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URANIUM RESOURCES IN NEW MEXICO

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ABSTRACT

New Mexico ranks 2nd in uranium reserves in the U. S., which amounts to 15 million tons ore at 0.277% U_3O_8 (84 million lbs U_3O_8) at $30/lb (EIA, 2006). The most important deposit in the state is sandstone within the Morrison Formation (Jurassic) in the Grants district. More than 340 million pounds of U_3O_8 have been produced from these deposits from 1948-2002, accounting for 97% of the total production in New Mexico and more than 30% of the total production in the United States. Sandstone uranium deposits are defined as epigenetic concentrations of uranium in fluvial, lacustrine, and deltaic sandstones. Three types of sandstone uranium deposits are recognized: tabular (primary, trend, blanket, black-band), roll-front (redistributed, post-fault, secondary), and fault-related (redistributed, stack, post-fault). Several companies are planning to mine these deposits by in-situ leaching.

INTRODUCTION

During a period of nearly three decades (1951-1980), the Grants uranium district in northwestern New Mexico (Fig. 1) yielded more uranium than any other district in the United States (Table 1, see Appendix). Although there are no producing operations in the Grants district today, numerous companies have acquired uranium properties and plan to explore and develop deposits in the district in the near future. The Grants uranium district is one large area in the San Juan Basin, extending from east of Laguna to west of Gallup and consists of eight subdistricts (Fig. 1; McLemore and Chenoweth, 1989). The Grants district is probably 4th in total world production behind East Germany, Athabasca Basin in Canada, and South Africa (Tom Pool, General Atomics, Denver, Colorado, written communication, December 3, 2002). 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).

The purpose of this report is to briefly describe the general types of uranium deposits (Tables 2 and 3, see Appendix) and their production, geology, resources, and future potential in New Mexico. Much of this report is summarized from McLemore (1983), McLemore and Chenoweth (1989, 2003), McLemore et al. (2002), and other reports as cited. This report also presents an update of the uranium industry in New Mexico since 2003. 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 probably very small.

John Wade of Sweetwater, Arizona first discovered uranium and vanadium minerals in the Carrizo Mountains in the northwestern San Juan Basin 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 Corp. of America (VCA) was the highest bidder on a 104 sq mi exploration lease for vanadium in the east Carrizo Mountains. The lease was known as the East Reservation Lease (no. I-149-IND-5705) and 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 via a uranium circuit at the Monticello mill for the Manhattan Project in 1943-1945. The total amount of recovered uranium is estimated as 44,000 lbs U_3O_8, mostly from King Tutt Mesa (Chenoweth, 1985b).

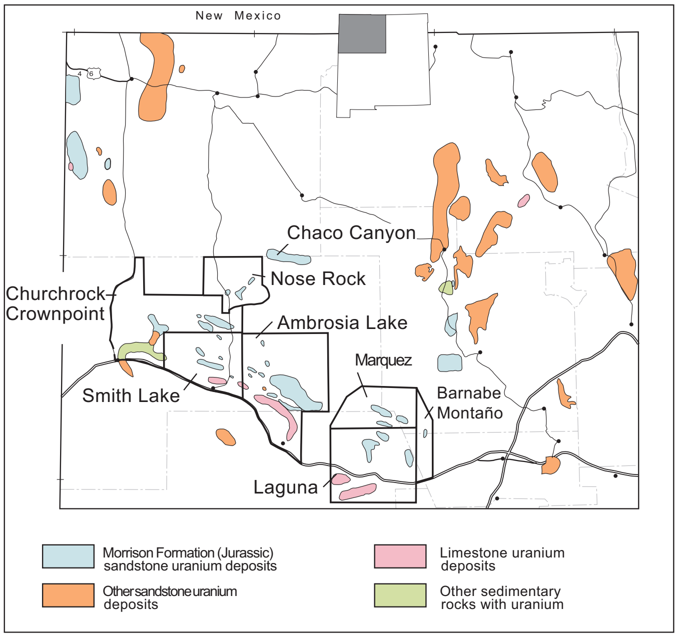


Figure 1. Grants uranium district, San Juan Basin, New Mexico. Polygons outline approximate areas of known uranium deposits.

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 of Paddy Martinez's discovery of uranium in the Todilto

Limestone at Haystack Butte in 1950 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 that 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.

The Anaconda Bluewater mill was built at Bluewater, west of Grants in 1953 to process ores from the Jackpile mine and closed in 1982. 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 Legacy Management program (formerly 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 and Chenoweth, 2003). The Homestake-Sapin Partners, a partnership between Homestake and Sabre Pinon Corp., in 1957 built a second, larger mill 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 the limited partner with Homestake forming the United Nuclear-Homestake partnership and continued operating 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 after and was decommissioned and demolished in 1990. In 2001, Homestake Corp. merged with Barrick Gold Corp. Homestake completed reclamation of the Homestake mill at Milan in 2004.

Kerr-McGee Oil Industries, Inc. built the Shiprock (Navajo) mill at Shiprock in 1954. It processed ore from their mines in the Lukachukai Mountains in Arizona and non-Vanadium Corporation of America (VCA) controlled mines on the Navajo Indian Reservation. 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 Legacy Management program of the DOE for monitoring.

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 from 1985-2002, the mill produced only from mine waters from the Ambrosia Lake underground mines. Quivira Mining Co. is no longer producing uranium and the Ambrosia Lake mill and mines will be reclaimed in 2007.

Phillips Petroleum Co. also built a mill at Ambrosia Lake in 1957-58. Ore 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 Legacy Management program.

Additional mills were built in the Laguna and Church Rock areas and are currently being reclaimed (McLemore and Chenoweth, 2003, table 5).

Annual uranium 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 that was shipped to mills and buying stations (McLemore, 1983; McLemore and Chenoweth, 1989, 2003).

All of the conventional underground and open-pit mines in New Mexico closed by 1989 for several reasons:

- The Three Mile Island incident resulted in finalizing a growing public perception in the U.S. that nuclear power was dangerous and costly, and, subsequently nuclear power plants became unpopular.
- There was an overproduction of uranium in the 1970s-early 1980s that led to large stockpiles of uranium. In addition, the dismantling of nuclear weapons by the U.S. and Russia also increased these stockpiles, reducing the need for mining uranium.
- At the same time, New Mexico uranium deposits in production were decreasing in grade by nearly half.
- The cost of mine and mill reclamation was increasing in cost and was not accounted for in original mine plans.
- Higher grade, more attractive uranium deposits were found elsewhere in the world.
- Large coal deposits were found throughout the U.S. that could meet the nation's energy needs.

Uranium was produced from 1966-2002 by mine-water recovery from underground mines by Quivira Mining Co., formerly Kerr McGee Corp. The decline in the price of uranium during 1989-2005 resulted in no uranium production (except mine water recovery), exploration, or development in the district. Many companies reclaimed and/or sold their properties. However, today with the recent increase in price and demand for uranium, numerous companies are acquiring new and old properties and exploring for uranium in the Grants district. The Grants district is once again an attractive area for uranium exploration, because:

- Major companies abandoned properties in the district after the last cycle leaving advanced uranium projects.
- Current property acquisition costs are inexpensive and include millions of dollars worth of exploration and development expenditures.
- Data and technical expertise on these properties are available.
- Recent advances in in-situ leaching technology allow for the Grants district sandstone uranium deposits to be economically attractive.

TYPES OF URANIUM DEPOSITS IN NEW MEXICO

The types of uranium deposits in New Mexico are summarized in Table 2, many of which are found in the Grants district. The most important type of deposit in terms of production (Table 3) and resources (Tables 4 and 5, see Appendix) is sandstone uranium deposits in the Morrison Formation (Jurassic).

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; 2003). The most significant deposits are those in the Morrison Formation, specifically the Westwater Canyon Member, where more than 340,565,370 pounds of U_3O_8 were produced from the Morrison from 1948 to 2002 (Table 2). In contrast, production from other sandstone uranium deposits in New Mexico amounts to 503,279 pounds 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, 3).

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 0.20% U_3O_8, and have sharp ore-to-waste boundaries (Fig. 2). The largest deposits in the Grants uranium district contain 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, 3).

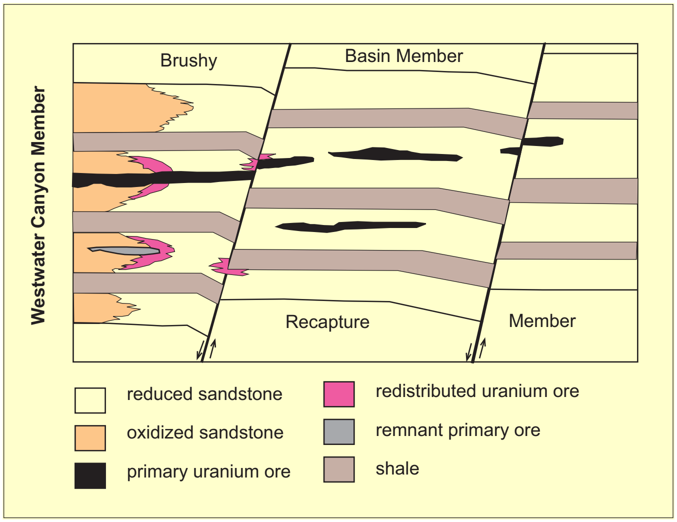
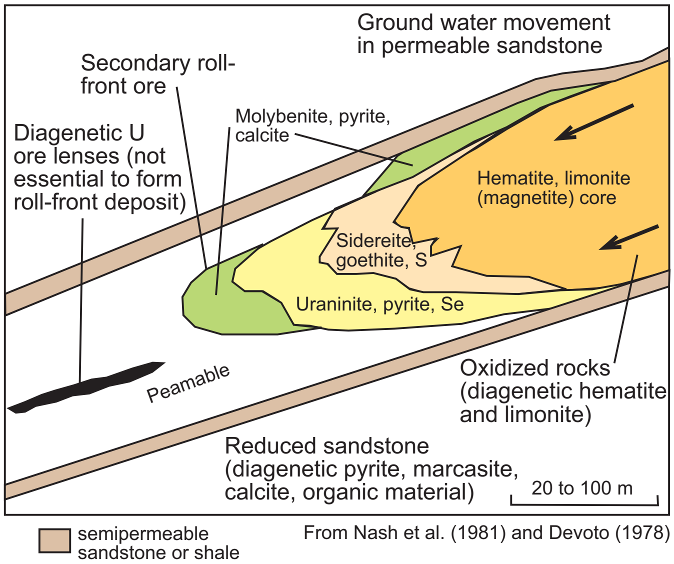


Figure 2. Sketch of the different types of uranium deposits in the Morrison Formation. See text for description.



From Nash et al. (1981) and Devoto (1978)

Figure 3. Sketch of the formation of redistributed sandstone uranium deposits. See text for description.

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 found 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 be 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 their formation 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 by a large playa lake into the underlying fluvial sandstones where humate or secondary organic material precipitated as a result of flocculation into tabular bodies. 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 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 down dip 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 up dip from deeper in the basin (Sanford, 1982, 1992). Modeling of the regional ground water 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 up-thrown 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 Grants district, 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, 3).

Sandstone uranium deposits occur in other formations in New Mexico, but were insignificant compared to the Morrison deposits (McLemore and Chenoweth, 1989); some companies are once again exploring in these units. 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, 2003).

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 (including the King Tutt Mesa area) and Chuska Mountains subdistricts of the Shiprock district, western San Juan Basin, where production totals 493,510 pounds 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 Formation, using older stratigraphic nomenclature (Anderson and Lucas, 1992), or 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 cross-cut bedding planes locally. The ore bodies typically float in the sandstone; locally, 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 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 suggests 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 pounds 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 of the Grants district, 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 Tesuque Formation (San Jose) and Ojo Alamo Sandstone (Farmington, Mesa Portales) areas of the San Juan Basin, where production totals 60 pounds 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). Past 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 suggests 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 syngenic organic material or iron oxides, or both, such as at the Boyd deposit near Farmington and in the Chinle Formation throughout northern New Mexico. 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 (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. 4), 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. 5; 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 only one deposit 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), low tonnage, and low grade. They rarely exceed for more than 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 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 Paddy Martinez's discovery in 1950 that resulted in 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).

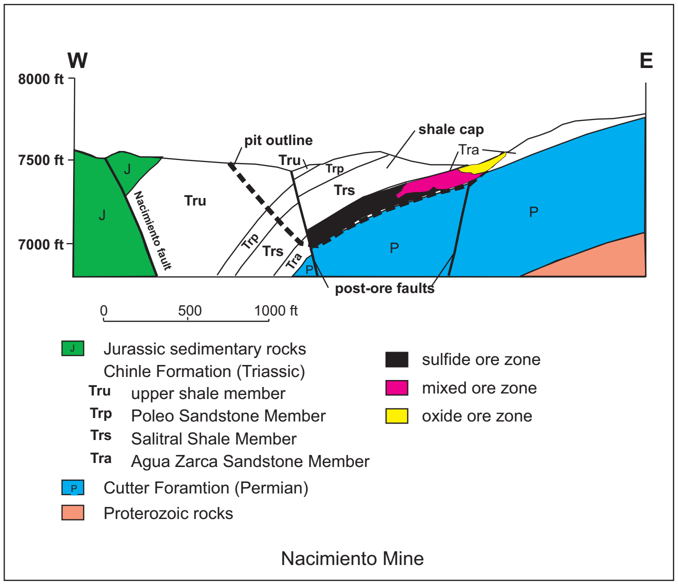


Figure 4. Cross section through Naciemento open pit mine exposing a sedimentary copper deposit (modified from Talbot, 1974).

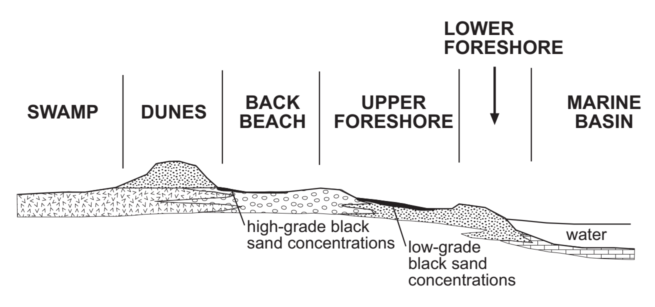


Figure 5. Idealized cross-section of formation of beach placer sandstone deposits (Houston and Murphy, 1970).

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. 6; 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, 1989).

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 gypsum-anhydrite beds are absent (Hilpert, 1969).

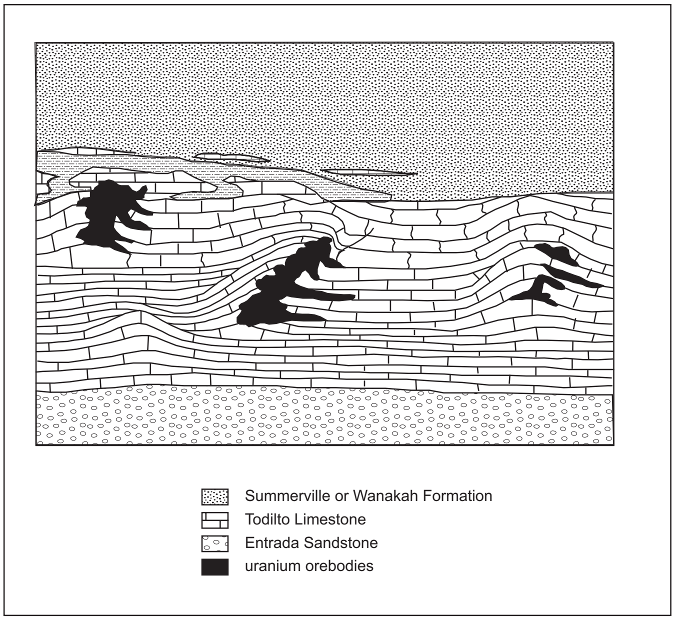


Figure 6. Control of Todilto uranium deposits by intraformational folds and fractures (modified from Finch and McLemore, 1989).

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 are 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 the1980s; 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 as part of mining 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 high. In Arizona, the mineralized Orphan Lode breccia-pipe is 150 to 500 ft in diameter and at least 1500 ft long (Gornitz and Kerr, 1970). More than 134,000 lbs of U_3O_8 at a grade of'1.26% U_3O_8 was 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.

Surficial uranium deposits

Ground-water anomalies and locally remote sensing data suggest that surficial or calcrete uranium deposits may exist in the Lordsburg Mesa area in southwestern New Mexico (Carlisle et al., 1978; Raines et al., 1985) and in the Ogalalla Formation in eastern New Mexico (Otton, 1984). However, mineralized zones high in uranium have not been found in these areas. Uranium minerals, typically carnotite, are found in voids and fractures within lenticular deposits of alluvium, soil, or detritus that have been cemented by carbonate forming calcretes (Nash et al., 1981).

FUTURE POTENTIAL

New Mexico ranks 2nd in uranium reserves in the U.S. (behind Wyoming), which amounts to 15 million tons ore at 0.28% U_3O_8 (84 million lbs U_3O_8) at a forward cost of $30/lb and 238 million tons of ore at 0.076% U_3O_8 at a forward cost of $50/lb (Table 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 2006 are in the Morrison Formation in the San Juan Basin (Table 7); although uranium exploration is occurring elsewhere in New Mexico.

Only one company in New Mexico, Quivira Mining Co. (successor to Kerr McGee Corp., owned now by BHP-Billiton Plc.), produced uranium in 1989-2002, 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 in 2007. Any conventional mining of uranium in New Mexico will require a new mill or the ore would have to be shipped 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 late as 1989 (Table 6). Reserves are estimated as 121 million pounds U_3O_8 at 0.25% U_3O_8, which includes 7.5 million pounds of U_3O_8 at 0.50% U_3O_8. Depths to ore average 3,300 ft.

The La Jara Mesa uranium deposit in Cibola County was originally owned by Homestake Mining Co and in 1997 was transferred to Anaconda and subsequently to Laramide Resources Ltd. 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. New Mexico Mining and Minerals Division has approved an exploration permit for Laramide Resources and a permit is pending for Urex Energy Corp., who also owns adjacent properties on Jara Mesa to Laramide. Laramide Resources also controls the nearby Melrich deposit (Table 6). Lakeview Ventures also acquired adjacent properties (press release, April 19, 2006).

Hydro Resources, Inc. (subsidiary of Uranium Resources Inc.) is waiting for final permit approvals and an increase in the price of uranium before mining uranium by in-situ leaching at Church Rock and Crownpoint. 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.

Strathmore Minerals Corp. has acquired numerous properties in the Grants district, including Roca Honda (33,300,000 pounds U_3O_8), Church Rock (15,300,000 pounds U_3O_8; Fitch, 2005), and Nose Rock. Strathmore hopes to mine uranium by both in situ leaching and conventional mining and milling. An exploration permit is pending for the Roca Honda deposit.

Quincy Energy Corp. merged with Energy Metals Corp in July 2006, and acquired properties in Crownpoint (section 24 contains 9.966 million pounds of U_3O_8 and sections 19 and 29 contains 13.672 million pounds of U_3O_8; Myers, 2006a, b) and Hosta Butte (14.822 million pounds of U_3O_8; Myers, 2006c). Quincy Energy Corp. is examining the uranium resource potential in northeastern New Mexico.

An exploration permit was approved by New Mexico Mining and Minerals Division for Western Energy Development to drill at the Treeline project, Ambrosia Lake subdistrict, McKinley County. An exploration permit is pending for Urex to explore for uranium on their properties in the Grants district.

Max Resources Corp. has filed for drilling permits for the C de Baca property in the Riley area, Socorro County, where Occidental Minerals in 1981-1982 identified 1.67 million tons of U_3O_8 grading 0.18% U_3O_8, found in sandstones of the Cretaceous Crevasse Canyon and Tertiary Baca Formations (press release June 8, 2006).

SUMMARY

Sandstone uranium deposits in New Mexico have played a major role in historical uranium production. Although other types of uranium deposits in the world are higher in grade and larger in tonnage, the Grants uranium district could soon become a significant source of uranium:

- As in situ leaching technologies improve, decreasing production costs.
- As demand for uranium increases world-wide, increasing the price of uranium.

However, several challenges need to be overcome by the companies before uranium could be produced once again from the Grants uranium district:

- There are no conventional mills remaining in New Mexico to process the ore, which adds to the cost of producing uranium in the state. New infrastructure will need to be built before conventional mining can resume.
- Permitting for new in situ leaching and especially for conventional mines and mills will possibly take years to complete.
- Closure plans, including reclamation must be developed before mining or leaching begins. Modern regulatory costs will add to the cost of producing uranium in the U.S.
- Some communities, especially the Navajo Nation communities, do not view development of uranium properties as favorable. The Navajo Nation has declared that no uranium production will occur on Navajo lands.
- High-grade, low-cost uranium deposits in Canada and Australia are sufficient to meet current international demands; but additional resources will be required to meet near-term future requirements.

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Appendix

Table 1. Uranium production by type of deposit from the San Juan Basin, New Mexico 1947-2002 (McLemore and Chenoweth, 1989, 2003; production from 1988-2002 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 (2006). [1] approximate figures rounded to the nearest 1000 pounds. There hasn't been any uranium production from New Mexico since 2002.

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	9,635,869	1963-2002	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	348,019,000[1]	1948-2002	100
Total in United States	927,917,000[1]	1947-2002	37.5 of total U.S.

Table 2. Classification of uranium deposits in New Mexico (modified from McLemore and Chenoweth, 1989; McLemore, 2001). Deposit types in bold are found in the Grants uranium district.

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

Appendix (cont'd)

Table 3. Uranium production and types of deposits by district or subdistrict in the San Juan Basin, New Mexico (McLemore and Chenoweth, 1989, production from 1988-2002 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 2.

DISTRICT	PRODUCTION (lbs U_3O_8)	GRADE (U_3O_8%)	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	>211,200,000	0.1-0.5	1950-2002	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

Appendix (cont'd)

Table 4. 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%)	Comments and Reference
NMCI0019	J. J.	35.17546	107.3266	1981	13,900,000	0.16	close out plan pending approval by state
NMCI0020	La Jara Mesa	35.28014	107.7449	1983	7,133,310	0.3	exploration permit approved
NMMK0245	Melrich (Section 32)	35.394462	107.7081		3,217,000	0.15	Laramide Resources
NMMK0210	Treeline (Section 24)	35.343556	107.7366		?	?	Western Energy Dev.
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	3,500,000	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	close out plan pending approval
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)

Appendix (cont'd)

Table 5. Uranium reserves by forward-cost category by state as of 2003 (Energy Information Administration, 2006). 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	0.28	84	102	0.167	341
Wyoming	41	0.129	106	238	0.076	363
Arizona, Colorado, Utah	8	0.281	45	45	0.138	123
Texas	4	0.077	6	18	0.063	23
Other	6	0.199	24	21	0.094	40
Total	74	0.178	265	424	0.105	890