UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Origin of the Mariano Lake Uranium Deposit,

McKinley County, New Mexico

By

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ABSTRACT

The Mariano Lake uranium deposit, hosted by the Brushy Basin Member of the Jurassic Morrison Formation, occurs in the trough of an east-west trending syncline at the western end of the Smith Lake-Mariano Lake group of uranium deposits near Crownpoint, New Mexico. The orebody, which contains abundant amorphous organic material, is situated on the reduced side of a regional reduction-oxidation (redox) interface. The presence of amorphous organic material suggests the orebody may represent a tabular (primary) deposit, whereas the close proximity of the orebody to the redox interface is suggestive that uranium was secondarily redistributed by oxidative processes from pre-existing tabular orebodies.

Uranium contents correlate positively with both organic carbon and vanadium contents. Petrographic evidence and scanning electron microscope-energy dispersive analyses point to uranium residence in the epigentically introduced amorphous organic material, which coats detrital grains and fills voids. Uranium mineralization was preceded by the following diagenetic alterations: precipitation of pyrite (δ^{34}S values ranging from -11.0 to -38.2 per mil); precipitation of mixed-layer smectite-illite clays; partial dissolution of some of the detrital feldspar population; and precipitation of quartz and adularia overgrowths. Alterations associated with uranium mineralization include emplacement of amorphous organic material (possibly uranium bearing); destruction of detrital iron-titanium oxide grains; co-precipitation of chlorite and microcrystalline quartz, and precipitation of

pyrite and marcasite (δ^{34}S values for these sulfides ranging from -29.4 to -41.6 per mil). After mineralization, calcite, dolomite, barite, and kaolinite precipitated, and authigenic iron disulfides were replaced by ferric oxides and hydroxides.

Geochemical data (primarily the positive correlation of uranium content to both organic carbon and vanadium contents) and petrographic observations (epigentically introduced amorphous organic matter and uranium residence in this organic matter) indicate that the Mariano Lake orebody is a tabular-type uranium deposit. Oxidative processes have not noticeably redistributed and reconcentrated primary uranium in the immediate vicinity of the deposit nor have they greatly modified geochemical characteristics in the ore. Preservation of the Mariano Lake deposit may not only be related to its position along the synclinal trough, where oxidative destruction of the orebody has been inhibited by stagnation of oxidizing ground waters by the structure, but also due to the deflection of ground waters (resulting from low orebody porosity) around the orebody.

INTRODUCTION

Sedimentary rocks in northwestern New Mexico host the largest known accumulation of uranium deposits in the United States. Most of these deposits are found in the Jurassic Morrison Formation, and occur in a zone roughly 130 km in length and 20 km in width. Collectively these deposits compose the Grants Mineral Belt (GMB). The purpose of this geochemical and mineralogic investigation is to contribute to our understanding of the origin of the Mariano Lake deposit, one of the uranium deposits in the GMB. The fundamental question addressed in this paper is whether the Mariano Lake deposit

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represents a primary (tabular) orebody or a secondary (redistributed) orebody. Such a distinction is important in understanding the mechanisms of uranium concentration and preservation of the uranium deposits in the GMB, and specifically those that define the Smith Lake-Mariano Lake trend along which the Mariano Lake deposit lies.

Tabular and redistributed deposits typically differ in orebody shape, geochemical signatures, and authigenic mineralogy. Tabular-type orebodies are elongate layers of mineralized rock typically suspended within a chemically reduced host sandstone such that upper and lower contacts of mineralized rock roughly parallel bedding of the host sandstone (Granger and others, 1961). On the other hand, redistributed orebodies of the GMB are characterized by uranium concentrations on the reduced (downdip) side of a commonly crescentic reduction-oxidation (redox) interface (Granger and others, 1961; Squyres, 1969), and thereby resemble roll-type uranium deposits of Wyoming and Texas (Granger and Warren, 1969; Harshman, 1972; Adler, 1974).

Geochemical characteristics shared by tabular deposits in the GMB include nearly equal weight percentages of organic carbon and uranium (Granger and others, 1961; Leventhal, 1980), and anomalously high concentrations of vanadium; however, vanadium content is typically equal or subordinate to uranium content. In addition, high concentrations of molybdenum and selenium may occur locally within or at the edges of mineralized rock in tabular deposits (Squyres, 1969). In contrast, organic carbon and molybdenum concentrations are very low and vanadium concentrations are usually in excess of those of uranium in ore zones of redistributed deposits (Granger and others, 1961; Squyres, 1969; Spirakis and others, 1981). A zone of selenium enrichment may also be present along the redox interface of redistributed

orebodies (Squyres, 1969). Sulfur and ferrous iron occur in anomalously high concentrations in ore zones of both tabular and redistributed deposits (Granger, 1966; Squyres, 1969).

Amorphous organic material, is ubiquitous in of tabular deposits. In addition, authigenic chlorite and iron disulfide (pyrite) are commonly found in and adjacent to tabular orebodies (Granger, 1962; Squyres, 1969). Redistributed orebodies of the GMB, on the other hand, contain little or no amorphous organic material and authigenic chlorite; however, an enrichment of vanadium oxides (montroseite and haggite) as well as iron disulfides occur in ore zones (Granger and others, 1961; Granger, 1962). Thus, aside from iron disulfides, tabular and redistributed deposits greatly differ in authigenic mineralogy.

The presence of amorphous organic material is perhaps one of the most important as well as diagnostic characteristics of tabular uranium deposits in the GMB. Granger and others (1961) postulated that the organic material was originally derived from the decomposition of vegetation. The organic material was probably introduced into the host sandstone as a soluble organic (humic) acid or colloidal organic material, collectively referred to as humic material (Swanson and Palacas, 1965; Leventhal, 1980). Precipitation or flocculation of the humic material resulted in an amorphous organic material that coats detrital grains and fills interstices (Granger and others, 1961; Adams and others, 1978). Localization of the humic material may have occurred at the interface between two solutions: one solution bearing humic material and another that may have been a stagnant saline ground water (Shawe, 1976; Granger and others, 1980; Carpenter, 1980). Because some organic material has the capacity to adsorb large amounts of uranium (Szalay, 1964), formation of

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tabular orebodies may have resulted from concentration of soluble uranium ions by the organic material. The localization and concentration of uranium probably began while the humic material was soluble, and may have continued after the humic material precipitated from solution (Squyres, 1969; Leventhal, 1980). Geological and isotopic age studies indicate that formation of tabular uranium deposits in the GMB probably occurred within a few millions or tens of millions of years after deposition of the host sandstone (Granger and others, 1961; Nash and Kerr, 1966; Lee and Brookins, 1978).

Redistributed deposits in the GMB form by oxidation-reduction processes similar to those responsible for forming roll-type uranium deposits (Granger and Warren, 1969). By these processes, oxygen-rich ground waters, which contain uranium removed from tabular orebodies as a soluble uranyl ion, flow down the hydraulic gradient and invade iron disulfide-bearing reduced ground. Such invasion leads to the formation of a tongue of oxidized rock (altered tongue) that is separated from reduced rock by a C-shaped reduction-oxidation (redox) interface. Continuous or periodic encroachment of oxygen-rich ground water into reduced ground results in solubilization and re-precipitation of uranium as well as a downdip migration of the redox interface (Adler, 1974). In the GMB, many redistributed deposits apparently formed during the past several hundred thousand years and uranium redistribution may be continuing at the present time (Granger and others, 1961; Squyres, 1980; Granger and Santos, 1981).

Geochemical and mineralogic studies were undertaken to not only determine whether the Mariano Lake uranium deposit represents a tabular or redistributed orebody but also to add to knowledge of uranium ore-forming processes. Geochemical studies emphasized the content and distribution of uranium,

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organic carbon, vanadium, sulfur, iron, molybdenum, and selenium in the host rock in and around the ore zone of the Mariano Lake orebody. Nearly equal concentrations of uranium and organic carbon in mineralized rock would be indicative of a primary origin of the Mariano Lake orebody. In addition, anomalously high concentrations of vanadium content but less (Spirakis and others, 1981) than uranium content would be expected in rock within or adjacent to the ore zones in a primary deposit. On the other hand, low concentrations of organic carbon in ore zones, as well as concentrations of vanadium in excess of those of uranium would strongly suggest a secondary (redistributed) origin.

Mineralogic studies and determination of the paragenetic sequence of post-depositional alterations complement geochemical studies. An abundance of uranium-bearing amorphous organic material and authigenic chlorite in mineralized rock would point to a primary origin, whereas a paucity of organic material and an abundance of vanadium oxides in the ore zone would suggest a secondary origin for the deposit. Because tabular deposits apparently form shortly after deposition of the host sandstone, uranium mineralization (perhaps by precipitation of uranium-bearing organic material) would probably have occurred relatively early in the paragenetic sequence. In contrast, uranium and vanadium mineralization in redistributed orebodies likely would have occurred very late in the temporal sequence of diagenetic alterations.

Particular attention was paid to the authigenic iron disulfide minerals and their sulfur isotopic compositions. Sulfur isotopic data from other deposits in the GMB are available (Jensen, 1963) to which results from the Mariano Lake deposit may be compared. Although sulfur isotopic studies of redistributed orebodies in the GMB are lacking, such studies of roll-type

deposits in Wyoming (Warren, 1972) and Texas (Goldhaber and others, 1978) indicate that vastly different isotopic ratios may characterize different iron disulfide generations (for example, pre-ore and ore-stage iron disulfides) in some mineralizing environments involving oxidation-reduction processes. Finally, carbon and oxygen isotopes were determined on authigenic calcite and dolomite from the Mariano Lake deposit to help determine the nature of the ground waters, whether saline or meteoric, from which the carbonates precipitated (Keith and Weber, 1964; Weber, 1964).

AGE OF URANIUM DEPOSITS IN THE MORRISON FORMATION

Throughout the GMB, the Morrison Formation consists of three members which in ascending order are the Recapture, the Westwater Canyon, and the Brushy Basin Members. Stratigraphic, sedimentological, and provenance studies on the Morrison Formation are discussed in Craig and others (1955); Freeman and Hilpert (1956); Santos (1968); Green (1975); Saucier (1978); and Ethridge and others (1980).

Most uranium deposits in the GMB occur in fluvial sandstone units in the Westwater Canyon and Brushy Basin Members of the Morrison Formation. Uranium incorporated into tabular deposits in the GMB was likely derived from volcanic debris although some contribution from intrusive igneous detritus is possible (Santos, 1968; Squyres, 1969).

Several attempts have been made to date the tabular deposits of the GMB. For two tabular deposits, U/Pb isotope data minimum ages of uranium mineralization at 94 m.y. B.P. (Nash and Kerr, 1966), and at least 100 m.y. B.P. (Granger, 1963). Other age determinations for tabular deposits in the GMB include Rb/Sr dates of authigenic clay minerals. The dated clays,

chlorite and mixed-layer smectite-illite or chlorite-illite, are interpreted to have formed during the mineralization event, so that their age of about 110-135 m.y. is believed to reflect the age of the ore deposits (Lee and Brookins, 1978). Some tabular orebodies in the Morrison Formation are closely associated with Jurassic structural features, suggesting that they were emplaced prior to deposition of the Upper Cretaceous Dakota Sandstone (Moench and Schlee, 1967). Thus, geological evidence and absolute age determinations all indicate that emplacement of the tabular uranium orebodies in the GMB occurred prior to deposition of the Dakota Sandstone.

Redistributed deposits, on the other hand, appear to be much younger in age. In fact, Saucier (1980), and Granger and Santos (1981) suggest that uranium redistribution may be occurring at the present time.

GEOLOGIC SETTING AND DESCRIPTION OF THE MARIANO LAKE DEPOSIT

The Mariano Lake uranium deposit is about 15 km southwest of Crownpoint, New Mexico (fig. 1), in the lowermost arkosic fluvial sandstone unit of the Brushy Basin Member (Jenkins and Cunningham, 1980; J. F. Robertson, oral communication, 1981). The orebody spans the trough of an approximately east-west-trending syncline and part of the southern flank of the associated anticline. In this report, these structures are referred to as the Mariano syncline and Mariano anticline, respectively. The Mariano syncline and anticline extend east of the Mariano Lake deposit for about 10 km, where they die out in the Bluewater fault zone (Green, 1975; fig. 2), a fractured monocline of postulated Laramide age (J. F. Robertson, oral communication, 1980). Because the Mariano syncline and anticline are not continuous across, and do not appear to have been displaced by the Bluewater fault zone, they are likely of Laramide age or younger.
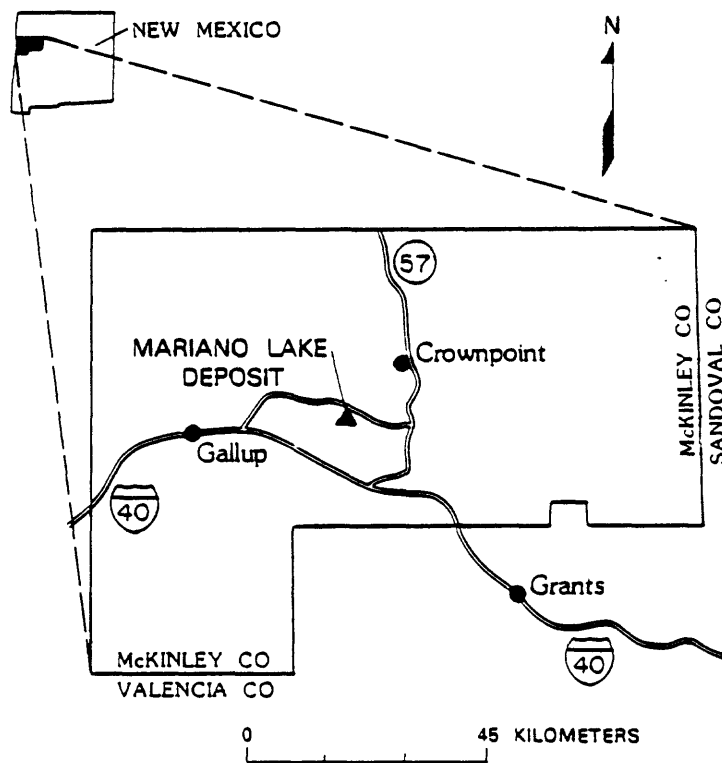
Figure 1.--Location map of the Mariano Lake uranium deposit.
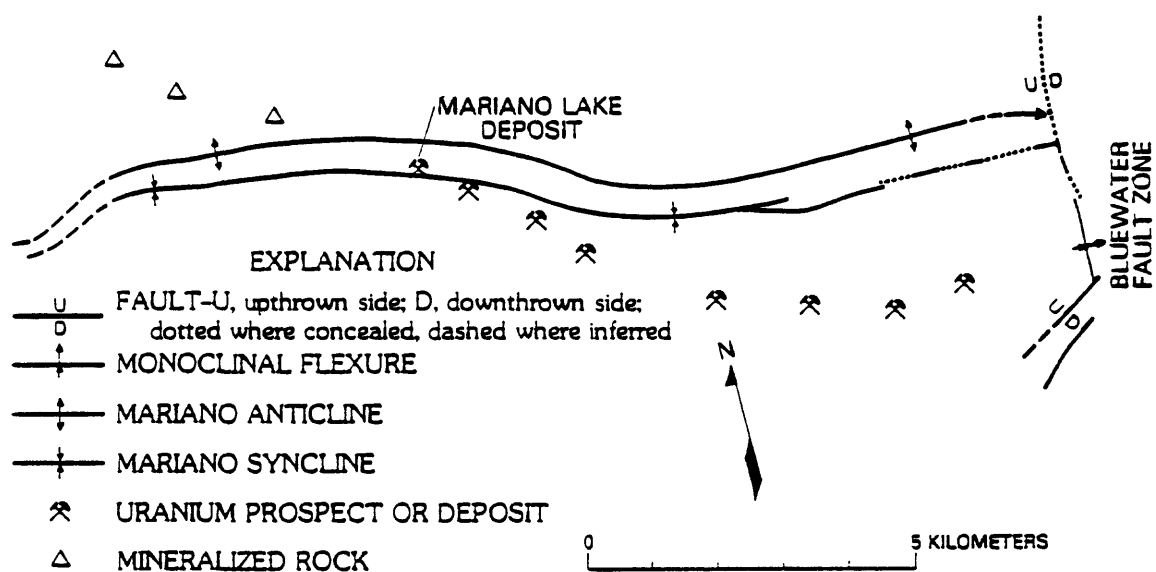
Figure 2.--Plan map of the Smith Lake-Mariano Lake group of
   mineralized rock and uranium deposits. Note the transection of
   mineralized rock across the Mariano syncline and anticline
   (modified from Green and Jackson, 1975; Robertson and Jackson,
   1975; J.F. Robertson, personal communication, 1981).

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The Mariano Lake deposit lies within the northwest trending Smith Lake-Mariano Lake trend of uranium orebodies (fig. 2). This orebody trend transects the Mariano structures, and mineralized rock in the trend extends from the Bluewater fault zone on the east to a few kilometers northwest of the Mariano Lake deposit.

Color of the host sandstone in the subsurface is variable ranging from dark-brown or black (mineralized rock) to white or green (unmineralized rock). Orange to red oxidized rock occurs locally in the ore zone. The host sandstone immediately south of the Mariano Lake deposit is red or yellow-orange oxidized rock as is rock that in part surrounds other deposits in the Smith Lake-Mariano Lake trend (Hoskins, 1963; MacRae, 1963; Ristorcelli, 1980).

The situation of the Mariano Lake orebody on the reduced side of a regional redox interface (fig. 3) has lead to the previous classification of this orebody as a roll-type deposit (Jenkins and Cunningham, 1980; Place and others, 1980; Sachdev, 1980). The apparent roll geometry of the Mariano Lake deposit is addressed below.

SAMPLING AND ANALYTICAL PROCEDURES

A total of 129 samples were collected at 26 mine localities (fig. 3). Additionally, 100 samples from seven drill cores were also obtained. Five cores are from holes drilled in rock south and north of the orebody, and two are from holes that penetrated the ore zone (fig. 3).

All of the 129 mine samples were analyzed for uranium by delayed neutron analysis; for organic carbon and sulfur using an induction furnace; for vanadium by inductively coupled argon plasma techniques; for selenium and iron
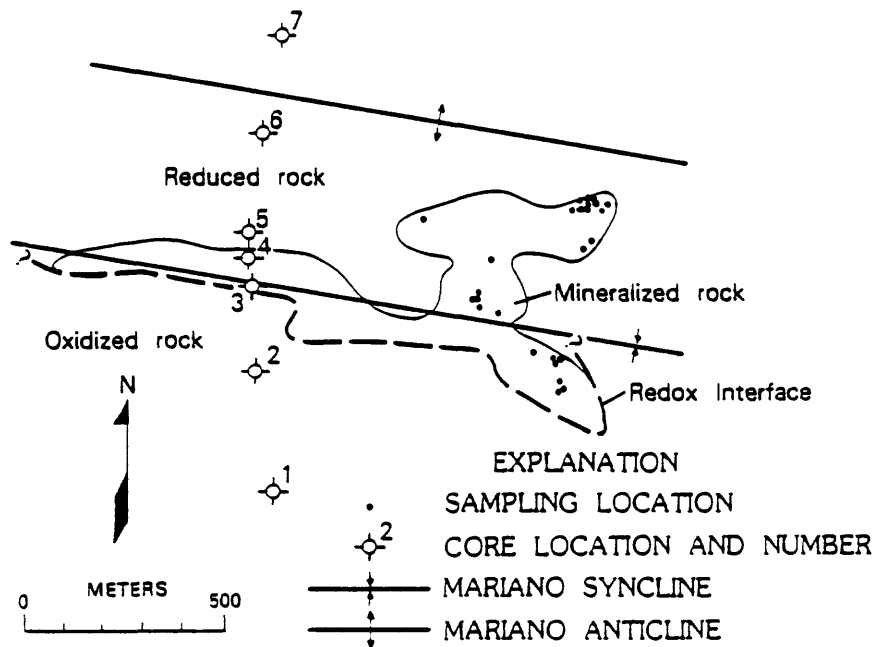
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Figure 3.--Plan map of the Mariano Lake deposit showing sampling
    localities and core hole locations. Note the presence of
    oxidized rock south and reduced rock north of the orebody
    (modified from Sachdev, 1980).

by x-ray fluorescence; and for molybdenum by emission spectrometry techniques. These analyses were performed by USGS personnel.

Separation of heavy minerals from the less than 44μm fraction were made on all 229 mine and core samples using standard heavy liquid procedures. Silt-size (2-62μm) and clay-size (<2μm) fractions of 21 mine samples were analyzed by standard x-ray diffraction procedures. The amount of interlayering in mixed-layer clays was determined by methods outlined in Reynolds and Hower (1970).

Petrographic observations were made of polished thin sections and polished grain mounts. Opaque minerals in thin sections were observed under vertically reflected light using oil immersion lenses. Reflected light microscopy was also used to observe the opaque minerals in polished grain mounts that were made of 135 of the heavy mineral separates. Rock chips were used for observation with a scanning electron microscope (SEM) that was equipped with an energy dispersive spectrometer (EDS).

Carbon, oxygen, and sulfur isotopes are expressed as the per mil difference in the ratio of $^{13}C/^{12}C$, $^{18}O/^{16}O$, and $^{34}S/^{32}S$ to those of a standard. These results are reported as $\delta^{13}C$, $\delta^{18}O$, and $\delta^{34}S$ respectively. For carbon and oxygen, the standard used for isotopic determinations was "Belemnitella americana" from the Peedee Formation (Cretaceous) in South Carolina. The standard used for sulfur isotopic determinations was troilite from the Cañon Diablo meteorite.

GEOCHEMISTRY

Elemental Concentrations and Residence

Uranium.--Uranium concentrations in sandstone samples from the Mariano Lake deposit were widely varied. For this report, unmineralized samples are

defined as those in which the uranium concentrations are less than 0.1%. Mineralized samples are those containing more than 0.1% uranium. The complete analytical data are given in Fishman (1981).

X-ray diffraction analysis of mineralized samples remote from the redox interface revealed the presence of coffinite (approximate composition being $U(SiO_4)_{1-x}(OH)_{4x}$) primarily in the clay-size fraction (<2 μm). The detection of uranium in amorphous organic material suggested that coffinite probably resided in this organic material. Energy dispersive analyses also detected the presence of uranium in authigenic chlorite that was present in the ore zone. The abundance and manner in which uranium resides in the authigenic chlorite is unknown.

Carbon.--As with uranium, carbon concentrations also varied widely. Organic carbon concentrations, however, correlate closely with those of uranium, exhibiting a nearly 1:1 ratio by weight percent, even at concentrations less than 0.10 percent (fig. 4a). Mineral carbon (carbonate) was detected in only 9 of the 129 mine samples upon which chemical analyses were determined. Mineral carbon amounts in those nine samples ranged from 0.05 to 1.70 percent. Organic carbon was present as an unstructured organic material that coated detrital grains and filled interstital voids. Mineral carbon was present as calcite and dolomite.

Vanadium.--Vanadium was present in all samples, ranging in concentrations from 0.002 to 0.7 percent. Vanadium concentrations show a positive correlation with those of uranium (fig. 4b).

Vanadium is associated with authigenic chlorite within mineralized rock. As with uranium though, the abundance and manner of vanadium residence in the chlorite is unknown. However, previous studies revealed that vanadium,
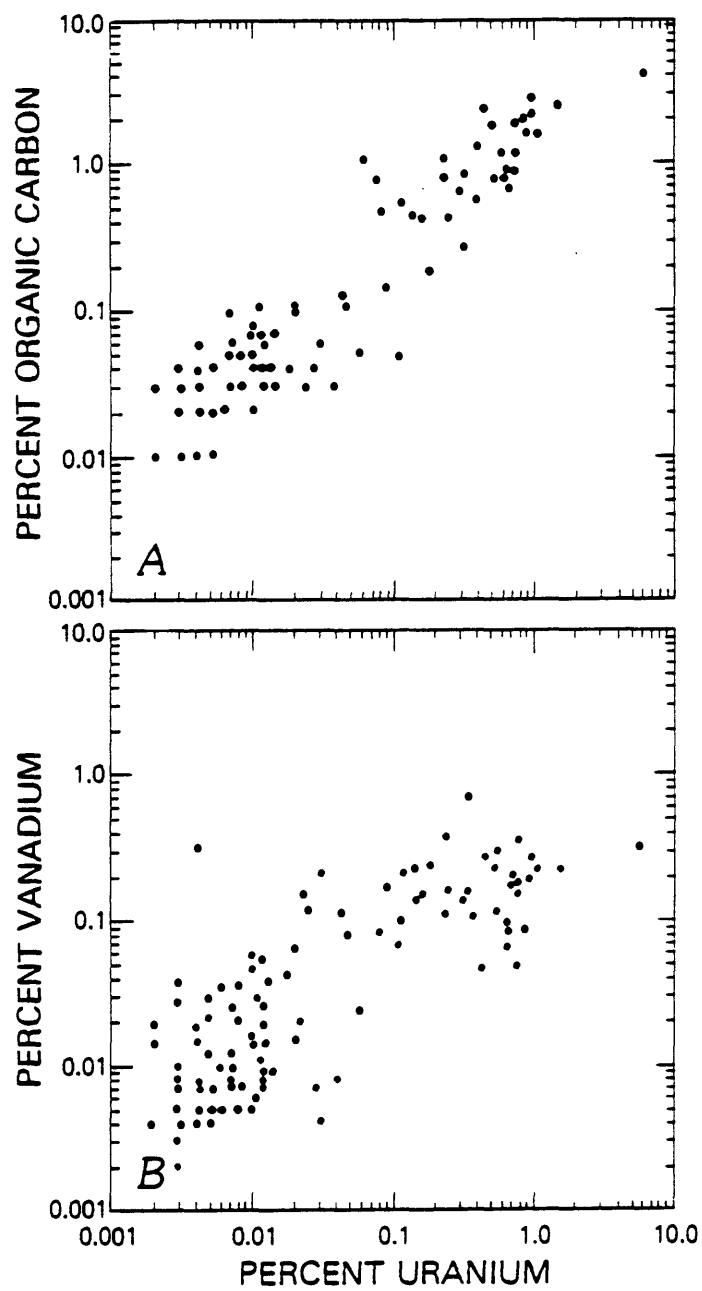
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Figure 4a.--Plot of uranium vs organic carbon contents.

Figure 4b.--Plot of uranium vs vanadium contents.

associated with chlorite in tabular deposits, is fixed within the crystal structure (Brookins, 1975). Chlorite found in unmineralized rock, although morphologically similar to ore-zone chlorite, is rarely vanadiferous. Petrographic, SEM-EDS, and x-ray diffraction analyses failed to detect vanadium minerals other than vanadiferous chlorite in either mineralized or unmineralized rock. Vanadium was, however, detected in some of the unstructured organic material.

Sulfur.--Sulfur, was very low or absent in oxidized, unmineralized rock, and was as high as 4.0 percent in mineralized rock. High concentrations of sulfur tend to correspond to high concentrations of uranium (fig. 5a).

Sulfur may be present in three forms: sulfide minerals; sulfate minerals; and organically bound sulfur. Most unmineralized and all mineralized samples contained iron disulfides (as determined by heavy mineral separations and petrographic observations). Barite ($BaSO_4$) was the only sulfate mineral detected in the Mariano Lake deposit, and it was found in only 4 of the 129 mine samples. It is unknown how much of the sulfur, if any, is organically bound.

Iron.--Iron was detected in all samples, ranging in concentrations from 0.26 to 6.55% (fig. 5b). High iron concentrations in mineralized rock reflects the presence of abundant iron-disulfide minerals, iron-bearing chlorite, and iron residence in the amorphous organic material. The lesser variable abundances of iron-disulfide minerals, iron-bearing chlorite, and iron-bearing amorphous organic material in unmineralized samples then results in the lower wide-ranging iron concentrations in such samples. In oxidized samples, iron is present primarily in iron-oxides and iron-hydroxides.
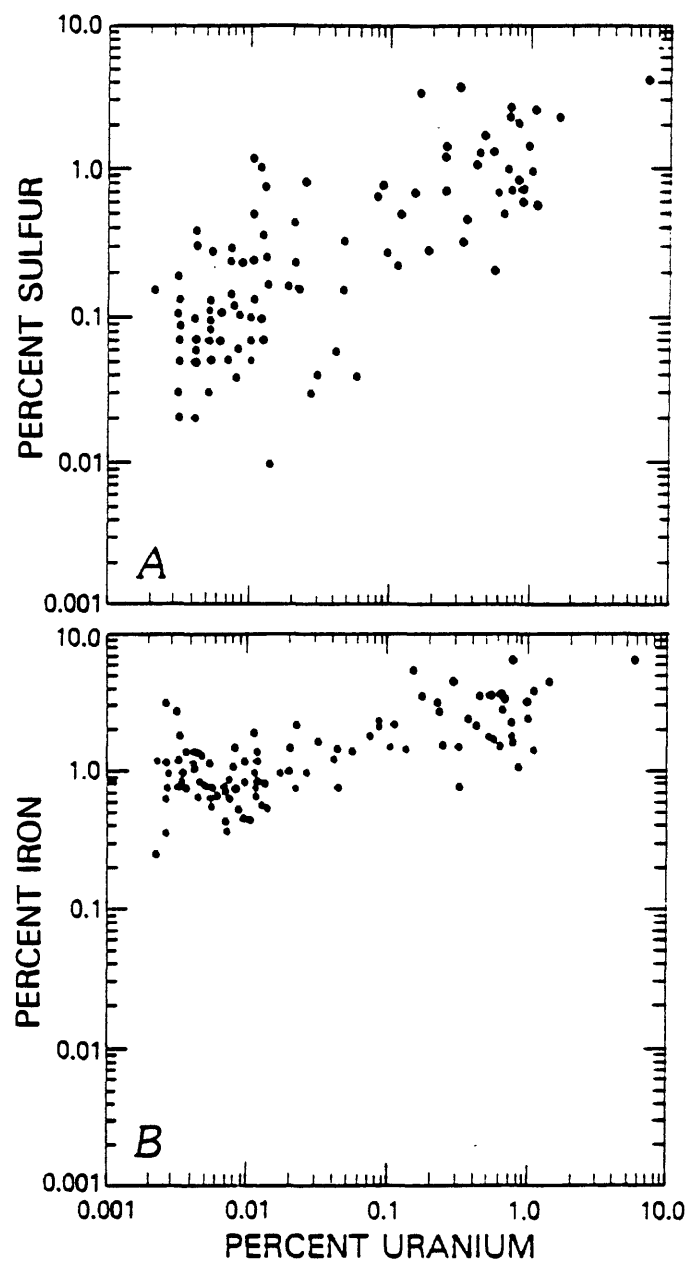
Figure 5a.--Plot of uranium vs sulfur contents.

Figure 5b.--Plot of uranium vs iron contents.

Molybdenum and selenium.--Both molybdenum and selenium showed variable

concentrations throughout the Mariano Lake deposit, and neither element showed

any correlation with uranium concentrations (Fishman, 1981). In addition,

molybdenum and selenium enrichment was not found in any particular zone or

zones within or adjacent to mineralized rock that were sampled; however,

potential locations of molybdenum and selenium enrichment may not have been

sampled adequately. Molybdenum was not observed either in a discrete mineral

phase or as a trace metal in other minerals. Seleniferous pyrite was noted

petrographically by its slight anisotropy and confirmed by electron microprobe

studies. Those sulfides containing selenium included unaltered pyrite as well

as partly to extensively oxidized pyrite. The presence of selenium in both

unaltered and altered iron disulfides suggests that it was incorporated in the

sulfides upon their formation, as described by Coleman and Delevaux (1957).

PETROLOGY

The host sandstone of the Mariano Lake deposit is generally a medium- to

coarse-grained arkosic sandstone (table 1). Sorting and cementation of the

sandstone are poor to fair; locally, however, the host sandstone is well-

cemented. Authigenic cements include clays, silica (quartz), potassium

feldspar (K-spar), organic material, iron disulfides, calcite, barite, and

dolomite. Detrital and authigenic constituents are discussed below.

Detrital Constituents

Detrital constituents of the host sandstone of the Mariano Lake deposit

include, in order of decreasing abundance, quartz, feldspar, lithic fragments,

and heavy minerals (table 1). Some lithic fragments may have contained minor

Table 1.--Modal Composition[a] of the Mariano Lake Deposit Host Sandstone

[--, not detected]

Sample number	Quartz	K-spar	Plag.	Lithic[b]	Other[c]	Pore space	Cements					Grain size	Sorting
							Quartz & Adularia	Organic material	Clay	Calcite	Sulfides		
M-10-1[A]	50	13	11	6	1	8	--	13	3	--	3	medium-coarse	poor
M-15-1[B]	55	13	10	2	4	9	7	--	9	--	--	medium-coarse	poor
M-17-1[A]	42	15	8	5	2	5	--	9	3	12	--	medium-coarse	poor
Core 2-3[B]	59	15	12	7	1	16	1	--	5	--	--	medium	fair
Core 3-2[B]	51	21	10	5	9	12	--	--	4	--	--	medium-coarse	poor
Core 6-5[C]	55	21	5	9	3	15	--	--	7	--	--	medium-coarse	poor
Core 7-2[C]	57	20	9	6	3	17	2	--	3	--	--	medium-coarse	poor

[a]Modal compositions were determined by point counts of 200 points; Pore space percentages not part of 100 percent rock composition.

[b]Lithic fragments from sedimentary, metamorphic, and igneous sources.

[c]Other includes unidentified grains and heavy minerals (detrital iron-titanium oxides, epidote, garnet, and zircon).

[A]Mineralized sample.

[B]Unmineralized, oxidized sample.

[C]Unmineralized, reduced sample.

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amounts of clay minerals. Monocrystalline and polycrystalline quartz comprise most of the detrital quartz population. Neither monocrystalline nor polycrystalline quartz show extensive alteration features.

K-spar dominates the feldspar population. Microcline and orthoclase are commonly present and typically unaltered. Other detrital k-spars were observed, but because of extensive dissolution their exact identity was undeterminable. Detrital plagioclase was commonly partly to extensively dissolved. Those grains that were partly dissolved usually contained relicts that displayed albite twinning. Partly to extensively sericitized grains were also present and were determined to be plagioclase by faint albite twinning.

Lithic fragments of volcanic, granitic and sedimentary origin also constitute part of the detrital grain population. Other fragments were observed, but extensive alteration made exact identification of the source of these grains impossible.

Detrital heavy minerals observed in the Mariano Lake deposit included iron-titanium oxides, epidote, zircon, and garnet. Most of the iron-titanium oxides were extensively altered, whereas epidote, zircon, and garnet showed only slight alteration.

Minor amounts of detrital carbonaceous (organic) material were also present in scattered localities throughout the host sandstone. This material included coalified plant debris and perhaps animal (dinosaur) remains. In places, the plant debris was extensively silicified.

Porosity of the host sandstone was determined by petrographic observations. The porosity in mineralized samples ranged from 5 to 8 percent, whereas porosity in unmineralized samples ranged from 12 to 17 percent (table 1). The relatively low porosity in mineralized samples in part resulted

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from the presence of unstructured organic material that coated detrital grains and filled some interstitial voids.

Diagenetic Alterations

Diagenetic alterations in the host sandstone have been divided into pre-mineralization, mineralization, and post-mineralization events. Individual alterations represent either authigenic mineral formation, dissolution of various detrital constituents, or a combination of the two. Criteria used in placing alterations in their respective positions are included in their descriptions. The paragenetic sequence is shown in figure 6.

<u>Pre-mineralization alterations.</u>--Authigenic pyrite formation is the earliest recognizable post-depositional alteration detected in the host rock. This pyrite forms as aggregates of euhedral pyrite crystals or as individual euhedral crystals, typically 5-20 μm across (fig. 7a). Framboidal pyrite, probably of a biogenic origin (Kalliokoski, 1969; Sweeney and Kaplan, 1973), was observed, but its relation to other authigenic minerals is unknown and its formation may have spanned many other diagenetic events.

Following formation of early diagenetic pyrite was the precipitation of authigenic clays onto the surfaces of some detrital grains (fig. 7a). These clays exhibit a honeycomb texture similar to that of authigenic smectites described by Wilson and Pittman (1977), and as such preclude a detrital or post-depositional mechanically introduced origin (Crone, 1975). X-ray diffraction analyses indicate the presence of smectite-rich clays, containing 20-30 percent illite layers, in the host sandstone (Paul Blackmon, written communication, 1981). The presence of these clays and their honeycomb texture suggest that they are, in fact, the mixed-layer smectite-illite clays detected by X-ray diffraction. Because pyrite euhedra are surrounded by these clays,

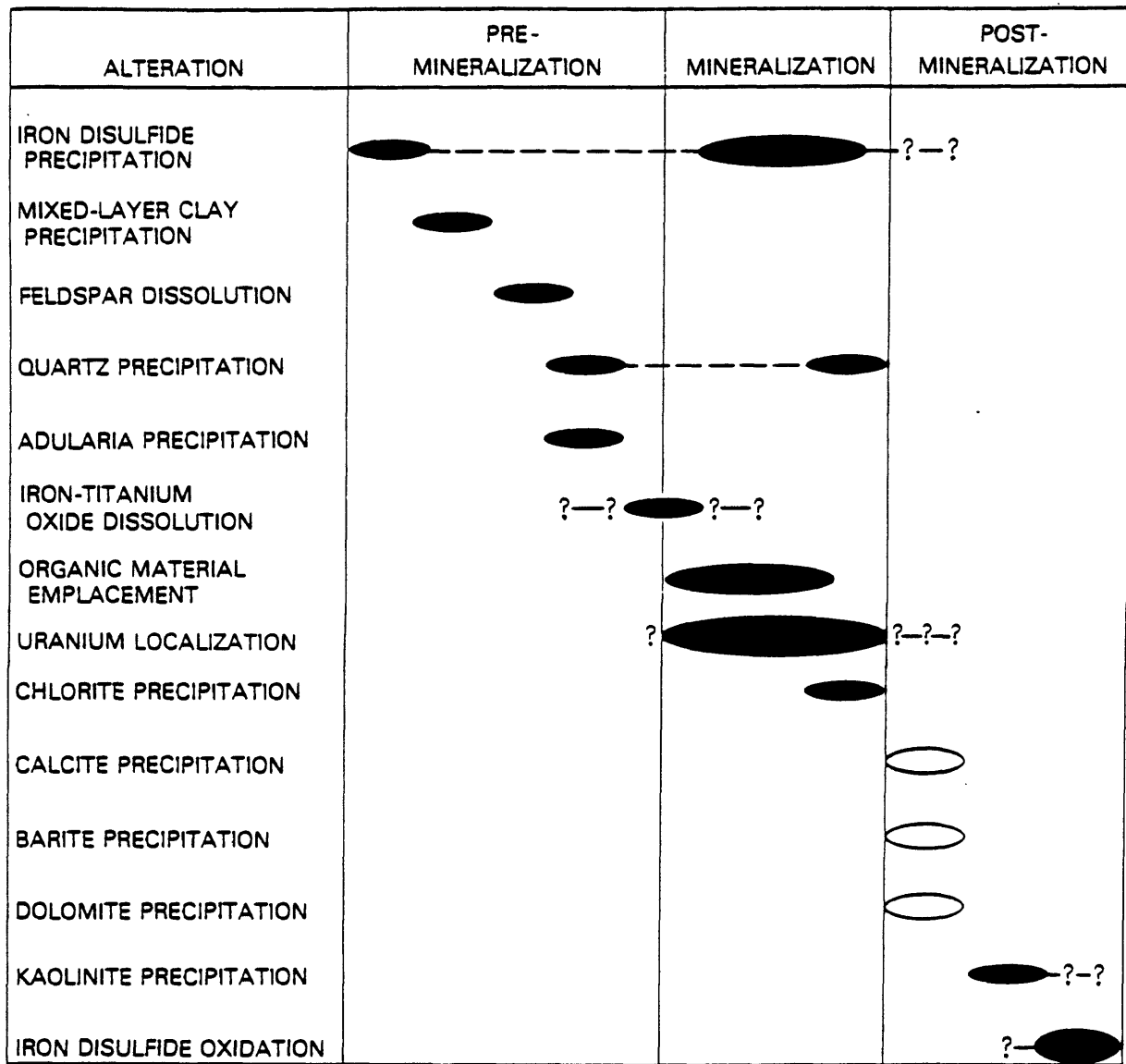| ALTERATION	PRE-MINERALIZATION	MINERALIZATION	POST-MINERALIZATION
IRON DISULFIDE PRECIPITATION	● − − − − − −	⬤	?−?
MIXED-LAYER CLAY PRECIPITATION	●		
FELDSPAR DISSOLUTION	●		
QUARTZ PRECIPITATION	● − − − −	●	
ADULARIA PRECIPITATION	●		
IRON-TITANIUM OXIDE DISSOLUTION	?−? ● ?−?		
ORGANIC MATERIAL EMPLACEMENT		⬤	
URANIUM LOCALIZATION	?	⬤	?−?−?
CHLORITE PRECIPITATION		●	
CALCITE PRECIPITATION			⬭
BARITE PRECIPITATION			⬭
DOLOMITE PRECIPITATION			⬭
KAOLINITE PRECIPITATION			●−?−?
IRON DISULFIDE OXIDATION			?−⬤

Figure 6.--Summary of post-depositional alterations in the host sandstone of the Mariano Lake deposit.
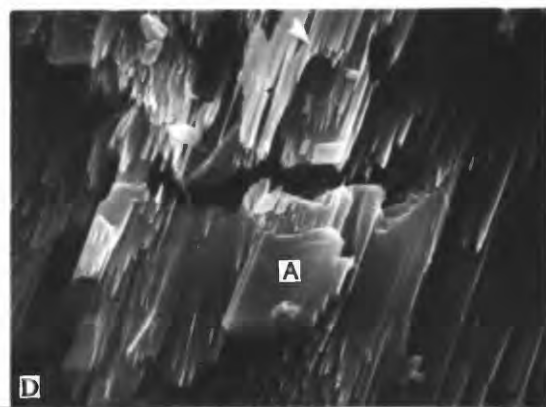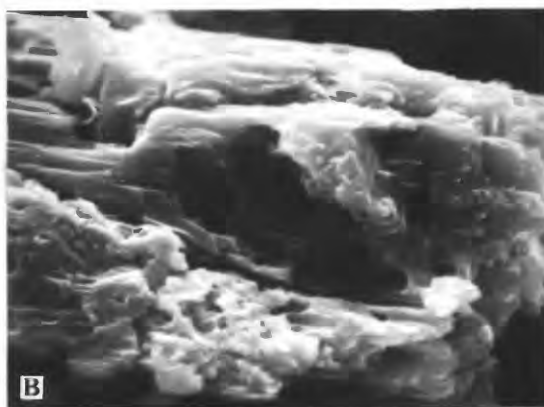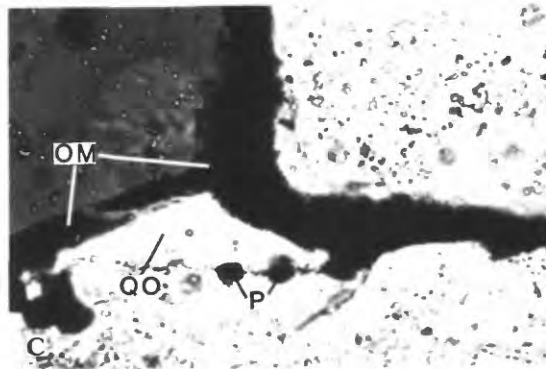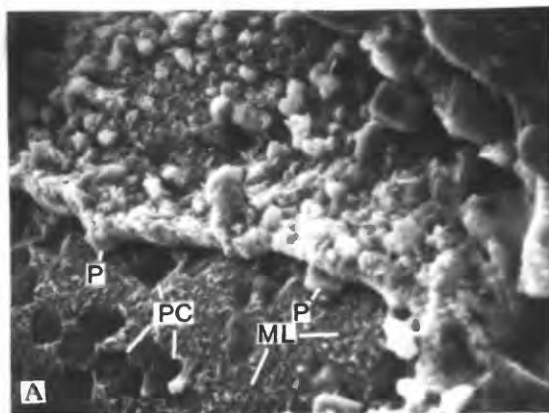
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Figure 7a.--SEM photomicrograph of pyrite (P) perched on the surface of a detrital quartz grain. Pyrite is partly covered by later ore-stage authigenic minerals (top half of picture.) Note casts of pyrite (PC) that resulted from the precipitation of mixed-layer clays (ML) around pyrite crystals. Pyrite previously positioned in these areas were plucked during SEM mount preparation. Field of view is 100 μm.

Figure 7b.--SEM photomicrograph of a partly dissolved detrital K-spar grain. The hollowed fragmented appearance of the grain resulted from dissolution. Field of view is approximately 35 μm.

Figure 7c.--Photomicrograph of quartz overgrowth (QO) which precipitated around and enveloped earlier formed pyrite (P). Note organic material (OM) that in turn coats the quartz over-growth. Field of view is approximately 700 μm.

Figure 7d.--SEM photomicrograph of partly dissolved detrital plagioclase grain. The splintered appearance resulted from dissolution. Note succeeding adularia (A) that formed on dissolved surfaces. Field of view is approximately μm.

mixed-layer smectite-illite clay formation likely followed precipitation of at least some of the pyrite.

Dissolution of both detrital plagioclase and K-spar, other than microcline and orthoclase, followed formation of mixed-layer clays. The splintered, hollowed, fragile appearance of altered feldspars precludes deposition of these grains in such a condition and indicates that dissolution occurred post-depositionally (fig. 7b). The absence of mixed-layer clays in secondary voids left by feldspar dissolution and the presence of succeeding authigenic minerals in these secondary voids (discussed below), indicates that feldspar dissolution followed the precipitation of mixed-layer clays but preceded formation of other authigenic minerals.

Precipitation of authigenic quartz and feldspar followed detrital feldspar dissolution. Electron microprobe and SEM-EDS analyses indicate the presence of potassium, silicon, and aluminum in the authigenic feldspars. Based on their composition and rhombohedral crystal habit (Sibley, 1978), these authigenic feldspars are identified as adularia ($KAl_2Si_3O_8$). Relationships with other post-depositional alterations place some constraints on the timing of quartz and feldspar precipitation. The incorporation of early pyrite euhedra in quartz overgrowths (fig. 7c) suggests that quartz overgrowths formed after early pyrite precipitation. The presence of adularia in secondary voids that resulted from feldspar dissolution indicates that adularia precipitation followed feldspar dissolution (fig. 7d). Quartz and adularia overgrowths are both coated by authigenic organic material indicating that they predate its emplacement.

Alterations associated with uranium mineralization.--Alterations and authigenic minerals associated with the uranium mineralization event include the precipitation of amorphous organic material, dissolution of detrital iron-

titanium oxide grains, co-precipitation of chlorite and microcrystalline quartz, and precipitation of pyrite and marcasite.

The amorphous organic material is brown and displays a resinous luster when viewed under vertically reflected light in oil. Using transmitted light, the organic material appears black. The organic material coats detrital grain surfaces and pre-mineralization authigenic minerals such as pyrite, mixed-layer clays, and quartz and adularia overgrowths. In addition, the organic material fills some secondary voids left by previous feldspar dissolution (fig. 8a). Organic material present along long and concave-convex grain contacts suggests that the organic material was emplaced prior to moderate compaction or pressure solution of detrital silicate grains. Fission track maps, electron microprobe, and SEM-EDS observations indicate that uranium commonly is distributed homogeneously throughout the organic material.

Detrital titanomagnetite grains have been extensively altered by removal of most of their iron leaving behind a titanium oxide residue, some of which mimics the original crystallographically controlled locations of ilmenite lamellae (Reynolds and Goldhaber, 1978; Ramdohr, 1980). The fragile nature of some of these grains is evidence for their post-depositional alteration. Dissolution of these grains must have begun prior to precipitation of the organic material because some dissolved iron-titanium oxide grains are filled with organic material (fig. 8b).

Chlorite, another ore-stage authigenic mineral (fig. 8c), was identified by X-ray diffraction analyses and the similarity in morphology it displayed to chlorite described by Wilson and Pittman (1977). Well-crystallized chlorite was the most abundant clay mineral in most samples from mineralized rock (Paul Blackmon, written communication, 1981). EDS analyses of chlorite from
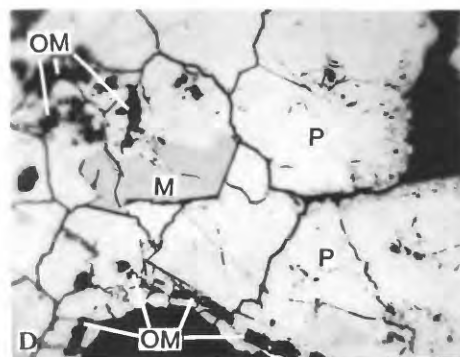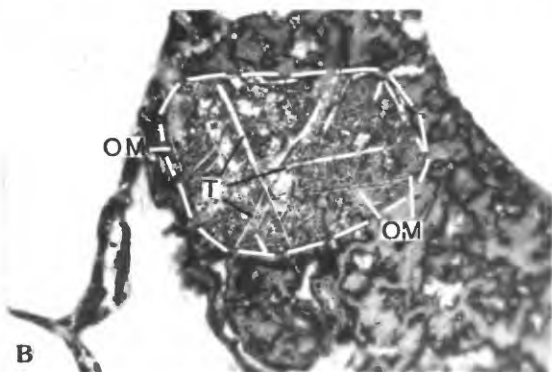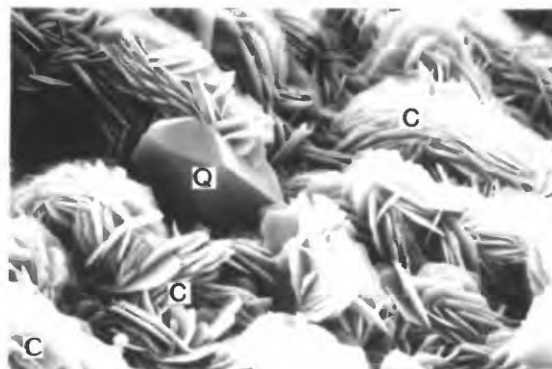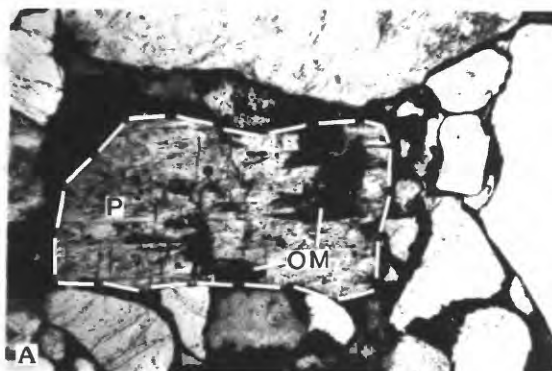
Figure 8a.--Photomicrograph of detrital plagioclase grain (out-lined area) with secondary dissolution voids filled with uraniferous organic material (OM). Organic material also coats the surfaces of detrital grains in field of view. Photomicrograph taken using transmitted light; field of view is approximately 1300 µm.

Figure 8b.--Photomicrograph of dissolved iron-titanium oxide grain (outlined area) with relict titanium-dioxide lamellae (T) and some voids filled with uraniferous organic material (OM). Organic material also fills interstices. Photomicrograph taken using vertically reflected light; field of view is approximately 300 µm.

Figure 8c.--SEM photomicrograph of co-precipitated ore-stage chlorite (C) and microcrystalline quartz (Q). Field of view is approximately 35 µm.

Figure 8d.--Photomicrograph of ore-stage pyrite (P) and marcasite (M). Pyrite is intimately mixed with organic material (OM). Photomicrograph taken using vertically reflected light; field of view is approximately 300 µm.

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mineralized rock revealed the presence of iron, vanadium, and uranium in addition to magnesium, silicon, and aluminum. Authigenic chlorite present in unmineralized reduced rock displays a similar morphology to chlorite in mineralized rock, but EDS analyses reveal that it is neither vanadiferous nor uraniferous. Chlorite in unmineralized rock is commonly subordinate in abundance to mixed-layer smectite-illite and/or kaolinite clays (Paul Blackmon, written communication, 1981). Although chlorite is situated on the surface of organic material and therefore post-dates emplacement of the organic material, the association of uranium with chlorite suggests that chlorite formation was closely related to the uranium mineralization event.

Microcrystalline quartz is intimately mixed with chlorite (fig. 8c) and as such, suggests co-genesis of the two authigenic minerals. Pre-mineralization quartz overgrowths, on the other hand, are not associated with admixed chlorite.

Pyrite and marcasite also formed during mineralization as subhedral and euhedral intergrowths with one another, and as intimate mixtures with organic material (fig. 8d). This intimate mixing of iron disulfides with organic material suggests that formation was contemporaneous with precipitation of organic material. The ore-stage iron disulfides in turn cement organic material, and thus their formation was not only contemporaneous with, but probably continued after precipitation of the organic material.

Post-mineralization alterations.--Following the uranium mineralization event, calcite, barite, and dolomite precipitated as cements of mineralized rock. However, paragenetic relationships with one another or with other preceding authigenic minerals (aside from organic material) are lacking.

Where they are present, sparry calcite and barite display luster mottling textures, indicative of a slow crystal precipitation (Pettijohn and others,

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1973). Calcite, barite, and dolomite precipitated in primary interstitial voids, in secondary voids left by feldspar dissolution, and fill remaining voids in rock containing uraniferous, amorphous organic material. Calcite was found in only 5, barite in 4, and dolomite only in 2 of the 129 thin sections studied.

Kaolinite formed after calcite, barite and dolomite. As with other authigenic clays, the presence of kaolinite was verified by both petrographic means and X-ray diffraction analyses. Kaolinite fills interstitial areas and replaces previously formed authigenic minerals including quartz, adularia, and calcite. Kaolinite not only forms embayments into calcite masses, but optically continuous relicts of calcite are found in kaolinite masses. The presence of kaolinite within the calcite (fig. 9) likely reflects kaolinite embayments into calcite from above or below the plane of the thin section.

Oxidation of the host rock, another post-mineralization alteration, resulted in replacement of iron disulfides by ferric oxide minerals. Additionally, ferric oxides in oxidized rock coat most detrital grains and pre-existing authigenic minerals, including some kaolinite. Although the evidence is inconclusive, the presence of both stained and unstained kaolinite in oxidized ground suggests that oxidation and kaolinite precipitation may have occurred simultaneously.

Distribution of Diagenetic Alteration Products

Petrographic observations indicate that early authigenic iron disulfides, mixed-layer clays, partly dissolved feldspars, and quartz and adularia overgrowths occur not only in the ore zone, but also in rock surrounding the orebody at least between Cores 1 and 7 (fig. 10). The extensive distribution

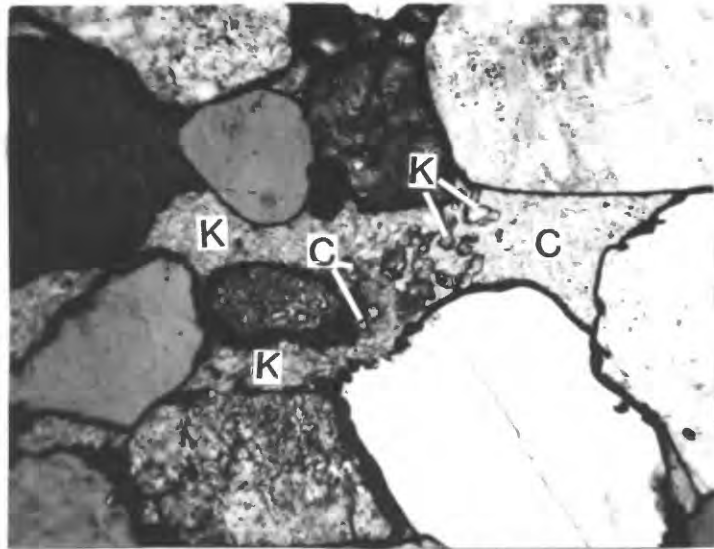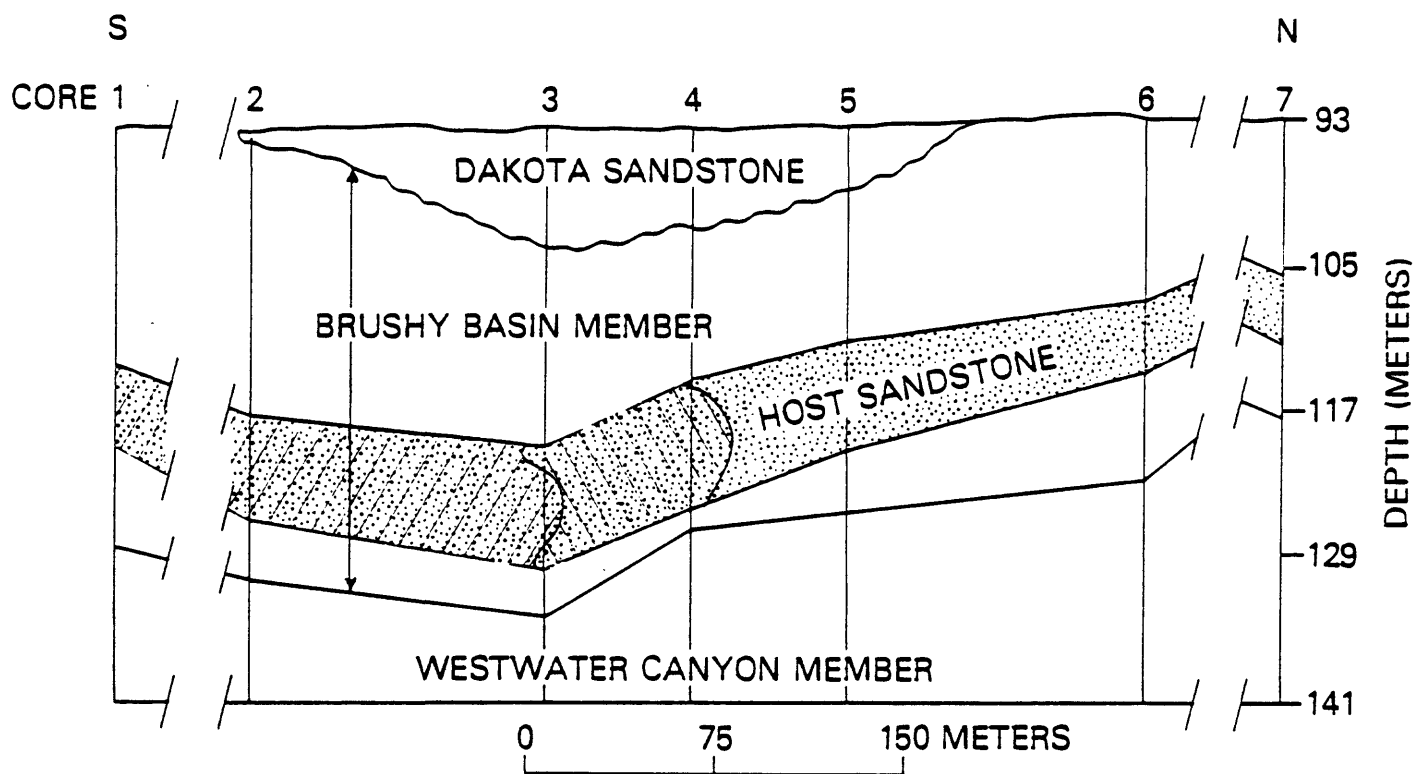Figure 9.--Photomicrograph of kaolinite (K) replacing calcite (C).
Note relict fragments of calcite surrounded by kaolinite; in
addition, kaolinite is present with the calcite cemented areas.
Photomicrograph taken using cross-nicols with a mica plate; field
of view is approximately 1300 μm.

Figure 10.--Geologic cross-section (modified from Sachdev, 1980)
showing the distribution of post-depositional alterations.

of these pre-ore alteration products suggests that prior to mineralization,
the entire host sandstone experienced a similar alteration history.

Unlike the ubiquitous occurrence of pre-ore alteration products in the
host rock, the mineralization event seems to have affected authigenic
mineralogy primarily in the ore zone. We saw no firm evidence for mineralogic
alteration haloes related to uranium mineralization beyond the ore zone.
Alterations associated with the uranium mineralization event (fig. 10) include
precipitation of authigenic organic material, dissolution of detrital iron-
titanium oxide grains, co-precipitation of chlorite and quartz, and
precipitation of iron disulfides. Partly altered magnetite and ilmenite occur
in rock which is north of the orebody; however, these iron-titanium oxides do
not show the complete dissolution features demonstrated by those in the ore
zone. The condition of detrital iron-titanium oxide grains updip from the
orebody was difficult to decipher, since those grains present were oxidized
and their pre-oxidation condition was indeterminate.

The distribution of post-mineralization authigenic minerals--calcite,
barite, and dolomite--is not well defined because of the rare occurrence of
these minerals. However, scattered occurrences of barite occur in the ore
zone and in unmineralized rock north of the ore zone, whereas calcite and
dolomite were found only in the ore zone. Kaolinite occurs throughout the
host rock (fig. 10). Oxidation effects are mainly seen in rock updip from the
ore body.

CARBON, OXYGEN, AND SULFUR ISOTOPES

Carbon and oxygen isotopes were determined on authigenic carbonate
minerals in nine samples (table 2). Eight of these samples were cemented with
sparry calcite; the ninth sample contained dolomite as the only detected

Table 2.--Carbon and oxygen isotopic values from carbonates in the Mariano Lake deposit.

Sample number	$\delta^{13}C$ (per mil)	$\delta^{18}O$ (per mil)	Carbonate type
M-13-1[A]	-7.9	-15.2	Calcite
M-13-2[A]	-18.8	-17.5	Dolomite
M-17-1[A]	-10.8	-15.6	Calcite
M-J-2[B]	-7.4	-15.3	Calcite
M-J-4[B]	-8.5	-15.9	Calcite
M-J-7[B]	-12.5	-15.2	Calcite
M-J-11[B]	-11.0	-13.6	Calcite
M-J-12B[B]	-8.3	-15.6	Calcite
M-J-14[B]	-11.1	-14.8	Calcite

[A]Sample collected by authors.

[B]Sample provided by Jacques Robertson.

authigenic carbonate. The calcite-cemented samples had a mean $\delta^{13}C$ of $-9.68\pm$ 1.75 per mil (one standard deviation). The dolomite sample had a $\delta^{13}C$ value of -18.82 per mil. The $\delta^{18}O$ values of the calcite cemented samples had a mean of $-15.14 \pm .65$ per mil (one standard deviation), whereas the dolomite sample had a $\delta^{18}O$ of -17.50 per mil.

Sulfur isotopes were determined on 28 samples containing authigenic sulfide minerals all from scattered localities throughout the deposit. These samples were divided into two groups: those from 8 mineralized samples, and those from 20 unmineralized samples. The sulfides in mineralized samples were dominantly pyrite or intergrown pyrite and marcasite that cemented ore. Sulfides in unmineralized samples varied in texture; however, in 11 of the samples, pyrite euhedra and euhedral pyrite crystals in aggregates dominated the sulfide population. The remaining 9 samples contained a mixture of sulfide textures. The sulfur isotopic composition of sulfides in the 8 mineralized samples ranged from -29.4 to -41.6. The isotopic composition of the 11 unmineralized samples containing primarily euhedral pyrite crystals ranged from -11.0 to -38.2 per mil. The isotopic composition of the remaining 9 samples ranged from $+2.2$ to -32.4 per mil. The sulfur isotopic data are summarized in figure 11. The complete sample and isotopic data are given in Fishman (1981).

DISCUSSION

Geochemically and petrographically, the Mariano Lake deposit closely resembles previously described tabular uranium deposits in the GMB. The following comparison of the Mariano Lake deposit to other tabular deposits is divided into three sections: (1) pre-mineralization alterations, (2)
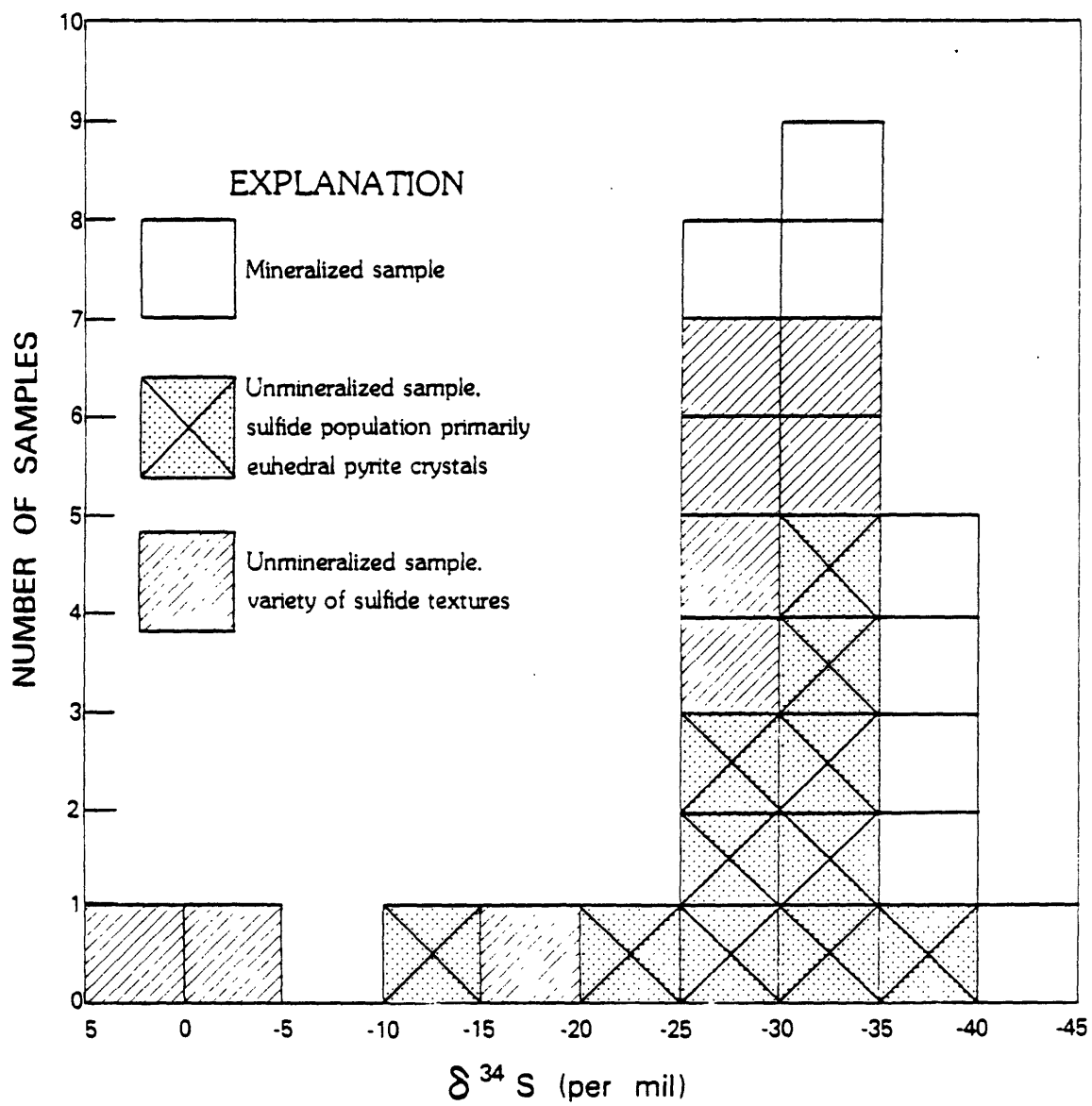
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Figure 11.--Histogram of sulfur isotope values.

alterations associated with mineralization and (3) post-mineralization
alterations.

Pre-mineralization Alterations

Authigenic iron disulfide minerals have been commonly noted in previous
studies of tabular orebodies. Austin (1963) suggested the possibility of
multiple generations of iron disulfides being present in a tabular deposit
located in the eastern part of the GMB. Petrographic observations from the
present investigation of the Mariano Lake tabular orebody reveal that, in
fact, iron disulfides formed at different times in the diagenetic evolution of
the Mariano Lake deposit. The earlier of the sulfide generations is the
earliest alteration detected.

The mean isotopic composition of the early diagenetic pyrite in
unmineralized samples is -27.95 ±6.85 per mil (one standard deviation). Such
isotopically light pyrite can form by either biogenic or nonbiogenic
processes. By biogenic processes, aqueous sulfide species, produced by
sulfate-reducing bacteria, are enriched in ^{32}S, the light sulfur isotope
(Thode and others, 1951). Sulfide minerals precipitated from bacterially
generated sulfide species are likewise enriched in ^{32}S (Goldhaber and others,
1978). Iron disulfides may form nonbiogenically from metastable sulfur
species created by oxidation of pre-existing biogenically derived pyrite
(Granger and Warren, 1969). Having originated from isotopically light pyrite,
these "reconstituted" iron disulfides are likely to be also isotopically light
(Granger and Warren, 1969; Goldhaber and others, 1978). Other nonbiogenic
processes involving chemical reactions between aqueous sulfate and sulfide
species under equilibrium conditions may produce isotopically light iron

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disulfides, but such equilibrium conditions are unlikely to be achieved at temperatures less than 200° C (Ohmoto, 1972).

Elevated temperatures (> 200° C) are unlikely to have occurred in Brushy Basin fluvial sediments shortly after deposition. Additionally, evidence for early oxidation in the Mariano Lake deposit is lacking; thus it is also unlikely that formation of isotopically light early pyrite resulted from the oxidation-reduction processes that form "reconstituted" sulfide minerals. A biogenic origin is then strongly suggested for the early pyrite in the Mariano Lake deposit. The presence of framboidal pyrite (Kalliokoski, 1969; Sweeney and Kaplan, 1973) lends additional support for a biogenic origin for at least some iron disulfide minerals.

Iron disulfide minerals in 9 additional unmineralized samples display a wide variety of isotopic compositions ranging from +2.2 to -32.4 per mil. These samples contain numerous different iron-disulfide textures and we can not explain the wide range in isotopic composition of such samples.

The presence of early authigenic smectite clays is typical of tabular deposits in the GMB (Granger, 1962; Brookins, 1975). These clays are thought to have formed as a result of alteration of volcanic debris incorporated into the Morrison Formation (Granger, 1962). Lee and Brookins (1978) interpreted these clays to have formed shortly after deposition and thus used the age dates of the clays to postulate a minimum age of Morrison Formation deposition. Although the early clays associated with the Mariano Lake deposit are mixed-layer smectite-illite (20-30 percent illite layers), they are presumably equivalent to the early authigenic smectite clays discussed by Granger (1962) and Lee and Brookins (1978). While it is somewhat conjectural to assume that the early smectite-illite clays in this deposit formed as a

result of volcanic debris alteration, the honeycomb texture displayed by these clays does suggest that they formed by precipitation from interstitial solutions. Paragenetic relationships suggest that in the Mariano Lake deposit, these clays followed formation of at least some early authigenic (biogenic) iron disulfides, but preceded feldspar dissolution.

Dissolved feldspars are another alteration feature commonly noted in tabular deposits of the GMB (Austin, 1963; Adams and others, 1978). The potassium and silica released during feldspar dissolution in the Mariano Lake deposit may have been a source for succeeding authigenic K-spar and quartz overgrowths.

Authigenic feldspar overgrowths are also typically associated with tabular deposits in the GMB. Adams and others (1978) noted authigenic albite in one tabular orebody, whereas Austin (1980) indicated that authigenic K-spar formed overgrowths on feldspars in other tabular deposits in the GMB. Authigenic feldspars in the Mariano Lake deposit are K-spars, identified as adularia.

Alterations Associated with Uranium Mineralization

The Mariano Lake deposit is similar to other tabular deposits in the GMB in that amorphous organic material is epigenetic, and the material is uraniferous. Although coffinite was not observed petrographically, it was detected by X-ray diffraction analyses. Fission track maps and SEM-EDS data revealed that uranium is primarily distributed throughout the organic material that coats detrital grains in the Mariano Lake deposit; thus, the coffinite likely resides on the amorphous organic material. The intimate association between uranium and organic material in tabular deposits of the GMB has been

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previously noted (Granger and others, 1961; Austin, 1963; Squyres, 1969; Adams and others, 1978; Granger and others, 1980). Degradation by aging and radiation (radiation from the associated uranium) has damaged the molecular structure of the organic material thus making identification of its exact source difficult (Leventhal, 1980). Among the possible sources for the organic material are intrinsic organic debris contained in the host sandstone, humic-material-bearing recharge waters (Granger and others, 1961), and humic-material-bearing pore fluids expelled from interbedded mudstone units (Peterson and Turner-Peterson, 1980). Humic-material-bearing recharge waters might have been derived from the swampy surficial environment postulated to have existed shortly after deposition of the Morrison Formation (Granger and others, 1961). Once introduced into the host sandstone, the humic material can be rendered insoluble as a result of (1) lowering of water pH, (2) increase in water salinity, or (3) loading of cations onto the organic acid molecule (Swanson and Palacas, 1965; Leventhal, 1980). These three geochemical changes that could render the humic material insoluble may occur at the interface between two solutions: the humic-material-bearing solution and a second, perhaps brine-like solution (Shawe, 1976; Granger and others, 1980).

Because of its capability to adsorb uranium (Szalay, 1964), the organic material is probably directly responsible for localization and concentration of uranium (Leventhal, 1980). Uranyl ions or uranium carbonate species can be readily chelated (bonded) onto a polar functional site on the organic acid molecule (Szalay, 1964; Leventhal, 1980). This chelation can occur while the organic acid is still soluble or after it has precipitated from solution (Squyres, 1969; Leventhal, 1980). The reducing conditions that resulted from

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the presence of organic material probably served to slowly reduce the uranium to the tetravalent state, enabling coffinite to form (Leventhal, 1980). At present we cannot better constrain among sources of organic matter or mechanisms of uranium enrichment of the organic matter in the Mariano Lake deposit.

Other alterations associated with uranium mineralization include the destruction of detrital iron-titanium oxides, co-precipitation of authigenic chlorite and microcrystalline quartz, and formation of authigenic iron disulfides. The extensive alteration of detrital iron-titanium oxides in the Mariano Lake deposit and in other tabular deposits in the GMB is noteworthy. These detrital grains are usually absent in mineralized rock (Austin, 1963; Adams and others, 1974; Shawe, 1976). Adams and others (1974) concluded that solutions bearing organic acids leached iron from magnetite-ilmenite in the Morrison sands. Although alteration of iron-titanium oxides may have begun shortly after sediment deposition, extensive alteration of these grains probably resulted from the presence of humic material during mineralization. Because organic material fills dissolved areas between titanium dioxide lattices, dissolution of iron-titanium oxides in the Mariano Lake deposit probably began prior to but continued through emplacement of the organic material. Because detrital iron-titanium oxides may contain vanadium in concentrations as high as 1500 ppm (Shawe, 1976), magnetite-ilmenite alteration may have been the source of much of the vanadium associated with tabular deposits in the GMB.

The close association of organic material with chlorite in mineralized rock in tabular deposits of the GMB has been noted in other studies (Granger, 1962; Lee and Brookins, 1978). This association has also been described in

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organic-bearing roll-type deposits in Wyoming (Files, 1970). Chlorite is

absent from roll-type deposits devoid of organic material in south Texas

(Reynolds and others, 1980) as well as redistributed deposits in the GMB

(Granger, 1962). Thus, it appears that organic material may in part have

influenced chlorite formation in organic-rich uranium deposits (Brookins,

1975).

In the Mariano Lake deposit, authigenic vanadiferous chlorite is closely

associated with organic grain coatings. The positive correlation of vanadium

with uranium (refer to fig. 5a), therefore, probably reflects the enrichment

of chlorite in mineralized rock. Chlorite in unmineralized rock is not

usually vanadiferous, and consequently, vanadium concentrations in such rock

are low.

Chlorite in the Mariano Lake deposit is closely associated with

uranium. Incorporation of vanadium and perhaps uranium into chlorite from the

Mariano Lake deposit may have resulted from (1) chlorite precipitation from a

gel or solution containing vanadium and uranium, or from (2) incorporation of

uranium and vanadium, originally chelated to organic matter, into chlorite

during its formation.

The intimate association between organic material and iron disulfides

suggests that a second sulfidization event occurred during uranium

mineralization. The mean isotopic composition of ore-stage iron disulfide

minerals is -35.33 ±3.42 per mil (one standard deviation). As with pre-ore

iron disulfide minerals, the isotopic composition of ore-stage sulfides is

probably indicative of biogenically derived sulfides. Isotopically light iron

disulfides, from both mineralized and unmineralized rock, have been reported

in studies of other uranium deposits in the GMB (Jensen, 1963); however, it is

unclear whether these data represent iron disulfides exclusively from tabular deposits.

Post-mineralization Host Rock Alterations

As in the Mariano Lake deposit, calcite and barite that formed after ore deposition have been noted in tabular deposits in the GMB (Granger, 1963). However, in the Mariano Lake deposit, these two minerals and post-ore dolomite are found only rarely. The sparse occurrence of calcite, barite, and dolomite suggests that either these minerals were never more than minor authigenic constituents in the host rock, or they were more abundant in the past and have since been widely eliminated. The absence of relict fragments of calcite, barite, and dolomite in most thin sections studied suggests that they were never common.

The carbon isotopic compositions of authigenic calcite and dolomite in the Mariano Lake deposit (table 2) are light and fall within the range of isotopic values of carbonates precipitated from freshwaters. Such light isotopic values may reflect carbonates at least partly derived from organic material (Hoefs, 1973). Calcite in another tabular deposit in the GMB likely precipitated from carbonate partly derived from the oxidation of organic material (Leventhal, 1980). The oxygen isotopes of the authigenic calcite and dolomite are similar to those reported by Keith and Weber (1964) for carbonates precipitated from meteoric water.

Kaolinite is another common post-mineralization authigenic mineral that is found in most tabular deposits (Granger, 1962), including the Mariano Lake deposit. As previously mentioned, kaolinite replaces preceding authigenic minerals and fills interstitial areas. In the Mariano Lake deposit, kaolinite

is present throughout the host rock, but is in relatively less abundance in mineralized rock than in unmineralized rock (P. D. Blackmon, written communication, 1981). The lesser abundance of kaolinite in the ore zone is probably due to the lowered porosity (refer to table 1) of mineralized rock that resulted from the presence of pre-ore and ore-stage authigenic matter in interstices. Consequently, the ore zone may have been less permeable to post-ore solutions from which kaolinite precipitated.

Host rock oxidation has been noted in close proximity to many tabular deposits in the GMB and, in some cases, has destroyed large parts of tabular deposits (Granger and others, 1961). Uranium released during oxidation of a tabular deposit may reprecipitate and form redistributed orebodies, usually within several hundred meters from the original tabular deposit (Granger and others, 1961). In spite of minor oxidation in parts of the Mariano Lake orebody, as well as oxidation which occurred along the extreme southern edge of the deposit, we did not find evidence for major uranium redistribution in the Mariano Lake orebody.

ORIGIN AND PRESERVATION MARIANO LAKE DEPOSIT

The striking similarity in geochemical signatures, and diagenetic alterations from the tabular deposits in the GMB and the Mariano Lake deposit lead us to conclude that the Mariano Lake deposit is a tabular orebody. Because of their similarities it is reasonable to assume then that these deposits are genetically and temporally related.

Preservation of the Mariano Lake deposit may have been influenced by the presence of the Mariano structures. The Mariano syncline and anticline may have impeded ground water flow in the vicinity of the Mariano Lake deposit

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since Laramide time, due to their axial trend being perpendicular to the regional hydraulic gradient. The Mariano structures impedance of originally northward flowing ground waters may have served to stagnate waters in the synclinal trough, retarding future encroachments of potentially destructive oxidizing ground waters. Additionally, the lower porosity of the orebody, resulting from abundant ore-stage authigenic minerals, may have served to partially deflect oxidizing waters around the orebody. Together, stagnation and deflection of aquifer waters probably contributed to preservation of the deposit.

CONCLUSIONS

Geochemical data and petrographic observations reveal that the Mariano Lake orebody is a tabular uranium deposit. Concentrations of organic carbon and uranium are nearly equal and a positive correlation also exists between uranium and vanadium concentrations.

Petrographic observations point to introduction of amorphous organic matter, in which most uranium resides, relatively early in the sequence of post-depositional alterations. The relatively homogeneous distribution of uranium within the amorphous organic material suggests that uranium may have bonded (chelated) with the organic material prior to emplacement of the organic material, or that uranium and organic material were not bonded, but present in the same solution and precipitated simultaneously. Destruction of detrital iron-titanium oxide grains, precipitation of vanadiferous and perhaps uraniferous chlorite, and precipitation of ore-stage iron disulfides accompanied mineralization. Pre-mineralization alterations include formation of authigenic iron disulfides, and mixed-layer clays, partial dissolution of

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some detrital feldspars, and formation of quartz and adularia overgrowths. Post-mineralization alterations include precipitation of authigenic calcite, barite, dolomite, and kaolinite, and a minor amount of oxidation of pyrite to limonite. Pre- and post-mineralization alterations described for the Mariano Lake deposit have also been commonly observed in tabular deposits throughout the GMB.

Pre-ore and ore-stage sulfides minerals differ texturally but are not vastly different isotopically. The light isotopic value of most sulfide sulfur (-25 to -42 per mil) suggests that these minerals are biogenic in origin. Similar sulfur isotopic values have been reported from sulfides in other tabular deposits in the GMB.

Although rock updip from the Mariano Lake orebody is oxidized (fortuitously imprinting a roll-like appearance on the orebody), oxidation has not noticeably redistributed uranium to rock within or adjacent to the Mariano Lake orebody. Stagnation of waters by the Mariano structures together with deflection of waters by the lowered orebody porosity may have contributed to preservation of the Mariano Lake deposit.

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