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URANIUM DEPOSITS IN THE EASTERN SAN JUAN BASIN, CIBOLA, SANDOVAL AND RIO ARRIBA COUNTIES, NEW MEXICO

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Abstract—Although the first report of uranium in New Mexico was from volcanic rocks in the Jemez Mountains, very little uranium has been produced (<20,000 lbs of U₃O₈) from the eastern San Juan Basin. Uranium occurs in Morrison Formation sandstones, other sandstones, the Todilto Formation, other sedimentary rocks, epithermal veins, and disseminated deposits in igneous and metamorphic rocks. Uranium deposits in the Morrison and Todilto Formations were deposited during the Jurassic, although Tertiary-Quaternary oxidation and remobilization of some deposits may have occurred. Deposits in the Precambrian rocks in the Tusas Mountains are magmatic and related to granitic and pegmatitic rocks. Other uranium deposits in the eastern San Juan Basin may have been derived from devitrification and leaching from the Bandelier Tuff. The potential for near-future development of uranium deposits in this area is nil because of lack of demand, low uranium prices and low grade.

INTRODUCTION

The first report of uranium in New Mexico was made by F. A. Jones (1904) in volcanic rocks of the Jemez Mountains. Subsequent exploration during the uranium booms of the 1950s and 1970s led to additional discoveries of uranium occurrences and deposits in the eastern San Juan Basin (Fig. 1, Table 1). Despite extensive drilling, exploration and numerous published reports (see bibliographies by Schilling, 1975; McLemore, 1983), only a few of these deposits were developed and mined. The development of uranium deposits in this area is unlikely in the near future. However, we are optimistic that in the long term, the price and demand for uranium will increase and the production of uranium in New Mexico will resume, but probably not to the level of uranium production in New Mexico during the 1970s (McLemore and Chenoweth, 1989). We feel that it is important to document and preserve some of the data generated during the exploration and development phases in this area for future exploration and mining geologists and also for administrators in local, state and federal government agencies who may need this data for environmental studies, land-use decisions and other planning actions.

The purpose of this report is threefold. First, we briefly summarize the history of uranium exploration and mining in this area. We then describe and locate the types of uranium deposits, production and future potential. Finally, we present some ideas on the origin of these deposits.

Different stratigraphic nomenclatures have been used in the eastern San Juan Basin for the Permian Abo-Cutler Formations and Todilto Member or Formation (Jurassic). Here, in order to be consistent with current nomenclature used in this guidebook, we refer to the Abo Formation as Cutler Formation and Todilto Limestone Member of the Wanakah Formation as Todilto Formation.

HISTORY OF EXPLORATION AND MINING

The presence of visible uranium minerals in sedimentary rocks of the eastern San Juan Basin region was brought to the attention of the Atomic Energy Commission (AEC) in 1952 by prospectors who were exploring outcrops of the Chinle and Morrison Formations. Since the region was known to contain "red bed" copper deposits, which elsewhere contain uranium, these old copper mines and prospects were additional prospecting targets. During the 1950s, the region was extensively prospected and numerous claims were located covering radioactive occurrences. Aerial radiometric surveys by the AEC also located numerous areas of surface radioactivity (U.S. Atomic Energy Commission, 1966). The more promising occurrences were explored with pits, trenches and short adits; a few prospects were drilled.

In the mid-1950s small shipments were made from a prospect in the Todilto Formation northeast of Youngsville; from three prospects in the Cutler Formation near Coyote; and from two prospects in the Cutler Formation south of Gallina (Table 2). Only those in the Youngsville

and Coyote areas proved to be of economic grade. Two small trial shipments from the Agua Zarca Sandstone Member of the Chinle Formation near Coyote were noneconomic. In 1954 and 1956 small trial shipments were made from a pegmatite in the Petaca district and from two vein-type deposits in the Tusas Mountains. In 1954, small ship-

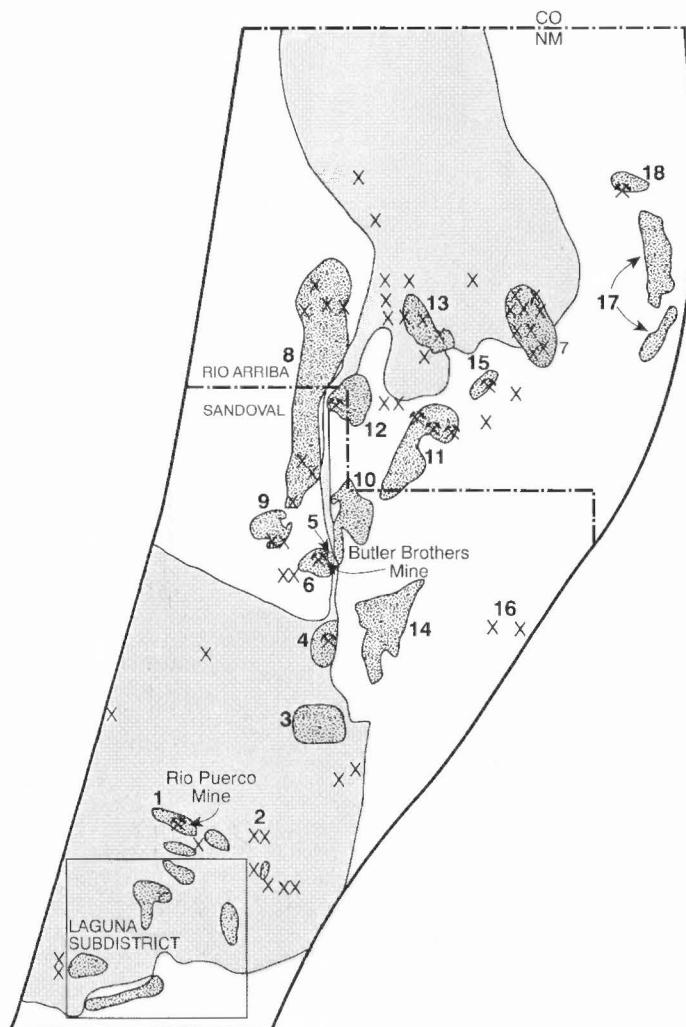


FIGURE 1. Uranium occurrences and districts in the eastern San Juan Basin (modified from McLemore and Chenoweth, 1989).

TABLE 1. Uranium districts and areas in the eastern San Juan Basin (modified from McLemore and Chenoweth, 1989).

Map No.	District or Area	Host Rock	Type of Deposit	References
1.	Marquez subdistrict Grants uranium district	Morrison Formation	primary	Livingston (1980), Moore and Lavery (1980)
2.	Bernabe-Montaño subdistrict Grants uranium district	Morrison Formation	primary, redistributed	Kozusko and Saucier (1980)
3.	Ojito Spring area	Morrison Formation	primary or redistributed	Santos (1975), Chenoweth (1974), Kittleman (1957)
4.	Collins-Warm Springs district	Morrison Formation	redistributed	Santos (1975), Chenoweth (1974)
5.	Dennison area	Morrison Formation	redistributed	Green et al. (1982b), Ridgley (1974, 1980)
6.	La Ventana	Dakota Sandstone, Menefee Formation	shale	Bachman et al. (1959), Green et al. (1982a)
7.	Abiquiu area	Burro Canyon Formation Chinle Formation Todilto Formation	sandstone (roll front) sedimentary copper limestone	Saucier (1974), Chenoweth (1974), Bingler (1968), Soulé (1956), Hilpert (1969)
8.	Eastern San Juan Basin area	San Jose Formation	sandstone (roll front)	Chamberlin (1988), Green et al. (1982a)
9.	Mesa Portales area	Ojo Alamo Sandstone	sandstone (roll front)	Green et al. (1982a,b), Vizcaino and O'Neill (1977)
10.	Nacimiento area	Cutler Formation, Chinle Formation	sedimentary copper, sandstone	Chenoweth (1974), McLemore (1983), Hilpert (1969), Soulé (1956)
11.	Coyote district	Cutler Formation, Chinle Formation, Todilto Formation	sedimentary-copper limestone	Chenoweth (1974), Hilpert (1969), Soulé (1956), Baltz (1955)
12.	Gallina district	Cutler Formation, Madera Formation	sedimentary-copper	McLemore (1983), Chenoweth (1974), Brown (1955)
13.	Chama Canyon district	Cutler Formation	sedimentary-copper	Light (1982, 1983)
14.	Jemez Springs area	Cutler Formation	sedimentary-copper	Chenoweth (1974), McLemore (1983)
15.	Box Canyon mine	Todilto Formation	limestone	Chenoweth (1974), Hilpert (1969)
16.	Cochiti district	Tertiary volcanics	epithermal vein	McLemore (1983), Chenoweth (1974)
17.	Petaca district	Precambrian	pegmatite	Bingler (1968), Redmon (1961), *Apsouri (1944)
18.	Bromide district	Precambrian	epithermal vein	Wobus and Manley (1982), Goodknight and Dexter (1974), Bingler (1968)

* The best report describing uranium in the pegmatite.

TABLE 2. Uranium production from deposits in the eastern San Juan Basin. Production figures prior to 1971 are from Atomic Energy Commission production records (McLemore, 1983). Production after 1971, estimated by authors. ¹Jmw = Westwater Canyon Member; Jmbj = Jackpile Sandstone Member; Jbm = Brushy Basin Member; Kd = Dakota Sandstone; Pc = Cutler Formation; TRc = Chinle Formation; Jt = Todilto Formation; PE = Precambrian rocks.

District (Map No.)	Mine	Location	Tons Ore	Pounds U ₃ O ₈	% U ₃ O ₈	Pounds V ₂ O ₅	% V ₂ O ₅	Host ¹ Rock	Periods of Production/Shipper
1. Marquez subdistrict	Rio Puerco Grace-Site II	19T12NR3W 13T12NR4W	<5,000 —	<16,000 minor	0.16 —	— —	— —	Jmw Jmbj	1979–1980—Kerr McGee 1970s
4. Collins-Warm Springs	Collins	25T17NR1W	395	989	0.12	116	0.07	Jmb	1957—E. H. Collins; 1959—Febeo Mines Inc.
6. La Ventana	Butler Brothers	23T19NR1W	23	290	0.63	56	0.12	Kd	1954, 1957—Butler Brothers
11. Coyote district	Coyote Hills Red Head #2 Lucky Strike Midcontinent	8T22NR3E 8T22NR3E 1T22NR2E 10T22NR3E	28 39 3 1	56 121 4 1	0.10 0.16 0.06 0.06	55 124 20 7	0.09 0.16 0.28 0.37	Pc Pc TRc TRc	1954—F. T. Bridges 1955—Boliver Uranium Co. 1957—Arroyo del Agua Mining Co. 1955—Midcontinent Exploration
12. Gallina district	Corral #3 White Flo #1	25T23NR1W 19T23NR7E	20 4	12 7	0.03 0.08	24 43	0.06 0.12	Pc Pc	1956—Sla-Tex Ventures 1954—Whiteflo Mining Co.
15. Box Canyon	Box Canyon	28T23NR42	132	253	0.10	212	0.11	Jt	1957—Box Canyon Mining Co.
17. Petaca district	Pineapple #1	30T26NR9E	4	2	0.03	1	0.02	PE	1954—S. H. Wells
18. Bromide district	JOL Tusas East Slope	24T28NR7E 24T28NR7E	8 13	6 18	0.04 0.07	5 24	0.03 0.09	PE PE	1956—Arriba Uranium Co. 1954—Colonial Uranium Co.

ments of ore-grade material were made from the Dakota Sandstone and Morrison Formation in the area between Cuba and San Ysidro. Another small shipment was made from the Dakota Sandstone in 1957. In 1959, a few hundred tons of ore were mined from a deposit in the Morrison Formation northwest of San Ysidro. Economic reserves were not developed in the remaining deposits, and activity in the area ceased.

Early exploration drilling in the Rio Puerco area was limited to the Jackpile Sandstone Member of the Morrison Formation, as this unit contained the known surface occurrences (Kittleman, 1957). In the late 1960s, based on logs of oil tests, companies determined that the Westwater Canyon Member was present in the subsurface and could be favorable for uranium deposits. In 1969, drilling located uranium deposits in the Westwater Canyon in the vicinity of Marquez and in the San Antonio Valley. Continued exploration found additional deposits in the Marquez Canyon area and elsewhere in the Rio Puerco area. Only one deposit (Kerr-McGee's Rio Puerco) was partially mined in 1979 and 1980.

TYPES OF URANIUM DEPOSITS IN EASTERN SAN JUAN BASIN

The uranium deposits in New Mexico have been divided into six categories by McLemore and Chenoweth (1989). Examples of all six categories are found in the eastern San Juan Basin (Table 1; Fig. 1): (1) Morrison Formation (Jurassic) sandstone uranium deposits, (2) other sandstone uranium deposits, (3) limestone uranium deposits, (4) other sedimentary rocks with uranium deposits, (5) vein-type uranium deposits, and (6) disseminated uranium deposits in igneous or metamorphic rocks.

Morrison Formation (Jurassic) sandstone-uranium deposits

Sandstones in the Morrison Formation contained the most economically important uranium deposits in New Mexico and the United States; more than 97% of the total uranium production in New Mexico and 38% of the total uranium production in the United States from 1948 through 1991 came from sandstones within this unit (McLemore and Chenoweth, 1989). In the eastern San Juan Basin, uranium occurs in the Westwater Canyon, Brushy Basin and Jackpile Sandstone Members of the Morrison Formation (Fig. 1). Most of the production from the eastern San Juan Basin came from these sandstones (Table 2).

Typically the orebodies are composed of lenticular, tabular masses of complex uranium and organic compounds that form roughly parallel

trends. Fine-grained barren sandstones lie between the orebodies, which are in medium-grained sandstone (Hazlett and Kreek, 1963; Crawley et al., 1985). Ore bodies occur as (1) primary, also known as pre-fault, trend, blanket, and black-band ores; (2) redistributed, also known as post-fault, stack, secondary, and roll-type ores; and (3) remnant ores. These deposits are described in detail in numerous publications (e.g., Rautman, 1980; Holen, 1982; Turner-Peterson et al., 1986; McLemore and Chenoweth, 1989). Most primary uranium deposits occur in long, narrow and blanket-like trends (McLemore and Chenoweth, 1991). Redistributed uranium deposits are present along the Tertiary-Quaternary oxidation front (Saucier, 1976; Crawley et al., 1985). Remnant uranium deposits are located behind the oxidation front, are sporadically distributed, and are difficult to locate.

Most uranium deposits in the eastern San Juan Basin are primary uranium deposits and are found in the southern part of the eastern San Juan Basin (Fig. 1). Below are brief descriptions of the uranium deposits in these areas.

Marquez area

The Marquez area (Fig. 1, No. 1) is an eastern extension of the Grants uranium district and lies north of the Laguna subdistrict in Sandoval, Cibola and McKinley Counties (Fig. 2). Only the Rio Puerco mine (Section 19) has produced from the area (Table 2), although several large uranium deposits of low grade occur in the Westwater Canyon Member (Table 3). Combined resources of more than 17 million lbs of U₃O₈ at depths of 270–700 m were reported (McLemore and Chenoweth, 1989).

In 1969, Humble Oil Co. (now Exxon) located several shallow, low-grade deposits in the San Antonio Valley area in Cibola County (Moore and Laverty, 1980). These deposits in the Westwater Canyon Member are flat-lying, primary uranium deposits and average 2–4 m thick. The dominant mineral is coffinite, and chemical assays range up to 0.38% U₃O₈. Depth to ore is about 244–305 m. At about the same time, W. Rodney De Villiers discovered a Westwater Canyon orebody near the village of Marquez. This orebody became known as the Juan Tafoya deposit.

Both Kerr-McGee Corp. and Bokum Resources Corp. found uranium deposits in the Marquez Canyon area. Bokum began sinking a shaft and constructing a mill in the late 1970s and early 1980s, but suspended operations due to large inflows of water into the shaft, financial difficulties and poor economic conditions. Three distinct ore horizons occur

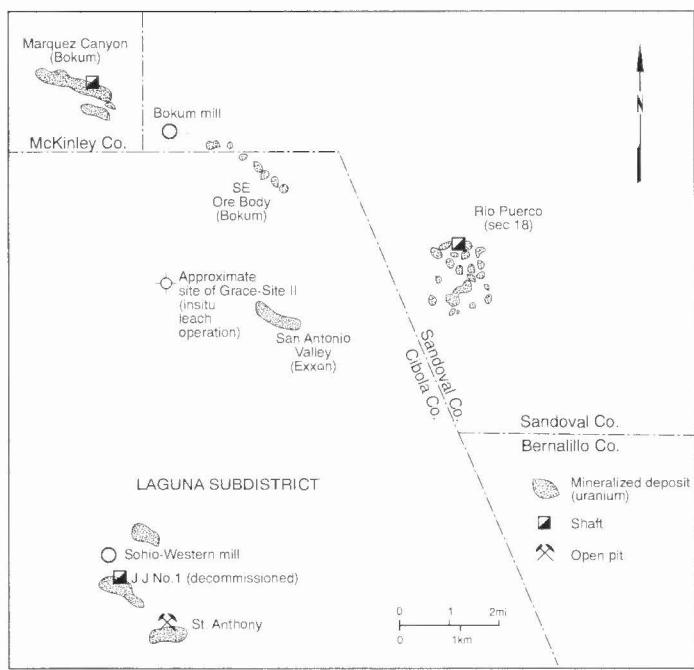


FIGURE 2. Uranium deposits in the Marquez area.

in the Westwater Canyon Member at depths of about 640 m (Livingston, 1980). Remobilization of the primary tabular ore is minor.

Ore at Marquez Canyon is controlled by shale breaks, high permeability and recurrence of meandering stream deposits. Where the shale beds are absent, uranium mineralization is dispersed throughout the sandstone and was subeconomic in the late 1970s. Mineralized sandstones tend to be permeable, but excessively permeable sandstones allow mineralization to be redistributed. Mudstone pebbles tend to reduce the permeability and concentrate uranium mineralization. Uranium deposits appear to be restricted to meandering channels within the dominantly braided-stream complex (Livingston, 1980).

The Rio Puerco deposit contains about 3.2 million lbs of less than 0.16% U_3O_8 in resources in the Westwater Canyon Member (Table 3; Perkins, 1979; NMBMMR files). Several zones of mineralization extend over an area roughly 1800 m long and 300 m wide, at a depth of approximately 244 m. Kerr-McGee produced less than 16,000 lbs of U_3O_8 from the Rio Puerco mine in 1979 and 1980, but the mine was closed because of low grade, decreasing price of uranium, extreme distance from the Ambrosia Lake mill and milling difficulties (too much shale in the ore).

Bernabe Montaño area

Conoco Minerals Co. discovered primary and redistributed uranium deposits in the Bernabe Montaño Grant (Fig. 1, No. 1) in 1971 and delineated ore reserves of 10–20 million lbs of U_3O_8 at a grade of 0.20% U_3O_8 (Table 3; Kozusko and Saucier, 1980; McCammon et al., 1986). The deposits are in the Rio Puerco fault zone at about 500–700 m in depth (Table 3). The U.S. Department of Energy (1980) estimated possible potential uranium resources in the area as 64,000 lbs of uranium averaging 0.35% U_3O_8 . Conoco divested itself of all uranium properties in the early 1980s, and the ownership of the property reverted back to the Pueblo of Laguna.

TABLE 3. Uranium deposits in the Morrison Formation in the Marquez and Bernabe-Montaño areas, eastern San Juan Basin. ¹Symbols explained in Table 2.

Property	Location	Estimated depth (ft)	Host ¹	Dominant type of deposit	Estimated size	References
Marquez Canyon (Kerr-McGee)	23 T13N R5W	1800–1900	Jmw	primary	6.8 mill lbs U_3O_8 reserves	McCammon et al. (1986)
Marquez Canyon (Bokum)	23 T13N R5W	1820–1830, 2100	Jmw	primary	10.7 mill lbs U_3O_8 reserves	Livingston (1980), Hatchell and Wentz (1981), McCammon et al. (1986)
Juan Tafoya (Bokum) (southeast orebody)	26,32 T13N R5W	1600	Jmw	primary	751,000 lbs U_3O_8 reserves	Livingston (1980), Hatchell and Wentz (1981), McCammon et al. (1986)
San Antonio Valley (Exxon)	15,21 T12N R4W	800–925	Jmw	primary	3.4 million lbs U_3O_8 at average grade of 0.098%	Moore and Lavery (1980), Holen and Hatchell (1986), McCammon et al. (1986)
*Rio Puerco (Kerr-McGee, Sec. 19 mine)	17,18,19, 20 T12N R3W	830	Jmw	primary	3.2 mill lbs U_3O_8 at 0.16% reserves. About 16,000 lbs U_3O_8 mined	Perkins (1979), McCammon et al. (1986)
Bernabe Montaño (Conoco)	35 T12N R2W	1500–2000	Jmw	primary, minor redistributed	10–20 mill lbs U_3O_8 at 0.2% reserves	Kozusko and Saucier (1980), McCammon et al. (1986)
East Group	4 T12N R4W	?	Jmw(?)	primary	—	McCammon et al. (1986)
*Grace-Site II (in situ)	13 T12N R4W	380	Jmbj	primary(?)	—	Holen and Hatchell (1986), Hatchell and Wentz (1981)

* Some production, mineralized zones still present.

Nacimiento Mountains

Uranium occurs in several areas along the western flanks of the Nacimiento Mountains (Fig. 1, Nos. 3, 4, 5) in at least three horizons of the Morrison Formation (upper Westwater Canyon Member, lower unit of the Brushy Basin Member, and lower Jackpile Sandstone Member). Only one mine yielded production, the Collins lease (Fig. 1, No. 4; Table 2). E. H. Collins leased a portion of the Ojo del Espiritu Santo Grant in 1957 from the Bureau of Land Management, acting as agent for the Bureau of Indian Affairs. Prior to Collins' lease, some of the same ground was leased by Cass Goodner. Early reports (Kittleman and Chenoweth, 1957) refer to these same occurrences as the Goodner lease. Goodner dug several pits but shipped no ore.

In 1957 and 1959, 395 tons of ore averaging 0.12% U₃O₈ were produced from the Collins lease (Table 2; Chenoweth, 1974). The ore was mined from two small pits in the Brushy Basin Member from fine-to medium-grained, lenticular, quartzose sandstone beds, 3–10 m thick (Fig. 3). The normal color of the sandstone is tan to light gray, but near the uranium deposits the sandstone is red (Kittleman and Chenoweth, 1957; Chenoweth, 1974).

Although most of the uranium on the Collins lease is in the Brushy Basin Member, some uranium also occurs in the Jackpile Sandstone and Westwater Canyon Members (Fig. 3). Visible yellow and green uranium minerals occur along fracture planes and are disseminated in sandstone, especially near greenish-gray clay galls and at interfaces with mudstone. Visible uranium minerals are also present in fracture planes in the underlying siltstone. Carnotite, tyuyamunite and metatyuyamunite have been identified in samples from the Collins lease (E. B. Gross, written comm. 1956). The mineralized rock ranges in thickness from a few centimeters to 1 meter. At the Section 11 deposit on the Ojo del Espiritu Santo Grant, a yellow uranium mineral occurs as a halo surrounding a small area where the sand grains are coated with a substance that resembles asphaltite. The southern half of the Grant, including the area of the former Collins lease, is now controlled by the Pueblo of Zia.

Several airborne radiometric anomalies occur on and near the Collins lease and in the Ojito Spring area west and southwest of San Ysidro (Fig. 1, No. 3), where radioactivity is concentrated around mudstone galls, at sandstone-mudstone interfaces, and in limonite-stained sandstone lenses in the Jackpile Sandstone and Brushy Basin Members. Visible uranium minerals are rare but have been observed on fractures in sandstone. Drilling in the vicinity of the mineralized outcrops has located additional low-order radioactivity which is not indicated on Fig. 3.

Uranium mineralization also occurs in the Westwater Canyon Member at the Dennison-Bunn claim south of Cuba (Fig. 1, No. 5). The

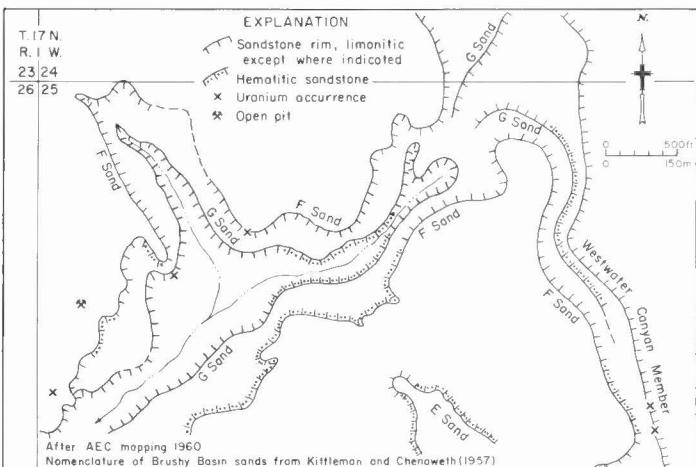


FIGURE 3. Uranium deposits and sandstone alteration at the Collins lease (from Chenoweth, 1974, fig. 2). Another open pit is located in NW^{1/4} SE^{1/4} sec. 25, T17N, R1W, outside of map area. According to Kittleman and Chenoweth (1957), the A, B and C sands were the Jackpile Sandstone (not present in map area).

Westwater Canyon Member is about 61 m thick and consists of medium-to fine-grained sandstones, siltstones and shales. The host sandstones are characteristic of low- to moderately low-energy fluvial environments, and the channels trend west-southwest (Ridgley, 1979, 1980). Uranium occurs throughout the Westwater Canyon Member in this area at the irregular boundary between oxidized and reduced sandstones. A selected sample assayed 0.082% U₃O₈ (McLemore, 1983), where uranium is associated with iron-stained zones and carbonaceous material. This deposit may be a roll-type deposit (Ridgley, 1980) or a remnant or relict orebody and may be indicative of additional deposits in the area. Bayleyite, a magnesium uranium carbonate, and liebigite, a calcium uranium carbonate, have been identified (E. H. Schot and R. S. Wegrzyn, personal comm. 1974) in samples from the Westwater Canyon Member at the Dennison-Bunn claims.

Other sandstone uranium deposits

Sandstone uranium deposits also occur in Pennsylvanian, Permian, Triassic, Cretaceous and Tertiary formations (Hilpert, 1969; Chenoweth, 1974; McLemore, 1983; McLemore and Chenoweth, 1989). Most of these occurrences are small, low grade, channel controlled, and associated with fossil plant material. They vary in size, but are much smaller than deposits in Morrison Formation.

Uranium deposits in the Dakota Sandstone

The Dakota Sandstone of Cretaceous age contains uranium at four localities southeast of Cuba in the La Ventana area (Fig. 1, No. 6), where the west-dipping sandstones form a hogback adjacent to the Nacimiento and Pajarito faults. At the Butler Brothers deposit, a total of 23 tons of ore containing 0.63% U₃O₈ were mined and shipped in 1954 and 1957. The ore came from a small pit in a 0.3-m-thick, carbonaceous shale or peat bed at the base of the formation, which dips 45° to 60° to the west. No uranium minerals were observed in the radioactive zone, which is present for approximately 30 m along the strike of the beds (Gabelman, 1956). Uranium occurrences similar to the Butler Brothers deposit, but of lower grade, occur at the Mauldin and Cleary prospects north of the Butler Brothers deposit, and at De Dos Gordos Wash to the south.

Uranium deposits in the Burro Canyon Formation

South of Canjilon, on the rim of Mesa Montosa in the Abiquiu area (Fig. 1, No. 7), uranium occurs in a white, fine-grained sandstone in the Burro Canyon Formation immediately below the Dakota Sandstone. This sandstone is considered to be equivalent to the Jackpile Sandstone Member by some geologists and as basal Dakota Sandstone by others. Low-grade roll-front sandstone uranium deposits occur at depths of 70–200 m (Saucier, 1974).

Uranium deposits in the San Jose Formation

Uranium is known at several localities in the eastern San Juan Basin in the Eocene San Jose Formation (Fig. 1, No. 8; Chenoweth, 1957). Uranium at three localities occurs in sandstone beds of the Llaves Member and is associated with carbonaceous plant debris in very coarse-to fine-grained light-gray, to light-yellowish-gray, feldspathic to arkosic, friable sandstone. Limonite staining of the sandstone is common near fossil plant material. Assays up to 0.20% U₃O₈ have been reported (Chenoweth, 1957).

West of Gallina at the State Lease, a yellowish-green mineral, probably meta-autunite, a calcium uranium phosphate, coats fractures in a gray-green mudstone of the Regina Member. Limonite staining and black manganese minerals are associated with the uranium mineral. Ground water and radiometric anomalies, together with surface uranium occurrences, indicate a potential for roll-type sandstone uranium deposits at shallow depths (<170 m; Chamberlin, 1988; McLemore and Chenoweth, 1989).

Uranium deposits in the Ojo Alamo Sandstone

Low-grade uranium deposits, possibly roll-type deposits, occur in several blanket-like horizons in the Ojo Alamo Sandstone in the Mesa

Portales area (Fig. 1, No. 9; Vizcaino and O'Neill, 1977; Green et al., 1982a, b). Depths to the deposits could be as much as 700 m. Radioactive and geochemical anomalies occur in the area.

Sedimentary-copper sandstone deposits

High concentrations of uranium occur locally in some stratabound, sedimentary copper deposits throughout the Nacimiento Mountains (Fig. 1, Nos. 10–14). These deposits occur within red-bed sequences deposited in intracratonic basins that lack volcanism or other magmatic activity. They occur within specific intervals of Pennsylvanian, Permian and Triassic fluvial to marginal-marine sedimentary rocks. Copper contents range up to a few percent; uranium contents vary.

Some radioactivity was detected in the Madera Limestone of Pennsylvanian age at the Pajarito Azul claims in the Gallina district (Fig. 1, No. 12). No uranium minerals were observed in the radioactive zones, which occur in a very coarse-grained, light-gray, arkosic sandstone containing carbonized plant debris and copper carbonates. Similar occurrences have been observed east of Cuba in the Nacimiento area at the Mining Mountain claims (Fig. 1, No. 10).

The Permian Cutler Formation contains more uranium occurrences in the Nacimiento-Jemez region than any other formation. Deposits are clustered near Coyote (Fig. 1, No. 11), south of Gallina (Fig. 1, No. 12), in the vicinity of Jemez Springs on the Cañon de San Diego Grant (Fig. 1, No. 14), and Chama Canyon (Fig. 1, No. 13). Single deposits are known southeast of Cuba and north of Abiquiu (Fig. 1, No. 7). The deposits south of Gallina were studied by Brown (1955) and those on Jemez Indian lands were examined by Brassfield (1956).

All of these deposits have similar characteristics, in that they occur in fine- to coarse-grained, feldspathic to arkosic sandstone lenses containing carbonized plant debris. The majority of the deposits are in the lower part of the Cutler Formation. The sandstone lenses range in thickness from a meter up to 20 m, and in most places are pinkish gray to medium gray and generally more lightly colored than adjacent barren sandstones. Reddish-brown mudstone and siltstone surround the sandstone lenses, commonly staining the sandstone reddish brown.

Most of the deposits are associated with carbonaceous plant material that contains copper minerals. Malachite and azurite are very common, and chalcocite and covellite are also present in several of the deposits, replacing fossil wood. Oxidized yellow uranium minerals are present in many of the deposits. Tyuyamunite, a calcium uranium vanadate and metatyuyamunite, a hydrated form, in association with malachite, have been identified in samples from the Jemez Indian Reservation (E. H. Schot and R. S. Wegrzyn, written comm. 1974). Deposits occur in the basal portion of the sandstone lenses containing clay galls, and the mineralized zones range in thickness from a few centimeters to 1.2 m. Calcium carbonate is a common cement in the mineralized zones, which are laterally very discontinuous. Uranium concentrations vary. A sample from the Max Jacque deposit in the Coyote district assayed 0.05% U_3O_8 (McLemore, 1983).

The only production of uranium from the Cutler Formation has occurred from the Coyote and Gallina deposits in sec. 8, T22N, R3E. A total of 67 tons, averaging 0.12% U_3O_8 , 0.14% V_2O_5 and 14.0% $CaCO_3$, were mined and shipped in 1954–55 from an open cut and short adit, an open cut and a 33-m adit (Coyote Hills and Red Head #2 mines, Fig. 1, No. 11). Small trial shipments from the Whiteflo I in 1954 and the Corral 3 in 1956, both south of Gallina (Fig. 1, No. 12), contained 0.08 and 0.03% U_3O_8 , respectively (Table 2).

Most uranium occurrences in the Jarosa and Jemez areas were found by prospectors and government geologists during the examination of old copper prospects. Of these, only the Spanish Queen mine has had significant copper production, about 19,200 lbs of copper between 1928 and 1937 (Elston, 1967). A sample from the Spanish Queen mine assayed 0.006% U_3O_8 and 3.49% Cu (McLemore, 1983). In general, the uranium and the copper contents of the occurrences are inversely proportional to each other.

In the region, uranium is known at six localities in the Chinle Formation of Triassic age. Two occurrences are near Coyote. Single occurrences are located north of Gallina, Coyote and Abiquiu, respectively, and a single occurrence is located southeast of Cuba. The Lucky Strike

property, the Mid Continent I claim, and the Jewell claims are in the Agua Zarca Sandstone Member and are similar in that uranium occurs with carbonized plant debris and copper carbonates in medium- to coarse-grained, gray sandstone beds. Yellow uranium minerals have been observed. Small trial shipments in 1955 from the Mid Continent I and in 1957 from the Lucky Strike contained 0.05% and 0.07% U_3O_8 , respectively.

North of Coyote, at the Pivot Rock claims, in the canyon of the Rio Chama, uranium occurs with carbonaceous plant debris in a coarse-grained sandstone and conglomerate in the top of the Agua Zarca Member, and in and around petrified logs and adjacent to thin limestone beds in the lower 5 m of the overlying Salitrillo Shale Tongue.

Uranium in the Todilto Limestone

Uranium in the Jurassic Todilto Formation is known from four localities near Coyote (Fig. 1, No. 11) and two localities southwest of Canjilon at Box Canyon (Fig. 1, No. 15). At the Box Canyon claims uranium occurs in a small intraformational fold, 7–10 m wide with an amplitude of several meters, in the upper part of the Todilto Limestone. Here the limestone is 3–5 m. Uraniferous limestones in the Todilto are not overlain by the gypsum unit (McLemore and Chenoweth, 1989). A total of 132 tons, containing 0.10% U_3O_8 , were mined from a small open pit in 1957 and shipped to the mill at Bluewater, New Mexico. Select samples assayed as high as 0.698% U_3O_8 (P. H. Knowles, written comm., Jan. 10, 1957). A yellow uranium mineral, probably tyuyamunite, occurs on fracture planes in the fold. Similar intraformational folds occur at the Rey and Lou claims and at the Jaramillo-Montoya claims, but contain lesser amounts of uranium.

Small folds containing secondary uranium minerals are present on the Heart claims in the canyon of the Rio Chama, and uranium also occurs in a limonite-stained sandstone which overlies the gypsum unit. This sandstone may be an equivalent to the Summerville Formation, but it is generally considered to be in the Morrison Formation. Float containing tyuyamunite is known from the Alex claims, also in the canyon of the Rio Chama. Uranium at the Mesa Alta claims occurs in a pod of limestone breccia overlying the Todilto gypsum unit and below a sandstone in the Morrison Formation (?).

Other sedimentary rocks with uranium deposits

Uranium in the Mesaverde Group

All three formations comprising the Upper Cretaceous Mesaverde Group in the La Ventana Mesa area south of Cuba contain uranium. The formations, in ascending order, are the Point Lookout Sandstone, Menefee Formation and the La Ventana Tongue of the Cliff House Sandstone. The majority of the uranium is in the Menefee Formation on North Butte and on South Butte in the La Ventana area (Fig. 1, No. 6). At these localities, uranium-bearing coal, carbonaceous shale and carbonaceous sandstone form a mineralized zone a few meters thick in the upper part of Menefee, immediately below the La Ventana Tongue. There are no visible uranium minerals, but coffinite, a uranium silicate, has been identified in samples from the coal (Bachman et al., 1959). Studies by the U.S. Geological Survey (Bachman et al., 1959) indicate that a resource of 132,000 tons of coal and carbonaceous shale, containing an average of 0.10% U_3O_8 , is present in the La Ventana area, principally on North Butte.

Disseminated uranium deposits in igneous or metamorphic rocks

Uranium in volcanic rocks

Uranium in volcanic rocks of the Cochiti (Bland) mining district (Fig. 1, No. 16) was reported by Jones (1904) and noted by Lindgren et al. (1910). At a single occurrence, uranium minerals fill interstices of a silicified rhyolite breccia in association with malachite. Although Jones reported "oxides of uranium and vanadium," the mineral was probably tobernite, a copper uranium phosphate, rather than carnotite. The host rocks in the Cochiti district are volcanic and intrusive rocks of Tertiary age (Smith et al., 1970).

Uranium in Precambrian rocks

Pegmatites containing uranium, thorium and rare-earth elements occur in the Precambrian terrane in the Petaca area of the Tusas Mountains (Fig. 1, No. 17). Monazite, samarskite, euxenite and hutchettolite are reported to occur (Apsouri, 1944; Redmon, 1961; Bingler, 1968). Some ore was produced in 1954 from the La Paloma pegmatite (Pineapple No. 1 mine) (Table 2) but pegmatites typically offer poor mining targets because of small size and discontinuity of ore minerals. Uranium contents vary; a sample from the Nambe pegmatite assayed 0.131% U_3O_8 and 610 ppm Th. A sample from the Globe pegmatite assayed 0.062% U_3O_8 and 1,983 ppm Th (McLemore, 1983).

Uranium occurs with fluorite in the Bromide district in the Tusas Mountains, Rio Arriba County (Fig. 1, No. 18). It is present in the Precambrian Tusas Mountain granite (Fig. 4) at the contact between the granite and Precambrian Moppin metavolcanic series, along the boundaries of inclusions, xenoliths, and roof pendants, and along fractures within the granite. The Tusas Mountain granite is white to pink, fine-grained, porphyritic, and only locally foliated (Kent, 1980; Wobus and Hedge, 1982; Wobus and Manley, 1982). The intrusive contact with the Moppin metavolcanic series is sharp and well exposed along the west edge of the intrusive. This granite is distinguished by its lack of pervasive foliation and its younger age compared with other Precambrian granites in northern New Mexico. The Tusas Mountain granite is between 1430 and 1500 Ma, compared to 1700 Ma foliated granites elsewhere in the Tusas Mountains (Wobus and Hedge, 1982).

In 1954, a total of 13 tons grading 0.07% U_3O_8 were produced from the Tusas East Slope #5 prospect. One 5-ton shipment from this prospect assayed 0.12% U_3O_8 . A shipment from the nearby JOL prospect in 1956 amounted to 8 tons grading 0.04% U_3O_8 . However, chemical analyses of samples collected by Goodknight and Dexter (1984) contained up to 0.31% U and 2% Th (Fig. 4). Anomalous amounts of Nb (720 ppm in #MFQ-806, Fig. 4) and La (580 ppm, Fig. 4) are present in some of the samples. Uranothorite, uraninite, fluorite and other uranium minerals have been reported (Goodknight and Dexter, 1984).

ORIGIN

There are several explanations for the origin of primary uranium deposits in the Morrison Formation. The size and shape of primary uranium deposits in the Grants district appear to depend upon associated humate deposits (Nash et al., 1981). Turner-Peterson and Fishman (1986) and Hansley (1988) proposed that the humates were derived from overlying greenish-gray lacustrine mudstones. During or after precipitation of the humates and humic acids, uranium was precipitated from ground water. Granger et al. (1988) and Granger and Santos (1986) developed an alternative model whereby uranium and humate were deposited during diagenesis by reduction at an interface of meteoric

freshwater and ground water brine. Other genetic models have been proposed. The source of uranium is still controversial.

Redistributed uranium deposits are younger than primary uranium deposits and probably formed from primary ore by a regional oxidation front, where oxidizing ground water moved down dip (Saucier, 1976, 1980) during Late Cretaceous–middle Tertiary through Quaternary time. Remnant uranium deposits were preserved in oxidized sandstones after the oxidation front that formed redistributed uranium deposits had passed.

The origin of uranium mineralization in the Todilto Formation is also controversial. Isotopic dating suggests that mineralization was Jurassic (Berglof, this guidebook). The largest Todilto uranium deposits occur in anticlinal portions of intraformational folds, the origin of which is controversial. Rapaport (1952a, b) and Hilpert and Moench (1960) attributed the folds to soft-sediment slumping or creep down a depositional slope on the flanks of anticlines. Other models include volumetric changes during dehydration and diagenesis (Gabelman, 1956) and differential loading and compaction near a subsiding reef or bioherm (Perry, 1963). Rawson (1980a, b) and Green (1982) suggested the folds are a result of migration of overlying Summerville dunes, which deformed the Todilto muds. Subsequently, hydraulic and evaporative processes allowed pumping of uraniferous waters from the underlying Entrada into the Todilto Limestone. The intraformational folds served as conduits and traps for uranium mineralization. Some Todilto deposits were subsequently oxidized and remobilized during the Tertiary and Quaternary (Saucier, 1976).

Uranium in the Bromide and Petaca districts probably originated during the Precambrian, in association with the granitic and pegmatic rocks.

There is no direct evidence regarding the origin of the uranium deposits in other rocks of the region. Field relationships suggest that the source of some of the uranium in the eastern San Juan Basin could have been in overlying volcanic rocks or possibly in thermal springs.

The rhyolitic Bandelier Tuff of the Tewa Group of Pleistocene age is the most widespread volcanic unit in the Jemez Mountains; it is composed of pumice, pumiceous tuff, breccia and ash flows. On the west flank of the mountains, almost all volcanic rocks west of a line connecting Coyote, Jemez Springs and Jemez Pueblo are composed of Bandelier rocks (Smith et al., 1970). At one time the Bandelier Tuff covered the entire Nacimiento region, but now only remnants remain in the San Pedro Mountain, on the east flank of Sierra Nacimiento, and in the Gallina, Coyote and Jarosa areas (Chenoweth, 1974, fig. 1; Goff and Shevenell, 1987).

Radioactivity in the Bandelier Tuff is sufficient to have induced the staking of claims in the early 1950s. During airborne radiometric surveys made by the U.S. Geological Survey in the areas of Coyote and Jarosa, Baltz (1955) noted that the radioactivity of the Bandelier was 1½ to 4 times the background of sedimentary rocks. AEC airborne surveys in the southern Nacimiento-Jemez region detected four radiometric anomalies in pumice beds in the Bandelier on the Cañon de San Diego Grant (Allison, 1954).

Grab samples of the pumice generally contained 0.003% U_3O_8 , and the highest grade sample contained only 0.008% U_3O_8 . Baltz (1955) stated that the uranium content in samples of the Bandelier collected by the U.S. Geological Survey in the southwestern part of the Jemez Plateau (probably the Cañon de San Diego Grant) averaged 0.003% U and varied from 0.003 to 0.006% equivalent uranium. Although this conclusion probably is based on analyses of relatively few samples, the Bandelier contains higher than average amounts of uranium than in similar rocks elsewhere.

Numerous thermal springs occur in and around the Valles caldera (Trainer, 1984). Other thermal springs are known near Jemez Springs, Jemez Pueblo and west and northwest of the San Ysidro. Radioactivity has been detected only at Soda Dam near Jemez Springs, and at the Arroyo Peñasco springs northwest of San Ysidro.

The temperature of the water from the Arroyo Peñasco springs averages 30°C, and calcareous tufa and travertine are being deposited. Some deposits are highly radioactive and are the source of three radioactive anomalies detected by AEC airborne surveys northwest of San Ysidro (Allison, 1954; Brassfield, 1956). Samples of water col-

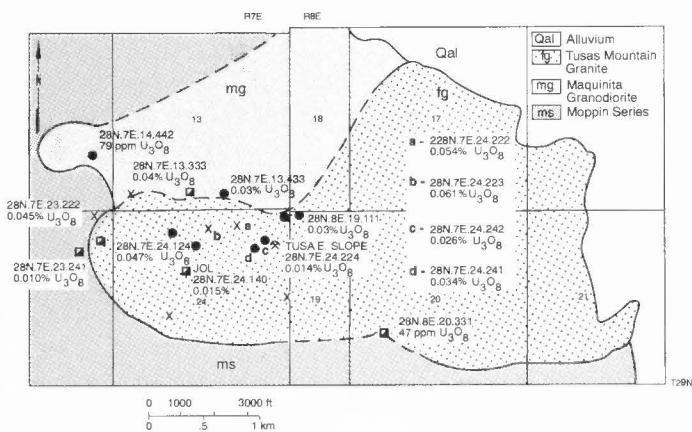


FIGURE 4. Uranium occurrences in Precambrian rocks in the Tusas Mountains, Rio Arriba County (from McLemore, 1983). Chemical analyses from McLemore (1983) and Goodknight and Dexter (1984).

lected from several of the radioactive springs contained from 0.002 to 0.036 ppm uranium. Warm water flowing from an abandoned oil test in the same area is also uraniferous and is depositing radioactive tufa.

The radioactive spring deposits at Soda Dam were studied by Granger in 1950 (Lovering, 1956) and Goff and Shevenell (1987). Temperature of the water from the springs at Soda Dam ranges from 32–48°C (Goff and Shevenell, 1987). Three of Granger's samples contained 0.036 ppm uranium and a fourth contained 0.04 ppm uranium. Samples by Goff and Shevenell (1987) contained 0.122–2.23 ppm uranium.

Renick (1931) concluded that the Arroyo Peñasco springs represent original volcanic waters modified by the addition of meteoric waters, whereas the springs at Soda Dam represent geothermal meteoric waters heated by igneous masses at depth then mixed with more dilute ground waters (Goff and Shevenell, 1987). Radioactivity in the spring deposits in both areas is probably caused by radium.

The radioactive thermal springs in the Nacimiento-Jemez region suggest a possible source for the uranium in the small deposits. The springs appear to be spatially related to major faults, but no radioactivity is known in the fault zones and there is no evidence of upward migration of deep-seated uraniferous solutions.

We favor the concept that uranium in some of the younger rocks was derived from the devitrification of tuffaceous Bandelier rocks. As the Bandelier was eroded, migrating ground waters may have carried soluble uranium complexes into permeable sandstones and other sedimentary rocks where it could have been precipitated under reducing conditions. A similar hypothesis was favored by Bachman et al. (1959) for the North and South Butte deposits at La Ventana. The relative proximity of the permeable sandstone of the La Ventana Tongue on the west side of the Pajarito fault to the surface on which the Bandelier Tuff was deposited, makes this hypothesis less speculative in this area than elsewhere.

The origin of uranium mineralization in sedimentary copper sandstone deposits may be from the Bandelier Tuff or other sources. Inasmuch as the uranium in the Cutler Formation is associated with copper, the relative lack of uranium in the Agua Zarca Member is surprising. The Agua Zarca contains the largest and most significant copper deposits in the region (Soulé, 1956; Kaufman et al., 1972), yet a reconnaissance of these mines yielded only trace amounts of uranium, suggesting that the periods of copper and uranium mineralization were unrelated. Woodward et al. (1974) placed the time of the copper deposition shortly after the deposition of the Agua Zarca, whereas we believe the uranium is much younger. The copper deposits may have formed by precipitation from low-temperature meteoric waters at favorable oxidation-reduction interfaces. Oxidizing waters could leach copper and associated metals from Precambrian rocks enriched in these metals, Precambrian base-metal deposits, and clay minerals and detrital grains within the host rocks (LaPoint, 1976, 1979). Uranium could have been transported by a similar mechanism and derived from the Bandelier Tuff.

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Exposures of the Upper Triassic Chinle Group (Petrified Forest Formation) make up the lower half of this photograph taken just west of N.M. Highway 44 northwest of San Ysidro. The Entrada Sandstone forms the light-colored cliffs above the Chinle and is capped by the Todilto Formation. View looking west. Photograph taken early morning of 11 April 1992. Copyright © Paul L. Sealey, 1992.