Energy and Mineral Resources of New Mexico

Volume C

Uranium Resources

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Cover: Drilling in one of the United Nuclear-Homestake Partners mine, Ambrosia Lake subdistrict, Grants uranium district in 1978. *Photo by William Chenoweth.*

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PREFACE

Virginia T. McLemore, Ronald F. Broadhead, Gretchen K. Hoffman, and Fraser Goff

New Mexico is called the Land of Enchantment, in part because of the diverse geologic formations of the state, which give rise to spectacular landscapes of mountains, valleys, mesas, canyons, rivers, deserts and plains. Major cities are concentrated along the Rio Grande, including Albuquerque, Las Cruces, Rio Rancho, and Santa Fe, with smaller population centers in the southeast, eastern plains, and northwest, such as Roswell, Hobbs, Alamogordo, Carlsbad, Clovis, and Farmington (Fig. 1). New Mexico is the 5th largest state in terms of land area in the lower United States and contains five major physiographic provinces (Fig. 2): Great Plains, Basin and Range, Transition Zone, Colorado Plateau, and Southern Rocky Mountains. The rocks, which date back nearly two billion years, have undergone multiple major tectonic events that were accompanied by faulting and igneous activity (Figs. 3, 4). This rich geologic history has yielded a diversity of valuable energy and mineral deposits, which occur in all of the physiographic provinces in New Mexico, and in a variety of tectonic and geologic settings (Fig. 3). For more information on the geology of New Mexico, see Mack (1997), Mack and Giles (2004), and Price (2010). In addition, mining districts and prospect areas are shown and briefly described in McLemore (2017).

Rock collecting (or rock hounding), prospecting, and non-commercial gold panning are considered a casual use of public lands under most circumstances. **However, it is up to each individual to know the laws and land ownership.** For more information on mining claims and mineral leasing in New Mexico see McLemore (2017), BLM website (http://www.blm.gov/lr2000/), and New Mexico Mining and Minerals Division website (http://www.emnrd.state.nm.us/MMD/MARP/marpmainpage.html).

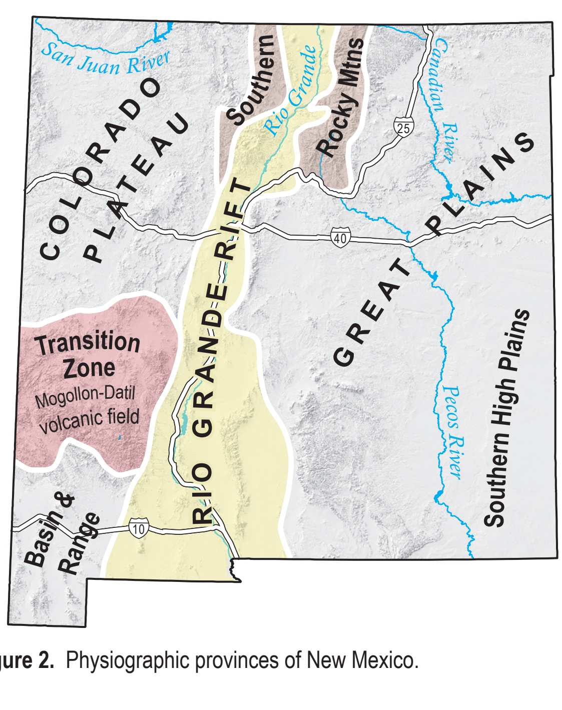
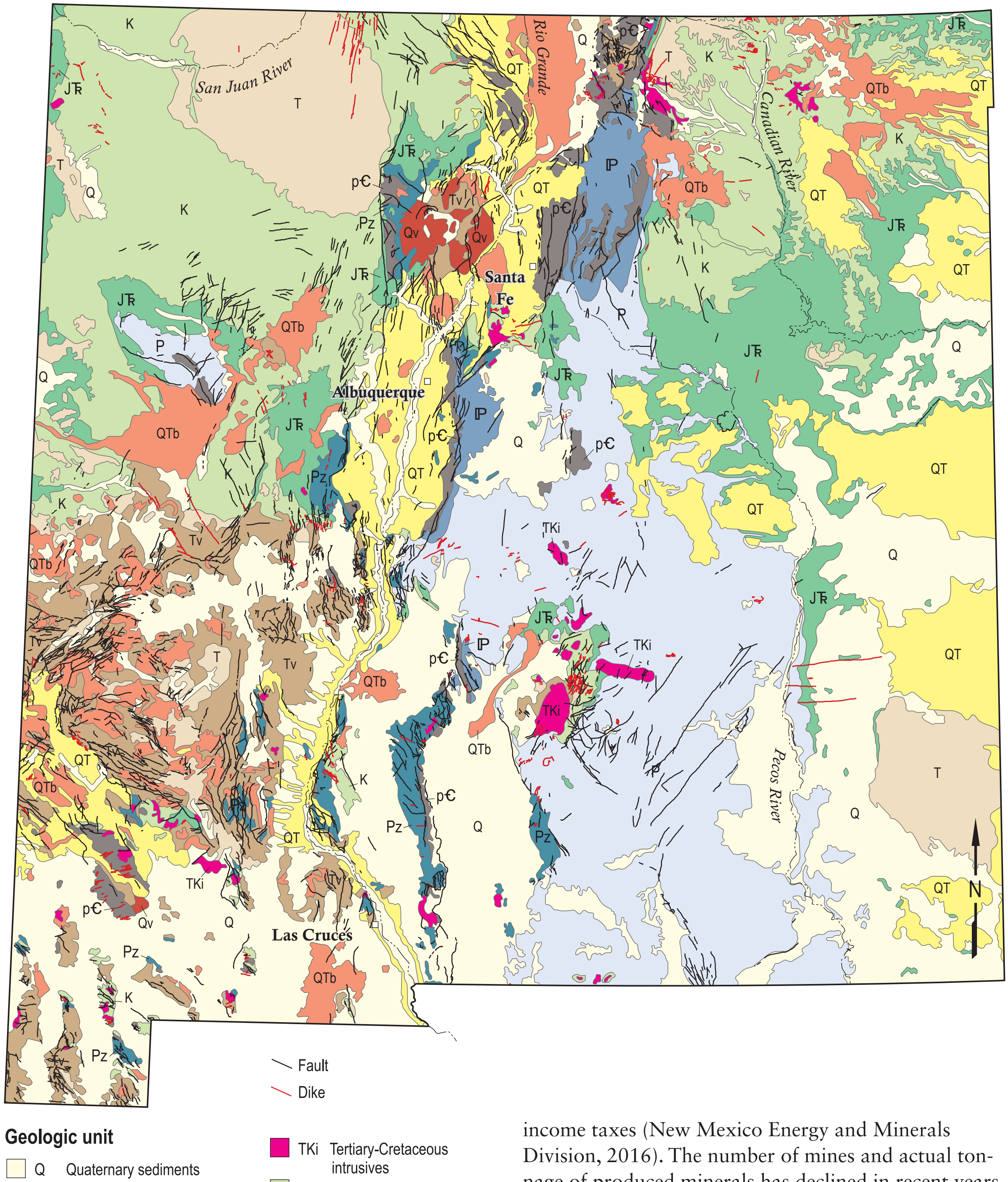


Figure 2. Physiographic provinces of New Mexico.

Importance of Energy and Minerals in New Mexico

New Mexico's mineral wealth is among the richest of any state in the United States. Oil and gas are the most important extractive industries in New Mexico in terms of production value (McLemore, 2017). In 2015, New Mexico ranked 6th in oil production, 8th in gas production, 12th in coal production, and 15th in non-fuel minerals production. Most of the state's mineral production comes from oil, gas, coal, copper, potash, industrial minerals and aggregates (Tables 1, 2). Other important commodities include a variety of industrial minerals (perlite, cement, zeolites, etc.), sulfuric acid, molybdenum, gold, uranium, and silver. New Mexico is fortunate to have geothermal resources in many locations. In December 2013, the Dale Burgett Geothermal Plant in the Animas Valley of southwest New Mexico started delivering up to 2 MW of electricity to the Public Service Company of New Mexico. Development of the Lightning Dock No. 2 project is underway with an additional 6 MW of generation planned.

A healthy energy and mineral industry is vitally important to the economy of New Mexico and to maintenance of public education and services (Table 2). The minerals industries provide property and corporate income taxes, while their ~35,000 direct employees contributed millions of dollars of personal



Geologic unit

- Q — Quaternary sediments
- QT — Quaternary - Tertiary sediments
- Qv — Quaternary rhyolites, tuffs
- QTb — Quaternary - Tertiary basalts, andesites
- T — Tertiary sediments
- Tv — Tertiary volcanics
- TKi — Tertiary-Cretaceous intrusives
- K — Cretaceous sediments
- JT̶R — Jurassic-Triassic
- P — Permian
- IP — Pennsylvanian
- Pz — Paleozoic undifferentiated
- p€ — Precambrian

Figure 3. Simplified geologic map of New Mexico.

income taxes (New Mexico Energy and Minerals Division, 2016). The number of mines and actual tonnage of produced minerals has declined in recent years (McLemore, 2017). This decline is a result of numerous complex and interrelated factors. Some of the more important factors include declining profits in mineral operations, decreased quality of ore (for example, lower grades and more difficult ore to process), competition from the global market, and a shift from coal-generated electricity to alternative energy sources.

Table 1. Estimated total production of major commodities in New Mexico, in order of estimated cumulative value (data from USGS, 1902–1927; USBM, 1927–1990; Kelley, 1949; Harrer, 1965; USGS, 1965; Howard, 1967; Harben et al., 2008; Energy Information Administration, 2015; New Mexico Energy, Minerals and Natural Resources Department, 1986–2016). Figures are subject to change as more data are obtained. Estimated cumulative value is in real, historic dollars at the time of production and is not adjusted for inflation.

Commodity	Years of production	Estimated quantity of production	Estimated cumulative value ($)
Natural Gas	1921–2015	>75 trillion cubic feet	$169 billion
Oil	1922–2015	>6.4 billion barrels	$119 billion
Coal	1882–2015	>1.46 billion short tons	>$21.7 billion
Copper	1804–2015	>11.7 million tons	>$21.6 billion
Potash	1951–2015	>113 million short tons	>$15.6 billion
Uranium	1948–2002	>347 million pounds	>$4.8 billion
Industrial minerals**	1997–2015	>41 million short tons	>$2.7 billion
Aggregates***	1951–2015	>674 short tons	>$2.6 billion
Molybdenum	1931–2013	>176 million pounds	>$852 million
Carbon dioxide	1931–2015	>3.3 trillion cubic feet	>$726 million
Gold	1948–2015	>3.3 million troy ounces	>$486 million
Zinc	1903–1991	>1.51 million tons	>$337 million
Silver	1848–2015	>119 million troy ounces	>$280 million
Lead	1883–1992	>367,000 tons	>$56.7 million
Iron	1888–2015	>6.7 million long tons	>$23 million
Fluorspar	1909–1978	>721,000 tons	$12 million
Manganese	1883–1963	>1.7 million tons	$5 million
Barite	1918–1965	>37,500 tons	>$400,000
Tungsten	1940–1958	113.8 tons (>60% WO_3)	na
Niobium-tantalum	1953–1965	34,000 pounds of concentrates	na
TOTAL	**1804–2015**	**—**	**>$359 billion**

*Oil and gas values are estimated from production data provided by https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Reporting/Production/ProductionInjectionSummaryReport.aspx (New Mexico Oil Conservation Division Natural Gas and Oil Production, continuously updated, accessed 2/1/16) and estimated average commodity price. Minerals data are from New Mexico Energy, Minerals and Natural Resources Department (2016). **Industrial minerals include the combined total of several industrial minerals (e.g., perlite, cement, decorative stone, pumice, zeolites, etc.), but excluding potash and aggregates. ***Aggregates include only sand and gravel from 1951–1997, after 1997 aggregates include crushed stone and scoria. na–not available.

Table 2. Summary of mineral production in New Mexico in 2015, including oil and natural gas (New Mexico Energy, Minerals and Natural Resources Department, 2016, https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Reporting/Production/ProductionInjectionSummaryReport.aspx; Gould, 2015). na—not available.

Mineral	Production in 2015	Production rank in the U.S. in 2015	Production value in NM in 2015	Employment in NM (# full time jobs)	Reclamation employment in NM (# full time jobs)	State revenue generated from extractive industries	Federal revenue generated from extractive industries
Oil	147 million bbls oil	6	~$7,143,000,000	~30,000*	na	~$1,600,000,000*	na
Gas	1.23 trillion ft^3 gas	8	~$6,470,000,000	—	na	—	na
Copper	397,441,145 lbs	2	$996,838,033	1,878	4	$8,086,903	—
Coal	19,676,277 short tons	12	$691,047,434	1,341	118	$17,656,313	$10,243,850
Gold	20,438 troy oz	—	$23,708,980	—	—	$191,947	—
Industrial minerals	1,411,731 short tons	—	$87,305,356	413	11	$269,261	$213,816
Aggregates	8,169,753 short tons	—	$62,625,896	837	53	$3,092,285	—
Other metals (iron, manganese)	18,358 short tons	—	$165,223	18	—	$761,027	—
Potash	1,433,245 short tons	1	$659,505,518	1,194	12	$6,542,580	$8,133,012
Silver	56,983 troy oz	—	$895,610	—	—	$9,737	—
Uranium	none	—	—	11	11	—	—
Carbon dioxide	106 billion ft^3	—	$112,000,000	—	—	—	na
Total	**—**	**15 (excluding oil, gas, and coal)**	**~$16,247,000,000**	**~35,000**	**209**	**~$1,628,000,000**	**$18,590,678**

*Estimate includes oil, gas, and carbon dioxide.

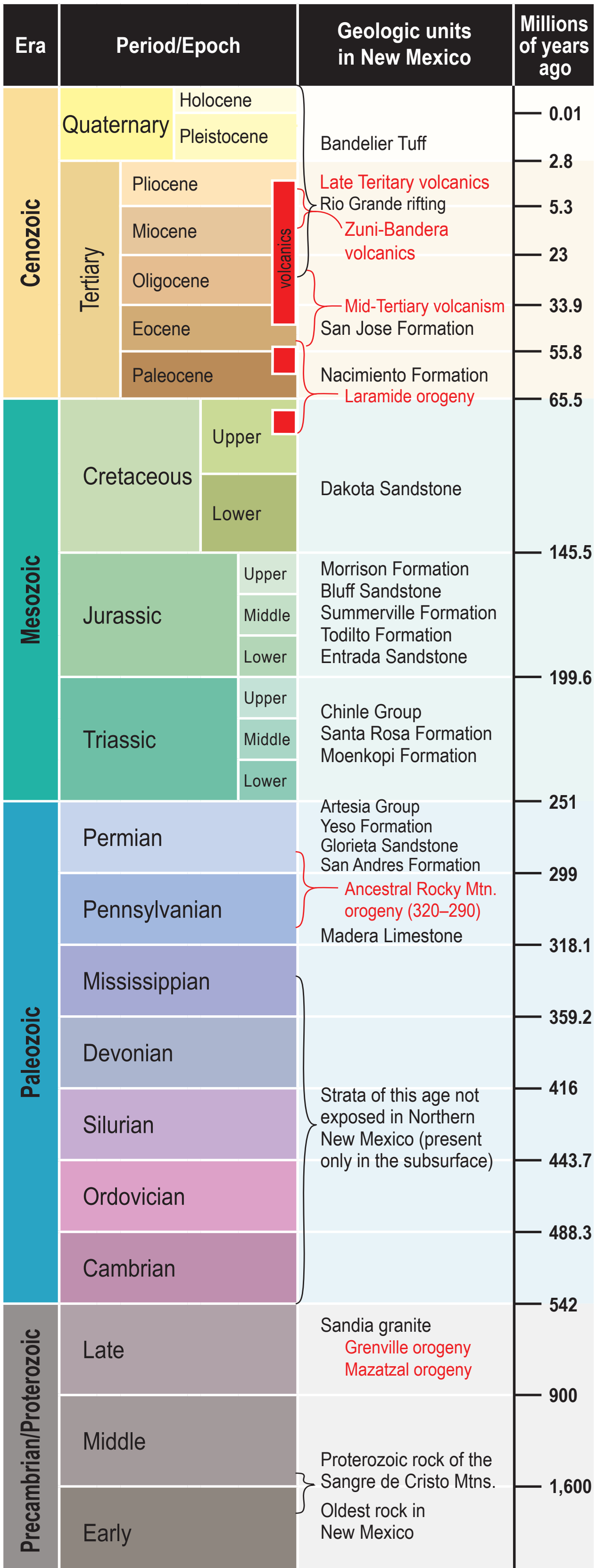


Figure 3. Geologic time scale. "Tertiary" is often used in these chapters to describe timing of events in the Paleogene and Neogene geologic periods.

New mines and petroleum drilling face a multitude of challenges, including water availability, water rights issues, public perceptions, a complex regulatory process and public opposition to petroleum drilling and mining.

Minerals and Society

The minerals industries (including oil and gas) play a vital role in the world economy by filling a persistent demand for the raw materials that are the foundation of our civilization. Our modern lifestyles are heavily dependent upon mining commodities that Americans use on a daily basis (Table 3). For example, petroleum, metals, and industrial minerals are used in every sector of construction and manufacturing. Coal, oil, gas, and uranium provide electricity and fuels. They are used in urban and industrial applications. Geothermal resources also provide electricity and heating (Table 3). Agriculture depends upon minerals for fertilizers and pesticides.

Mineral production in New Mexico and the world has increased dramatically in the last 100 years (Fig. 5, Wagner, 2002). Most industries no longer follow the casual mining and safety practices of the past. "*One of the greatest challenges facing the world today is integrating economic activity with environmental*

Table 3. Selected uses of commodities found in New Mexico.

Commodity	Selected Uses
Oil	Fuel, electricity generation, pesticides, fertilizers, chemicals, plastics
Gas	Fuel, electricity generation
Copper	Electrical wire, pipe, plumbing, motors, machinery, computers
Coal	Electricity generation, steel production, manufacture of cement, liquid fuel, chemical and pharmaceutical industries
Aggregates	Manufacture concrete and cement, road construction, railroad ballast
Molybdenum	Stainless and structural steel, superalloys, chemicals, cast iron
Potash	Agricultural fertilizers
Silver	Currency, jewelry, electronics, photography, silverware, mirrors
Gold	Currency, jewelry, electronics, computers, dentistry, glass
Uranium	Fuel for nuclear reactors, projectiles, shielding of radioactive materials
Perlite	Building construction materials, soil amendment, filter aid
Zeolites	Water purification, animal feed, sorbents
Rare earth elements	Catalyst, glass, polishing, re-chargeable batteries, magnets, lasers, glass, TV color phosphors
Geothermal resources	Electricity generation, space heating, greenhouse heating, aquaculture (fish farms), spas, and bath houses

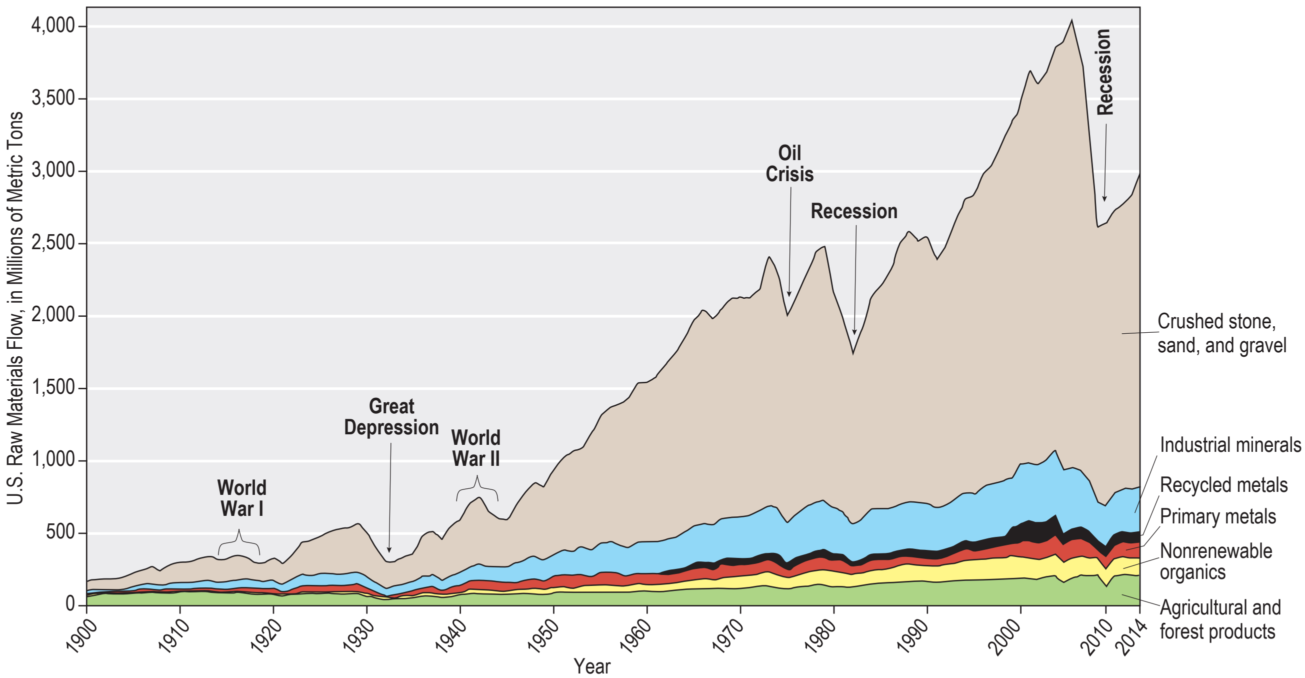


Figure 5. United States flow of raw materials by weight from 1900–2014. The use of raw materials increased dramatically during the last 100 years (modified from Wagner, 2002).

integrity and social concerns… The fulfillment of 'needs' is central to the definition of sustainable development" (IIED, 2002). The permitting process applied to most extractive industries includes archeological surveys, identification of rare and endangered species, and environmental monitoring during and after production. Today, another important aspect of mine planning in a modern regulatory setting is the philosophy, and often the requirement, that new mines and mine expansions must have plans and designs for closure. This philosophy is relatively new. It attempts to prevent environmental accidents common in the past and has increased the cost of mining.

Organization of this Series

This Memoir/Special Publication is the first modern summary of New Mexico's energy and mineral resources since work by the U.S. Geological Survey (USGS, 1965) and Howard (1967). This series of volumes is a joint publication of the New Mexico Bureau of Geology and Mineral Resources and the New Mexico Geological Society. This publication consists of six individual volumes under the theme of Energy and Mineral Resources of New Mexico.

Energy and Mineral Resources of New Mexico,
New Mexico Bureau of Geology and Mineral Resources, Memoir 50
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- **Petroleum Geology**
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- **Overview of the Valles Caldera (Baca) Geothermal System**
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SUMMARY

Uranium deposits play an important role for both New Mexico and the United States. Examining the different types of deposits and their geology creates a better understanding of the development of uranium. New Mexico has world-class uranium deposits in the Grants district and ranks second in uranium reserves in the United States. These reserves amount to 64 million short tons of ore at 0.14% U_3O_8 (179 million pounds U_3O_8) at $50/pound. The most important deposits in the state are within the sandstones of the Jurassic Morrison Formation in the Grants district. More than 340 million pounds of U_3O_8 have been produced from Morrison Formation deposits from 1948–2002, accounting for 97% of the total production in New Mexico and more than 30% of the total production in the U.S. Three types of uranium deposits are in the Westwater Canyon Member of the Morrison Formation: 1) primary, tabular (trend or blanket), 2) redistributed (roll-type or stack), and 3) remnant-primary sandstone. A fourth type, tabular sandstone uranium-vanadium deposits, is found in the Salt Wash and Recapture Members of the Morrison Formation in the western San Juan Basin. Other types of uranium deposits are found in New Mexico, but have not been major producers. Several companies are planning to mine these deposits by in-situ recovery or conventional mining and milling methods. Other areas outside of the Grants district in New Mexico have been examined for uranium potential and some of these areas yielded minor production and have future potential. Uranium from New Mexico provides much needed materials for nuclear fuel and a variety of industrial uses. As technology changes, geologic information concerning uranium deposits will provide decision makers with valuable insights.

Steam rising from the head frame at the Mt. Taylor mine (NMCI0027), Ambrosia Lake subdistrict, Grants uranium district. The Mt. Taylor mine is 3,300 ft deep. *Photo by V.T. McLemore.*

I. INTRODUCTION

During a period of nearly three decades (1951–1980), the Grants district in northwestern New Mexico (Figs. 1, 2) yielded more uranium than any other district in the United States (Table 1), thereby making New Mexico a major producer of uranium. Today, uranium is used primarily in nuclear reactors to produce electricity via nuclear fission. Although no producing operations exist in New Mexico today, numerous companies have acquired uranium properties within the Grants, Hooks Ranch-Riley, and Red Basin-Pietown districts (Fig. 1) and plan to explore and develop deposits in the future. The Grants district is a large area in the San Juan Basin, extending from east of Laguna to west of Gallup, and includes eight subdistricts (Fig. 2; McLemore and Chenoweth, 1989). The Grants district is probably 7th in total world uranium production behind East Germany, Athabasca Basin in Canada, Australia, South Africa, Russia, and Kazakhstan (Tom Pool, International Nuclear, Inc., Golden, Colorado, written communication, January 10, 2014). Other areas in New Mexico have potential for uranium (Fig. 1).

The seven purposes of this volume are to 1) describe what uranium is, 2) describe the types of uranium deposits found in New Mexico; 3) summarize the history of the uranium industry in New Mexico; 4) summarize the National Uranium Resource Evaluation (NURE) data; 5) describe the predominant uranium deposits in New Mexico; 6) summarize the environmental issues of the uranium industry in New Mexico; and 7) describe the future potential for uranium production in New Mexico. Much of this volume is summarized from Hilpert (1969), Anderson (1980), McLemore (1983, 2011), McLemore and Chenoweth (1989, 2003), McLemore et al. (2002), and other reports as cited. Information on specific mines and deposits in New Mexico are found in cited references, Hilpert (1969), Anderson (1980), McLemore (1983), and McLemore et al. (2002, 2013).

Throughout this paper, the district identification numbers, prefixed by DIS, and mine identification numbers, prefixed by NM, are from the New Mexico Mines Database and refer to the mines and districts listed in the text (McLemore et al., 2002, 2005a, 2005b). Uranium mines and prospects can be found at geoinfo.nmt.edu/maps. The production figures are the best data available and were obtained

Table 1. Uranium production from 1947–2002 by type of deposit from New Mexico (McLemore and Chenoweth, 1989, 2003; production from 1988–2002 estimated by the authors). Type of deposits refers to Table 2. Total U.S. production from McLemore and Chenoweth (1989) and Energy Information Administration (2010).

Type of deposit	Production (lbs U_3O_8)	Period of production (Years)	Production total in NM (%)
Primary, redistributed, remnant sandstone uranium deposits (Morrison Formation, Grants district)	330,453,000[1]	1951–1988	95.4
Mine water recovery (Morrison Formation, Grants district)	9,635,869	1963–2002	2.4
Tabular sandstone uranium deposits (Morrison Formation, Shiprock district)	493,510	1948–1982	0.1
Other Morrison Formation sandstone uranium deposits (San Juan Basin)	991	1955–1959	—
Other sandstone uranium deposits (San Juan Basin)	503,279	1952–1970	0.1
Limestone uranium deposits (Todilto Formation[2], predominantly Grants district)	6,671,798	1950–1985	1.9
Other sedimentary rocks with uranium deposits (total NM)	34,889	1952–1970	—
Vein-type uranium deposits (total NM)	226,162	1953–1966	—
Igneous and metamorphic rocks with uranium deposits (total NM)	69	1954–1956	—
Total in New Mexico	348,019,000[1]	1948–2002	100
Total in United States	**927,917,000[1]**	**1947–2002**	**NM is 37.5 of total U.S.**

[1]Production rounded to the nearest 1,000 pounds. There has been no uranium production in New Mexico since 2002. [2]Todilto Formation (Cather et al., 2013).

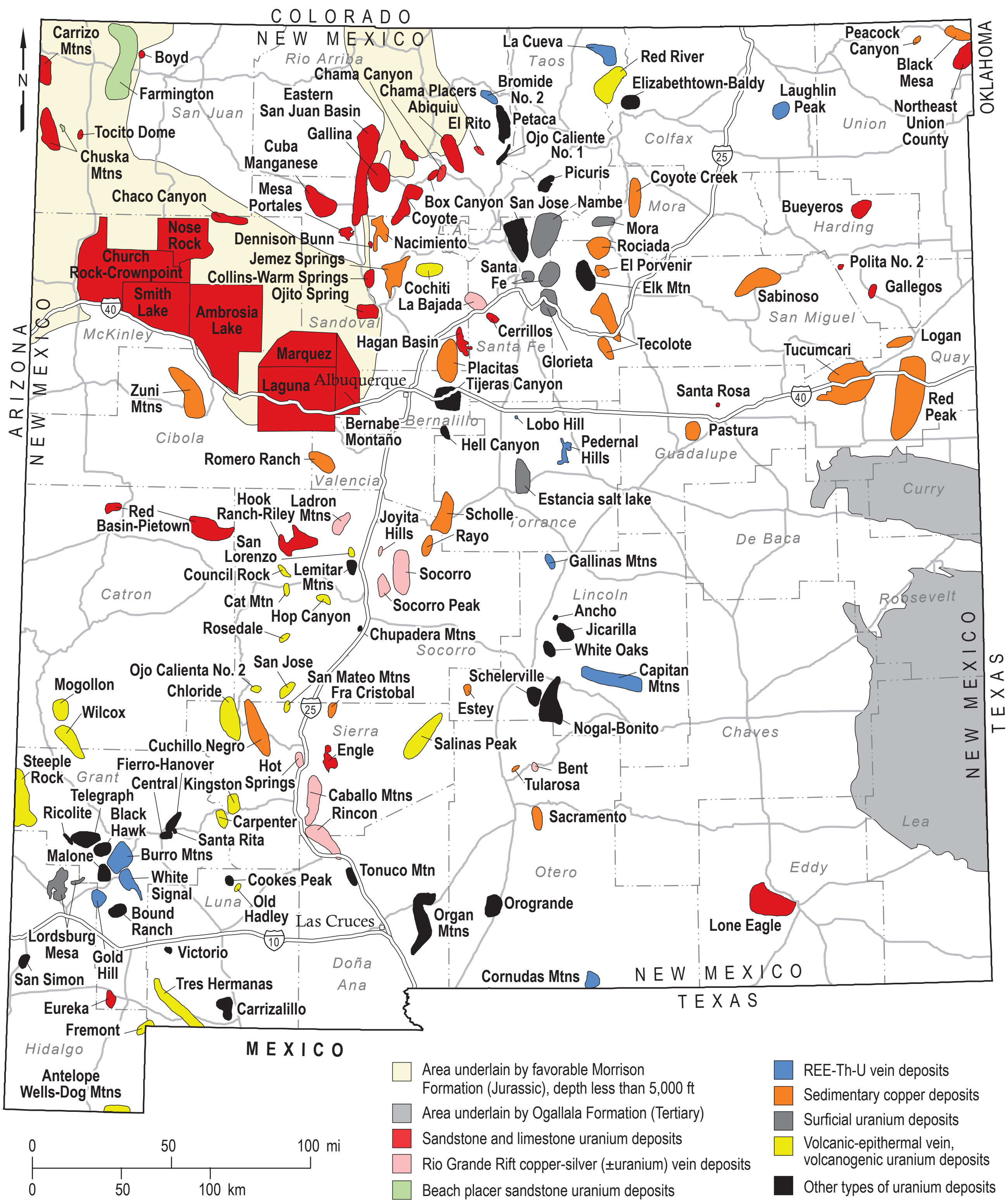


Figure 1. Mining districts that have uranium deposits and other areas favorable for uranium in New Mexico (modified from McLemore and Chenoweth, 1989). Each district is color-coded according to the predominant type of deposit; other types of uranium deposits are found in most districts.

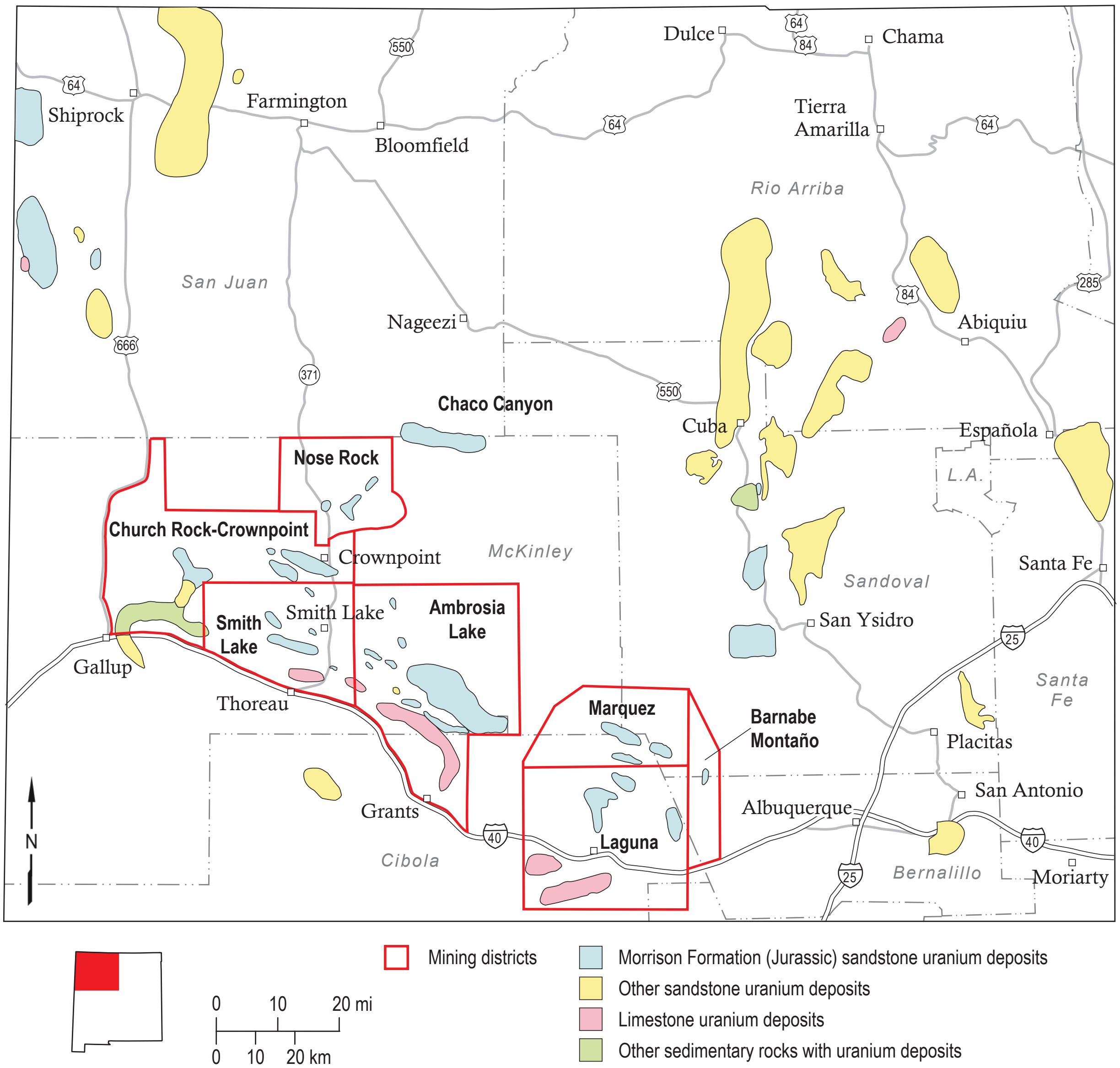


Figure 2. The predominant regions of uranium deposits and production in New Mexico are in the San Juan Basin and include the subdistricts of the Grants district (red outlined regions). Polygons outline approximate areas of known uranium deposits.

from published and unpublished sources (U.S. DOE and NMBGMR file data). Production figures are subject to change as new data are obtained. Some resource and reserve data presented in this report are historical and are provided for informational purposes only. These data do not conform to Canadian National Instrument NI 43-101 requirements, unless otherwise stated (http://web.cim.org/standards/documents/Block484_Doc111.pdf, accessed 10/8/14). Stratigraphic nomenclature is currently being revised as the geologic mapping program administered by the New Mexico Bureau of Geology and Mineral Resources progresses. We have attempted to use the most current nomenclature as suggested by Cather et al. (2013). However, changes are expected in the future.

Uranium grades (or concentration), by convention, are generally reported as percent or parts per million (ppm) U_3O_8. Uranium production and reserves in the United States are typically reported in pounds or tons, although many companies are beginning to use the international system that uses grams per metric ton and metric tons. We will continue to use the historic conventions in this volume, unless otherwise noted.

U-Th-REE veins at the McCory prospect (NMLI0056) in the Capitan Mountains, Lincoln County. *Photo by V.T. McLemore.*

II. WHAT IS URANIUM?

Uranium is a naturally occurring hard, dense, metallic silver-gray, radioactive element, and like many other commodities, uranium was deposited by geologic processes over time and, in some places, concentrated into large enough deposits to be exploited. Most of the uranium produced in the world is used in nuclear power plants to generate electricity. A minor amount of uranium 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, and in analytical chemistry applications. Depleted uranium is used in metal form in yacht keels, as counterweights, armor-piercing ammunition, and as radiation shielding, as it is 1.7 times denser than lead. Uranium also provides pleasing yellow and green colors in glassware and ceramics, a use that dates back to the early 1900s.

Nuclear power is important to New Mexico and the United States. Since 1990, the total annual U.S. electricity generation provided by nuclear power plants has averaged 20%. There are currently 99 commercial nuclear power reactors at 61 nuclear power plants in the U.S. (www.eia.gov/energyexplained/index.cfm?page=nuclear_use, accessed 7/27/15). The first step in understanding the importance of uranium and nuclear power to New Mexico is to understand the nuclear fuel cycle. The nuclear fuel cycle consists of ten steps (Fig. 3):

1. *Exploration*—using geologic data to discover an economic deposit of uranium.
2. *Mining*—extracting uranium ore from the ground and includes reclamation after mining.
3. *Milling*—concentrating or removing uranium as a concentrate (called yellow cake or uranium oxide, U_3O_8) and includes reclamation after milling.
4. *Uranium conversion*—uranium oxide concentrate is converted into the gas, uranium hexafluoride (UF_6).
5. *Enrichment*—most nuclear power reactors require enriched uranium fuel in which the content of the U-235 isotope has been raised from the natural level of 0.7% to approximately 3.5%. The enrichment process removes 85% of the U-238 isotope. Some reactors, especially in Canada, do not require uranium to be enriched.
6. *Fuel fabrication*—enriched UF_6 is converted to uranium dioxide (UO_2) powder and pressed into small pellets. The pellets are encased into thin tubes, usually of a zirconium alloy (zircalloy) or stainless steel, to form fuel rods. The rods are then sealed and assembled in clusters to form fuel elements or assemblies for use in the core of the nuclear reactor.
7. *Power generation*—generate electricity from nuclear fuel.
8. *Interim storage*—spent fuel assemblies taken from the reactor core are highly radioactive and give off heat. They are stored in special ponds, located at the reactor site, to allow the heat and radioactivity to decrease. Spent fuel can be stored safely in these ponds for decades.
9. *Reprocessing*—chemical reprocessing of spent fuel is technically feasible and used elsewhere in the world. However, reprocessing of spent fuel is currently not allowed in the United States because of legislation enacted during the Carter administration.
10. *Waste disposal*—the most widely accepted plans of final disposal involve sealing the radioactive materials in stainless steel or copper containers and burying the containers underground in stable rock, such as salt, granite, volcanic tuff, or shale.

Historically, New Mexico has roles in three of these steps: exploration, mining, and milling. In 2010, URENCO USA built a gas centrifuge uranium enrichment plant in Eunice, NM, adding a fourth role in enrichment processes.

In exploration and mining, some economic terms are used to define uranium deposits. A *uranium occurrence* is any naturally occurring, anomalous concentration of uranium, generally greater than 100 ppm U_3O_8. A *uranium mineral deposit* is any occurrence of uranium that is of sufficient size and grade (concentration) for potential economic development under past, present, or future favorable conditions, and includes any mine that produced uranium in the

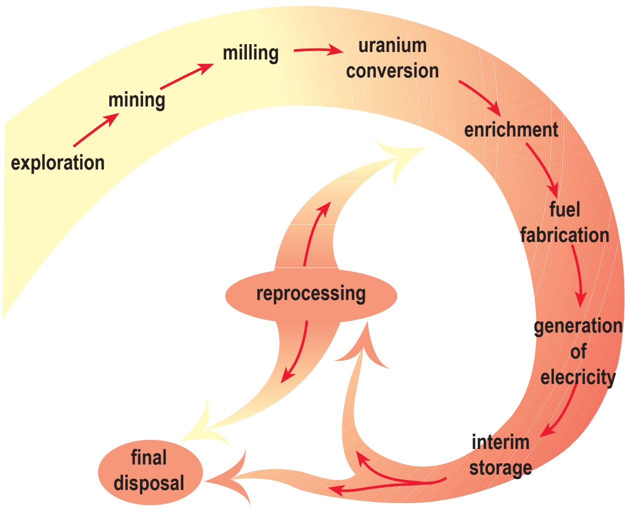


Figure 3. The nuclear fuel cycle (www.eia.gov/energyexplained/index.cfm?page=nuclear_fuel_cycle, accessed 7/27/15).

past. A *uranium ore deposit* is a well-defined uranium deposit that has been tested and found to be of sufficient size, grade, and accessibility to be extracted (i.e., mined) and processed at a profit in the future.

Uranium deposits are not found just anywhere in the world. Instead, they are relatively rare and their formation depends upon specific natural geologic conditions to form, as described in this report. Uranium deposits require a source of constituent elements, transport and concentration mechanisms, and preservation from geochemical and mechanical destruction. The requirement that a uranium deposit must be extracted at a profit makes them even rarer.

Uranium ore bodies come in many sizes and geometric shapes and mining methods must conform to each specific ore body and metal recovery economics. Mining can be classified into four basic methods: surface, underground, placer, and solution (or in situ) mining. Summaries of the types of mining can be found in Hartman (1992) and the USEPA (1995, 1997). *Surface mining* involves the extraction of minerals located close to or at the surface by removing soil and waste rock overlying, adjacent to, or intermixed with uranium minerals of the deposit. Typically, it involves overburden removal, blasting, mucking (picking up), loading and hauling, and dumping. There are three types of surface mining: strip, open pit, and quarry. *Strip mining* involves the removal or stripping of an overburden layer to expose an underlying layer of ore. *Open pit mining* methods are employed where the shape of the ore body will not accommodate strip mining and the ore is close enough to the surface to be mined at a profit from an open pit. Open pit mining involves the systematic removal of successive layers of rock (benches) from the surface to depth, thus forming an open bowl or pit. The term *quarry,* though somewhat non-specific, is used typically to differentiate a metal or uranium surface mine from an open pit mine that recovers either aggregate or dimension stone. *Underground mining* extracts minerals from underground leaving a roof (or back) or rock above the mining levels. Such mines are either too far below the surface to be accessed by either an open pit or strip mine or are more profitably mined by underground methods and can be an extension of an open pit mine. *Placer mining* is a variation of surface mining involving the removal of natural concentrations of heavy minerals, such as gold, tungsten, tin, zircon, or apatite, from unconsolidated sediment or soil by gravity processing. Uranium is rarely recovered by placer mining. *Solution* or *in situ mining* involves the circulation of leaching solutions directly into ore zones and subsequent recovery of the leachates (mineralizing fluids) for processing through a series of injection and recovery wells. Thus, the ore is recovered from its original geologic location negating the need for excavation and transport to a processing facility as is typical of conventional mining. In New Mexico, uranium has been mined by open pit, underground and solution or in situ mining techniques.

III. TYPES OF URANIUM DEPOSITS IN NEW MEXICO

Uranium deposits are quite diverse, forming during nearly all stages of the geological cycle and in rocks of any age (Cuney, 2009). Uranium geochemistry is predominantly governed by oxidation state and is found more in than 40 common minerals. Uranium can be found with a variety of other elements, depending upon environment of deposition, including thorium, rare earth elements, copper, fluorine, vanadium, molybdenum, and others. Uranium can be elevated in many other types of mineral deposits (McLemore and Lueth, 2017).

Mineral deposits, including uranium deposits, are classified into types of deposits, which are based on features such as host rock composition, mineralogy, and environment of deposition. Numerous classifications have been applied to uranium deposits to aid in exploration and evaluation of uranium resources (Lindgren et al., 1910; Lindgren, 1933; Guilbert and Park, 1986; Cox and Singer, 1986; Roberts and Sheahan, 1988; Sheahan and Cherry, 1993; International Atomic Energy Agency, 2009; Cuney, 2009). In New Mexico, North and McLemore (1986, 1988) and McLemore (2001) classified the silver and gold (and some uranium) deposits of New Mexico according to age, mineral assemblages, form, alteration, tectonic setting, and perceived origin. McLemore and Chenoweth (1989) classified the uranium deposits in New Mexico using previous classifications as modified by the International Atomic Energy Agency (2009). The McLemore and Chenoweth (1989) classification, with some modifications and additions, is retained in this volume (Table 2).

Most of the uranium production in New Mexico has come from sandstone uranium deposits in the Jurassic Morrison Formation in the Grants district in McKinley and Cibola (formerly Valencia) Counties, primarily from the Westwater Canyon Member of the Morrison Formation (Table 2; McLemore, 1983). Sandstone uranium deposits are found in sandstones that were deposited in continental or marginal marine environments. Uranium is precipitated from groundwater containing dissolved uranium in void spaces within the sandstone matrix under reducing conditions. In New Mexico, tabular uranium deposits are the most important economically and consist of uranium disseminated with the sandstone matrix, typically with organic material in irregularly shaped lenticular deposits. Redistributed and roll-type uranium deposits also are important and form from complex hydrologic interactions of uranium-bearing groundwater with other groundwaters, including brines and fluids containing hydrocarbons. The different types of sandstone uranium deposits are classified and discussed separately in this report, highlighting the economic importance in New Mexico (Table 2).

Limestone uranium deposits are rare in the world because limestone is generally not a favorable host rock for uranium deposits. However, unique geologic processes have occurred, as discussed below, to form economic primary uranium deposits within the Jurassic Todilto Formation in New Mexico.

Other sedimentary rocks with uranium deposits in New Mexico include uranium found in carbonaceous shale, coal and lignite. Surficial uranium deposits are defined as young, near-surface uranium concentrations in sediments and soils and include uranium found in calcrete and playa lake deposits. These deposits formed in deeply weathered uranium-rich basement rocks in arid to semi-arid climates. Uranium is in fine-grained surficial sand and clay that has been cemented by calcium and magnesium carbonates.

In vein-type uranium deposits (Table 2), uranium minerals fill fractures of variable thickness in a variety of host rocks. Many of the vein-type uranium deposits are associated with volcanic calderas. Mineralization is largely controlled by structures.

Igneous and metamorphic rocks with disseminated uranium deposits include those associated with metasomatized or igneous rocks. During metasomatism (alkali alteration or low-temperature metamorphism) of some Proterozoic rocks in New Mexico, uranium, thorium and other minerals were precipitated from the alteration fluids and these rocks are called episyenites. Uranium in igneous rocks typically is found in primary minerals that crystalized from the magma.

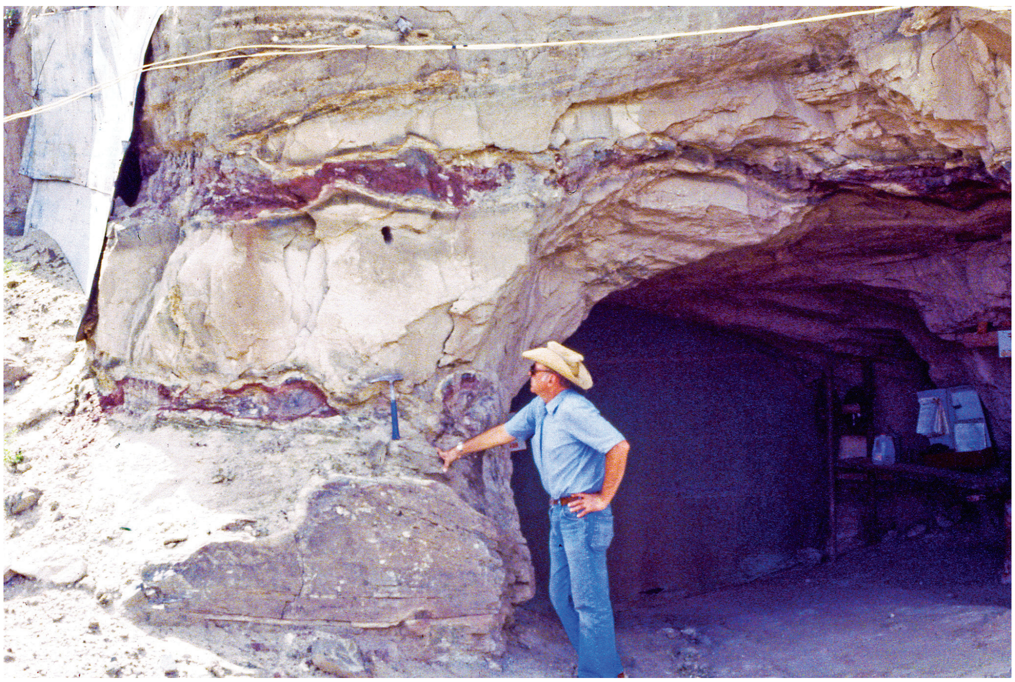
Other potential types of uranium deposits in New Mexico include collapse breccia pipe deposits where uranium is found in circular, vertical collapse structures filled with coarse fragments of sedimentary host rocks. The uranium minerals fill the void spaces within the collapse structures. The collapse structures are typically caused by solution collapse of underlying limestone. Other types of uranium deposits in New Mexico are listed in Table 2 and described below.

Table 2. Classification of uranium deposits in New Mexico (modified from McLemore and Chenoweth, 1989; McLemore, 2001; International Atomic Energy Agency, 2009). Deposit types in bold are found in the Grants district.

I. 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-type sandstone uranium deposits in Cretaceous and Tertiary sandstones
- Sedimentary uranium deposits
- Sedimentary copper deposits
- Beach placer 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
- Calcrete
- Playa lake deposits
II. Fracture-controlled uranium deposits
E. Vein-type uranium deposits
- Rio Grande Rift (RGB) 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
III. Disseminated uranium deposits in igneous and metamorphic rocks
F. Igneous and metamorphic rocks with disseminated uranium deposits
- Pegmatites
- Alkaline rocks
- Granitic rocks
- Carbonatites
- Caldera-related volcanogenic deposits
IV. Other potential types of uranium deposits
Iron Oxide-Cu-Au (IOCG) (Olympic Dam deposits)
By-product copper processing

Table 3. Uranium production and types of deposits by district or subdistrict in the San Juan Basin, New Mexico (McLemore and Chenoweth, 1989, and updated production from 1988–2002 as estimated by the authors). Districts have reported occurrences of uranium or thorium (>0.005% U3O8 or >100 parts per million Th). Some district names have been changed from McLemore and Chenoweth (1989) to conform to McLemore (2001) and the New Mexico Mines Database. District numbers 1-68 refers to number on map and table 3 in McLemore and Chenoweth (1989). District ID refers to the New Mexico Mines Database (McLemore et al., 2002, 2005a, 2005b). See McLemore (1983), McLemore and Chenoweth (1989, table 3), and McLemore et al. (2002, 2013) for more details and locations of additional minor uranium occurrences. Types of deposits (A-F) are defined in Table 2.

District (District ID)	**Production** (lbs U_3O_8)	**Grade** (U_3O_8%)	**Period of production** (years)	**Types of deposits**
Grants district				
1. Laguna (DIS014)	>100,600,000	0.1–1.3	1951–1983	A, C, E
2. Marquez (DIS015)	28,000	0.1–0.2	1979–1980	A
3. Bernabe Montaño (DIS012)	None			A
4. Ambrosia Lake (DIS115)	>211,200,000	0.1–0.5	1950–2002	A, B, C, E
5. Smith Lake (DIS122)	>13,000,000	0.2	1951–1985	A, C
6. Church Rock-Crownpoint (DIS117)	>16,400,000	0.1–0.2	1952–1986	A, B
7. Nose Rock (DIS120)	None			A
8. Chaco Canyon (DIS116)	None			A
Shiprock area				
9. Carrizo Mountains (DIS152)	159,850	0.23	1948–1967	A
10. Chuska Mountains (DIS153)	333,685	0.12	1952–1982	A, C, B
11. Tocito Dome area (DIS160)	None			A
12. Toadlena area (DIS159)	None			B
Other areas and districts in the San Juan Basin				
13. Zuni Mountains (DIS017)	None			B, E, F
14. Boyd (DIS151)	74	0.05	1955	B
15. Farmington (DIS154)	3	0.02	1954	B
18. Chama Canyon (DIS140)	None			B
19. Gallina (DIS144)	19	0.04	1954–1956	B
20. Eastern San Juan Basin (DIS268)	None			B
21. Mesa Portales (DIS175)	None			B
22. Dennison Bunn (DIS267)	None			A
23. La Ventana (DIS174)	290	0.63	1954–1957	D
24. Collins-Warm Springs (DIS169)	989	0.12	1957–1959	A
25. Ojito Spring (DIS177)	None			A
26. Coyote (DIS141)	182	0.06	1954–1957	B, C
27. Nacimiento (DIS176)	None			B
28. Jemez Springs (DIS173)	None			B
Other areas in New Mexico				
31. La Cueva (DIS232)	None			E, F
37. San Jose (DIS188)	12	0.05	1957	B
39. Hagan Basin (DIS273)	None			B
46. Socorro (DIS228)	4,679	0.20	1955–1963	E
47. Ladron Mountains (DIS218)	58,562	0.33	1954–1958	E
50. Hook Ranch-Riley (DIS214)	306	0.18	1954–1961	B
51. Red Basin-Pietown (DIS008)	1,194	0.17	1954–1957	B
55. Engle (DIS274)	None			B
62. White Signal (DIS068)	1,337	0.22	1953–1964	E
68. Lordsburg Mesa (DIS082)	None			D
71. Cornudas Mountains (DIS128)	None			E, F
83. Sabinoso (DIS165)	81	0.08	1956	B
86. Ogallala Formation	None			D



W.C. Chenoweth at the entrance of the Enos Johnson mine (NMSJ0047) in August 1983. *Photo by V.T. McLemore.*

IV. HISTORY OF THE URANIUM INDUSTRY IN NEW MEXICO

Uranium exploration and production in New Mexico occurred in several periods: 1) radium boom, 1918–1923; 2) vanadium production, 1926–1940s; 3) post WWII, 1948–1970; 4) uranium boom, 1970–1982; and 5) a new uranium boom, 2008–present. During the early radium boom, radium was used for medicinal purposes and many of the radium deposits were actually uranium deposits. Vanadium was produced from sandstone deposits that also contained uranium minerals in the Carrizo and Chuska Mountains (Fig. 2) during the vanadium period. Vanadium is used in manufacturing steel. The first uranium boom in 1970–1982, uranium was used primarily in nuclear weapons. However, once nuclear reactors were built in the early 1960s, uranium was then used to fuel those reactors for electricity.

Annual uranium production in New Mexico increased steadily from 1948–1960, from 1965–1968, and from 1973–1978. Peak production was achieved in 1978, with a record production of 9,371 short tons of U_3O_8 that was shipped to mills and buying stations (McLemore, 1983; McLemore and Chenoweth, 1989, 2003). Nine mills were built to process uranium ore from throughout the state, but mostly ore from the Grants district (Table 4). The Marquez (Bokum) mill was built but never operated.

In 1918, uranium and vanadium minerals were discovered in the Carrizo Mountains in San Juan County, New Mexico (Fig. 4), and Apache County, Arizona, by John F. Wade of Sweetwater, Arizona (personal communication, 1955). The discoveries, made with the help of local Navajo Indians, were in a sandstone unit that was later named the Salt Wash Member of the Morrison Formation. At the time of the discovery, the Navajo Reservation ("the Reservation," Fig. 4) was closed to prospecting and mining. The Congressional Act of June 30, 1919, opened the Reservation to prospecting and mining. A prospector could stake claims and then lease the ground from the Office of Indian Affairs, part of the U.S. Department of the Interior (DeVoto and Huber, 1982).

John Wade later formed the Carriso Uranium Company and staked 41 claims in the area of milepost 16 on the New Mexico-Arizona state line (J. Wade, personal communication, 1955). The General Services Administration (GSA), Indian Trust Accounting Division (GSA, 1981), could not find a copy of the lease, but a rental of $44.36 for 177.55 acres was paid on May 19, 1922. However, no ore was ever produced (GSA, 1981). Wade had staked these claims because there was a market for uranium ore in Colorado for the extraction of radium. When W.H. Staver examined the area in 1921 (Staver, 1921), he noted that only 5 of the 41 claims were in New Mexico, and the others were in Arizona. He reported there had been mining operations on the claims in New Mexico (Staver, 1921). He also recorded that 37 sacks of high-grade ore were stored at the Beclabito Trading Post (Fig. 4). In 1926, Hess (1929) reported that the Utah Vanadium Company obtained vanadium ore from the Carrizo Mountains. The ore was shipped to Denver and helped produce vanadium oxide (V_2O_5) for use as a steel alloy. This stored ore could have been what Staver recorded being at Beclabito. Around this time, radium also was found in several additional places in New Mexico (McLemore, 1983); small amounts were produced from the White Signal district (DIS068) in Grant County (Gillerman, 1964), and Scholle district (DIS246) in Torrance, Socorro, and Valencia Counties (U.S. Bureau of Mines unpublished files, 1949) (Fig. 1). The boom for radium was over by 1923.

On March 25, 1936, the Secretary of the Interior closed the Navajo Reservation to prospecting and mining. Two years later, the Congressional Act of May 11, 1938, reopened the Reservation to mining under new regulations, due to the interest in vanadium. The Navajo Tribal Council also could enter into leases with mining companies with the Secretary of the Interior's approval. On April 9, 1941, the Tribal Council requested the Secretary of the Interior to lease lands to the highest bidder (DeVoto and Huber, 1982).

On May 21, 1942, the Office of Indian Affairs held an exploration lease sale for 104 square miles in the eastern Carrizo Mountains. Vanadium

Corporation of America (VCA) submitted the highest bid. The East Reservation lease (NMSJ0044) was executed on July 14, 1942, for 10 years (GSA, 1981). Mining commenced in August of 1942 on mineralized outcrops of the Salt Wash sandstone on King Tutt Mesa in the Carrizo Mountains district (VCA, personal communication, 1955) (Fig. 4). VCA produced 10,294.74 short tons of vanadium ore that averaged 2.47% V_2O_5 from 1942 to 1947 (GSA, 1981). During 1942–1945, the ore was shipped to a vanadium mill in Monticello, Utah that was operated by VCA. At this mill, the Manhattan Engineer District (MED) secretly recovered uranium from the ores from 1943–1945 (Chenoweth, 1985b, 1997). A small shipment of vanadium ore was made in July 1947 to the VCA mill in Naturita, Colorado.

To secretly determine the uranium resources of the United States, the MED formed a civilian company called the Union Mines Development Corporation (UMDC). Beginning in 1943, UMDC geologists examined all areas in New Mexico where uranium minerals had been reported in the literature. Coleman (1944) mapped the rock outcrops of the Salt Wash Member of the Morrison Formation in the King Tutt area in the eastern Carrizo Mountains district (Fig. 4). Coleman (1944) described all of the mineralized outcrops he found. The White Signal district in Grants County (Fig. 1) was the only area outside of the Carrizo Mountains where UMDC determined there were uranium production possibilities (Keith, 1944).

On January 1, 1947, the U.S. Atomic Energy Commission (AEC) took over all functions of the MED. Uranium procurement was no longer secretive as the AEC announced prior schedules for ore, offered bonuses for new discoveries, and encouraged the prospecting and mining of uranium for the Cold War. With a market for uranium established, VCA resumed mining on their lease tracts on King Tutt Mesa in March 1948 (VCA, personal communication, 1955). Mining of uranium-vanadium ores in the Salt Wash Member of the Morrison Formation on VCA's lease continued until August 1967 (Chenoweth, 1996).

In 1949, the Navajo Tribal Council adopted a resolution that permitted individual Navajos to prospect and stake claims (mining permits). Because of this action, many Navajos were issued Navajo Tribal Mining Permits for ground adjacent to VCA's lease

Table 4. Uranium mills in New Mexico. Mine ID refers to mine identification number in the New Mexico Mines Database (McLemore et al., 2002).

Mine Id (degrees latitude, longitude[1])	**Mill name**	**Year built**	**Year first operated**	**Year last operated**	**Maximum milling capacity** (short tons of ore per day)	**Amount of tailings** (estimated in million short tons)	**Mill owner**	**Current status**
NMCI0110 (35.240118 107.854103)	Homestake (formerly Homestake-New Mexico Partners, Homestake-Sapin Partners)	1957	1958	1990	3,500	22.225	Homestake Mining Co.	Decommissioned in 1993, reclamation nearly completed
NMMK0349 (35.401332, 107.835687)	Ambrosia Lake (Kerr-McGee Corp., Rio Algom Mining)	1957	1958	2000	7,000	unknown	Quivira Mining Co., subsidiary of BHP-Billiton	Reclamation nearly completed
NMCI0109 (35.258249, 107.949985)	Bluewater	1953	1953	1982	6,000	24	ARCO (Anaconda)	Decommissioned, reclamation completed
NMMK0125 (35.649425, 108.612362)	Church Rock	1977	1977	1982	3,000	3.5	United Nuclear	Decommissioned in 1993, Being reclaimed
NMMK0353 (35.408819, 107.791604)	Phillips (Ambrosia Lake)	1958	1958	1963	1,750	6.931	Phillips Petroleum Co., United Nuclear Corp.	Decommissioned, reclamation completed under UMTRCA[2]
NMMK0354 (35.316222, 107.3195)	Bokum	1980	none	none	unknown	none	Bokum Resources	declared bankruptcy in 1981, mill demolished
NMSJ0115 (36.771944, 108.685083)	Shiprock (Navajo)	1954	1954	1968	500	2.52	Foote Mineral Co.	Decommissioned, reclamation completed under UMTRCA[2] in 1986
NMCI0108 (35.629028 108.550833)	L-Bar	1976	1976	1981	1,600	unknown	Kennecott Energy Co. (formerly Sohio)	Being reclaimed

[1] Datum is NAD27, [2] UMTRCA = Uranium Mill Tailings Radiation Control Act

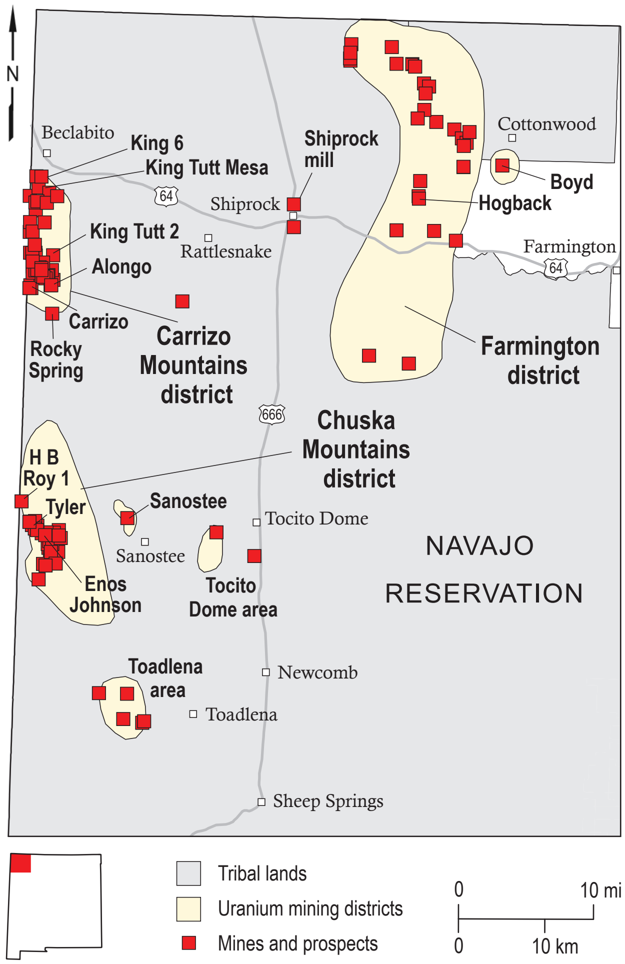


Figure 4. Uranium mines and districts in the Farmington–Shiprock area, San Juan County, northwestern New Mexico.

plots. On September 19, 1951, new regulations were adopted that allowed mining permits to be assigned to non-Navajos for exploration and mining. Permits and assignments were subject to approval by the Navajo Tribal Council and the Bureau of Indian Affairs (DeVoto and Huber, 1982).

Although uranium was found in the Grants district in the 1920s (Fig. 5), the economic potential of the area was not realized until much later. In the spring of 1950, Paddy Martinez, a Navajo sheepherder, showed some businessmen from Grants a sample of the mineralized Todilto Formation. This sample was from the area of Haystack Butte in the Ambrosia Lake subdistrict (Fig. 5) that contained yellow uranium minerals (Chenoweth, 1985a). News of this discovery started the uranium boom in New Mexico. In the area northwest of Grants, numerous mineralized exposures of the Todilto Formation were leased or claimed. Exploration spread south and east of the Reservation, in McKinley County, to the "checkerboard area" (so named because many townships contain a mixture of ownerships including railroad, state, Navajo allotment, Navajo tribal, private, and public sections; Fig. 5). An allotment is a 160-acre tract held by a Navajo family.

The first economic discovery of uranium in sandstone was made on January 4, 1951, east of Haystack Butte in an area called Poison Canyon (Fig. 5), named for the abundance of locoweed. The host rock was a tongue of the Westwater Canyon Member and the lower part of the overlying Brushy Basin Member of the Morrison Formation (Hilpert, 1969). This unit would later be called the Poison Canyon Sandstone. By 1951, prospectors had spread out all over the Jurassic rocks exposed along the north flank of the Zuni uplift north of the Zuni Mountains between Grants and Gallup (now known as the Grants district; Fig. 2, 5). Uranium was discovered in both the Morrison Formation and the Cretaceous Dakota Sandstone in the Gallup area in the Church Rock-Crownpoint subdistrict (Fig. 2).

In the Chuska Mountains, west of the village of Sanostee (Fig. 4), New Mexico, prospectors located uranium minerals in the Morrison Formation in 1951. The uranium occurred in both the Salt Wash and Recapture Members of the Morrison Formation. Uranium minerals also were found in the Todilto Formation. Enos Johnson and Enos Johnson Jr. claimed the most promising area. The Enos Johnson mine (NMSJ0047), also known as the South Peak mine, produced ore from the Recapture Member during 1952–1982, and is the largest producing uranium mine in New Mexico outside the Grants district (Chenoweth and McLemore, 2010).

On November 8, 1951, an aerial radiometric survey of the Laguna Indian Reservation by the Anaconda Copper Mining Company ("Anaconda") discovered a uranium-bearing outcrop near the village of Paguate in the Laguna subdistrict (Fig. 5; Kittel, 1963). Drilling north of the outcrop of sandstone at the top of the Morrison Formation led to the discovery of the huge Jackpile ore deposit (NMCI0018). This host rock would later be named the Jackpile Sandstone Member of the Morrison Formation. With numerous uranium mines being developed in the Grants area, Anaconda signed a contract with the AEC on December 27, 1951. This contract allowed for the production of uranium concentrate by a mill that was to be built near Bluewater (Table 4, Fig. 5). This was the first of nine mills to be built in New Mexico (Table 4). The first yellowcake was produced in September 1953 (Albrethsen and McGinley, 1982).

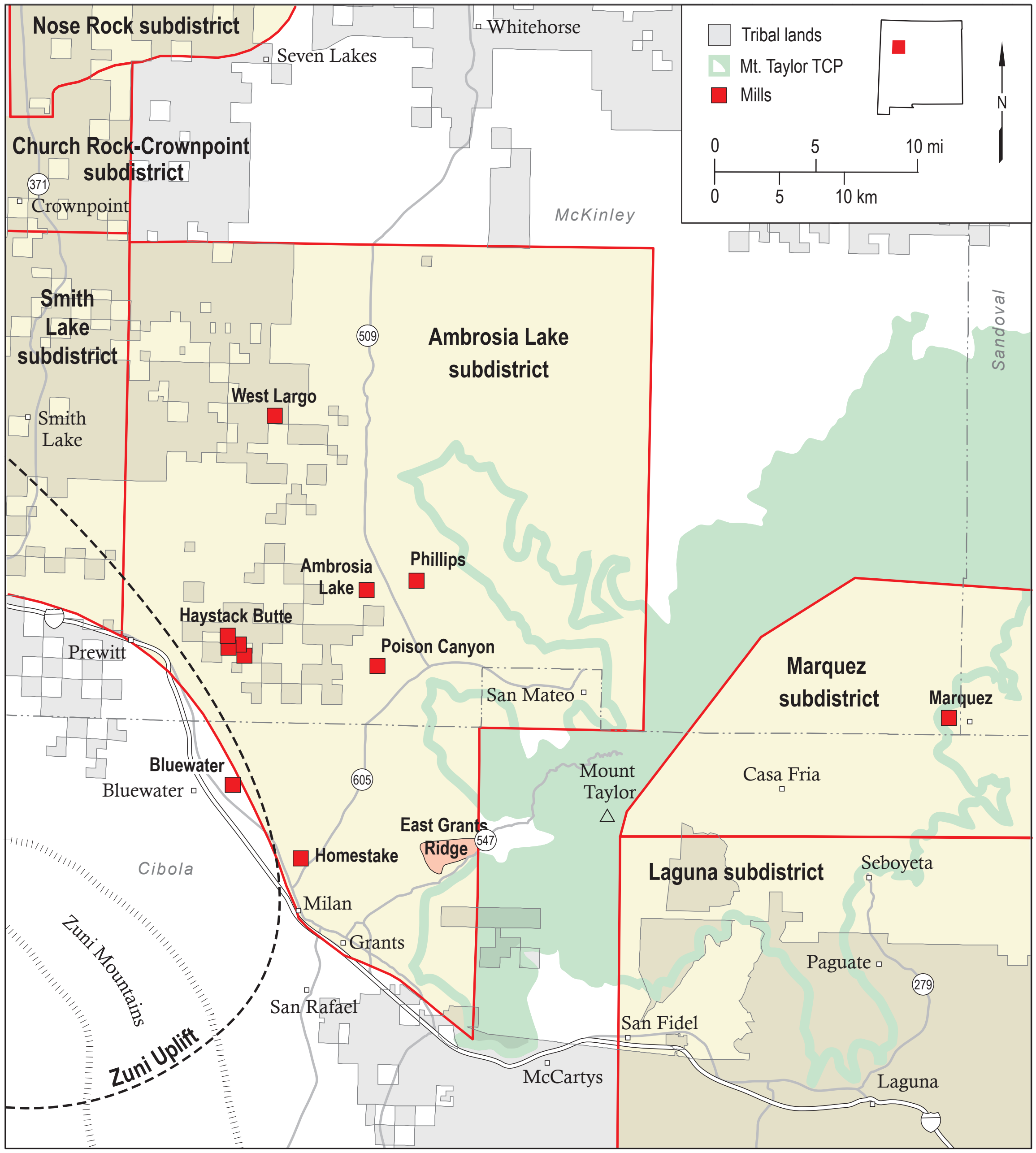


Figure 5. Mills in the Ambrosia Lake and adjacent subdistricts of the Grants uranium district. The boundaries of the Mt. Taylor Traditional Cultural Property (TCP) are shown. The Mt. Taylor TCP is listed by the State Register of Cultural Properties (www.nmhistoricpreservation.org/documents/cprc/passage_release.pdf).

The second mill built in New Mexico was near Shiprock in 1954 by Kerr-McGee Oil Industries, Inc. (Kerr-McGee) (Table 4, Fig. 4). The AEC opened an ore-buying station there on January 17, 1952 (O'Rear, 1966). The station and the mill provided a market for non-VCA ores mined on the Navajo Reservation and ores from the Gallup and Poison Canyon areas. By the mid-1950s, the uranium boom had spread across the entire state, including deposits in 15 counties, and these areas were producing ore (listed in McLemore, 1983; McLemore and Chenoweth, 1989).

In 1955, Louis Louthman was interested in testing the Morrison Formation near Ambrosia Lake approximately 9 mi northwest of the Poison Canyon mining area in the Ambrosia Lake subdistrict (Fig. 5). At the New Mexico Bureau of Mines and Mineral Resources (now the New Mexico Bureau of Geology and Mineral Resources), Louthman examined logs of oil tests to determine drilling depths to the Morrison Formation. Using information gleaned from oil test wells, Louthman began drilling for uranium in the Ambrosia Lake area. On March 17, 1955, his second drill hole penetrated uranium mineralization in the Westwater Canyon Member of the Morrison Formation (Chenoweth and Holen, 1980). Development from this drilling resulted in the discovery of the Dysart No. 1 mine (NMMK0051).

News of this discovery created a claim-staking and leasing boom in the Ambrosia Lake area. Exploration drilling followed, and several more ore deposits were located. The small operators merged with well-funded companies such as Homestake Mining Company (Homestake), Kerr-McGee, and Phillips Petroleum Company to develop mines. On July 5, 1956, the AEC opened an ore-buying station in Milan (Fig. 5) to provide a market for uranium in central New Mexico.

In June 1956, exploration drilling by Anaconda, in the area west of the Jackpile open pit mine (NMCI0018), made a major discovery (Kittel, 1963). This would be developed into the Paguate open pit mine (NMCI0064), which is adjacent to the Jackpile open pit mine, both of which are located in the Laguna subdistrict of the Grants uranium district (Fig. 2). Then, in early 1957, Phillips Petroleum Company began an exploration drilling program on Santa Fe Railroad lands in the checkerboard area northeast of Gallup. By the next year, this drilling located the Church Rock ore deposit in the Church Rock-Crownpoint subdistrict (Fig. 2), where ore occurred in both the Westwater Canyon Member and the Dakota Sandstone (Chenoweth and Laverty, 1964).

By the fall of 1958, four new mills in the Ambrosia Lake area were producing yellowcake (Table 4). The mill operators were Homestake-New Mexico Partners, Homestake-Sapin Partners, Kermac Nuclear Fuels Corporation, and Phillips Petroleum Company (Albrethsen and McGinley, 1982). Development of the mines in the Ambrosia Lake subdistrict (Fig. 2) was hampered by stability problems caused by abundant groundwater and the friable sandstone of the Westwater Canyon Member. Figures 6–9 illustrate some of the mining methods in the Ambrosia Lake underground mines.

In September 1957, the Bureau of Indian Affairs held a lease sale for Navajo allotments in the checkerboard area in the Smith Lake subdistrict (Fig. 2). The Blackjack Corporation was the highest bidder on 96 allotments. Drilling on these allotments resulted in the discovery of the Blackjack Nos. 1 and 2 ore deposits (NMMK0015, NMMK0016) in the Westwater Canyon Member (Chenoweth and Laverty, 1964).

The Sabre-Piñon Corporation took over the Phillips Petroleum Company leases in the Church Rock-Crownpoint subdistrict (Fig. 2) in September 1961. They began exploring where earlier drilling by Phillips Petroleum Company had found uranium. This exploration drilling led to the discovery of the Northeast Church Rock ore deposit (NMMK0117) in 1963. Another major merger occurred in 1962, when United Nuclear Corporation (UNC) merged with Sabre-Piñon Corporation and the Sabre-Piñon name was dropped. UNC acquired the former Phillips mines and mill in February 1963 and closed the Phillips Petroleum Company mill. The mill feed was instead sent to the Homestake-Sapin Partners mill, which had merged with the adjacent Homestake-New Mexico Partners mill (Chenoweth, 1989b).

In March 1963, VCA acquired the Shiprock mill and Navajo Reservation mines of Kerr-McGee. In 1967, VCA was acquired by the Foote Mineral Company, who closed the Shiprock mill in May of 1968 (Albrethsen and McGinley, 1982). In April 1968, the Homestake-Sapin Partners became the UNC-Homestake Partners (Albrethsen and McGinley, 1982). In 1963, operators of the mines in the Ambrosia Lake subdistrict began to recover uranium from water pumped from the mines. Mine-water uranium recovery would continue to 2002.

Figure 6. Driller at the face of the ore body in Section 10 mine (NMMK0175), Ambrosia Lake subdistrict during the 1970s. *Photo by Kenneth Hatfield.*

In 1965, Kerr-McGee leased a block on Navajo Reservation land adjacent to where UNC was developing their Northeast Church Rock mine (NMMK0117) in the Church Rock-Crownpoint subdistrict (Fig. 2). Drilling would locate Kerr-McGee's Northeast Church Rock ore deposits (NMMK0113).

In 1968, the main Ambrosia Lake subdistrict mining area expanded eastward due to the discovery of ore on the Lee (Fernandez) Ranch by the Fernandez Joint Venture. The discovery, at a depth of 2,700 ft, was approximately 2 mi northwest of the village of San Mateo (Fig. 5). This ore body is now called the Roca Honda deposit (NMMK0355) and is being developed by Energy Fuels, formerly Strathmore Resources Inc. (McLemore et al., 2013). Eastern mining continued in March 1970, when drilling by Bokum Resources Corporation discovered ore on the northwest flank of Mount Taylor. This ore was at a depth of 4,000 ft in the Westwater Canyon Member. The discovery was less than a mile northeast of San Mateo. In 1971, Gulf Oil Corporation acquired the property.

Figure 7. Geologist measuring the grade of ore in Section 25 mine (NMMK0220), Ambrosia Lake subdistrict during the 1970s. *Photo provided by William L. Chenoweth, from the U.S. Atomic Energy Commission Historical Photo Collection.*

Figure 8. Underground loader in Section 25 mine (NMMK0220), Ambrosia Lake subdistrict during the 1970s. *Photo provided by William L. Chenoweth, from the U.S. Atomic Energy Commission Historical Photo Collection.*

In 1969, Gulf Minerals, drilling on a Kerr-McGee farmout, discovered ore in the northern portion of the Ambrosia Lake subdistrict in the West Largo area (NMMK0340). The ore was at a depth of 2,200 ft in the Westwater Canyon Member. During 1969–1970, Kerr-McGee, Humble Oil (now Exxon), and Bokum Resources also made discoveries in the Westwater Canyon on the east side of Mount Taylor. Sohio-Reserve expanded the ore reserves at the L-Bar deposit (NMCI0019) north of the Jackpile mine in the Laguna subdistrict.

When the AEC's uranium procurement program ended on December 31, 1970, the six mills in New Mexico had produced 145,480,607 lbs of U_3O_8 for the federal government. An additional 17,420,127 lbs were produced from 1967 to 1970 for sale to electric utilities (Albrethsen and McGinley, 1982). Beginning in 1971, all uranium produced in the U.S. was for utilities.

Drilling by Conoco Oil in 1971 discovered ore in the Bernabe Montaño subdistrict (Fig. 2; NMBE0047, NMSA0023), part of the Laguna Indian Reservation. This ore body in the Westwater Canyon Member marked the eastern limit of the Grants uranium district (Fig. 2). In the same year, a sale of Navajo Reservation uranium leases in April and May of 1971, was significant as it initiated deeper exploration in the northeast Church Rock area and eastward to Crownpoint (Church Rock-Crownpoint subdistrict, Figs. 2, 5). From 1972 to 1974, United Nuclear and Pioneer Nuclear discovered deposits on the Reservation. Conoco Oil and Mobil Oil made discoveries off the Reservation in the checkerboard area.

In 1972, Western Nuclear, Inc. announced the discovery of the Ruby 1–4 deposits (NMMK0145, NMMK0146, NMMK0147, NMMK0148), southeast of the Black Jack No. 2 mine (NMMK0016) in the Smith Lake subdistrict (Fig. 2), in an area overlooked by past exploration. Continued exploration by Western Nuclear (in partnership with New Mexico-Arizona Land Company and Reserve Oil and Minerals) located additional deposits in this area, which was part of the Westwater Canyon Member.

Figure 9. Underground truck in Section 25 mine (NMMK0220), Ambrosia Lake subdistrict during the 1970s. *Photo provided by William L. Chenoweth, from the U.S. Atomic Energy Commission Historical Photo Collection.*

In the mid 1970s, Exxon Oil obtained a large exploration lease from the Navajo Tribal Council in San Juan County, east of the Carrizo and Chuska Mountains. Drilling on this lease reportedly revealed a small to medium-sized ore body in the Tocito dome subdistrict (NMSJ0100) east of Sanostee (Fig. 4). The ore was in the Westwater Canyon Member at a depth of about 2,000 ft (McLemore and Chenoweth, 1989).

In 1973, Phillips Petroleum Company began leasing Santa Fe Railroad lands in the Seven Lakes area, 12 mi north of Crownpoint, northern portion of the Church Rock-Crownpoint subdistrict (Figs. 2, 5). When drilling to the Westwater Canyon Member in this area, depths were in excess of 3,000 ft. In August 1974, drilling penetrated ore grade material in sec. 31, T19W, R11N. This led to the discovery of the Nose Rock ore bodies (NMMK0119, NMMK0120, NMMK0121, NMMK0347, NMMK0348) in the Nose Rock subdistrict (Fig. 2) in December 1975.

In 1976, the Sohio-Reserve L-Bar mill began operating in Cibola County (Fig. 5; Table 4). This was a joint venture between Sohio Western Mining Co. and Reserve Oil and Minerals Corp. Until its closure in 1980, this mill processed ore from the nearby L-Bar (NMCI0019) and St. Anthony deposits (NMCI0047) in the Jackpile Sandstone Member. The Church Rock mill of UNC, adjacent to the company's northeast Church Rock mine, began operating in 1977 and closed in 1981 (Table 4). Similarly, Conoco discovered an ore body in the Westwater Canyon Member in 1977 in the Borrego Pass area (NMMK0020), which is 12 mi southeast of Crownpoint.

During 1978, a drilling program in the east Chaco Canyon subdistrict (Fig. 1, 2) was carried out by the Grand Junction Office of the U.S. Department of Energy (DOE) in an effort to learn more about the uranium favorability of the Westwater Canyon Member in the deeper, untested portions of the San Juan Basin. Two of the holes in the Chaco Canyon area encountered significant mineralization in the Westwater Canyon Member at depths exceeding 4,000 ft, proving that uranium mineralization is found at depth in the San Juan Basin, although these deeper deposits are not currently economic.

Gulf Minerals completed the Mount Taylor shaft (NMCI0027) in 1979 in the eastern Ambrosia Lake subdistrict. The shaft had a depth of 3,300 ft; this would become the deepest uranium mine in the U.S. The mine was put on standby in November 1982.

The Three Mile Island incident occurred on March 28, 1979 and nuclear power was no longer popular as a source of electricity. The Three Mile Island Unit 2 reactor at Middleton, Pennsylvania partially melted down as a result of mechanical or electrical failure (http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html, accessed 7/27/15). Although no one was injured and the small radioactive releases had no detectable health effects on workers or nearby residents, the incident was the most serious accident in the U.S. commercial nuclear power plant industry and ultimately resulted in cancellation of construction of many nuclear power plants in the U.S. for decades.

Although, several uranium projects continued development after the Three Mile Island incident, most uranium exploration in New Mexico ceased and many uranium mines began to close. In 1980, Bokum Resources built a mill in the Marquez subdistrict (Fig. 2) to process ore discovered in the Westwater Canyon. A 2,100-ft-deep shaft was started but never completed (NMMK0103). Bokum was bankrupt by 1981, and the mill was later demolished (Table 4). Homestake and UNC dissolved their partnership in March 1981. Homestake became the sole owner of the Section 13, 15, 23, 25 and 33 mines in the Ambrosia Lake subdistrict (NMMK0181, NMMK0183, NMMK0208, NMMK0220, NMMK0248). That year all mines but Section 23 were closed; UNC closed all of its mines the same year. In 1981, Mobil Oil began an in situ leaching pilot test on its Westwater Canyon ore body in section 9, T17N, R.13W (NMMK0038), near Crownpoint in the Church Rock-Crownpoint subdistrict. This operation would continue to 1987 (McLemore and Chenoweth, 1991).

Kerr-McGee's New Mexico uranium mining and milling operations at Ambrosia Lake became Quivira

Mining Co. in 1983. The next year, the Ambrosia Lake and the northeast Church Rock mines were closed. Recovery of uranium from mine-water continued in both areas until 2002. Anaconda closed its mill at Bluewater in 1983 after processing Jackpile and Paguate ore for 30 years (since 1953). Anaconda later merged into the Atlantic Richfield Co.

In 1984, Chevron Resources Co. acquired the Mount Taylor project (NMCI0027) from Gulf Mineral Resources. In March 1985, the mine was reopened after its three-year closure. Ore from the mine was shipped by train approximately 900 mi to the company's mill at Panna Maria, Texas. In 1988, ore from Mount Taylor and Section 23 was being processed at the Homestake mill in the Ambrosia Lake subdistrict (Table 3), but the next year, Homestake closed its Section 23 mine. In 1989, Quivira Mining Company was acquired by Rio Algom Mining Corp. In 1990, Homestake closed its mill and mine-water recovery operations and began reclamation of the mill site. The Mount Taylor mine also was closed that year. General Atomics, as Rio Grande Resources, acquired the Mount Taylor mine from Chevron in August 1991. The pumps were turned off and Rio Grande Resources allowed the mine to flood. The Mount Taylor mine is on standby status with plans to reopen in the future and, therefore, is not currently required to begin reclamation. In 2001, Homestake merged with Barrick Gold Corp. and continued the reclamation of the Homestake millsite.

On October 18, 2000, Billiton Plc. announced that it had acquired 95% of the common shares of Rio Algom Ltd. The acquisition was completed on November 29, 2000. On December 15, 2000, the Rio Algom Ltd.'s U.S. uranium mining business was sold to Billiton Base Metals, a wholly owned subsidiary of Billiton Plc. On June 29, 2001, Billiton Plc. and BHP merged to form BHP Billiton Plc. As of 2015, Rio Algom Mining Corp., operates as a subsidiary of BHP-Billiton and is reclaiming the Quivira millsite and mines at Ambrosia Lake.

In April 2005, Navajo Nation President Joe Shirley announced that the Navajo Nation Council had adopted a resolution banning all uranium mining and milling on "Indian Lands." This term was applied to stop the planned development of ore bodies on non-Navajo lands in the checkerboard area near Church Rock and Crownpoint. In 2010, the Federal courts ruled in favor of the uranium companies and mining. Subsequently, most of Mount Taylor and adjacent mesas have been designated as the "Mount Taylor Traditional Cultural Property," but the effect of this designation on uranium exploration and mining is uncertain.

All of the conventional underground and open pit mines in New Mexico were 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. Subsequently, nuclear power plants became unpopular.
- There was an overproduction of uranium in the late 1970s to early 1980s that led to large stockpiles of uranium. Additionally, the dismantling of nuclear weapons by the U.S. and Russia also increased these stockpiles, reducing the need to mine uranium.
- At the same time, the New Mexico uranium deposits in production were decreasing in grade by nearly half because the higher-grade deposits were mined out.
- The cost of mine and mill reclamation was increasing and was not accounted for in original mine plans.
- Higher grade, more economically attractive uranium deposits were found elsewhere in the world, especially deposits in Canada, Kazakhstan, and Australia.
- 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, and Homestake. The decline in the price of uranium during 1989–2005 resulted in no uranium production (except mine-water recovery), exploration, or development in the state. Many companies reclaimed and/or sold their properties.

V. SUMMARY OF THE NATIONAL URANIUM RESOURCE EVALUATION (NURE) DATA

The National Uranium Resource and Evaluation (NURE) program was established in 1974 and terminated in 1984 and was administered by the Grand Junction Office of the U.S. Atomic Energy Commission and succeeding agencies, the U.S. Energy and Development Administration and the U.S. Department of Energy (DOE). The main purposes of the NURE program were to provide an assessment of the nation's uranium resources and to identify favorable areas for uranium mineralization. Elements of the NURE program include: geochemical surveys, compilation of quadrangle geologic maps, geophysical surveys, quadrangle assessments for uranium resources, miscellaneous geologic investigations, and drilling projects. Data have been released as DOE open-file reports and maps (McLemore and Chamberlin, 1986). Some of these reports are cited in this volume as appropriate.

A regional geochemical database, including stream sediments (Fig. 10) and waters (Fig. 11), was developed as part of the NURE program for the state of New Mexico and now is part of the USGS National Geochemical database. The NURE data are typically displayed by 1x2 degree (one degree of latitude by two degrees of longitude) quadrangles, although a few areas were sampled and evaluated in greater detail (the Estancia Basin, Grants district, and San Andres and Oscura Mountains areas).

In New Mexico, a total of 27,798 stream-sediment samples and 12,383 surface water and groundwater samples were analyzed. Stream sediments are up to 1 kg of sediment from a major stream or river from at least three adjacent spots within the stream at each location. Water samples are up to 50 ml of water collected from wells, springs, or surface waters. Field collection procedures are described by Sharp and Aamodt (1978). Chemical analyses for these samples were performed at two national laboratories (Los Alamos and Oak Ridge). Each laboratory used the same procedures for analyzing for uranium. However, each laboratory used different analytical techniques and analyzed samples for different additional elements (Hansel and Martell, 1977; Cagle 1977; Aredt et al., 1979).

Some of the NURE data are problematic (Haxel, 2002; McLemore, 2010a), and the entire data set should be used with caution. McLemore (2010a) describes the methods used in the interpretation of and problems encountered with the NURE data. The NURE data were not designed to reveal specific uranium or other mineral deposits, but if the data are used with caution, they can be used to identify areas of potential geochemical interest for further study. Ultimately, field examination of any NURE-identified areas must be conducted. Recognized problems include inconsistent sampling techniques, variability in the density of samples and the size of fractions for analysis. There were also differences in laboratories, analytical techniques, analytical errors at each laboratory, and analytical detection limits. However, several areas in New Mexico where subsequent stream-sediment surveys have been completed show similar geochemical patterns to those with the NURE data. This illustrates that despite the aforementioned problems, the data are in general adequate for regional surveys (Ellinger, 1988; Ellinger and Cepeda, 1991; Watrus, 1998; New Mexico Bureau of Mines and Mineral Resources et al., 1998).

Numerous studies have utilized the NURE data for New Mexico to 1) evaluate mineral-resource potential (Laughlin et al., 1985; Bartsch-Winkler and Donatich, 1995; Bartsch-Winkler, 1997; New Mexico Bureau of Mines and Mineral Resources et al., 1998; McLemore et al., 2001), 2) map geochemical regions (Zumlot et al., 2009), 3) identify areas of geochemical anomalies (Chamberlin, 2009), 4) provide insight into sedimentological depositional processes (Chamberlin et al., 1992), and 5) help conduct environmental studies, including identifying areas of elevated levels of radon.

The mean for 27,351 stream-sediment samples from the NURE data for New Mexico is 3.38 parts per million (ppm) uranium (Table 5). The median is 2.9 ppm uranium and the values range

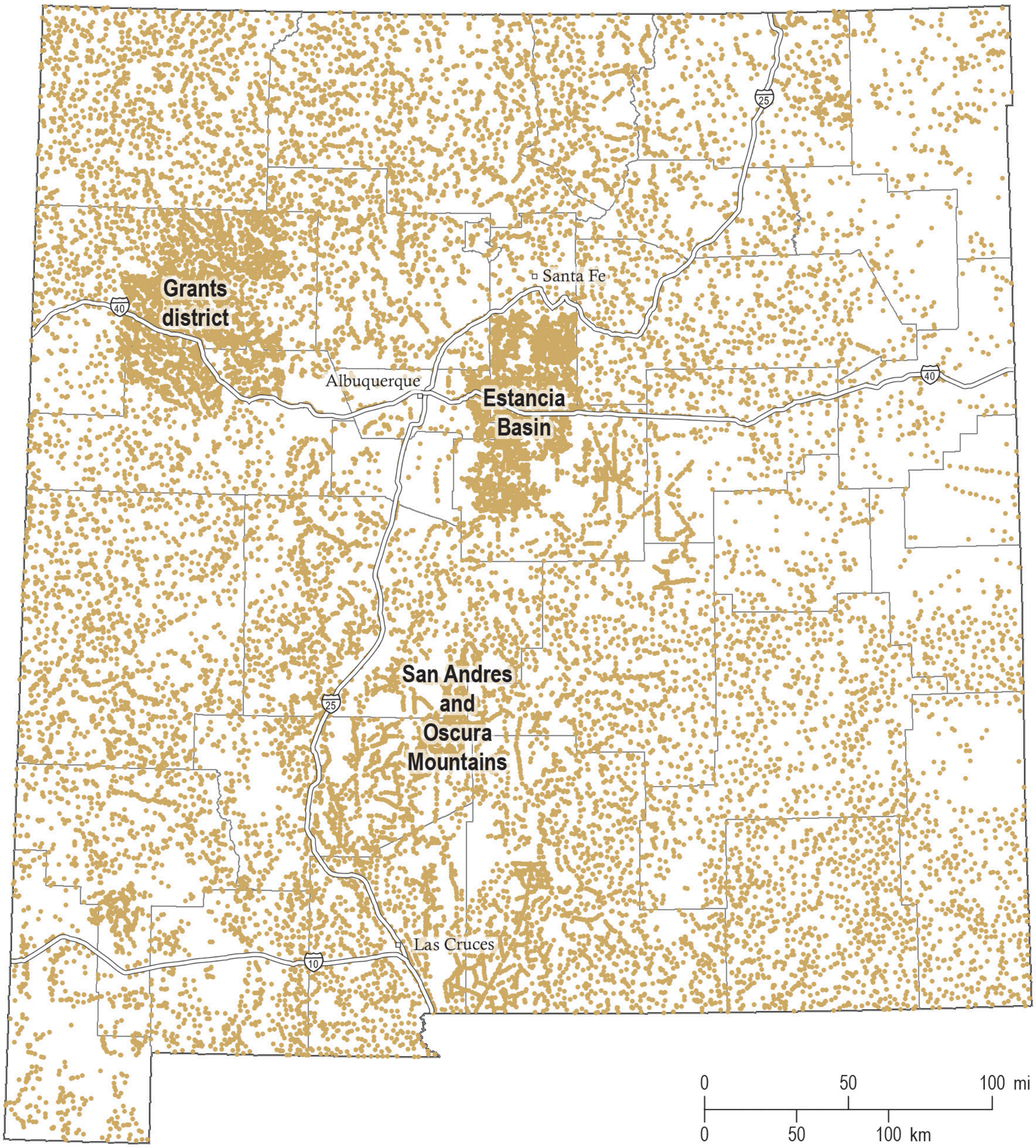


Figure 10. Distribution of NURE stream-sediment samples in New Mexico (data from Smith, 1997). A few areas were sampled and evaluated in greater detail and show a greater density of samples (the Estancia Basin, Grants district, and San Andres and Oscura Mountains areas).

Table 5. Average uranium concentrations in stream sediments in New Mexico. Any stream-sediment value above 12 ppm could be considered a geochemical anomaly.

Method	U Concentration (ppm)	Reference
Upper crustal abundance	2.7	Rudnick and Gao (2005)
Mean	3.38	NURE data
Median	2.9	NURE data
Mean + 2σ	12.2	Hawkes and Webb (1962)

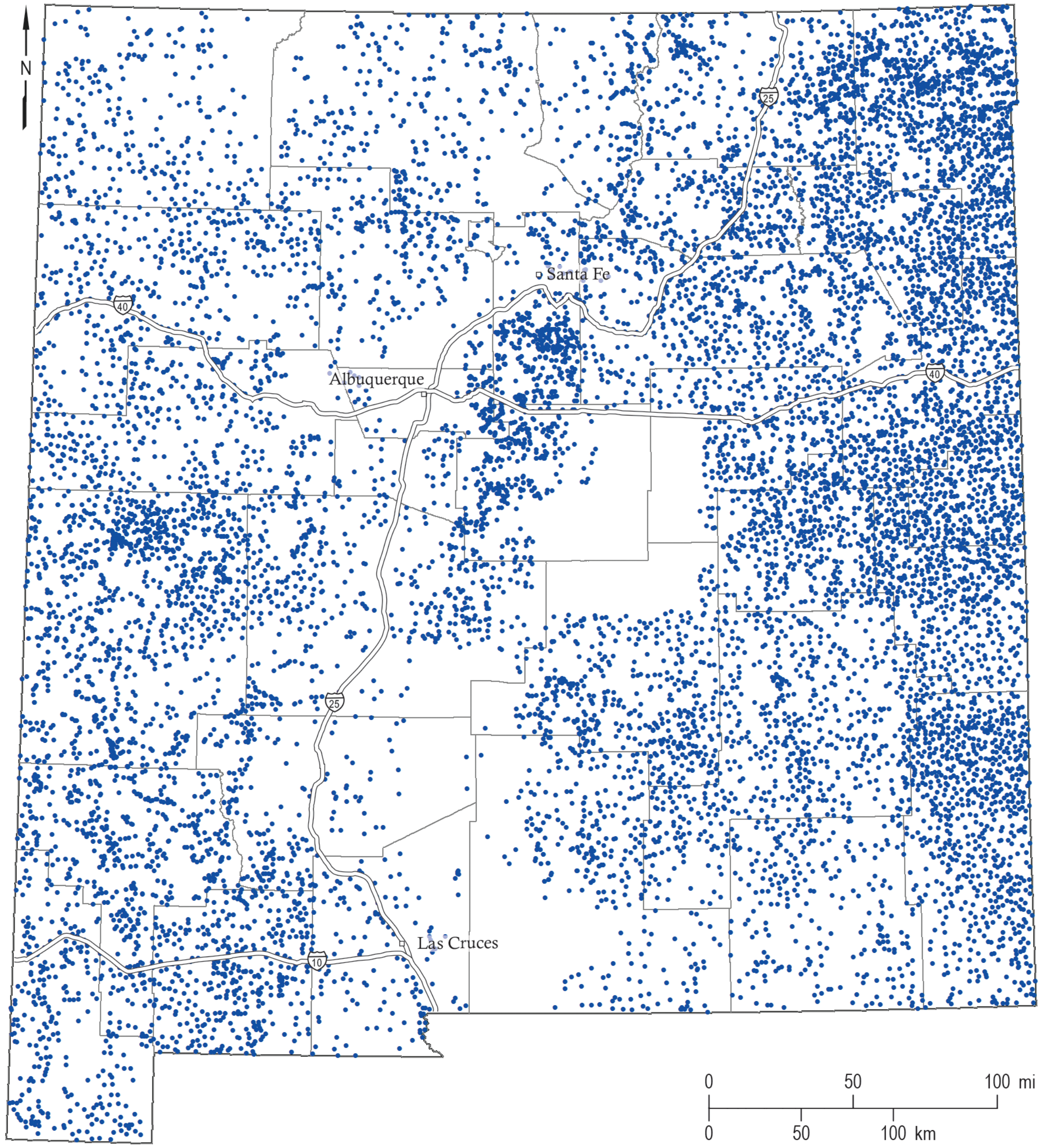


Figure 11. Distribution of NURE water samples in New Mexico (data from Smith, 1997). Areas of large data gaps represent areas where water samples could not be collected.

from 0.1 to 445.1 ppm uranium. Any stream-sediment value above 12 ppm uranium could be considered a geochemical anomaly (McLemore, 2010a). Determining the average concentration of uranium in waters from this data set would be misleading because the waters are quite diverse in depth and host formation. In 2005, the New Mexico Environment Department established the standard uranium concentration in drinking water must be below 0.03 mg/l uranium (or 30 ppb). Thus, any water sample exceeding 30 ppb uranium could be considered anomalous. Maps showing NURE stream-sediment or water concentrations and uranium occurrences of selected areas in New Mexico were plotted using ArcGIS and are included throughout this volume and in McLemore (2010a).

U-Th-REE in matrix of breccia at Fuzzy Nut prospect (NMLI0019) in the Capitan Mountains, Lincoln County. *Photo by V.T. McLemore.*

VI. DESCRIPTION OF THE PREDOMINANT URANIUM DEPOSITS IN NEW MEXIO

Sandstone uranium deposits account for the majority of the uranium production in New Mexico (McLemore and Chenoweth, 1989). The most significant deposits are those in the Morrison Formation, specifically the Westwater Canyon Member, where more than 169,500 short tons of U_3O_8 were produced from 1948 to 2002. In contrast, production from other sandstone uranium deposits in New Mexico amounted to 234 short tons U_3O_8 (1952–1970). Sandstone uranium deposits occur in other formations in New Mexico, but are insignificant compared to the Morrison Formation deposits (McLemore and Chenoweth, 1989). Uranium reserves and resources remain in the Grants district that could be mined in the future by both conventional underground techniques and by in situ leaching technologies (Table 6).

The types of uranium deposits in New Mexico are summarized in Table 2, many of which are found in the Grants district. Major uranium deposits are listed in Table 6 as updated from McLemore et al. (2013). The most important type of deposit in terms of production (Table 3) and resources (Table 6) is sandstone uranium deposits in the Morrison Formation (Jurassic) (Type A, Table 2).

Uranium Deposits in Sedimentary Host Rocks

Morrison Formation (Jurassic) sandstone uranium deposits

Three types of deposits are found in the Westwater Canyon Member of the Morrison Formation: 1) primary, tabular (also called trend or blanket), 2) redistributed (also called roll-type or stack), and 3) remnant-primary sandstone uranium deposits (Table 2, Figs. 12, 13). A fourth type, tabular sandstone uranium-vanadium deposits are found in the Salt Wash and Recapture Members of the Morrison Formation in the western San Juan Basin (Fig. 2).

***Primary, tabular sandstone uranium-humate deposits in the Morrison Formation*—**Primary, tabular sandstone uranium-humate deposits, also called as prefault, trend, blanket, and black-band ores, are found as blanket-like, roughly parallel ore bodies along linear 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 boundaries between mineralized sandstone and waste (unmineralized) rock (Fig. 12). The largest deposits in the Grants district contain more than 30 million lbs of U_3O_8 and contain large amounts of humates. These are the first uranium deposits to form in the Morrison Formation. These high carbon ores are well known to be difficult to recover by conventional milling techniques and will provide challenges to in situ recovery (ISR) operations (Holen and Hatchell, 1986).

***Redistributed sandstone uranium deposits in the Morrison Formation*—**Redistributed sandstone uranium deposits, also called post-fault, stack, secondary, and roll-type ores, are younger than the primary, tabular sandstone-hosted uranium deposits

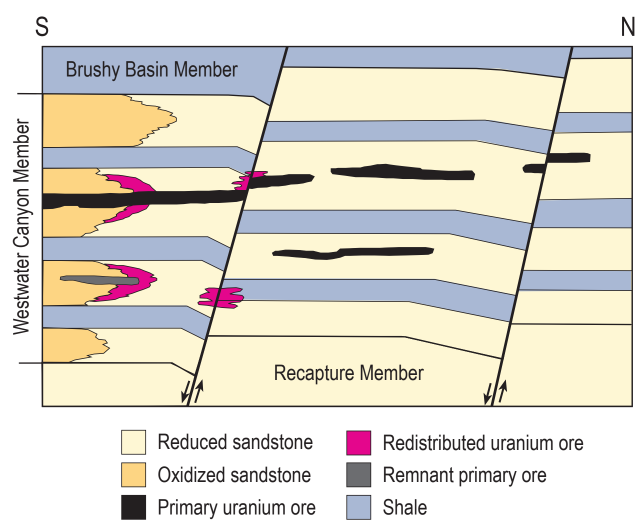


Figure 12. Sketch of the different types of uranium deposits in the Morrison Formation. See text for description.

Table 6. Estimated uranium resources in the Grants district, New Mexico (updated from McLemore, et al., 2011, 2013). Mine id (Mine identification number) and Subdistrict are from the New Mexico Mines Database (McLemore et al., 2002, 2013). Most deposits are delineated on maps by McLemore and Chenoweth (1991) and described in more detail by McLemore et al. (2002). Note that the information presented is from the best data available and is subject to change as new data are obtained. Resource statistics are generally historic and not Canadian Instrument 43-101 compliant. Host rock abbreviations are: Kd=Dakota Formation, Jm=Morrison Formation, Jj=Jackpile Sandstone, Jp=Poison Canyon Sandstone, Jb=Brushy Basin Member, Jwc=Westwater Canyon Sandstone, Js=Wanakah (Summerville) Sandstone, Jt=Todilto Formation, Datum is NAD27.

Mine Id	Subdistrict	Mine name	Latitude	Longitude	Host rock	Total resource (lbs U_3O_8)	Primary company
NMMK0003	Ambrosia Lake	Ann Lee	35.414444	107.79547	Jwc, primary	resources remain	Phillips Petroleum Co.
NMMK0008	Ambrosia Lake	Barbara J 2	35.328320	107.83393	Jt	resources remain	Mid-Continent Uranium Corp.
NMMK0009	Ambrosia Lake	Barbara J 3	35.333098	107.82497	Jt	resources remain	Todilto Exploration and Development Co.
NMBE0047	Laguna	Bernabe	35.210595	106.96538	Jwc	11,540,000	
NMSA0023	Laguna	Bernabe	35.227611	107.01086	Jwc, primary, redistributed	1,500,000	Laguna Pueblo
NMMK0020	Ambrosia Lake	Borrego Pass	35.620119	107.94362	Jwc, primary	45,000,000	Conoco
NMMK0025	Church Rock-Crownpoint	Canyon	35.656988	108.20692	Jwc, redistributed	600,000	
NMMK0034	Church Rock-Crownpoint	Church Rock (Section 17)	35.622209	108.55273	Jwc, Kd, redistributed	8,443,000	Uranium Resources Inc. (URI)
NMMK0033	Church Rock-Crownpoint	Church Rock 8, 2	35.606229	108.58616	Jwc	resources remain	
NMMK0128	Church Rock-Crownpoint	Church Rock ISL (Section 8)	35.630313	108.55064	Jwc, redistributed	6,529,000	URI
NMMK0316	Church Rock-Crownpoint	Church Rock (Section 4)	35.642301	108.53346	Jwc, redistributed	11,848,007	Energy Fuels (formerly Strathmore)
NMMK0035	Ambrosia Lake	Cliffside (Frosty Ox)	35.395569	107.74929	Jwc, primary, breccia pipe	resources remain	URI (formerly Trans America Industries, Neutron Energy)
NMMK0036	Church Rock-Crownpoint	Crownpoint	35.68475	108.16042	Jwc	resources remain	originally Conoco, Uranium Resources Inc.
NMMK0039	Church Rock-Crownpoint	Crownpoint	35.680444	108.13092	Jwc	resources remain	Originally Conoco, Uranium Resources Inc.
NMMK0038	Church Rock-Crownpoint	Crownpoint	35.717510	108.22681	Jwc, primary	resources remain	Mobil (Nufuels)
NMMK0040	Church Rock-Crownpoint	Crownpoint ISL (Unit 1)	35.706678	108.22052	Jwc, primary	27,000,000	Mobil-TVA
NMMK0346	Church Rock-Crownpoint	Crownpoint (Section 24)	35.684585	108.1677	Jwc, primary	38,959,000	Uranium Resources Inc.
NMMK0043	Church Rock-Crownpoint	Dalton Pass	35.678492	108.26496	Jwc, redistributed	600,000	UNC-TVA
NMMK0044	Church Rock-Crownpoint	Dalton Pass	35.681298	108.27829	Jwc, redistributed	200,000	UNC-TVA
NMCI0251	Ambrosia Lake	East Area	35.279174	107.74755	Jp	388,434	Laramide Resources
NMMK0712	Ambrosia Lake	East Roca Honda	35.373201	107.65319	Jwc, primary	resources remain	URI (formerly Trans America Industries Ltd.)
NMCI0012	Ambrosia Lake	F-33 (Grants Ridge)	35.219167	107.78369	Jt	resources remain	Uranium Energy Corp.
NMMK0065	Ambrosia Lake	Fernandez-Main Ranch	35.348611	107.66456	Jwc, primary	850,000	Gulf
NMMK0711	Smith Lake	Hosta Butte	35.64592	108.20164	Jwc, redistributed	14,822,000	Quincy
NMMK0087	Ambrosia Lake	Johnny M	35.362444	107.72219	Jwc, primary	3,500,000	Ranchers Exploration
NMMK0088	Marquez	Juan Tafoya-Marquez Grant	35.313362	107.31706	Jwc	751,000	Neutron Energy Inc.
NMCI0019	Laguna	L Bar (JJ)	35.175458	107.32655	Jj	12,653,000	Neutron Energy Inc. Uranium Energy Corp.
NMCI0020	Ambrosia Lake	La Jara Mesa	35.280139	107.74489	Jp	7,257,817	Laramide Resources
NMMK0094	Ambrosia Lake	Lee	35.360222	107.70275	Jwc	9,620,000	Roca Honda-Kerr-McGee

Table 6. Continued from previous page.

Mine Id	Subdistrict	Mine name	Latitude	Longitude	Host rock	Total resource (lbs U_3O_8)	Primary company
NMMK0101	Church Rock-Crownpoint	Mancos-Section 12	35.626449	108.58327	Jwc, redistributed	11,300,000	Energy Fuels (formerly Strathmore)
NMMK0100	Church Rock-Crownpoint	Mancos (Section 7)	35.628936	108.58055	Jwc, redistributed	4,164,000	Uranium Res. Inc.
NMMK0102	Smith Lake	Mariano Lake	35.547083	108.278	Jb	840,000	Gulf
NMMK0105	Ambrosia Lake	Marquez	35.343326	107.75994	Jp	resources remain	UNC
NMMK0104	Marquez	Marquez Canyon	35.324250	107.33005	Jwc	9,130,343	Kerr-McGee, TVA
NMMK0103	Marquez	Marquez Canyon (Bokum)	35.319194	107.32433	Jwc	10,700,000	Neutron Energy Inc.
NMSA0057	Marquez	Marquez Grant	35.305139	107.2908	Jwc, primary	676	
NMMK0245	Ambrosia Lake	Melrich (Section 32)	35.394462	107.70806	Jwc, primary	3,217,000	Homestake
NMRA0057	Coyote	Mesa Alta (Yeso)	36.220833	106.66239	Jt	resources remain	Magnum Uranium Corp.
NMCI0027	Ambrosia Lake	Mt. Taylor	35.334977	107.63558	Jwc, primary, redistributed?	30,250,000	Rio Grande Resources Corp., General Atomics
NMMK0111	Church Rock-Crownpoint	Narrow Canyon	35.644836	108.29841	Jwc, primary	828,000	Pioneer Nuclear
NMMK0117	Church Rock-Crownpoint	NE Church Rock	35.658409	108.50853	Jwc, redistributed	2,250,000	UNC
NMMK0112	Church Rock-Crownpoint	NE Church Rock 1	35.666496	108.50273	Jwc, primary, redistributed	708,589	Navajo Indian Reservation
NMMK0114	Church Rock-Crownpoint	NE Church Rock 2	35.676632	108.52621	Jwc, primary	2,850,000	Kerr-McGee
NMMK0115	Church Rock-Crownpoint	NE Church Rock 3	35.697561	108.54866	Jwc, primary	4,200,000	Kerr-McGee
NMMK0119	Nose Rock	Nose Rock	35.884364	107.99161	Jwc, primary, redistributed?	21,900,000	URI
NMMK0122	Nose Rock	Nose Rock	35.830361	108.06414	Jwc	3,620,000	Phillips Petroleum Co.
NMMK0350	Nose Rock	Nose Rock	35.844966	108.05007	Jwc	2,070,800	Phillips Petroleum Co.
NMMK0120	Nose Rock	Nose Rock 1	35.83556	108.05528	Jwc, primary, redistributed?	14,017,298	Energy Fuels (formerly Strathmore)
NMSA0074	Ambrosia Lake	Rio Puerco	35.271444	107.19803	Jwc, primary	11,362,640	Ausamerican Mining
NMMK0142	Ambrosia Lake	Roca Honda	35.365717	107.6966	Jwc, primary	17,512,000	Energy Fuels (formerly Strathmore)
NMMK0143	Ambrosia Lake	Roca Honda	35.363139	107.69961	Jwc, primary	14,700,000	Uranium Resources Inc.
NMCI0046	Laguna	Saint Anthony	35.159088	107.30614	Jt	8,208,000	51 percent Neutron Energy Inc., 49 percent Uranium Energy Corp.
NMCI0050	Marquez	San Antonio Valley	35.256361	107.25844	Jwc	resources remain	
NMMK0149	Ambrosia Lake	Sandstone	35.396194	107.769	Jwc, primary	resources remain	UNC
NMMK0179	Ambrosia Lake	Section 13	35.348778	107.63547	Jp	resources remain	URI
NMMK0198	Ambrosia Lake	Section 18	35.44625	107.93733	Jwc	resources remain	URI (formerly Trans America Industries Ltd.)
NMMK0210	Ambrosia Lake	Section 24 (Treeline)	35.347278	107.74672	Jb	resources remain	Western Uranium Corp.
NMMK0222	Ambrosia Lake	Section 26	35.408972	107.76286	Jwc, primary	resources remain	URI (formerly Trans America Industries Ltd.)
NMMK0223	Ambrosia Lake	Section 26	35.40776	107.75696	Jwc, primary	resources remain	Kerr-McGee
NMMK0239	Ambrosia Lake	Section 31 (Frosty Ox)	35.398194	107.72336	Jwc	1,002,160	URI (formerly Trans America Industries, Neutron Energy)
NMMK0126	Church Rock-Crownpoint	Section 32-Dalton Pass	35.664222	108.23567	Jwc, redistributed	1,529,823	
NMMK0250	Ambrosia Lake	Section 35 (Elizabeth)	35.398861	107.75842	Jwc, primary	resources remain	Quivira Mining Company (Rio Algom LLC)

Table 6. Continued from previous page.

Mine Id	Subdistrict	Mine name	Latitude	Longitude	Host rock	Total resource (lbs U_3O_8)	Primary company
NMMK0251	Ambrosia Lake	Section 36 (Ambrosia Lake)	35.399083	107.73394	Jwc, primary, redistributed	resources remain	Neutron Energy
NMCI0056	Ambrosia Lake	Section 4	35.296777	107.78773	Jt	Minor reserves remaining	UNC
NMMK0170	Ambrosia Lake	Section 6 (Mesa Redonda)	35.46975	107.92969	Jwc	resources remain	URI (formerly Trans America Industries Ltd.)
NMMK0173	Ambrosia Lake	Section 8	35.461639	107.92347	Jwc	resources remain	URI (formerly Trans America Industries Ltd.)
NMCI0057	Ambrosia Lake	Section 9	35.288667	107.79544	Js, Jt	resources remain	UNC
NMMK0338	Ambrosia Lake	Vanadium	35.333391	107.85629	Jm	2,500,000	
NMMK0340	Ambrosia Lake	West Largo	35.5257	107.92151	Jwc	19,600,000	Gulf, Santa Fe Industries, Strathmore
NMMK0247	Smith Lake	West Ranch (Begay Allotment)	35.49039	108.01622	Jwc, redistributed	2,600,000	UNC
Total Grants district						**403,122,587**	Plus undetermined resources remaining
NMSO0515	Hook Ranch-Riley	C de Baca	34.2958753	107.248917	Baca Formation	6,000,000	Max Resource Corp.
Total New Mexico						**409, 122,587**	Plus undetermined resources remaining

in the Morrison Formation. They are discordant, asymmetrical, irregularly shaped, characteristically more than 8 ft thick, have diffuse boundaries between mineralized sandstone and waste (unmineralized) rock, and cut across sedimentary structures. The average deposit in the Morrison Formation contains approximately 18.8 million lbs U_3O_8 with an average grade of 0.16% and contains little humates. Some redistributed uranium deposits are vertically stacked along faults (Figs. 12). After formation of the primary, tabular sandstone uranium deposits, oxidizing groundwaters migrated through the primary, tabular sandstone uranium deposits and remobilized some of the uranium into the groundwater (Saucier, 1981). Uranium was then reprecipitated ahead of the oxidizing waters forming redistributed sandstone uranium deposits (Fig. 13).

Remnant sandstone uranium deposits in the Morrison Formation—Remnant sandstone 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 were not oxidized by the oxidizing groundwater. 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 deposit in the Morrison Formation is approximately 2.7 million lbs U_3O_8 at a grade of 0.20%.

There is no consensus on the origin of the Morrison Formation primary, tabular sandstone uranium deposits (Sanford, 1992). The source of the uranium and vanadium deposits both in the Todilto Formation and Morrison Formation sandstones in the Grants district is not well understood. The uranium could be derived from alteration of

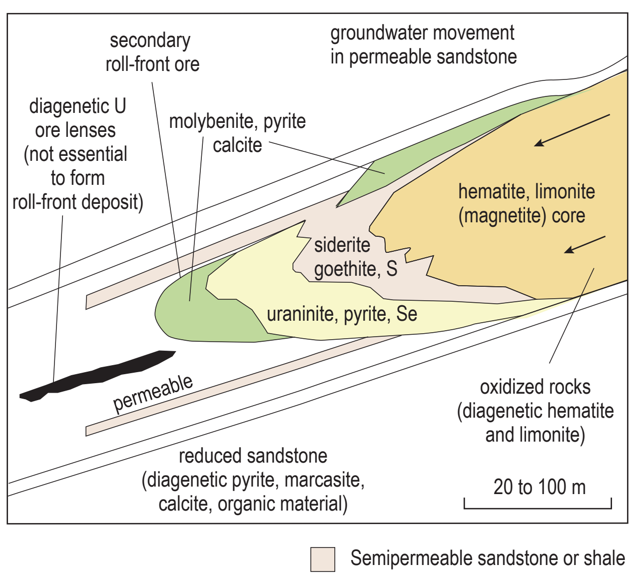


Figure 13. Sketch of the formation of redistributed sandstone uranium deposits. See text for description. *From Nash et al. (1981) and Devoto (1978).*

volcanic detritus within the shales in the Morrison Formation that were erupted from the volcanoes that form the Jurassic arc to the west of New Mexico (Fig. 14; Thamm et al., 1981; Adams and Saucier, 1981; Turner-Peterson, 1985; Turner-Peterson and Fishman, 1986; McLemore, 2011). The uranium also could be from groundwater derived from a volcanic highland to the southwest (i.e., the Jurassic arc) (Sanford, 1982, 1992). Knowing the source of uranium is important in understanding how the Grants deposits formed, establishing U.S. Geological Survey (USGS) geologic deposit type and geoenvironmental models, and locating additional uranium provinces elsewhere in the world.

The ages of the uranium deposits in the Grants district are constrained by numerous isotopic studies (Table 7; Fig. 15) and support a Jurassic arc as the potential source. Jurassic volcanism, intra-arc sedimentation, and plutonism are well-documented throughout the Jurassic arc (Saleeby and Busby-Spera, 1992; Miller and Busby, 1995; Blakey and Parnell, 1995; Lawton and McMillan, 1999; Kowallis et al., 1999, 2001; du Bray, 2007).

Another potential source of uranium in the Grants district is a Proterozoic granitic highland, enriched in uranium, which lies south of the district (i.e., the Zuni Mountains, Fig. 1). Gruner (1956) proposed that weathering and erosion of Proterozoic granitic rocks could have released large quantities of uranium, which along with uranium derived from volcanic ash, would have been sufficient to produce the uranium deposits in the Grants district. Silver (1977) was one of the first to note a regional anomaly in uranium concentration in the Proterozoic basement granitic rocks of the Colorado Plateau (Fig. 2). The Zuni Mountains area (south and southwest of the Grants district) is known for its high heat flow of approximately 2–2.5 heat flow units (Reiter

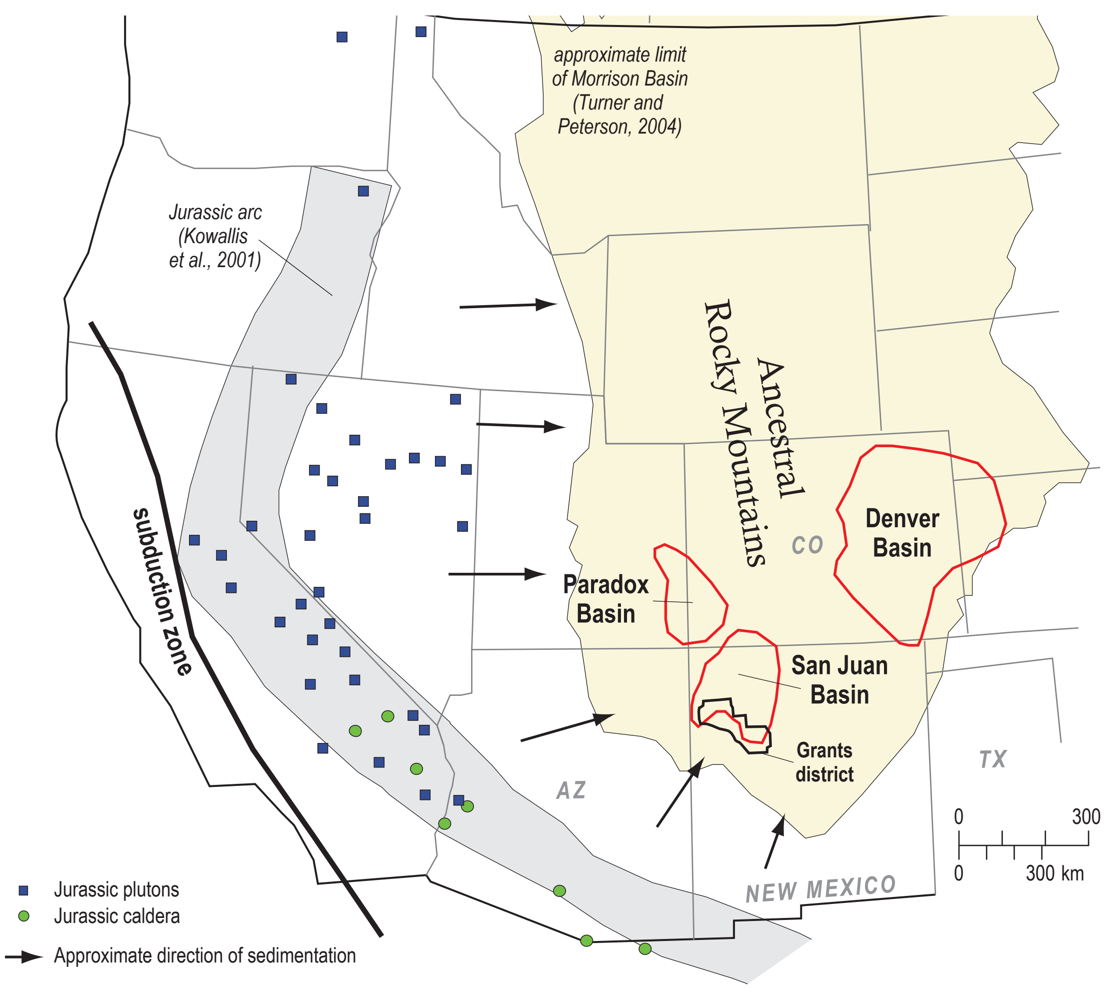


Figure 14. Approximate location of the Jurassic arc in relation to the Morrison Basin (McLemore, 2011). The gray polygon represents the chain of volcanoes formed during the Jurassic Period, with the Morrison Basin in beige. Three subbasins also are delineated, including the Grants district in the southern San Juan Basin. *From Kowallis et al. (1999), du Bray 2007), Lawton and McMillan (1999), Jurassic Mexican Borderland rift, Lawton and McMillan (1999).*

Table 7. Sequence of uranium deposition in the Grants district (from youngest to oldest). The age of the mineralizing event is from isotopic dating (Fig. 12) or is estimated by the author based upon stratigraphic position.

Depositional event	Age	Reference
Secondary Todilto Formation deposits	Tertiary, 3–7 Ma	Berglof (1989)
Redistributed uranium deposits (Cretaceous Dakota Sandstone, Jurassic Brushy Basin and Westwater Canyon Sandstone members)	Tertiary, 3–12 Ma	Miller and Kulp (1963), Nash and Kerr (1966) , Nash (1968), Brookins et al. (1977), Brookins (1980), Ludwig et al. (1982), Hooper (1983)
Redistributed uranium deposits (Cretaceous Dakota Sandstone, Jurassic Brushy Basin and Westwater Canyon Sandstone members)	Cretaceous, 80–106 Ma	Smith, R., and V.T. McLemore (unpublished)
Uranium in the Jackpile Sandstone	110–115 Ma	Lee (1976)
Uranium in the Poison Canyon Sandstone	Unknown, estimated 130–115 Ma	
Uranium in the Brushy Basin Member	Unknown, estimated 130–115 Ma	
Uranium in the Westwater Canyon Sandstone Member	148–130 Ma	Miller and Kulp (1963), Nash and Kerr (1966) , Nash (1968), Brookins et al. (1977), Brookins (1980), Ludwig et al. (1982), Hooper (1983)
Deposition of the Morrison Formation units	Unknown, estimated before 130 Ma	
Todilto Formation uranium deposits	155–150 Ma	Berglof (1970, 1989)
Deposition of the Todilto Formation	Before 155 Ma	

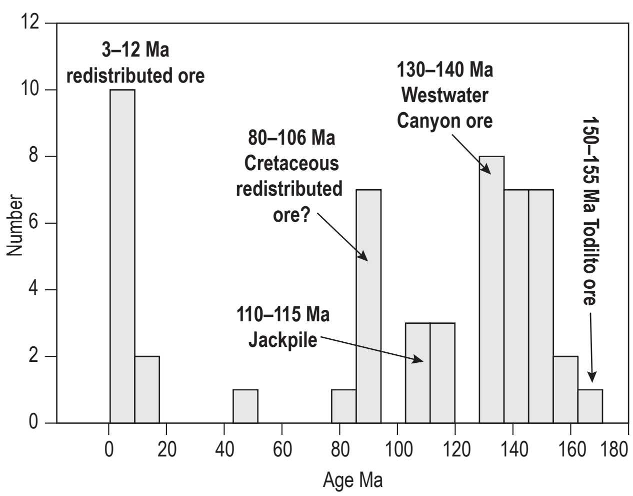


Figure 15. Age determinations of Grants district mineralization (McLemore, 2011). Includes Pb/U, K/Ar, Rb/Sr, and fission track dates from Miller and Kulp (1963), Nash and Kerr (1966), Nash (1968), Berglof (1970, 1989), Brookins et al. (1977), Brookins (1980), Ludwig et al. (1982), Hooper (1983) and is summarized by Wilks and Chapin (1997).

et al., 1975), and Proterozoic granites in the Zuni Mountains contain as much as 11 ppm uranium (Brookins and Rautman, 1978), thus suggesting that these granites could have been a local uranium source.

Uranium leached from the altered volcanic ash and from erosion of the Proterozoic granitic highland could have been carried by groundwater and surface waters into the Todilto Formation and later into the Morrison Formation, forming the uranium deposits found in the Grants district. The presence of organic material caused the precipitation of the uranium in the deposits, as summarized in Table 7.

The majority of the proposed models for formation of the Grants sandstone uranium deposits suggest that deposition occurred at a groundwater 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, groundwater was expelled by compaction from lacustrine muds formed by a large playa lake. The groundwater was expelled 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 groundwater (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 groundwater brines (Granger and Santos, 1986). In another variation of the brine-interface model, groundwater flow is driven by gravity, not compaction. Groundwater 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 groundwater flow in the Colorado Plateau during Late Jurassic and Early Cretaceous times supports the brine-interface model (Sanford, 1982). The groundwater flow was impeded by up-thrown blocks of Proterozoic 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 Formation sandstones and the geometry of tabular uranium-vanadium bodies floating in sandstone beds support the reaction of two chemically different waters, most likely a dilute meteoric water and a saline brine from deeper in the basin. The intimate association of uranium-vanadium minerals with organic material further indicates that uranium and vanadium minerals 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.

After formation of the primary, tabular sandstone uranium deposits during Tertiary time, oxidizing groundwater migrated through the uranium deposits and remobilized some of the primary, tabular sandstone uranium deposits (Fig. 13; 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 (Figs. 12, 13).

Sandstone uranium deposits occur in other formations in New Mexico, but are insignificant compared to the Morrison Formation deposits (McLemore and Chenoweth, 1989), although some companies are once again examining these units. Uranium reserves and resources remain in the Grants district. These reserves 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 Carrizo Mountains (including the King Tutt Mesa area) and Chuska Mountains districts in the Shiprock area (Fig. 4; western San Juan Basin) where production totaled 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). The Salt Wash Member 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 sandstone uranium deposits are generally elongated parallel to paleostream channels and are associated with carbonized fossil plant material. They tend to form subhorizontal clusters that are elongated and blanket-like (Fig. 16). A cluster of small ore bodies along a trend could contain as much as 4,000 short tons of ore averaging 0.23%

Figure 16. Tabular sandstone uranium deposits (dark gray) above the adit to the King Tutt mine (NMSJ0069). *Photo by Kenneth Hatfield.*

U_3O_8 (Hilpert, 1969; Chenoweth and Learned, 1984; McLemore and Chenoweth, 1989, 1997). Ore bodies in the King Tutt Mesa area (Fig. 4) are small and irregular and only a few ore bodies have yielded more than 1,000 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 the uranium deposits in the Grants district, the deposits at King Tutt Mesa are high in vanadium content. The uranium to vanadium concentration ratio averages 1:10 and ranges from 1:1 to 1:16.

The deposits are largely 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 sandbars, swamp and lake deposits, and humates. Small, high-grade ore pods (>0.5% U_3O_8) are associated with fossil wood. The uranium-vanadium minerals

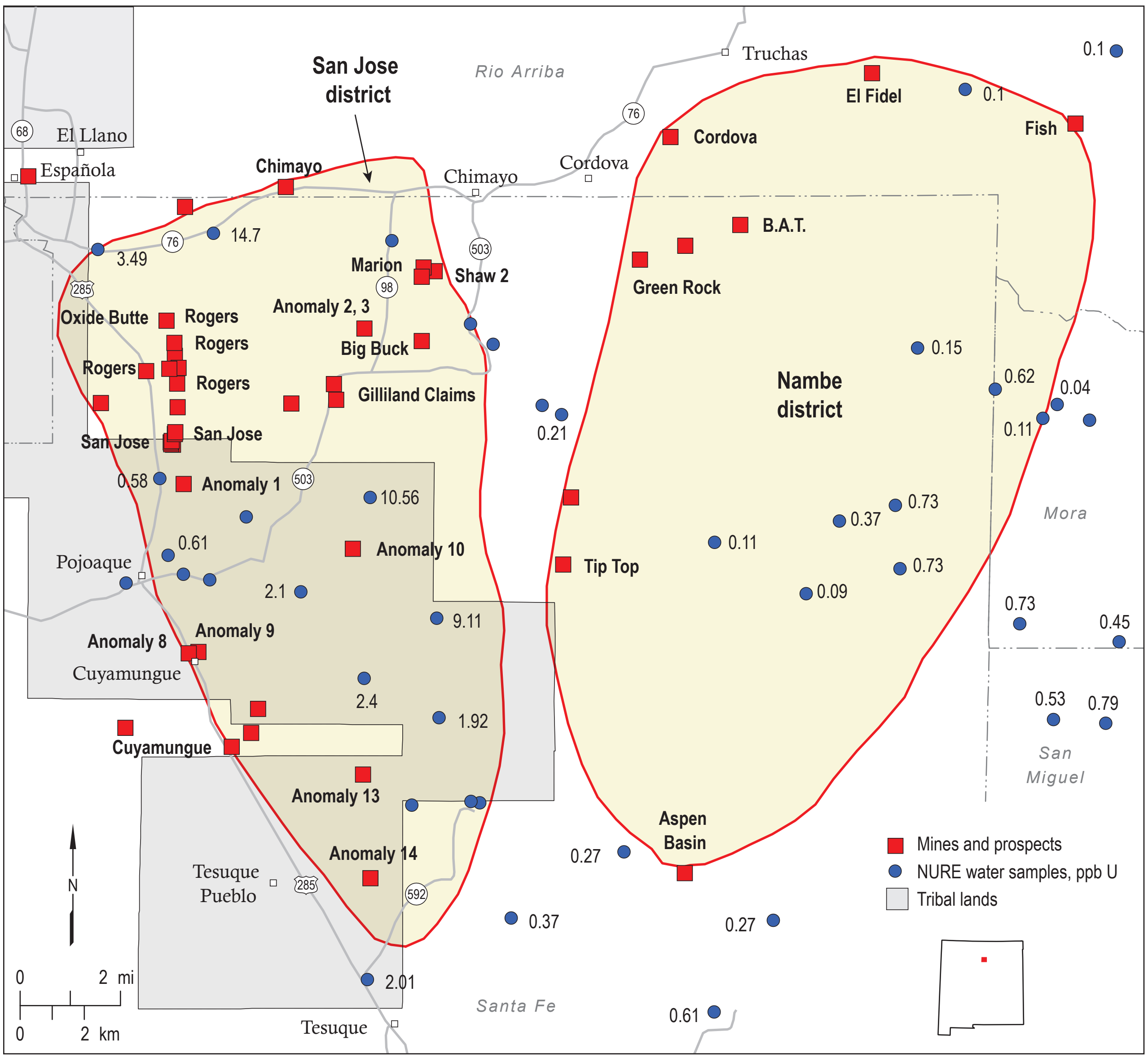


Figure 17. Uranium mines and occurrences and NURE water samples in the San Jose and Nambe districts, Espanola Basin, Santa Fe County, New Mexico. Any water sample exceeding 30 ppb uranium could be considered anomalous.

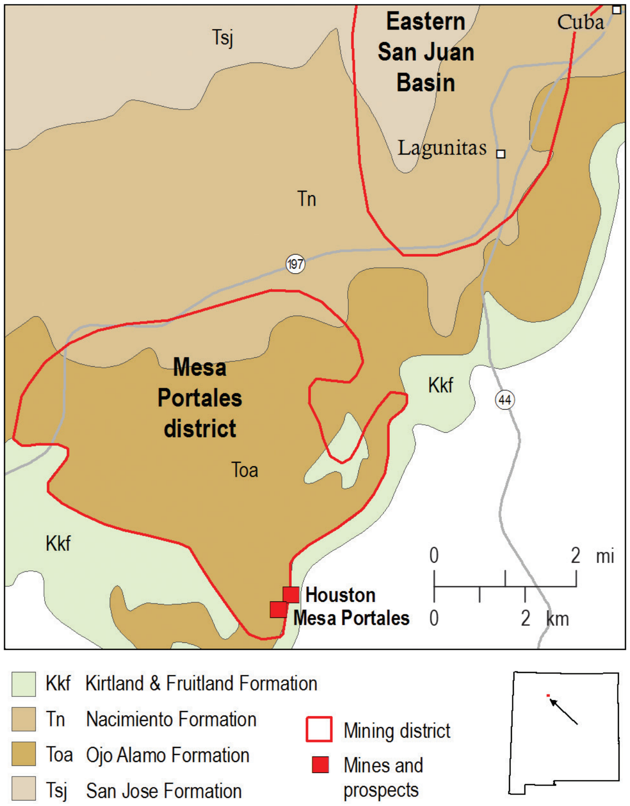


Figure 18. Mesa Portales area, Sandoval County, New Mexico.

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 groundwater flow in the Colorado Plateau during Late Jurassic and Early Cretaceous times supports the brine-interface model for these deposits and indicates that the regional groundwater flow in the King Tutt Mesa area was to the northeast (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; Fig. 2; Chenoweth, 1989a). These deposits are similar to redistributed uranium 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 2,500 ft long and 1,000 ft wide. The larger deposits are only a few feet thick, but some are as up to 25 ft thick (Hilpert, 1969). Ore grades ranged from 0.12–0.30% 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, 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 of the Morrison Formation.

The largest deposits in the Dakota Sandstone are found in the Church Rock mine (NMMK0034, Old Church Rock) in the Church Rock subdistrict of the Grants district (Fig. 2), 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 Church Rock mine (NMMK0034; Chenoweth, 1989a).

Roll-type sandstone uranium deposits in Cretaceous and Tertiary sandstones—Roll-type sandstone uranium deposits are found in the Tesuque Formation (San Jose district, DIS188) in the Espanola Basin (Fig. 17) and Ojo Alamo Sandstone (Farmington, DIS154, Mesa Portales, DIS175; Fig. 18) areas of the San Juan Basin, where production totals 60 lbs of U_3O_8 (Table 2; McLemore and Chenoweth, 1989). Roll-type sandstone uranium deposits are found elsewhere in New Mexico but were not significant producers. Roll-type 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 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, 1980b). 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, 1980b).

Three varieties of roll-type sandstone uranium deposits are found in the Tesuque Formation in the San Jose district, Santa Fe County (Fig. 17): 1) medium-grained sandstone with uranium associated with clay galls and carbonaceous material; 2) poorly consolidated fine-to medium-grained sandstone with disseminated uranium and little carbonaceous material; and 3) coarse-grained sandstone to conglomerate with abundant uranium associated with carbonaceous material (McLemore et al., 2011). Carnotite ($K_2(UO_2)_2V_2O_8 \cdot 3H_2O$), schroeckingerite ($NaCa_3(UO_2)(CO_3)SO_4)F \cdot 10H_2O$), and meta-autunite ($Na_2(UO_2)_2(PO_4)_2 \cdot 6\text{-}8H_2O$) coat fractures and bedding surfaces in sandstone, siltstone and shale within the Tesuque Formation, especially near clay galls and carbonaceous material (Chenoweth, 1979). Uranium in the San Jose district also occurs as a coating around opal and chert grains, with organic debris, in clay zones, and in fossil bone fragments within the Tesuque Formation. Anomalously high uranium concentrations are found in both NURE water and stream-sediment samples and local residents have high concentrations of uranium and radon in their drinking water (McQuillan et al., 2012; McLemore et al., 2012). Concentrations of natural uranium vary from less than 0.002 mg/L to 1.82 mg/L in groundwater within the Española Basin (McQuillan et al., 2012). Uranium concentrations exceeding the EPA drinking water standard of 0.030 mg/L are of public health concern. The sandstone uranium occurrences in the Tesuque Formation represent natural precipitation and concentration from uraniferous groundwater, likely derived from: 1) rhyolitic volcanic ash beds within the Tesuque Formation; 2) the alteration of granitic and/or volcanic detritus within the sedimentary host rocks; and 3) Proterozoic rocks in the Nambe district in the Sangre de Cristo Mountains to the east (Fig. 17; McLemore et al., 2011, 2012).

Roll-type sandstone uranium deposits were discovered in the Red Basin-Pietown district (DIS008) and Hook Ranch-Riley (DIS214), Catron and Socorro Counties south of the Grants district (Figs. 1, 19) around 1954. From 1954–1957, 1,194 lbs of U_3O_8 (grade 0.17% U_3O_8) were produced from the district. The Cretaceous Crevasse Canyon Formation consists of interbedded sandstones, siltstones, shales, and coal deposited in a coastal-plain environment. The Cretaceous Crevasse Canyon Formation is unconformably overlain by mudstones, siltstones, sandstones, and conglomerates belonging to the Eocene Baca Formation that was deposited in a braided-alluvial plain, meander belt, and lacustrine environment. Additional deposits are found in the Baca Formation in the Riley area (Fig. 1).The majority of the uranium deposits are found in a 25–150 ft thick paleosol

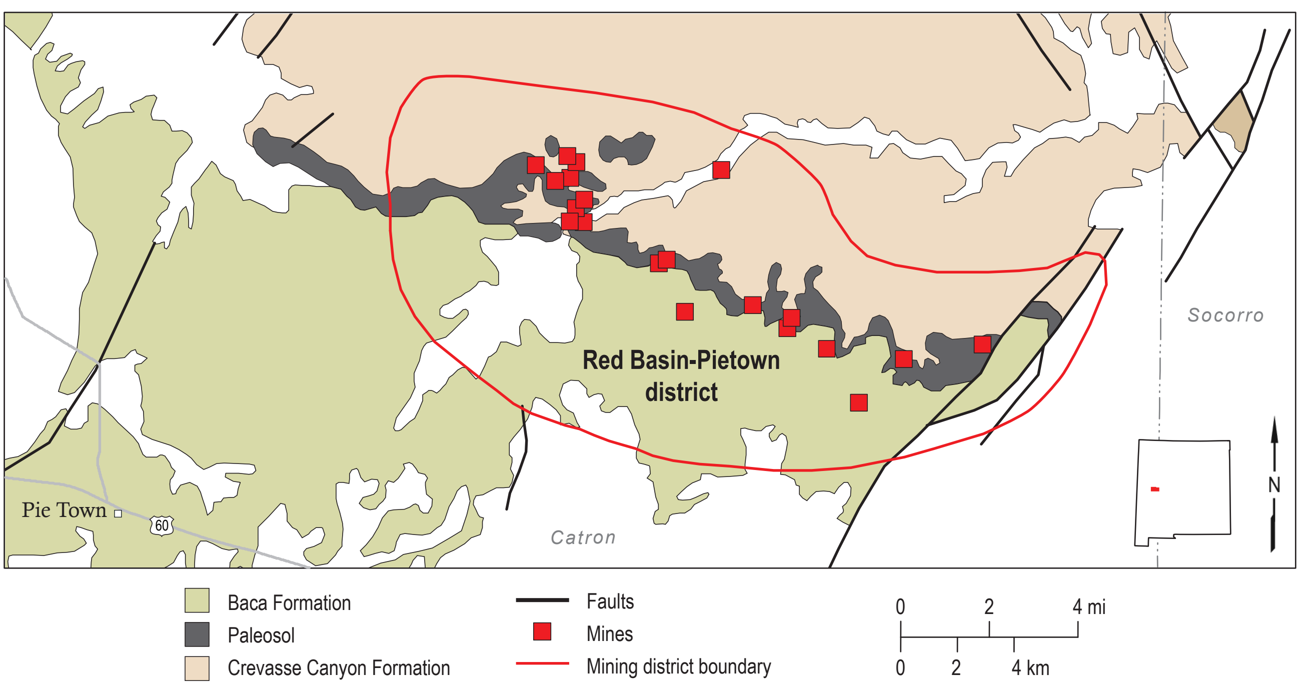


Figure 19. Uranium mines and prospects along the paleosol between the Crevasse Canyon Formation and Baca Formation in the Red Basin-Pietown district, Socorro and Catron Counties, New Mexico.

formed at the top of the Crevasse Canyon Formation, just below the Baca Formation (Fig. 19; Chamberlin, 1981). These uranium occurrences are associated with organic material, clay galls, iron staining, and sandstone-shale interfaces (i.e., oxidation-reduction interfaces). Selected samples contain as much as 0.024% U_3O_8, although reported assays are as much as 1.28% U_3O_8. Uranium is locally found associated in the overlying Baca Formation. Numerous NURE water samples from wells in the area contain greater than 20 ppb uranium, further indicating uranium mineralization in the subsurface; the highest value is 682.6 ppb uranium (Morgan, 1981). Several companies have recently explored in the Red Basin-Pietown and Hooks Rach districts (Fig. 19).

Several origins have been proposed for the Red Basin-Pietown deposits, but only one is consistent with the geologic history (Chamberlin, 1981). Uranium was deposited in the Crevasse Canyon sandstones after the formation of a lateritic weathering soil profile (indicating a hot and humid climate) at the top of the sandstone. Uranium was leached from shales and volcanic detritus in the Crevasse Canyon Formation. Roll-type sandstone deposits formed at the oxidation-reduction boundaries between actively flowing groundwater and basin pore waters. Subsequently, these older uranium deposits were buried by the Baca Formation and Tertiary volcanic rocks. Additional uranium leached from these rocks and minor redistribution likely occurred by groundwater flowing into the Baca Basin.

In the Hagan Basin in southern Sandoval County (T13N,R6E; T14N,R6E), more than 1,000 claims were staked from 1974–1978 by Union Carbide, Mobil Oil, and Western Nuclear (Moore, 1979), Uranium Energy Corporation restaked in 1998, and again in 2006. Roll-type sandstone mineralization was found in steeply dipping Galisteo Formation sandstones, a few miles northwest of the Placitas district in the Sandia Mountains (Fig. 20). Grades in excess of 0.20% U_3O_8 were encountered in the drilling. A historical resource of approximately 900,000 short tons of ore with a grade of 0.05% U_3O_8 was delineated at the Diamond Tail deposit (NMSA0045).

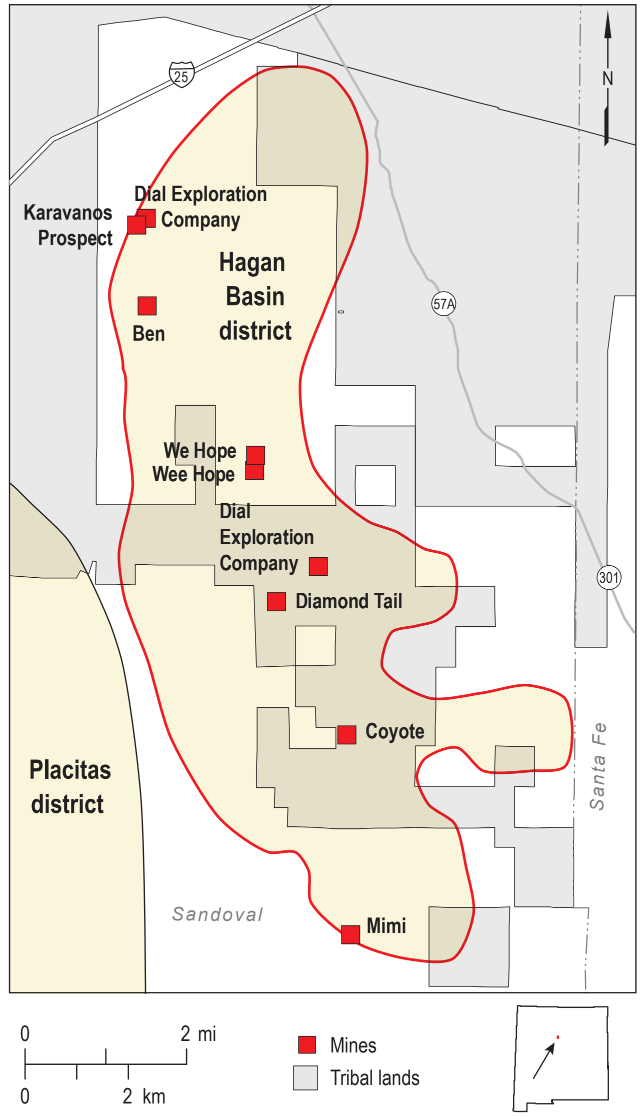


Figure 20. Uranium mines and occurrences in the Hagan Basin, Sandoval County, New Mexico.

Sedimentary 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 (NMSJ0028) near Farmington and in the Chinle Group throughout northern New Mexico (McLemore, 1983). Uranium was precipitated from uranium-bearing groundwater. 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 copper, silver, and locally gold, lead, zinc, uranium, vanadium, and molybdenum are found throughout New Mexico (Fig. 1). 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. These sequences consist of red, brown, purple, or yellow sedimentary rocks deposited in fluvial, deltaic or marginal-marine environments of Pennsylvanian, Permian, or Triassic age (such as deposits in the Coyote, DIS141 and Gallina, DIS144, districts). 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 (DIS017) and Nacimiento (DIS176) districts (McLemore, 1983; McLemore and Lueth, 2017), 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 amounts of uranium minerals. Copper and uranium minerals in these sedimentary-copper deposits are commonly associated with organic debris and other carbonaceous material.

Copper, uranium and other metals were probably transported in low-temperature brine solutions through permeable sediments, along bedding planes, and faults, shortly after burial. Replacement textures and diagenetic features of the organic material indicate mineralization occurred during or after diagenesis. Oxidizing waters could have leached copper and other metals from 1) Proterozoic rocks enriched in these metals, 2) Proterozoic base-metal deposits, and 3) clay minerals and detrital grains within the red-bed sequences (La Point, 1976, 1979, 1989; Brown, 1984). Sources for chloride and carbonate needed to form soluble cuprous-chloride or cuprous-carbonate and other metal complexes (Rose, 1976) occur in older Paleozoic evaporite and carbonate sequences. Transport of metal-bearing waters occurred laterally through the aquifers from Proterozoic highlands or, in some cases, by circulating, ascending fluids (Brown, 1984). Geologic, mineralogic, and isotopic studies of similar deposits elsewhere in the United States suggest that these waters are in approximate chemical equilibrium with quartz, feldspar, hematite, and mica at temperatures less than 75°C (Rose, 1976). Precipitation occurred at favorable oxidation-reduction interfaces in the presence of organic material or H_2S-rich waters. Geologic membrane processes have been proposed as a possible concentration mechanism in these deposits, but the role of this process in deposition is still a matter of debate (Lueth and Whitworth, 2001; 2009). Subsequent geologic processes, such as groundwater, igneous intrusions (such as at Sacramento), and/or structural events could have modified, altered, or even destroyed some deposits (La Point, 1979).

Beach placer 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 (Houston and Murphy, 1970, 1977; McLemore, 2010b; McLemore and Lueth, 2017). Many beach-placer sandstone deposits contain high concentrations of thorium, rare earth elements, zirconium, hafnium, titanium, nobelium, tantalum, and iron; uranium is rare, and only one deposit, the Hogback deposit in sec.15, T30N, R16W (NMSJ0054; Fig. 4), yielded minor uranium production (McLemore, 1983, 2010b). In 1954, a test shipment of 8 short tons of ore was shipped to an AEC ore-buying station by Willie Davidson (McLemore, 1983). This shipment yielded 3 lbs of ore grading 0.02% U_3O_8 and 23 lbs of V_2O_5. Detrital heavy minerals comprise approximately 50–60% of the sandstones and typically consist of titanite, zircon, magnetite, ilmenite, monazite, apatite, and allanite, among other minerals. Although beach-placer sandstone deposits are found in strata of all ages throughout the world, the deposits in the San Juan Basin in New Mexico are restricted to Late Cretaceous rocks belonging to the Gallup, Dalton, Point Lookout, and Pictured Cliffs Sandstones (Chenoweth, 1957; Houston and Murphy, 1970, 1977; McLemore, 2010a). The beach-placer sandstones range in color from black to dark gray to olive-brown. They are also resistant to erosion, and radioactive due to zircon, monazite, apatite, and thorium minerals (Fig. 21). They rarely exceed several hundred feet in length, are only tens of feet wide, and 3–5 ft thick. However, the known deposits in the San Juan Basin collectively contain 4,741,200 short tons of ore containing 12.8% TiO_2, 2.1% zirconium, 15.5% iron 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 near 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 Formation are some of the largest and most productive (Chenoweth, 1985a; Gabelman and Boyer, 1988). Uranium minerals were found in the Todilto Formation in the early 1920s, although it was Paddy Martinez's discovery in 1950 that resulted in development of the Grants district. From 1950 to 1981, mines in the Grants district yielded 6,671,798 lbs of U_3O8 from the Todilto Formation, 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, 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 Formation. 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 (beginning of the Jurassic arc, Fig. 14) migrated through the Entrada Sandstone. Groundwater migrated into the Todilto Formation by evapotranspiration or evaporative pumping. Uranium precipitated in the presence of organic material within the intraformational folds and associated fractures in the limestone (Figs. 22, 23; Rawson, 1981; Finch

Figure 21. Dark-brown beach placer sandstone at Sanostee, San Juan County (NMSJ0088). *Photo by Virginia T. McLemore.*

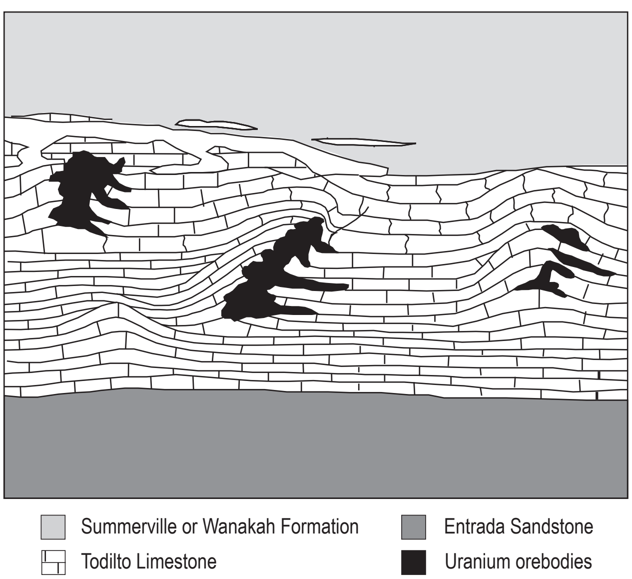


Figure 22. Control of Todilto Formation uranium deposits by intraformational folds and fractures within the limestone *(modified from Finch and McLemore, 1989).*

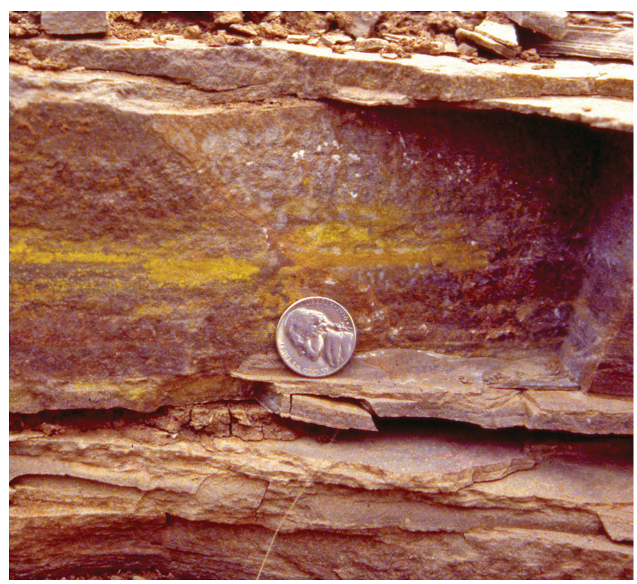


Figure 23. Yellow carnotite and tyuyamunite within Todilto Formation limestone bed at the Section 32 Quarry (NMMK0242). *Photo by Virginia T. McLemore.*

and McLemore, 1989). Museum-quality minerals such as uranophane (Fig. 24) and santafeite (Fig. 25) are found in the Ambrosia Lake subdistrict in the Todilto Formation. The Todilto Formation uranium deposits are 150–155 Ma, based on uranium-lead (U-Pb) isotopic dating, and are older than the 130 Ma Morrison Formation sandstone uranium deposits (Fig. 15; Berglof, 1970, 1989).

More than 100 uranium mines and occurrences are found in the Todilto Formation in New Mexico, and 42 mines have documented uranium production (McLemore, 1983; McLemore and Chenoweth, 1989; McLemore et al., 2002). Most of these are in the Grants district, although minor occurrences are found in the Chama Basin (Las Minas de Pedro or Abiquiu, NMRA0019; Box Canyon, NMRA0027), and Nacimiento district (DIS176) (Fig. 1). Minor mineralization extends into the underlying Entrada Sandstone or overlying Summerville Formation in some areas. Uranium is found in the Todilto Formation only where gypsum-anhydrite beds are absent (Hilpert, 1969).

Other limestone deposits—Uraniferous limestones, exclusive of the Todilto Formation, are not common in New Mexico. Most uranium in limestones (exclusive of the Todilto Formation) are vein-type of uncertain origin and are described as vein deposits. However, two areas, the Rocky Arroyo area (NMED0018) in the Eagle district in Eddy County and uraniferous marlstones of the Jurassic Morrison Formation (NMUN0001) in Northeast Union County district contain uranium occurrences in limestone (Fig. 1; McLemore, 1983). Future economic potential is low for most limestone deposits, except for some of the Todilto uranium deposits.

Other sedimentary rocks with uranium deposits

Carbonaceous shale, coal and lignite uranium deposits—Some uranium has been produced from shale, coal and lignite in the Dakota Sandstone in the Grants 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; McLemore, 1983). Mineralized zones are thin and range from a few inches to 1.5 ft thick. Most of these occurrences are isolated, small, and low grade, and do not have any significant uranium potential (McLemore, 1983).

Surficial uranium deposits—Surficial uranium deposits are broadly defined as young (Miocene to

Figure 24. Uranophane in Todilto Formation limestone, Ambrosia Lake subdistrict. The yellow uranophane is 1.5 by 1.5 in. *Photo courtesy of New Mexico Bureau of Geology and Mineral Resources Mineral Museum.*

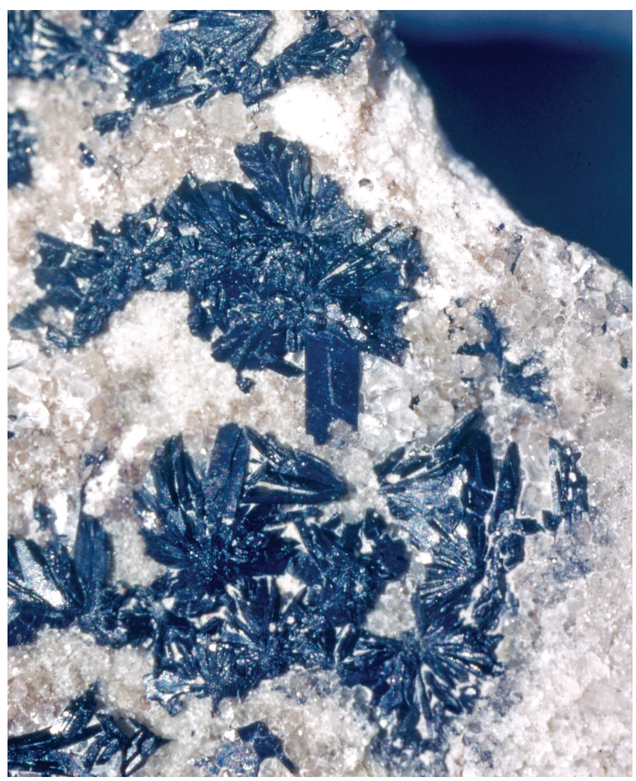


Figure 25. Santafeite in Todilto Formation limestone from Ambrosia Lake. The photo is approximately 2 in wide. *Photo courtesy of New Mexico Bureau of Geology and Mineral Resources Mineral Museum.*

recent) near-surface uranium concentrations in sediments or soils (International Atomic Energy Agency, 2009). Two types of surficial uranium deposits are found in New Mexico: calcrete and playa lake deposits. Groundwater anomalies and local remote sensing data suggest that surficial or calcrete uranium deposits may exist in the Lordsburg Mesa area in southwestern New Mexico (Fig. 1; Carlisle et al., 1978; Raines et al., 1985) and in the Ogallala Formation in eastern New Mexico (Fig. 1; 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).

Several anomalously high uranium occurrences, including the water sample with the highest uranium concentration in the NURE data for New Mexico (Fig. 26), are found in water samples in eastern New Mexico. They are thought to be in the Miocene-Pliocene Ogallala Formation (McLemore and Chenoweth, 1989). The Ogallala Formation consists of fluvial, eolian, and lacustrine deposits and layers of calcrete or caliche that formed during alternating wet and dry climatic periods (Otton, 1984). The uranium found in the Ogallala Formation is likely a result of diagenetic weathering of volcanic ash detritus found in the sedimentary rocks. Surficial uranium deposits, also known as calcrete uranium deposits, are found in several areas in the Ogallala Formation in the Lubbock, Texas, area, where one occurrence is 4.5–7.5 ft thick, contains carnotite, 0.5–5% strontium, 27–245 ppm uranium, and 44–120 ppm vanadium (Otton, 1984). None of the calcrete deposits found in New Mexico have been found to contain high concentrations of uranium, but numerous water samples from calcrete deposits found throughout eastern New Mexico contain slightly elevated concentrations of uranium, some in sample clusters of three or more samples as shown in Figure 26. It also is possible that some of these NURE water sample geochemical anomalies are a result of uranium leaching from agricultural fields because phosphate fertilizer is known to carry high uranium concentrations (Kratz and Schung, 2006). This area warrants further examination to understand the significance of these geochemical anomalies and to determine if public health is at risk.

Several NURE water samples near a playa lake in the northern Estancia Basin, Torrance County, contain anomalously high uranium. Two of these samples have the highest uranium concentrations in the NURE water data in New Mexico (Figs. 1, 27; McLemore, 2010a). The Estancia Basin is a closed basin bounded on the east by the Pedernal Hills and on the west by the Sandia and Manzano Mountains. The water samples also contain anomalously high concentrations of lithium (as much as 624 ppb), strontium (as much as 6,091 ppb), magnesium (as much as 1,320 ppm), and boron (as much as 5,013 ppb). Union Pacific Railroad (Natural Resources Division) drilled approximately 30 shallow holes in the Laguna del Perro area of the Estancia Basin (Fig. 27) and encountered numerous, scattered zones averaging 1–2 ft thick that contained 50–80 ppm in grade. The model for this drilling was the discovery of surficial uranium deposits in western Australia (Yeelirrie and Lake Maitland, Dickson, 1984). The playa lake deposit being developed at Lake Maitland averaged 1.2 m containing 100 ppm uranium. These geochemical anomalies could indicate migration of uraniferous waters from the Pedernal Hills or Manzano Mountains. Another possibility is that these anomalies suggest that the basement

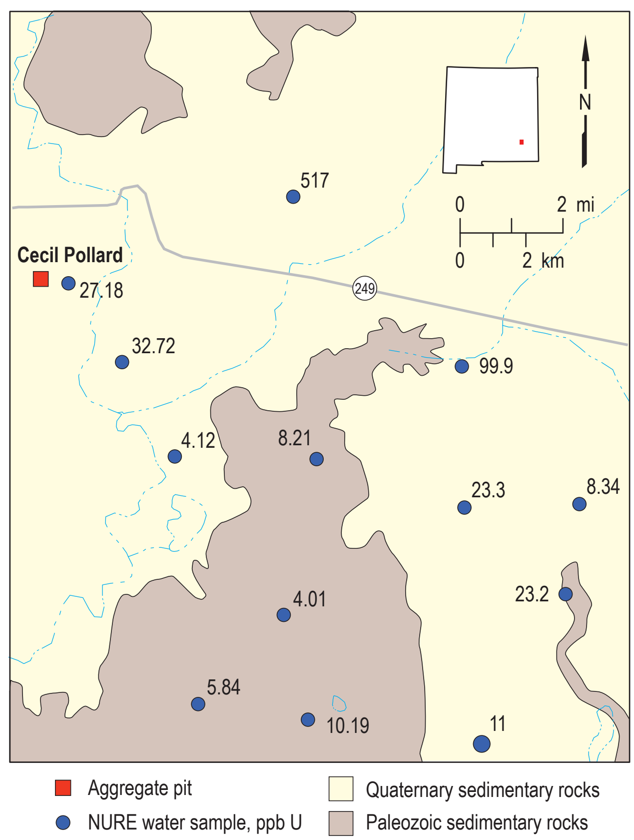


Figure 26. Uranium in NURE water samples in eastern New Mexico (T14S, R26E), possibly from the Ogallala Formation. Location of Cecil Pollard aggregate pit (NMCH0011) is latitude 33.0972°, longitude 104.3089° (NAD27). Any water sample exceeding 30 ppb Uranium could be considered anomalous.

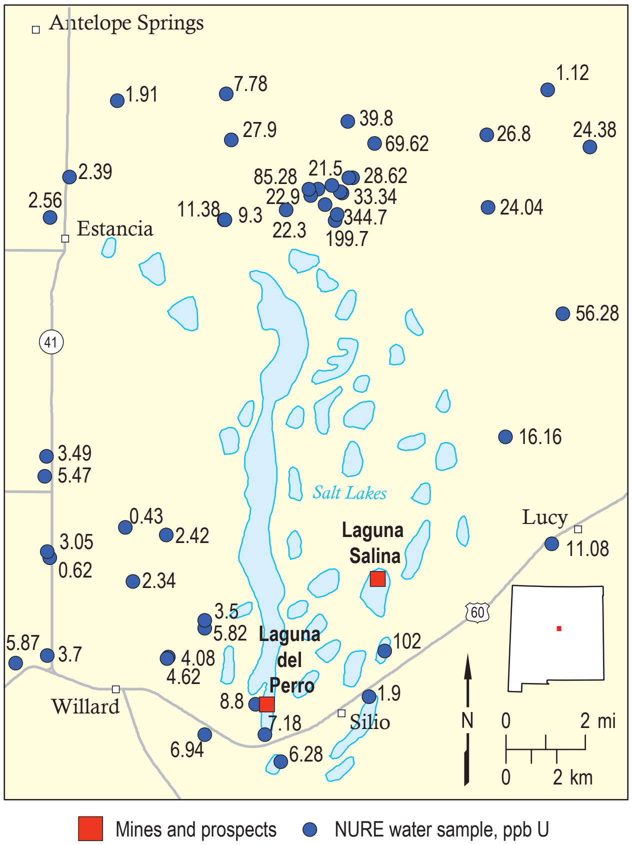


Figure 27. Uranium in NURE water samples in and near playa lakes in the Estancia district (Fig. 1), Torrance County, New Mexico. Two of these samples are the 2nd (344.7 ppb) and 3rd (199.7 ppb) highest uranium concentrations in the NURE water data for New Mexico. Any water sample exceeding 30 ppb Uranium could be considered anomalous.

rocks in the subsurface of the Estancia Basin consists of REE-uranium-thorium-rich alkaline episyenites and granites, similar to those exposed in the Lobo and Pedernal Hills as described by McLemore et al. (1999). A possible explanation for these anomalously high concentrations of lithium could be that lithium-rich brines occur in the area. This area warrants further examination to understand the significance of these geochemical anomalies.

Fracture-Controlled Uranium Deposits

Vein-type uranium deposits

Rio Grande Rift (RGR) copper-silver (uranium) veins—North and McLemore (1986) originally classified two deposits in New Mexico as supergene-copper-uranium (silver) deposits: La Bajada (NMSF0024) and Jeter (NMSO0023, Ladron Mountains). McLemore (1983) and McLemore and Chenoweth (1989) described them as Jeter-type low-temperature, vein-type uranium deposits and La Bajada-type low-temperature, uranium-base metal, vein-type uranium deposits. Similar copper-silver vein deposits have been identified in other areas in New Mexico and the deposit type has been renamed Rio Grande Rift (RGR) copper-silver (±uranium) vein deposits (McLemore and Lueth, 2017). These vein deposits were formed at low temperatures, near-surface, and along Tertiary-age faults in Rio Grande Rift basins.

Veins at the La Bajada and Jeter mines are along faults and appear to be controlled by the distribution of organic material (Haji-Vassiliou and Kerr, 1972) or carbonaceous mudstone (Collins and Nye, 1957). At the Jeter mine, the Jeter fault is a gently-dipping, normal fault that places upper Santa Fe Group fanglomerates against Proterozoic Capirote granite. Only uranium and vanadium were produced from the Jeter mine (McLemore, 1983; Chamberlin et al., 1982). At La Bajada mine, La Bajada fault cuts a north-northwest striking fault with a steep dip in the Oligocene Espinaso Formation (Haji-Vassiliou and Kerr, 1972). From 1923 to 1966, 52 oz silver, 5,345 lbs copper, 27,114 lbs U_3O_8 and 42 lbs V_2O_5 were produced from La Bajada mine (McLemore, 1999).

Collapse-breccia pipe and clastic plug deposits—Uraniferous collapse-breccia pipe deposits were mined in northern Arizona for uranium in the 1950s through 1980s. Average production grades of 0.5–0.7% U_3O_8 were common. 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 and uranium minerals. The pipes were probably formed by solution collapse of underlying limestone or evaporites (Hilpert and Moench, 1960; McLemore, 1983; Wenrich, 1985). Similar deposits occur in New Mexico, but only a few contained economic concentrations of uranium. Clastic plugs in the Black Mesa district (DIS247), northeastern New Mexico (Fig. 1), are similar in appearance to the collapse-breccia pipes and a similar solution-collapse origin is suggested (McLemore and North, 1987). However, the New Mexico uraniferous collapse-breccia pipes and clastic plugs are not common and much smaller than the Arizona uraniferous collapse-breccia pipes and have not been major exploration targets.

More than 600 breccia-pipes are found in the Ambrosia Lake and Laguna subdistricts, but only a few are uranium-bearing (Hilpert, 1969; Nash, 1968; Moench, 1962). Pipe structures in the Cliffside (NMMK0035, Clark and Havenstrite, 1963), Doris (NMMK0049, 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 (NMCI0106) is the largest uranium producer from a breccia pipe in New Mexico (McLemore, 1983) and is 24–34 ft wide and at least 300 ft deep. In contrast, the mineralized Orphan Lode breccia pipe in Arizona is 150–500 ft wide and at least 1,500 ft long (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 (NMCI0106). Future mining potential of New Mexico breccia pipes is minimal.

Volcanic-epithermal veins—Volcanic-epithermal deposits include a broad range of deposits that formed by ascending waters at shallow to moderate depths (<4,500 ft), low to moderate temperatures (50–300°C), and are typically associated with intrusive and/or volcanic rocks (McLemore and Lueth, 2017). Uranium is locally found in some of these deposits, although production has been minor (McLemore, 1983).

Polymetallic veins (formerly Laramide veins)—Polymetallic vein deposits of probable Laramide age (Late Cretaceous-early Eocene, 75–40 Ma) occur in a number of districts (McLemore and Lueth, 2017). Uranium is locally found in some of the veins, but not in economic concentrations (McLemore, 1983).

Disseminated Uranium Deposits in Igneous and Metamorphic Rocks

Episyenites or metasomatites

Episyenites or metasomatites are commonly associated with carbonatites and alkaline igneous rocks and also are found in New Mexico without any direct association with carbonatites or alkaline rocks. Episyenites containing anomalous uranium and REE concentrations are found in the Caballo (Fig. 28), Burro, Zuni, and Nacimiento Mountains, Pedernal Hills, Lobo Hill, and Fra Cristobal Mountains. Episyenites are brick-red, K-feldspar-rich rocks that

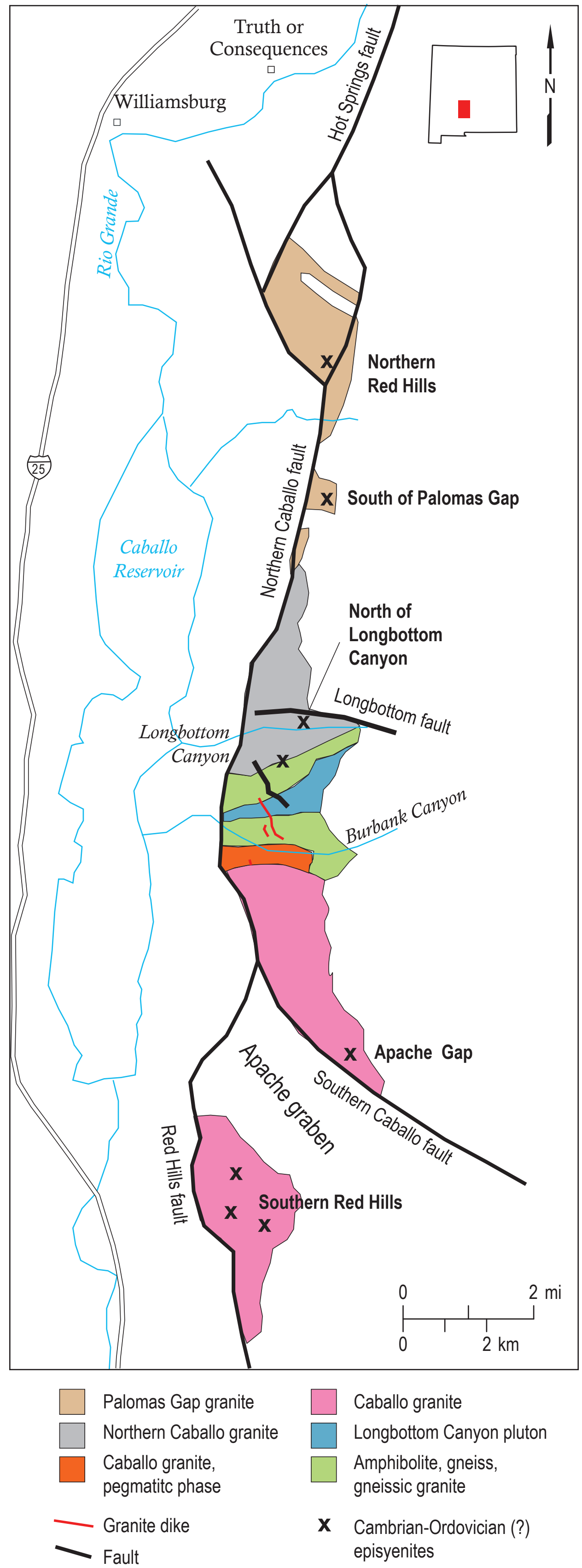


Figure 28. Location of episyenites in the Caballo Mountains, Sierra County, New Mexico.

were desilicated and metasomatized by alkali-rich fluids, possibly related to alkaline or carbonatite magmas. Field relationships and $^{40}Ar/^{39}Ar$ dating indicates that New Mexico episyenites are ~500 Ma (Cambrian-Ordovician age) or older (McLemore et al., 1999a; Riggins, 2014). The New Mexico episyenites contain as much as 16% K_2O and have greater concentrations of REE (as much as 3,167 ppm total REE), Th (as much as 9721 ppm) and U (as much as 2,329 ppm) than most igneous rocks and exhibit textures consistent with a metasomatic origin. K-feldspar, hematite, and REE-bearing minerals have replaced the protolith granites and metamorphic gneisses. Recent electron microprobe studies on episyenites from the Caballo Mountains have identified synchysite ($Ca(Ce, La)(CO_3)_2F$), aeschynite ($(Y, Ca, Fe, Th)(Ti, Nb)_2(O, OH)_6$), xenotime ($YPO_4$), thorite ($(Th,U)SiO_4$), uranophane ($Ca(UO_2)2SiO_3(OH)_2 \bullet 5(H_2O)$) (Fig. 29) and apatite (Riggins, 2014); bastnaesite was reported previously (McLemore, 1986). These episyenites may be representative of alkaline or carbonatite plutons at depth and are possibly related to the widespread Cambrian-Ordovician magmatic event that occurred throughout New Mexico and southern Colorado. See McLemore and Austin (2017) and McLemore and Lueth (2017) for more information.

Igneous and metamorphic rocks with disseminated uranium deposits

More than 200 uranium occurrences are found in igneous and metamorphic rocks, including pegmatites, alkaline rocks, granitic rocks, carbonatites, and caldera-related volcanogenic deposits, but most in New Mexico are uneconomic (McLemore, 1983). One area of possible economic importance is the La Cueva district (DIS232) in northern Taos County (Fig. 30).

REE-thorium-uranium veins, veins in Proterozoic rocks (±uranium, thorium, REE, copper, gold, zinc), and pegmatites (±uranium, thorium, REE, beryllium, mica) are associated with the southern part of the Proterozoic Costilla granitic massif in the La Cueva district (also known as Vermejo Park or Costilla Creek district) in the vicinity of Costilla Creek, northern Taos County (Fig. 30; Zelenka, 1984; Goodknight and Dexter, 1984; McLemore, 1990; McDonnell, 1984). The Costilla massif consists of granite gneiss, pegmatitic granite, and granite to quartz monzonite emplaced into a complex

Figure 29. Yellow uranophane in episyenites from the southern Red Hills in the Caballo Mountains, Sierra County, New Mexico (NMSI0069). *Photo by Virginia T. McLemore.*

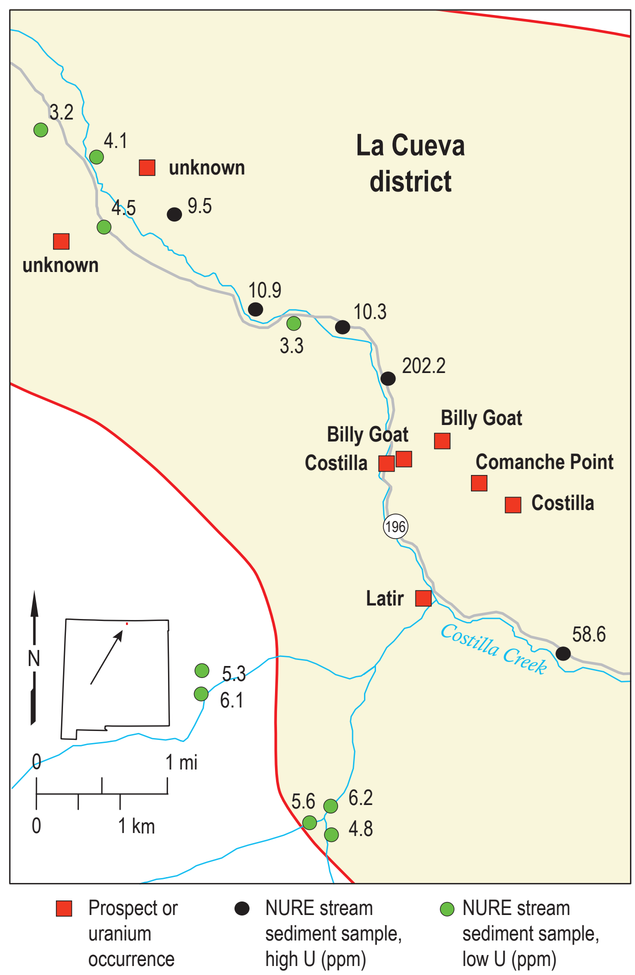


Figure 30. Uranium in NURE stream-sediment samples in the La Cueva mining district, Taos County, New Mexico (T30, 31N, R15E). The uranium anomalies in stream sediments (black) are downstream of several identified uranium prospects. Location of Latir mine (NMTA0005) is latitude 36.846917°, longitude 105.381389° (NAD27).

Proterozoic terrain of metamorphic and igneous rocks. The uranium-rich pegmatites intruded both the granite and metamorphic rocks. The Proterozoic rocks are overlain by Tertiary volcanic and volcaniclastic rocks related to the Questa caldera (Questa district, Fig. 1) to the south and the formation of the Rio Grande rift. The granitic rocks are subalkaline, metaluminous to peraluminous. Mineralization in the district was discovered in the 1950s during prospecting for radioactive veins and pegmatites. Exploration was carried out in the 1970s and 1980s by Phillips Petroleum Co. and Duval Corp. There has been no mineral production from the area.

Mineralized zones at the surface contain uranium, thorium, and REE minerals along fractures and in veins and pegmatites, including zircon, uraniferous magnetite, allanite, uranothorite, thorite, uraninite, thorogummite, uranophane, and uranium-bearing hematite (Zelenka, 1984). Clay-rich zones at La Cueva prospect (NMTA0559) contain uranophane and thorogummite and as much as 1,522 ppm uranium, 1,643 ppm thorium, 625 ppm lanthanum, and 1,560 ppm cerium in selected samples (Zelenka, 1984). Stream sediments downstream of known prospects contain as much as 202.2 ppm uranium, 51 ppm thorium, 48 ppm lanthanum, and 96 ppm cerium. Note the highest uranium sample (202.2 ppm uranium) along Costilla Creek is the second highest uranium sample in the entire NURE data set for New Mexico. These stream-sediment anomalies are most likely due to weathering of natural anomalously high concentrations of uranium, thorium, and REE associated with the mineral occurrences in the area.

Other Potential Types of Uranium Deposits

Iron oxide-Cu-Au (IOGC) deposits (Olympic Dam deposits, hematite breccia)

The Olympic Dam deposit in Australia, an iron oxide-copper-gold ±uranium (IOCG) deposit (also known as hematite breccia deposits), is one of the largest copper-uranium deposits in the world and is reported to contain a measured resource of 650 million metric tons (Mt) of 500 g/t U_3O_8 (425 ppm uranium), 1.5% copper, and 0.5 g/t gold with a total resource estimated to be approximately 3.8 billion metric tons of 400 g/t U_3O_8 (339 ppm uranium), 1.1% copper, and 0.5 g/t gold (Hitzman and Valenta, 2005). Many mineral deposits in the world are being re-examined for the potential for this class of deposit and some of the minor deposits along the Capitan, Santa Rita, and Morenci lineaments in the Chupadera Mesa area are suggestive of undiscovered IOCG deposits because they have similar structural features and metal associations (Fig. 31; McLemore and Zimmerer, 2009). IOCG deposits are found in continental rift settings and appear to be controlled by regional lineaments. IOCG deposits contain essentially titanium-poor magnetite and/or hematite and most are associated with saline hydrothermal fluids,

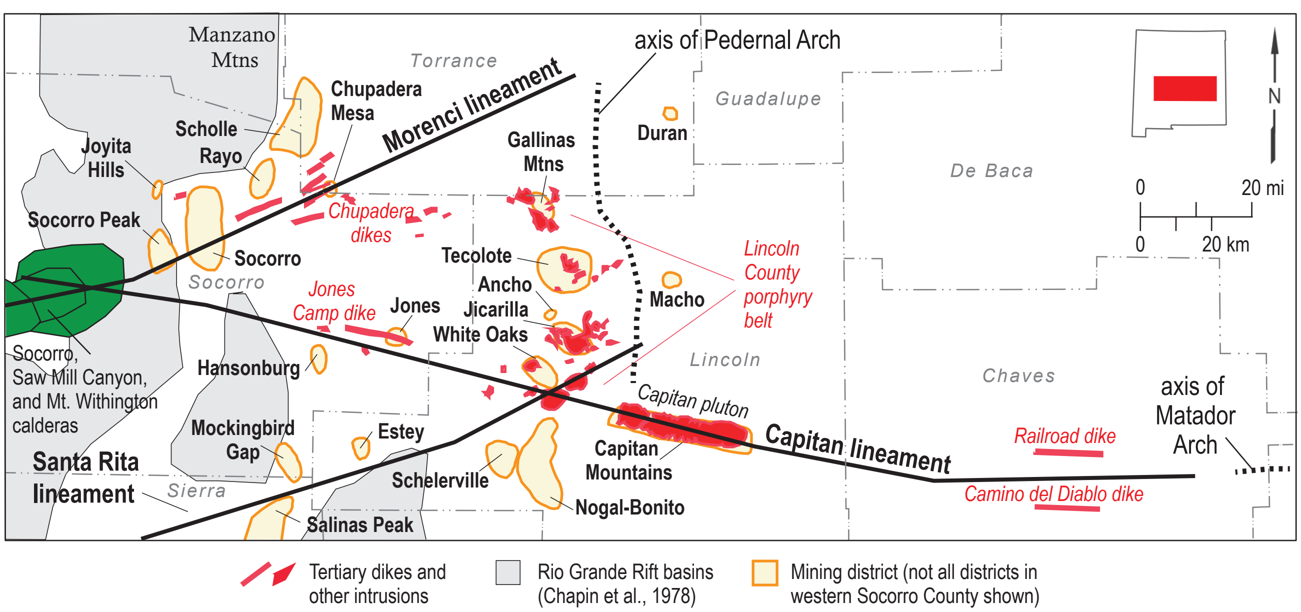


Figure 31. Magmatic activity and mineral deposits along the Capitan, Santa Rita, and Morenci lineaments in the Chupadera Mesa area, central New Mexico. Green polygons are calderas.

calcalkaline to subalkaline to alkaline A-type igneous rocks, low sulfur contents, and enrichment in REE, copper, gold, silver, and uranium (Barton et al., 2000).

The various hematite and magnetite-rich mineral deposits found along these lineaments in the Chupadera Mesa area have similar metal associations as IOCG deposits (Fig. 31; McLemore and Zimmerer, 2009). Barton and Johnson (1996) present evidence that sulfate deposits are found in known areas of IOCG oxide deposits and that they actually control mineralization, not the magmas. Permian evaporate sedimentary deposits are common in central New Mexico and Rio Grande rift deposits (some with uranium; see McLemore and Lueth, 2017). Replacement textures, zoned alteration patterns (iron-, sodium-, and potassium-metasomatism), and alteration-associated veins of a hydrothermal origin are common. The origin of IOCG deposits is uncertain and seems to range from magmatic to non-magmatic types (Hunt et al., 2007). The various mineral deposits in the Chupadera Mesa area range from deposits associated with the alkaline intrusions in Lincoln County and the dikes in the Chupadera Mesa area to Rio Grande rift copper-silver-uranium (±iron, gold) vein deposits, which are not associated with igneous activity.

Byproduct copper processing

Uranium is found in low concentrations in many porphyry copper deposits and has been recovered from copper mines (International Atomic Energy Agency, 2009). In Arizona, uranium was recovered from copper leach solutions at the Twin Buttes mine (Lorenz, 1982). However, most of the uranium is disposed of along with the mine waste materials. Although, uranium has not been recovered from the copper porphyry deposits in New Mexico, these deposits should be examined for their uranium content and potential recovery.

VII. ENVIRONMENTAL ISSUES

Uranium mining in New Mexico left a legacy of former mines, prospects, and mills scattered throughout New Mexico, especially in the Grants district (Anderson, 1980; McLemore, 1983; https://www.epa.gov/sites/production/files/2015-08/documents/uranium-mine-brochure.pdf, accessed 10/8/14). Most uranium mines closed with few requirements for reclamation or remediation. Most uranium mills are reclaimed by the Uranium Mill Tailings Remedial Action (UMTRA) program administered by the DOE (http://www.eia.gov/nuclear/umtra/, accessed 8/2/15). The DOE office of Legacy Management monitors the mill sites once reclaimed. Federal and state water quality regulators began enacting significant water-quality requirements in the 1970s. State surface reclamation laws were not passed until the New Mexico Mining Act of 1993. Historical releases to groundwater and surface water, soil, and air have been documented from legacy uranium mine and mill sites throughout the Grants district (McLemore, 2010a; U.S. EPA, 2010a), and have the potential to release contaminants to the environment in the future. Physical hazards, including open adits and shafts and uncontrolled waste rock and ore piles, remain at many mine sites (Anderson, 1980; McLemore, 1983; U.S. EPA, 2010a, b).

Aerial surveys were conducted near Ambrosia Lake and Grants, New Mexico, during August and October, 2011, to determine if residual surface contamination exceeding natural background concentrations was present. The terrestrial background exposure rate in the area ranged between 5 to 10 µR/h. Results indicate that areas associated with elevated radiation levels ranged from 20 µR/h to 435 µR/h (U.S. EPA, 2011a; b).

Since the 1980s, several federal, state and tribal agencies and former mining companies have pursued clean-up and reclamation under various laws. Contamination associated with former uranium extraction activities within the Shiprock district (Fig. 4) and the Church Rock–Crownpoint, Nose Rock and Smith Lake subdistricts and part of the Ambrosia Lake subdistrict (Fig. 2) are partly under the jurisdiction of the Navajo Nation and are being addressed by U.S. Environmental Protection Agency (EPA) Region 9. Details of the EPA Region 9 and Navajo Nation activities can be found in the Health and Environmental Impacts of Uranium Contamination in the Navajo Nation Five-Year Plan (website: http://epa.gov/region09/superfund/navajo-nation/index.html accessed 7/2/14). The remainder of the Ambrosia Lake subdistrict, as well as the Bernabe Montaño, Laguna and Marquez subdistricts contain legacy uranium sites that are under the jurisdiction of EPA Region 6 and the State of New Mexico. Superfund sites include the Homestake Mining Company site (http://www.epa.gov/region6/6sf/newmexico/homestake_mining/index.html, accessed 10/8/2014), United Nuclear Corporation Mill site (http://www.epa.gov/region6/6sf/newmexico/united_nuclear/index.html, accessed 10/8/14), Jackpile-Paguate uranium mine (http://www.epa.gov/region6/6sf/pdffiles/jackpile-nm.pdf, accessed 10/8/14), and Grants mining district (http://www.epa.gov/grants-mining, accessed 10/8/14). Details of the EPA Region 6 and State of New Mexico activities can be found in the five-year plan for the Grants district (US EPA, 2011b; http://www.epa.gov/sites/production/files/2015-05/documents/nm_grants_5yr_plan-3-2014.pdf, accessed 7/2/14).

Uranium also is naturally found in some groundwater in New Mexico. The San Jose district (DIS188) in the Espanola Basin in Santa Fe County (Fig. 17; discussed above) is particularly interesting because the district includes uranium prospects, one small mine that yielded some uranium production, uranium anomalies in both NURE water and stream-sediment samples (Fig. 17), and residents locally have high concentrations of uranium and radon in their drinking water (McQuillan et al., 2012). This area warrants further examination to understand the significance of these geochemical anomalies and to determine if public health is at risk. The New Mexico Environment Department also recommends home owners test their drinking water in Dona Ana County, Grants–Gallup areas, and Tucumcari–San Jon areas for uranium because a large number of previously tested samples are high in natural uranium concentration.

Rock hammer at the Jackpile mine (NMCI0018), Laguna subdistrict, Grants uranium district (August 1963). *Photo by W.C. Chenoweth.*

VIII. FUTURE POTENTIAL FOR URANIUM PRODUCTION IN NEW MEXICO

New Mexico ranks second in uranium resources according to the DOE in the U.S., behind Wyoming (Table 8). As of 2017, several companies are evaluating their resources throughout the Grants uranium district for conventional underground mining or in situ recovery (Fig. 32; Table 6; McLemore et al., 2013). Similarly, heap leaching of the Todilto Formation ore is being investigated by one company. With the recent increase in price and demand for uranium, however, 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 for five main reasons:

- Major companies abandoned properties in the district after the last cycle leaving uranium projects that were identified by exploration drilling.
- Currently, property acquisition is inexpensive and includes millions of dollars' worth of exploration and development expenditures (including assay and drill hole data).
- Data and technical expertise on these properties are available.
- Recent advances in in situ leaching technology allow for some of the Grants district sandstone uranium deposits to be economically attractive in today's economy.
- Since nuclear energy produces no CO_2 emissions, it offers an attractive alternative energy to coal.

Other areas in New Mexico have potential for additional uranium resources (Fig. 32; Table 3). Exploration has occurred during the last decade in the Hook Ranch-Riley and Red Basin-Pietown (DIS008) districts, and at least one deposit has reported potential resources (Table 6). Other basins in New Mexico, such as the Las Vegas, Sabinoso, Nacimiento, Chama, and Hagan-La Bajada basins and at Mesa Portales should be evaluated for sandstone uranium deposits (McLemore, 1983).

Table 8. Uranium reserves by forward-cost category by state as of 2008 according to the U.S. Department of Energy (DOE; Energy Information Administration, 2010). The DOE classifies uranium reserves into forward-cost categories of $50 and $100 per pound. Forward-costs are estimated 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. See Energy Information Administration (2010) for more information on how the DOE determines these reserves.

STATE	$50 PER POUND			$100 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)
Wyoming	145	0.076	220	398	0.056	446
New Mexico	64	0.14	179	186	0.105	390
Arizona, Utah Colorado,	22	0.145	63	117	0.084	198
Texas	15	0.089	27	32	0.062	40
Other	28	0.09	50	95	0.081	154
Total	**275**	**0.098**	**539**	**828**	**0.074**	**1227**

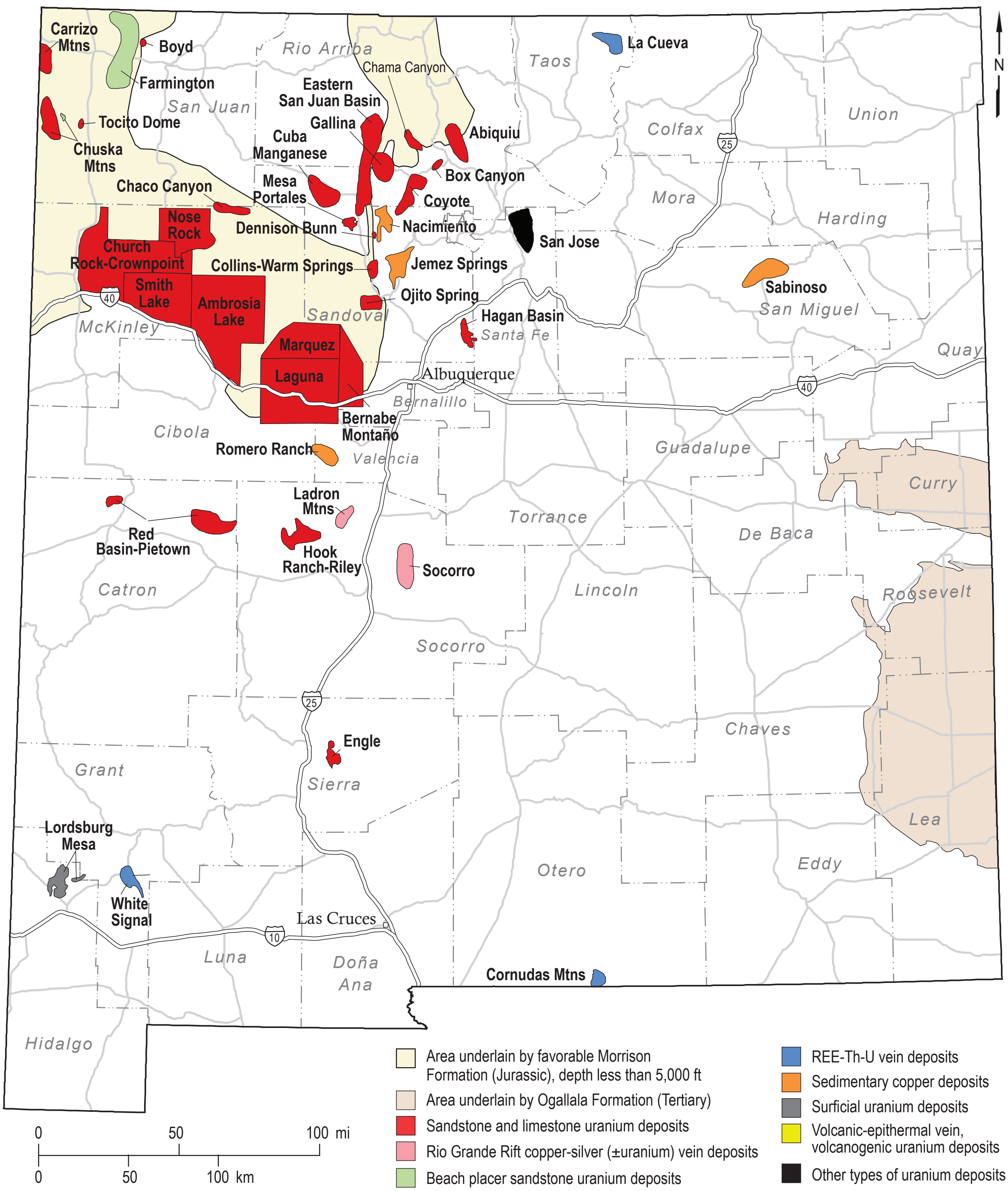


Figure 32. Mining districts and other areas that have future potential for development of uranium deposits in New Mexico (modified from McLemore, 1983). Many of these districts are listed in Table 3 and McLemore and Chenoweth (1989).

IX. CONCLUSION

Sandstone and limestone uranium deposits in New Mexico have played a major role in historical uranium production. Although worldwide, other types of uranium deposits are higher in grade and larger in tonnage, the Grants district has been a significant source of uranium and has the potential to become an important future source, as low-cost technologies, such as in situ recovery techniques improve, and as demand for uranium increases, thereby 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 district and elsewhere from New Mexico, including:

- No conventional mills remain in New Mexico to process the ore, adding to the cost of producing uranium in the state. Currently, all conventional ore must be processed by the White Mesa Mill near Blanding, Utah, or heap-leached on site. New infrastructure will need to be built before conventional mining can resume.
- Permitting for new in situ recovery and conventional mines and mills, will take years to complete.
- Closure plans, including reclamation, must be developed before mining or in situ recovery 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 tribal lands. Most of Mount Taylor and adjacent mesas have been designated as the Mount Taylor Traditional Cultural Property; the effect of this designation on uranium exploration and mining is uncertain.
- High-grade, low-cost uranium deposits in Canada and Australia and the large low-grade deposits in Kazakhstan are sufficient to meet current international demands; additional resources will be required to meet long-term future requirements.

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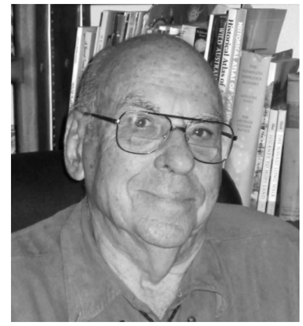
She has edited and authored 2 books recently published by SME (Society for Mining, Metallurgy, and Exploration, Inc.) on mining environmental issues: 1) Management Technologies for Metal Mining Influenced Water, Volume 1: Basics of Metal Mining Influenced Water and 2) Management Technologies for Metal Mining Influenced Water, Volume 6: Sampling and monitoring for the mine life cycle.

Ginger also is an adjunct professor and teaches graduate level courses for the Department of Earth and Environmental Sciences and Department of Mineral Engineering at New Mexico Tech. Many graduate students have benefited from her advising.



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William (Bill) Chenoweth received his BA in geology from Wichita State University in 1951. While at WSU he attended a 1950 summer field camp in the Zuni Mountains sponsored by the New Mexico School of Mines. After seeing New Mexico's geology he decided to enroll in graduate school at the University of New Mexico, where he received a MS in geology in 1953. His thesis was a study of the Morrison Formation in the southeastern part of the San Juan Basin, Valencia County, New Mexico, and was funded by the U.S. Atomic Energy Commission (AEC). After graduation, he was offered employment by the AEC to work on uranium exploration drilling projects on the Navajo Indian Reservation in northeastern Arizona. For the next 11 years he studied uranium ore deposits in northeastern Arizona and northwestern New Mexico. In 1964 he was transferred from Grants, New Mexico to the AEC's main office in Grand Junction, Colorado and was assigned to study uranium ore deposits in South Dakota and Wyoming. Bill was appointed Chief of the Geologic Branch in Grand Junction office in 1970 and was responsible for the activities of the AEC geologists in the 14 western states. During this time he examined all the major uranium mining area in the US. In 1983, his job was moved to Washington, DC by the Department of Energy. Rather than relocate, Bill began consulting and became a research associate at Bureau of Geology and Mineral Resources. He was also the Chairman of the Nuclear Minerals Committee of the Energy Minerals Division of the American Association of Petroleum Geologists from 1983–1998. He is the author and coauthor of over eighty reports on uranium mining history, geology and resources in New Mexico, Arizona, Colorado and Utah. Bill has been a member of the New Mexico Geological Society since 1952.

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GLOSSARY

This glossary includes terms related to economic geology, mining, and reclamation.

For a glossary of general mining and processing terms, see
http://www.coaleducation.org/glossary.htm
http://www.miningandmetallurgy.com/mining/glossary-mining-terms

Many mine features and mine terms are shown in Figure G1 below.

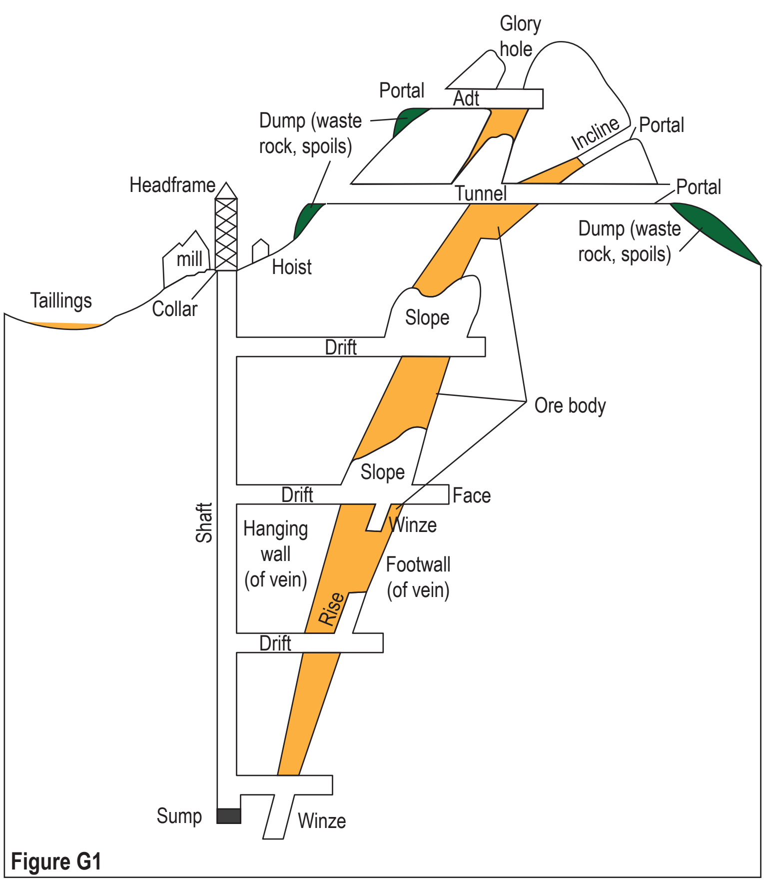

Figure G1

Abandoned mine—An abandoned mine, at which exploration, development, mining, reclamation, maintenance, and inspection of facilities and equipment, and other operations ceased and with no evidence demonstrating that the miner intends to resume mining.

Adit—A horizontal or nearly horizontal passage driven from the surface for the development or dewatering of a mine (Fig. G1). If an adit is driven through the hill or mountain to the surface on the opposite side, it is called a "tunnel."

Acid mine drainage (AMD) or Acid rock drainage (ARD)—Results from oxidation of sulfide minerals exposed to weathering by mining producing sulfuric acid that further dissolves minerals in the rocks, to release metals into the water. Acid mine drainage implies that acid drainage is caused by the mining process and does not include natural drainage.

Alluvium—Unconsolidated mud, sand, and gravel deposited by flowing water.

Anthracite—A hard black vitreous coal containing a high percentage of fixed carbon and a low percentage of volatile matter. Commonly referred to as hard coal.

Anthropogenic—Formed through or related to the activities of humans.

Aquifer—A body of rock or sediments capable of storing and transmitting water.

ArcGIS—A geographic information system (GIS) that allows storage, retrieval, and analysis of spatially related information in both graphical and database formats.

Background—Natural concentrations of an element in natural materials that exclude human influence. A "background measurement" represents an idealized situation and is typically more difficult to measure than a "baseline".

Beneficiation—The processing of ores for the purpose of regulating the size of a desired product, removing unwanted constituents, and improving the quality, purity, or assay grade of a desired product.

Carbonates—A family of rocks containing Ca and/or Mg carbonate, such as limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) and which excludes siderite ($FeCO_3$).

Chimney—an orebody that is irregular-shaped, chimney- or pipe-shaped vertical carbonate-hosted ore deposits, generally copper, lead, zinc, silver, and/or manganese.

Compaction—Increase in soil bulk density and reflected in increased penetrometer resistance caused by loading at the surface, generally by wheel traffic.The action of moving soil particles closer together by compressing the pore space.

Contaminant—Any physical, chemical, biological, or radiological substance or matter that has an adverse effect on air, water, or soil.

Concentrating—The mechanical process, often involving flotation, by which the valuable part of an ore (the "concentrate") is separated from the "gangue", or non-economical rock minerals to be disposed of as "tailings."

Concentrator—Part of the mining plant used to separate valuable minerals from the ore. In mineral sand mining, the concentrator is often referred to as the “wet” mill because it uses a water slurry for separation, and it is often floated on pontoons in a dredge pond.

Drainage—Any water draining from a natural or man-made feature. Includes natural surface water runoff, mine drainage, and groundwater that has come to the surface.

Drainage basin—The surface between topographic divides that receives precipitation. This water is conveyed down slope as surface runoff or ground water. Also known as a catchment or watershed.

Dredge mining—Frequently used in mineral sand mining to recover the ore from the mine face as a water slurry by suction. The dredge houses a powerful pump and is floated on pontoons in the dredge pond. In a suction cutter dredge, ore recovery is assisted by a revolving open basket (cutter) mounted over the suction inlet. In hard ground, the cutter can be replaced by a rotating underwater bucketwheel. This term can also be applied to a mine waste material associated with placer dredge mining.

Drill—A machine with a rotating bit used to drill holes in overburden materials. In the case of hard rock mining, these holes then are partially filled with explosives for loosening up the rock to be removed in mining.

Drusy quartz—Texture where a layer of closely spaced, small quartz crystals lines a surface or cavity.

Environmental impact assessment—A process required under the National Environmental Protection Act for projects involving federal or state money, in which potential physical and social impacts and mitigation measures are discussed and analyzed. A provision for notifying citizens and considering their comments is integral to the process.

Erosion—The entrainment and transportation of soil through the action of wind, water, or ice.

Extraction—The process of mining and removal of coal or ore from a mine. This term often is used in relation to all processes of obtaining metals from ores, which involve breaking down ore both mechanically (crushing) and chemically (decomposition), and separating the metal or other valuable commodity from the associated gangue.

Fine tailings—Fine-grained clastic materials (silts and clays) and/or residual bitumen that consolidate very slowly.

Flotation—The method of mineral separation in which a froth, created in water by a variety of reagents, floats valuable finely crushed minerals while other minerals sink.

Fly ash—A powdery material of predominately small glass spheres that is very light and usually collected in electrostatic precipitators, bag houses, or cyclones during burning of coal in electrical power generation combustion chambers.

Galls—Small balls of clay in sedimentary deposits.

Gangue—The valueless minerals in an ore; that part of an ore that is not economically desirable, but cannot be avoided when mining the deposit. It is separated from the ore during beneficiation.

Groundwater—Zone below the surface of the earth where voids are filled with water and the pressure is 9.9 MPa (1 atm). This is in contrast to surface water.

Heap-leach recovery—Industrial process that recovers metals using chemicals sprayed onto a pile of crushed ore.

Heavy mineral sands—Valuable minerals such as rutile, ilmenite, leucoxene, zircon, and monazite occurring as a sand-sized fraction, with a high specific gravity relative to that of the host sand.

Hematite—A type of iron ore with the composition formula of Fe_2O_3.

Hydrocarbons—Organic chemical compounds of hydrogen and carbon atoms that form the basis of all petroleum products.

Inactive mine—The area in which no active mining is currently taking place relative to extraction of metal ores, industrial minerals, and other minerals of economic value.

Incline—Sloped entrance to underground mine, mined from the surface usually along the dip of a vein or stratigraphic horizon (Fig. G1). Sometimes called “decline,” or “declined shaft.”

Jarosite—A pale yellow to gray-green potassium iron sulfate mineral [$KFe_3(OH)_6(SO_4)_2$] that forms under active acid sulfate conditions. Can be a pathfinder mineral for areas of oxidation of iron sulfides and associated acid generation.

Jasperoid—a dense, siliceous rock where silica (fine-grained quartz) has replaced carbonate minerals of limestone, dolomite, or other carbonaceous sedimentary rock

Leaching—Removal of dissolved, adsorbed, or absorbed substances from a matrix by passing liquids through the material.

Limestone—A sedimentary rock composed chiefly of calcium carbonate ($CaCO_3$). Limestone can form by either organic or inorganic means.

Lithology—The character of a rock described in terms of its structure, color, mineral composition, grain size, and arrangement of its component parts; all those visible features that in the aggregate impart individuality to the rock.

Lode—Metallic deposit found in veins or stratabound in sedimentary rocks.

Maars—A low-relief volcanic crater caused by a phreatomagmatic eruption (an explosion, which occurs when groundwater comes into contact with hot lava or magma).

Magnetite—A magnetic iron mineral that has the formula Fe_3O_4. Can form iron ore.

Manto—An orebody that is stratabound irregular-shaped, blanket-like carbonate-hosted ore deposits, generally copper, lead, zinc, silver, and/or manganese that are usually horizontal or near horizontal in attitude.

Metallogenesis—Study of the origin of mineral deposits and their relationship of geologic time and space with other geologic processes such as tectonics.

Metallurgy—The science and technology of extracting and refining metals and the creation of materials or products from metals.

Mica—An aluminosilicate mineral in which two silica tetrahedral sheets alternate with one octahedral sheet, with entrapped potassium atoms fitting between the sheets.

Milling—The grinding or crushing of ore. The term may include the operation of removing valueless or harmful constituents from the ore and preparation for additional processing or sale to market.

Mine—An opening or excavation in the ground for the purpose of extracting minerals (Fig. G1).

Mineralogy—The study of minerals and their formation, occurrence, use, properties, composition, and classification. Also refers to the specific mineral or assemblage of minerals at a location or in a rock unit.

Mining—The process of extracting useful minerals from the Earth's crust.

Mining district—A section of country usually designated by name, having specified boundaries within which mineral deposits are found and mined, in some cases under rules and regulations prescribed by the miners therein or by a government body. There is no limit to its territorial extent, and its boundaries may be changed if vested mineral or property rights are not thereby interfered with. Can be either an informal name for a mineral area or a legally defined area encompassing all or part of a collection of mineral deposits and/or mines.

Mineral deposit—Any occurrence of a valuable commodity or mineral that is of sufficient size and grade (concentration) for potential economic development under past, present, or future favorable conditions.

Oolitic—A rock consisting of small round grains, usually of iron oxide or calcium carbonate cemented together.

Open stope (or stope)—Linear opening mined from underground to the surface along the course of a vein or mineralized zone (Fig. G1).

Ore—The naturally occurring material from which a mineral or minerals of economic value can be extracted profitably or to satisfy social or political objectives. The term is generally, but not always, used to refer to metalliferous material, and is often modified by the names of the valuable constituents.

Ore deposit—A well-defined mineral deposit that has been tested and found to be of sufficient size, grade, and accessibility to be extracted and processed at a profit over a specific time.

Organic matter—The accumulation of disintegrated and decomposed biological residues, and other organic compounds synthesized by microorganisms, found in soil.

Overburden—Designates material of any nature, consolidated or unconsolidated, that overlies a deposit of useful and mineable materials, ores, or coal, especially those deposits that are mined from the surface by open cuts.

Oxidation—A chemical process involving reaction(s) that produce an increase in the oxidation state of elements such as iron and sulfur.

Oxidize—The chemical reaction involving the removal of electrons from an element (e.g., Fe^{2+} Fe^{3+}).

Oxidized zone—That part of the soil-geologic column from which sulfide minerals have been completely oxidized away, compared with the reduced zone. May be equivalent to the "zone of weathering".

Paleoenvironment—The ancient geologic setting (climate, geography, etc.) under which strata were deposited.

pH—A measure of the acidity (less than 7) or alkalinity (greater than 7) of a solution; a pH of 7 is considered neutral. A measure of the hydrogen ion concentration (more specifically, the negative log of the hydrogen ion activity) of a soil suspension or water.

Placer deposits—An alluvial deposit of an economically important mineral or material, usually as a mineral-gravel or sand, typically containing gold or gemstones. Also high-grade concentrations of heavy mineral sands formed as lenses on present or ancient beach berms by wave action.

Pollutant—Any substance introduced into the environment that adversely impacts the usefulness of a resource.

Porewater—Water occupying the voids in soil or sediment.

Processing—The methods employed to clean, process, and prepare coal and metallic ores for the final marketable product.

Production—The total amount of mass produced by a plant, mine, aquifer, etc.

Pyrite—An iron sulfide (FeS_2), which forms acid mine drainage upon exposure to oxidizing conditions and in the absence of $CaCO_3$. Sometimes called "fool's gold".

Quarry—Any open or surface working, usually for the extraction of sand and gravel, building stone, slate, limestone, etc.

Quartz—A very hard, inert mineral of SiO_2, commonly found in sand and sedimentary, igneous, and metamorphic rocks.

Reclamation—Restoring mined or disturbed land to the conditions that are acceptable under regulatory requirements and which return the site to a safe and useful condition (e.g., grazing, recreation, agriculture, wildlife habitat, etc.).

Refining—The purification of a crude metal product; normally the stage following smelting. For bitumen it is the fractionation into various components such as gasoline.

Relational database—An electronic database comprising multiple files of related information, usually stored in tables of rows (records) and columns (fields), and allowing a link to be established between separate files that have a matching field, as a column of invoice numbers, so that the two files can be queried simultaneously by the user.

Remediation—Cleanup or other methods used to remove or contain a toxic spill or hazardous materials from a site. The process of correcting, counteracting, or removing an environmental problem, often referring to the removal of potentially toxic materials from soil or water by use of bacteria (bioremediation) or plants (phytoremediation).

Remining—Returning to abandoned underground or surface mines or previously mined areas for further coal removal by surface mining and reclaiming to current reclamation standards. Also refers to the process of mining and processing of non-coal mine and mill wastes (processed or unprocessed) to extract additional metals or other commodities due to a change in extraction technology or economics that make such remining profitable.

Representative sample—A portion of material or water that is as nearly identical in content and consistency as possible to that in the larger body of material or water being sampled.

Room and pillar—Also sometimes called "board and pillar" in Europe. A form of underground mining in which typically more than half of the ore is left in the mine as pillars to support the roof. Room and pillar mines generally are not expected to subside, except where retreat mining is practiced. Also a mining method used for thick and/or flat-lying industrial, metal, and non-metal mineral deposits, such as coal, limestone, trona, salt, etc.

Sample—A representative portion of a population.

Sands—Tailings particles of a size (generally >0.05mm) and weight that readily settle in water.

Scrubber—Equipment that entraps and removes potential pollutants with water before they are released to the atmosphere.

Sedimentation—The process of depositing entrained soil particles or geologic materials from water. In a mining context, usually resulting from erosion of disturbed land and considered a negative impact to streams and other water bodies.

Sewage—The mainly organic, solid residual materials resulting from the treatment of sewage, often used as a soil amendment.

Shaft—Vertical (or near-vertical) entrance to underground mine (Fig. G1). Climbing or powered man cage (elevator) is required to get out.

Shale—A finely laminated, hardened sediment composed of silt and clay or clay-sized particles.

Silicate ore—An ore in which the valuable metal is combined with silica rather than sulfur.

Sintering—The use of heat to fuse ores or concentrates preparatory to further processing.

Skarn—metamorphic zone developed in sedimentary rocks at the contact with igneous intrusions and containing calc-silcate minerals, such as wollastonite, diopside, forsterite, garnet

Slate—In old coal mining usage, "slate" or "draw slate" is fine-grained sedimentary rock often black (carbonaceous) and tending to split along cleavage or bedding planes, resulting in flat rocks. Usually found above and next to some coal beds. In correct geologic terminology, it is a metamorphic rock derived from shale that has been subjected to heat and/or pressure.

Slimes—The refuse material, silt or clay in size, resulting from the washing, concentration, or treatment of ground ore.

Slope—The degree to which the ground angle deviates from horizontal, expressed as a percent rise over run or as a degree angle.

Smelter—An industrial plant or process that extracts a metal from an ore at high temperature by chemical and physical processes that occur in the molten state.

Smelting—The chemical reduction of a metal from its ore by a process usually involving fusion, so that earthy and other impurities separate as lighter and more fusible slags and can readily be removed from the reduced metal. The process commonly involves addition of reagents (fluxes) that facilitate chemical reactions and the separation of metals from impurities.

Stream channel—A trough in the landscape that conveys water and sediment. Channel formed is the product of the flow. Includes ephemeral, intermittent, and perennial stream channels. Also known as gullies, washes, runs, creeks, brooks, and rivers, with the term used often depending on size of the channel or waterway.

Surface-mine (strip mine)—A procedure of mining which entails the complete removal of overburden material. May generally refer to either an area and/or contour mine.

Surface water—Water at or near the land surface, such as lakes and streams as opposed to ground water.

Swamp—A forested wetland with little peat development.

Tailings—See Figure G1. The solid waste product (gangue and other refuse material) resulting from the milling and mineral concentration process (washing, concentration, and/or treatment) applied to crushed ore (Fig. G1). Term usually used for sand to clay-sized refuse that is considered too low in mineral values to be treated further, as opposed to the concentrates.

Unoxidized zone—See "reduced zone."

Ventilation drift or shaft—A horizontal adit or tunnel or vertical shaft in a mine having the prime purpose of exchanging gases with the outside atmosphere.

Volcanic ash—Fine-grained uncemented material ejected during a volcanic eruption.

Vuggy textures—Texture having vugs.

Waste rock—Barren or mineralized rock that has been mined, but is not of sufficient value to warrant treatment and, therefore, is removed ahead of the milling processes and disposed of on site (Fig. G1). Term usually used for wastes that are larger than sand-sized material and can be up to large boulders in size. Waste rock pile also called dump, spoil pile, or spoils.

Weathering—Process whereby earthy or rocky materials are changed in color, texture, composition, or form (with little or no transportation) by exposure to atmospheric agents.

Workings—The entire system of openings (underground as well as at the surface) in a mine (Fig. G1).

ABBREVIATIONS

Ag—silver
A-S—acid-sulfate
Au—gold
Be—beryllium
Bbls—barrels
BBO—billion bbls oil
BCF—billion cubic feet (ft^3)
BHP—Broken Hill Proprietary or bottom hole pressure if one is discussing geothermal, oil wand gas wells
BHT—Bottom hole temperature (in a well)
BLM—U.S. Bureau of Land Management
Btu/lb—British thermal units per pound of fluid
CPD—Carlsbad potash district
CSDP—Continental Scientific Drilling Program
CO_2—Carbon dioxide
Cu—copper
D—Derivative waters (geothermal)
DPA—Designated Potash Area
DG—Deep geothermal waters
EMNRD—Energy, Mineral, and Natural Resources Department (New Mexico)
GCC—Grupo Cementos de Chihuahua (cement)
GPM—Great Plains Margin
HDR—hot dry rock (geothermal)
I/S—illite/smectite clays
JPSB—Jemez Pueblo-San Juan Basin type
ka—thousand years ago
KCl—potassium chloride
km—kilometers
LANL—Los Alamos National Laboratory
LBL—Lawrence Berkeley Laboratory
lbs—pounds
Li—lithium
m—meters
Ma—million years ago
Myr—million years old
MBO—thousand bbls oil
mi—miles
MOP—muriate of potash
MORB—mid-ocean ridge basalt
MRI—magnetic resonance imaging
MSHA—Mine Safety and Health Administration
MVT—Mississippi Valley-type
MWe—megawatts (electrical)
NMBMMR—New Mexico Bureau of Mines and Mineral Resources
NMBGMR—New Mexico Bureau of Geology and Mineral Resources
NMMMD—New Mexico Mining and Mineral Division
NMIMT—New Mexico Institute of Mining and Technology
NURE—National Uranium Resource and Evaluation
OSHA—Occupational Safety and Health Administration
oz—ounces
oz/short ton—ounces per short ton
P&A'd—plugged and abandoned (well)
PGE—platinum group elements (platinum, Pt; palladium, Pl; osmium, Os; ruthenium, R; iridium, I; and rhodium, Rh)
Pb—lead
PNM—Public Service Company of New Mexico
ppb—parts per billion
ppm—parts per million
REE—rare earth elements
RGR—Rio Grande Rift
SMCRA—Surface Mine Control and Reclamation Act
Th—thorium
TCF—trillion cubic feet (ft^3)
U—uranium
μm—micrometers
UNOCAL—Union Oil Company of California
USDOE—U.S. Department of Energy
USGS—U.S. Geological Survey
USBM—U.S. Bureau of Mines
VCNP—Valles Caldera National Preserve
VMS—Volcanogenic massive sulfide
WIPP—Waste Isolation Pilot Plant
Wt%—weight per cent
Y—yttrium
Zn—zinc
Zr—zirconium
δ—delta value used in isotope measurements
°C—degrees centigrade

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