Uranium-Vanadium Deposits of the Slick Rock District, Colorado

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With a section on **Appendix on District Production**
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GEOLOGIC INVESTIGATIONS IN THE SLICK ROCK DISTRICT,
SAN MIGUEL AND DOLORES COUNTIES, COLORADO

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Detailed comprehensive study of the uranium-vanadium deposits and their host rocks contributes to the understanding of the origin and formation (genesis) of the deposits.

U.S. Department of the Interior
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Abstract

The area of the Slick Rock district saw the first production of uranium on the Colorado Plateau. Four periods of mining followed, initially for uranium from about 1900 to 1910, then for radium to about 1923. Following a decade of inactivity, mining resumed, this time for recovery of vanadium, in the early 1930s until 1944. Mining began again in 1949 for major production of uranium, with vanadium as a byproduct. This period lasted until 1983, ending when the price of uranium went into serious decline. Presently (2008) renewed interest in demand for uranium is pointing toward additional mining in the district.

Upper Triassic Moss Back Member of the Chinle Formation and Upper Jurassic Salt Wash Member of the Morrison Formation are the principal host rocks of uranium-vanadium deposits in the district. Only small deposits are known in the Moss Back. However, favorable stratigraphic and structural settings, similar to those in the Lisbon Valley district, Utah, to the northwest where numerous very large uranium deposits have been mined, make the unit in the Slick Rock district worthy of further evaluation. Numerous large deposits in the Salt Wash have been mined, and the Slick Rock district has been the principal uranium-vanadium producer in the Uravan mineral belt. Most of this report is devoted to the ores in the Salt Wash, located mostly in the north half of the district.

Certain geologic events in the area of the Western United States, from Cambrian to early Tertiary time, influenced provenance and deposition of the sedimentary rocks that were part of the overall genesis of, or which hosted, the Slick Rock uranium-vanadium deposits. Those events shaped not only the character of the rock facies and related pore fluids that were part of the immediate genesis of the deposits, but they also formed rocks and related fluids developed much earlier and in more distant settings that also were part of the genesis.

Critical to origin of the ore deposits was deposition of evaporitic-sapropelic sedimentary units of the Paradox Formation of the Hermosa Group of Middle and Late Pennsylvanian age. Those sedimentary units determined composition of fluids that subsequently accounted for development of altered facies rocks which are spatially associated with the ores.

The upper unit in the Salt Wash Member, the ore-bearing sandstone, is known throughout the Uravan mineral belt as the main host of Salt Wash ore deposits. In the Slick Rock district it consists mostly of fluvial, fine-grained sandstone deposited in meandering channels of a braided stream system. It contains local zones of abundant carbonaceous plant material with which the deposits occur exclusively. Studies of heavy minerals in the Salt Wash and other Mesozoic sandstone and mudstone units in the district indicate three distinctive lithologic facies: a reduced “carbon facies” confined to the zones of carbonaceous plant material, an oxidized “red-beds facies” as the dominant lithologic type, and a chemically reduced “altered facies.” The carbon facies and red-beds facies developed in near-surface, diagenetic environments; the altered facies formed during a much later epigenetic event when deeply buried.

Each of the three facies is significant in the genesis of the ore deposits. Much of the Morrison Formation is of the red-beds facies; such rocks in the upper Brushy Basin Member were the likely immediate source of uranium in the deposits. The red-beds facies formed near the ground surface not long after sediment deposition. Carbon facies in the ore-bearing sandstone of the underlying Salt Wash Member provided the chemically reducing conditions that favored accumulation and (or) precipitation of ore components. Altered-facies rocks, developed by alteration of both red-beds facies and carbon facies as a result of introduction of an extraneous solution at a much later time, interacted with water in carbon facies to form the present geometry and mineralogy of the ore deposits. Uranium from volcanic ash in the Brushy Basin was moved incrementally during a protracted period, probably mostly along faults and partly by compaction from weight of overlying Cretaceous sediments, into the underlying ore-bearing sandstone where the uranium was extracted by adsorption upon humates formed from decaying plant material in carbon facies rocks. Biogenic sulfide developed in the zones of decaying plant material during the early stages of burial. Introduced altering solution, following deep burial of the rocks many millions of years later, encroached through permeable fracture zones and sandstone units into the local zones of carbon facies to establish a more or less stable interface between introduced water and formation water in a zone surrounding the carbonaceous material. Chemical differences between the solutions in carbon facies and in encroaching altered facies resulted in

precipitation of uranium-vanadium minerals, as well as metal sulfides and selenides.

Detailed studies of the forms, internal textures, mineralogy, and chemistry of the Salt Wash uranium-vanadium ore bodies show convincingly that the ores were precipitated at an interface between formation water (strongly reducing carbon-facies fluid) and introduced water (less reducing altered-facies fluid). Inferred contrasting chemical contents of the two fluids (including mostly uranium, uranogenic lead, and sulfur in formation water and mostly vanadium, titanium, iron, chromium, copper, silver, molybdenum, nickel, and common lead in introduced water) account for the resulting chemistry of the deposits. The specific elements also indicate the sources of the elements. The presence of Liesegang-ringlike forms in some of the roll ore bodies suggest diffusion, likely through a gel, as part of the process of deposition.

Magmas which emplaced the La Sal Mountains laccoliths in Utah northwest of Slick Rock, in early Tertiary time, expelled fluids at depth which heated Paradox Formation waters and drove them upward along favorable structural zones into the Slick Rock district as well as elsewhere in the Uravan mineral belt. The reducing waters from the Paradox, with an increment of water expelled from magmas, served as the altering fluids which leached elements (vanadium, titanium, and other elements) from sedimentary rocks, or carried elements from the magmas (copper, silver, selenium, and other elements) that were deposited at the interface between strongly reducing formation water in the Salt Wash Member and less reducing introduced water.

Regional similarities of lead isotopes, chemical compositions, and ages of mineral deposits and igneous bodies within and adjacent to the Colorado Plateau, indicate that the ores were deposited in their present form during latest Oligocene time (33.9 ± 0.1 to 23.03 ± 0.05 Ma).

Introduction

Recent (2006–2008) revival of interest in uranium resources in the United States, spurred by a national effort to increase the use of nuclear power for the generation of electrical energy, has been the impetus for completion of this report on the uranium-vanadium deposits of the Slick Rock district. A large body of observations and data has led to several critical concepts that provide a rational interpretation of origin and formation (genesis) of the deposits. The report presents these observations, data, concepts, and interpretation.

This report on uranium-vanadium ore deposits is the sixth and final in a series describing geologic investigations during 1953–58 in the Slick Rock mining district in southwestern Colorado. The first five reports dealt with stratigraphy of the district and vicinity (Shawe, Simmons, and Archbold, 1968); petrography of the sedimentary rocks (Shawe, 1968); structure (Shawe, 1970); sedimentary rock alteration (Shawe, 1976a); and geologic history (Shawe, 1976b). Other published reports growing out of these studies (Shawe, 1956a, 1956b, 1962, 1969; Archbold, 1959; Shawe, Archbold, and Simmons, 1959; Bowers and Shawe, 1961; Rogers and Shawe, 1962) described the geologic setting as well as some details of the uranium-vanadium ores. More recent studies (Breit and others, 1990; Breit and Goldhaber, 1995; Breit and Meunier, 1990) have clarified aspects of origin and formation of the deposits.

The report consists of a summary of the principal elements of the geology of the district and surrounding areas, as presented in the early reports just referred to, which constitutes the framework for interpretation of the processes of origin and formation of the uranium-vanadium deposits. The data in these reports are extensively supplemented here with details of the forms, textures, and compositions of the ore deposits. Much of that data was obtained during the original project studies, but it is supplemented with more recent unpublished data from other studies.

The terms “ore” and “mineralized” rock are referred to frequently in later discussions of the uranium-vanadium deposits at Slick Rock. Ore is a term applied to mineralized rock that can be mined economically. Mineralized rock (usually sandstone in the Salt Wash Member of the Morrison Formation) contains introduced minerals whose components include elements for which the deposits are mined, in this instance uranium and vanadium.

In addition to descriptive information herein and an evaluation of the genesis of the Slick Rock uranium-vanadium deposits, the report provides detailed information, such as history of the district, mineralogy of the ore deposits, and uranium-vanadium production of the district, much of which has not been fully incorporated in the present analysis, but which may be useful in subsequent investigations by others.

Several important conclusions reported in the papers cited bear critically on understanding the uranium-vanadium ore deposits. Permeable carbonaceous fluvial-sandstone strata of the Moss Back Member of the Chinle Formation were deposited in the district during Triassic time. Small uranium-vanadium deposits are known in these rocks in the district, and numerous large uranium-vanadium deposits occur in the Moss Back northwest of Slick Rock, in Utah. The principal ore-bearing unit of the Salt Wash Member of the Morrison Formation was deposited in the district and throughout the Uravan mineral belt in Jurassic time. Most of this report deals with the ore-bearing sandstone of the Salt Wash. Permeable carbonaceous fluvial sandstone strata locally characterize the ore-bearing sandstone, which hosts most of the deposits in the mineral belt. Some faulting preceded, accompanied, and followed deposition of the terrestrial Mesozoic strata. Permeable zones of fluid movement thus have existed within and between sandstone strata since shortly following sedimentation.

Uranium-vanadium mineralization took place within the few carbonaceous strata interlayered in the red beds, and extensive chemical reduction occurred widely, but locally, in the red beds apparently at the time of mineralization. The extensive reduction of the red beds implies introduction of reducing fluids from an extraneous source. Because uranium-vanadium mineralization and reduction of red beds apparently were part of a single episode, I infer that deposition of the deposits, and introduction of at least part of the components of the deposits, were the result of solutions introduced from a source outside the red beds. A source of the voluminous reducing fluid which widely altered the red-bed host rocks and deposited the ores in the Salt Wash and Moss Back Members, in restricted favorable zones characterized by abundant decaying plant material, probably was the underlying Middle and Upper Pennsylvanian Hermosa Group. Additional fluid likely was derived from magmas which intruded into the nearby La Sal Mountains. I earlier speculated (Shawe, 1976a) that part of saline (marine) pore waters driven out of compacting organic mud in overlying Mancos Shale of Late Cretaceous age following deposition, may have been forced downward into underlying strata because of high fluid density and high pore pressure in the Mancos that resulted from the weight of overlying sediments. Based on more complete knowledge of the age of the Slick Rock ores and movement of fluids to the site of ore deposition, I now believe saline water was mobilized by intrusion of magmas, which then moved up to form igneous bodies in the nearby La Sal Mountains. As the magmas passed through evaporite strata of the Paradox Formation of the Pennsylvanian Hermosa Group, fluids were developed which moved upward into Mesozoic red beds in the early Tertiary, accounting for precipitation of the ores near carbonaceous plant material. Whatever the source, these fluids were fundamental to deposition of the uranium-vanadium ores.

The forms, lithologic relations, and detailed mineralogical and chemical character of the ore deposits indicate that they precipitated at an interface between two fluids. A fluid developed within the Morrison Formation (humate-rich formation water that evolved in the vicinity of carbonaceous plant debris) and an extraneous second fluid introduced into the Morrison Formation are believed to have been the interacting fluids. Evidence described in later pages suggests that uranium (and some other elements) in the Slick Rock ore deposits at the time of ore deposition came mostly from humate-rich formation water, and vanadium (and some other elements) came mostly from introduced fluid. This report presents interpretations of origins (sources) of the elements in the ores, and of interactions between the fluids within carbonaceous sandstone strata (the favorable host rocks), which caused deposition (formation) of the uranium-vanadium deposits.

History of the District

Mining of the near-surface "carnotite" deposits in the Slick Rock district has taken place during four periods, each marked by efforts to recover different metals. Mining of the deeper reduced ores began in the most recent period. During the first decade of mining, starting about 1900, uranium was the chief metal sought, and vanadium was recovered as a by-product. In the next decade or so, until about 1923, the ores were worked primarily for their radium content. A decade of inactivity followed the mining for radium, and then from the early 1930s until about 1944 the carnotite ores were mined almost exclusively for their vanadium content. After five years of inactivity in the Slick Rock mines, the fourth period of mining started. Exploitation of the carnotite ores had come full cycle in 1949 with resumption of major recovery of uranium, with vanadium as a by-product. Since then mining has progressed to deep levels below the water table where unoxidized ("black") ores are found. Uranium-vanadium production was continuous, with some fluctuation, for more than 3 decades, when all mining in the district again ceased in 1983 owing to the depressed price of uranium. In recent months, circa 2006, renewed interest worldwide in further development of nuclear power has resulted in a rapid rise in the price of uranium which has brought the Colorado Plateau uranium deposits again into sharp focus. This renewed interest (2008–2010) has prompted a thorough re-evaluation of previously unpublished data, and preparation of this report.

The Slick Rock mining district, whose principal producing area was known originally as the McIntyre district, was one of the first in the Colorado Plateau region to attract attention for its deposits of uranium, vanadium, and radium. Kimball (1904), writing in the Engineering and Mining Journal of June 16, 1904, stated "The area lying along the Dolores river and side gulches, in which the mineral [carnotite] is found, are (sic) of sedimentary formation, broken and cut by deep canons and cup-like valleys lying 1,200 to 2,500 ft. below the mesa levels. The ore occurs along rims of canons in white or Dakota sandstone [now identified as the Salt Wash Member of the Morrison Formation], usually over a clay bed, in disseminated grains, bedded veins, seams, occasional pockets, and vugs. Near Snyders, on the Dolores river, San Miguel county, great blocks of sandstone of several tons weight that have broken away from the 'rim' are impregnated with carnotite to the extent of probably one to two percent. Several years ago concentration works were established near there, but the enterprise met with indifferent success."

Probably the earliest uranium production from the Colorado Plateau, by the efforts of two Frenchmen, came at about the turn of the twentieth century. In the region now known as the Uravan mineral belt, M. Poulot and M. Voilleque "in 1900 began operating at a copper mine at Cashin in Paradox Valley, where they used leaching vats to extract uranium" (Moore and Kithil, 1916, p. 18), and in 1901 they built a small mill in the McIntyre district, at the mouth of Summit Creek (Coffin, 1921, p. 152). The two Frenchmen formed a company which became known as the Rare Metals Mining and Mfg. Co., of Cashin, Colo., and constructed the mill at an estimated cost of $8,000 (Fleck and Haldane, 1907, p. 48). Moore and Kithil (1916, p. 18–19) wrote further that "the mill ran until 1902, and during this time produced about 15,000 lbs of uranium oxide. The mill was started again in 1903 by the Western Refining Co., but ran only until 1904. Shortly afterwards the Dolores Refining Co. built a new mill a short distance from the old one, but after running for some years, it too shut down. The concentrate, which was obtained by the Engle process, retained uranium and vanadium only, not the radium. In addition to this concentrate, some ore was shipped during this period. In 1912 the American Rare Metals Co. acquired the mill of the Dolores Refining Co." and was operating it in 1914. The site of this mill was near the Dolores River, opposite the mouth of Burro Canyon.

According to R.C. Coffin (1921, p. 152) carnotite mining in southwestern Colorado was limited almost entirely to the McIntyre district from 1901 to 1904, "and had the recovery of uranium as its primary object and vanadium as a secondary one."

In 1910 radium apparently had succeeded uranium and vanadium as the principal metal sought in the southwestern Colorado carnotite ores, and demand for radium to be used in the treatment of cancer created a new impetus to activity in the district. According to Moore and Kithil (1916, p. 103), during 1913 "Paradox Valley and the surrounding districts in the southwestern part of Colorado were the scenes of the greatest activity since the opening of the carnotite deposits. Most of the mining was done in the districts that were producing ore toward the close of 1912…but…the McIntyre district during the latter part of 1913 was not very active." Moore and Kithil (1916, p. 103) also stated that in 1913 the "plant owned by the American Rare Metals Co., in the McIntyre district, south of Paradox, was in operation to some extent in the early part of the year, but since that time has been shut down. The larger part of the radium concentrates produced by them in 1912 and the early part of 1913 [was] sold abroad in December 1913."

During the first decade or so of activity in the McIntyre district, "mining made only small inroads on the ore supply" and "the larger part of the ore [was] rather low grade" (Moore and Kithil, 1916, p. 29). However, Moore and Kithil (1916, p. 20) wrote that the grade of ore mined between about 1901 and 1910 probably averaged slightly more than 2 percent U_3O_8 and between 3 percent and 4 percent V_2O_5; this would be high-grade ore for sandstone-type ore deposits by the 1950s. Shipments of concentrates from the district were made by way of the town of Dolores, about 50 mi to the south, which was served by a railroad.

Production from the McIntyre district during the first two years of activity (1901–1902) was probably about 300 tons of uranium-vanadium ore, based on figures from Moore and Kithil (1916). During the following decade until the district became relatively inactive in 1914, average production may have been close to this rate and totaled about 1,500–2,000 tons. However, Coffin (1921, p. 152) implied that little mining was done in the district from 1904–1910. Production during the decade 1918–1928 appears to have been only a few hundred tons of ore, mined for its radium content. Hess (1933, p. 462) reported that "from 1907–1920 the deposits in (the Morrison Formation on the Colorado Plateau) furnished most of the world's radium."

According to Coffin (1921, p. 151), because of the increasing demand for radium, "activity in mining these ores increased each year from 1910 until 1914, when the war [World War I] stopped their sale. Up to that time they had been largely sold to foreign buyers. After the slump of the carnotite market at the beginning of the war, demand for this ore increased, although not uniformly, until 1919 the quantity of ore mined exceeded that of any previous year". Fischer (1942, p. 364) reported that mining in Montrose County and adjacent areas ceased in 1923, "when the Belgian Congo pitchblende began to supply radium."

By 1915 about 160 mining claims had been staked in the McIntyre district, according to a claim survey by Charles L. Harrington (Coffin, 1921). Apparently many of these claims lapsed following the period of radium mining, and were re-staked under different names when mining activity picked up in the early 1930s, but many of them have survived to the present day with their original names.

The third period of activity in the Slick Rock district, that of vanadium mining, began in about 1931 when the Shattuck Chemical Co. of Denver built a new mill with a capacity of 10 to 15 tons of ore per day, at the site of the American Rare Metals Co. mill near the Dolores River opposite the mouth of Burro Canyon. In 1934 North Continent Mines, Inc. acquired the mill and several groups of claims from the Shattuck Chemical Co. and in 1942 increased the capacity of the mill to 30 tons daily. The mill operated intermittently, but was shut down in 1943, although the company continued mining for about a year. The ore was sold to the Metals Reserve Company until that agency discontinued its ore-buying program. The last shipments of ore were sold to the Union Mines Development Corp., a subsidiary of Union Carbide Corp., in the summer of 1944 (B.N. Webber, Union Mines Development Corp., written commun., 1947). B.N. Webber and colleagues of Union Mines Development Corp., then under contract to the AEC, mapped several mines in the Slick Rock district; some of the maps are used in this report.

According to J.E. Motica of Union Carbide Corp. (written commun., 1959) a mill called the Mesa mill was built in 1938 near Disappointment Creek about one-quarter mile from the Dolores River. The mill operated less than a year.

Important groups of mining claims during the vanadium period were the Spud Patch claims owned by the U.S. Vanadium Corp. and the Vanadium Corp. of America, the Lower and Charles T groups of claims owned by North Continent Mines, Inc., and the Radium group of claims that was acquired in 1943 by F.A. Sitton from Michael O'Neal.

The district's production of ore for vanadium recovery was chiefly during the late 1930s and early 1940s, and totaled probably at least 60,000 tons of ore averaging about 2.5 percent V_2O_5 (1,500 tons V_2O_5). Most of this production came from the Spud Patch, Lower, Charles T, and Radium groups of claims, and the remainder came from the Legin, Georgetown, and Upper groups of claims, and the Ellison-Burro claims.

In 1944 some of the mines in the district were worked by the Union Mines Development Corp. for the uranium content of the ores. The ores averaged about 0.25 percent U_3O_8 and the uranium was used by the Manhattan District, predecessor of the Atomic Energy Commission, in the development and construction of the first atomic bombs.

The old McIntyre district and the Dolores River district farther south were consolidated and became known as the Slick Rock district in the late 1940s, when the U.S. Geological Survey (USGS) began numerous extensive studies that culminated during 1953–1958.

Prior to November 1953, an estimated 87,000 ft of diamond drilling and wagon drilling was done by private industry in the Slick Rock district (Bell, 1950, 1953; Bush and others, 1950; Trace, 1950). From November 1953 to November 1954, an estimated 125,000 ft of diamond drilling was done by private industry in the district. The U.S. Bureau of Mines drilled about 12,500 ft before 1946 (Huleatt and others, 1946), and the USGS completed about 373,200 ft of diamond drilling by March 1956.

The decade of the 1950s saw considerable activity in the mines of the Slick Rock district, during which time almost 1,000,000 short tons of ore were mined. These ores averaged about 0.22 percent U_3O_8 (2,200 tons) and 1.7 percent V_2O_5 (5,880 tons), and about $50 (1950 dollars) per ton in value for the contained uranium and vanadium. Most of the production for this period came from mines in the Burro, Summit-Mercantile, Lower, Radium, Legin, Georgetown, Middle, and Charles T groups of claims. Major operators during the period were Union Carbide Nuclear Co., Dulaney Mining Co., Skidmore Mining Co., Ortmayer Mining Co., Holling Mining Co., and several independent leasors.

Since 1960 substantial additional drilling has been done, and an additional 1,000,000 tons of ore have been mined, including that from new properties (Deremo, Carnation, and Awold No. 3 mines, Union Carbide Nuclear Co.; Dolores River and Suncup mines, North American Uranium Co.).

A description of mining activity in the district in early 1965 is given in Appendix B.

Most of the mining properties in the Slick Rock district are about 40–50 mi from the site of a government-operated mill at Monticello, Utah, which closed in about 1960, and the Vancorum Corp. of America uranium mill at Vancorum, Colo., which was shut down in 1957. Some operators shipped ore about 180 mi to the Climax Uranium Co. mill in Grand Junction, Colo., or about 100 mi to the Vanadium Corp. of America mill in Durango, Colo. Following construction of an upgrading mill on Poverty Flat in the Slick Rock district by Union Carbide Nuclear Co. in 1956–1958, some operators delivered ore to this plant. The plant closed circa 1970. Concentrates from this plant were trucked about 250 mi to the Union Carbide Nuclear Co. mill in Rifle, Colo. During the later years of mining in the district, production from the Deremo and Sunday mines was shipped to the mill in Uravan.

Production data for the Slick Rock district up to 1978, compiled by William Chenoweth (Shawe and others, 1991) indicate approximately 9,000 tons of U_3O_8 and 50,000 tons of V_2O_5 mined. Up to 1978, the district was the largest producer of both uranium and vanadium in the Uravan mineral belt. Production since, up to about 1983, amounted to approximately 4,839,000 tons of ore, when production virtually ceased (see Appendix A). At present, with renewed interest resulting from the high price of uranium, it seems that uranium exploration and mining in the Slick Rock district are again likely.

Geologic Setting of the Ore Deposits

The Slick Rock uranium-vanadium district lies in the western parts of San Miguel and Dolores Counties, Colorado, (fig. 1) at the south end of the Uravan mineral belt. Sedimentary rocks that crop out in the district range in age from Permian to Cretaceous (fig. 2) and are as much as 4,700 ft thick. These rocks and older Paleozoic sedimentary rocks that underlie them and rest on igneous and metamorphic rocks of a Precambrian basement total about 13,000 ft thick (see table 1 in Shawe, 1970).

Uranium-vanadium deposits in the district are known in the Moss Back Member at the base of the Chinle Formation (Upper Triassic) and at several levels of the Morrison Formation (Upper Jurassic); important production has come mainly from the top sandstone or so-called “ore-bearing sandstone” of the Salt Wash Member of the Morrison. Locations of mine groups and individual mines known in the 1950s in the Slick Rock district are shown in Shawe and others. (1968, pl. 1). Locations of areas of mines in the district (SM 1-29) as of 1983 are shown on plate 1 of this report, and lists of mines in those areas are given in Appendix A.

The district is in the Paradox Basin at the southeast end of the Paradox fold and fault belt (Kelley, 1958). Major folds in the district are broad and open, trend about N. 55° W., and are parallel to the collapsed Gypsum Valley salt anticline bounding the northeast edge of the district (fig. 2). The Dolores anticline lies about 10 mi southwest of the Gypsum Valley anticline; the Disappointment syncline lies between the two anticlines.

Several zones of faults traverse the district (fig. 2). One zone bounds the southwest edge of the collapsed core of the Gypsum Valley salt anticline at the northeast margin of the district. A second zone, the Dolores, lies about 2 mi northeast of the parallel Dolores anticline. A few faults form a conjugate set normal to the Dolores zone of faults in the north part of the district. The south part of the district is cut by the Glade zone of faults which trends about N. 80° E. Prominent joint sets, mostly parallel to individual faults in all the zones of faults, are widespread throughout the district (William B. Rogers, USGS, unpub. data, 1957). Most of the uranium-vanadium deposits in the district form a zone centered on the broad northwest-southeast-trending Dolores ore zone where it is intersected by the conjugate set of northeast-southwest-trending faults.

Much of the faulting occurred after lithification of the Upper Cretaceous sedimentary units in Late Cretaceous-early Tertiary time. The faults were significant because some of

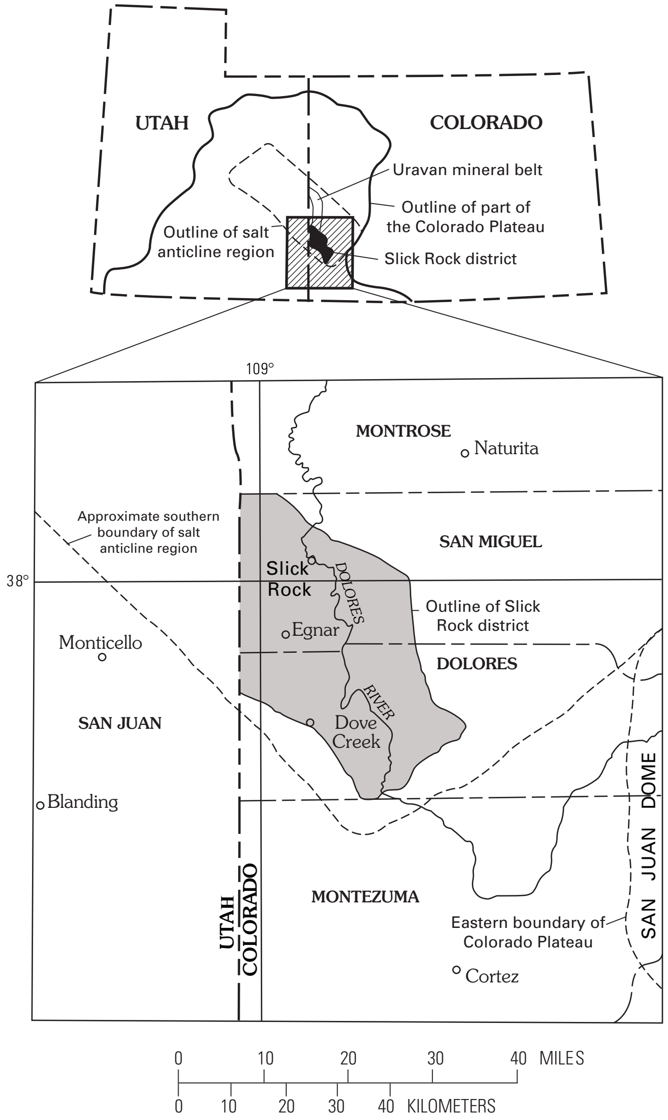

Figure 1. Index map showing location of the Slick Rock district.

them provided access into the Slick Rock district of altering and mineralizing fluids involved in deposition of the uranium-vanadium ore deposits. A few were related to minor deformation in the district in the late Tertiary following ore deposition.

Characteristics of the Host Rocks

The stratigraphy (lithology, distribution, configuration, and relation to adjacent units), petrography, and geochemical alteration of the principal ore-bearing formations in the district—Chinle Formation of Late Triassic age and Morrison Formation of Late Jurassic age—have been described in detail in previously published reports (Shawe and others, 1968; Shawe, 1968, 1976a). Characteristics of the ore-bearing formations will be reviewed briefly here to provide a framework in which to discuss the distribution, form, mineralogy, and chemical composition of the ore deposits.

Chinle Formation

The Chinle Formation, although it contains only small known uranium-vanadium deposits in the Slick Rock district, contains very large deposits a few tens of miles to the northwest in the Lisbon Valley district, Utah. Information regarding the lithology and stratigraphy of the formation in the Slick Rock district, of value in possible future exploration of the formation, is given in the following pages.

The Chinle Formation in the Colorado Plateau was deposited on an erosional surface of the Cutler (Lower Permian) and Moenkopi (Lower and Middle(?) Triassic) Formations. The older members of the Chinle (Temple Mountain, Shinarump, Monitor Butte, and Owl Rock) were laid down in what is now western and southern Utah and northern Arizona, and in a general way successively younger members were spread to the northeast, or their deposition was localized to the northeast, so that the younger members are in contact with the underlying Cutler and Moenkopi in that direction (Stewart and others, 1959, figs. 73, 81).

The Chinle Formation consists of a lower part containing variegated bentonitic claystone, clayey siltstone, clayey sandstone, and thin widespread layers of sandstone and conglomerate, and an upper part containing reddish-brown horizontally bedded or structureless siltstone and generally minor amounts of limestone, ripple-laminated siltstone and sandstone, limestone pebble conglomerate, and cross-stratified sandstone, extending throughout most of the Colorado Plateau (Stewart and others, 1972).

In the Slick Rock district (Shawe and others, 1968) several hundred feet of clastic terrestrial red beds comprising the Chinle unconformably overlie the Cutler and Moenkopi Formations. The lowest Chinle strata in the district, the Moss Back Member, consist of 20–75 ft of light greenish-gray calcareous arkosic and quartzose sandstone and gray to greenish-gray calcareous sandstone and conglomerate. Small amounts of greenish-gray and even less reddish-brown mudstone, siltstone, and shale are present. The Petrified Forest(?) Member overlying the Moss Back consists of 0–100 ft of greenish-gray mudstone, siltstone, and shale, with minor reddish-brown mudstone, and greenish-gray sandstone and conglomerate. The uppermost member of the Chinle, the Church Rock Member, consists of 340–505 ft of reddish-brown siltstone, sandstone, silty sandstone, and mudstone, and locally, thin layers of dark reddish-brown and dark greenish-gray conglomerate. The Wingate Sandstone (Lower Jurassic) disconformably overlies the Chinle in the district.

Sandstone in the Moss Back is light greenish gray, mostly fine grained, and in part clayey, in strata 1–35 ft thick. Conglomerate is greenish gray, contains pebbles mostly of limestone and lesser amounts of quartzite, in strata 1-15 ft thick and commonly near the base of the member. Shale is greenish

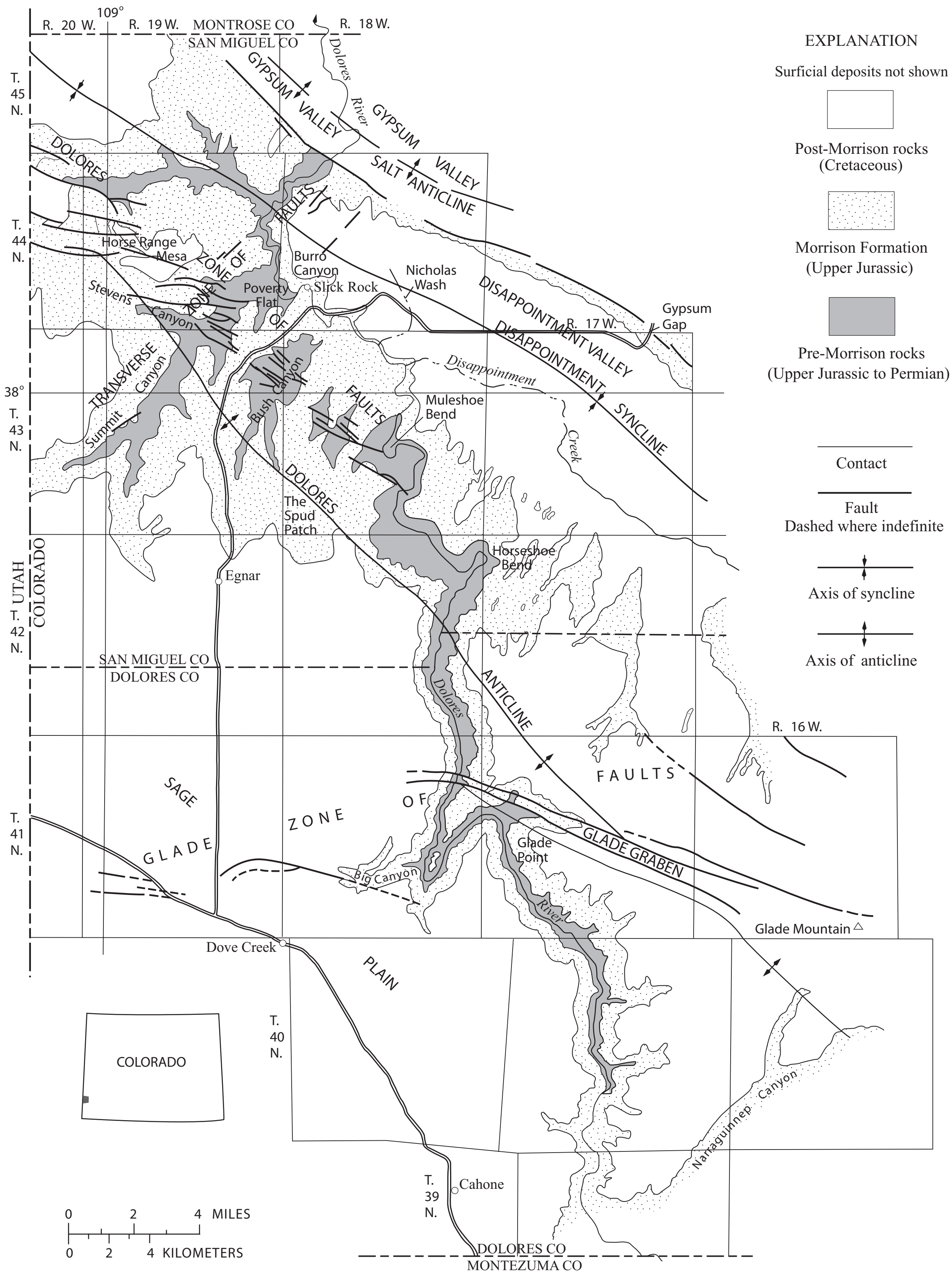

Figure 2. Generalized geologic map of the Slick Rock district.

gray, in strata 1–5 ft thick. Proportion of sandstone to conglomerate to shale in the member in the district is about 11 to 2 to l. These lithologies are interlayered in complex fashion, as lenses of varied size and configuration.

Carbonaceous material is widespread in the member, perhaps most abundant near its base. For example, a one-foot-thick layer 10 ft above the base of the member in the Dolores River Canyon (Shawe and others, 1968, section F, pl. 4) contains about 10 percent carbonaceous material.

The Moss Back Member covers about 10,000 sq mi in the central part of the Colorado Plateau, and averages about 60 ft thick (Stewart and others, 1972, p. 90, pl. 2). Sediment was deposited in the Moss Back probably mostly by meandering streams, and was derived largely from the Mogollon highland of southern Arizona and southwestern New Mexico, south of the present day Colorado Plateau (Stewart and others, 1972, p. 92). Source rocks were volcanic rocks probably of early Mesozoic age, marine cherty carbonate rocks of Paleozoic age, and gneiss, schist, granite, and metasedimentary rocks of Precambrian age (Stewart and others, 1972, p. 93–94).

The Moss Back Member in the Slick Rock district appears to be made up of a system of coalescing channel-fill deposits which trend northwestward reflecting deposition from streams flowing from the southeast. Thicker parts of the Moss Back represent fill of the deeper channels in this system (Shawe and others, 1968, fig. 13).

The Moss Back Member is the only known host rock for uranium deposits in the Chinle Formation in the district. Greenish-gray sandstone, conglomerate, and mudstone in the member contain abundant carbonized and silicified plant fragments locally; where mineralized rock occurs it is associated invariably with carbonized plant material. The unit also contains fossil reptile bones in places. Cross-beds, current ripple marks, and scour and fill characters are typical of the member and suggest terrestrial stream deposition of most of the unit.

The Moss Back Member was not an object of studies sponsored by the Atomic Energy Commission in the Slick Rock district. However, above-background radioactivity was detected with a scintillation counter in many places at the base of the member in the Dolores River Canyon, mostly within about one mile of the Bullsnake prospect just north of Horseshoe Bend. In this stretch, background radioactivity is about 0.013 milliroentgens per hr (mr/hr) and readings as high as 0.028 mr/hr were measured in conglomerate. Anomalous radioactivity also was detected with a gamma-ray Geiger counter near the base of the member in several drill holes in Summit Canyon put down by Hunt Oil Co. The mineralized zone in the Dolores River Canyon is at an elevation of about 6,000 ft, nearly on line with the southeastward projection of the Dolores zone of faults. The mineralized zone in Summit Canyon is at an elevation of about 5,300–5,400 ft within about one mile of the Dolores zone of faults, and on the projection of the southwest-trending fracture zone which crosses the Dolores zone.

Thin veinlets of carbonaceous material (resembling asphaltite) in the Strawberry Roan mine are as much as 1 in. wide and 10–12 ft long (locations of mines cited in the text are shown on pl. 1, Shawe, 1968, or given in Appendix A, keyed to mining groups shown on pl. 1, this report). The veinlets cut sharply across sandstone bedding. These veins have not been observed in outcrops. Similar material has been found in fossil logs in the Sarah Ellen mine, suggesting that the veinlets are derived from woody rather than petroliferous sources. They may have formed as the result of solidification of humate gels derived from the organic material and localized in fractures that formed following lithifaction. Unfortunately their composition has not been studied adequately.

Uranium-Vanadium Ore Deposits

The following pages give details of the relation between weathered and unweathered deposits, distribution of the deposits, relation to altered rocks, localization controls, forms of the deposits, textural variations, mineral and chemical compositions, isotopic compositions of some elements of the deposits, and their implications to origin and formation (genesis) of the deposits.

Associated with the ore minerals are others precipitated along with them as part of the process of mineralization, such as sulfides and other authigenic minerals. Deposits near or at the surface that have been exposed to recent weathering contain numerous secondary (supergene) minerals formed by oxidation of primary (hypogene) minerals. Ore mineralogy generally is incidental to mining, except as visible indication of ore, but some minerals determine the methods of separation of the valued elements from the ore, a topic not dealt with in this report. Many of these minerals, however, contribute to understanding the genesis of the deposits, as elaborated in later pages.

Mineralized rock is arbitrarily subdivided as weakly mineralized, strongly mineralized, or ore. Because uranium was the principal element sought in the Slick Rock ores during the latest period of mining, it determined the classification. At the time of our studies in the district (1953–58), rock containing uranium up to 0.01 weight percent was classified by the USGS as weakly mineralized, that with >0.01 weight percent and up to 0.1 weight percent was classified as strongly mineralized, and that with >0.1 weight percent uranium was classified as ore. Because analyses of mineralized rocks were reported as either percent U or percent U_3O_8 content, they are similarly recorded in this report. Experience has shown that distinction between mineralized and unmineralized rock, based on numerous chemical determinations of the uranium and vanadium content of rocks, can be made by visual recognition of uranium and vanadium minerals. A further distinction of the term mineralized is made in a later section (p. 47).

Weathered and Unweathered Deposits

Uranium-vanadium ore deposits in the Slick Rock district consist both of "oxidized" or weathered deposits that are above the present water table near the surface (characterized by high-valent uranium and vanadium minerals), and of "unoxidized" or unweathered deposits that are below the water table and relatively deeply buried (characterized by low-valent uranium and vanadium minerals). Aside from some differences in mineralogy, most characteristics of ore bodies of the two types of deposits, particularly their forms, are quite similar. In places, a weathered deposit near the surface grades into less weathered ore farther below the surface, and in such places the essential identity of most aspects of the weathered and less weathered ores is evident. An excellent example is illustrated in plate 4, a map and cross sections of the Strawberry Roan deposit, where carnotite-type ore near the surface grades at greater depth below the surface into much less oxidized corvusite-type ore. Along with changes in mineralogy which accompanied oxidation of deposits, some movement of chemical components probably occurred, although such changes are not well known and may have been minor; study under the microscope of oxidized mineralized samples suggest little movement of components (see later discussion, p. 39). Certain details of the ores, established from study of oxidized deposits, thus have been extrapolated to unoxidized ores of similar form and composition and are used in interpretation of ore controls and genesis of the deposits.

At the time of our studies in the district (1953–1958), ore deposits accessible for mapping and detailed study were mostly near-surface and oxidized, although some studies were made in deeper less-oxidized and unoxidized deposits. Studies of mineralized and adjacent altered rocks obtained from unoxidized cores of deep drill holes will be described in the section on relation of the deposits to altered rocks (p. 17–19).

Distribution of Uranium-Vanadium Deposits

Uranium-vanadium deposits are distributed widely in the Morrison Formation throughout the Slick Rock district. In addition to the deposits in the upper unit or ore-bearing sandstone of the Salt Wash Member, a few deposits are found in sandstone layers in the lower part of the overlying Brushy Basin Member. Minor mineralized zones are known in the Moss Back Member of the Chinle Formation.

Most of the known Salt Wash deposits are in the north part of the district in a belt called the Dolores ore zone, centered on a northwest-trending Dolores zone of faults and widest where a northeasterly set of faults crosses the Dolores zone (fig. 2). The ore zone is about 20 mi long, more than 10 mi wide near the intersection of the fault sets, and narrows southeastward to about 2 mi wide. It lies within and normal to the Uravan mineral belt near the south end of the belt as defined by Fisher and Hilpert (1952). The Salt Wash deposits west of Egnar are centered along the southwestward projection of an inferred transverse fault structure underlying the parallel surface faults. Some deposits lie in a narrow zone along the faults bordering the northeast edge of the district (see pl. 1) along Gypsum Valley. A few Salt Wash deposits are located along the Dolores River Canyon east of Dove

Creek. Uranium-vanadium deposits in the lower part of the Brushy Basin Member are chiefly in a small area a few miles southeast of the town of Slick Rock. Mined ore deposits and areas are shown on a map of the north part of the Slick Rock district (pl. 1), and on a geologic map of the district (Shawe and others, 1968, pl. 1). Principal producing areas (SM-1 to 5) of the district (pl. 1) are roughly grouped along the inferred northeast-southwest transverse fault structure.

Subparallel northeast-southwest-oriented surface faults, shown on figure 2, suggest a deeper through-going structure. Although the surface faults show no evidence of having controlled mineralization (Shawe, 1970), they may be a late (post-alteration) reactivation of a deeper and older structure that earlier had channeled mineralizing fluid.

Within the ore zone several ore “trends” or elongate clusters of ore bodies (pl. 1, Shawe and others, 1968) are thought to reflect their distribution within major stream channel systems. One notable ore trend extends southeastward from the Lower group of deposits (including the Cougar mine) north of Slick Rock, across the gap of the Dolores River Canyon, through the Georgetown group to the Burro group of deposits on the north side of Burro Canyon, and probably beyond to unmined mineralized zones underlying Disappointment Valley (fig. 2). The major stream channel systems in the ore-bearing sandstone are zones of coalescing elongate sandstone lenses in which current lineations are subparallel to the trend of the sandstone lenses. These systems form the thicker parts of the host sandstone layers whose maximum permeability parallels the elongate sandstone lenses.

Within the major stream channel systems, the deposits occur in seemingly random distribution. Certain locations within the host sandstone layers are preferred, however, where sandstone permeability and (or) flat impermeable mudstone seams influenced position and form of the deposits. Plate 5, a derivative map of the Cougar mine area in the Lower group of mines, shows a part of a braided-stream system of sandstone lenses that localized the ore bodies.

The ore deposit at the Cougar mine consists of interconnecting ore bodieswhich lie in an originally subhorizontal zone at and near the base of the ore-bearing sandstone. Initial sandstone deposition was by generally northeast-flowing streams, upon a somewhat uneven surface of underlying mudstone (pl. 5; Shawe and others, 1968, fig. 31). Subsequently a braided system of southeast flowing streams cut into the initial sandstone layer and deposited additional sand lenses. In places this system scoured completely through the earlier sand layer, and elsewhere remnants of the earlier layer remained beneath the southeast-trending channels. Interfluves consisting of the earlier system remained between strands of the later system. Subsequently these sand layers were buried beneath a layer deposited by streams again flowing predominately northeastward.

Despite locally irregular distribution of carbonaceous material or of thin, irregular, and discontinuous mudstone layers or lenses within the sandstone lenses, the uranium-vanadium deposits tend to occur at a particular subhorizontal horizon within the larger host sandstone lenses (plate 3), probably influenced by density variation of fluids involved. But also, local concentrations or fragments of carbonaceous material within the subhorizontal horizons have influenced positions of mineral deposition, as did impermeable mudstone layers within the sandstone. The example shown in plate 3 illustrates uranium-vanadium localization just above the middle of the sandstone lens. Localization also is common near the base of the ore-bearing sandstone, as at the Norma Jean No. 2 mine and the Belmont claim, Spud Patch group of mines (pl. 6), as well as the Cougar mine. An example of ore localization near the base of the host ore-bearing sandstone at the Cougar mine is illustrated in figure 8. Roll ore deposits (described in detail in later pages) formed in sandstone above a basal channel scour. In a few places, carbonized logs, largely replaced by calcite, localized minor roll ore bodies. In order to show the extremely varied effect of local lithologic (sedimentation) character upon ore deposition, other ore deposits near the base of sandstone layers will be described in detail in later sections.

Deposits occur commonly within sandstone near the edges of broad (several hundred feet), thin (less than 10 ft) impermeable mudstone layers or lenses within sandstone (for example, Shawe and others, 1968, pl. 8). At the Little Max and Sunday mines, Spud Patch group of mines (pl. 7), irregular tabular and associated roll deposits are localized in and near a zone of irregular and discontinuous mudstone layers and lenses within the lower part of the ore-bearing sandstone.

Roll Ore Deposits

In an earlier report (Shawe, 1956a, p. 239–240), I described roll ore bodies as generally layered bodies that cut across sandstone bedding in sharply curving forms (see also Fischer, 1942). In cross section, rolls commonly show “C”, “S”, and “socket” shapes, but in plan are linear (with well-defined longitudinal axes); many elongate rolls curve abruptly at their extremities into “noses.” Most roll ore deposits (some consisting of numerous roll bodies) are near the base of thick sandstone units where several thin well-defined mudstone layers are interbedded with thin sandstone layers (for example, fig. 8). Rolls commonly terminate against an upper and lower mudstone layer, but in places they are split into two distinct rolls by a third thin mudstone layer. Rolls may be continuous for several hundreds of feet along thin sandstone layers. Essentially, roll ore bodies in any particular sandstone layer bounded by mudstone layers are all segments of a continuous roll front, and in places rolls flatten into tabular form. The axes are characteristically sinuous in plan and commonly double back on themselves (at noses) so that cross sections through loops in the roll fronts show mirror images of the roll shapes on either side of the loops (for example, figs. 12, 13, and 14). Another example of opposed roll ore bodies is shown in figure 15, which also shows the inferred position of deposition of uranium-vanadium ore at an interface between an introduced fluid and trapped connate (formation) water. The concept of ore deposition at an interface will be discussed more thoroughly in later sections of this report.

Roll ore bodies in the Slick Rock district range from several inches to more than 5 ft wide, a foot or so to almost 20 ft high, several feet to several hundreds of feet long, and contain a few tons to a few thousands of tons of ore. Detailed mapping of sedimentary structures in mine workings has shown the general coincidence of the long axes of rolls with the trend of sedimentary structures such as current lineations. Some rolls lie against mineralized carbonized logs (one example shown in fig. 8), or rolls are indented where logs lie across their general trends.

Rolls are bounded by fractures that separate mineralized rock from barren rock (figs. 16*A*,*B*, 17, 18*A*,*B*, and 19*A*,*B*). Commonly, the concave surfaces of rolls show sharp transitions into barren rock, whereas the convex sides of rolls show more gradual transitions into barren rock, or even may be continuous laterally into tabular ore bodies. Within roll ore bodies, ore minerals are more abundant along certain bedding layers, in zones with abundant clay galls and pebbles, and carbonaceous material (figs. 20, 21, and 22).

The uranium-vanadium ore deposit at the Cougar mine, Lower Group of mines, perhaps epitomizes roll ore bodies of the Colorado Plateau sandstone-type ore deposits. The deposit consists of a large number of interconnected roll ore bodies whose subparallel axes trend about southeast; in aggregate the roll ore bodies form a southeast-trending ore deposit whose erosional remnant is almost 1,900 ft long and about 800 ft wide (pls. 4, 14, 15, and 16). Plate 14 is a geologic map of the Cougar mine showing essential elements of the deposit and its host sandstone. Cross section lines on the map (*A–A′* to *X–X′*) show the positions of geologic cross sections in plate 15 which were used to construct the prospective diagram of the roll ore deposit depicted in plate 16.

Plate 16 shows that the Cougar ore deposit is essentially only a few extremely convoluted single ore layers. The ore layers are made up of a large number of ore rolls, many of which flatten both laterally and longitudinally into thin interconnecting tabular layers. A more detailed perspective view of a small part of the Cougar deposit at its west-central edge (sections *B–B′*, *C–C′*, and *D–D′* on pl. 14) is shown in figures 12, 13, and 14. The axes of the ore rolls (shown as single lines on pls. 4 and 14) generally are linear and subparallel, although they locally are sharply curved where they “double back” on themselves. Such points mark the “tongues” or “noses” of roll ore bodies, many of which can be seen on plate 16; the detailed appearances of a few of these are shown in figure 14. The complex system of generally subparallel interconnected roll ore bodies, as just noted (also pls. 5 and 16), occupies a braided stream system of coalescing elongate sandstone lenses (see parallelism of roll axes and current lineations shown on pls. 4 and 14).

Figures 16*A*,*B* provide perspective views of a typical roll surface showing the development of loops in an otherwise linear roll axis. The perspective cross sections of plate 15 and figure 12 show that the positions, sizes, and shapes of the ore rolls in sandstone have been controlled in detail by generally thin mudstone layers at or near the base of the ore-bearing sandstone. Figure 8 also shows this relationship.

The uranium-vanadium ore deposit at the Strawberry Roan mine located about 1 mi south of the Legin group of mines is a particularly good example of a deposit that contains paired subparallel rolls whose mirror-image character is seen in cross section *A–A′* (pl. 4). The rolls are aligned with the east-northeasterly trend of greatest permeability of elongate sandstone lenses. Current lineations that suggest the trend of greatest permeability in sandstone were not recorded on the Strawberry Roan mine map; the trend is suggested by the subparallel alignment of fossil carbonized logs which were mapped near the mine portal (pl. 5).

At the Bennie T. No. 1 mine, Charles T. group of mines, an intricate network of interlayered crossbedded sandstone lenses and thin mudstone layers has resulted in the formation of a complex assemblage of subparallel fingerlike roll forms (pl. 17). Mapped current lineations and the trend of a fossil carbonized log at the mine are subparallel to the south-southeast trend of the roll ore bodies.

The forms of roll ore bodies, as obviously controlled by lithologic variations in enclosing rocks that reflect permeability differences, indicate that an introduced mineralizing fluid was conducted along permeable pathways. Precipitation of minerals along the margins of the permeable pathways implies the presence of a precipitating agent, that is, a formation fluid of different chemical composition through which the introduced fluid moved. This presence, in places of Leisegang flow upward rather than laterally. Fluid likely did not move laterally from the present position of the laccoliths, but rather, it entered the fracture systems at depth, to move up faults into the zone where the ores were deposited.

Age Correlations

Ages of the Colorado Plateau uranium deposits have been the subject of speculation beginning with studies in the late 19th century. More recently, radiometric analyses of uranium minerals and associated lead minerals have provided firmer age data. Stieff and others (1953) concluded that the Colorado Plateau uranium deposits were of Late Cretaceous-early Tertiary age. Ludwig and others (1984) determined an age of about 132 Ma for ores in the Grants, N. Mex. district. The early Tertiary (Eocene-Oligocene) was the likely time of uranium ore deposition, based on uranium-lead data (Lorin Stieff, written and oral communs., 2003–2008). Uncertainties remain, related to locations of deposits, assumed process of origin, and assumptions used in calculation of ages.

Geologic evidence indicates that the existing forms of the Slick Rock uranium deposits are no older than Late Cretaceous or Tertiary. Faults breaking Upper Cretaceous rocks (Dakota Sandstone and Mancos Shale) controlled introduction of extraneous mineralizing fluids. Epigenetic alteration of the Salt Wash sandstones resulted from introduction of an extraneous solution along zones of faults coincident with the distribution of the uranium deposits (Shawe, 1976a).

Shawe and others (1959) speculated that intrusion of the La Sal Mountains laccoliths may have been related to mineralization of the Slick Rock deposits. Stern and others (1965) suggested that because the lead isotope compositions of feldspars from the La Sal igneous rocks are similar to lead isotope compositions of some galenas from Colorado Plateau uranium ores, the leads may share a common progenitor. An early attempt to date intrusion of the La Sal Mountains rocks (Stern and others, 1965) by zircon uranium-lead and thorium-lead analyses indicated an age of 32 ± 2Ma (based on Pb^{206}/U^{238}) and 28 ± 2 Ma (based on Pb^{208}/Th^{232}) for soda syenite porphyry, and 32 ± 2 Ma (based on Pb^{206}/U^{238}) and 40 ± 6 Ma (based on Pb^{208}/Th^{232}) for monzonite porphyry. Much older dates obtained for diorite porphyry were attributed by Stern and others (1965) to the effect of inherited Precambrian zircons. Potassium-argon dates (Stern and others, 1965) for aegerine-augite from soda syenite porphyry of 25.5 ± 2.5 Ma and aegerine-augite from monzonite porphyry of 22.5 ± 3.3 Ma suggest that similarities amongst the determined dates indicate likely time of emplacement in latest Oligocene-earliest Miocene time. More recently, Nelson and others (1992), using the $^{40}Ar/^{39}Ar$ dating method on potassium feldspars from the intrusive rocks of the La Sal Mountains, determined ages of 28–25 Ma (latest Oligocene) that provide specific corroboration of the earlier determined ages.

Mineral fluid inclusions in the overlying Mancos Shale (Shawe, 1976a), which are probably indicative of a maximum temperature attained when most deeply buried in the early Tertiary, about 110° C, may indicate the approximate temperature of deposition of the Slick Rock ores. On the other hand, such temperature could have existed at shallower depths if hydrothermal activity had raised rock temperature.

Date of intrusion of laccoliths in the La Sal Mountains, dates of igneous and mineralizing activity in the San Juan Mountains (late Oligocene and Miocene, Bove and others, 2001), and inferred age of the Slick Rock ore deposits are broadly coincident, reflecting an extensive regional geologic episode.

Genesis of the Uranium-Vanadium Deposits

The observations made and the data collected during our study of the Slick Rock uranium-vanadium ores allow several firm conclusions: 1) The ore bodies were deposited at an interface between two fluids of different chemical composition and redox potential; 2) One fluid was stagnant formation water and one fluid was introduced fluid which caused epigenetic alteration of the rocks through which it passed; 3) The ore bodies were deposited where pockets of strongly reducing formation water had developed around accumulations of carbonaceous plant material; 4) Lead isotope data indicate two distinct compositions (and hence sources) of uranogenic lead in the ore bodies, one typical of common (crustal) lead and one enriched in uranium; 5) Altered rocks, which formed as a result of the passage of an introduced fluid, are distinguished by the presence of lead minerals whose isotopic composition is typical of common lead; 6) The other fluid (formation water) carried lead greatly enriched in uranogenic lead and hence derived from a uranium-rich source; and 7) Formation water was enriched in uranium before it was encountered by introduced, altering fluid.

In the context of the above parameters, a rational concept of the origin and formation of the Slick Rock uranium-vanadium deposits can be inferred. Recognition of these critical elements of genesis did not occur simultaneously, but instead were recognized sporadically throughout our studies. Supplemented with much additional information, the elements now form the foundation of my current concept of genesis.

Evolution of the Genesis Concepts

Alteration events involved in genesis of the Slick Rock ores as described in an earlier report (Shawe, 1976a) included an early episode of diagenesis of the sedimentary rocks, forming both red-beds-facies and carbon-facies sandstone, processes not directly related to ore formation. I suggested acquisition to the ores of most ore components by way of a later introduced (and altering) solution (that formed altered-facies sandstone). The inference was based in part on the higher content of uranium in altered-facies (not mineralized) sandstone compared to red-beds-facies sandstone, and to elevated amounts of uranium in iron-rich deposits formed locally at contacts between altered-facies and red-beds-facies sandstone. The ore bodies were precipitated when introduced water carrying the ore elements came in contact with organic-rich formation (carbon facies) water, mostly concentrated in the upper sandstone unit of the Salt Wash Member. I described (Shawe, 1976a) a late episode of oxidation of the rocks resulting from uplift and recent weathering.

Studies (Breit and others, 1990; Breit and Goldhaber, 1995) that evaluated isotopes (of sulfur and strontium in barite), provided a better understanding of the timing and nature of the altering prosesses. These later studies indicated four major episodes of alteration: 1) Initial diagenesis which took place near the surface shortly following deposition of the sediments in the Late Jurassic (my episode of red-beds-facies sandstone and carbon-facies sandstone development); 2) An episode that witnessed accumulation of some of the ore components (most importantly, uranium) that occurred following early diagenesis probably in the Early Cretaceous and prior to the time of precipitation of the ores as they now are configured (an episode which I had not considered); 3) An alteration event that accompanied precipitation of the ores in the early Tertiary (the event I postulated as precipitating the ores); and 4) Surficial weathering resulting from near-surface oxidation of deposits following uplift and erosion in the late Tertiary-Quaternary, that allowed ingress of meteoric waters (an altering event that I also had suggested). Although more specific than my earlier evaluations of alteration, the more recent studies defined events similar to those earlier described. Evidence provided in this report now suggests (as did Breit and Goldhaber, 1995) that uranium (perhaps other ore components) accumulated early in the history of the sedimentary rocks and was precipitated in its present form only upon introduction of an extraneous (altering) fluid.

In earlier studies (Shawe and others, 1959; Shawe, 1976a), I postulated that the uranium-vanadium ores were deposited during the early Tertiary, at a time when the sediments were deeply buried (perhaps about 10,000 ft). I also suggested that the Upper Cretaceous Mancos Shale was a feasible source of water to have been introduced into the Salt Wash Member of the Morrison Formation to cause alteration and mineralization. With further study, I have concluded that chemically similar water from the underlying Hermosa Group was the more likely agent (Breit and others, 1990), as previously described.

Extending the Concepts

A long period of sporadic tectonism in the Western United States, from Cambrian to early Tertiary time, influenced provenance and deposition of sedimentary rocks which hosted the uranium-vanadium deposits in the Slick Rock district (Shawe, 1976b). This prolonged series of geologic events formed the character of the various rock units which ultimately controlled the genesis of the deposits. It influenced hydrologic regimes of various stratal units, and moved stratal fluids mobilized by igneous activity and controlled by rock permeability and fractures, by which components were moved from sources, through various stages, to ultimate deposition.

Deposition of a series of Paleozoic marine sedimentary strata on the western continental shelf of North America, including much of what is the present Western United States, followed development of a relatively flat erosional surface on Precambrian rocks (Shawe, 1976b). Organic-rich sapropelic strata and interlayered evaporite beds of the Paradox Formation of the Pennsylvanian Hermosa Group, deposited in a shallow basin (Paradox Basin) on the shelf, according to Breit and others (1990) constituted a stratigraphic facies favorable for development of a reducing fluid capable of altering red-beds-facies strata, and with composition capable of transporting many of the components that ultimately were precipitated in the Slick Rock ores.

During the Jurassic and Early Cretaceous a magmatic (volcanic and intrusive) belt developed along the western margin of the continent, forming a broad basin which extended far to the east. Late Jurassic deposition in the basin of mostly terrestrial beds of the Salt Wash and Brushy Basin Members of the Morrison Formation set the stage for ultimate localization of sites of deposition of the uranium-vanadium ores. A local basin, overlying the earlier Paradox Basin, formed on the alluvial plain of the Salt Wash causing an alluvial-fan modification of deposition which shaped the position of the Uravan mineral belt (Shawe, 1962), the south part of which became the Slick Rock district. The Salt Wash sandstones were characterized locally by abundant plant remains which formed a chemically reducing environment (Shawe, 1976a). This environment favored accumulation of uranium introduced from overlying uranium-bearing volcanic materials of the Brushy Basin derived from the western magmatic belt.

In the environment of abundant organic material in the uppermost sandstone, introduced uranium became complexed by humic acids during early stages of burial. Throughout the Cretaceous Period and into the early part of the Tertiary (perhaps a hundred million years), uranium-bearing sandstone was buried to a depth of several thousand feet where humates were not formed owing to increased heat. During this period the pockets of stagnant organic-rich fluid in the Salt Wash became greatly enriched in uranium. I believe that continually forming uranogenic lead was precipitated as galena by associated biogenic sulfide ions. However, generation of uranogenic lead in formation water continued, increasing the amount of uranogenic lead sulfide present. Much of the radiogenic lead in formation water in the Salt Wash had been accumulating in successive environments for a long period of time.

A period of extensive tectonic and magmatic activity, dominantly volcanic around the periphery of the Colorado Plateau and intrusive within the plateau, began in the early Tertiary, and culminated in late Oligocene time. Emplacement of La Sal Mountains laccoliths just northwest of the Slick

Rock district in latest Oligocene time likely induced movement of saline, reducing fluid from the underlying Hermosa Group through fractures into the Salt Wash Member.

Altering fluid driven by heat from the laccolithic intrusions and carrying vanadium and other elements from the magmas or picked up in transit, came in contact with trapped uranium-charged water around accumulations of organic material in the Salt Wash Member. Reduction of components in red-beds-facies sandstone (for example, conversion of iron-titanium-oxide minerals to pyrite), as a result of reaction with introduced reducing fluid, would decrease the fluid's reducing potential. Introduced fluid adjacent to forming ore bodies thus was probably less reducing than humate-charged formation water with which it came in contact. Precipitation of the uranium-vanadium ores took place by interaction of the two fluids at an interface.

Evidence of dominant amorphous uranium oxides (as UO_3—see earlier discussion of mineralogy of the deposits, p. 37–39) in much of the ore suggests that uranium may not have precipitated in crystal form because it was still adsorbed on humate gel. Unusually high amounts of uranium in unmineralized sandstone on the convex side of the ore roll, reflecting its inferred earlier concentration in formation water, may have resulted from precipitation of humate gel that did not migrate close to the interface. Addition of some elements (especially copper) in a separate, later mineralizing event which deposited minerals in close accord with the forms of earlier ore bodies seems unlikely. Changed hydrologic conditions, related to a difference in cause of solution flow, such as source of heat or other activating means, and different structural conditions (frequency and nature of conducting fractures) would likely exist if there had been a significant time gap between initial deposition and addition of other elements. Such a change in geologic conditions likely would have caused differences in the forms and element distributions in the earlier and later depositional bodies. Late Tertiary-Quaternary uplift and erosion exposed some of the ore deposits to weathering and oxidation.

Acknowledgments

From the start of geologic investigations by USGS in the Slick Rock district in 1947, and lasting into 1958, 12 separate drilling programs and more than 35 man-years of field and office work were completed. Many of the results of the drilling programs and geologic studies have been incorporated in this report. Between November 1947 and August 1953, USGS completed nine exploratory and development diamond-drilling programs in the district. These were directed by A.L. Bush, R.D. Trace, Henry Bell, III, C.F. Withington, L.S. Hilpert, W.L. Emerick, and J.L. Gualtieri. These geologists were assisted by geologists D.O. Beehler, Leonid Bryner, J.J. Folger (geologic field assistant), R.B. Hall, H.M. Icke, H.L. Jicha, H.S. Johnson, J.A. MacKallor, R.L. McDonald, C.H. Meissner, F.B. Moore, R.W. Osterstock, B.K. Replogle, H.S. Samsel, C.L. Setzer, E.M. Shoemaker, H.K. Stager, L.R. Stieff, C.M. Tschanz, and J.D. Vogel, and by engineers C.E. Blunt, M.F. Gilkey, W.T. Millar, T.W. Oster, E.V. Reinhardt, J.I. Schumacher, and J.E. Warner. D.C. Duncan, W.L. Stokes, and D.A. Phoenix, USGS, made some geologic studies in the district during this period.

Geologic work in the district was expanded and drilling programs were continued in September 1953 under the supervision of D.R. Shawe. Some of the drilling in the Disappointment Valley area in early 1956 was supervised by D.A. Phoenix. Other geologists who worked in the district from 1953 into 1958 are N.L. Archbold, G.C. Simmons, E.L. Boudette, W.B. Rogers, W.B. Gazdik, W.L. Emerick, J.A. Madsen, O.T. Marsh, R.L. McDonald, W.R. Barton, Jr., J.J. Connor, and O.B. Raup. Engineers who aided the project during this period were Clyde Duren, C.N. Brown, and John Miller. Geologic studies and exploratory drilling in the district during the period 1953-1958 were done under the general direction of Harold Kirkemo and J.W. Hasler.

Appreciation is extended to many individuals and companies engaged in mining, and mineral, oil, and gas exploration in the district, for information, cooperation, or permission to publish data. Among these are John Motica, John Emerson, Milton Genes, Bruce Hanson, and other representatives of Union Carbide Nuclear Co. (formerly United States Vanadium Corp.), R.J. Wright, A.M. Mastrovich, Dick Darnell, and other representatives of Climax Uranium Co. (American Metals Climax, Inc.), Dennis Viles, Page Edwards, and other representatives of Vanadium Corporation of America, Donald Hoffman, Donald Manke, and other representatives of Hunt Oil Co., Leroy Hemphill, C.H. Dulaney, Frank H. Macpherson, Jim Hershel, and other representatives of Dulaney Mining Co., Henry Holling of Holling Mining Co., C.G. Ortmayer and Frank Terman of Ortmayer Mining Co., Irving Rapaport of Four Corners Exploration Co., C.H. Reynolds of Reynolds Mining Co., Robert D. Fulton of Newmont Mining Co., Arthur Canfield of Canfield Mines, Melvin C. Bowles of Equitable Uranium Corp., Fallas M. Kelly and other representatives of Green River Oil and Uranium Co., Ray Fahnlender of United Uranium Corp., T.J. Weaver of Ajax Uranium Co., T.H. Skidmore of Skidmore Mining Co., Messrs. Knapp and Grover Williams of San Juan Development Co., Mr. Winger of Rosario Mining Co., William Gillespie of Uranium Metals Co., Charles Butler of Duncan Mining Co., as well as numerous representatives of Phillips Petroleum Co., The California Co., Superior Oil Co., Marcey Exploration Co., Carter Oil Co., Continental Oil Co., Bowles Heflin Mining Co., Johannsen and Kelly Mining Co., Bolles Brothers of Grand Junction, the Sitton brothers of Dove Creek, Fritz-Erickson Mining Co., Messrs. Gomez and Blaire Burwell of Egnar, Marion R. Watters of Dolores, W.D. Tripp Mining Co., Messrs. Davis and Goforth of Dove Creek, C. Eggers of Dove Creek, and Messrs. McCormick, Jim Knowles, Ernie Blair, and A.L. Wilhite.

Robert G. Coleman contributed much to the project by mineralogical studies and by valuable discussions in the field. W.D. Allen assisted in the compilation of data for a few weeks