Uranium Ore in the Mariano Lake–Lake Valley Cores and the Genesis of Coffinite in the Grants Uranium Region, New Mexico

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Chapter A

Uranium Ore in the Mariano Lake–Lake Valley Cores and the Genesis of Coffinite in the Grants Uranium Region, New Mexico

By PAULA L. HANSLEY

U.S. GEOLOGICAL SURVEY BULLETIN 1808

EVOLUTION OF SEDIMENTARY BASINS—SAN JUAN BASIN

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

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Uranium Ore in the Mariano Lake–Lake Valley Cores and the Genesis of Coffinite in the Grants Uranium Region, New Mexico

By Paula L. Hansley

Abstract

Petrographic and geochemical research on uranium-bearing sandstones in the Upper Jurassic Morrison Formation in the Grants uranium region, northwestern New Mexico, indicate that compactional fluids, which migrated from fine-grained fluvial and lacustrine units into adjacent sandstone intervals during early diagenesis, were instrumental in primary ore formation. These pore fluids carried uranium and other elements derived from the alteration of abundant volcanic material in the Brushy Basin Member of the Morrison Formation. Where these fluids reacted with concentrations of organic matter in sandstones of the Westwater Canyon Member, uranium was adsorbed, reduced, and concentrated into primary ore deposits.

Primary (carbonaceous) ore has undergone a significant amount of diagenesis due to the bacterial and thermal maturation of amorphous organic matter. Progressive diagenesis decreased the organic carbon:uranium ratio in primary ore, transforming it to various mixtures of microbotryoidal ore and coffinite. Coffinite formed where silica activity was high due to dissolution of aluminosilicate minerals by organic-acid-bearing solutions. Organic acids were responsible for a wide variety of water-rock reactions, which were catalyzed by a warm (at least 100°C) deep-basin fluid that migrated updip through permeable ore-bearing sandstones in the mid-Tertiary. Regularly interstratified illite-smectite, chlorite, adularia, quartz, and ankerite precipitated at this time. From the late Tertiary to the present(?) time, downdip migration of meteoric waters from outcrops along the southern margin of the San Juan basin caused widespread oxidation of organic matter and redistribution of uranium into orebodies along a regional oxidation-reduction front.

Recognition that diagenesis can transform organic-rich ore into organic-poor ore and that organic acids may facilitate low-temperature formation of coffinite has important implications for interpreting the genesis of sediment-hosted ore deposits. Many organic-poor uranium deposits in the Westwater Canyon Member of the Morrison Formation in the Grants uranium region and in the Salt Wash Member of the Morrison Formation on the northern part of the Colorado Plateau may have formerly been organic-rich (primary) ore.

INTRODUCTION

In the Grants uranium region of the southern San Juan basin, the Upper Jurassic Morrison Formation contains some of the World's largest known sedimentary uranium deposits (fig. 1). Despite intense interest in this region during the uranium boom of the 1950s and again during a flurry of mining activity in the 1970s, the genesis of these deposits is still not clearly understood. Two genetic types of uranium ore traditionally are recognized in the Grants uranium region: primary (pre-fault) and secondary (post-fault or redistributed) ore (Granger and others, 1961). Primary ore occurs as a matrix that is commonly a 1:1 mixture of carbonaceous material and uranium in bulk samples (Leventhal, 1980). Most uranium is present as cryptocrystalline coffinite, although some may reside in uranium-organic complexes. Uranium was probably derived from the hydrolysis of abundant volcanic glass during early diagenesis (Waters and Granger, 1953). Blanket-like bodies of primary ore as much as 1000 m long and 5 m thick are suspended in sandstone units without apparent relation to tectonic structures. Many orebodies are oriented with long axes parallel to current directions in fluvial channels. Kirk and Condon (1986) noted that ore tends to occur in thickened sandstone intervals that are related to syndepositional growth faults.

Radiometric age determinations (U/Pb) indicate that primary ore was deposited in Late Jurassic to Early Cretaceous time (Ludwig and others, 1984). This time span leaves room for debate as to the nature of ore-forming processes, particularly the origin of the epigenetic noncellular organic material (amorphous organic material) that served as a concentrating agent for uranium. Most agree that the organic material was epigenetic, although some models promote an extrinsic origin, and others an intrinsic origin (Granger, 1968).

Remobilization of both uranium and carbon during an Early Cretaceous erosional interval may account for younger (Early Cretaceous) ages on primary ore and the roll-front features of tabular (organic-rich) ore. Oxidation and removal of uranium from primary deposits and the subsequent reprecipitation of reduced uranium at an oxidation-reduction boundary or along a Laramide geologic structure resulted in formation of redistributed orebodies (Granger and others, 1961). Redistribution more than a few hundred meters was rare (Adams and Saucier, 1981). Radiogenic ages indicate that most redistribution occurred in the late Tertiary (Ludwig and

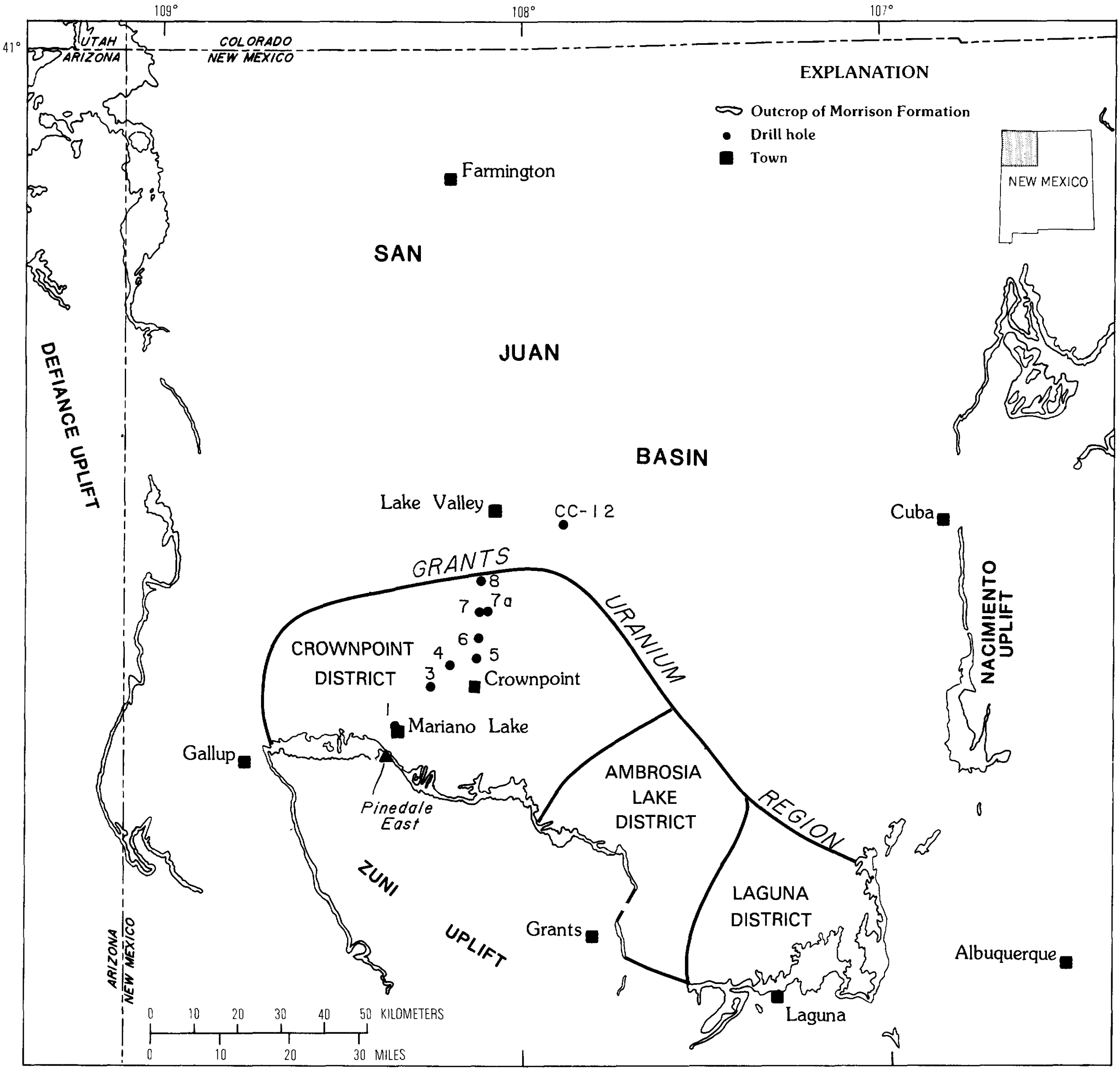

Figure 1. Map of Grants uranium region, southern San Juan basin, northwestern New Mexico showing the locations of uranium districts and drill holes discussed in the text.

others, 1982; Ludwig and others, 1984), although some Pleistocene ages have been reported (Rosenberg and Hooper, 1982), and younger ages suggest that redistribution is occurring at the present time (Ludwig and others, 1982).

A unique opportunity to examine a suite of core samples from drill holes that transected the Grants uranium region from Mariano Lake to Lake Valley (ML-LV) was afforded by a drilling program designed by the U.S. Geological Survey (Kirk and others, 1986). Within the Grants uranium region core was recovered from eight drill holes; four contained uranium ore (defined as >1000 ppm in this study). The detrital and authigenic petrology of ML-LV core samples has been described previously and will not be repeated in this report (Steele, 1984; Hansley, 1986a, 1986b, 1986c); and Reynolds and others, 1986). The most northern samples analyzed were from a hole (CC-12) drilled by the U.S. Department of Energy located just north of core 8. Ore samples were also collected from various mines in the Ambrosia Lake district, the Nose Rock deposit, and numerous barren and mineralized cores in the Grants uranium region; the petrology of these samples was compared with that of ore in the ML-LV cores.

The present study was part of a multidisciplinary effort to understand the provenance, sedimentology, clay mineralogy, geochemistry, and geophysics of uranium ore-bearing rocks in the Morrison Formation. The ore mineralogy was characterized using modern techniques such as the scanning electron microscope and the electron microprobe. (The fine-grained nature of the ore and the intimate mixture of uranium with organic material have precluded its characterization in the past). Early diagenetic alterations and primary uranium ore were found to be related in part to depositional and diagenetic alteration patterns in overlying units.

As a result of this investigation, a new ore type, diagenetically altered (carbon-deficient) primary ore was identified. Diagenetically altered ore formed during thermal and bacterial maturation of primary ore. As the amorphous organic matter in primary ore broke down into organic acids and carbon dioxide, the primary ore evolved from mixtures of organic matter and uranium to mixtures of clay minerals and coffinite. At the same time, a complex assemblage of authigenic minerals precipitated. During the mid-Tertiary when the Morrison Formation was most deeply buried, migration of warm deep-basin fluids through ore-bearing units (Northrop and Whitney, 1985) facilitated the alteration of primary ore.

Diagenetically altered primary ore includes ore previously described as primary and as redistributed. Recognition that amorphous organic matter can be broken down into soluble components during diagenesis has profound implications for the re-interpretation of organic-poor sedimentary uranium deposits.

GEOLOGIC SETTING OF THE MORRISON FORMATION IN THE SAN JUAN BASIN

The sedimentology and stratigraphy of the Morrison Formation in the San Juan basin is summarized below. For a complete discussion of the regional geology and tectonics in the San Juan basin, see Hilpert (1969), Kelley (1957), and Santos and Turner-Peterson (1986). The ML-LV drillholes lie on the Chaco slope, a homocline formed during the Laramide uplift, that dips gently (<5°) northward from the Zuni Mountains along the southern edge of the San Juan basin. In this area, the Morrison Formation is composed of three members, in ascending order the Recapture, Westwater Canyon, and Brushy Basin Members (fig. 2). The Morrison Formation was deposited primarily by braided streams on a broad alluvial floodplain during the Late Jurassic (Turner-Peterson, 1985, 1986), although Galloway (1980) interpreted the depositional environment of the Westwater Canyon Member to have been an alluvial fan complex deposited by laterally migrating streams. Source areas for these sediments lay to the west and southwest of the depositional basin in the vicinity of the ancient Mogollon highlands (Cooley and Davidson, 1963) and possibly farther to the west where continental-margin volcanism occurred during the Late Jurassic (Silver and Williams,

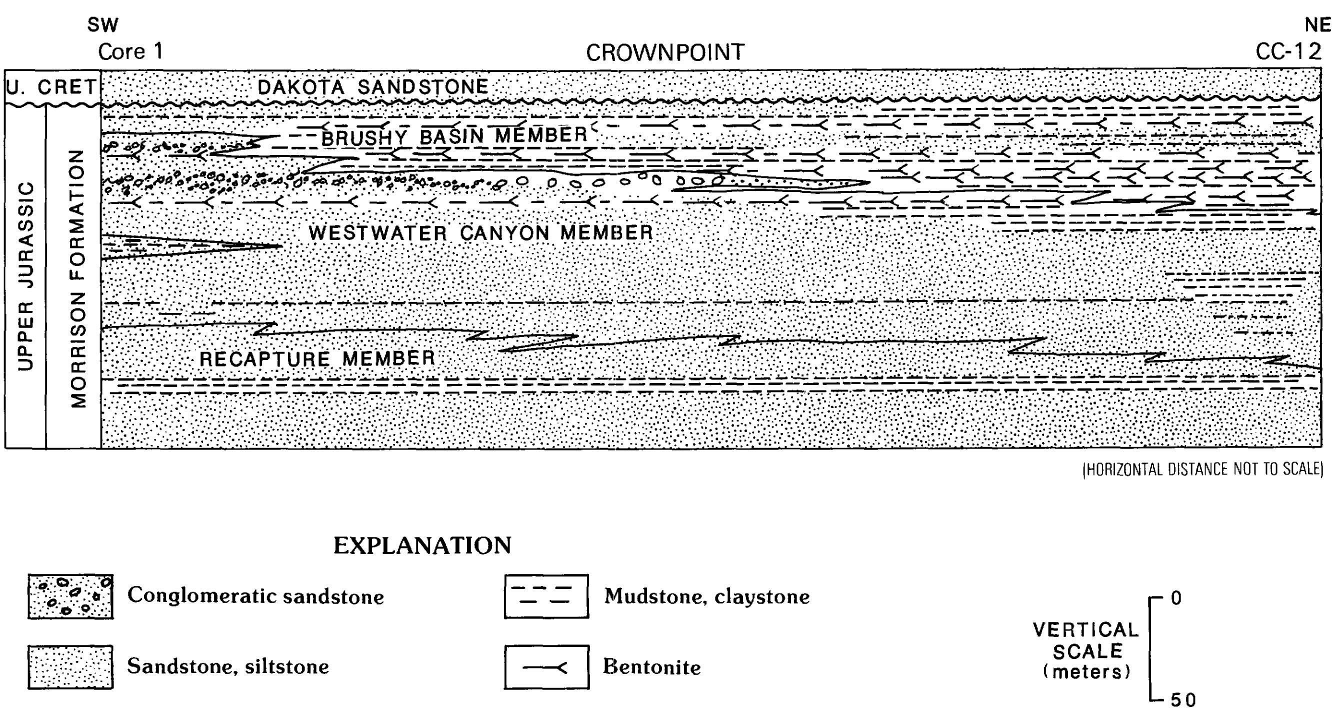

Figure 2. Generalized cross section of the Morrison Formation in the southwestern San Juan basin, New Mexico.

1981). Nearby positive areas such as the Defiance and Zuni uplifts shed minor amounts of debris into the San Juan basin.

Thinly bedded sandstone and interbedded red and green mottled mudstone units of the Recapture Member overlie the Middle Jurassic Todilto Limestone Member of the Wanakah Formation in the Crownpoint area. The Recapture was deposited primarily by low-energy meandering streams, but some Recapture units were formed in local sahbka, playa-lake, and eolian environments (Condon and Peterson, 1986). Sandstones in the Recapture are typically moderately to well sorted and very fine to fine grained.

The Westwater Canyon Member consists of moderately well-sorted and fine- to coarse-grained feldspathic litharenites and lithic arkoses which were deposited primarily by braided streams. In general, sandstone units in the upper part contain fewer mudstone breaks and are coarser and more massive than sandstone units in the lower part of the member and in the Recapture.

The Brushy Basin Member is composed of an alluvial facies nearest the basin margin, a mudflat facies farther into the basin, and, finally, a lacustrine (playa-lake) facies in the center of the San Juan basin (Bell, 1986). The concentric pattern formed by these facies is characteristic of sediments deposited in a closed saline-alkaline lake basin (Sheppard and Gude, 1968). The alluvial facies is predominantly smectitic sandstone and mudstone; the mudflat facies consists of smectitic mudstone and claystone, and the lacustrine facies is characterized by smectitic claystone interbedded with discrete tuff beds, which have been silicified and/or altered to zeolites.

Nonmarine deposits of the Upper Cretaceous Dakota Sandstone unconformably overlie the Brushy Basin Member. A regional erosion surface that represents all or part of Early Cretaceous time truncates the Brushy Basin Member from south to north in the southwestern part of the San Juan basin. In places, the Dakota rests directly on intensely kaolinitized sandstones of the Westwater Canyon Member. In Late Cretaceous to early Tertiary time, tectonism associated with the Laramide orogeny tilted the Morrison Formation, exposing it in outcrops around the periphery of the San Juan Basin.

Uranium ore in the ML-LV cores occurs only in the Westwater Canyon Member, although it is occasionally found in the Brushy Basin Member in other ore deposits. Ore-bearing zones consist of thick sandstone channels interbedded with thin bentonitic mudstone overbank deposits.

On the north-central part of the Colorado Plateau, tabular uranium deposits are found in fluvial quartzose sandstones of the Salt Wash Member, the oldest member of the Morrison Formation. Major uranium deposits in the Salt Wash Member are found in the Henry basin of south-central Utah and the Uravan mineral belt in eastern Utah and western Colorado (fig. 3). Primary uranium ore in these deposits, unlike primary ore in the Westwater Canyon Member, is not generally associated with amorphous organic matter.

METHODS OF SAMPLE PREPARATION

Uranium ore samples were examined from each Westwater Canyon Member ore zone in MV-LV cores 3, 4, 7, and 7a (fig. 4). Ore samples from various mines in the Ambrosia Lake district and more than one hundred samples from other mineralized and barren localities in the Grants uranium region were also analyzed. Ore from core CC-12 was not available.

Polished sections from all ore samples were examined in oil under direct, reflected light with a petrographic microscope. A Cambridge 250 Mark 2 scanning electron microscope[1] (SEM) with an attached energy dispersive X-ray analyzer (EDX) was used to study textural and paragenetic relations among ore zone phases. The EDX system was also used for qualitative and semi-quantitative elemental determinations. In order to study the spatial relationships among elements and phases in ore samples, an ARL electron microprobe was used to generate X-ray fluorescence elemental maps. Samples were coated with aluminum so that carbon could be detected with the wavelength dispersive system (WDS) of the electron microprobe. Quantitative analyses were conducted on coffinite-bearing samples. Because of their fine-grained nature, uranium-bearing phases in ore samples were identified by X-ray diffraction and X-ray powder camera methods.

DESCRIPTION OF URANIUM ORE IN THE MARIANO LAKE–LAKE VALLEY CORES

Both primary and secondary ore and a new type of secondary ore, diagenetically altered primary ore, are present in the Westwater Canyon Member in the ML-LV cores. Gradations between primary and secondary ore suggest that they are genetically related through the processes of diagenesis.

Primary Ore

In all ore zones, uranium occurs in amorphous carbonaceous matrix that shows no visible morphology under the SEM. The matrix is medium-gray and has a

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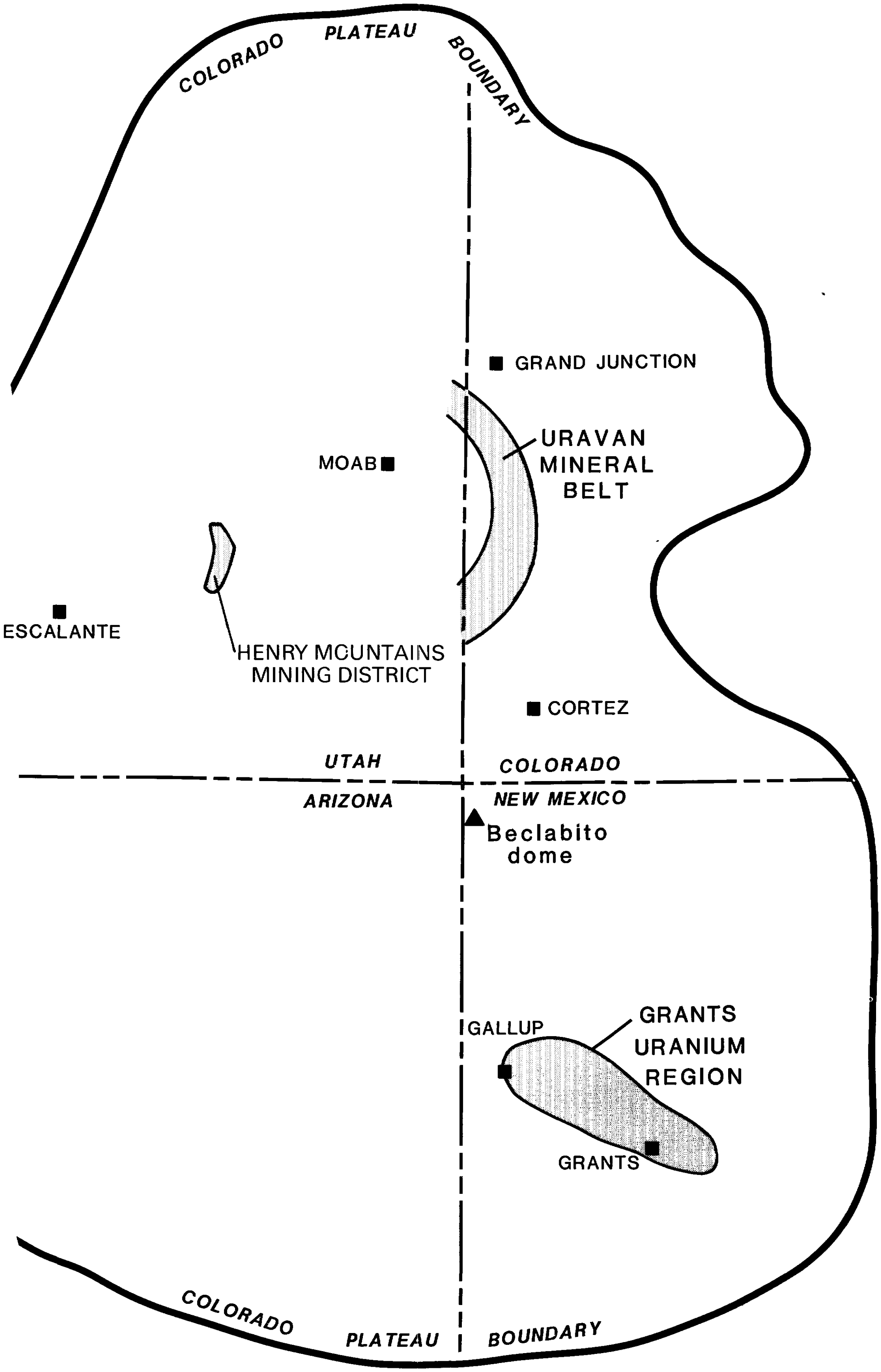


Figure 3. Major areas of uranium production from the Morrison Formation on the Colorado Plateau.

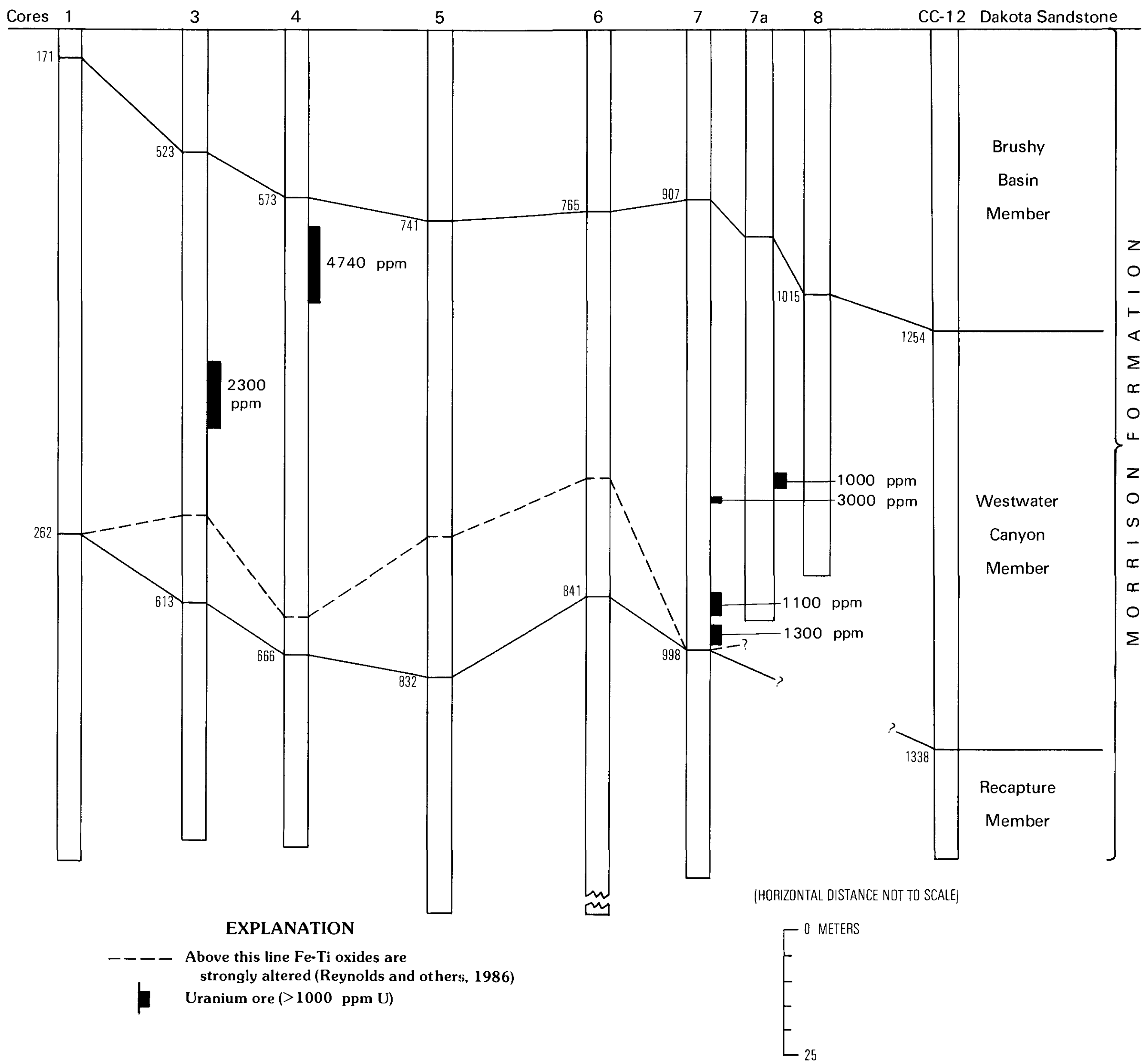


Figure 4. Cross section of Mariano Lake–Lake Valley cores showing locations of uranium ore zones and iron-titanium oxide alteration zone. Datum is base of Dakota Sandstone.

low reflectivity in direct reflected light. This ore exhibits all characteristics of primary ore (Adams and Saucier, 1981; Fishman and others, 1985; Hansley 1986a, 1986c). For instance, autoradiographs and fission-track maps (fig. 5) revealed that uranium is concentrated in detrital-grain coatings and at grain contacts and also occurs within altered iron-titanium (Fe-Ti) oxide grains. In high-grade deposits, ore filled primary pores (fig. 6) and corroded detrital quartz margins causing them to fluoresce dull red due to radiation damage (Don Marshall, Nuclide Corporation, written commun., 1978). Uranium concentrations are highest near pyrite grains in primary ore (Hansley, 1986a, 1986c; Webster, 1983). The presence of cryptocrystalline coffinite is suggested by the close association of uranium and silicon as seen in elemental X-ray fluorescence maps (fig. 7) and was confirmed by weak coffinite peaks on X-ray diffractograms. Where coffinite does not appear on X-ray traces, crystals may be too small to be detected. Uranium may also be present in urano-organic complexes.

Qualitative SEM and EM energy dispersive spectra showed that primary ore has a relatively high carbon:uranium ratio (usually >1), major but variable silicon and minor yttrium, aluminum, titanium, iron, potassium,

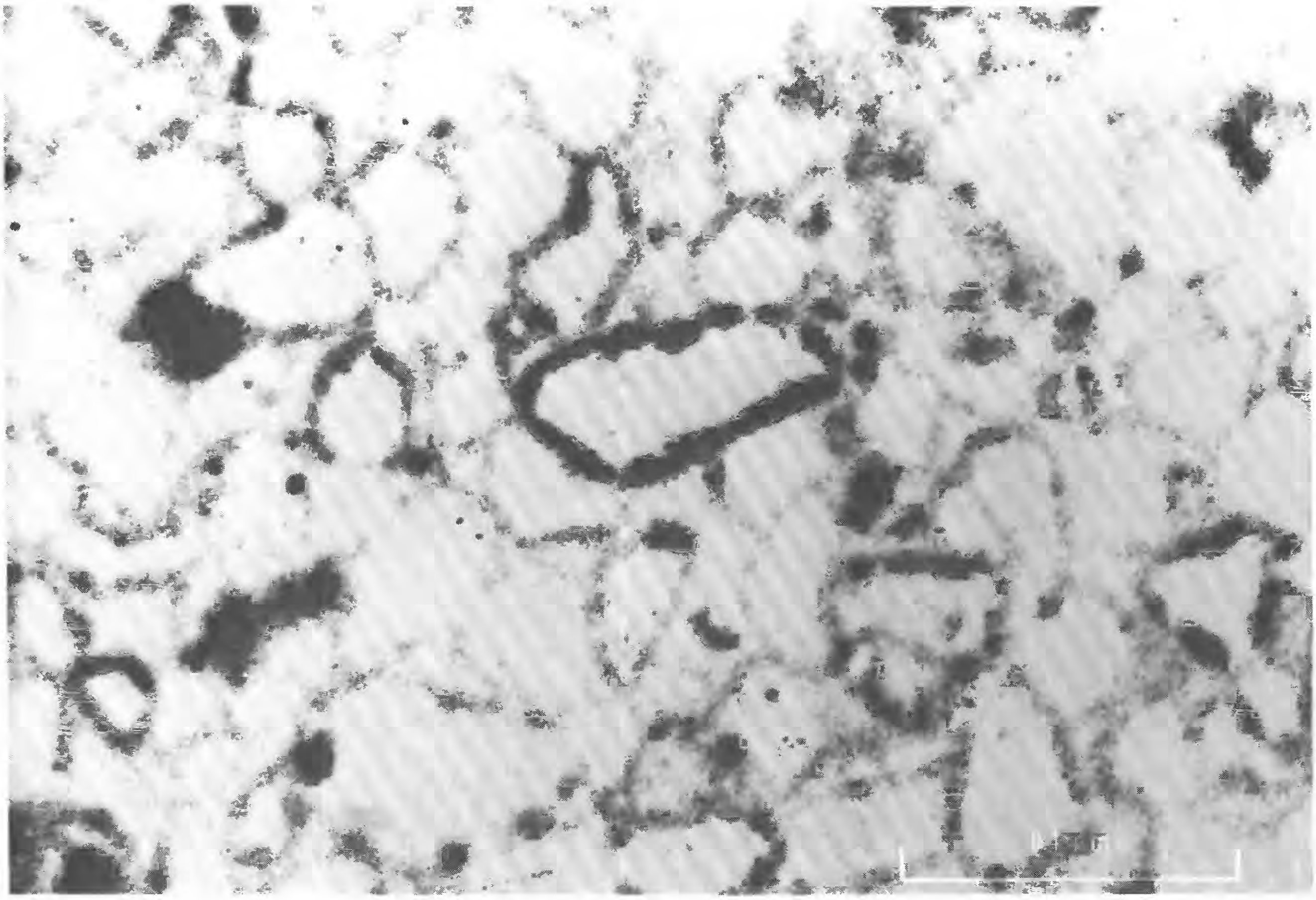


Figure 5. Photomicrograph of fission tracks in a mica detector showing concentrations of uranium on grain rims and in primary pores. Neutron flux of 100 kilowatts for 4 hours. Plane-polarized light. Core 3, sample 1864 (568 m).

calcium, sulfur, vanadium, magnesium, manganese, zinc, chromium, phosphorus, selenium, molybdenum, and lead (radiogenic?). The silicon peak varies from half to twice the intensity of the uranium peak.

Primary ore occurs in relict Fe-Ti oxide grains, which have been altered to titanium dioxide (anatase?) and pyrite. Some grain-sized areas of ore were interpreted to be altered Fe-Ti oxide grains, because of the presence of iron and titanium. Qualitative electron microprobe analyses showed that ore within altered Fe-Ti oxide grains contained less uranium than did grain margins; variable amounts of titanium, silicon, and carbon; and also minor but variable iron, aluminum, potassium, calcium, magnesium, phosphorus, yttrium, and manganese. The highest concentrations of organic carbon generally correlate with lower silicon and titanium and minor iron, sulfur, magnesium, calcium, potassium, and phosphorus.

A light-gray, highly reflective phase containing uranium, titanium, and silicon replaced ilmenite lamellae in altered Fe-Ti oxide grains. Similar alterations in Fe-Ti oxides from the Ambrosia Lake district were thought to be a uranium-titanium silicate phase (Simova, 1982). The widespread uranium-silicon association and SEM observations of tiny anatase crystals and blade-like coffinite crystals (fig. 8) occupying former ilmenite lamellae in altered Fe-Ti oxide grains, however, suggest that two phases, coffinite and titanium dioxide, are present. This close association of uranium and titanium in altered Fe-Ti oxides has been noted by others in the ML-LV cores (Reynolds and others, 1986), in ore from the Nose Rock uranium deposit (Rhett, 1980), and in south Texas roll-type uranium deposits (Reynolds and others, 1977).

The main mineralized interval in core 3 is interpreted to be remnant primary ore, because isolated pockets of carbonaceous, uraniferous matrix are commonly surrounded by large open, secondary pores filled with kaolinite containing inclusions of ore. Uranium ore is intergrown with euhedral pyrite and, locally, with partly oxidized pyrite grains and feathery needles containing iron and selenium (ferroselite?). Primary ore that remains within Fe-Ti oxide grains was probably insulated from later oxidizing, ore-destructive fluids. Ore from mines in the nearby Smith Lake district has been interpreted to be primary (Fishman and others, 1985); nevertheless,

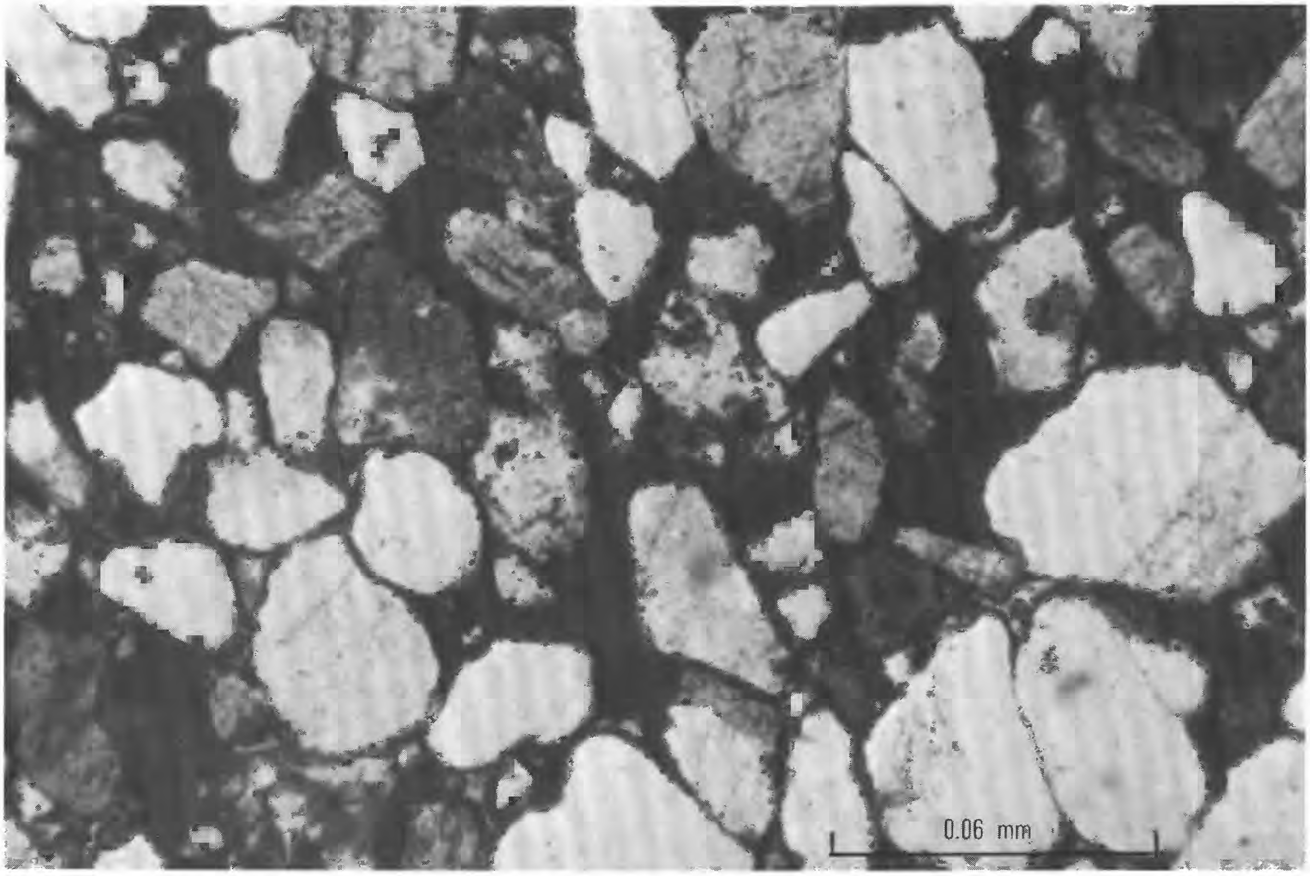


Figure 6. Photomicrograph of primary uranium ore (interstitial black material) from the Ambrosia Lake district. Plane-polarized light.

others contend that it is redistributed (Place and others, 1980). Both Smith Lake and core 3 ores exhibit a variety of diagenetic alterations such as skeletal plagioclase, and contain potassium feldspar overgrowths that Fishman and others have interpreted to be pre-primary-ore alterations. Other petrographic evidence, however, has shown that most feldspar alterations were post-primary ore (Hansley, 1986a). Furthermore, no primary ore samples from the Ambrosia Lake district contain pre-ore feldspar alterations. Ore-stage chlorite rims skeletal feldspar grains; therefore, feldspar dissolution postdated precipitation of chlorite and ore. Carbonaceous ore within skeletal feldspar grains is probably primary ore that was redistributed during early diagenesis (See "Early Cretaceous(?) Alteration"). This interpretation may explain why "primary" ore from the Smith Lake district is consistently younger than primary ore from the Ambrosia Lake district (Ludwig and others, 1984).

In core 4, remnant uranium ore is contained in medium- to dark-gray, fine- to medium-grained feldspathic sandstone characterized by abundant kaolinite nests visible in hand specimen. A low correlation between organic carbon and uranium and the association of uranium with titanium and silicon (also noted by Reynolds and others, 1986) indicates that the ore has been oxidized. Petrographic evidence for oxidation includes hematite on post-ore chlorite rims, on kaolinite, and within altered grains on the peripheries of the ore zone (fig. 9) (Hansley, 1986a, 1986c). Below the ore zone, an interval of hematitic alteration contains uraniferous overgrowths (oxidized ore?) on anatase and pyrite. Both ferroan carbonate and kaolinite cements locally contain remnants of unoxidized primary ore (Hansley, 1986c).

Drillhole 4 may intercept a limb of Conoco's Section 29 uranium deposit near Crownpoint (Wentworth and others, 1980). The Section 29 deposit has been interpreted to be primary ore, 100–139 m.y. (Lee and Brookins, 1978; Ludwig and others, 1984), that was oxidized in the middle to late Tertiary (Wentworth and others, 1980). A regional (late Tertiary?) oxidation-reduction front that has been mapped throughout the Grants uranium region crosses through the Crownpoint area (Saucier, 1980). Uranium that was originally deposited in east-southeast trending fluvial channels was remobilized by oxidizing groundwaters to locations downdip and north of former sites of accumulation.

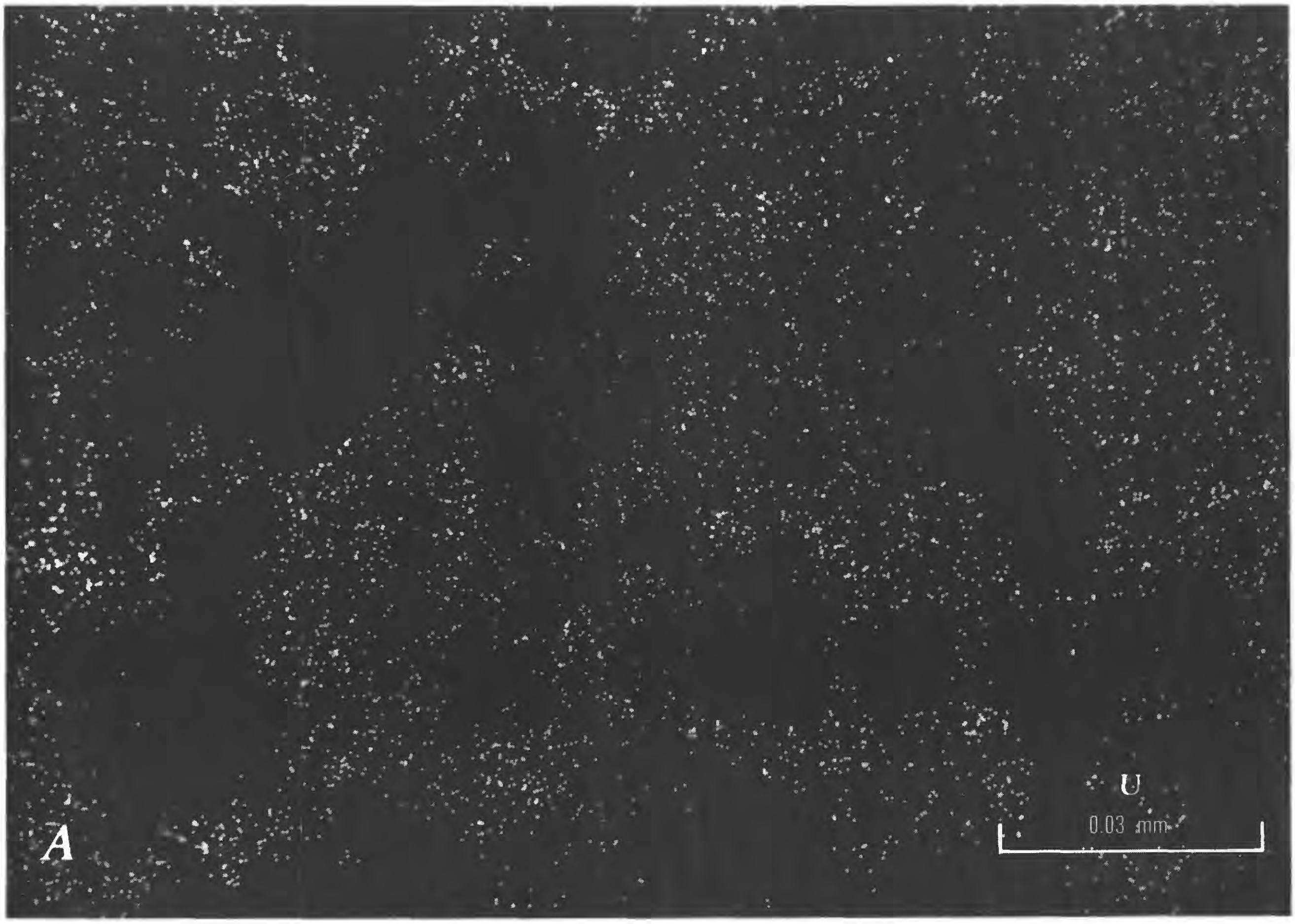


Figure 7. X-ray fluorescence micrographs that depict the distribution of uranium (*A*) silicon (*B*), and carbon (*C*) in primary ore. Core 7, sample 3179 (969 m).

Typical $\delta^{34}S$ values on ore-stage euhedral pyrite in cores 3 and 4 range from -21.4 to -9.9 per mil. These light values are similar to $\delta^{34}S$ values from other primary uranium orebodies in the Grants uranium region. The $\delta^{34}S$ values on ore-stage pyrite from the Smith Lake district just south of the ML–LV core fence range from -29 to -42 per mil (Fishman and others, 1985). These light values reflect the large isotopic fractionation characteristic of biogenic pyrite produced by bacterial sulfate reduction in the presence of organic matter (Kaplan, 1983). Sulfur isotopes from primary Ambrosia Lake ore, however, are generally heavier (Jensen, 1963). Heavier values may reflect a mixture of pyrite generations in the ore sample. Early diagenetic (pre-ore) pyrite cement in the ML-LV cores and in other Morrison deposits has consistently heavy $\delta^{34}S$ values of near +20 per mil; mixing heavy pre-ore and light ore-stage pyrite would result in intermediate values depending on the relative proportions of each generation of pyrite.

Rhett (1980) and Clark (1980) interpreted the Nose Rock orebodies to be Late Jurassic to Early Cretaceous roll-front deposits. The data gathered in this study from cores 7 and 7a and the Nose Rock samples, however, suggest that this ore was originally a primary deposit that was transformed during later (Tertiary?) diagenesis into partly oxidized orebodies with roll-front features. A strong organic carbon-uranium correlation indicates that primary ore was originally deposited in the Nose Rock area. The highest uranium concentration in the ML–LV cores is at 969.2 m in core 7. Here a poorly sorted, medium-grained sandstone is impregnated with uraniferous organic matter in a manner identical to that of unaltered primary ore from the Ambrosia Lake district.

Diagenetically Altered Primary Ore

Most ore with a low carbon content in the cores was interpreted to be diagenetically altered primary ore. Diagenetically altered ore may have different morphologies ranging from microbotryoidal to amorphous

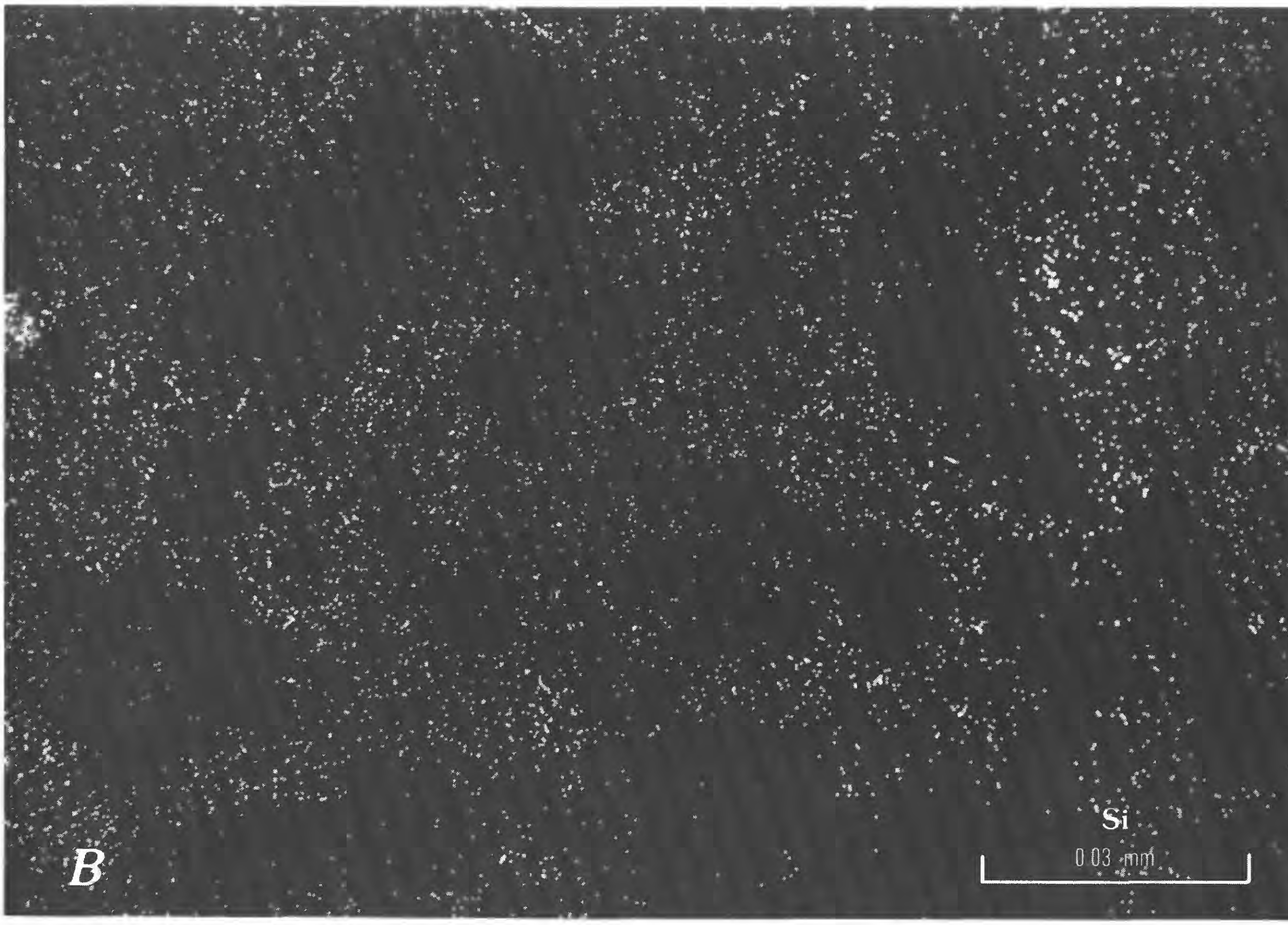


Figure 7.—Continued.

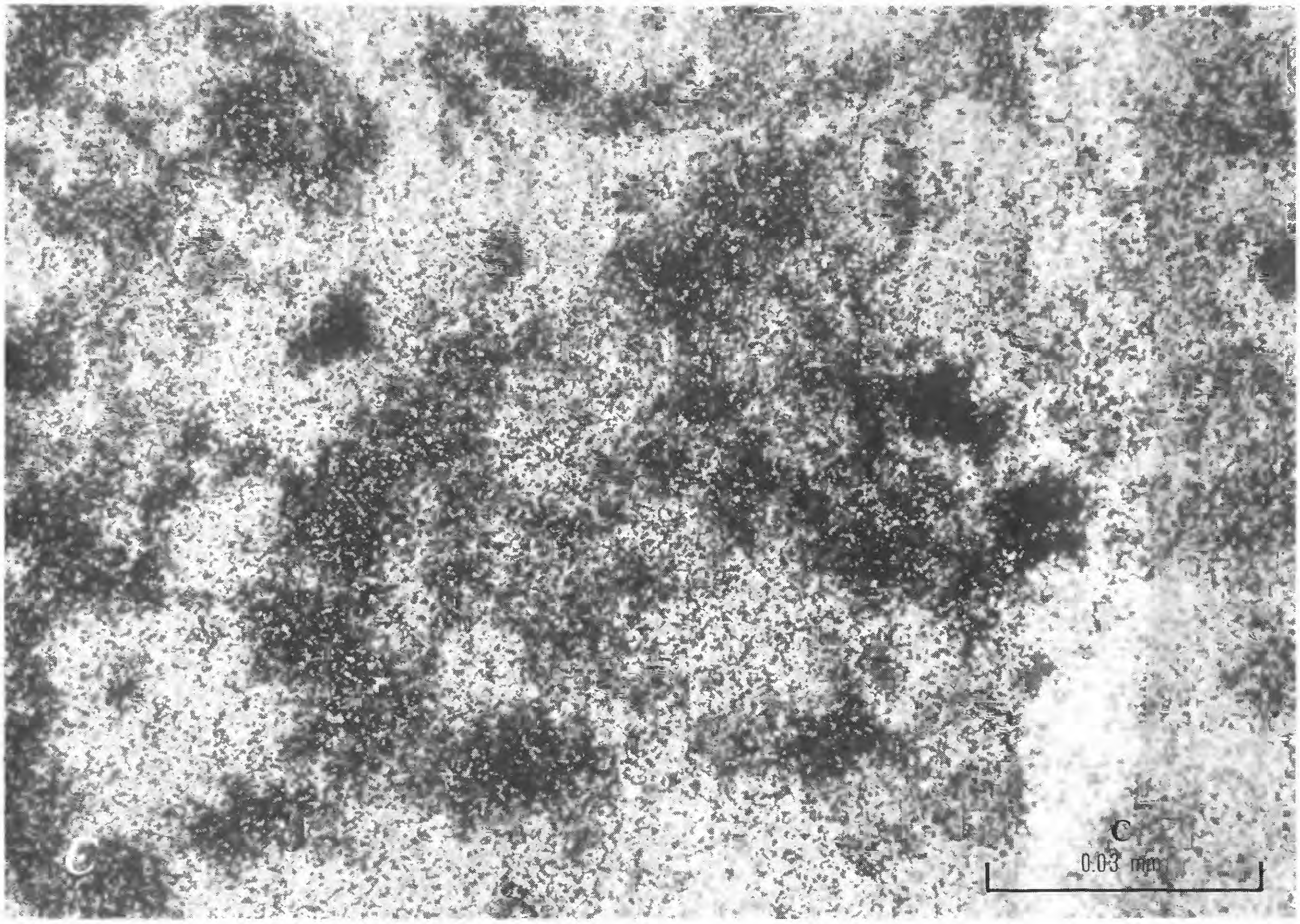
with <1 micrometer coffinite crystals to coarsely crystalline coffinite with carbon inclusions.

Under direct reflected light in oil, microbotryoidal ore appears amorphous, but SEM observation revealed that it is composed of irregularly shaped microspheres <2 micrometers in diameter (fig. 10). It has a higher reflectivity than primary ore due to a lower carbon: uranium ratio. The compositional of microbotryoidal ore is variable. In addition to uranium, other elements present in the microspheres include silicon, carbon, aluminum, vanadium, copper, titanium, potassium, iron, phosphorus, calcium, yttrium, ytterbium, and sulfur. The presence of only uranium and silicon peaks in SEM spectra of some microspheres implies that they contain cryptocrystalline coffinite. When associated with coffinite, microbotryoidal ore commonly forms perfectly smooth spheres containing mostly aluminum, silicon, and uranium with traces of iron and vanadium. Some spheres are almost pure aluminum, while others contain only uranium (uraninite?).

Similar encrusting, microbotryoidal material from other ore deposits in the Morrison Formation in the Grants uranium region has been identified as coffinite (Brookins, 1979, figs. 16 and 41). Nevertheless, microspheres from sandstone-type uranium deposits in Pakistan, which are morphologically similar to the ones described here, are uraninite (Basham and Shilston, 1978). No uraninite was detected in analyses conducted during this study, but this does not rule out the presence of X-ray-amorphous uraninite. Minor uraninite has been reported from the Grants uranium region, but virtually all occurs above the water table and is, therefore, interpreted to be a product of the oxidation (and subsequent reduction) of primary ore (Granger and others, 1961).

In the core 4 ore zone, small (<1 micrometer) coffinite crystals are embedded in uraniferous, carbonaceous matrix (fig. 11). Clay minerals, particularly ferroan chlorite, are abundant in this ore zone. This ore is interpreted to be altered primary ore that may be an intermediate stage of alteration between amorphous primary ore and microbotryoidal coffinite-rich ore.

Coarse-grained coffinite, a uranous silicate $[U(SiO_4)_{4-x}(OH)_{4x}]$ was discovered by Stieff and others (1956). It commonly occurs with microbotryoidal ore as



single, micron-size crystals or as large void-filling clusters of radiating colloform crystals that commonly contain shrinkage(?) cracks (fig. 12). It is brownish gray in direct reflected light and has a low reflectivity. Qualitative SEM–EDS and quantitative EM–WDS analyses of coffinite showed a consistent uranium:silicon ratio of 4:1 to 3:1; minor calcium, yttrium, phosphorus, radiogenic lead, and heavy rare earth elements are also present in the coffinite structure (Hansley and Fitzpatrick, in press). Because quantitative electron microprobe analyses do not total 100 percent, water of hydration, carbon, and uranium in the +6 (oxidized) valence state are also thought to be present. Micrometer-size inclusions of titanium dioxide and organic carbon are common within the large coffinite crystals. Electron microprobe analyses of coarsely crystalline coffinite from the Woodrow mine one mile east of the Jackpile mine in the Laguna district (fig. 1) found calcium, phosphorus, vanadium, and aluminum to be minor constituents (Kim, 1978). The aluminum is either a contaminant from associated clay minerals or may actually be one or more rare earth elements as some rare earth elements emit X-rays in the same wavelength range as aluminum.

A light-gray-red sandstone interval (990.2–996.3 m) in core 7 near the base of the Westwater Canyon Member contains discrete areas of interstitial ore composed of coffinite and microbotryoidal ore. In coffinite-rich ore, colloform coffinite crystals coat quartz grains without evidence of having replaced the quartz and are finely mixed with both primary and microbotryoidal ores. Sphalerite and areas of nickel and cobalt enrichment were also detected. Interestingly, cobaltite (CoAsS) is present in coffinite-rich ore from the Woodrow mine (Moench, 1962); arsenic was not detected, however, in EDX analyses of cobalt-rich spots in the Nose Rock ore. Some highly reflective material mixed with coffinite contained only nickel and sulfur.

Although most amorphous organic material in the cores was mineralized, curiously, some epigenetic organic material in the Nose Rock ore did not contain detectable uranium. For instance, nearly pure carbonaceous bands alternate with coffinite bands on detrital grains (fig. 13). Only organic carbon and traces of other elements were detected in the Nose Rock carbonaceous bands, unlike the uraniferous, carbonaceous ore from other parts of the Grants uranium region. This texture is similar to that

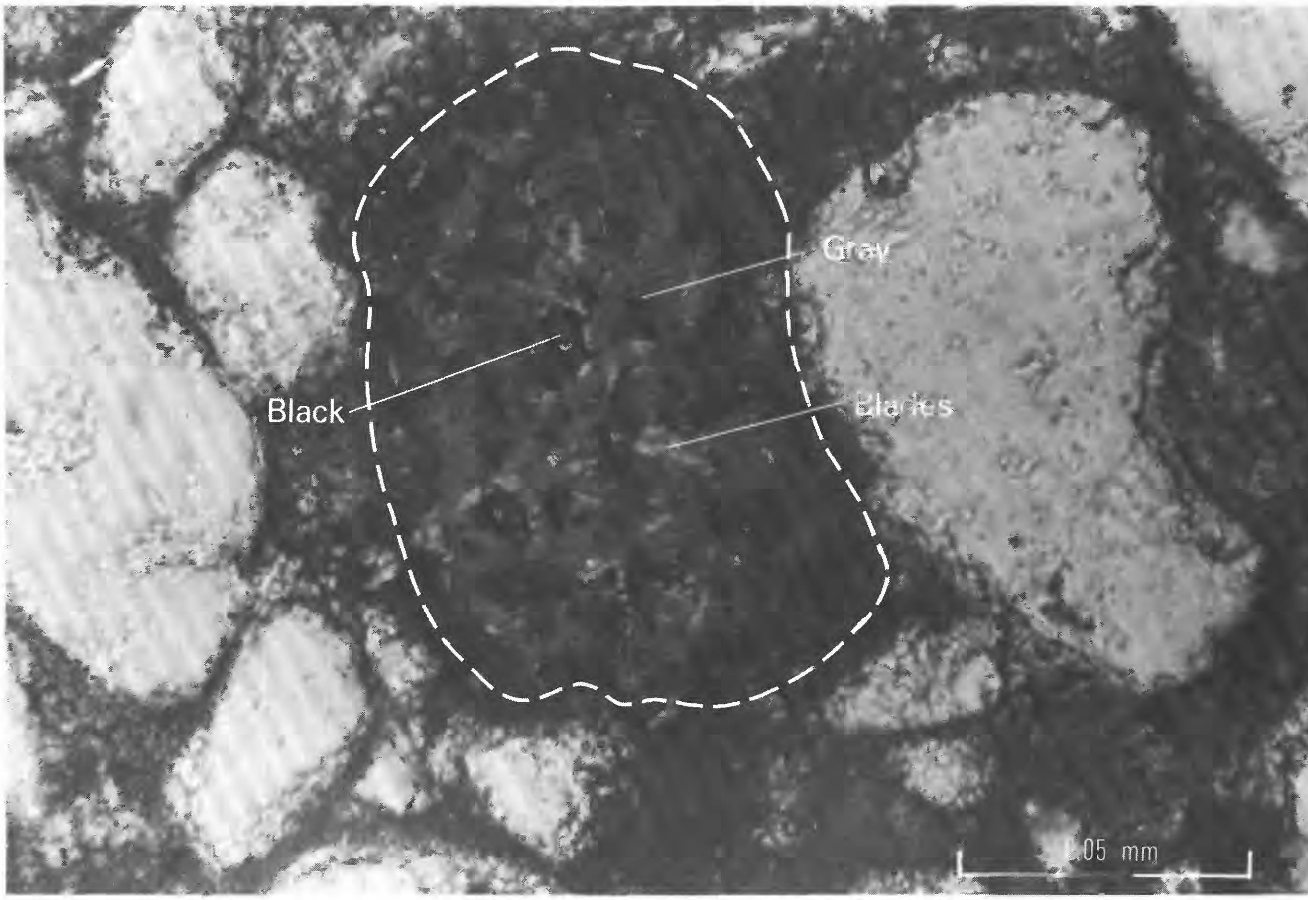


Figure 8. Photomicrograph of altered iron-titanium oxide grain (dashes outline grain) infilled by black and gray phases of primary uranium ore. Black areas consist of carbon, titanium, iron, silicon, uranium, aluminum, and magnesium; gray areas consist of carbon, titanium, iron, silicon, aluminum, magnesium, calcium, potassium, and a trace of uranium; and the light gray bladed areas are titanium, uranium, silicon, and calcium. The light gray blades are inferred to be former ilmenite lamellae replaced by a mixture of coffinite and anatase (titanium dioxide). Reflected light. Core 7, sample 3259, (994 m).

in some Ambrosia Lake samples in which coffinite alternates with pyrite bands (fig. 14). Carbonaceous and pyrite bands are always closest to detrital grain margins indicating that the organic matter and pyrite were precipitated before coffinite.

Some coffinite is interpreted to be a product of the diagenetic alteration of primary ore *in situ* as evidenced by inclusions of primary ore and anatase in the large coffinite crystals and coffinite embayment of primary ore (fig. 15). In addition, various stages in the replacement of primary ore by coffinite could be seen (fig. 16). The radiogenic lead content was measured in quantitative microprobe analyses of coffinite from cores 7, 7a, and the Nose Rock deposit. The relatively low lead content, which is small relative to that in primary Ambrosia Lake ore, suggests that the coffinite is fairly young, possibly mid-Tertiary in age.

Virtually all uranium ore with a low organic carbon content has traditionally been called redistributed ore, implying movement and reprecipitation of uranium (Granger and others, 1961). The diagenetically altered ore of this report, however, is not a product of the movement of uranium away from a primary ore deposit, but rather it is the result of the alteration of primary ore in place. Diagenetically altered primary ore is characterized by a variety of alterations including moldic and intergranular porosity, chlorite, potassium feldspar, and a lower uranium:carbon ratio than unaltered primary ore. Where skeletal plagioclase feldspar and etched garnets (Hansley, in press) occur in primary ore zones, some alteration of ore can be inferred to have taken place, for pristine primary ore zones contain almost no evidence of previous diagenetic alteration. Microbotryoidal ore is commonly found within skeletal plagioclase grains (fig. 17) only millimeters from primary ore. Low-grade, carbon-deficient primary ore that contains chlorite grain coatings may have originally been primary ore of a higher grade. Squyres (1963) suggested that brown ore from the

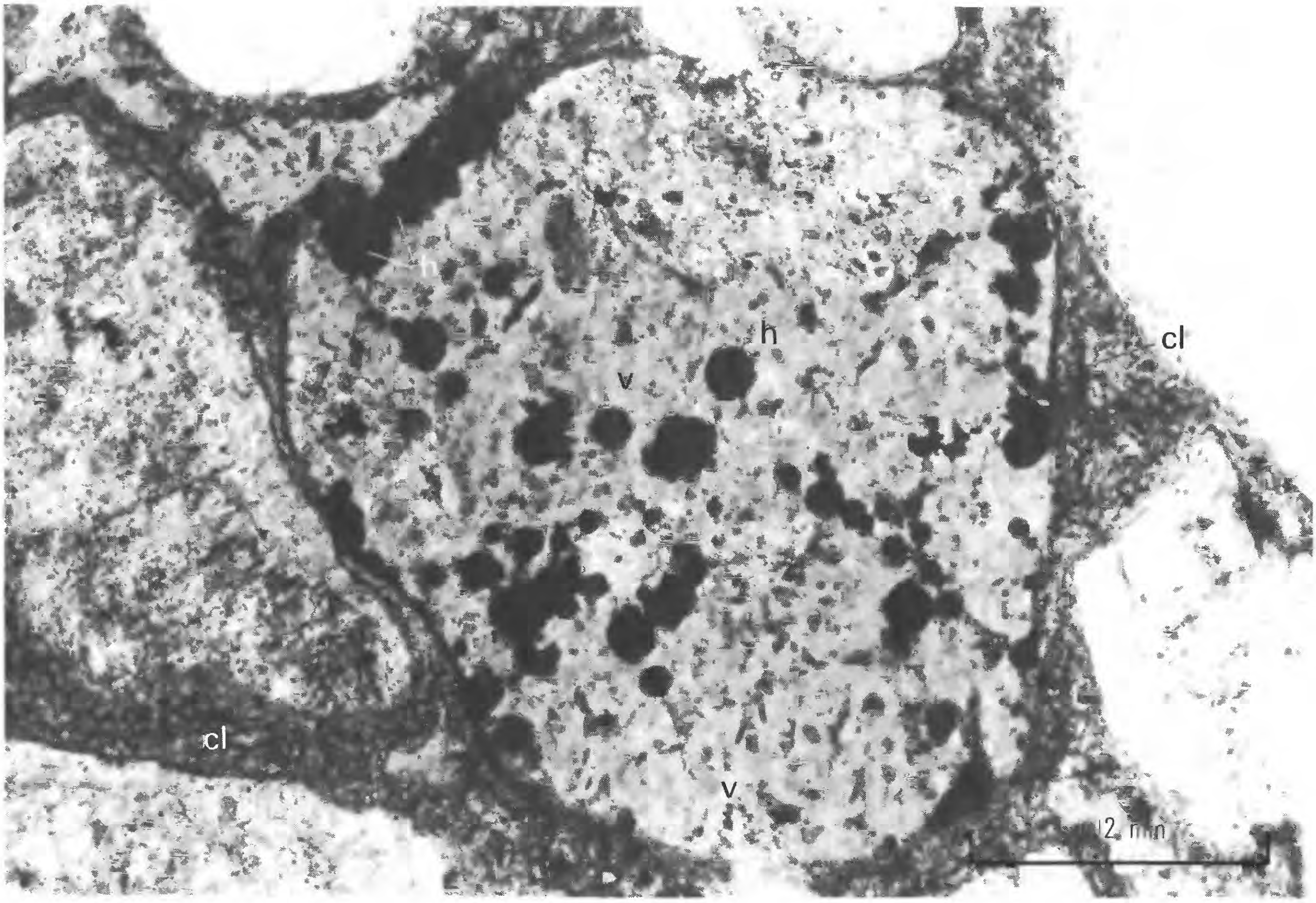


Figure 9. Photomicrograph of late diagenetic hematite spheres (h) within dissolution cavity (v) in detrital plagioclase grain in oxidized ore zone. Chlorite (cl) coats grain rim. Plane-polarized light. Core 4, sample 1933 (589 m).

Ann Lee mine in the Ambrosia Lake district was leached primary ore.

Some microbotryoidal ore and coffinite may be redistributed uranium ore; however, in most cases, movement of uranium was no more than a few meters. Coffinite that is not intimately associated with primary ore and that does not have carbon inclusions may have formed during local redistribution and reprecipitation of uranium ore.

ORE FORMATION—EVIDENCE FROM MARIANO LAKE–LAKE VALLEY CORES

Origin of Epigenetic Amorphous Organic Matter

Identification of the type of organic material in primary ore has been difficult. Radiation and diagenesis have altered the organic molecules to an insoluble amorphous carbonaceous residue deficient in hydrogen and oxygen that cannot be identified by conventional infrared or chemical techniques (Leventhal, 1980). The organic matter is referred to as amorphous because it lacks observable morphology when observed petrographically (Tissot and Welte, 1984). Based on chemical tests and on the solubility of some of the organic matter in alkaline solutions, Granger and others (1961) concluded that degraded vegetal matter was probably the source of the carbonaceous material. Nuclear magnetic resonance data on the organic matter also indicate that it was derived from terrestrial plant material or humate (Hatcher and others, 1986).

The origin of the organic matter, however, remains a subject of controversy, although most agree that it is epigenetic. Major theories of its origin are, as follows: (1) organic matter was intrinsic to the uranium-bearing sandstones (Squyres, 1980); (2) organic matter originated in Early Cretaceous swamps that were eroded prior to deposition of the Upper Cretaceous Dakota Sandstone (Granger and Santos, 1982); and (3) organic matter was derived from solubilization of plant material during early

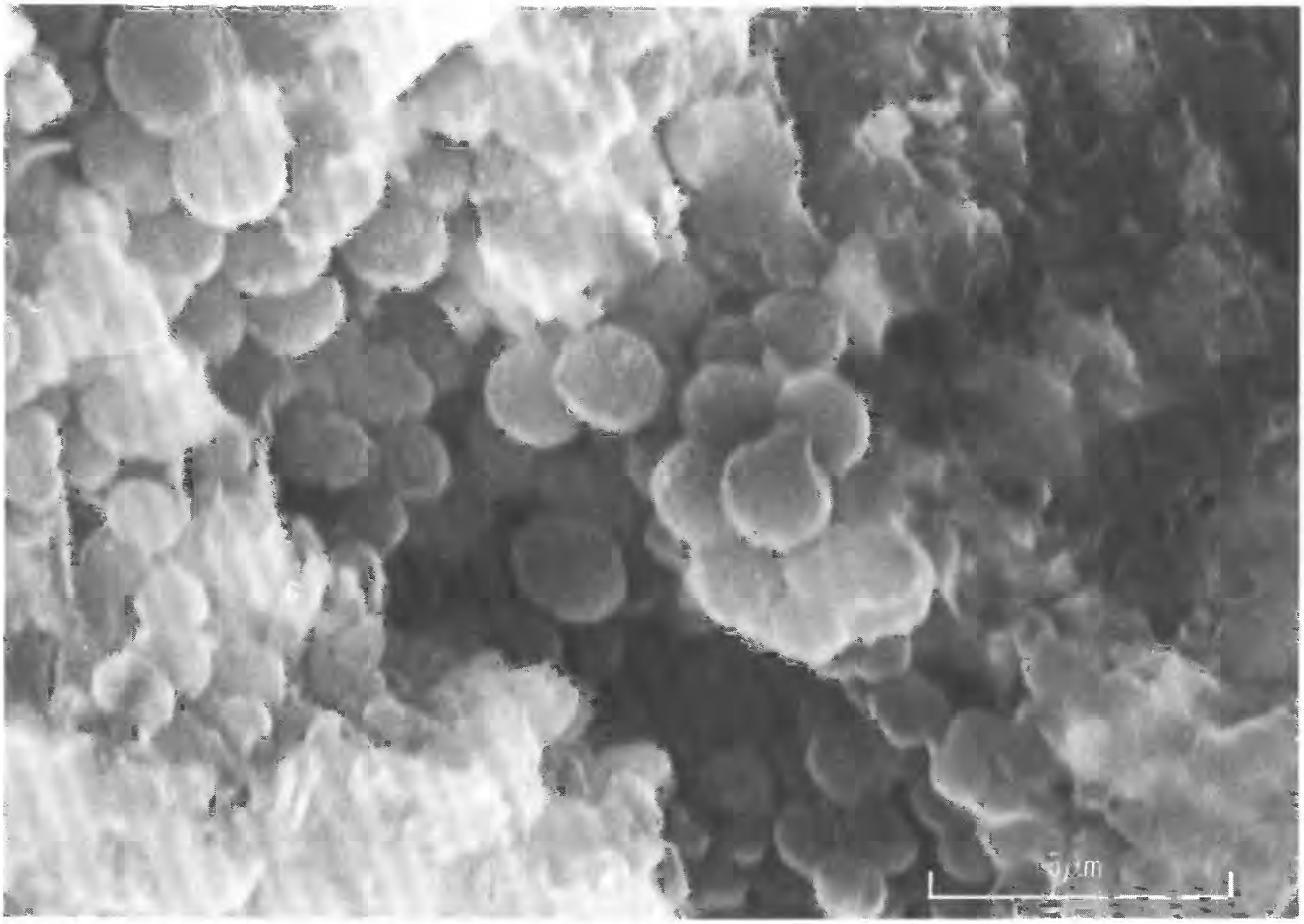


Figure 10. Scanning electron micrograph of diagenetically altered primary ore with microbotryoidal morphology. Poorly formed coffinite (c) is present. Core 7, sample 3259 (994 m).

diagenesis of mudflat sediments associated with saline-alkaline lake deposits overlying ore-bearing units (Turner-Peterson and others, 1980; Turner-Peterson, 1985).

Abundant detrital plant material in the Westwater Canyon Member suggests that at least some of the humate was derived from intrinsic plant material (Squyres, 1980). However, Granger (1968) asserted that not enough detrital material is present to account for the amount of amorphous organic material present in the ore deposits. Abundant plant material must have been present in the Morrison Formation at the time of deposition, because of the great numbers of large animals such as dinosaurs that are known to have existed in the Late Jurassic (Dodson and others, 1980). Soluble organic acids may have also been derived from plant material in upstream fluvial facies of the Westwater Canyon Member.

Evidence for nearly simultaneous precipitation of organic matter and uranium indicate that organic acids precipitated sometime in the Late Jurassic to Early Cretaceous interval of ore formation. Thus, Late Cretaceous swamps could not have been the source of the organic material as proposed by Granger and others (1961).

On the basis of sedimentological studies, others have suggested that humic and fulvic acids were derived from early compaction of mudstones in the lower part of the Brushy Basin Member and were subsequently carried downward by reducing, alkaline solutions into underlying sandstones (Turner-Peterson and others, 1980; Turner-Peterson, 1985). All known primary ore in the Grants uranium region lies under the mudflat facies of the Brushy Basin Member (Fishman and others, 1984). The downward movement of alkaline, humic-acid-bearing pore fluids was driven by compaction and salinity gradients, a common phenomenon where fine-grained lacustrine sediments overlie permeable strata (Chilingarian, 1983) and which has been modeled in modern lakes by Winter (1981). This hypothesis is supported by Fe-Ti-oxide alteration patterns in the upper part of the Westwater Canyon Member in the ML-LV cores (Reynolds and others, 1986) and by regional Fe-Ti oxide alteration patterns in the Morrison Formation in the

Figure 11. Scanning electron micrograph of diagenetically altered ore consisting of rod-shaped coffinite and microspheres intergrown with primary ore. Core 4, sample 1933 (589 m).

Grants uranium region (Adams and others, 1974). Iron-titanium oxide alteration is thought to have been caused by reducing organic acid-bearing solutions.

A 7–10 m thick, organic-rich, pyritic green mudstone and claystone unit (fig. 18) in the lower part of Brushy Basin Member in all ML-LV cores lends credence to the theory that organic-acid-bearing waters may have been expelled from this unit during early diagenesis. Electron microprobe analyses of abundant black, irregular areas (<2mm) in this interval showed enrichment of organic carbon of 2–10 times background, significant iron, and minor aluminum and silicon. The presence of carbon and no detectable calcium imply that these carbon-bearing areas were originally fragments of plant material in a soil zone. Apparently, most organic material was removed as soluble organic acids from the green (reduced) mudstone before or during compaction. The hydrolysis of abundant volcanic ash that fell on the mudflat formed basic solutions favorable for solubilization of organic matter.

Primary Ore

Organic acid-bearing solutions migrated through permeable, uncompacted sandstones in the Westwater Canyon Member and leached iron and possibly other cations such as vanadium and chromium from detrital Fe-Ti oxides (Adams and others, 1974; Reynolds and others, 1986; Della Valle, 1981). These reducing solutions had a relatively high silica activity due to the dissolution of volcanic ash and probably carried some uranium in organic-acid complexes. Due to cation-loading of the humic acids (Fishman and Turner-Peterson, 1986) or to contact with a brackish or saline formation water in which organic acids were insoluble (Granger and Santos, 1982),

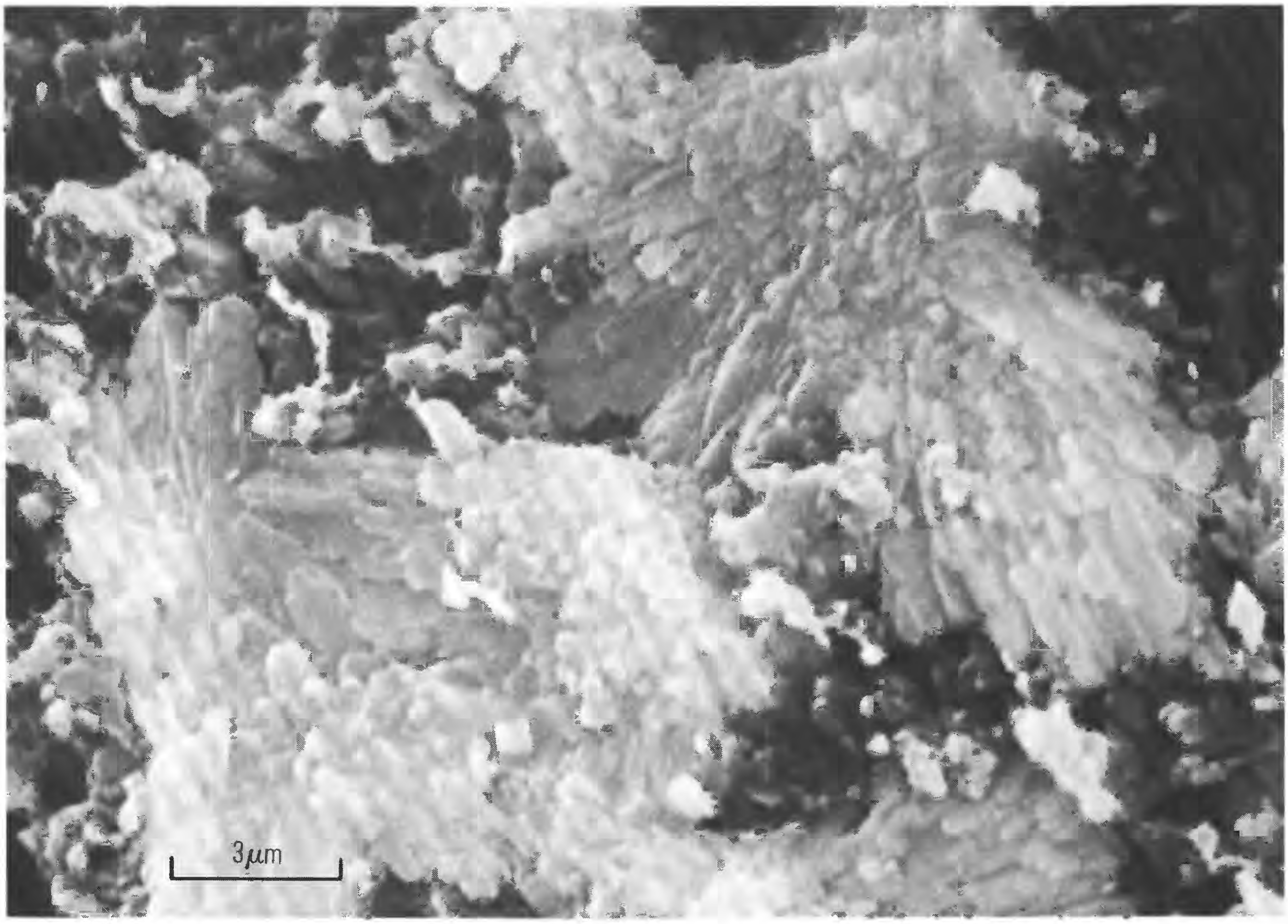


Figure 12. Scanning electron micrograph of radiating coffinite crystals. Core 7, sample 3260 (994 m).

metal-organic complexes in these solutions precipitated in tabular layers. Although cation-loading was probably a factor, the tabular form of the organic-rich layers and the fact that they are suspended in sandstone units without regard for bedding imply that organic acids precipitated at a hydrologic interface (Granger and others, 1961; Granger and Santos, 1982). The planar upper and lower surfaces of orebodies are very similar to those of humate layers that have precipitated at a fresh water-salt water interface in modern coastal Florida sands (Swanson and Palacas, 1965). The water below the interface may have been brackish sulfate-rich water, for sulfate is known to have dissolved at about that time in formations underlying the Morrison Formation (Hilpert and Moench, 1960; Ridgley, 1984).

Uranium enrichment on grain margins and on edges of pores infilled with primary ore indicates that most uranium mineralization occurred after organic matter precipitated (Webster, 1983; Hansley, 1986a). This conclusion is supported by chemical data that show organic material will carry only 10 weight percent chelated metals (Swanson and others, 1966). In addition, the long span in radiometric ages of primary uranium ore (130–110 m.y., Ludwig and others, 1984) indicates that uranium mineralization of humate layers continued for millions of years (although loss of radiogenic lead may account for some of the younger ages). Uranium was transported primarily as uranyl dicarbonate complexes (Langmuir, 1978) in meteoric fluids that flowed downdip through Westwater Canyon sandstones, although a significant amount of uranium may have been expelled from the lower part of the Brushy Basin Member during compaction (see next section). Upon contact with gel-like masses of organic matter, uranium was adsorbed and then reduced to the uranous (+4) ion (Leventhal, 1980). Where silica activity exceeded the solubility of amorphous silica, cryptocrystalline coffinite formed within the organic layers, which were very porous (see "Genesis of Coffinite"). During the latter stages of mineralization, oxidizing solutions probably redistributed uranium locally and early anhedral pyrite was dissolved and reprecipitated as euhedral pyrite in the ore zones.

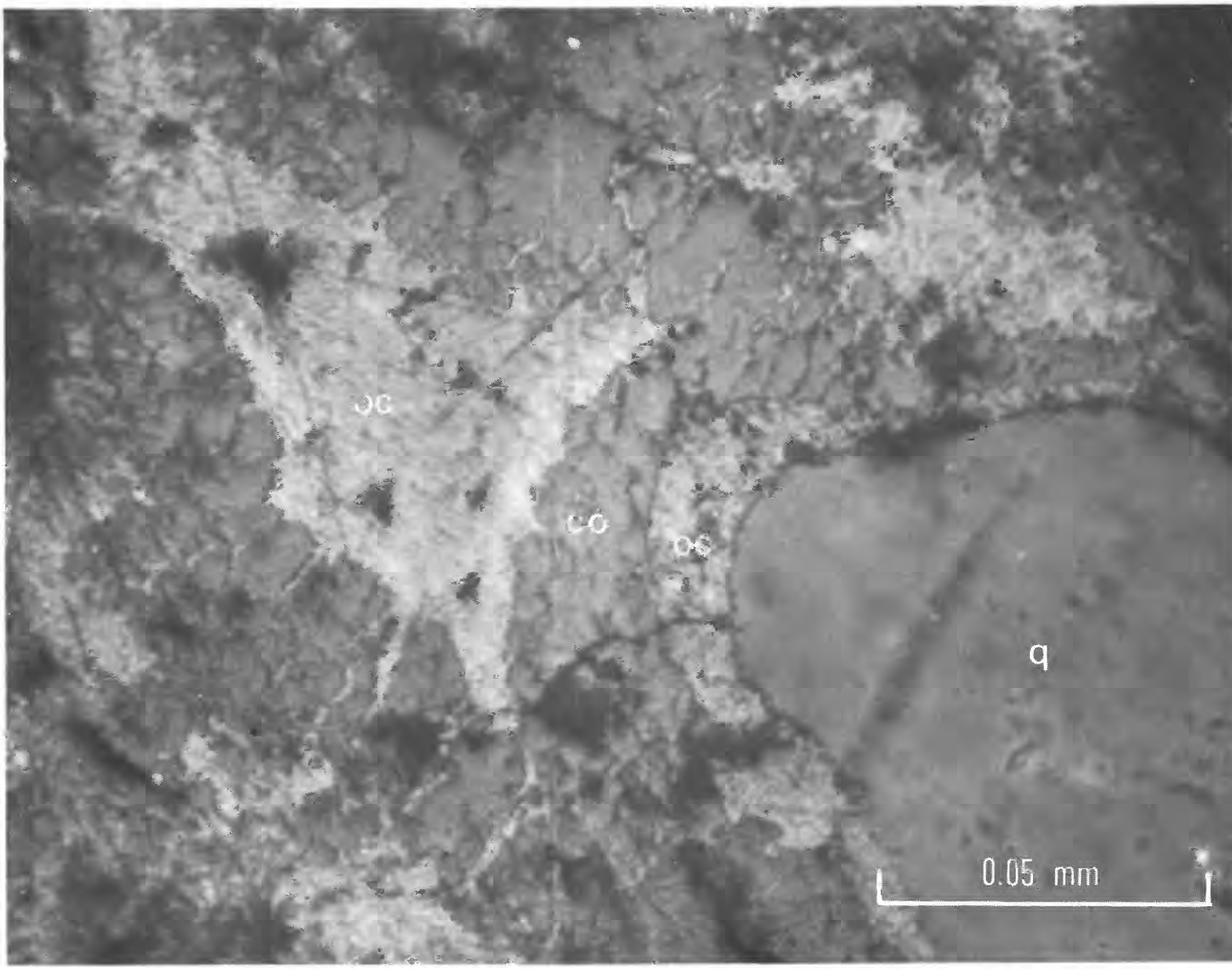


Figure 13. Photomicrograph showing bands of coffinite (co) and organic carbon (oc). Organic carbon is always closest to detrital quartz grains (q). Direct reflected light, oil immersion. Nose Rock deposit.

Influence of the Brushy Basin Member of the Morrison Formation

The distribution of depositional facies and early diagenetic phases in the Brushy Basin Member, which overlies the Westwater Canyon Member, in the ML-LV cores suggest that alkalinity and salinity of interstitial fluids increased basinward. In cores 1, 3 and 4, the Brushy Basin is composed of tuffaceous mudstone, claystone, and minor sandstone containing abundant authigenic smectite matrix. Farther basinward in cores 5–7a, discrete altered tuff beds and abundant millimeter-size orange spots of clinoptilolite and calcite pseudomorphs after clinoptilolite in tuffaceous claystone and mudstone intervals reflect a distinct change in depositional and diagenetic facies. These lithologic and mineralogic changes are interpreted to represent a transition from mudflat to playa margin facies in the Brushy Basin Member, similar to facies changes that Bell (1986) recognized in the southeastern part of the Grants uranium region. Rapid facies changes are typical of a saline-alkaline lake environment (Sheppard and Gude, 1968).

The ML-LV cores do not extend to the playa facies of the Brushy Basin Member, but core CC–12 contains analcime and albite cements in the Westwater Canyon Member, indicating that the playa facies was present in this area. Hicks and others (1980) also noted the presence of analcime in the Westwater Canyon Member in the Chaco Canyon cores. Unfortunately, no core was recovered from the Brushy Basin interval in the CC–12 core. Analcime precipitated when sodium-rich pore waters, derived from early diagenetic reactions in the lacustrine facies of the Brushy Basin, moved downward into Westwater Canyon Member sandstones and reacted with earlier zeolites (clinoptilolite?) or detrital feldspars.

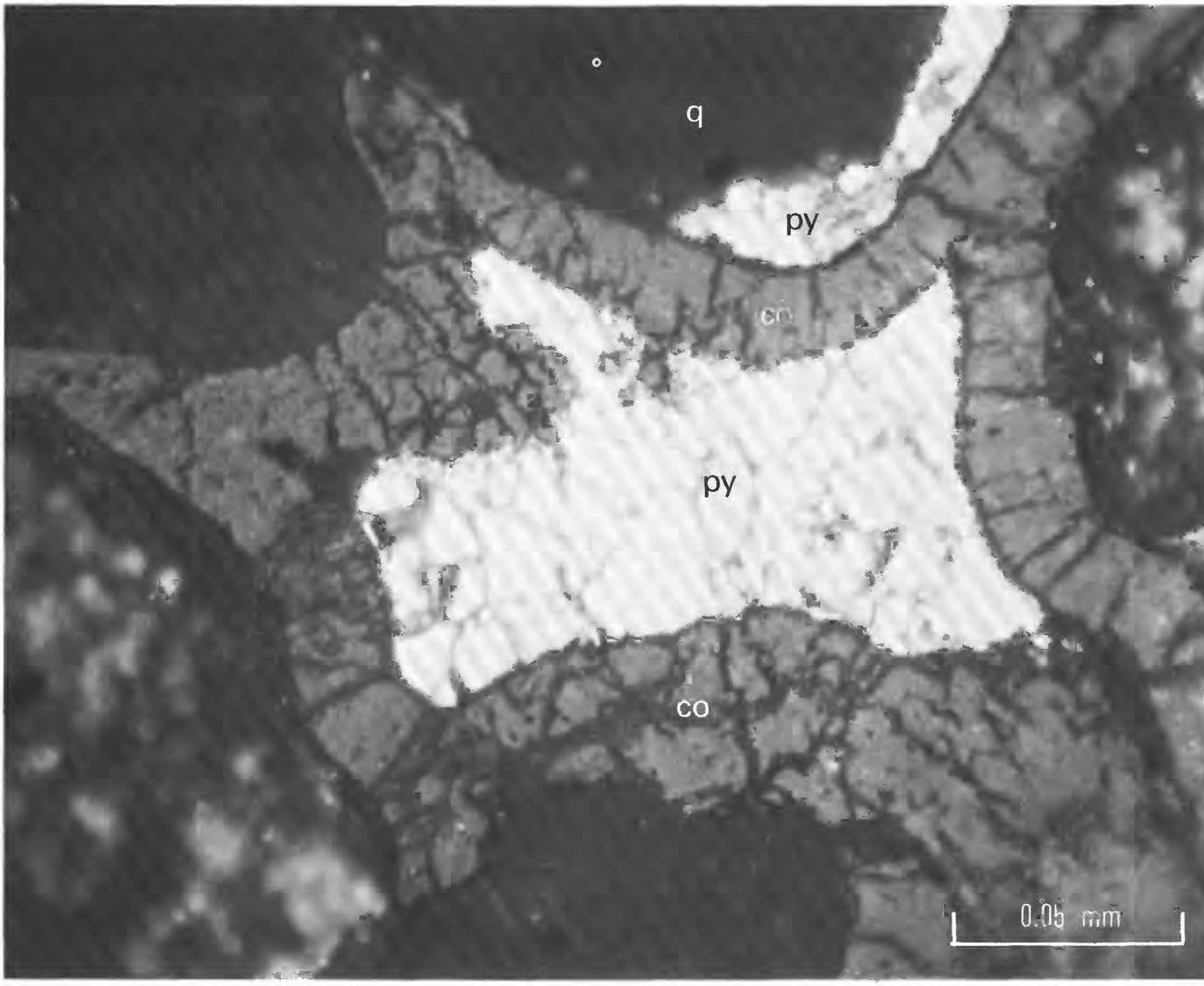


Figure 14. Photomicrograph showing bands of coffinite (co) and pyrite (py). Pyrite is always closest to detrital quartz grains (q). Direct reflected light, oil immersion. Ambrosia Lake district.

Authigenic albite probably formed during burial diagenetic alteration of the analcime.

Authigenic mineral phases in the upper Westwater Canyon Member show a progressive increase in salinity and silica activity basinward (Hansley 1984, 1986a, 1986c), mimicking the documented chemical gradients in the Brushy Basin Member (fig. 19). These authigenic phases form bands that parallel margins of the San Juan basin. Progressing northward from the southern margin of the basin they are: a smectitic plagioclase dissolution zone, a siliceous potassium feldspar zone, and a silica-rich analcime and albite zone (Hansley, 1984). The alteration bands are apparently not caused by varying depths of burial, as similar alteration zones occur in the upper Westwater Canyon Member along the western margin of the basin in sediments that have been buried to about the same depth (Hansley, 1984). The decrease in intensity of each feldspar alteration zone downward from the Brushy Basin-Westwater Canyon contact implies that solutions migrated downward and outward into sandstones from overlying units. As many as four generations of authigenic silica in the same pore suggest that pulses of fluids, perhaps related to the dewatering of units in the Brushy Basin Member, moved into sandstones in the upper part of the Westwater Canyon Member. These fluids had relatively high silica, sodium, and potassium activities due to the alteration of rhyolitic volcanic ash. Feldspar alteration patterns in the Jackpile sandstone unit, an informal economic unit in the uppermost Brushy Basin Member in the Laguna district, are the mirror image of alteration patterns in the Westwater Canyon Member indicating that fluids moved upward into the Jackpile sandstone unit from underlying fine-grained Brushy Basin units (Adams and others, 1978).

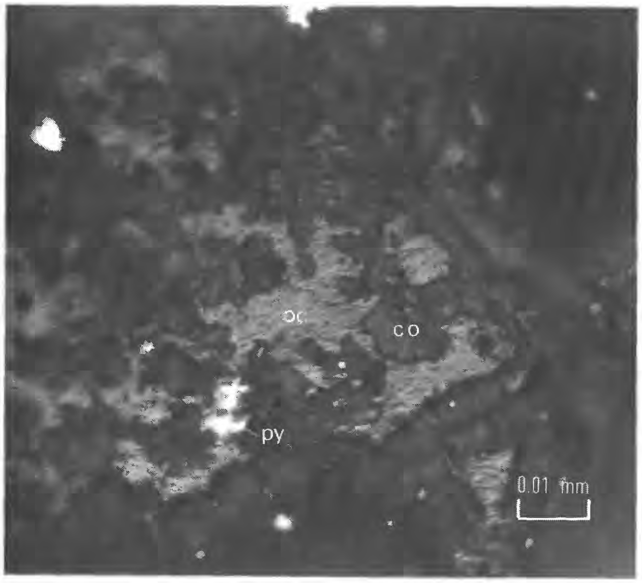


Figure 15. Photomicrograph of dark gray coffinite (co) that has replaced light gray organic carbon phase (oc) and pyrite (py). Matrix is almost pure carbon with traces of silicon, lead, molybdenum, and sulfur. Direct reflected light, oil immersion. Nose Rock deposit.

That pore water moved down is supported by geochemical studies showing that the whole-rock and the <2-micrometer fraction of the upper part of the Westwater Canyon Member are enriched in sodium, light rare earths, and uranium (Della Valle, 1981). Della Valle attributed the enrichment of these elements to solutions derived from compacting sediments in the overlying Brushy Basin Member. Dilute meteoric fluids that migrated downdip through permeable Westwater Canyon sandstone units also contributed elements needed to form authigenic phases and uranium ore, but the closed basin environment of the Brushy Basin Member allowed for higher concentrations of elements in the escaping pore fluids. These fluids may also have carried organic acids derived from decaying organic matter in Brushy Basin sediments (Fishman and others, 1984; Turner-Peterson and Fishman, 1986).

High contents of silica and cryptocrystalline coffinite in ore farthest into the basin (cores 4–8 and the Nose Rock deposit) may be related, in part, to chemical gradients in the Brushy Basin Member (Hansley and Turner-Peterson, 1984). At pH values greater than nine, not uncommon in lacustrine facies of a saline-alkaline lake environment (Sheppard and Gude, 1968; Hay, 1966), the dissolution rate of volcanic ash increases dramatically (Zielinski, 1982) as does the solubility of silica (Krauskopf, 1959). Thus, escaping Brushy Basin pore fluids may have had higher silica contents than fluids closer to the basin margin.

Alteration of Primary Ore

Early Cretaceous(?) Alteration

Primary ore was remobilized locally during the latter stages of primary mineralization when mildly oxidizing uranyl-bearing solutions continued to react with earlier-formed primary orebodies. Tabular bodies of amorphous carbonaceous, uraniferous ore were re-shaped into S-shaped rolls. The two-dimensional nature of the line of cores, however, prohibited observation and interpretation of orebody morphology. Adams and others (1978) proposed that Jackpile ore was remobilized accounting for younger ages (115 ± 9 m.y.), and Brookins (1980) thought that major diagenetic alteration took place during the Early Cretaceous. Light ore-zone pyrite characteristic of many primary orebodies may have formed when early pyrite cement was locally oxidized and the iron and sulfur reprecipitated downdip as isotopically light euhedral pyrite in the manner that Granger and Warren (1969) described for roll-type deposits. The close association of primary ore and diagenetically altered primary ore may account for numerous theories of origin for the same ore body, for depending on which part of the orebody was sampled, different conclusions as to the type of ore present could be reached.

Mid-Tertiary Alteration

Petrologic and stable isotope data indicate that most primary ore was altered during the mid-Tertiary when the Morrison Formation was most deeply buried. Regularly interstratified illite-smectite (Perry and Hower, 1970), albitized plagioclase (Boles, 1982), and ankerite (Boles, 1978) indicate that formation temperatures within the Morrison Formation reached 100°C at this time. Deeply etched garnets occur only within the illite-smectite zone (Hansley, 1987). Etch-patterns on garnets identical to those these naturally etched Morrison garnets have been created experimentally by warm (80°C) organic-acid-bearing solutions (Hansley, 1985, 1987).

On the basis of oxygen and deuterium isotope data on illite-smectite and cogenetic chlorite, Northrop and Whitney (1985) suggested that a warm deep-basin fluid with the composition of an oil-field brine moved updip through the Westwater Canyon Member during burial of the Morrison Formation. Updip fluid migration may have occurred during the mid-Tertiary as oil was generated in the San Juan basin at this time (Rice, 1983). Warm fluids would have increased the solubility of silica (Siever, 1962) and, therefore, stabilized coffinite (Hemingway, 1982) and explain the presence of silicified Fe-Ti oxides containing traces of organic carbon in altered ore zones. Temperatures greater than 80°C promoted the breakdown of

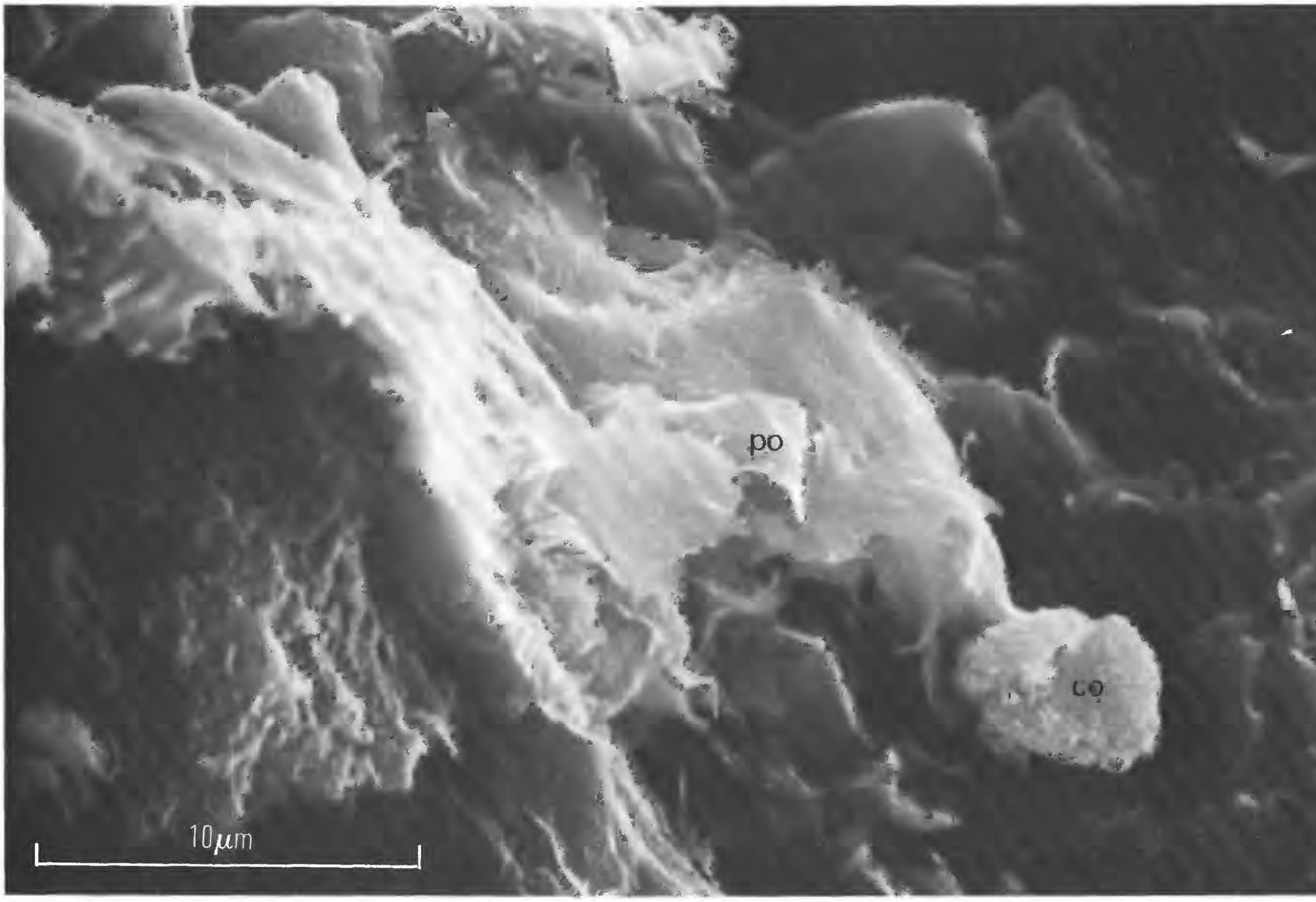


Figure 16. Scanning electron micrograph of coffinite (co) that has replaced primary ore (po). Core 7, sample 3260 (994 m).

organic molecules releasing soluble oxygenated functional groups and carbon dioxide; maximum generation of carboxylic acids occurs between 80°–100°C (Surdam and others, 1984). The resultant acid pore waters dissolved framework grains and carbonate cement thus producing abundant secondary porosity. Dicarboxylic acids derived from the oxidative degradation of immature type III kerogen are excellent solvents of plagioclase, because dicarboxylic acids have the ability to complex aluminum, which is insoluble in most natural inorganic solutions (Surdam and others; 1984; Surdam and Crossey, 1985). Binding of aluminum by organic complexes accounted for the lack of alteration products on skeletal grains. The maturation of type III kerogen would have resulted in the release of larger amounts of reactive oxygenated functional groups than either type I or type II kerogen (Tissot and Welte, 1984).

The fine-grained, idiomorphic nature of quartz, chlorite, and adularia, which are commonly intergrown in diagenetically altered ore, may also be the result of rapid precipitation in a zone of mixing between two formation waters (Heald and Renton, 1966; Engelhardt, 1977). Where this authigenic assemblage is now present, primary ore may once have existed (Spirakis and Hansley, 1986). Isotopically light carbonate carbon in uranium ore zones (Leventhal, 1980; Hansley, 1986a) may have been derived from the diagenesis of organic material at this time.

It is curious that the migration of organic acids through permeable sandstones prior to and during primary ore formation did not cause widespread dissolution of framework grains. The hydrolysis of abundant silicic volcanic ash in the sandstones may have buffered the pH to moderately alkaline values (Zielinski, 1982) stablizing feldspars in the presence of organic acids.

Late Tertiary Alteration

During the late Tertiary, a tongue of oxidizing waters migrated downdip through the Crownpoint area northward to the Nose Rock vicinity (Saucier, 1980). Roll-front features and associated oxidized phases such as hematite and sulfates formed at this time. Corroded pink barite containing ferric oxide pseudomorphs of pyrite is overgrown by euhedral pyrite that represents a post-barite stage of sulfidization. Similar resulfidization textures have been observed in altered parts of the Mariano Lake ore (Place and others, 1980; Rhett, 1980; Hansley, 1986a, 1986c).

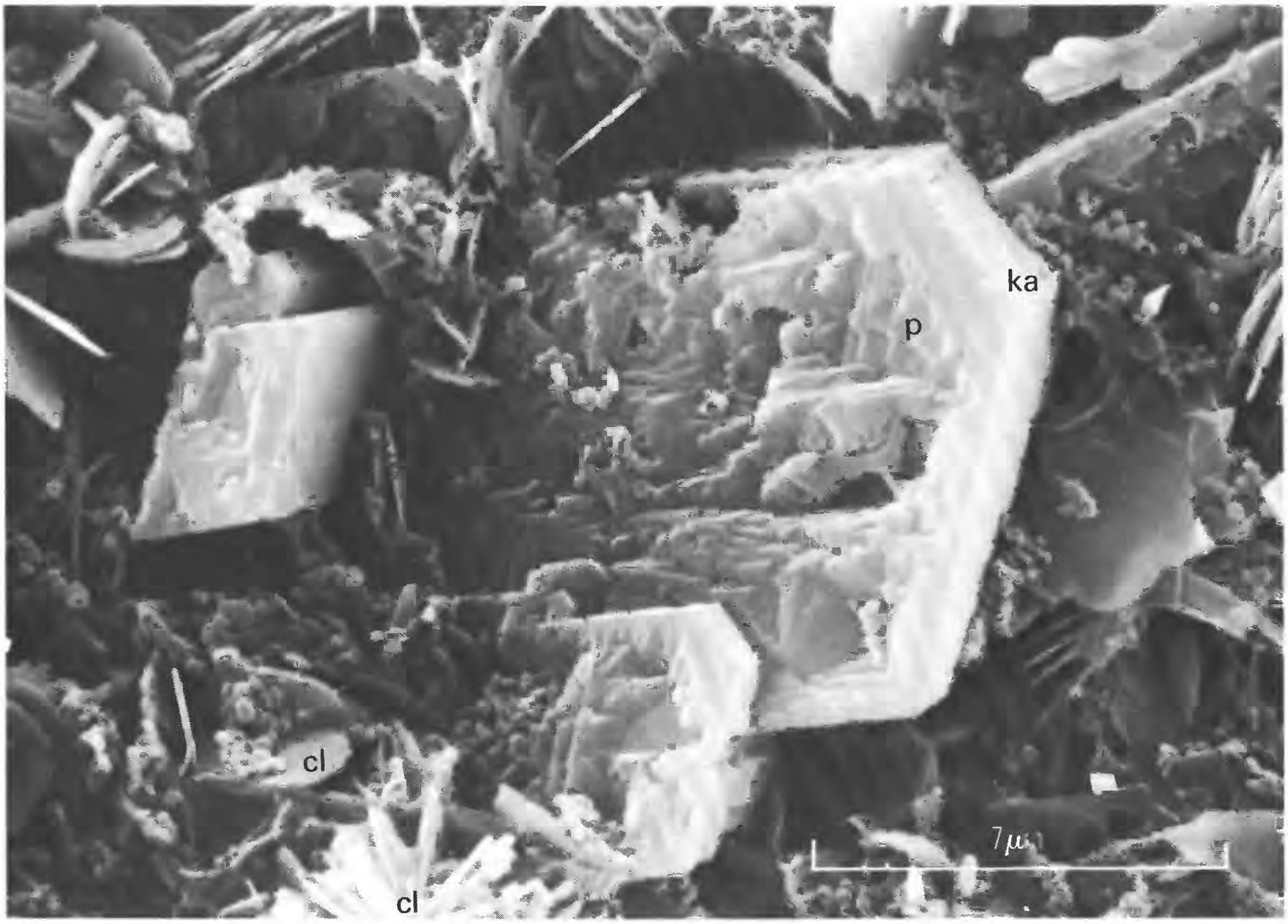


Figure 17. Scanning electron micrograph of microbotryoidal uranium ore within a skeletal plagioclase grain (p) rimmed by a potassium feldspar overgrowth (ka). Note ore on top of chlorite (cl). Core 7a, sample 3136 (956 m).

Abundant interstitial kaolinite in ore-bearing sandstones that show little alteration of detrital feldspar grains may have precipitated as a result of destabilization of the aluminum-organic complexes derived from the alteration of primary ore zones. Apparently anomalous mineral associations in deeper ore zones, such as (later) kaolinite and calcite, may be explained by the buffering capacity of organic acids. If carboxylic acids control the alkalinity of water calcite will become less soluble and precipitate as the partial pressure (P) of CO_2 rises; if the alkalinity is buffered by the carbonate system, calcite will become more soluble and dissolve as P_{CO_2} rises (Surdam and Crossey, 1985).

GENESIS OF COFFINITE

Coarsely crystalline coffinite is rare in sedimentary uranium deposits. Rhett (1979, 1980) noted abundant coarse-grained coffinite in radiating clusters in Nose Rock ore, and Granger and others (1961, p. 1198) described coffinite as "microscopic jet black columnar crystals perched individually or in clusters on sand grains" in postfault (redistributed) ore from the Ambrosia Lake district. Large coffinite crystals having "radially fibrous internal structure" are visible in thin sections from the Woodrow mine, a collapsed pipe in the Laguna district (Moench, 1962). Vanadium-uranium deposits on the north-central part of the Colorado Plateau contain micrometer-sized tetragonal crystals of coffinite intergrown with chlorite (Northrop and others, in press(a); Goldhaber and others, 1987, in press). Wyoming roll-front uranium deposits contain colloform coffinite-uraninite mixtures (Ludwig and Grauch, 1980).

The origin of coffinite in low-temperature, sandstone-hosted uranium deposits is enigmatic, because it has not yet been synthesized at temperatures <200°C (Hemingway, 1982). Fuchs and Hoekstra (1959) synthesized coffinite in basic solutions (pH of 8.0 to 10.5) between 200°C and 360°C. Using an estimated free

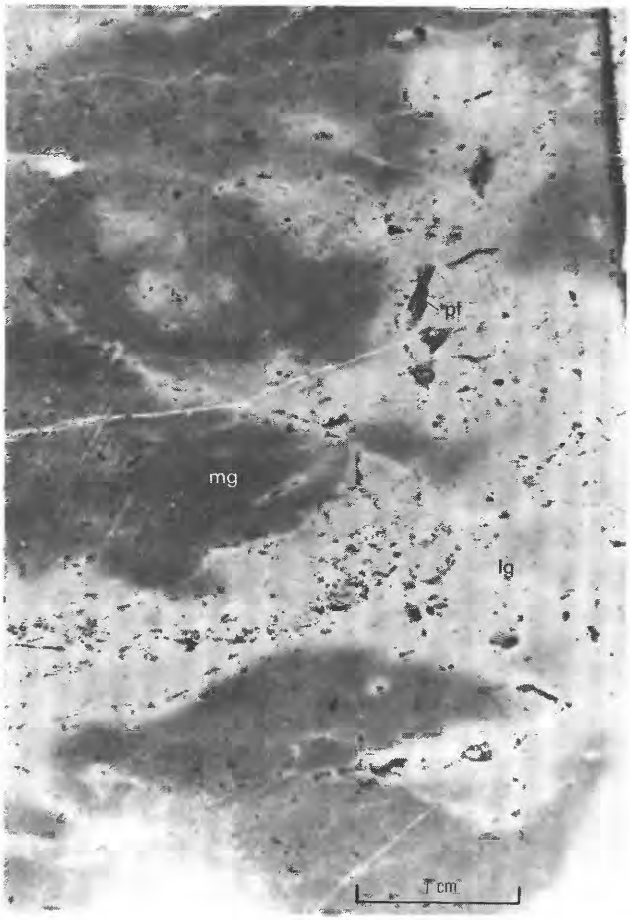


Figure 18. Photograph of altered plant(?) fragments in pyritic green mudstone from the lower part of the Brushy Basin Member. Light gray areas (lg) are green (reduced) mudstone, medium gray (mg) areas are red mudstone, and black areas are inferred to be plant fragments (pf). Note light gray (reduced) halos around organic fragments. Core 4, 550 m.

energy of formation for coffinite of -1886 ± 6 kilojoules per mole at 298.15 Kelvin, a figure derived from known free energy values of isostructural minerals (e.g. zircon), Hemingway (1982) determined that the activity of silica (as $[H_4SiO_4]$) necessary for coffinite to form is $10^{-3.59}$. This value is similar to that (10^{-3}) proposed by Langmuir (1978) but is considerably higher than that ($10^{-6.9}$) suggested by Brookins (1975). Importantly, this latter value exceeds the equilibrium solubility of amorphous silica ($10^{-3.68}$; Cuney, 1978). A value as high as $10^{-3.59}$ would not have been unreasonable at the time of uranium mineralization (due to the hydrolysis of large volumes of silicic volcanic ash) or later in diagenesis (due to widespread dissolution of silicates), but it does not explain why coffinite is commonly associated with quartz rather than amorphous silica in Morrison deposits (Hansley, 1986c; Goldhaber and others, 1987). Perhaps the age of these deposits has allowed amorphous silica originally present in ore zones to recrystallize to quartz. On the other hand Goldhaber and others (1987) proposed that high aluminum concentrations and acidic pH values generated by clay formation in ore zones inhibited the polymerization of silica and, thus, stabilized quartz relative to amorphous silica even at high concentrations of silica. Their conclusions are based on authigenic mineralogy, isotopic data on clay minerals in the ore zones in the Salt Wash Member of the Morrison Formation in the Henry basin, and on experimental data (Mohagheghi, 1985). Abundant ore-stage clay minerals, particularly vanadium-bearing chlorite, in Salt Wash ore zones attest to high concentrations of aluminum at the time of coffinite formation; clay mineral precipitation lowered the pH by consuming hydroxyl groups (Garrels and others, 1959; Byorkkle, 1982). Silica polymers were destabilized by high ionic strengths due to the presence of a brine in ore-forming horizons (Goldhaber and others, 1987).

Isotopic data on ore-zone clay minerals and dolomite indicate that a solution interface between an overlying meteoric water and an underlying brine of seawater composition was present at the time of ore formation in the Salt Wash ores (Northrop, 1982; Northrop and others, in press(b)). In the mixing zone between the brine and meteoric water, a drop in pH of the saline fluid promoted adsorption of uranyl ion onto detrital grain surfaces. Subsequent two-step reduction of UO_2 (uranyl) to UO_2+ and then to UO_2++ by sulfide species such as hydrogen sulfide or HS^- in the presence of high silica activities promoted formation of coffinite plus quartz (Goldhaber and others, 1987).

In the Grants uranium region, early diagenetic clay minerals and bacterial metabolism of organic matter during sulfate reduction provided abundant hydrogen ions that favored the adsorption of uranium and, thus, promoted formation of cryptocrystalline coffinite in zones of organic matter accumulation. The later migration of a warm fluid through primary ore-bearing strata may have facilitated recrystallization of cryptocrystalline coffinite and precipitation of coarsely crystalline coffinite by causing breakdown of organic compounds and increasing the solubility of silica. Banded gel-like coffinite/organic matter textures may have formed when organics were remobilized and uranium diffused out of the organic matter during redistribution in the warm fluids.

COMPARISON OF DEPOSITS IN THE WESTWATER CANYON MEMBER WITH DEPOSITS IN THE SALT WASH MEMBER OF THE MORRISON FORMATION

One of the major differences between primary uranium ore in the Salt Wash Member and primary ore in the Westwater Canyon Member is the relative amount of amorphous organic material: Westwater Canyon primary ore contains a large amount of amorphous

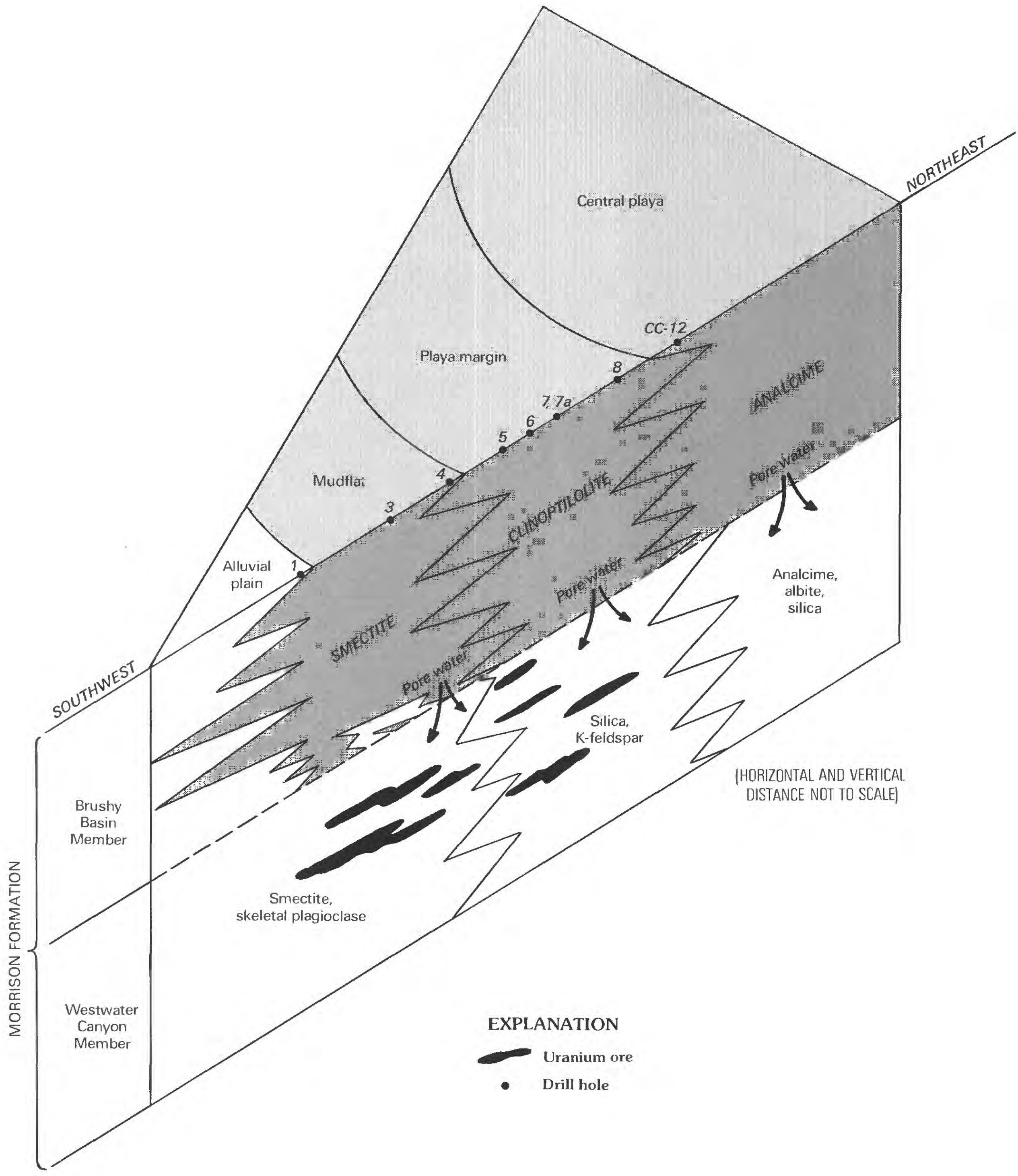


Figure 19. Pie diagram showing depositional and diagenetic facies of the Brushy Basin Member and corresponding diagenetic facies of the Westwater Canyon Member. Inferred directions of fluid movement during compaction are shown. Drill holes are located on southwest-northeast line.

organic matter; Salt Wash ore, almost none. In both members, orebodies have tabular shapes and planar upper surfaces, ore horizons rise stratigraphically basinward, and the ore forms a matrix that fills primary pore spaces. Realization that organic matter can undergo diagenesis at low to moderate temperatures (<100 °C) provides a mechanism whereby organic-rich ore can be converted into organic-poor ore; thus, Salt Wash deposits might have originally contained more amorphous organic matter that was converted to organic acids during post-ore diagenesis. If this were the case, all tabular-type uranium deposits in the Morrison Formation may have had a common genesis (Spirakis and Hansley, 1986).

SUMMARY AND CONCLUSIONS

Chemical, sedimentologic, and mineralogic data suggest that mineralizing fluids were expelled downward and outward during compaction of tuffaceous Brushy Basin mudstones and claystones. These uranium-bearing solutions migrated through Westwater Canyon Member sandstones and precipitated uranium in and around concentrations of amorphous organic matter. Some organic matter was undoubtedly intrinsic to the ore-bearing fluvial sandstones, and some may have been derived from organic matter in overlying and interfingering fluvial and lacustrine mudstones of the Brushy Basin Member. The tabular nature of organic-rich primary orebodies suggest that organic acids precipitated at an interface between meteoric water and a brackish formation water.

Both primary and secondary ore are present in the ML-LV cores. Widespread diagenesis of primary ore resulted in the formation of diagenetically altered, carbon-poor ore containing coffinite. Bacterial and thermal alteration of primary ore resulted in the production of soluble organic acids and carbon dioxide increasing the acidity and complexing ability of pore fluids. Subsequent water-rock reactions resulted in dissolution of aluminosilicate minerals, formation of abundant secondary porosity and precipitation of chlorite, quartz, adularia, and ferroan carbonates.

Alteration of primary ore took place at several times during the postdepositional history of the Morrison Formation, but most diagenesis is inferred to have taken place in the mid-Tertiary. In contrast, late Tertiary oxidation of primary ore formed roll-front deposits characterized by oxidized minerals.

Petrologic similarities between carbonaceous primary ore in the Westwater Canyon Member and carbon-poor ore in the Salt Wash Member imply that ore in the Salt Wash Member may simply be diagenetically altered carbonaceous primary ore. Thus, lack of organic carbon in an ore zone may not be a valid criterion for dismissing the role of organic matter in the genesis of an ore deposit.

REFERENCES CITED

Adams, S.S., Curtis, H.S., and Hafen, P.L., 1974, Alteration of detrital magnetite-ilmenite in continental sandstones of the Morrison Formation, New Mexico, *in* Formation of uranium ore deposits; Vienna, International Atomic Energy Agency, Proceedings Series, No. STI/PUB/374, p. 219–253.

Adams, S.S., Curtis, H.S., Hafen, P.L., and Salek-Nejad, H., 1978, Interpretation of postdepositional processes related to the formation and destruction of the Jackpile-Paguate uranium deposit, northwest New Mexico: Economic Geology, v. 58, n. 6, p. 1635–1654.

Adams, S.S., and Saucier, A.E., 1981, Geology and recognition criteria for uraniferous humate deposits, Grants uranium region, New Mexico: U.S. Department of Energy Report GJBX-2(81), 225 p.

Basham, I.R., and Shilston, A.M., 1978, A scanning electron microscope study of sandstone-type uranium-vanadium mineralization from Pakistan, *in* Whalley, W.B., ed., Scanning electron microscopy in the study of sediments: Norwich, England, Geo Abstracts, p. 347–353.

Bell, T.E., 1986, Deposition and diagenesis in the Brushy Basin and upper part of the Westwater Canyon Member of the Morrison Formation, San Juan basin, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 77–92.

Bjorlykke, Knut, 1982, Diagenetic reactions in sandstones, *in* Parker, Andrew, and Sellwood, B.W., eds., Sediment diagenesis: Boston, D. Reidel Publishing Company, NATO Advanced Study Institutes Series C, v. 115, p. 169–213.

Boles, J.R., 1978, Active ankerite cementation in the subsurface Eocene of southwest Texas: Contributions to Mineralogy and Petrology, v. 68, p. 13–22.

______1982, Active albitization of plagioclase, Gulf Coast Tertiary: American Journal of Science, v. 282, no. 2, p. 165–180.

Brookins, D.G., 1975, The Grants mineral belt, New Mexico—Comments on the coffinite-uraninite relationship, probable clay mineral reactions, and pyrite formation, *in* Woodward, L.A., and Northrop, S.A., eds., Tectonics and mineral resources of southwestern North America: New Mexico Geological Society Special Publication 6, p. 158–166.

______1979, Uranium deposits of the Grants mineral belt, New Mexico: U.S. Department of Energy Report GJBX-141 (79), 411 p.

______1980, Geochronologic studies in the Grants mineral belt, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 52–58.

Chilingarian, G.V., 1983, Compactional diagenesis, *in* Parker, Andrew, and Sellwood, B.W., Sediment diagenesis: Boston, D. Reidel Publishing Company, NATO Advanced Study Institutes Series C, v. 115, p. 57–168.

Clark, D.S., and Havenstrite, S.R., 1980, Geology and ore deposits of the Cliffside mine, Ambrosia Lake area, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 52–58.

Condon, S.M., and Peterson, F., 1986, Stratigraphy of Middle and Upper Jurassic rocks in the San Juan Basin—Historical perspective, current ideas, and remaining problems, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 7–26.

Cooley, M.E., and Davidson, E.S., 1963, The Mogollon highlands—Their influence on Mesozoic and Cenozoic erosion and sedimentation: Arizona Geological Society Digest, v. 6, p. 7-35.

Cuney, M., 1978, Geologic environment, mineralogy, and fluid inclusions of the Bois Noirs-Limouzat uranium vein, Forez, France, *in* Nash, J.R., ed., Uranium geology in resource evaluation and exploration: Economic Geology, v. 73, no. 8, p. 1567-1610.

Della Valle, R.S., 1981, Geochemical studies of the Grants mineral belt, New Mexico: Albuquerque, N. Mex., University of New Mexico Ph.D. thesis, 450 p.

Dodson, Peter, Behrensmeyer, A.K., Bakker, R.T., and McIntosh, J.S., 1980, Taphonomy and paleoecology of the dinosaur beds of the Jurassic Morrison Formation: Paleobiology, v. 6, no. 2, p. 208-232.

Engelhardt, W.V., 1977, The origin of sediments and sedimentary rocks: Sedimentary petrology, Part III, (2d ed.), New York, John Wiley and Sons, 359 p.

Fishman, N.S., and Reynolds, R.L., 1986, Origin of the Mariano Lake uranium deposit, McKinley County, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 211-226.

Fishman, N.S., Reynolds, R.L., and Robertson, J.F., 1985, Uranium mineralization in the Smith Lake District of the Grants uranium region, New Mexico: Economic Geology, v. 80, no. 5, p. 1348-1364.

Fishman, N.S., and Turner-Peterson, C.E., 1986, Cation scavenging—An alternative to a brine for humic acid precipitation in tabular uranium ore, *in* Dean, W.A., ed., Organics and ore deposits: Denver Regional Exploration Geologists Society Symposium, Proceedings, p. 197-204.

Fishman, N.S., Turner-Peterson, C.E., and Reynolds, R.L., 1984, Alteration of magnetite and ilmenite in Upper Jurassic Morrison Formation, San Juan Basin, New Mexico: Relationship to facies and primary uranium mineralization [abs]: American Association of Petroleum Geologists Bulletin, v. 66, no. 7, p. 937.

Fuchs, L.H., and Hoekstra, H.R., 1959, The preparation and properties of uranium (1V) silicate: American Mineralogist, v. 44, nos. 9-10, p. 1057-1063.

Galloway, W.E., 1980, Deposition and early hydrologic evolution of Westwater Canyon wet alluvial fan system, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 59-69.

Garrels, R.M., Larsen, E.S., 3d, Pommer, A.M., and Coleman, R.G., 1959, Detailed chemical and mineralogical relations in two vanadium-uranium ores, *in* Garrels, R.M., and Larsen, E.S., 3d, eds., Geochemistry and mineralogy of the Colorado Plateau uranium ores: U.S. Geological Survey Professional Paper 320, p. 165-182.

Goldhaber, M.B., Hemingway, B.S., Mohagheghi, A., Reynolds, R.L., and Northrop, H.R., 1987, Origin of coffinite in sedimentary rocks by a sequential adsorption-reduction mechanism: Société francaise de Minéralogie et de Cristallographie, Bulletin Minéralogie, v. 110, p. 131-144.

Goldhaber, M.B., Reynolds, R.L., Campbell, Jack, Wanty, Rich, Grauch, R.I., and Northrop, H.R., in press, Genesis of the tabular-type vanadium-uranium deposits of the Henry structural basin, Utah—Mechanisms of ore and gangue mineral formation at the interface between brine and meteoric water: Economic Geology.

Granger, H.C., 1968, Localization and control of uranium deposits in the southern San Juan Basin mineral belt, New Mexico—An hypothesis: U.S. Geological Survey Professional Paper 600-B, p. B60-B70.

Granger, H.C., and Santos, E.S., 1982, Geology and ore deposits of the Section 23 mine, Ambrosia Lake District, New Mexico: U.S. Geological Survey Open-File Report 82-207, 70 p.

Granger, H.C., Santos, E.S., Dean, B.G., and Moore, F.B., 1961, Sandstone-type uranium deposits at Ambrosia Lake, New Mexico—An interim report: Economic Geology, v. 56, no. 7, p. 1179-1210.

Granger, H.C., and Warren, C.G., 1969, Unstable sulfur compounds and the origin of roll-type uranium deposits: Economic Geology, v. 64, no. 2, p. 160-171.

Hansley, P.L., 1984, Feldspar alteration patterns in the Upper Jurassic Morrison Formation, northwestern New Mexico [abs], *in* Society of Economic Paleontologists and Mineralogists First National Midyear Meeting, Golden, Colo., 1985, Technical Program, p. 37.

______1985, A zone of chemically etched garnets in the Upper Jurassic Morrison Formation, northwestern New Mexico—an indicator of a unique diagenetic fluid? *in* Society of Economic Paleontologists and Mineralogists Annual Midyear Meeting, Technical Program, v. II, p. 39-40.

______1986a, Regional diagenetic patterns and uranium mineralization across the Grants uranium region, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 277-302.

______1986b, The relation of detrital, nonopaque heavy minerals to diagenesis and provenance of the Morrison Formation, southwestern San Juan basin, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 257-276.

______1986c, Diagenesis and uranium mineralization in the Westwater Canyon Member of the Morrison Formation, Grants uranium region, northwestern New Mexico, *in* U.S. Geological Survey Diagenesis Workshop: U.S. Geological Survey Bulletin 1578, p. 265-280.

______1987, Petrologic and experimental evidence for the etching of garnets by organic acids in the Upper Jurassic Morrison Formation, northwestern New Mexico: Journal of Sedimentary Petrology, v. 57, no. 4, p. 666-681.

Hansley, P.L., and Fitzpatrick, Joan, in press, Compositional and crystallographic data on rare-earth-bearing coffinite from the Grants uranium region, northwestern New Mexico: American Mineralogist.

Hansley, P.L., and Turner-Peterson, C.E., 1984, Anomalous primary uranium ore in the San Juan Basin—Its relationship to alkaline lake facies [abs.]: Geological Society of America, Rocky Mountain Section Abstracts with Program, v. 16, no. 4, p. 223.

Hatcher, P.G., Spiker, E.C., Orem, W.H., Romankiw, L.A., Szeverenyi, N.M., Maciel, G.H., 1986, Organic geochemical studies of uranium-associated organic matter from the San Juan Basin—A new approach using solid-state ^{13}C nuclear magnetic resonance, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 171-184.

Hay, R.L, 1966, Zeolites and zeolitic reactions in sedimentary rocks: Geological Society of America Special Paper 85, 123 p.

Heald, M.T., and Renton, J.J., 1966, Experimental study of sandstone cementation: Journal of Sedimentary Petrology, v. 36, no. 4, p. 977-991.

Hemingway, B.S., 1982, Thermodynamic properties of selected uranium compounds and aqueous species at 298.15K and 1 bar and at higher temperatures— Preliminary models for the origin of coffinite deposits: U.S. Geological Survey Open-File Report 82-619, 60 p.

Hicks, R.T., Lowry, R.M., Della Valle, R.S., and Brookins, D.G., 1980, Petrology of Westwater Canyon Member, Morrison Formation, East Chaco Canyon drilling project, New Mexico—Comparison with Grants mineral belt *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 208-214.

Hilpert, L.S., 1969, Uranium resources of northwestern New Mexico: U.S. Geological Survey Professional Paper 603, 166 p.

Hilpert, L.S., and Moench, R.H., 1960, Uranium deposits of the southern part of the San Juan Basin, New Mexico: Economic Geology, v. 55, no. 3, p. 429-464.

Jensen, M.L., 1963, Sulfur isotopes and biogenic origin of uraniferous deposits of the Grants and Laguna districts, *in* Kelley, V.C., compiler, Geology and technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources, Memoir 15, p. 182-190.

Kaplan, I.R., 1983, Stable isotopes of sulfur, nitrogen, and deuterium in recent marine environments, *in* Stable isotopes in sedimentary geology: Society of Economic Paleontologists and Mineralogists Short Course 10, p. 2-1 to 2-108.

Kelley, V.C., 1957, Tectonics of the San Juan Basin and surrounding area *in* Geology of southwestern San Juan Basin: Four Corners Geological Society Second Field Conference, p. 44-52.

Kim, S.J., 1978, Chemical composition of the coffinite from the Woodrow mine, New Mexico: Journal of the Korean Institute of Mining Geology, v. 11, p. 183-186.

Kirk, A.R., and Condon, S.M., 1986, Structural control of sedimentation patterns and the distribution of uranium deposits in the Westwater Canyon Member of the Morrison Formation, northwestern New Mexico—A subsurface study, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 105-144.

Kirk, A.R., Huffman, A.C., and Zech, R.S., 1986, Design and results of the Mariano Lake-Lake Valley drilling project, northwestern New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 227-240.

Krauskopf, K.B., 1959, The geochemistry of silica in sedimentary environments, *in* Ireland, H. A., ed., Silica in sediments: Society of Economic Paleontologists Special Publication 7, p. 4-19.

Langmuir, Donald, 1978, Uranium solution-mineral equilibria at low temperatures with applications to sedimentary ore deposits: Geochimica et Cosmochimica Acta, v. 42, no. 6B, p. 547-570.

Lee, M.J., and Brookins, D.G., 1978, Rubidium-strontium minimum ages of sedimentation, uranium mineralization, and provenance, Morrison Formation (Upper Jurassic), Grants mineral belt, New Mexico: American Association of Petroleum Geologists Bulletin, v. 62, no. 9, p. 1673-1683.

Leventhal, J.S., 1980, Organic geochemistry and uranium in the Grants mineral belt, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 75-85.

Ludwig, K.R., and Grauch, R.I., 1980, Coexisting coffinite and uraninite in some sandstone-hosted uranium ores of Wyoming: Economic Geology, v. 75, no. 2, p. 296-302.

Ludwig, K.R., Rubin, Bruce, Fishman, N.S., and Reynolds, R.L., 1982, U-Pb ages of uranium ores in the Church Rock uranium district, New Mexico: Economic Geology, v. 77, no. 8, p. 1942-1945.

Ludwig, K.R., Simmons, K.R., and Webster, J.D., 1984, U-Pb isotope systematics and apparent ages of uranium ores, Ambrosia Lake and Smith Lake districts, Grants mineral belt, New Mexico: Economic Geology, v. 79, no. 2, p. 322-337.

Moench, R.H., 1962, Properties and paragenesis of coffinite from the Woodrow Mine, New Mexico: American Mineralogist, v. 46, p. 26-33.

Mohagheghi, Ali, 1985, The role of aqueous sulfide and sulfate-reducing bacteria in the kinetics and mechanism of the reduction of uranyl ion: Golden, Colo., Colorado School of Mines Ph.D. thesis, 380 p.

Northrop, H.R., 1982, Origin of the tabular-type vanadium-uranium deposits in the Henry structural basin, Utah: Golden, Colo., Colorado School of Mines Ph.D. thesis, 340 p.

Northrop, H.R., Goldhaber, M.B., Landis, G.P., and Unruh, D.M., in press (a), Genesis of the tabular-type vanadium-uranium deposits in the Henry structural basin, Utah—Evidence for the sources of mineralization fluids: Economic Geology.

Northrop, H.R., Goldhaber, M.B., Whitney, C.G., Landis, G.P., and Rye, R.O., in press (b), Genesis of the tabular-type vanadium-uranium deposits of the Henry structural basin, Utah—Evidence from the mineralogy and geochemistry of clay minerals: Economic Geology.

Northrop, H.R., and Whitney, C.G., 1985, Sediment-hosted ore deposits—Genetic processes inferred from the mineralogic, chemical, and isotopic composition of clay minerals, *in* Kraft, Kathleen, ed., USGS research on mineral resources--1985, Program and Abstracts: U.S. Geological Survey Circular 949, p. 38-39.

Perry, Ed, and Hower, John, 1970, Burial diagenesis in Gulf Coast pelitic sediments: Clays and Clay Minerals, v. 18, no. 3, p. 165-177.

Place, Jeanne, Della Valle, R.S., and Brookins; D.G., 1980, Mineralogy and geochemistry of Mariano Lake uranium deposit, Smith Lake district, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Technology Memoir 38, p. 172-184.

Reynolds, R.L., Fishman, N.S., Scott, J.H., and Hudson, M.E., 1986, Iron-titanium oxide minerals and magnetic susceptibility anomalies in the Mariano Lake-Lake Valley cores—Constraints on conditions of uranium mineralization in the Morrison Formation, San Juan Basin, New Mexico, *in* Turner-Peterson, C. E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 303-314.

Reynolds, R.L., Goldhaber, M.B., and Grauch, R.I., 1977, Uranium associated with iron-titanium oxide minerals and their alteration products in a south Texas roll-type deposit, *in* Campbell, J.A., ed., Short Papers of the Geological Survey uranium-thorium symposium, 1977: U.S. Geological Survey Circular 753, p. 37-39.

Rhett, D.W., 1979, Mechanism of uranium retention in intractable uranium ores from northwestern New Mexico: Journal of Metals, v. 31, no. 10, p. 45-50.

______1980, Heavy-mineral criteria for subsurface uranium exploration, San Juan Basin, New Mexico, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 202-207.

Rice, D.D., 1983, Relation of natural gas composition to thermal maturity and source rock type in the San Juan Basin, northwestern New Mexico and southwestern Colorado: American Association of Petroleum Geologists Bulletin, v. 67, no. 8, p. 1199-1218.

Ridgley, J.L, 1984, Paleogeography and facies distribution of the Todilto Limestone and Pony Express Limestone Member of the Wanakah Formation, Colorado and New Mexico [abs.]: Geological Society of America, Rocky Mountain Section Abstracts with Program, v. 16, n. 4, p. 252.

Rosenberg, P.E., and Hooper, R.L., 1982, Fission-track dating of sandstone-type uranium deposits: Geology, v. 10, p. 481-485.

Santos, E.S., and Turner-Peterson, C.E., 1986, Tectonic setting of the San Juan Basin in the Jurassic, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region: American Association of Petroleum Geologists Studies in Geology 22, p. 27-30.

Saucier, A.E., 1980, Tertiary oxidation in Westwater Canyon Member of Morrison Formation, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 116-121.

Sheppard, R.A., and Gude, A.J., 3d, 1968, Distribution and genesis of authigenic silicate minerals in tuffs of Pleistocene Lake Tecopa, Inyo County, California: U.S. Geological Survey Professional Paper 597, 38 p.

Siever, Raymond, 1962, Silica solubility, 0-200°C, and the diagenesis of siliceous sediments: Journal of Geology, v. 70, p. 127-160.

Silver, L.T., and Williams, I.S., 1981, Zircons and isotopes in sedimentary basin analysis—A case study of the upper Morrison Formation, southern Colorado Plateau [abs.]: Geological Society of America Abstracts with Program, v. 13, no. 7, p. 554-555.

Simova, F.G., 1982, Uranium-titanium silicates from the Ambrosia Lake (New Mexico, USA) and Mitterberg (Salzburg, Austria) deposits: Academie Bulgare des Sciences, Comptes rendus, v. 35, no. 2, p. 203-206.

Spirakis, C.S., and Hansley, P.L., 1986, The formation and alteration of tabular-type uranium-vanadium deposits as a variant of normal diagenetic processes in organic-rich sediments [abs.], *in* Carter, L.M.H., ed., USGS research on energy resources—1986, Program and Abstracts: U.S. Geological Survey Circular 974, p. 64-65.

Squyres, J.B., 1963, Geology and ore deposits of the Ann Lee mine, Ambrosia Lake area, *in* Kelley, V.C., compiler, Geology and Technology of the Grants uranium region: New Mexico Bureau of Mines and Mineral Resources Memoir 15, p. 90-101.

______1980, Origin and significance of organic matter in uranium deposits of Morrison Formation, San Juan Basin, New Mexico, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 86-97.

Steele, B.A., 1984, Preliminary report on the petrography of the Upper Jurassic Morrison Formation, Mariano Lake-Lake Valley Drilling Project, McKinley County, New Mexico: U.S. Geological Survey Open-File Report 84-170, 43 p.

Stieff, L.R., Stern, T.W., and Sherwood, A.M., 1956, Coffinite, a uranous silicate with hydroxyl substitution—A new mineral: American Mineralogist, v. 41, nos. 9 and 10, p. 675-688.

Surdam, R.C., Boese, S.W., and Crossey, L.J., 1984, The chemistry of secondary porosity, *in* McDonald, D.A., and Surdam, R.C., eds., Clastic diagenesis: American Association of Petroleum Geologists Memoir 37, p. 127-149.

Surdam, R.C., and Crossey, L.J., 1985, Mechanisms of organic/inorganic interactions in sandstone/shale sequences, *in* Relationship of organic matter and mineral diagenesis: Society of Economic Palaeontologists and Mineralogists Short Course No. 17, p. 177-279.

Swanson, V.E., Frost, I.C., Rader, L., and Huffman, Claude, Jr., 1966, Metal sorption by northwest Florida humate, *in* Geological Survey Research 1966: U.S. Geological Survey Professional Paper 550-C, p. C174-C177.

Swanson, V.E., and Palacas, J.G., 1965, Humate in coastal sands of northwest Florida *in* Geological Survey Research 1965: U.S. Geological Survey Bulletin 1214-B, p. B1-B29.

Tissot, B.P., and Welte, B.P., 1984, Petroleum formation and occurrence [2d ed.]: New York, Springer-Verlag, 699 p.

Turner-Peterson, C.E., 1985, Lacustrine-humate model for primary uranium ore deposits, Grants uranium region, New Mexico: American Association of Petroleum Geologists Bulletin, v. 69, no. 11, p. 1999-2020.

______1986, Fluvial sedimentology of a major uranium-bearing sandstone—A study of the Westwater Canyon Member of the Morrison Formation, San Juan Basin, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 47-76.

Turner-Peterson, C.E., and Fishman, N.S., 1986, Geologic synthesis and genetic models for uranium mineralization in the Morrison Formation, Grants uranium region, New Mexico, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 357-388.

Turner-Peterson, C.E., Gunderson, L.C., Francis, D.S., and Aubrey, W.M., 1980, Fluvio-lacustrine sequences in the Upper Jurassic Morrison Formation and the relationship of facies to tabular uranium ore deposits in the Poison Canyon area, Grants mineral belt, New Mexico, *in* Turner-Peterson, C.E., ed., Uranium in sedimentary rocks—Application of the facies concept to exploration: Society of Economic Paleontologists and Mineralogists, Rocky Mountain Section, p. 177-210.

Waters, A.C., and Granger, H.C., 1953, Volcanic debris in uraniferous sandstones and its possible bearing on the origin and precipitation of uranium: U.S. Geological Survey Circular 224, 26 p.

Webster, J.D., 1983, Petrography of some Ambrosia Lake, New Mexico prefault uranium ores, and implications for their genesis: U.S. Geological Survey Open-File Report 83-8, 72 p.

Wentworth, D.W., Porter, D.A., and Jensen, H.N., 1980, Geology of Crownpoint Sec. 29 uranium deposit, McKinley County, *in* Rautman, C.A., compiler, Geology and mineral technology of the Grants uranium region 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 139-144.

Whitney, C.G., 1986, Petrology of clay minerals in the subsurface Morrison Formation near Crownpoint, southern San Juan Basin, New Mexico—An interim report, *in* Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., eds., A basin analysis case study—The Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 315-330.

Whitney, C.G., Northrop, H.R., and Hansley, P.L., 1986, The use of mineral alteration patterns and stable isotopic compositions to infer a paleohydrologic regime [abs], *in* Carter, L.M.H., ed., USGS research on energy resources—1986, Program and Abstracts: U.S. Geological Survey Circular 974, p. 73-74.

Winter, T.C., 1981, Effects of water-table configuration on seepage through lakebeds: Limnology and Oceanography, v. 26, no. 5, p. 925-934.

Zielinski, R.A., 1982, Experimental leaching of volcanic glass—Implication for evaluation of glassy volcanic rocks as sources of uranium, *in* Goodell, P.C., and Waters, A.C., eds., Uranium in volcanic and volcaniclastic rocks: American Association of Petroleum Geologists Studies in Geology 13, p. 1-11.

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