistry of the French and St. Francois Mountains granitic terranes would be useful for exploration or resource appraisal. Based on available data and my limited understanding of the area, I judge that there is some small potential for intra-granitic vein deposits. The plutonic rocks are favorable and there is indirect evidence for appropriate structures, but evidence for "episyenite" or other locally intense hydrothermal alteration and migration of uranium is lacking. The granites also seem to lack appropriate fracturing and foliation to fit the French model.

Two other conceptual environments for uranium deposits are related to surficial processes operating when the uraniferous granites were at or near the surface during the late Precambrian or early Paleozoic. In one concept uranium is envisioned to accumulate in or near the regolith or in fracture zones below the unconformity. The term "unconformity deposits" has been used by Canadian geologists (Beck, 1977), for this environment and the genetic model was applied to the Rabbit Lake, Saskatchewan deposit (Kipping, 1974). The other possible environment is syngenetic or epigenetic accumulation of uranium in Paleozoic sedimentary rocks such as the Cambrian Lamotte Sandstone.

There is currently (1977) a great dispute over the supergene genesis of many uranium deposits located immediately below unconformities in Canada and Australia (Beck, 1977; Morton, 1977). Although I side with the previously cited authors in favoring a metamorphic/hydrothermal genesis for these deposits, let us consider the supergene hypothesis (c.f. Kipping, 1974). The major requisites for this genesis include (1) source of uranium; (2) weathering of source rocks; (3) structural or sedimentary permeability to create a trap; and (4) reductant or chemical precipitant. We have established item 1. Item 2 is poorly fulfilled as there is not much of a regolith on the unconformity. Field measurements suggest that leaching of uranium did not extend far below the unconformity (about 10 m). Likely structural traps are not exposed but could be along the lineaments described by Kisvarsanyi and Kisvarsanyi (1976A, 1976B). Reducing pyritic or graphitic metasediments do not occur below the unconformity but are important in major unconformity-type deposits of Canada and Australia. I am not aware of anomalous amounts of elements such as phosphorus or vanadium in mobile form that could cause precipitation of hexavalent uranium minerals such as autunite or carnotite. Considering these four parameters, number 1 is rated high, number 2 is rated low (and in a large sense negates number 1), number 3 is poorly known and considered questionable, and number 4 is not met, although local deposits of hexavalent uranium minerals might be possible. In summary, I estimate that only small, local uranium deposits should be expected to occur near the unconformity.

The fourth possible environment for uranium is syngenetic or epigenetic deposits in Paleozoic sedimentary rocks onlapping the Precambrian. Several types of deposits could form in clastic and carbonate host rocks. Sedimentary uranium deposits require two fundamental genetic components in addition to a source rock: (1) hydrology that could carry uranium from the source rock to sites of deposition; and (2) a precipitation agent, generally a reductant. Because the granitic basement was positive structurally during the Paleozoic, it seems quite likely that in some areas ground water flow could have been outward from the granitic rocks into sedimentary basins. I cannot further refine this gross estimate in terms of possible paleochannels. The major problem for the formation of sedimentary uranium deposits would be the chemical environment required to precipitate uranium. The Cambrian Lamotte Sandstone, a sandstone and conglomerate 0 to 150 m thick that unconformably overlies the Precambrian rocks, would seem to be a prime host rock. The Lamotte has been considered to be a marine deposit

(Ojakangas, 1963), but recently has been reinterpreted to be an alluvial sequence of fan and braided fluvial deposits capped by thin marginal marine deposits (Houseknecht and Ethridge, 1977). The fluvial nature of most of the Lamotte would seem to make it a favorable host for uranium deposits, but the rocks are generally reddish and to my knowledge contain only small amounts of pyrite in a few localities. Reduced uranium deposits do not seem likely for the Lamotte, but oxidized deposits might be possible.

Carbonate rocks are generally considered unfavorable for uranium deposits of economic importance, but one possibility exists in the Mississippi Valley-type environment of lead-zinc sulfide deposits. Very speculatively, uranium-bearing ground water coming from the Precambrian granites might deposit uranium at the interface of mixing with sulfide- and sulfate-rich brines (Heyl and others, 1974) in the carbonate rocks. Lead and zinc might be deposited with the uranium. This speculation is keyed to reductants in the brine. To date only a few local occurrences of pitchblende are known from Mississippi Valley deposits in Missouri (A. V. Heyl, oral commun., 1976). The size of potential deposits in Paleozoic carbonate rocks cannot be estimated as none are known to exist anywhere, but their geometry would presumably be tabular and controlled by sedimentary features.

Conclusions

The Graniteville, Butler Hill, and Breadtray Granites are enriched in uranium and should be considered as potential source rocks for uranium deposits. Because much of the uranium is in a mineralogical association that allows leaching, and because the granites are in an oxidized state, uranium could have been extracted by supergene or hydrothermal solutions in some places. However, there is little evidence for uranium having been leached in large quantities over large areas. Potential resources of uranium appear to be small but possible in French-type intragranitic veins or in tabular deposits in Paleozoic sedimentary rocks. Explorationists in southeast Missouri should be alert for lamprophyre dikes and "episyenite" alteration as possible guides to vein deposits, and should check for radioactivity in drill holes or drill hole samples from lead-zinc exploration programs. More data on the distribution of pyrite in Paleozoic rocks would be of value in outlining possible zones favorable for uranium reduction.

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Appendix 1.—Sample locations, St. Francois Mountains.

Number	Unit	Location[1]	Comments
1	Bg	34-3E: 11 cdb	Quarry, chips, recently blasted.
2	Bb	35-4E: 36 acd	Quarry.
3	Bbm	33-4E: 1 db	Outcrop.
4	Bb	33-5E: 4 ad	Roadcut.
6	Bk	34-5E: 8 aa	Quarry.
7	Bh	34-5E: 5 cb	Quarry, a bit weathered.
8	Ms	34-5E: 35 a	Roadcut, somewhat weathered.
9	Bg	34-3E: 22 dab	Quarry.
10	Bg	34-3E: 22 dab	Quarry.
11	Bg	34-3E: 22 dab	Quarry.
12	Bg	34-3E: 22 dba	Quarry.
13	Bg	34-3E: 10 add	Quarry NE corner, recently
14	Bg	34-3E: 10 add	Quarry SE corner, very coarse.
15	Bg	34-3E: 10 add	Quarry SE corner, aplitic.
16	Bg	34-3E: 10 add	Quarry SW corner, recently blasted.
17	Bbi	36-4E: 20 cb	Quarry, chips.
18	Bbi	36-4E: 20 cb	Quarry, chips.
19	Mst	35-4E: 24 ccd	Outcrop.
21	Mst	35-4E: 25 bdd	Roadcut.
22	Bb	35-4E: 36 cda	Roadcut, recently blasted.
23	Bb	34-5E: 6 dcb	Roadcut.
27	Bh	35-5E: 36 bb	Roadcut, recently blasted.
29	Bh	34-5E: 4 da	Roadcut, near contact Bb/Bh.
30	Bb(Bh?)	35-5E: 29 bdc	Roadcut.
31	Bb(Bh?)	35-5E: 29 abb	Outcrop.
32	Bb(Bh?)	35-4E: 24 aac	Outcrop.
33	Bs	33-5E: 12 dc	Outcrop, altered "blue granite."
34	Bs	33-5E: 12 cd	Mine dump, altered "blue granite."
35	Bs	33-5E: 12 cd	Roadcut.
37	Bh	33-5E: 1 ac	S side Rt 72; mapped as Bs.

Appendix 1.--Sample locations--continued

Number	Unit	Location[1]	Comments
38--------	Bh	34-5E: 25 aa	Outcrop.
39--------	Bk	34-6E: 4 bcb	Quarry, SE corner.
40--------	Bh	34-6E: 5 ac	Quarry, NW corner.
41--------	Bk	34-6E: 9 bb	Quarry, SW corner.
42--------	Bg	34-3E: 11 cdb	Quarry dump, recently blasted.

[1]Location scheme is that employed by Missouri Geological Survey in which letters stand for fractional quarters of a section. The location 34-3E: 11 cdd is the same as NW1/4SE1/4SE1/4 sec. 6, T. 34 N., R. 3 E., and shown below: