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A Model of Uranium Mineralization in the Dripping Spring Quartzite, Gila County, Arizona

by

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ABSTRACT

Stratabound uranium occurrences are found in the upper part of the Dripping Spring Quartzite, a formation in the Proterozoic Apache Group of central Arizona. Proterozoic diabase sills intrude the Dripping Spring Quartzite and are in the vicinity of uranium occurrences. The upper part of the Dripping Spring Quartzite is a potassium feldspar-rich carbonaceous siltstone, deposited in a saline, nearshore to intertidal or lacustrine environment. Diagenesis/low-grade metamorphism and contact metamorphism have extensively altered the rock, which was originally volcaniclastic.

Uranium occurrences in the Dripping Spring Quartzite are sedimentary concentrations that have been modified and remobilized by later igneous intrusions and chloritic alteration. Primary concentration of uranium was controlled by diagenetic processes, which were responsible for derivation of uranium from the volcaniclastic rocks and for uranium transport. Uranium was precipitated and adsorbed where fluids encountered zones that had abundant carbonaceous matter, pyrite, altered iron-titanium and iron-oxides, and changes in pH. Primary uranium concentrations were remobilized during intrusion of diabase sills. A later chloritic alteration event also caused some remobilization and replacement of uraninite by coffinite.

The Dripping Spring Quartzite uranium occurrences are examples of sedimentary concentrations that have been modified by later igneous and metamorphic events. They may be used as a model for the intermediate stages of uranium concentration, situated between sedimentary low-grade deposits and highly remobilized and concentrated deposits, such as those found in the Alligator Rivers region of Australia.

INTRODUCTION

Uranium occurrences in the Dripping Spring Quartzite have been known since the 1950's. During the 1950's, more than 100 occurrences were identified by exploration, although less than 20 produced ore for shipment. Field examinations and studies of the uranium occurrences were conducted during this period of active exploration and mining. Publications based on more recent work on the uranium occurrences are lacking.

The uranium occurrences are in the Dripping Spring Quartzite of Proterozoic age, in a stratigraphic unit containing abundant carbonaceous matter and pyrite. Uranium is both disseminated and in veinlets. Proterozoic diabase sills intrude the Dripping Spring Quartzite and are commonly in the vicinity of uranium occurrences.

The origin of the uranium in the Dripping Spring Quartzite has been the subject of controversy. Granger and Raup (1969b), impressed by the spatial relationship between the uranium occurrences and diabase intrusions, proposed that the uranium was derived from the diabase. Williams (1957) noted the stratabound character of the ore, and hypothesized remobilization of sedimentary uranium concentrations. A preliminary model presented in this paper favors primary uranium concentration occurring during extensive diagenesis, with later remobilization associated with diabase intrusion and chlorite alteration.

This work is primarily based on samples that H. C. Granger collected during his field studies and on core samples from Wyoming Mineral Corporation drill holes. Both the core samples and the majority of Granger's ore samples are from the Workman Creek area. Although the Workman Creek area is more highly contact metamorphosed than some, the stratigraphic position and form of

the uranium occurrences are similar throughout the area. Conclusions, with local modifications, should be applicable to the area as a whole.

Previous work

The most detailed work on the Dripping Spring Quartzite and related uranium occurrences was done by Granger and Raup (1964,1969a,1969b). Neuerburg and Granger (1960) discussed the possibility of diabase as the source of uranium. Williams (1957) worked on the structural controls and genesis of the uranium deposits. Schwartz (1978) wrote a summary paper on the uranium occurrences. Otton and others (1980) and Bergquist and others (1980) identified mineral resources of the area and mapped rock units.

Acknowledgments

This study was greatly aided by the cooperation of Wyoming Mineral Corporation, who allowed examination and sampling of their core. Harry Granger was most helpful, giving free access to his samples, discussing the uranium occurrences, and sharing his knowledge of the area. I would like to acknowledge the thorough and helpful reviews of the formal reviewer, Harry Granger, and the informal reviewers, Rich Reynolds and Rick Sanford.

SETTING

The Dripping Spring Quartzite and associated uranium deposits are in the Sierra Ancha region of central Arizona (fig. 1). Nearly all uranium occurrences in the Dripping Spring Quartzite are within Gila County, although the areal extent of the Dripping Spring Quartzite is more extensive. The region of interest is in the southern section of the Colorado Plateau province, in a zone transitional to the Basin and Range province to the south

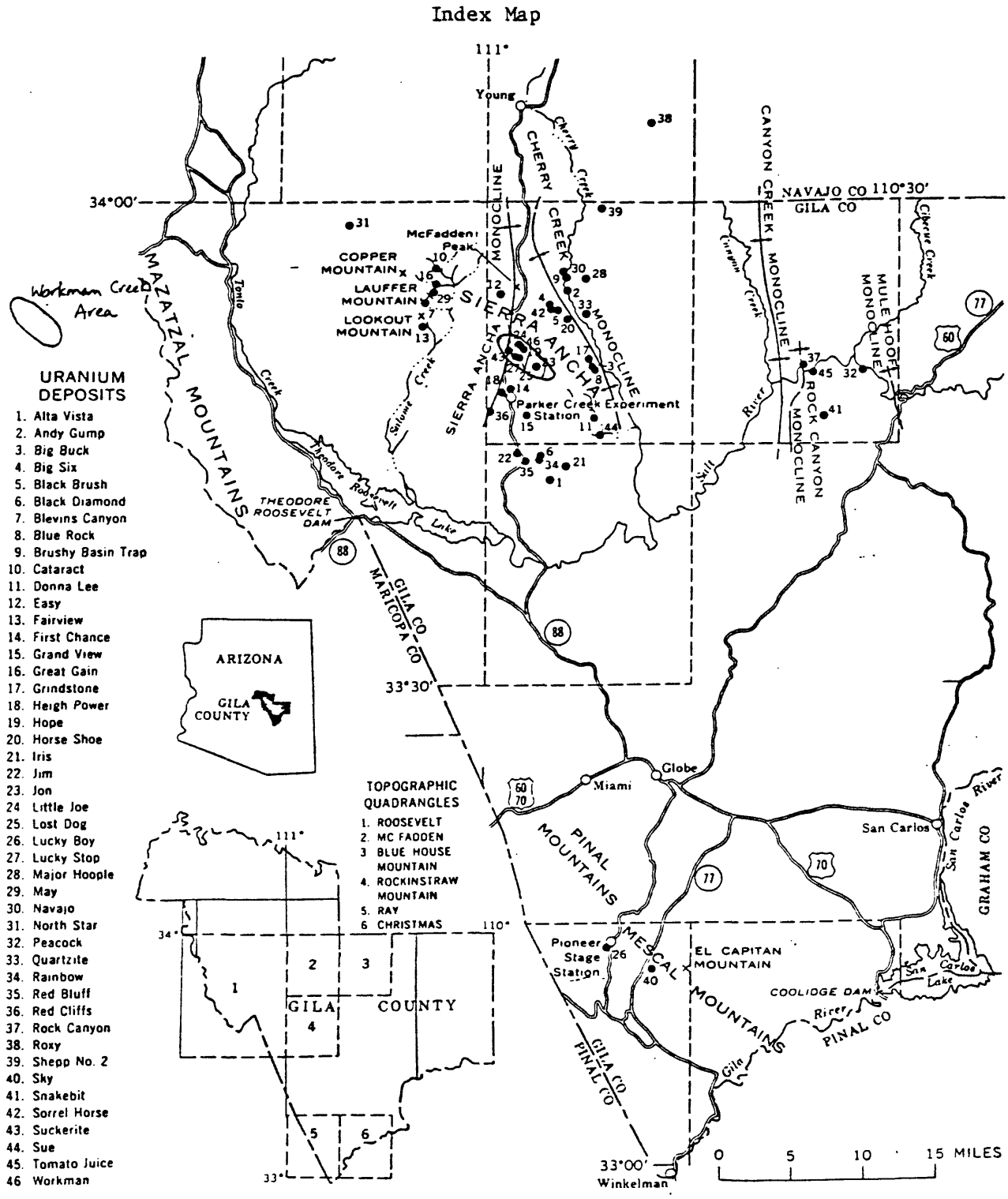


Figure 1.--Index map of part of Gila County, Arizona, showing location of monoclines and uranium deposits. From Granger and Raup (1969b).

(Hayes, 1969). As is typical throughout the Colorado Plateau province, sedimentary beds are nearly horizonal except where they are affected by monoclines, the major structural features of the area.

The Dripping Spring Quartzite is part of the Apache Group of Proterozoic age (fig. 2). The Apache Group is a sedimentary sequence consisting of the Pioneer Formation, the Dripping Spring Quartzite and the Mescal Limestone. Descriptions of the Pioneer and Mescal are from Shride (1967), Granger and Raup (1964,1969b) and Bergquist and others (1980). Description of the Dripping Spring Quartzite is based on thin-section examination and Granger and Raup (1964, 1969b). Diabasic sills intrude Apache sections throughout the area. The Apache Group is overlain by the Troy Quartzite, also of Proterozoic age. Underlying the Apache Group are older Precambrian gneissic and granitic rocks.

STRATIGRAPHY

Rocks of the Apache Group, other than the Dripping Spring Quartzite

Pioneer Formation

The Pioneer Formation, 30-85 m thick, nonconformably overlies the older Proterozoic metamorphic and granitic basement. It is composed of arkosic and feldspathic sandstone and tuffaceous siltstone. Devitrified glass shards, replaced by muscovite and chalcedony, have been identified (Gastil, 1954). The basal sequence of the formation is the Scanlan Conglomerate Member, composed of quartzite pebbles and cobbles in an arkosic matrix.

Stratigraphic Section of the Apache Group

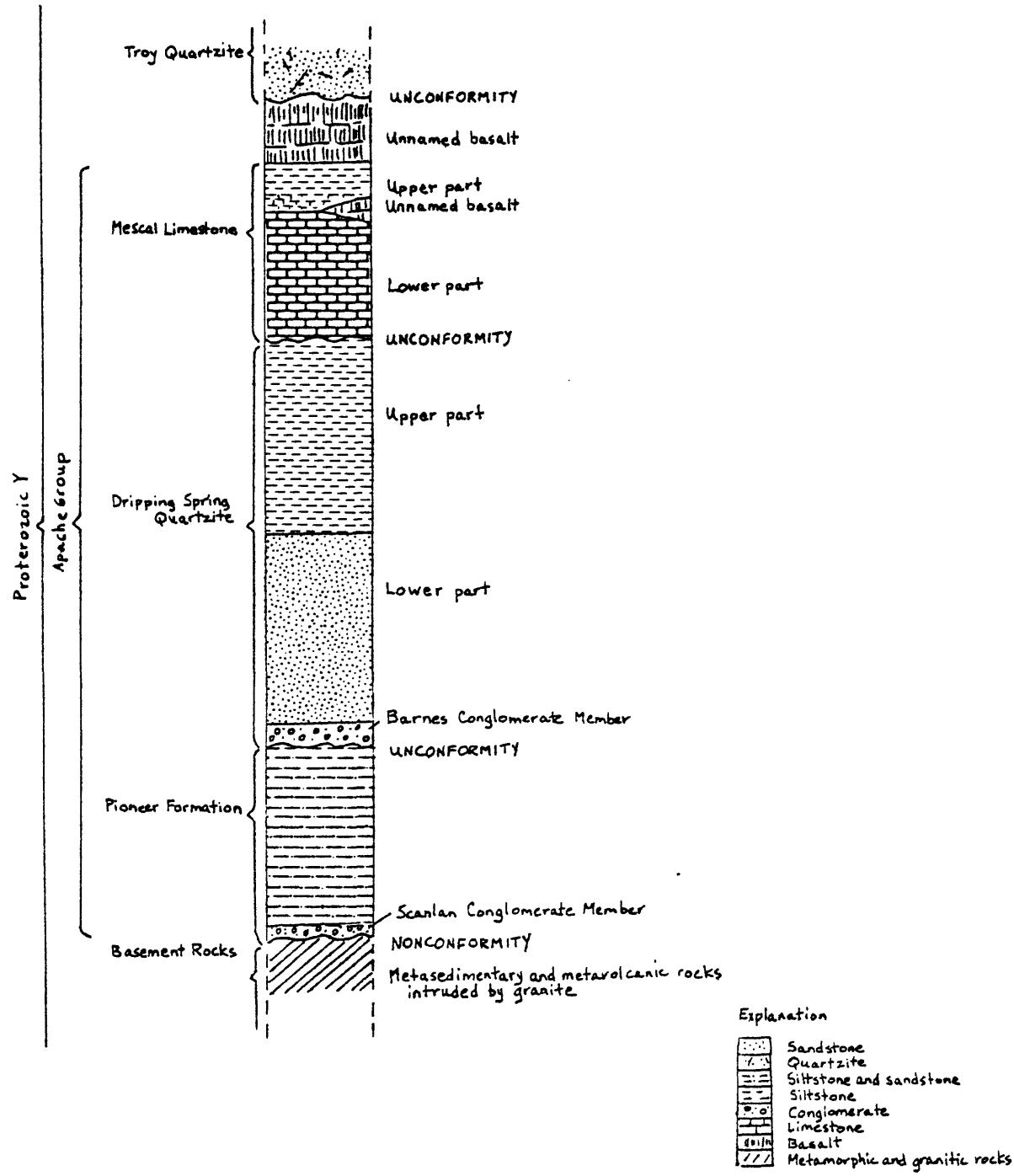


Figure 2.--Stratigraphic section of the Apache Group, Gila County, Arizona. Modified from Granger and Raup (1964).

Mescal Limestone

The Mescal Limestone overlies the Dripping Spring Quartzite. The formation has been divided into two parts, a lower and upper (Bergquist and others, 1980). The lower part is composed of cherty dolomite, commonly metamorphosed near diabase intrusions to silicious marble. It is 60-85 m thick. The upper part contains cherty, stromatolitic dolomite, locally contact-metamorphosed to silicate-bearing marble, and, higher in the sequence, argillite. Post-Mescal basalt flows cap the argillite and dolomite sequence, and form the upper section between the upper part and the Troy. The upper part is 55-85 m thick.

The Mescal Limestone has been extensively modified by leaching and solution and by metamorphism associated with diabase intrusion. A stratigraphically continuous, 4.5 to 12.0-m-thick carbonate breccia underlying the carbonate sequence has been interpreted by Shride (1967) to be the result of solution of evaporites and the subsequent collapse of higher sections. Halite casts in the lower part are also indicative of the removal of evaporite minerals from the sequence. Post-consolidation solution caused development of karst topography. Contact metamorphism affected most of the section, producing impure marble from cherty dolomite and obscuring primary features.

The upper argillite has a high background radioactivity, but does not contain significant uranium concentrations. The K_2O content of this rock type is high (Neuerburg and Granger, 1960), suggesting that potassium is the source of the high radioactivity background.

The contact separating the Mescal Limestone and underlying Dripping Spring Quartzite was mapped as an unconformity by Bergquist and others (1980). Granger and Raup (1964), who first proposed that it was not a

conformable surface, suggested that the boundary does not represent an extended haitus, and that in deeper parts of the basin sedimentation may have been continuous.

Diabase

Diabase intrudes nearly all sections of the Apache Group. Granger and Raup (1969b) estimated that in most Apache Group sections, diabase thickness is more than 10 percent of that of the sedimentary rocks. The diabase occurs predominantly in sill-like sheets, but contacts are locally discordant. Thickness of the sheets range from about 10 to 300 m.

The Sierra Ancha sill, one of the larger sheets, has been extensively studied by Smith (1969, 1970), Smith and Silver (1975) and Nehru and Prinz (1970). Silver, 1960, determined the age of the sill to be 1100-1150 m.y. The sill is composed of multiple intrusions. The center section is feldspathic olivine-rich diabase, and the lower and upper sections are olivine diabase. Typical diabase mineralogy is plagioclase, augite, olivine, iron-titanium oxide, biotite, rare orthopyroxene and deuteric alteration (Smith and Silver, 1975). The compositions of sedimentary rocks in the vicinity of diabase indicate that there was limited major-element metasomatism caused by the diabase, confined to rocks nearby and in some places partially melted by the diabase (Smith, 1969).

Granophyres associated with the diabase are thought to be predominantly composed of melted sedimentary rocks (Smith 1969; Smith and Silver, 1975). Their sedimentary origin is obscured by total melting. The composition of these rocks is variable, but primarily is alkali feldspar, quartz, calcic pyroxene, biotite and hornblende, with minor plagioclase, sphene, ilmenite, pyrrhotite, chlorite, zircon, apatite, and allanite (Smith and Silver, 1975).

Dripping Spring Quartzite

The Dripping Spring Quartzite, which unconformably overlies the Pioneer Formation, consists of siltstone and fine-grained sandstone. The unit has been divided into a lower part composed predominantly of sandstone and an upper part of siltstone. The lower part contains the basal Barnes Conglomerate Member, composed of pebbles and cobbles of quartzite and arkose in an arkosic matrix. The upper part is the host of the uranium occurrences.

The Dripping Spring Quartzite, like all the Apache Group, is intruded by diabase, which was preferentially emplaced into the thinly bedded strata. Contact metamorphism and diagenesis to low-grade metamorphism have greatly affected the upper part, to the extent that it could probably be considered a meta-siltstone. However, as there has not been a systematic petrographic study of the unit throughout the region, and the unit is in a sedimentary sequence and is obviously of sedimentary origin, it will be referred to as a siltstone except where hornfels have formed near diabase intrusions.

Lower part

The lower part, 85-110 m thick, is fine- to medium-grained feldspathic to arkosic sandstone and orthoquartzite; quartz and feldspar are the dominant minerals. Both potassium feldspar, including microcline and perthite, and plagioclase are present. Rock fragments of quartzite and rarely of schist are less than 5 percent of the total rock. Quartz commonly shows undulatory extinction. Arkose and feldspathic siltstone are moderately sorted, and have subrounded to angular grains. The quartzite consists of well-sorted, rounded grains.

Accessory minerals include rutile, magnetite, zircon, apatite, sphene, and muscovite (Granger and Raup, 1964). Sphene is ubiquitous. All thin sections examined contain fine sphene grains (6-30 μm) clustered in interstitial spaces.

The cement is predominantly quartz and feldspar overgrowths. Less common cement includes clay, chert, carbonate, iron-oxides, and mica. Fine-grained feldspar was also observed in one speciman. Overgrowths are identified by fine iron-oxides(?) outlining the original grain. Shride (1967) noted that "the arkose member is so firmly cemented that details of bedding are obscure, and the member forms massive outcrops".

Upper part

The upper part consists of commonly pyritic, thinly bedded siltstone. Granger and Raup (1964,1969b) further divided the section into four units from bottom to top: red, gray, buff, and white. Because this report is concerned with the stratigraphy of the upper part, Granger and Raup's subdivisions will be used.

The red unit, which is the basal section of the upper part, is composed of interlayered hematitic micaceous siltstone and fine-grained sandstone. The unit is about 0-25 m thick.

The gray unit, host to the uranium concentrations, consists of pyritic and carbonaceous fine-grained feldspathic siltstone locally interbedded with fine-grained sandstone layers. The gray unit has an unusually high K_2O content, generally greater than 10 percent (table 1). Near the middle of the section is an approximately 1.5-m-thick sandstone and orthoquartzite layer that has been named the barren quartzite. The unit is approximately 15-80 m thick.

Table 1.--Chemical analyses of the Dripping Spring Quartzite, Arizona

[Asterisk, *, indicates not measured. LOI, loss on ignition.]

Sample No.	[1]1-172	[2]1-175	[3]1-205	[4]2-119	[5]5-95	[6]5-126	[7]7-71	[8]7-88	[9]DS78-5	[10]DS78-20A2	[11]21	[12]20
SiO_2	62.2	60.8	56.8	56.8	43.6	57.8	61.3	59.0	62.9	62.0	66.73	74.75
Al_2O_3	15.2	14.8	14.1	14.1	10.8	14.8	16.2	14.7	16.4	15.2	12.78	11.56
Fe_2O_3	2.2	2.9	4.5	2.8	11.1	4.2	2.1	4.0	0.28	1.7	2.92	0.46
FeO	1.3	0.76	1.2	1.7	2.8	1.6	1.2	1.7	0.08	4.9	1.26	0.14
MgO	0.46	0.93	1.6	2.7	5.2	1.8	0.62	1.3	0.12	2.3	0.54	0.53
CaO	1.4	1.9	2.4	3.1	0.97	0.82	0.68	0.2	0.18	0.18	0.61	0.50
Na_2O	0.21	0.17	0.59	0.20	0.07	0.11	0.10	0.11	0.16	0.23	0.43	0.13
K_2O	12.5	12.4	11.9	11.9	8.0	12.1	13.8	12.3	13.3	8.8	10.54	9.60
H_2O^+	0.47	0.71	0.80	1.2	2.6	1.3	0.62	1.1	0.82	2.7	1.13	0.72
H_2O^-	0.10	0.31	0.37	0.79	2.5	0.86	0.24	0.82	0.40	0.25	0.59	0.65
TiO_2	1.2	1.4	1.2	1.2	0.95	0.94	0.77	0.72	0.92	0.66	1.31	0.52
P_2O_5	0.17	0.13	0.17	0.09	0.15	0.16	0.17	0.08	0.18	0.13	0.10	0.07
MnO	0.04	0.05	0.08	0.08	0.10	0.03	0.01	0.04	0.02	0.10	0.07	0.01
CO_2	0.01	0.01	0.11	0.32	0.11	0.07	0.12	0.02	0.02	0.02	*	*
Total	98	98	96	97	92	97	98	97	99	99	99.01	99.64
LOI	*	*	*	N	2.7	0.6	0.31	0.68	3.1	--	*	*
Organic C	0.05	1.15	0.05	0.14	1.15	0.27	0.13	0.25	2.92	0.03	*	*
Cu (ppm)	1000	1600	2200	930	41000	640	30	2400	*	*	*	*
Pb (ppm)	40	300	375	500	1020	200	90	830	*	*	*	*
Mo (ppm)	50	<10	189	56	<10	36	91	43	*	*	*	*
V (ppm)	*	*	*	95	82	80	46	89	*	*	*	*
Zn (ppm)	13	17	46	54	76	6	6	26	*	*	*	*

Samples 1-10, rapid rock analyses of major elements measured at USGS laboratories by F. Brown, N. Skinner, D. Kobilis, and Z. Hamlin.

Samples 1-10, C, Cu, Pb, Mo, V, Zn determined by optical spectroscopy at USGS laboratories by F. E. Liche, J. H. Christie, P. Briggs, G. Riddle, and V. Shaw.

Samples 11-12, analytical data from Smith and Silver (1975).

[1] Gray unit, hornfelsic siltstone. No visible uranium minerals, but radioluxograph shows uranium concentrated in finely layered strata. Sample from Workman Creek core.

[2] Gray unit, hornfelsic siltstone with very fine laminations and stylolites. Rarely, fine uraninite and coffinite are visible. Sample from Workman Creek core.

[3] Gray unit, coarse-grained hornfels with visible uraninite. Sample from Workman Creek core.

[4] Gray unit, finely laminated hornfelsic siltstone, with some visible uraninite and coffinite. Sample from Workman Creek core.

[5] Gray unit, hornfelsic siltstone with intense chloritic alteration, coffinite in veinlets and disseminated. Sample from Workman Creek core.

[6] Gray unit, hornfelsic siltstone with chloritic alteration, rare coffinite and uraniferous chloritic veinlets. Sample from Workman Creek core.

[7] Gray unit, hornfelsic(?) siltstone, No visible uranium minerals, but radioluxograph shows uranium disseminated. Sample from Workman Creek core.

[8] Gray unit, hornfelsic siltstone with intense chloritic alteration, coffinite in veinlets and disseminated. Samplefrom Workman Creek core.

[9] Gray unit, (meta?) siltstone. Collected by Jim Otton, from Deep Creek area (fig. 3).

[10] Gray unit, very fine grained hornfelsic siltstone to sandstone. Collected by Jim Otton, from near Buckaroo Flats (fig. 3).

[11] Gray unit, metasiltstone, SE1/4 sec. 7, T. 6 N., R. 14 E., from Smith and Silver (1975).

[12] Buff unit, altered tuff (?), metamorphic effects almost absent, SE1/4 sec. 7, T. 6N., R. 14 E., from Smith and Silver (1975).

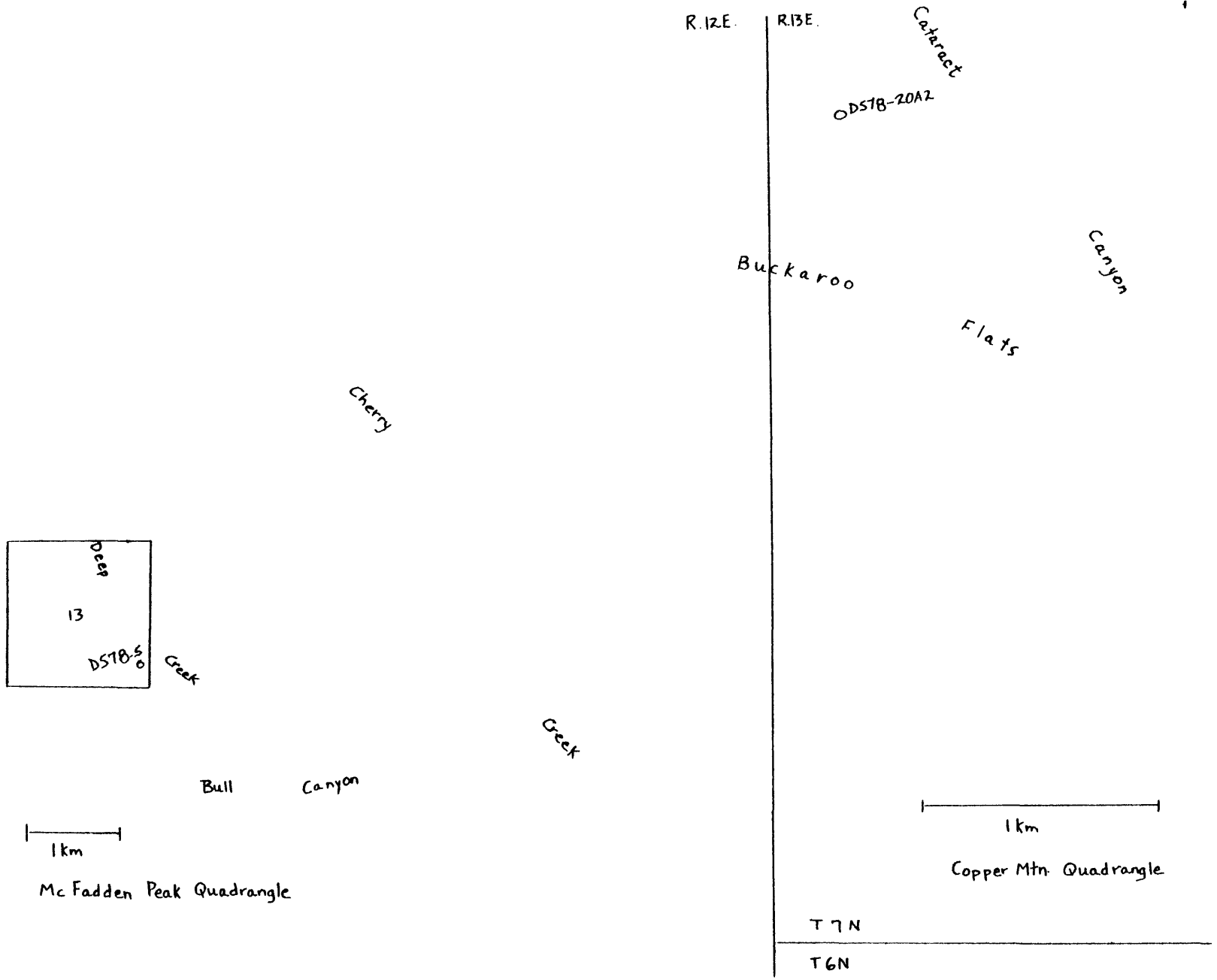


Figure 3.--Localities of samples DS78-5 and DS78-20A2

The buff unit is a feldspathic, fine- to coarse-grained sandstone differing from the underlying gray unit in its light color, reflective of the lack of carbonaceous matter and abundant pyrite, and coarser grain size. Fine-grained potassium feldspar is present, but in lower quantities than in the gray unit; in thin sections examined the percentage of fine-grained feldspar was about 50-60 percent. Smith (1969) found high K_2O content in the buff unit, which is probably caused by the presence of abundant potassium feldspar. Thickness of the unit is about 12-50 m.

The white unit is a thinly laminated to thinly bedded siltstone that caps the upper member. It consists predominantly of quartz and feldspar, cemented by overgrowths and clay. The unit is 0-37 m thick.

Mineralogy of the gray unit

The gray unit, the host to uranium occurrences, consists predominantly of feldspar and quartz. There are two populations of potassium feldspar. The major population is very fine grained (average <5 μm) and makes up 50-90 percent of the rock. High K_2O content and high background radioactivity reflect the high percentage of potassium feldspar (table 1). Granger and Raup (1964) and Smith (1969) determined that this feldspar is monoclinic and is nearly pure potassium feldspar. Under cathodoluminescence, the feldspar does not luminesce; this may be a function of fine grain size as well as low trace-element content. The second type of feldspar is coarser, usually in the range 50 to 200 μm, is commonly in nearly equant grains, and has a light-brown surface alteration (clay?) that aids in distinguishing it from the other variety of potassium feldspar. It is disseminated in the fine-grained fraction and is concentrated in coarse-grained layers. Subangular plagioclase is present, but in low quantities of generally <5 percent.

Quartz occurs in coarse-grained lenses and is also scattered throughout the fine-grained feldspar groundmass. In the coarse-grained strata, quartz is subrounded to subangular, may compose as much as 50 percent of the layer, and has an average grain size in the range 100-300 μm. In the fine-grained fraction, quartz is angular to subangular, rarely forms more than 10 percent of the rock, and is generally 20-70 μm. although size is variable. The edges of these quartz grains are generally irregular and embayed.

Sphene, about 1-5 percent but locally as high as 12 percent of the rock, is generally fine grained (average <30 μm in fine-grained strata) although it may be as large as 120 μm, and is subhedral. Sphene commonly contains a rutile core (fig. 4), and, rarely, an ilmenite core. Sphene is disseminated and concentrated along bedding planes and stylolites. Fine-grained sphene in some places is interstitial to quartz grains, and outlines the coarse quartz grains.

Subhedral to anhedral iron-sulfide, both pyrite and pyrrhotite, is scattered through both fine and coarse-grained strata and is concentrated along stylolites. Clinopyroxene occurs as near-monomineralic layers, disseminated in the fine-grained layers, and interstitial to quartz and feldspar in the coarse-grained layers. Carbonaceous material and graphite are disseminated and are along bedding planes and stylolites. Chlorite is disseminated, is in veinlets, and is along stylolites and bedding planes. Zircon and muscovite are present in accessory amounts.

The cement in the gray unit is predominantly fine-grained feldspar. In the coarse-grained lenses and layers, quartz and feldspar overgrowths are present, and pyroxene is interstitial to the quartz and feldspar grains.

Photomicrograph-I

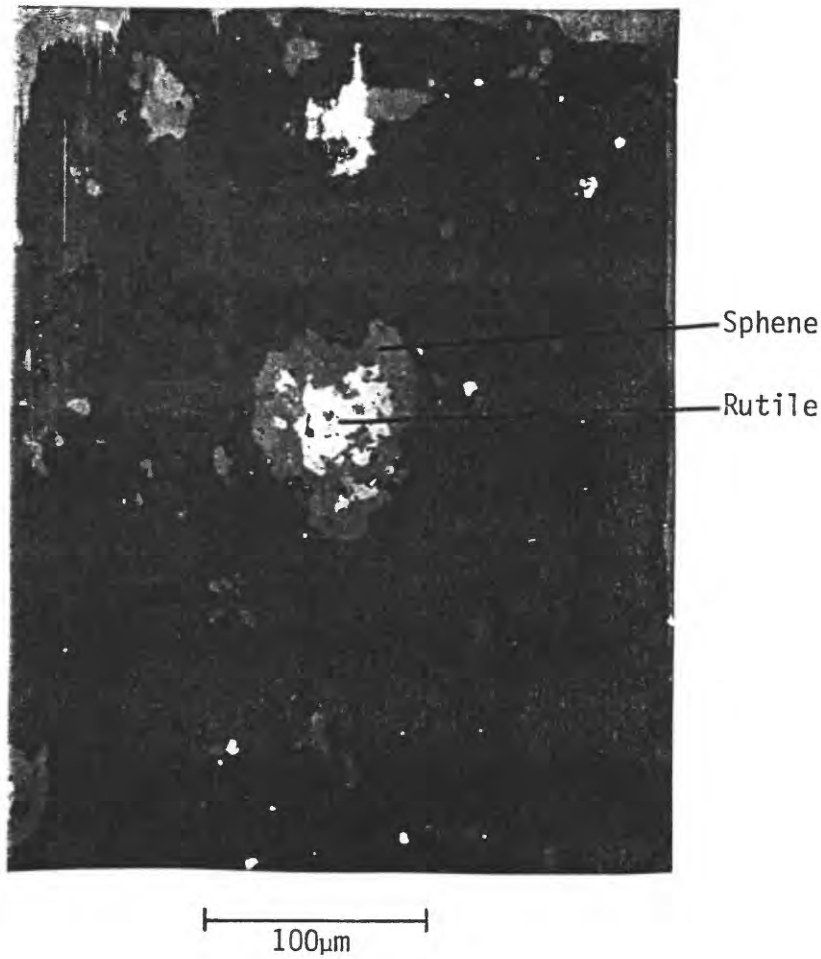


Figure 4.--White to gray rutile forms core of darker, less reflective sphene. Reflected light.

Sedimentary structures

Sedimentary structures of the upper part include cross-bedding, ripple marks, shrinkage cracks, "pseudochannels", fucoidlike markings, and stylolites (Granger and Raup, 1964). The origin of the stylolites and their effect on permeability and volume of host rocks are important because stylolites commonly contain uranium.

The upper part of the Dripping Spring Quartzite has extensive development of stylolites. Stylolites commonly separate coarse and fine-grained strata and are within fine-grained layers. The residium along the stylolites is predominantly sphene, with lesser amounts of pyrite, carbonaceous matter, and graphite. Stylolites apparently postdate fine-grained feldspar formation, because, if stylolites had preceded feldspar, they would have been at least partially destroyed during conversion of the original volcanic sediments to feldspar. The matter removed during pressure solution may have included thin beds of soluble carbonate or evaporites.

Stylolites are sedimentary structures thought to be formed primarily by pressure solution (Pettijohn, 1975). Dissolution associated with stylolite formation may cause thinning of the stratigraphic section. The published estimates of volume loss can approach 50 percent (Glover, 1969). Loss is probably greatest in carbonates, and least in sandstones. Solution causes an insoluble residual to accumulate along the stylolite, whereas the more soluble material is lost to intrastratal fluids (Logan and Semeniuk, 1976).

The timing of stylolite formation is a subject of controversy, generally between proponents of prelithification and postlithification. According to the prelithification theory, stylolites form during early diagenesis (Park and Schot, 1968). In contrast, Logan and Semeniuk (1976) presented evidence for late, postconsolidation stylolite formation. Probably, as stated by Glover

(1969), stylolite formation is often a long process, beginning in porous rocks and continuing until pore space is eliminated. Where there are stylolites in rock that contains authigenic feldspar, they cross-cut the feldspar (Kastner and Siever, 1979).

The effect of stylolites on permeability is unknown. The solute material may precipitate in pore spaces, causing cementation and loss of permeability. Lawyer and Larson (1972) found through the use of electron photomicrographs that stylolite growth increased permeability in limestones and that the stylolites function as permeability channels. According to Bissell (1972), stylolites are paths along which oil and gas can migrate.

DIAGENESIS AND METAMORPHISM OF THE UPPER PART OF THE DRIPPING SPRING QUARTZITE

The upper part of the Dripping Spring Quartzite has a complex mineralogy, consisting of a mixture of detrital grains, diagenetic and low-grade metamorphic minerals, and contact metamorphic assemblages. The origin of the minerals often is difficult to determine, as they can form under a variety of conditions. This section includes interpretations of the origins of the observed minerals.

The primary detrital minerals are quartz, coarse-grained potassium feldspar with brown alteration dustings, and plagioclase. These minerals are rounded to subangular, and are similar to the minerals of the lower part, which are almost exclusively clastic. Rounded zircons are clastic, although later overgrowths are present. Muscovite either is detrital or is formed early during diagenesis. Pyrite formed syngenetically or diagenetically in the carbonaceous sediments.

Diagenetic to low-grade metamorphic minerals are predominantly overgrowth

cements, sphene, and fine-grained potassium feldspar. The overgrowth cements, quartz and feldspar, formed during early diagenesis. The overgrowths are almost exclusively in coarse-grained lenses and strata, and are similar to those observed in the lower part. What are tentatively identified as overgrowths are rarely seen on quartz and feldspar in the fine-grained matrix.

Sphene can form either as a diagenetic mineral or as a metamorphic mineral (Larsen and Chilingar, 1967; Deer and others, 1966), or can be detrital. In the Dripping Spring Quartzite, the irregular outline of the sphene and the rutile cores indicate that sphene is not detrital. Granger and Raup (1969b) used the presence of sphene as diagnostic of contact-metamorphosed sedimentary rocks. However, this study determined that all rocks in the stratigraphic section, including the lower part, contain sphene. Either the entire Dripping Spring Quartzite has been contact metamorphosed, or sphene is really indicative of widespread diagenetic to low-grade metamorphism. The second alternative is favored for the majority of the sphene, although it appears that thermal metamorphism was extensive and that much of the sphene, especially near the diabase, is the result of thermal metamorphism. Formation of sphene either by contact metamorphism or by diagenesis/low-grade metamorphism could have proceeded by such a reaction as $CaCO_3 + TiO_2 + SiO_2 \rightarrow CaTiSiO_5 + CO_2$ or by alteration of clays.

The fine-grained potassium feldspar is thought to be authigenic (Granger and Raup, 1964; Smith, 1969), formed by the alteration of volcaniclastics. The feldspar has the following characteristics diagnostic of diagenetic or low-grade metamorphic feldspar: fine-grained, compositionally pure, and shows no luminescence. Where fine-grained sedimentary rocks contain authigenic feldspar in amounts greater than a few percent, the precursor is hypothesized to be volcaniclastic (Kastner and Siever, 1979). The Dripping Spring

Quartzite, which commonly has 70-80 percent fine-grained potassium feldspar, is probably a volcaniclastic rock. The feldspar of the Dripping Spring Quartzite has the following features similar to authigenic feldspar formed in volcanic rocks, as defined by Kastner and Siever, (1979): a potassic, instead of sodic, composition, monoclinic structure, and lack of detrital cores.

The presence of potassium feldspar in diagenetically altered rocks is well documented. Authigenic potassium feldspar in altered tuffs is found in the alkaline and hypersaline facies (Sheppard and Gude, 1968,1969,1973; Surdam, 1977), although Boles and Surdam (1979) have documented feldspar in a moderately saline but not highly alkaline environment. Authigenic potassium feldspar and volcanic glass do not occur together (Sheppard and Gude, 1968,1969,1973; Surdam, 1977), suggesting that the alteration of glass goes through an intermediate stage of zeolite formation, which then alters to potassium feldspar. A typical intermediate reaction is $NaAlSi_2O_6 \cdot H_2O + SiO_2 + K^+ \rightarrow KAlSi_3O_8 + H_2O + Na^+$ (Surdam, 1977), resulting in loss of H_2O and Na.

Authigenic potassium feldspar forms in an environment with high K^+/H^+, high H_4SiO_4, and a supply of aluminum (Kastner and Siever, 1979). In the Dripping Spring Quartzite, these components could have been supplied by hydrolysis of volcanics and slow dissolution of detrital, high-temperature granitic and metamorphic feldspars, which are unstable in pore waters. The high pH would also promote quartz dissolution (Surdam, 1977). The resorbed edges of quartz and detrital feldspar in the upper part indicate that dissolution did occur, resulting in angular grains and the appearance of poor sorting which were interpreted by Williams (1957) and Smith (1969) as evidence that they were volcanic crystals.

The high K_2O and low Na_2O contents (table 1) of these rocks is puzzling and cannot easily be explained by isochemical alteration of volcanics, which

generally have $K_2O/Na_2O < 1$. Saline pore waters trapped or evolved during burial, or descending saline waters are the probable source of potassium. Sodium loss may have occurred during alteration of zeolite to potassium feldspar. Dissolution of quartz and feldspar could have resulted in loss of silica.

The abundance and complexity of secondary minerals indicate that diagenesis included more than one event, and was at least partly dependent on evolution of interstital fluids. Quartz, feldspar, and carbonate cements formed early, and were probably accompanied by breakdown of Ti-bearing minerals (ilmenite?) to Ti-oxides. In the later stages of diagenesis or low-grade metamorphism, feldspar and sphene formed. Changes in interstitial fluid composition during breakdown of volcanics may have affected the stability of the early cements.

Metamorphism associated with diabase intrusions produced hornfelsic rocks, and, in some areas, melted the sedimentary rocks. The recrystallized rocks include fine-grained, dense hornfels with well-preserved relict stratification, coarse-grained hornfelsic rocks with relict stratification well to faintly preserved, and a spotted rock containing small disseminated spheroids of secondary minerals (Granger and Raup, 1969b). Melting of large volumes of sedimentary rocks resulted in potassic granophyre, and, on a smaller scale, felsic dikelets and small melted spots in the hornfels. The granophyre has an usually high K_2O content of 7-11 percent, suggesting that it was derived from the highly potassic Dripping Spring Quartzite siltstones (Smith 1969; Smith and Silver, 1975).

Metamorphic minerals in the hornfels include graphite, phlogopite, pyroxene, rutile needles, pyrite with concentric banding, pyrrhotite, coarse-grained feldspar, Mg-chlorite, and sphene. Pyroxene, in near-monomineralic

layers and interstitial in coarse-grained strata, probably replaced carbonate layers and cement.

The extent of contact metamorphism is unknown because at lower temperatures its effects are difficult to distinguish from those of diagenesis/low-grade metamorphism. The existence of fine-grained authigenic assemblages of potassium feldspar and sphene suggest only local recrystallization occurred. Obvious hornfelsic rocks are generally restricted to about 30 m from the diabase (Granger and Raup 1964). However, most sections of the upper part have been intruded by diabase, and undoubtably diabase has been eroded in some areas. The spotted rocks, which probably formed during incipient contact metamorphism, are widespread. This distribution suggests that metamorphism related to diabase intrusion is really quite extensive and may have affected most of the upper part.

ENVIRONMENT OF DEPOSITION OF THE DRIPPING SPRING QUARTZITE AND MESCAL LIMESTONE

The source of sediment and environment of deposition of the lower and upper parts of the Dripping Spring Quartzite appear to have been markedly different. The lower part consists predominantly of moderately to well-sorted, rounded to subrounded grains of quartz and feldspar, with minor rock fragments. The composition of the unit suggests that it was derieved from a granitic and/or metamorphic terraine, probably the basement rocks. The existence of rare anthigenic potassium feldspar in the unit indicates a small volcanic component, increasing upwards. The environment of deposition may have been shallow water, producing grain sorting and rounding.

The upper part of the Dripping Spring Quartzite consists predominantly of fine-grained potassium feldspar, and only relatively minor detrital grains.

The lack of detrital grains and the presence of carbonate layers, carbonaceous matter, and shrinkage cracks indicate that the environment of deposition was quiet shallow water. The environment was probably nearshore or intertidal, as proposed by Granger and Raup (1964). This sequence, however, also could have formed in a lacustrine environment. High salinity is suggested by the existence of authigenic feldspar, which generally forms in saline, alkaline environments. The abundant stylolites in this section may be, in part, the result of dissolution of evaporitic and carbonate layers. The buff unit, containing a greater percentage of detrital grains, and the interlayered quartzite beds may have formed during sudden influxes of sediments or changes in the shoreline.

The abundance of potassium feldspar, probably formed from alteration of volcaniclastics, is indicative of volcanic activity during deposition of the upper part of the Dripping Spring Quartzite. Volcanic activity apparently was sporadic during deposition of the Apache Group, as volcaniclastics are found in the Pioneer Formation and basalts are in the Mescal Limestone. Within the Dripping Spring Quartzite, the amount of feldspar progressively increases upward, with the highest percentage being in the gray unit, and then decreases toward the upper contact.

Carbonate minerals, evaporite casts, and stromatolites in the Mescal Limestone suggest that this unit was deposited in a supratidal to intertidal environment. However, like the upper part of the Dripping Spring Quartzite, this sequence could also be lacustrine. The Mescal sequence is similar to that formed in a sabkha environment. The hiatus separating deposition of the upper part of the Dripping Spring Quartzite and Mescal Limestone may not represent much time, as both units were deposited in saline, shallow-water

environments. The environment appears to have been increasingly saline upward during deposition of the Dripping Spring Quartzite and Mescal.

STRUCTURE OF THE SIERRA ANCHA REGION

The Sierra Ancha area, like the rest of the Colorado Plateau province, contains generally flat-lying strata. There are, however, at least five monoclines affecting the Apache Group in the Sierra Anchas (Granger and Raup, 1969b). These monoclines generally trend N-S to NW-SE, and commonly are downwarped on the eastern side (fig. 1). The monoclines exert some structure control on the intrusion of the diabase.

Faults in the area preceded diabase intrusion, accompanied diabase intrusion, and are post-diabase. Some of the diabase intrusions are localized along early faults. Later faulting is Late Cretaceous(?), Tertiary, and Quaternary (Granger and Raup, 1969b). Joint sets are present throughout the area.

URANIUM MINERALIZATION

Description

Uranium mineralization in the Dripping Spring Quartzite consists of low-grade disseminations and concentrations in fine-grained strata and along bedding planes and stylolite surfaces, and higher-grade layers and veinlets. The samples studied are predominantly from the Workman Creek area, which has been extensively contact metamorphosed. In these samples, the uranium is in hornfelsic siltstone of the gray unit. Uraninite and coffinite have been identified.

The uranium occurrences are stratabound both on the macroscale, in that they are confined to specific stratigraphic intervals, and on the microscale,

in that certain layers are enriched in uranium. The most favorable horizons for uranium concentrations are the middle of the upper member, 6-10 m below and 0-12 m above the barren quartzite horizon (Granger and Raup, 1969b). Diagnostic features of these feldspathic siltstone sequences are thin bedding and finely disseminated carbon or graphite, pyrite, and sphene that give the rocks their gray to black color. No uranium concentrations are known in the lower part or in the red, buff, or white units.

There are two types of uranium occurrences in the Dripping Spring Quartzite (Granger and Raup, 1969b). The type that was developed in the 1950's and on which Granger and Raup concentrated their work are vein occurrences. Granger and Raup also identified blanket occurrences, which they thought were of secondary importance. These blankets are tabular and parallel to bedding. Granger and Raup do note that some occurrences, for example the Black Bush, have features of both blankets and veins.

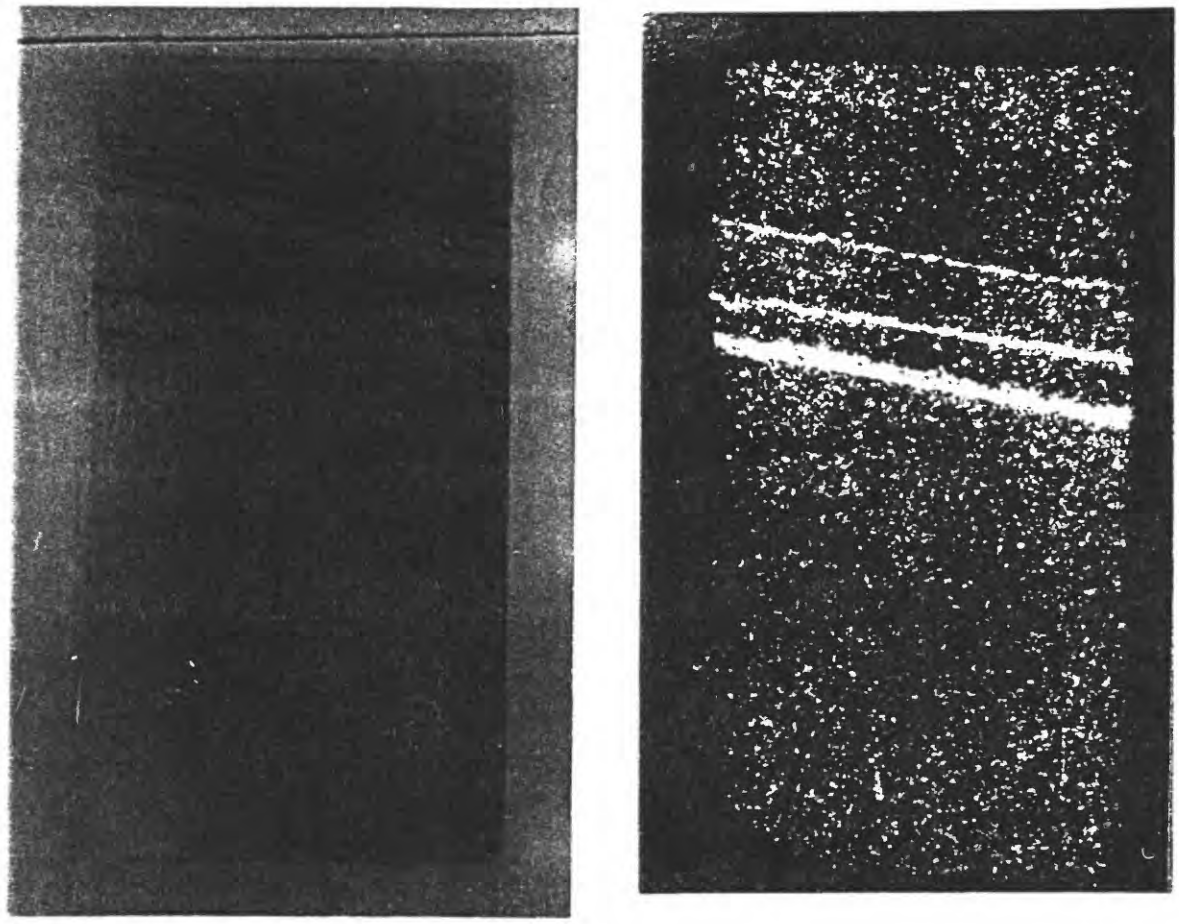
In their description of the veins, Granger and Raup (1969b) noted that these veins are "unlike most veins in that they do not occupy well-defined fissures and are not clearly distinguishable, megascopically, by mineral content and structure from the enclosing rocks". They described the veins as steeply dipping tabular bodies, with disseminated uranium-bearing minerals and minor stringers in the richer veins. Veinlets are predominantly in the hornfels, and "where siltstone is the host rock no uraninite veinlets are present; all the uranium is disseminated in the wall rock" (Granger and Raup, 1969b).

Low-grade uranium concentrations are disseminated in fine-grained strata and along bedding planes, stylolites, and fractures (table 2). These distributions are seen on radioluxographs (fig. 5a). Uranium commonly is concentrated in layers that contain numerous fine laminations or stylolites

Table 2--Comparison of uraniferous layers and nonuraniferous layers of thin sections. Uraniferous layers identified by radioluxographs. Mineral percentages determined by point counts.

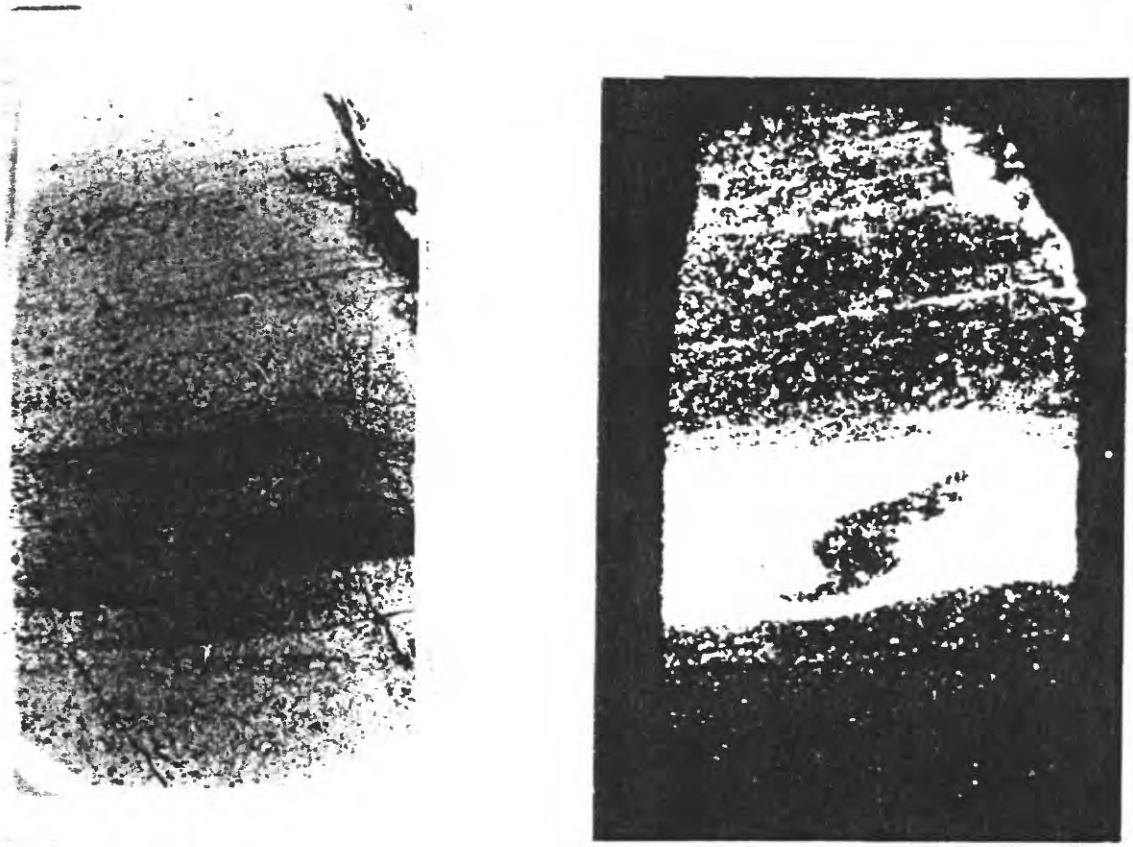
Sample No.	(nonuraniferous) 1-175	(uraniferous) 1-175	(nonuraniferous) 2-119	(uraniferous) 2-119	(nonuraniferous) 5-88	(uraniferous) 5-88	(nonuraniferous) 1-200	(uraniferous) 1-200
Potassium feldspar	767	712	625	795	650	787	884	563
Quartz	60	48	18	4	138	96		
Pyroxene	35		288		126		39	
Sphene	94	109	49	106	34	75	28	36
Phlogopite	11	3						
Chlorite	4	13	4	71	1	21		
Iron-silicate(?)		2		2		1		
Calcite			1			1		
Zircon						1		
Pyrite	10		7	8				3
Pyrrhotite	12	75	8	4	51	18	31	17
Chalcopyrite	7	16		2			4	3
Galena		1						
Graphite							14	8
Uraninite		9		5				
Coffinite		12		3				7
Total	1000	1000	1000	1000	1000	1000	1000	937
Estimated average grain size	5-75	5-60	10-80	3-30	30-6-	10-45	10-30	10-30
Approximated number of stylolite and laminations/cm	--	20/cm	--	30/cm	--	--	8/cm	30/cm

Figure 5.—Radioluxographs of Uraniferous Rocks

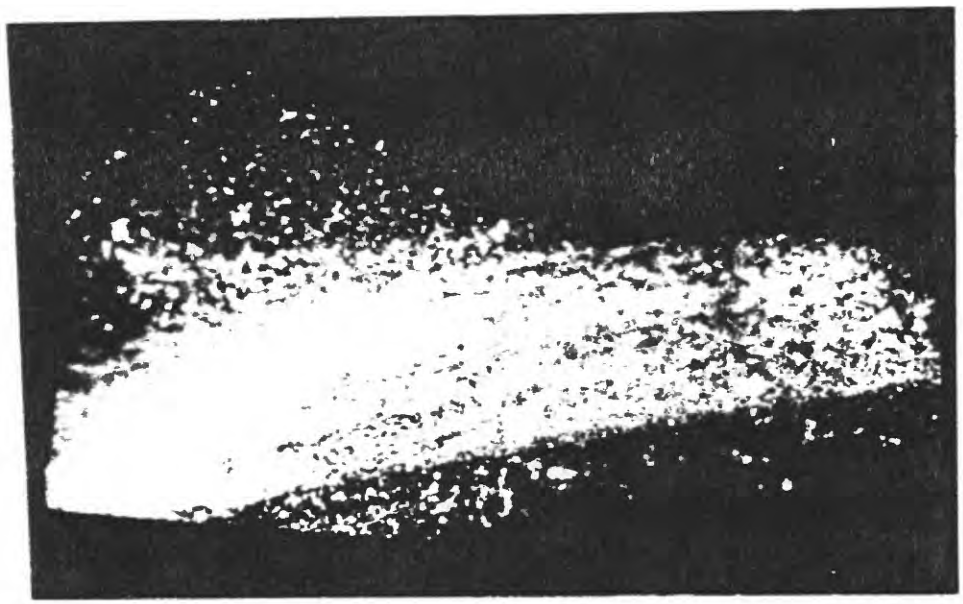


a) Uranium is disseminated and concentrated along stylolites. Radioluxograph exposure time, 69 hours.

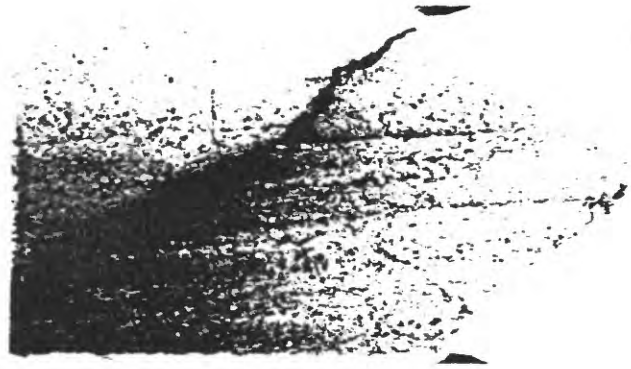
b) Strata containing numerous laminations and stylolites (outlined in black) are enriched in uranium. Radioluxograph exposure time, 68.25 hours.



c) Uranium is noticably absent in coarse-grained lense (outlined in black) within fine-grained, stylolite-rich section. Cross-cutting uraniferous chlorite veinlet is at top right. Radioluxograph exposure time, 28.5 hours.



d) Coarsely recrystallized hornfels. Uranium is concentrated in strata (outlined in black) containing remnant fine laminations and/or stylolites. Radioluxograph exposure time, 25 hours.



e) Coffinite veinlet cross-cutting coffinite-rich layers/veinlets along bedding planes. Radioluxograph exposure time, 48 hours

Figure 5.--Thin sections (left or bottom) and radioluxographs (right or top). Uraniferous areas are white on radioluxographs. Method used to make radioluxographs is described in Dooley (1958).
is described in

(fig. 5b, table 2). Uranium is strikingly absent in pyroxene-rich layers and in coarse-grained strata (fig. 5c, table 2). Fine, scattered uraninite and coffinite are visible in some rocks, but much of the uranium is incorporated into other minerals, especially sphene, or is too fine-grained for observation. Cross-fractures only rarely are mineralized.

High-grade uraninite concentrations are stratabound in fine- and coarse-grained hornfelsic siltstone. The uraninite occurs as discrete euhedral to subhedral grains, generally in the range of 1-20 μm, concentrated in thin layers; as much as 40 percent of the layer may be uraninite. The uraninite-rich layers may be surrounded by strata high in disseminated uraninite. In the coarse-grained, highly recrystallized hornfels, the uranium is restricted to certain strata, and remnants of uraninite layers are present in some rocks (fig. 5d). Small spots of melting disrupt and redistributed preexisting uraninite layers (fig. 6). Uraninite commonly is surrounded by fine rims, identified by microprobe EDS as consisting of silica and uranium. Coffinite is concentrated along the edges of some of the uraninite-rich layers. As in the low-grade concentrations, the uranium is not in pyroxene-rich layers.

Uraninite is associated with chalcopyrite, pyrite, galena, molybdenite, pyrrhotite, sphene, phlogopite, graphite, and rarely ilmenite. Uraninite was observed as inclusions in all these minerals except graphite and molybdenite, as well as in the recrystallized feldspar matrix. Where uraninite is associated with ilmenite, both are surrounded by sphene. In two thin sections from the Red Bluff deposit, uraninite that had replaced pyrite was observed (fig. 7a). EDS microprobe identification shows that the Pb content of this uraninite is lower than in other uraninite, suggesting that it may be a late replacement.

Photomicrograph-II

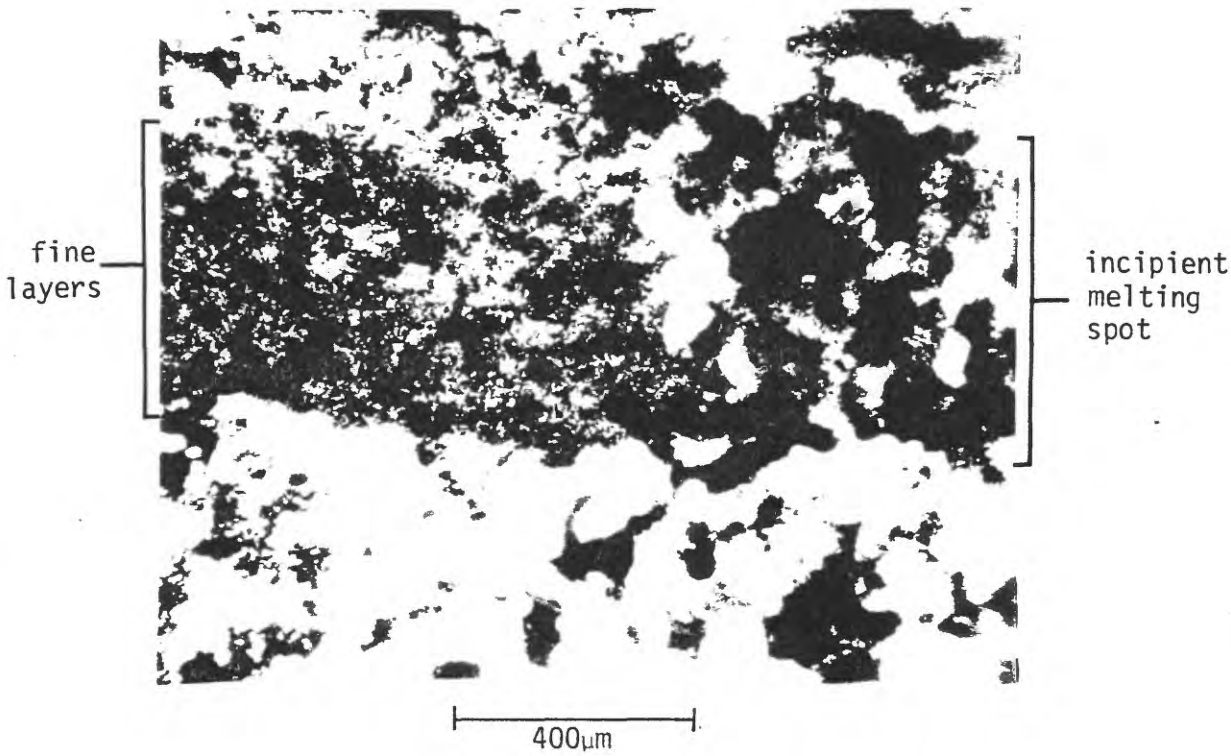


Figure 6.--Uraniferous fine layers disrupted by incipient melting. Uranium mineralization appears to be disperesed in melted spot. Transmitted light.

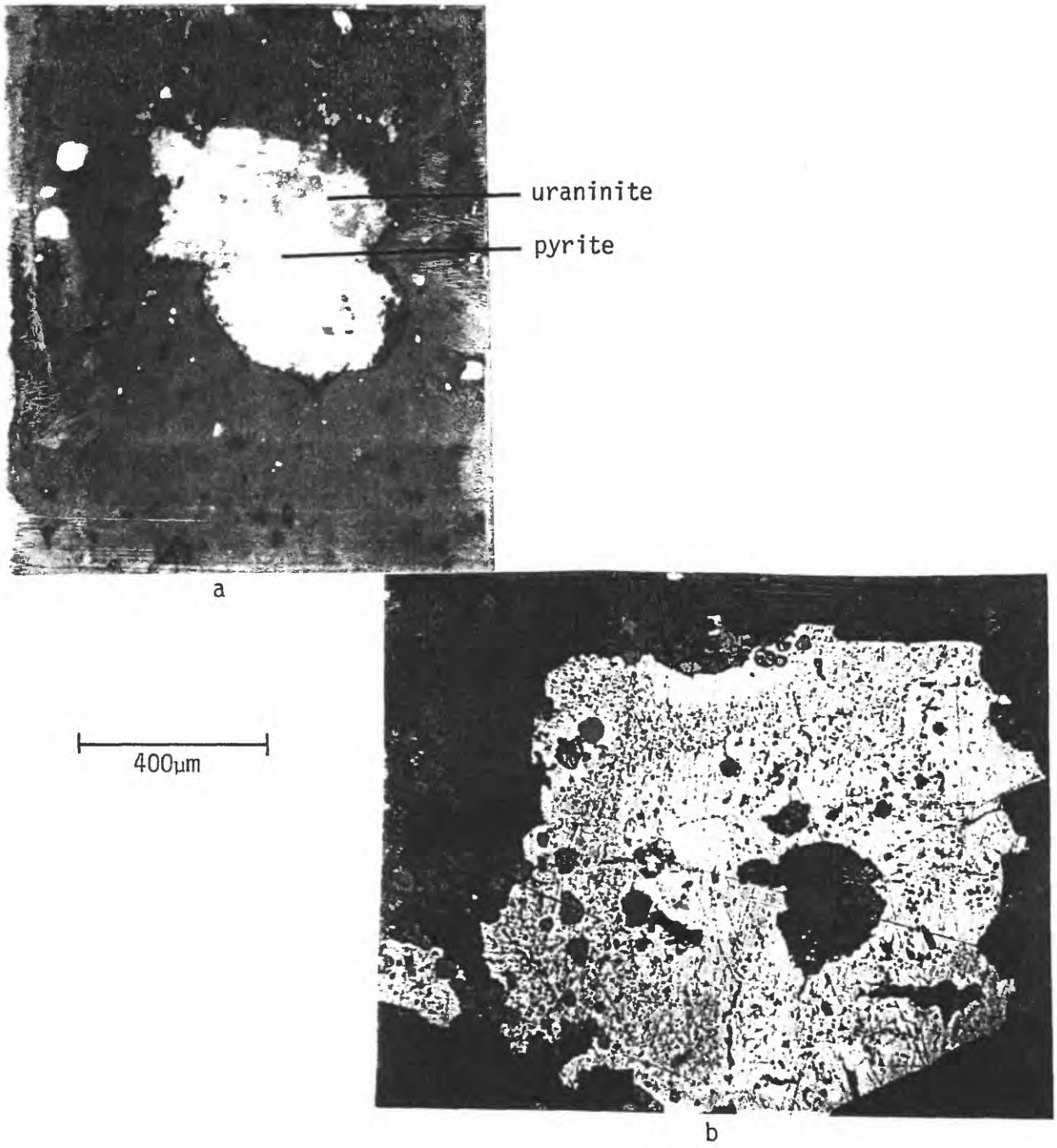


Figure 7.--a) Uraninite replacing pyrite in a sample from the Red Bluff occurrence. Reflected light.

b) Pyrite with magnetite(?) inclusions associated with uraninite. Inclusions are in the outer zone of the grain (outlined). The interior of the pyrite grain is inclusion-free and contains no uraninite. Reflected light.

Pyrite associated with uraninite ore commonly contains fine inclusions. This pyrite can occur as discrete grains or zones in otherwise pure pyrite (fig. 7b). The inclusions are reflective, isotropic, and the regions with numerous inclusions have higher Fe-S ratios than does pyrite without inclusions; they are thought to be magnetite. The magnetite-pyrite grains could be either the result of replacement of iron oxide by pyrite or simultaneous growth of pyrite and magnetite.

Coffinite occurs in veinlets that generally are 0.1-0.3 cm thick and are parallel to and crosscut bedding, and in disseminations that generally are near coffinite veins. Coffinite veins at an angle to bedding crosscut concentrations that are disseminated and parallel to bedding (fig. 5e). Coffinite distribution is similar to that of uraninite, localized by sedimentary features.

Coffinite is yellow brown and is in crystals that commonly are 1-25 μm long. Some of the coffinite, especially where disseminated, is euhedral to subhedral. Most of the coffinite, especially that in veins, occurs as amorphous blebs, with highly variable reflectance and ability to transmit light. Sampled coffinite veins are apparently metamict, as no X-ray pattern was obtained. The coffinite, identified with the use of the microprobe, is equivalent to the uraninite 2 of Granger and Raup (1969b).

Coffinite is associated with chalcopyrite, pyrrhotite, pyrite, molybdenite, and galena. Fine galena cubes are always scattered through coffinite veinlets, and aid in the identification of coffinite. Pyrrhotite and pyrite occur as fine needles, as well as large anhedral grains. Pyrite with magnetite(?) inclusions also is present. The coffinite veinlets contain variable amounts of anhedral uraninite, and in some samples euhedral uraninite inclusions are in pyrite and galena within the veinlets. In one section from

the Red Bluff area, coffinite was associated with covellite. Late marcasite and pyrite veinlets crosscut the uranium mineralization.

Chlorite is almost invariably associated with coffinite both in veinlets and in disseminations. Fine hematite is also found with the chlorite. The microprobe EDS examination of chlorite commonly showed the presence of Ca and Ti, suggesting substitution in the chlorite or that fine sphene was mixed with the chlorite. The chlorite is stratabound, commonly with sharp contacts separating it from less altered layers. Chlorite veinlets are in some places radioactive with no apparent uranium mineral association; in these instances the uranium-bearing mineral is probably submicroscopic. The chlorite veinlets are commonly associated with carbonate-hematite and quartz-pyrite assemblages. In these veinlets, the sequences from the outer edge to the center of the vein are chlorite-hematite-calcite and chlorite-quartz-pyrite. This order is also the paragenetic sequence, from earliest to latest deposition. In many veinlets, the hematite and chlorite are intimately mixed.

Very little alteration other than chloritic was associated with uraninite or coffinite mineralization. Some samples show less brown (clay?) alteration of feldspars in the vicinity of uranium-rich layers and veinlets, whereas in others, brown (clay?) alteration of feldspar accompanies high uranium values. Many samples have no altered haloes. Neither the pattern nor the importance of alteration has been determined as yet.

Age determinations

Uraninite ages were determined to be about 1050 m.y., nearly the same age as the diabase (Granger and Raup, 1969b). The samples dated were high-grade veinlets of uranium mineralization. However, Granger and Raup (1969b) did not recognize the coffinite-crystallization event. Their samples commonly contain

coffinite, which may have affected U-Pb ratios. Valuable data would be obtained by comparing the ages of uraninite and coffinite vertical veinlets, stratabound disseminations, and veinlets along bedding and stylolite planes.

Structure and uranium mineralization

Granger and Raup (1969b) and Williams (1957) proposed that structure played some role in localizing uranium. Both found that uranium mineralization was at least partially controlled by two fracture sets striking NNE and WNW. Granger and Raup (1969b) noted a spatial relationship between monoclines and uranium occurrences, in which most of the uranium was on the downthrown side of the monocline.

MODEL OF URANIUM MINERALIZATION

Introduction

Uranium mineralization in the Dripping Spring Quartzite could have been controlled by sedimentary, igneous, or metamorphic processes. The three most probable hypotheses of uranium concentration are as follows:

1) Uranium was concentrated in a sedimentary environment. The uranium occurrences and enclosing rocks were later metamorphosed in place during intrusion of diabase.

2) Low-grade disseminations of uranium in the sedimentary rocks were remobilized and concentrated during the contact metamorphism associated with diabase intrusion.

3) Uranium was derived from the diabase intrusions, as proposed by Granger and Raup (1969b).

This paper proposes a model for uranium concentration in which the source, transport, and deposition of uranium all were associated with the diagenetic/low-grade metamorphic processes that affected the Dripping Spring Quartzite, and that this uranium was remobilized and further concentrated by metamorphism associated with diabase intrusion. Figure 8 diagramatically shows the relationship between uranium and various diagenetic events. The characteristics of the Dripping Spring Quartzite that are pertinent to its role as host rock are (1) the presence of fine-grained, potassium feldspar-rich strata, (2) development of stylolites and thin bedding, and (3) the presence of reductants, such as carbonaceous matter and HS^-.

Primary concentration of uranium

The source of the uranium was the volcanic sediments of the upper part of the Dripping Spring Quartzite. During diagenesis and conversion of volcaniclastics to zeolites and, ultimately, to potassium feldspar, uranium was released from the volcanics. The uranium could not be incorporated into the feldspar structure. The uranium did not migrate except on a microscale at this time, either because of a lack of migrating solutions or because it was adsorbed on carbonaceous matter or on clays.

Major transport and concentration of uranium was during or following stylolite formation, as stylolites and bedding planes were the primary channelways of uranium-bearing solutions. As noted, stylolites could have formed over a long time span, ranging from early compaction to postconsolidation. Two alternatives for transporting solutions are proposed: (1) intraformational solutions derived from pressure solution and compaction, including water released during the conversion of zeolite to feldspar; and (2) epigenetic solutions migrating along planar features. The first hypothesis is favored, but the possibility of later solutions, perhaps

Relationship between diagenesis/low-grade metamorphism and uranium concentration

Quartz-feldspar overgrowths, cement	Authigenic feldspar formation	stylolite formation	sphene formation*

release of U from volcanoclastics

- - - - - - - - transport of U - - -

- - - deposition of U - - -

crystallization of uraninite

*may have also formed during contact metamorphism

Figure 8.--Diagram shows how diagenetic/low-grade metamorphism controlled uranium concentration.

similar to those that form more typical deposits, should be recognized. The dissolution of strata that accompanied stylolite formation is hypothesized to have supplied the uranium contributed to migrating solutions. The released uranium probably was derived primarily from nonreducing, carbonaceous-poor strata.

The proximity of uranium occurrences to overlying evaporites suggests that evaporite pumping or reflux could have played a role in migration of uranium-bearing fluids. This mechanism has been used to explain transport and deposition of uranium in the Jurassic Todilto Limestone of New Mexico (Rawson, 1975). However, in the Dripping Spring Quartzite there is no need to introduce distantly derived uranium-bearing fluids into the formation. Both uranium and fluids probably were derived from the Dripping Spring Quartzite. The significance of the evaporites may be primarily that they suggest the presence of an evolving interstitial brine during deposition and diagenesis of the upper part of the Dripping Spring Quartzite and the Mescal Limestone.

The transporting solutions derived from the upper part sediments probably would have been alkaline, as suggested by the presence of authigenic potassium feldspar, which generally forms in alkaline environments, the inferred interbedded carbonates, and the hypothesized increasingly saline environment of deposition of the Dripping Spring Quartzite. In an alkaline solution, uranium probably would have been carried in carbonate or hydroxide complexes.

Transporting solutions were limited to movement along planar features, such as bedding and stylolites, and to migration through the finer grained strata. Uranium was concentrated primarily in these planar features and fine-grained strata. The coarse-grained, quartz-rich and quartz-cemented strata were impermeable to the uranium-bearing solutions, although quartz along the edges of the coarse-grained layers is partially resorbed, indicating some

reaction with the solutions. Carbonate cement would have been insoluble, and thus impermeable to the alkaline solutions. This impermeability may explain the lack of uranium in pyroxene-rich layers, the metamorphosed equivalents of impure carbonate layers.

Uranium deposition was accomplished by reduction by carbonaceous matter or HS^- and adsorption onto Fe- and Ti-oxides. The affinity of uranium for Ti-oxides is documented by Reynolds and others (1977) and Zielinski (1978), and the rutile cores of sphene attest to the original presence of Ti-oxides. These oxides probably formed during alteration of ilmenite. The association of uraninite and ilmenite, both surrounded by sphene, suggests that the sphene may have formed from Ti-oxides derived from ilmenite, and that the uranium was originally adsorbed onto these Ti-oxides.

Uranium was deposited in microenvironments containing abundant reductants, adsorbers or local changes in pH which favored precipitation. The stratabound blanket form of some occurrences is a result of the fluids encountering these reducing environments. The fact that both the inferred source and the site of deposition of uranium are restricted to the upper part indicates limited movement of the uranium. Disseminated uranium may mimic the original distribution of reductants and oxides in these zones. Solution along stylolites and bedding planes concentrated insolubles such as oxides, which scavenged large quantities of uranium. Only rarely do cross-cutting fractures contain primary uranium minerals, and these few also are filled with sphene or chlorite. This association emphasizes the role of Ti-oxides, and suggests that there had been little fracturing at the time of initial uranium concentration. The ore-related pyrite with magnetite(?) inclusions may have formed at this time, suggesting that sulfurization accompanied uranium deposition.

Concentration of the ore in a specific stratigraphic interval suggests that these strata had abundant reductant and nearby uranium source, and, in addition, may have had some feature, such as thin bedding, that would have allowed access to migrating solutions. The barren quartzite in the middle of the section may have acted as an aquifer for uranium-bearing solutions. However, throughout the section the quartz-rich and quartz-cemented strata are uranium-poor and apparently were impermeable to fluids. The proximity of quartzite to the uranium occurrences may be because uranium concentrated along boundaries separating permeable and impermeable strata.

The lower part and buff unit do not contain uranium concentrations, although there are similarities between them and the gray unit. The buff unit contains abundant stylolites and potassium feldspar, although clastics are in greater proportion than in the gray unit. The lower part has authigenic feldspar in minor quanities. Apparently, the critical factor in uranium concentration was the presence of abundant reductants, which are unique to the gray unit.

Although the Pioneer Formation contains volcanogenic sediments, it does not contain uranium concentrations. The Pioneer does not appear to have undergone the extensive diagenesis that affected the Dripping Spring Quartzite. The low uranium concentration in the Pioneer is probably a result of lack of interstital brine triggering potassium-feldspar formation and uranium release, lack of wide-scale dissolution and fluid migration, and the absence of carbonaceous matter to reduce and to concentrate uranium.

The effect of diabase intrusions on uranium concentrations

Diabase intrusion, associated contact metamorphism, and uranium remobilization occurred after primary uranium mineralization. This conclusion is supported by the following evidence:

1. Uranium mineralization is primarily stratabound on both macroscale and microscale. Even where the sedimentary rock has been coarsely recrystallized, uraninite remains predominantly stratabound.
2. Uraninite is within metamorphic minerals, most commonly coarsened potassium-feldspar groundmass, sphene, pyrite, chalcopyrite, pyrrhotite, and phlogopite.
3. Incipient melting spots disrupt uraninite layering, indicating that some uranium mineralization predated at least the highest grade metamorphism.
4. Smith (1969) found no evidence of major-element transfer between diabase and siltstone outside the immediate contact area. This lack of migration suggests that there was no large-scale transfer of uranium from the diabase.

Remobilization of uranium occurred during diabase intrusion. The uranium-mineral ages probably represent remobilization and crystallization associated with contact metamorphism. Uranium was concentrated in vertical veinlets and in veinlets along bedding planes and stylolites. The samples used in this study were insufficient to determine the extent of remobiliztion. Veinlets along planar features could be either remobilized uranium or primary mineralization concentrated during diagenesis, recrystallized and only slightly mobilized during metamorphism.

The spatial association of diabase and uranium mineralization is real, but may not be the causal relationship presented by Granger and Raup (1969b). There are at least four other alternatives that explain the spatial relation between uranium mineralization and diabase.

(1) The uranium mineralization and diabase intrusions were both controlled by the same structural features such as thin bedding and monoclines, and therefore were concentrated in the same areas.

(2) Diabase intrusions are so widespread that it is nearly impossible to find a section that has not been affected by the diabase. The spatial relationship between diabase and uranium mineralization may be merely fortuitous.

(3) The vertical veinlets and the more spectacular uranium concentrations were formed by remobilization during contact metamorphism. It is these occurrences that are most easily found and, therefore, where exploration has concentrated.

(4) Remobilization associated with contact metamorphism was necessary for concentration of uranium into economic or near-economic grades and tonnages.

The blanket occurrences of Granger and Raup (1969b) are probably the primary mode of uranium mineralization, varying in size and grade and modified by metamorphism. This remobilization explains the poor definition of vein outline, the disseminated form of uraninite in the hornfelsic siltstone, and the uraniferous stringers in the hornfels and remobilized sedimentary rocks. Melting and high grade metamorphism produced the vertical veinlets. The Black Brush, which has characteristics of both vein and blanket occurrences, may be an example of a partly remobilized blanket occurrence.

Chloritic alteration and coffinite formation

Rocks in the ore horizon were modified by a chloritic alteration event. Coffinite resulted from reaction of uraninite with these later solutions, that presumably followed the same channelways as did the primary mineralization. The discrete uraninite grains in well-defined layers were replaced by coffinite veinlets. Coffinite replacement of uraninite represents introduction of silica. Evidence of replacement is the similar distribution of the two types of uranium mineralization, fine uranium-silica rims around uraninite, the anhedral uraninite in coffinite, and the coffinite concentrated along the edges of uraninite layers. The anhedral uraninite in coffinite is probably a relict of the primary mineralization, and the variation in the quantity of uraninite present is a function of the degree of replacement. The fine euhedral galena cubes associated with coffinite probably are composed of radiogenic lead derived from the uraninite. Only uraninite included in sulfides was protected from the alteration fluid, which explains the presence of euhedral uraninite in sulfides within coffinite veins. Groundmass uraninite in part was converted to coffinite, but much of the uraninite was enclosed by other minerals and therefore avoided reaction.

Magnesium-chlorite alteration and chalcopyrite and iron-sulfide minerals commonly are associated with coffinite. The iron-sulfide minerals are commonly fine-grained. Chemical analyses (table 1) indicate that the coffinite-rich rocks are enriched in magnesium and ferric iron, reflecting the association with chlorite and fine hematite, and have high Cu values. Uraniferous chlorite veinlets are associated with hematite-carbonate and quartz-pyrite assemblages. The paragenetic sequence of veins suggests that hematite was later than chlorite, perhaps even deposited by supergene processes. However, in some veins and in the groundmass, chlorite and

hematite are intimately mixed. This mixing may be the result of replacement of iron-sulfide minerals by hematite. Vein compositions indicate that uraninite replacement was the result of interaction with a fluid carrying Mg, Si, Fe, Cu, and S. Silicon, as well as Al, also may have been derived from wall-rock reactions, as total Si content is low in coffinite-rich rocks. The high Mg content may be related to derivation from or flow through evaporites. The fine sulfide needles associated with coffinite suggests Fe and S saturation and rapid deposition.

Movement of uranium during this event apparently was not too extensive, because coffinite commonly only replaces pre-existing uraninite. Chlorite alteration assemblages do extend out into the wall rocks, and uraniferous cross-cutting veinlets do indicate some remobilization. The timing of coffinite deposition is unknown. Chloritic alteration may be related to retrograde metamorphism associated with the diabase intrusion. However, if the galena cubes in the coffinite contain radiogenic lead expelled during replacement of uraninite, appreciable uranium decay must have occurred prior to replacement. This radiogenic lead content would suggest the chlorite-coffinite event was related to later, perhaps Tertiary, thermal activity.

COMPARISON OF THE DRIPPING SPRING QUARTZITE URANIUM OCCURRENCES WITH WORLD CLASS DEPOSITS

The Dripping Spring Quartzite uranium occurrences are apparently located in a marginal marine sedimentary sequence. This setting and the rock types of the Dripping Spring Quartzite and Mescal Limestone, including carbonaceous siltstone, dolomite and evaporites, are being recognized increasingly as favorable environments for uranium mineralization (McMillan, 1977; Nash, 1980).

There are interesting similarities between the Dripping Spring Quartzite and the Australian Alligator Rivers uranium deposits. Both are in Proterozoic, probably marginal marine sequences containing carbonaceous matter, carbonates and evidence of evaporites, both have undergone remobilization during metamorphism, and both have been affected by a low-temperature chloritic alteration (Crick and Muir, 1980). However, the Alligator Rivers deposit has higher grades and tonnages of uranium; this is probably the result of greater remobilization during high-grade metamorphism and chloritic alteration or higher initial uranium content. In contrast, most of the Dripping Spring Quartzite has undergone only low-grade metamorphism, and extensive remobilization has been restricted to high-grade contact aureoles of intruding diabase. The later chloritic alteration had only a small effect on uranium distribution, primarily changing uraninite to coffinite. The Dripping Spring Quartzite uranium deposits might be considered a model of the intermediate stages between protore and remobilized concentrations like that found in the Alligator Rivers region, where high-grade metamorphism, alteration, and structures such as an unconformity separating vastly different rock types may have played important roles in upgrading uranium concentrations.

CONCLUSIONS

The uranium occurrences in the Dripping Spring Quartzite are sedimentary concentrations that were remobilized during intrusion of diabasic sills and later chloritic alteration. The occurrences are stratabound within the upper part of the formation, a carbonaceous siltstone composed of 50-90 percent potassium feldaspar. Uranium is concentrated in fine grained and finely laminated and stylolite-rich layers.

The uranium was derived from the upper part of the Dripping Spring Quartzite, which was originally predominantly volcaniclastic. Extensive diagenesis of the volcaniclastics in saline, interstitial brines resulted in the formation of authigenic potassium feldspar and the release of uranium. Primary concentration of uranium occurred during late-stage diagenesis, when pressure solution caused widespread dissolution and stylolite formation. These stylolites and bedding planes were major channelways of uranium-bearing fluids. Uranium precipitated where the fluids encountered areas with high content of carbonaceous matter, pyrite, titanium and iron oxides, and changes in pH.

Remobilization of uranium occurred during intrusion of diabase sills. The extent of remobilization is unknown. Vertical veinlets and veinlets along bedding planes and stylolites probably formed at this time. However, the veinlets parallel to bedding may represent only minor remobilization, as these are also thought to be the sites of primary deposition.

Extensive chloritic alteration affected the upper part and caused replacement of uraninite by coffinite. This alteration was probably a later event, perhaps associated with Tertiary igneous activity in the region. It may, however, have occurred during late retrograde metamorphism accompanying diabase intrusion.

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