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URANIUM RESOURCES IN THE SAN JUAN BASIN, NEW MEXICO

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ABSTRACT.—New Mexico ranks second in uranium reserves in the United States, with a total of 15 million tons of ore at 0.279% U_3O_8 at $30/lb or less. The most important uranium deposits in the state are in sandstone within the Morrison Formation (Jurassic) in the Grants and Shiprock uranium districts, San Juan Basin. More than 340 million lbs of U_3O_8 were produced from these uranium deposits from 1948 through 2001, accounting for 97% of the total uranium production in New Mexico and more than 37% of the total uranium production in the United States. Conventional mining ceased in 1988. From 1989 to 2002, only one company in New Mexico, Quivira Mining Co., owned by BHP-Billiton (successor to Kerr-McGee Corp.), produced uranium from waters recovered from inactive underground operations at Ambrosia Lake, Grants district (mine-water recovery). The Quivira mines and mill are closed and scheduled for reclamation by 2006. Rio Grande Resources Co. is maintaining the closed facilities at the flooded Mt. Taylor underground mine in Cibola County. In late 1997, Anaconda Uranium acquired the La Jara Mesa uranium deposit in Cibola County from Homestake Mining Co. Hydro Resources, Inc. has put its plans to mine uranium at Church Rock and Crownpoint by in-situ leaching on hold until the price of uranium increases. Future development of these reserves and resources will depend upon an increase in the price of uranium and in the lowering of production costs, perhaps by the use of in-situ leaching techniques.

INTRODUCTION

Uranium is a hard, dense, metallic silver-gray, naturally occurring heavy element with an atomic number of 92 and an atomic weight of 238.02891 (Web Elements, 2001). It is ductile, malleable, and a poor conductor of electricity. Uranium was discovered in 1789 by Martin Klaproth in Germany and was named after the planet Uranus. There are three naturally occurring radioactive isotopes (^{234}U, ^{235}U, and ^{238}U); ^{238}U is the most abundant. The fissionable isotope ^{235}U is used in nuclear reactors.

Most of the uranium produced in the world is used in nuclear power plants to generate electricity (Finch, 1997). A minor amount of uranium also is used in a variety of additional applications, including components in nuclear weapons, as X-ray targets for production of high-energy X-rays, photographic toner, inertial guidance devices, in gyrocompasses, and in analytical chemistry applications. Depleted uranium is used in metal form in yacht keels, as counterweights in aircraft, armor piercing ammunition, and as radiation shielding, because it is 1.7 times denser than lead. Uranium also provided pleasing yellow and green colors in colored glassware and ceramics in the early 1900s.

Nuclear power is important to New Mexico and the United States. Nuclear power plants operate in basically the same way that fossil-fuel-fired plants do, with one major exception: nuclear energy supplies the source of the heat required to make steam that generates electricity in the power plant. Processing of uranium for nuclear power plants is more complex than processing coal for power plants (Finch, 1997). Nuclear power plants account for 19.8% of all electricity generated in the United States in 2000 (Table 1). This generated electricity comes from 66 nuclear power plants composed of 104 commercial nuclear reactors that are licensed to operate in the United States in 2002. Although New Mexico does not generate electricity from nuclear power in the state, the Public Service Co. of New Mexico (PNM) owns 10.2% of the Palo Verde nuclear power plant in Maricopa County, Arizona (Energy Information Administration, 2001). PNM sells the generated electricity from Palo Verde to its customers in New Mexico.

Throughout a period of nearly three decades (1951-1980), the Grants district in northwestern New Mexico (Fig. 1) yielded more uranium than any other district in the United States (Table 2). The Grants uranium district is a large area in the San Juan Basin, extending from east of Laguna to west of Gallup, and consists

TABLE 1. Net generation and industry capability of electricity generated by fuel in the United States in 2000 (From Energy Information Administration, 2001).

Electricity Fuel Source	Net generation by fuel source (billion kilowatt hours)	Net generation by fuel source (%)	Industry capability by fuel source (megawatts)	Industry capability by fuel source (%)	Fuel costs (Dollars per million Btu)
Coal	1,968	51.8	315,249	38.9	1.2
Petroleum	109	2.9	39,253	4.8	4.45
Gas	612	16.1	97,632	12.1	4.3
Nuclear	754	19.8	97,557	12.0	
Hydroelectric	273	7.2	99,068	12.2	
Other (geothermal, wind, multifuel, biomass, etc.)	84	2.2	162,866	20.0	
Total industry	3,800	100	811,625	100	

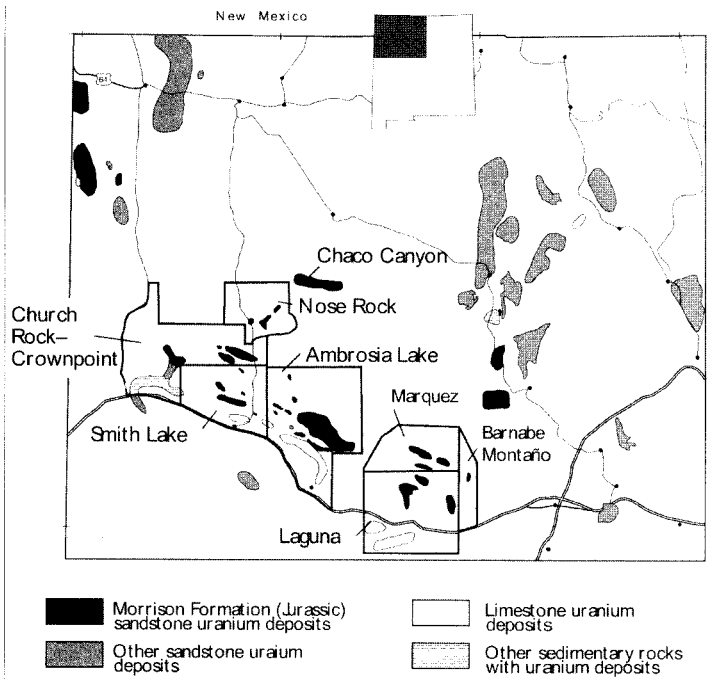

FIGURE 1. Uranium in the San Juan Basin, New Mexico (from McLemore and Chenoweth, 1989; McLemore, 2002).

of eight subdistricts (Fig. 1; McLemore and Chenoweth, 1989). The Grants district is probably fourth in total world production behind East Germany, the Athabasca Basin in Canada, and South Africa (Tom Pool, General Atomics, Denver, Colorado, personal commun., 2002). However, as of spring 2003, all of the conventional underground and open-pit mines in New Mexico have closed because of a decline in demand and price. The only recent production of uranium in New Mexico has been by mine-water recovery at Ambrosia Lake (Fig. 1). However, several companies are currently exploring for uranium in sandstone in the Grants district for possible production by in-situ leaching.

The purpose of this report is to briefly describe the general types of uranium deposits (Tables 3, 4) and their production, geology, resources, and future potential in New Mexico. Much of this report is summarized from McLemore (1983), McLemore and Chenoweth (1989), McLemore et al. (2002), and other reports as cited. This report also presents an update of the uranium industry in New Mexico since 1989. Information on specific mines and deposits in New Mexico can be found in cited references, McLemore (1983), and McLemore et al. (2002).

MINING AND MILLING HISTORY AND PRODUCTION

Interest in uranium as a commodity began in the early 1900s, and several deposits in New Mexico were discovered and mined for radium. Radium was produced from the White Signal district in Grant County (Gillerman, 1964) and the Scholle district in Torrance, Socorro, and Valencia Counties (McLemore, 1983). Exact production figures are unknown, but were probably very small.

John Wade, of Sweetwater, Arizona, made the first discovery of uranium and vanadium minerals in the San Juan Basin in the Carrizo Mountains about 1918 (Fig. 1; Chenoweth, 1993, 1997). At that time, the Navajo Reservation was closed to prospecting and mining, but on June 30, 1919, a Congressional Act opened the reservation to prospecting and locating mining claims in the same manner as prescribed by the Federal mining law. The locator of the claim could then lease the claim under contract with the Office of Indian Affairs. By 1920, Wade, operating as the Carriso Uranium Co., had located 40 claims in the eastern Carrizo Mountains, near Milepost 16. The area remained inactive from 1927 to 1942, at which time the Vanadium Corporation of America (VCA) was the highest bidder on a 104 sq mi exploration lease for vanadium in the east Carrizo Mountains. The lease, known as the East Reservation Lease (no. I-149-IND-5705), was subsequently reduced to 12 plots or claims. When production began, ore from the East Reservation Lease was shipped to Monticello, Utah, where VCA operated the mill for the Metals Reserve Co. Uranium in the vanadium ore was secretly recovered for the Manhattan Project from 1943 to 1945 via a uranium circuit at the Monticello mill. The total amount of recovered uranium is estimated as 44,000 lbs U_3O_8, mostly from King Tutt Mesa (Chenoweth, 1985b).

The U. S. Atomic Energy Commission (AEC) was created in 1947, and soon after, the VCA began exploring their East Reservation Lease for uranium. This led to the first uranium ore shipments in March 1948. Mining ceased in the east Carrizo Mountains in 1967.

From 1948 through 1966, the AEC purchased all of the uranium concentrate produced in New Mexico. During the last few years of the AEC program (1967-1970), the AEC allowed mill operators to sell uranium to electric utilities. In New Mexico this amounted to over 17 million pounds of U_3O_8 (USAEC unpublished records). The price schedules, bonuses, and other incentives offered by the AEC created a prospecting boom that spread across the Four Corners area to all parts of New Mexico. Discoveries were made in the Chuska Mountains near Sanostee and in the Todilto Limestone near Grants. The announcement in 1950 of the discovery of uranium in the Todilto Limestone at Haystack Butte by Paddy Martinez brought uranium prospectors to the Grants area. It was Lewis Lothman's discovery in March 1955 at Ambrosia Lake that created the uranium boom in the area. These discoveries led to a significant exploration effort in the San Juan Basin between Laguna and Gallup and ultimately led to the development of the Grants uranium district. Production from the Todilto Limestone deposits began in 1950, with a shipment of ore to the AEC ore-buying station at Monticello, Utah. Mills were soon built and operated in the San Juan Basin of New Mexico (Table 5).

The Anaconda Bluewater mill was built in 1953 at Bluewater, west of Grants, to process ores from the Jackpile mine; the mill closed in 1982 (Table 5). ARCO Coal Company (formerly Anaconda) completed encapsulation of the tailings in 1995 and the U. S. Department of Energy (DOE) monitors the site as part of the Long-Term Surveillance and Maintenance (LTSM) program.

The Homestake mill, 5.5 mi north of Milan, actually consisted of two mills. The southern mill, built in 1957, was known as the Homestake-New Mexico Partners mill and was closed in 1962 (Chenoweth, 1989b; McLemore, this guidebook). The Homestake-Sapin Partners, a partnership between Homestake and

TABLE 2. Uranium production by type of deposit from the San Juan Basin, New Mexico 1947-2001 (McLemore and Chenoweth, 1989; production from 1988 to 2001 estimated by the senior author). Type of deposit refers to Table 3. Total U.S. production from McLemore and Chenoweth (1989) and Energy Information Administration (2002). [1] approximate figures rounded to the nearest 1000 pounds.

Type of deposit	Production (pounds U_3O_8)	Period of production (years)	Production per total in New Mexico (%)
Primary, redistributed, remnant sandstone uranium deposits (Morrison Formation, Grants district)	330,453,000 [1]	1951-1988	95.4
Mine-water recovery	9,617,869	1963-2001	2.4
Tabular sandstone uranium deposits (Morrison Formation, Shiprock district)	493,510	1948-1982	0.1
Other Morrison sandstone uranium deposits	991	1955-1959	—
Other sandstone uranium deposits	503,279	1952-1970	0.1
Limestone uranium deposits (Todilto Formation)	6,671,798	1950-1985	1.9
Other sedimentary rocks with uranium deposits	34,889	1952-1970	—
Vein-type uranium deposits	226,162	1953-1966	—
Igneous and metamorphic rocks with uranium deposits	69	1954-1956	—
Total in New Mexico	348,001,000[1]	1948-2001	100
Total in United States	925,517,000[1]	1947-2001	37.6 of total U.S.

TABLE 3. Classification of uranium deposits in New Mexico (modified from McLemore and Chenoweth, 1989; McLemore, 2001). Deposit types in bold are found in the San Juan basin.

I. Peneconcordant uranium deposits in sedimentary host rocks

- **A.** **Morrison Formation (Jurassic) sandstone uranium deposits**
  - **Primary, tabular sandstone uranium-humate deposits in the Morrison Formation**
  - **Redistributed sandstone uranium deposits in the Morrison Formation**
  - **Remnant sandstone uranium deposits in the Morrison Formation**
  - **Tabular sandstone uranium-vanadium deposits in the Salt Wash and Recapture Members of the Morrison Formation**
- **B.** **Other sandstone uranium deposits**
  - **Redistributed uranium deposits in the Dakota Sandstone (Cretaceous)**
  - **Roll-front sandstone uranium deposits in Cretaceous and Tertiary sandstones**
  - **Sedimentary uranium deposits**
  - **Sedimentary-copper deposits**
  - **Beach placer, thorium-rich sandstone uranium deposits**
- **C.** **Limestone uranium deposits**
  - **Limestone uranium deposits in the Todilto Formation (Jurassic)**
  - Other limestone deposits
- **D.** **Other sedimentary rocks with uranium deposits**
  - **Carbonaceous shale and lignite uranium deposits**
  - Surficial uranium deposits

II. Fracture-controlled uranium deposits

- **E.** **Vein-type uranium deposits**
  - Copper-silver (uranium) veins (formerly Jeter-type, low-temperature vein-type uranium deposits and La Bajada, low-temperature uranium-base metal vein-type uranium deposits)
  - **Collapse-breccia pipes (including clastic plugs)**
  - Volcanic epithermal veins
  - Laramide veins

III. Disseminated uranium deposits in igneous and metamorphic rocks

- **F.** **Igneous and metamorphic rocks with disseminated uranium deposits**
  - Pegmatites
  - Alkaline rocks
  - Granitic rocks
  - Carbonatites
  - Miscellaneous

TABLE 4. Uranium production and types of deposits by district or subdistrict in the San Juan Basin, New Mexico (McLemore and Chenoweth, 1989, production from 1988 to 2001 estimated by the senior author). Districts have reported occurrences of uranium or thorium (>0.005% U_3O_8 or > 100 ppm Th). Some district names have been changed from McLemore and Chenoweth (1989) to conform to McLemore (2001). District number refers to number on map and Table 3 in McLemore and Chenoweth (1989). See McLemore (1983), McLemore and Chenoweth (1989, table 3), and McLemore et al. (2002) for more details and locations of additional minor uranium occurrences. Types of deposits defined in Table 3.

DISTRICT	PRODUCTION (lbs U3O8)	GRADE (U3O8%)	PERIOD OF PRODUCTION	TYPES OF DEPOSITS
Grants district				
1. Laguna	>100,600,000	0.1-1.3	1951-1983	A, C, E
2. Marquez	28,000	0.1-0.2	1979-1980	A
3. Bernabe Montaño	None			A
4. Ambrosia Lake	>211,200,00	0.1-0.5	1950-2001	A, B, C, E
5. Smith Lake	>13,000,000	0.2	1951-1985	A, C
6. Church Rock-Crownpoint	>16,400,000	0.1-0.2	1952-1986	A, B
7. Nose Rock	None			A
8. Chaco Canyon	None			A
Shiprock district				
9. Carrizo Mountains	159,850	0.23	1948-1967	A
10. Chuska	333,685	0.12	1952-1982	A, C, B
11. Tocito Dome	None			A
12. Toadlena	None			B
Other areas and districts				
13. Zuni Mountains	None			B, E, F
14. Boyd prospect	74	0.05	1955	B
15. Farmington	3	0.02	1954	B
18. Chama Canyon	None			B
19. Gallina	19	0.04	1954-1956	B
20. Eastern San Juan Basin	None			B
21. Mesa Portales	None			B
22. Dennison Bunn	None			A
23. La Ventana	290	0.63	1954-1957	D
24. Collins-Warm Springs	989	0.12	1957-1959	A
25. Ojito Spring	None			A
26. Coyote	182	0.06	1954-1957	B, C
27. Nacimiento	None			B
28. Jemez Springs	None			B

Sabre Pinon Corp., built a second, larger mill in 1957 north of the first facility. In 1962 United Nuclear Corp. merged with Sabre Pinon Corp., but maintained the United Nuclear Corp. name. United Nuclear Corp. became a limited partner with Homestake, forming the United Nuclear-Homestake partnership, and continued to operate the mill. In March 1981 the United Nuclear-Homestake Partnership was dissolved and Homestake became the sole owner. The Homestake mill ceased production in 1981, but reopened in 1988 to process ore from the Section 23 mine and Chevron's Mount Taylor mine. The mill closed soon afterward and was decommissioned and demolished in 1990. In 2001, Homestake Corp. merged with Barrick Gold Corp. Homestake completed reclamation drilling in January 2002 and plans to complete the reclamation of the Homestake mill at Milan in 2004.

Kerr-McGee Oil Industries, Inc. (Table 5) built the Shiprock (Navajo) mill at Shiprock in 1954. It processed ore from their mines in the Lukachukai Mountains in Arizona and from mines on the Navajo Indian Reservation that were not controlled by the Vanadium Corporation of America (VCA). It also processed ores from the Gallup and Poison Canyon areas in the Grants district. The mill was acquired by VCA in 1963 and closed in May 1968, one year after VCA merged into Foote Mineral Company. The DOE began cleanup of the site in 1968 as part of the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978. Cleanup was achieved in 1996 and the site turned over to the LTSM program of the DOE for monitoring.

TABLE 5. Uranium mills in New Mexico. Mine ID refers to Mine Identification Number and location in McLemore et al. (2002). From Energy Information Agency (2001, 2002) and U.S. Department of Energy files.

Mine ID	Mill Name	Mill owner	Year built	Year first operated	Year last operated	Maximum Milling Capacity (short tons of ore per day)	Amount of tailings (estimated in short tons)	Current status
NMCI0110	Homestake	Homestake Mining Co.	1957	1958	1990	3080	22.225 million	Decommissioned in 1993, reclamation nearly completed
NMMK0349	Ambrosia Lake (Kerr-McGee Corp., Rio Algom Mining)	Quivira Mining Co., subsidiary of BHP-Billiton	1957	1958	2002	6350	>30.4 million	Not currently producing, produced mine water recovery 1985-2002, tailings under reclamation
NMCI0109	Bluewater	ARCO (Anaconda)	1953	1953	1982	5440	24 million	Decommissioned, reclamation completed
NMMK0125	Church Rock	United Nuclear	1977	1977	1982	2720	3.5 million	Decommissioned in 1993
NMMK0353	Phillips (Ambrosia Lake)	Phillips Petroleum Company, United Nuclear Corp.	1958	1958	1963	1750	6.931 million	Decommissioned, reclamation completed under UMTRCA
NMMK0354	Marquez	Bokum Resources	1980	none	None	1820	none	Never operated, declared bankruptcy in 1981
NMSJ0115	Shiprock (Navajo)	Foote Mineral Co.	1954	1954	1968	500	2.52 million	Decommissioned, reclamation completed under UMTRCA in 1986
NMCI0108	L-Bar	Kennecott Energy Co. (formerly Sohio)	1976	1976	1981	1450	1.9 million	Decommissioned, to be transferred to LTSM program

Kermac Nuclear Fuels Corp., a partnership of Kerr-McGee Oil Industries, Inc., Anderson Development Corp., and Pacific Uranium Mines Co., built the Kerr-McGee mill at Ambrosia Lake in 1957-58. In 1983, Quivira Mining Co., a subsidiary of Kerr-McGee Corp. (later Rio Algom Mining LLC, currently BHP-Billiton) became the operator. The mill began operating in 1958, and since 1985 has produced uranium only from mine waters from underground mines at Ambrosia Lake. Quivira Mining Co. is no longer producing uranium and the Ambrosia Lake mill and mines will be reclaimed by 2006 (Energy, Minerals and Natural Resources Department, 2002).

Phillips Petroleum Co. also built a mill at Ambrosia Lake in 1957-58. Ore milled was from the Ann Lee, Sandstone, and Cliffside mines. Production began in 1958. United Nuclear Corp. acquired the property in 1963, when the mill closed. The DOE remediated the site between 1987 and 1995 as part of the UMTRCA of 1978. DOE monitors the site as part of the LTSM program.

Additional mills were built in the Laguna and Church Rock areas (Table 5).

Most of the uranium production in New Mexico has come from the Morrison Formation in the Grants uranium district in McKinley and Cibola (formerly Valencia) Counties, mainly from the Westwater Canyon Member in the San Juan Basin (Table 2; McLemore, 1983). Annual production in New Mexico increased steadily from 1948 to 1956, from 1957 to 1960, from 1965 to 1968, and from 1973 to 1979. Peak production was attained in 1978, with a record yearly production of 9,371 tons of U_3O_8 from ore that was shipped to mills and buying stations (McLemore, 1983; McLemore and Chenoweth, 1989).

TYPES OF URANIUM DEPOSITS IN THE SAN JUAN BASIN

The types of uranium deposits in New Mexico are summarized in Table 3; many of these types are found in the San Juan Basin. Sandstone uranium deposits in the Morrison Formation (Jurassic) represent the most important type of deposit in terms of production (Table 4) and resources (Tables 6, 7).

Sandstone Uranium Deposits in the Morrison Formation (Jurassic)

Sandstone uranium deposits account for the majority of the uranium production from New Mexico (McLemore and Chenoweth, 1989). The most significant deposits are those in the Morrison Formation, specifically the Westwater Canyon Member, where more than 340,565,370 lbs of U_3O_8 were produced from the Morrison from 1948 to 2001 (Table 2). In contrast, production from other sandstone uranium deposits in New Mexico amounts to 503,279 lbs of U_3O_8 (Table 2, 1952-1970; McLemore and Chenoweth, 1989). There are three types of deposits in the Westwater Canyon Member of the Morrison Formation: primary (trend or tabular), redistributed (stack), and remnant-primary sandstone uranium deposits (Fig. 2).

Primary sandstone-hosted uranium deposits, also known as prefault, trend, blanket, and black-band ores, are found as blanket-like, roughly parallel ore bodies along trends, mostly in sandstones of the Westwater Canyon Member. These deposits are characteristically less than 8 ft thick, average more than

TABLE 6. Estimated uranium resources for New Mexico. All of these resources are in sandstone uranium deposits in the Morrison Formation (Jurassic). Mine ID refers to Mine Identification Number in McLemore et al. (2002). Most deposits are delineated on maps by McLemore and Chenoweth (1991) and described in more detail by McLemore et al. (2002).

Mine ID	Mine name	Latitude N	Longitude W	Year of resource estimate	Quantity of ore (pounds)	Grade (U_3O_8%)	Reference
NMCI0019	J. J.	35.17546	107.3266	1981	13,900,000	0.16	
NMCI0020	La Jara Mesa	35.28014	107.7449	1983	8,000,000	0.25	
NMCI0027	Mount Taylor	35.33498	107.6356	1982	121,000,000	0.25	http://www.gat.com/riogrande/index.html(1/9/03)
NMMK0025	Canyon	35.65699	108.2069	1983	5,000,000	0.12	
NMMK0043	Dalton Pass	35.67849	108.2650	1983	5,000,000	0.12	
NMMK0044	Dalton Pass	35.68130	108.2783	1983	20,000,000	0.10	
NMMK0065	Fernandez-Main Ranch	35.34861	107.6646	1970	8,500,000	0.10	Holmquist (1970)
NMMK0087	Johnny M	35.36244	107.7222	1983	35,000,000	0.10	
NMMK0102	Mariano Lake	35.54708	108.2780	1983	35,000,000	0.24	
NMMK0103	Marquez Canyon	35.31919	107.3243	1983	10,700,000	0.112	
NMMK0104	Marquez Canyon	35.32425	107.3300	1983	6,800,000	0.10	
NMMK0111	Narrow Canyon	35.64484	108.2984	1983	6,900,000	0.12	
NMMK0112	NE Church Rock No. 1	35.66650	108.5027	1983	2,868,700	0.247	
NMMK0114	NE Church Rock No. 2	35.67663	108.5262	1979	15,000,000	0.19	Perkins (1979)
NMMK0115	NE Church Rock No. 3	35.69756	108.5487	1983	21,000,000	0.20	
NMMK0117	NE Church Rock	35.65841	108.5085	1969	15,000,000	0.15	Hazlett (1969)
NMMK0128	Church Rock (Section 8)	35.630313	108.55064	2002	6,529,000		Odell (2002), Pelizza and McCarn (2002, 2003a)
NMMK0034	Church Rock (Section 17)	35.622209	108.552728	2002	8,443,000		Odell (2002), Pelizza and McCarn (2002, 2003a)
NMMK0100, NMMK0101	Mancos	35.628936	108.580547	2002	4,164,000		Pelizza and McCarn (2002, 2003a)
NMMK0346, NMMK0036, NMMK0039	Crownpoint	35.684585	108.16769	2002	38,959,000	0.16	Odell (2002), Pelizza and McCarn (2002, 2003a)
NMMK0040	Crownpoint (Unit 1)	35.706678	108.22052	2002	27,000,000		Pelizza and McCarn (2002, 2003a)
NMMK0119	Nose Rock	35.88436	107.9916	1983	9,700,000	0.167	
NMMK0120	Nose Rock No. 1	35.83556	108.0553	1983	25,000,000	0.10	
NMMK0122	Nose Rock	35.83036	108.0641	1983	36,200,000	0.10	
NMMK0020	Borrego Pass	35.620119	107.943617	1983	15,000,000	0.15	Tom Pool (WC, 12/3/02)
NMMK0245	Section 32 (Melrich)	35.394462	107.708055		5,000,000	0.25	Tom Pool (WC, 12/3/02)
NMMK0338	Vanadium	35.33339	107.8563	1983	25,000,000	0.10	
NMMK0340	West Largo	35.52570	107.9215	1983	15,000,000	0.15	
NMMK0350	Nose Rock	35.84497	108.0501	1983	12,400,000	0.167	
NMSA0023	Bernabe	35.22761	107.0109	1971	15,000,000	0.10	
NMSA0057	Marquez Grant	35.30514	107.2908	1981	751,000	0.09	
NMCI0046	Saint Anthony	35.159088	107.306139	1982	8,000,000	0.10	Tom Pool (WC, 12/3/02)
NMCI0050	San Antonio Valley	35.256361	107.258444		3,500,000	0.10	Tom Pool (WC, 12/3/02)
NMMK0143	Roca Honda	35.363139	107.699611	Late 1980s	3,000,000	0.19	Tom Pool (WC, 12/3/02)

0.20% U_3O_8, and have sharp ore-to-waste boundaries. The largest deposit in the Grants uranium district contains more than 30 million lbs of U_3O_8.

Redistributed sandstone-hosted uranium deposits, also known as post-fault, stack, secondary, and roll-type ores, are younger than the primary sandstone-hosted uranium deposits. They are discordant, asymmetrical, irregularly shaped, characteristically more than 8 ft thick, have diffuse ore-to-waste contacts, and cut across sedimentary structures. The average deposit contains approximately 18.8 million lbs U_3O_8 with an average grade of 0.16%. Some redistributed uranium deposits are vertically stacked along faults (Fig. 2).

TABLE 7. Uranium reserves by forward-cost category by state, 2001 (Energy Information Administration, 2002). The DOE classifies uranium reserves into forward cost categories of $30 and $50 per pound. Forward costs are operating and capital costs (in current dollars) that are still to be incurred to produce uranium from estimated reserves. Modern regulatory costs yet to be incurred would have to be added.

STATE	$30 per pound			$50 per pound		
	ORE (million tons)	GRADE (% U_3O_8)	U_3O_8 (million pounds)	ORE (million tons)	GRADE (% U_3O_8)	U_3O_8 (million pounds)
New Mexico	15	0.279	84	102	0.167	341
Wyoming	42	0.130	108	239	0.077	368
Arizona, Colorado, Utah	7	0.288	41	42	0.138	115
Texas	4	0.079	7	19	0.064	24
Other	7	0.200	28	25	0.105	51
Total	75	0.179	268	426	0.106	899

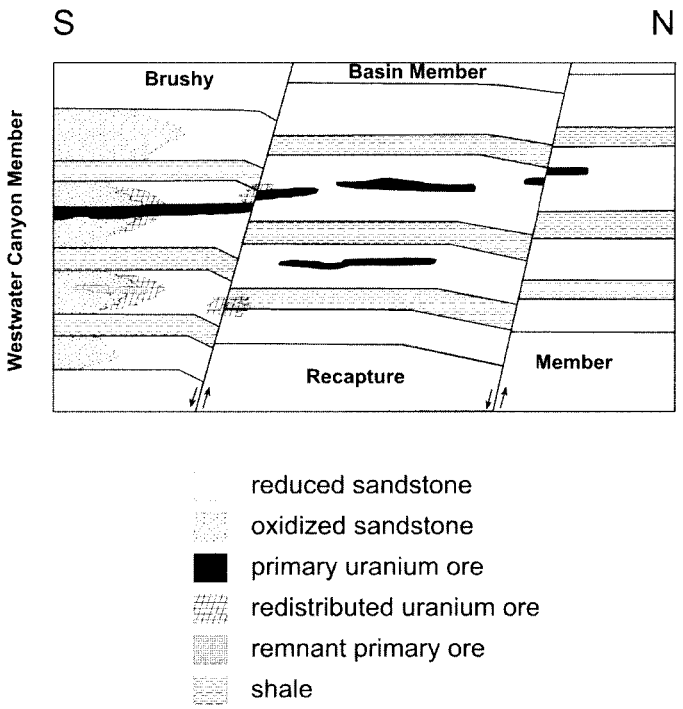

FIGURE 2. Schematic figure showing the relationship of primary, redistributed, and remnant primary sandstone uranium ore bodies in the Westwater Canyon Member of the Morrison Formation (modified from Turner-Peterson and Fishman, 1986).

Remnant sandstone-hosted uranium deposits were preserved in sandstone after the oxidizing waters that formed redistributed uranium deposits had passed. Some remnant sandstone-hosted uranium deposits were preserved because they were surrounded by or occurred in less permeable sandstone and could not be oxidized by the oxidizing ground waters. These deposits are similar to primary sandstone-hosted uranium deposits, but are difficult to locate because they occur sporadically within the oxidized sandstone. The average size is approximately 2.7 million lbs U_3O_8 at a grade of 0.20%.

There is no consensus on details of the origin of the Morrison primary sandstone uranium deposits (Sanford, 1992). The source of the uranium and vanadium is not well constrained. It could have been derived from alteration of volcanic detritus and shales within the Morrison Formation (Thamm et al., 1981; Adams and Saucier, 1981) or from ground water derived from a volcanic highland to the southwest. The majority of the proposed models for the formation of the deposits suggest that deposition occurred at a ground water interface between two fluids of different chemical compositions and/or oxidation-reduction states. Deposition involving two fluids was proposed many years ago during the early stages of exploration and production of uranium (Fischer, 1947; Shawe, 1956).

Subsequent models, such as the lacustrine-humate and brine-interface models, have refined or incorporated portions of these early theories. In the lacustrine-humate model, ground water was expelled by compaction from lacustrine muds formed in a large playa lake into the underlying fluvial sandstones, where humate or secondary organic material precipitated into tabular bodies as a result of flocculation. During or after precipitation of the humate bodies, uranium was precipitated from ground water (Turner-Peterson, 1985; Fishman and Turner-Peterson, 1986). This model proposes that the humate bodies were formed prior to uranium deposition.

In the brine-interface model, uranium and humate were deposited during diagenesis by reduction at the interface of meteoric fresh water and ground water brines (Granger and Santos, 1986). In another variation of the brine-interface model, ground water flow is driven by gravity, not compaction. Ground water flowed downdip and discharged in the vicinity of the uranium deposits. Uranium precipitated in the presence of humates at a gravitationally stable interface between relatively dilute, shallow meteoric water and saline brines that migrated updip from deeper in the basin (Sanford, 1982, 1992). Modeling of the regional groundwater flow in the Colorado Plateau during Late Jurassic and Early Cretaceous times supports the brine-interface model (Sanford, 1982). The ground-water flow was impeded by upthrown blocks of Precambrian crust and forced upwards. These zones of upwelling are closely associated with uranium-vanadium deposits throughout the Colorado Plateau (Sanford, 1982).

In the San Juan Basin area, the bleaching of the Morrison sandstones and the geometry of tabular uranium-vanadium bodies floating in sandstone beds supports the reaction of two chemically

different waters, most likely a dilute meteoric water and saline brine from deeper in the basin. The intimate association of uranium-vanadium minerals with organic material further indicates that they were deposited at the same time. Cementation and replacement of feldspar and quartz grains with uranium-vanadium minerals are consistent with deposition during early diagenesis.

During the Tertiary, after formation of the primary sandstone uranium deposits, oxidizing ground waters migrated through the uranium deposits and remobilized some of the primary sandstone uranium deposits (Saucier, 1981). Uranium was reprecipitated ahead of the oxidizing waters forming redistributed sandstone uranium deposits. Where the sandstone host surrounding the primary deposits was impermeable and the oxidizing waters could not dissolve the deposit, remnant-primary sandstone uranium deposits remain (Fig. 2).

Sandstone uranium deposits occur in other formations in New Mexico, but were insignificant compared to the Morrison deposits (McLemore and Chenoweth, 1989). Uranium reserves and resources remain in the Grants uranium district that could be mined in the future by conventional underground techniques and by in-situ leaching technologies (Table 6; Holen and Hatchell, 1986; McLemore and Chenoweth, 1991).

Tabular sandstone uranium-vanadium deposits in the Salt Wash and Recapture Members

Tabular sandstone uranium-vanadium deposits in the Salt Wash and Recapture Members of the Morrison Formation are restricted to the east Carrizo and Chuska Mountains subdistricts of the Shiprock district, western San Juan Basin, where production totals 493,510 lbs of U_3O_8 (Table 2). The Salt Wash Member is the basal member of the Morrison Formation and is overlain by the Brushy Basin Member (Anderson and Lucas, 1992, 1995; McLemore and Chenoweth, 1997). It unconformably overlies the Bluff-Summerville Formations. The latter units are known by those names in much of the stratigraphic literature (e.g., Anderson and Lucas, 1992), or as the Wanakah Formation as proposed by Condon and Peterson (1986). The Salt Wash Member consists of 190-220 ft of interbedded fluvial sandstones and floodplain mudstones, shales, and siltstones. The mudstone and siltstone comprise approximately 5-45% of the total thickness of the unit (Masters et al., 1955; Chenoweth, 1993).

The tabular uranium deposits are generally elongated parallel to paleostream channels and are associated with carbonized fossil plant material. A cluster of small ore bodies along a trend could contain as much as 4000 tons of ore averaging 0.23% U_3O_8 (Hilpert, 1969; Chenoweth and Learned, 1984; McLemore and Chenoweth, 1989, 1997). They tend to form subhorizontal clusters that are elongated and blanket-like. Ore bodies in the King Tutt Mesa area are small and irregular and only a few ore bodies have yielded more than 1000 lbs of U_3O_8. A typical ore body in the King Tutt Mesa area is 150-200 ft long, 50-75 ft wide, and approximately 5 ft thick (McLemore and Chenoweth, 1989, 1997). The deposits are typically concordant to bedding, although discordant lenses of uranium-vanadium minerals locally cut across bedding planes. The ore bodies typically float in the sandstone; infrequently, they occur at the interface between sandstone and less permeable shale or siltstone. However, unlike uranium deposits in the Grants district, the deposits at King Tutt Mesa are high in vanadium. The U:V ratio averages 1:10 and ranges 1:1 to 1:16.

The deposits are largely black to red, oxidized, and consist of tyuyamunite, meta-tyuyamunite, uranium/organic compounds, and a variety of vanadium minerals, including vanadium clay (Corey, 1958). Uranium and vanadium minerals are intimately associated with detrital organic material, such as leaves, branches, limbs, and trunks, derived from adjacent sandbar, swamp, and lake deposits, and with humates. Small, high-grade ore pods (>0.5% U_3O_8) were associated with fossil wood. The uranium-vanadium minerals form the matrix of the mineralized sandstones and locally replace detrital quartz and feldspar grains. Mineralized beds are associated with coarser-grained sandstone, are above calcite-cemented sandstone or mudstone-siltstone beds, are associated locally with mudstone galls, and are near green to gray mudstone lenses. Limonite is commonly associated with the ore bodies (Masters et al., 1955). Field and petrographic data suggest that the uranium-vanadium deposits formed shortly after deposition of the host sediments (Hilpert, 1969).

Modeling of the regional ground-water flow in the Colorado Plateau during Late Jurassic and Early Cretaceous times supports the brine-interface model and indicates that the regional ground-water flow was to the northeast in the King Tutt Mesa area (Sanford, 1982). In the King Tutt Mesa area, the bleaching of the sandstones and the geometry of tabular uranium-vanadium bodies floating in sandstone beds supports the reaction of two chemically different waters, most likely a dilute meteoric water and saline brine from deeper in the basin (McLemore and Chenoweth, 1997). The intimate association of uranium-vanadium minerals with organic material further indicates that they were deposited at the same time.

Other Sandstone Uranium Deposits

Redistributed uranium deposits in the Dakota Sandstone (Cretaceous)

A total of 501,169 lbs of U_3O_8 has been produced from redistributed uranium deposits in the Dakota Sandstone in the southern part of the San Juan Basin (Table 2; Chenoweth, 1989a). These deposits are similar to redistributed uranium deposits in the Morrison Formation and are found near primary and redistributed deposits in the Morrison Formation. Deposits in the Dakota Sandstone are typically tabular masses that range in size from thin pods a few feet long and wide to masses as much as 2500 ft long and 1000 ft wide. The larger deposits are only a few feet thick, but a few are as much as 25 ft thick (Hilpert, 1969). Ore grades ranged from 0.12 to 0.30% U_3O_8 and averaged 0.21% U_3O_8. Uranium is found with carbonaceous plant material near or at the base of channel sandstones or in carbonaceous shale and lignite and is associated with fractures, joints, or faults and with underlying permeable sandstone of the Brushy Basin or Westwater Canyon Members.

The largest deposits in the Dakota Sandstone are found in the Old Church Rock mine in the Church Rock subdistrict where uranium is associated with a major northeast-trending fault. More

than 188,000 lbs of U_3O_8 have been produced from the Dakota Sandstone in the Old Church Rock mine (Chenoweth, 1989a).

Roll-front sandstone uranium deposits

Roll-front sandstone uranium deposits are found in the Tesuque Formation (San Jose) and Ojo Alamo Sandstone (Farmington, Mesa Portales) areas of the San Juan Basin, where production totals 60 lbs of U_3O_8 (Table 2; McLemore and Chenoweth, 1989). Roll-front uranium deposits typically are found in permeable fluvial channel sandstones and are associated with carbonaceous material, clay galls, sandstone-shale interfaces, and pyrite at an oxidation-reduction interface (Nash et al., 1981). Although only a few minor and unverified uranium occurrences have been reported at Mesa Portales (McLemore, 1983), radiometric anomalies are detected by water, stream-sediment, and aerial-radiometric studies (Green et al., 1980a, b). Recent drilling at Mesa Portales indicated that low-grade uranium is found in blanket-like bodies in several horizons. The lack of a clear mineralization pattern may suggest that these deposits are modified roll-type or remnant ore bodies (Green et al., 1980a, b).

Sedimentary sandstone uranium deposits

Sedimentary sandstone uranium deposits are stratabound deposits associated with syngenetic organic material or iron oxides, or both, such as at the Boyd deposit. Uranium contents vary, but average grades of shipments from these deposits rarely exceeded 0.1% U_3O_8. These deposits tend to be small, containing only a few tons of ore, and the potential for future production is low.

Sedimentary-copper deposits

Stratabound, sedimentary-copper deposits containing Cu, Ag, and locally Au, Pb, Zn, U, V, and Mo are found throughout New Mexico. These deposits also have been called "red-bed" or "sandstone" copper deposits by previous workers (Soulé, 1956; Phillips, 1960; Cox and Singer, 1986). They typically occur in bleached gray, pink, green, or tan sandstones, siltstones, shales, and limestones within or marginal to typical thick red-bed sequences of red, brown, purple, or yellow sedimentary rocks deposited in fluvial, deltaic or marginal-marine environments of Pennsylvanian, Permian, or Triassic age (Fig. 1; Coyote, Gallina). The majority of sedimentary-copper deposits in New Mexico are found at or near the base of these sediments; some deposits such as those in the Zuni Mountains and Nacimiento districts (Fig. 3) are in sedimentary rocks that unconformably overlie mineralized Proterozoic granitic rocks. The mineralized bodies typically form as lenses or blankets of disseminated and/or fracture coatings of copper minerals, predominantly chalcopyrite, chalcocite, malachite, and azurite with minor to trace uranium minerals. Copper and uranium minerals in these sedimentary-copper deposits are commonly associated with organic debris and other carbonaceous material.

Beach placer, thorium-rich sandstone uranium deposits

Heavy mineral, beach-placer sandstone deposits are concentrations of heavy minerals that formed on beaches or in longshore bars in a marginal-marine environment (Fig. 4; Houston and Murphy, 1970, 1977). Many beach-placer sandstone deposits contain high concentrations of Th, REE (rare earth elements), Zr, Ti, Nb, Ta, and Fe; U is rare, but some deposits have yielded minor uranium production (McLemore, 1983). Detrital heavy minerals comprise approximately 50-60% of the sandstones and typically consist of titanite, zircon, magnetite, ilmenite, monazite, apatite, and allanite, among others. These deposits in New Mexico are found in Cretaceous rocks, mostly in the San Juan Basin, and are small (<3 ft thick), contain low tonnage, and are low in grade. They rarely exceed several hundred feet in length, are only tens of feet wide, and 3-5 ft thick. However, collectively, the known deposits in the San Juan Basin contain 4,741,200 tons of ore containing 12.8% TiO_2, 2.1% Zr, 15.5% Fe and less than 0.10% ThO_2 (Dow and Batty, 1961). The small size and difficulty in recovering economic minerals will continue to discourage development of these deposits in the future.

Limestone uranium deposits

Limestone uranium deposits in the Todilto Formation (Jurassic)

Uranium is found only in a few limestones in the world, but the deposits in the Jurassic Todilto Limestone are some of the largest and most productive (Chenoweth, 1985a; Gabelman and Boyer, 1988). Uranium minerals were found in the Todilto Limestone in the early 1920s, although it was the discovery by Paddy Martinez in 1950 that resulted in the development of the Grants district. From 1950 through 1981, mines in the Grants district yielded 6,671,798 lbs of U_3O_8 from the Todilto Limestone, amounting to approximately 2% of the total uranium produced from the Grants district (Table 2; Chenoweth, 1985a; McLemore and Chenoweth, 1989, 1991).

Limestone is typically an unfavorable host rock for uranium because of low permeability and porosity and lack of precipitation agents, such as organic material. However, a set of unusual geological circumstances allowed the formation of uranium deposits in the Todilto Limestone. The organic-rich limestones were deposited in a sabkha environment on top of the permeable Entrada Sandstone. The overlying sand dunes of the Summerville (or Wanakah) Formation locally deformed the Todilto muds, producing the intraformational folds in the limestone. Uraniferous waters derived from a highland to the southwest migrated through the Entrada Sandstone. Ground water migrated into the Todilto Limestone by evapotranspiration or evaporative pumping. Uranium precipitated in the presence of organic material within the intraformational folds and associated fractures in the limestone (Fig. 5; Rawson, 1981; Finch and McLemore, 1989). The Todilto uranium deposits are 150-155 Ma, based on U-Pb isotopic dating, and are older than the 130 Ma Morrison sandstone uranium deposits (Berglof, 1992).

More than 100 uranium mines and occurrences are found in the Todilto Limestone in New Mexico; 42 mines have documented uranium production (McLemore, 1983; McLemore and Chenoweth, 1989; McLemore et al., 2002). Most of these are in the Grants uranium district, although minor occurrences are found in the Chama Basin (Abiquiu, Box Canyon), Nacimiento district, and Sanostee in the Chuska subdistrict of the Shiprock district. Minor mineralization extends into the underlying Entrada Sandstone or overlying Summerville Formation in some areas. Uranium is found in the Todilto Limestone only where

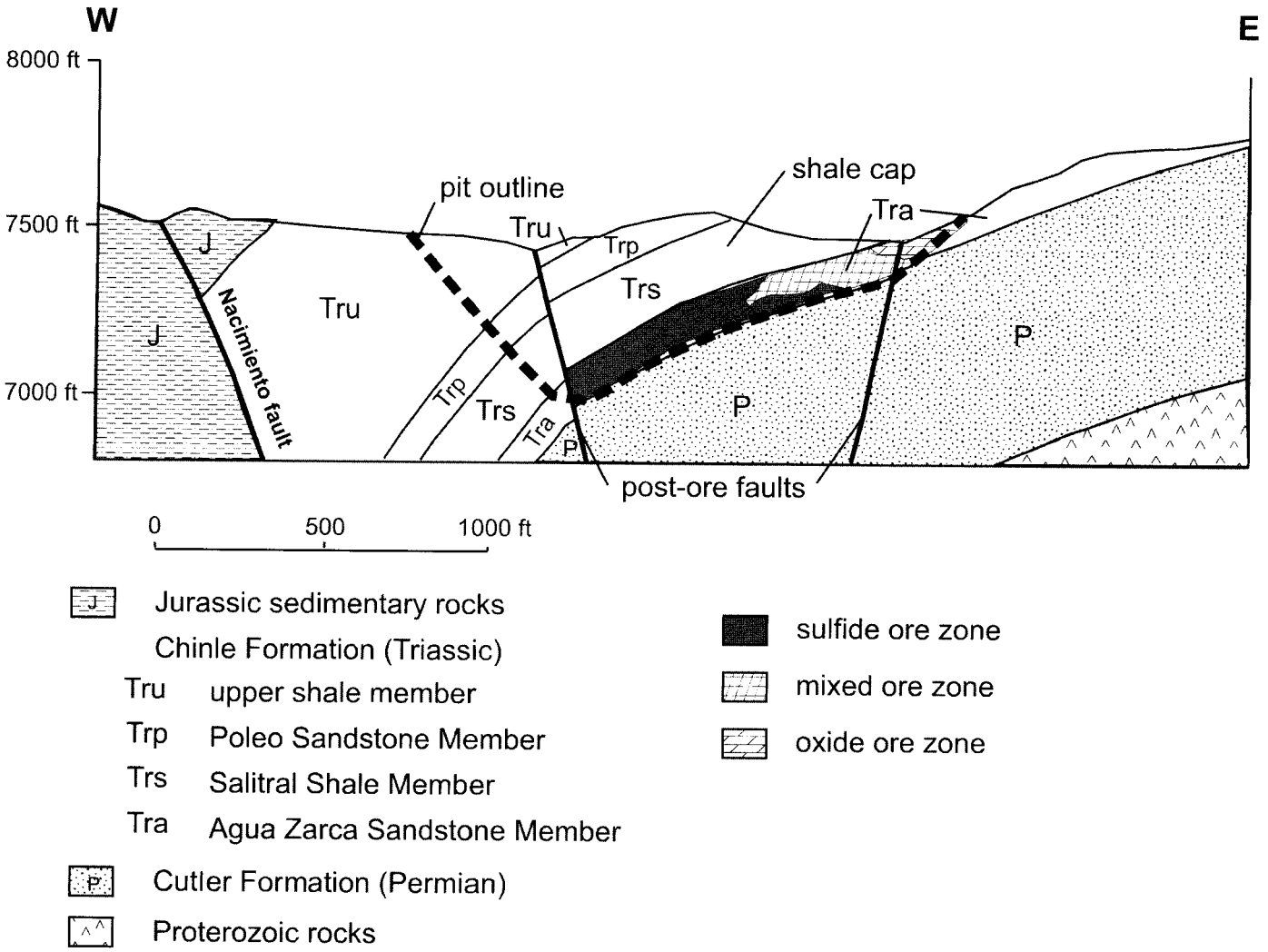

FIGURE 3. Cross section through Nacimiento open pit mine exposing a sedimentary copper deposit (modified from Talbot, 1974).

gypsum-anhydrite beds, overlying the limestone in other areas, are absent (Hilpert, 1969).

Other Sedimentary Rocks with Uranium Deposits

Carbonaceous shale and lignite uranium deposits

Some uranium has been produced from shale and lignite in the Dakota Sandstone in the Grants uranium district. Concentrations as high as 0.62% U_3O_8 may be found in coal, whereas the coal ash has uranium concentrations as high as 1.34% U_3O_8 (Bachman et al., 1959; Vine et al., 1953). Mineralized zones are thin and range in thickness from a few inches to 1.5 ft. Most of these occurrences are isolated, small, and low grade, and do not have any significant uranium potential.

Vein-type Uranium Deposits

Collapse-breccia pipe and clastic plug deposits

Uraniferous collapse-breccia pipe deposits were mined in northern Arizona for uranium beginning in 1951 and continuing into the 1980s; average production grades of 0.5-0.7% U_3O_8 were common. Similar deposits are found in the Grants uranium district. Uraniferous collapse-breccia pipes are vertical or steeply dipping cylindrical features bounded by ring fractures and faults and filled with a heterogeneous mixture of brecciated country rocks containing uranium minerals. The pipes were probably formed by solution collapse of underlying limestone or evaporites (Hilpert and Moench, 1960; McLemore, 1983; Wenrich, 1985).

More than 600 breccia pipes are found in the Ambrosia and Laguna subdistricts, but only a few are uranium bearing (Hilpert, 1969; Nash, 1968; Moench, 1962). Pipe structures in the Cliffside (Clark and Havenstrite, 1963), Doris (Granger and Santos, 1963), and Jackpile-Paguate mines (Hilpert and Moench, 1960) have yielded ore in conjunction with mining of adjacent sandstone deposits; the exact tonnage attributed to these breccia pipes is not known. Very little brecciation has occurred at the Cliffside and Doris pipes; however, these pipes appear to be related to other breccia pipes in the area. The Woodrow deposit is the largest uranium producer from a breccia pipe in New Mexico (McLemore, 1983) and is 24 to 34 ft in diameter and at least 300 ft in depth.

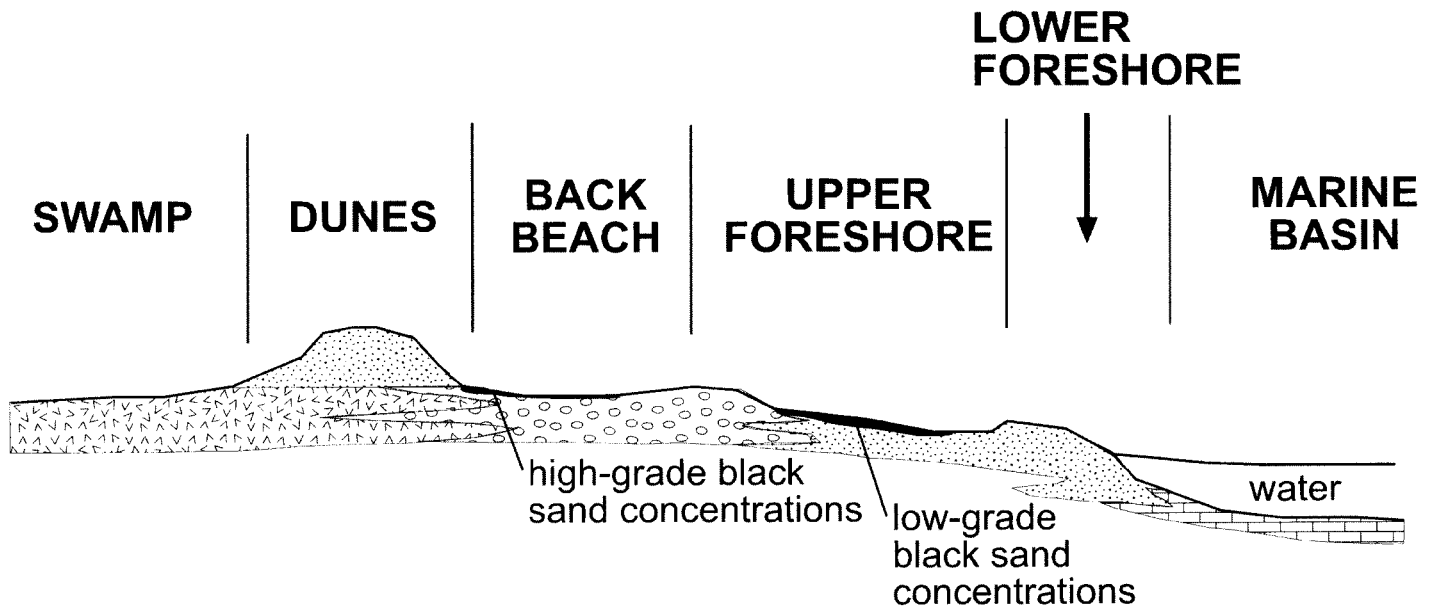

FIGURE 4. Idealized cross section of formation of beach placer sandstone deposits (modified from Houston and Murphy, 1970).

In Arizona, the mineralized Orphan Lode breccia pipe is 150 to 500 ft in diameter and at least 1500 ft in depth (Gornitz and Kerr, 1970). More than 134,000 lbs of U_3O_8 at a grade of 1.26% U_3O_8 were produced from the Woodrow deposit. However, the New Mexico uraniferous collapse-breccia pipes are uncommon and much smaller in both size and grade than the Arizona uraniferous collapse-breccia pipes. Future mining potential of New Mexico breccia pipes is minimal.

FUTURE POTENTIAL

New Mexico ranks second in uranium reserves in the U. S., with an estimated 15 million tons of ore at 0.277% U_3O_8 (84 million lbs U_3O_8) at a forward cost of $30/lb (Tables 6, 7). The DOE classifies uranium reserves into forward cost categories of $30 and $50 U_3O_8 per pound. Forward costs are operating and capital costs (in current dollars) that are still to be incurred to produce uranium from estimated reserves. All of New Mexico's uranium reserves in 2003 are in the Morrison Formation in the San Juan Basin (Table 7).

Only one company in New Mexico, Quivira Mining Co. (successor to Kerr McGee Corp., owned by Rio Algom LLC), produced uranium from 1989 to 2002, from waters recovered from inactive underground operations at Ambrosia Lake (mine-water recovery). Quivira Mining Co. is no longer producing uranium and the Ambrosia Lake mill and mines will be reclaimed by 2006 (Energy, Minerals and Natural Resources Department, 2002). Any conventional mining of uranium in New Mexico will require construction of a new mill, or shipment of ore to the White Mesa mill in Blanding, Utah.

Rio Grande Resources Co. is maintaining the closed facilities at the flooded Mt. Taylor underground mine in Cibola County, where primary sandstone-hosted uranium deposits were mined as recently as 1989 (Table 6; http://www.gat.com/riogrande/index.html, accessed 1/9/03). In late 1997, Anaconda Uranium acquired the La Jara Mesa uranium deposit in Cibola County from Homestake Mining Co. This primary sandstone-hosted uranium deposit, discovered in the Morrison Formation in the late 1980s, contains approximately 8 million pounds of ore averaging 0.25% U_3O_8 (Table 6). It is above the water table and is not suited to current in-situ leaching technologies.

Hydro Resources, Inc. (subsidiary of Uranium Resources Inc.) has put its plans to mine uranium at Church Rock and Crownpoint by in-situ leaching on hold until the price of uranium increases. Hydro Resources, Inc. also leases properties at Crownpoint from New Mexico and Arizona Land Company LLC (formerly NZU). Production costs are estimated as $13.54 per pound of U_3O_8 (Pelizza and McCarn, 2002, 2003 a, b). Reserves at Church Rock (Section 8, 17) and Mancos mines are estimated as 19 million pounds of U_3O_8 (Table 6; Pelizza and McCarn, 2002, 2003 a, b). Hydro Resources, Inc. estimates production costs at Crownpoint to be $11.46-12.71 per pound U_3O_8 (Pelizza and McCarn, 2002, 2003 a, b). Hydro Resources, Inc. also owns the Santa Fe Railroad properties in the Ambrosia Lake subdistrict.

Future development of these reserves and resources will depend upon an increase in the price of uranium and the lowering of production costs, which are unlikely in the next few years. The potential for uranium production from New Mexico in the near future is dependent upon international demand for uranium, primarily for fuel for nuclear power plants. The demand for raw uranium is low for several reasons. The U.S. uranium stockpile is being sold. Modern regulatory costs will add to the cost of producing raw uranium in the U. S. There are no conventional mills remaining in New Mexico to process the ore, which adds to the cost of producing uranium in the state. Currently, nuclear weapons from the former U.S.S.R. and the U.S. are being converted into nuclear fuel for nuclear power plants, which has reduced

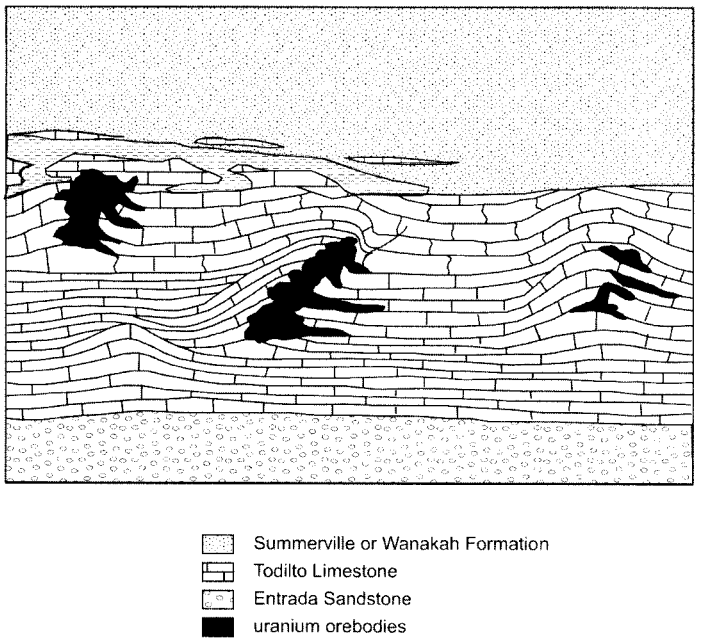

FIGURE 5. Control of Todilto uranium deposits by intraformational folds and fractures (modified from Finch and McLemore, 1989).

the demand for raw uranium (http://www.usec.com/v2001_02/HTML/megatons.asp, accessed February 10, 2003). In addition, high-grade, low-cost uranium deposits in Canada and Australia are sufficient to meet current international demands. Thus, it is unlikely that conventional underground mining of uranium in New Mexico will be profitable in the near future. However, in-situ leaching of the sandstone-hosted uranium deposits in the Grants district may begin in the future as the demand for and price of uranium increases in the decades to come.

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Dutton's (1885, fig. 12) woodcut photograph, described as "the Navajo Church near Fort Wingate. The rocks are the upper members of the Jura-Trias, and strongly cross-bedded."

Resource Estimates
Unmined Orebodies
(Including those on
the Rez.)

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