In situ recovery of sandstone-hosted uranium deposits in New Mexico: past, present, and future issues and potential

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Abstract

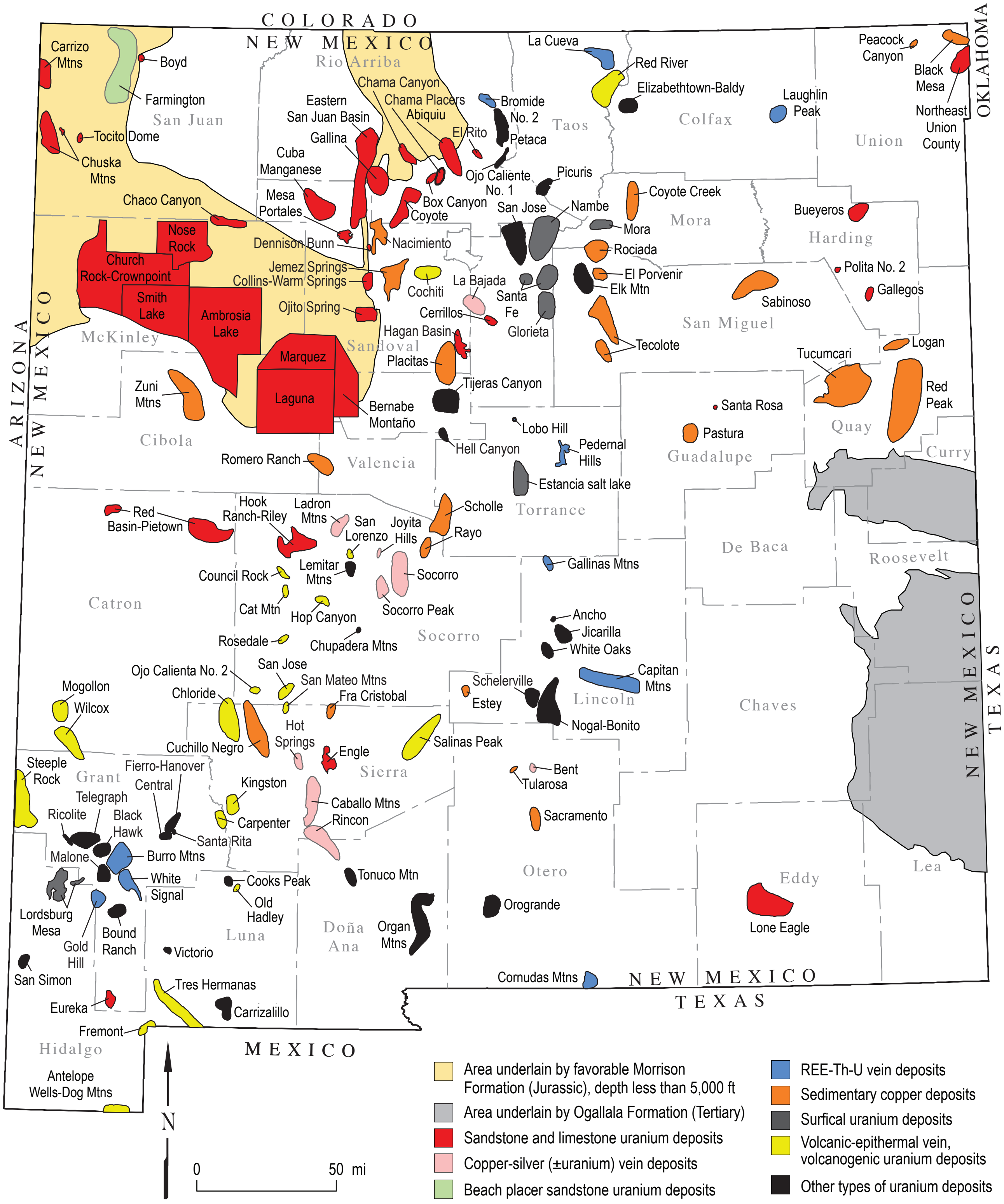
In situ recovery (ISR) operations have been proposed to recover uranium from sandstone-hosted uranium deposits in New Mexico. ISR (also known as in situ leaching, solution mining, solution-leach mining, leach mining) is conducted by wells that circulate native groundwater, amended with oxygen (or other forms of oxidant) to dissolve the uranium and gaseous carbon dioxide (or some form of sodium bicarbonate) to complex the uranium in order to keep it in solution through the ore zone. This amended groundwater is commonly referred to as lixiviant. The lixiviant dissolves uranium as it is drawn from injection wells through the uranium-bearing host rock by pumps in nearby extraction wells, and is subsequently piped to a processing plant where the uranium is extracted from the solution. The groundwater is then refortified and sent back to the ore zone through the injection wells to recover additional uranium. The cycle continues until the desired uranium extraction is complete. Thereafter groundwater restoration is conducted. Several technical and regulatory criteria must be met in order for ISR to be successful. To comply with post-mining restoration criteria dictated by state and federal regulations, the groundwater in the mined areas is restored to baseline or other agreed upon water quality standards. This is usually accomplished by circulating clean groundwater through the mined zones to remove the lixiviant. Because groundwater is the fundamental leaching agent, the uranium deposit must be hosted within permeable sandstone below the water table and generally confined by less permeable strata for proper hydrodynamic wellfield control. The mineralized portion of the aquifer must qualify for an "Exemption" from the EPA (U.S. Environmental Protection Administration) from being an underground source of drinking water. A number of ISR test and pilot operations have been conducted in New Mexico in the past (Mobil, Crownpoint; UNC-Teton, Section 23; Grace Nuclear, Hook's Ranch, Seboyeta, Church Rock; Anaconda, Windwhip). Also, analogous to the ISR process, United Nuclear and Kerr-McGee (later Quivira Mining Co., Rio Algom) successfully produced uranium from mine-water recovery (recirculated mine water) from underground mines in the Ambrosia Lake area during the mid-1960s to 2002. Potential ISR site locations in the U.S., including in New Mexico, require careful aquifer characterization and project operational design and monitoring. With such proper site characterization and design, ISR is a viable alternative mining technology to provide future uranium recovery from many of New Mexico's known uranium deposits. This initial investigation suggests that a significant portion of deposits in the Grants uranium district may be amenable to ISR production.

Introduction

Uranium in New Mexico is found in rocks of all ages and lithologies, ranging from Precambrian granites to recent travertine deposits (Fig. 1; McLemore, 1983, 2007; McLemore and Chenoweth, 1989, 2017). Uranium is found in sandstones, coals, limestones, shales, igneous and metamorphic rocks, pegmatites, veins, volcanic rocks, and breccia pipe deposits. However, most of the economic uranium deposits are hosted by sandstones and most of the uranium production in New Mexico has come from the Westwater Canyon Member of the Jurassic Morrison Formation in the Grants uranium district, in McKinley and Cibola (formerly Valencia) Counties (Table 1; McLemore, 1983). The Grants uranium district represents one large area in the southern part of the San Juan Basin, extending from east of Laguna to west of Gallup and consists of eight sub-districts (Fig. 2; McLemore and Chenoweth, 1989, 2016; McLemore, 2007). During a period of nearly three decades (1951–1980), the Grants uranium district yielded nearly 347 million lbs of U_3O_8, almost all of New Mexico's production, and more uranium than any other district in the United States (Table 1). The Grants district is probably 7th in total world production behind East Germany, the Athabasca Basin in Canada, Kazakhstan and South Africa (Tom Pool, International Nuclear, Golden, Colorado, written communication, December 3, 2002). Although there are no operating mines in the Grants district today, numerous companies have acquired uranium properties and plan to explore and develop deposits in the district in the future.

Several ISR operations have been proposed to recover uranium from sandstone-uranium deposits in New Mexico, mostly in the Grants uranium district, although one operation was tested in the Hooks Ranch area in Socorro County (Hook Ranch—Riley district). In situ recovery (also known as in situ leaching, solution mining, solution-leach mining, leach mining) uses a series of injection and extraction wells, which circulate amended native groundwater through the ore zone. This groundwater solution, commonly referred to as lixiviant, dissolves and complexes uranium as it is drawn from injection wells through the uranium-bearing host rock by pumps in nearby production wells, which then sends the uranium-rich water to the processing plant where the uranium is removed. The water is then refortified and sent back to the ore zone through the injection wells to recover more uranium. The cycle continues until the desired uranium extraction is complete. Thereafter, groundwater restoration is conducted.

The purpose of this paper is to briefly describe the production histories, geology, resources, environmental issues, and future potential of uranium deposits in New Mexico that are possibly amenable to ISR. Although



🟨 Area underlain by favorable Morrison Formation (Jurassic), depth less than 5,000 ft

▨ Area underlain by Ogallala Formation (Tertiary)

🟥 Sandstone and limestone uranium deposits

▨ Copper-silver (±uranium) vein deposits

🟩 Beach placer sandstone uranium deposits

🟦 REE-Th-U vein deposits

🟧 Sedimentary copper deposits

⬛ Surfical uranium deposits

🟨 Volcanic-epithermal vein, volcanogenic uranium deposits

⬛ Other types of uranium deposits

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.

there has been no large-scale commercial ISR production in New Mexico, several small-scale pilot projects have been conducted in the past. This paper will include a summary of these past ISR operations, mostly summarized and updated from Holen and Hatchell (1986). Much of this paper is summarized from McLemore (1983), Holen and Hatchell (1986), McLemore and Chenoweth (1989, 2017), McLemore et al. (2002), McLemore (2007) and other reports as cited. Information on specific mines and deposits in New Mexico can be found in cited references, McLemore (1983, 2007), McLemore and Chenoweth (1989, 2016), and McLemore et al. (2002).

In situ recovery

What is in situ recovery?

ISR is the extraction of uranium by recirculating, through wells, groundwater fortified with relatively benign chemical solutions; oxidizing, complexing, and mobilizing the uranium; and recovery of the uraniferous solutions through production wells and pumping the solution to the surface for further processing. ISR is commonly called in situ leaching or ISL. The term ISR is appropriately used when the entire uranium recovery cycle is described from subsurface dissolution, through processing, drying and packaging. The injection solution is fundamentally groundwater that has been pumped from the ore body aquifer, to which relatively small concentrations of an oxidant such as liquid oxygen or hydrogen peroxide and a complexing agent such as sodium bicarbonate have been added. Restoration of the aquifer is mandatory in the U.S. regardless of the type of lixiviant used. Sulfuric acid is an effective lixiviant regent that is used elsewhere in the world, but in the U.S. using an acid lixiviant system is generally not done because acid lixiviants may cause mineralogical changes to the host sandstones that could adversely impact hydrological conditions and post-mining restoration efforts. As a result, commercial operations in the U.S. have used the sodium bicarbonate-type alkaline lixiviant chemistry that has been described previously.

From 2004–2009, ISR production was the source of 20–34% of the total world production, mostly from mines in Australia, China, Kazakhstan, United States, and Uzbekistan, whereas in 2014, ISR production increased to 51% of the total world production of uranium (IAEA, 2004; The Changing World of Uranium Mining, A Monday Morning Musing from Mickey the Mercenary Geologist, **http://www.goldgeologist.com/mercenary_musings/musing-160125-The-Changing-World-of-Uranium-Mining.pdf**, accessed 1/28/16). Uranium ISR production costs are generally lower than those associated with conventional (open pit or underground) mining and milling, with considerably lower capital and operating costs. Certain environmental considerations associated with ISR operations are more favorable than traditional conventional mining and milling operations because there are no surface waste rock dumps, mill tailings, or dewatering of aquifers. Labor costs for ISR operations are appreciably lower, as fewer workers are required in ISR operations as compared to conventional mining.

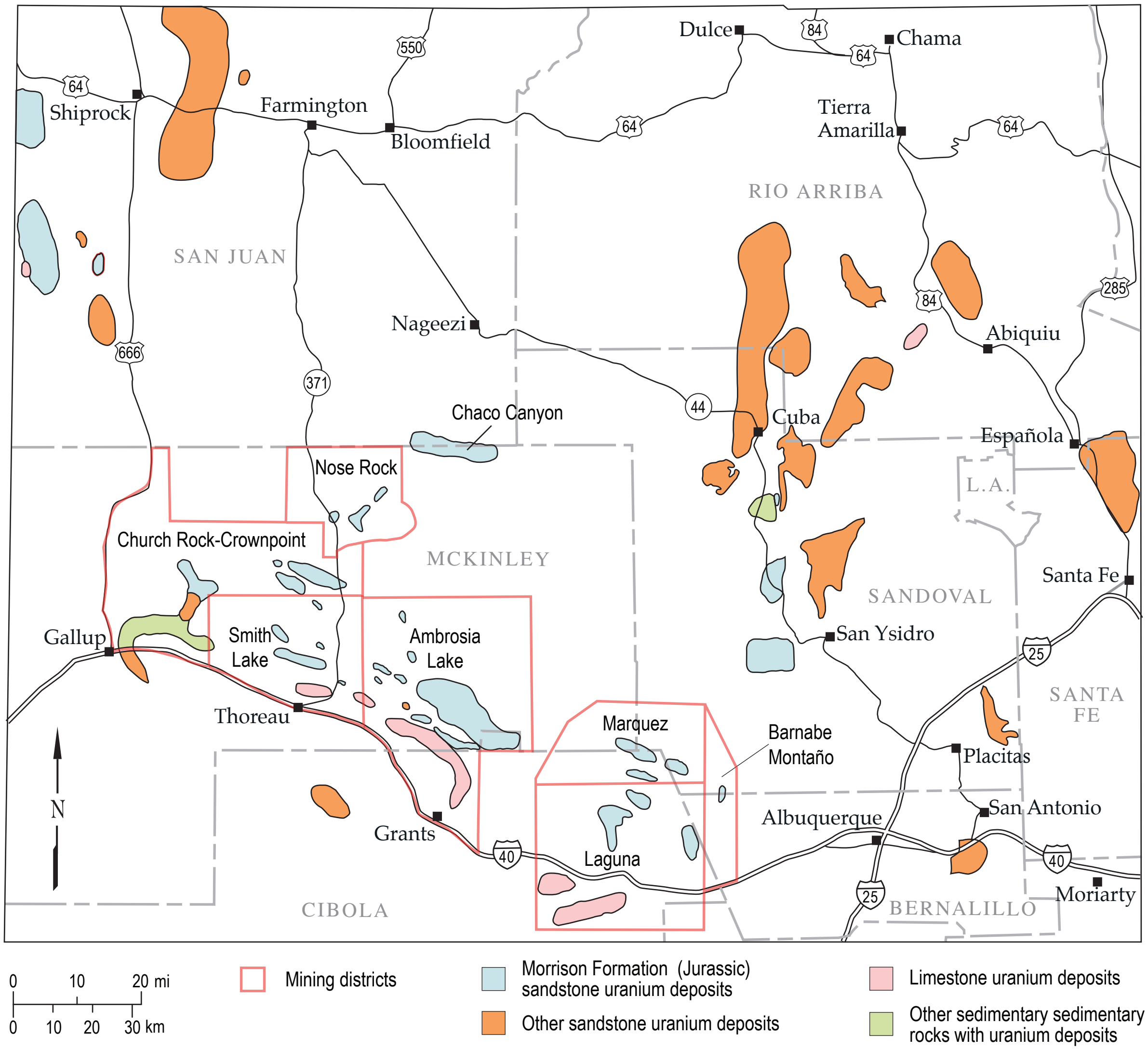


FIGURE 2. Northwestern part of New Mexico showing uranium deposits in the San Juan Basin and subdistricts of the Grants uranium district. Polygons outline approximate areas of known uranium deposits (McLemore and Chenoweth, 1989).

Although ISR recoveries can be lower than those realized from conventional mining, this disadvantage is offset by lower operational, labor, and environmental costs and exploitation of lower-grade and smaller deposits than are economical by conventional mining. For these reasons, it is expected that ISR production will increase in the future. However, there are some other potential issues, which are summarized in this paper.

Criteria required for successful in situ recovery

Several technical criteria are required for ISR to operate effectively. The uranium deposit must lie beneath the water table in a saturated zone at all times during ISR operations. The uranium host rock should be horizontal or nearly horizontal and confined by less permeable strata, above and below the uranium-bearing unit. The deposit must be permeable and remain permeable throughout the life of the ISR operation. The uranium minerals must be amenable to dissolution by the mild lixiviant chemistry. Other challenges can exist. Some uranium minerals are insoluble or in host rock that lacks permeability and/or, depending on uranium market prices, some may be too deep for commercially viable ISR operations because of well construction costs. Finally, the surface topography must be suitable for placing of multiple injection and recovery wells (well fields). Many of the deposits in the Grants uranium district fulfill many of the above criteria.

Uranium deposits in New Mexico

The types of uranium deposits in New Mexico are summarized in Table 2, many of which are found in the Grants district. The most important type of deposit in terms of production (Table 2) and resources are sandstone-hosted uranium deposits in the Morrison Formation (Jurassic), which are also the most important type amenable to ISR. More than 340,565,370 lbs of U_3O_8 were produced from the Morrison from 1948 to 2002 (Table 1). The largest ore deposits in the Grants uranium district contain more than 30 million lbs of U_3O_8 each. Other sandstone deposits throughout New Mexico also could have potential for ISR production and are described below. Other types of uranium deposits are described by McLemore (1983, 2007) and McLemore and Chenoweth (1989, 2017).

Sandstone uranium deposits in the Morrison Formation (Jurrasic)

Sandstone uranium deposits account for the vast majority of the historical uranium production from New Mexico (McLemore and Chenoweth, 1989, 2003, 2017). The most significant deposits are those in the Morrison Formation, specifically the Westwater Canyon Member (see McLemore and Chenoweth, 2017, table 3 for production statistics and table 6 for a summary of major uranium deposits and reserves in New Mexico). There

TABLE 1. Uranium production by type of deposit from the San Juan Basin, New Mexico 1947–2002 (McLemore and Chenoweth, 1989, 2003, 2017; production from 1988–2002 estimated by the senior author based upon company annual reports and total yearly production values). Type of deposit refers to Table 3. 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 New Mexico (Percent)
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 US

[1] Approximate production figures rounded to the nearest 1,000 pounds. There has been no uranium production from New Mexico since 2002.

[2] Todilto Formation (Cather et al., 2013).

are three types of deposits in the Westwater Canyon Member of the Morrison Formation: primary (trend or tabular), redistributed, and remnant-primary sandstone uranium deposits.

Primary sandstone-hosted uranium deposits, also known as prefault, trend, blanket, and black-band ores, are found as blanket-like, roughly parallel ore bodies along trends, mostly in sandstones of the Westwater Canyon Member. These deposits are characteristically less than 8 ft thick, average more than 0.20% U_3O_8, and have sharp ore-to-waste boundaries. Primary deposits are high in organic carbon and are known to be difficult to recover by conventional milling techniques and will provide challenges to ISR operations (Holen and Hatchell, 1986).

Redistributed sandstone-hosted uranium deposits, also known as post-fault, stack, secondary, roll-type and

TABLE 2. Classification of uranium deposits in New Mexico (modified from McLemore and Chenoweth, 1989; McLemore, 2001, 2007). Deposit types **in bold** are possibly amenable for ISR operations. [1]Mine identification numbers, prefixed by NM, and district identification numbers, prefixed by DIS are from the New Mexico Mines Database (McLemore et al., 2002, 2005a, 2005b).

Type of Deposit	Example[1]
I. Peneconcordant uranium deposits in sedimentary host rocks	
Morrison Formation (Jurassic) sandstone uranium deposits	
• **Primary, tabular sandstone uranium-humate deposits in the Morrison Formation**	Roca Honda (NMMK0142)
• **Redistributed sandstone uranium deposits in the Morrison Formation**	Church Rock (Section 17) (NMMK0034)
• **Remnant sandstone uranium deposits in the Morrison Formation**	Ruby 3 (NMMK0147)
• Tabular sandstone uranium-vanadium deposits in the Salt Wash and Recapture Members of the Morrison Formation	Enos Johnson 1–4 (NMSJ0047)
Other sandstone uranium deposits	
• **Redistributed uranium deposits in the Dakota Sandstone (Cretaceous)**	Church Rock (NMMK0034)
• **Roll-front sandstone uranium deposits in Cretaceous and Tertiary sandstones**	C de Baca (NMSO0515)
• **Sedimentary uranium deposits**	Boyd (NMSJ0028)
• **Sedimentary-copper deposits**	Nacimiento (NMSA0064)
• Beach placer sandstone uranium deposits	Sanostee (NMSJ0088)
Limestone uranium deposits	
• Limestone uranium deposits in the Todilto Formation (Jurassic)	Barbara J 2 (NMMK0008)
• Other limestone deposits	Rocky Arroyo (NMED0018)
Other sedimentary rocks with uranium deposits	
• Carbonaceous shale and lignite uranium deposits	Butler Brothers (NMSA0031)
• Surficial uranium deposits	
Calcrete	Lordsburg Mesa (DIS266)
Playa lake deposits	Estancia Salt (DIS243)
II. Fracture-controlled uranium deposits	
Vein-type uranium deposits	
• Rio Grande Rift (RGR) Copper-silver (±uranium) veins (formerly called Jeter-type, low-temperature vein-type uranium deposits and La Bajada-type, low-temperature uranium-base metal vein-type uranium deposits)	Jeter (NMSO0023)
• Collapse-breccia pipes (including clastic plugs)	Woodrow (NMCI0106)
• Volcanic epithermal veins	Union Hill (NMGR0112)
• Polymetallic veins (formerly Laramide veins)	Merry Widow (NMGR0054)
III. Disseminated uranium deposits in igneous and metamorphic rocks	
Igneous and metamorphic rocks with disseminated uranium deposits	
• Metasomatic or metasomatite deposits	Red Rock 1 (NMSI0072)
• Pegmatites	Harding (NMTA0015)
• Alkaline rocks	Pajarito (NMOt0095)
• Granitic rocks	La Cueva prospect (NMTA0559)
• Carbonatites	Lemitar (NMSO0115)
• Caldera-related volcanogenic uranium deposits	San Juan Peak (NMSO0080)
IV. Other potential types of uranium deposits in New Mexico	
• Iron Oxide-Cu-Au (IOCG) (Olympic Dam deposits, hematite breccia deposits)	Possibly Chupadera Mesa (DIS241)
• By-product copper processing	None in NM

roll-front ores, are younger than the primary sandstone-hosted uranium deposits. By definition the uranium has been "redistributed" into the present deposit by a natural process in the past. They are discordant, asymmetrical, irregularly shaped, characteristically more than 8 ft thick, have diffuse ore-to-waste contacts, and cut across sedimentary structures. The average redistributed deposit contains approximately 18.8 million lbs U_3O_8 with an average grade of 0.16%. Some redistributed uranium deposits are vertically stacked along faults. These deposits are not associated with significant amounts of organic material and are generally amenable for ISR.

Remnant sandstone-hosted uranium deposits were preserved entirely within oxidized sandstones after the oxidizing waters that formed redistributed uranium deposits had migrated down dip. Some remnant sandstone-hosted uranium deposits were preserved, because they were surrounded by or found in less permeable sandstone and could not be oxidized as oxidizing groundwaters moved through the aquifer system. These deposits are similar to primary sandstone-hosted uranium deposits, but are more difficult to locate because they occur sporadically within the oxidized sandstone. The average size is approximately 2.7 million lbs U_3O_8 at a grade of 0.20%. These deposits are not associated with significant amounts of organic material, are relatively insoluble and/or hosted by less-permeable sandstones and are generally not amenable to anthropogenic ISR for the same reason they were not subject to natural redistribution processes.

Tabular sandstone uranium-vanadium deposits in the Salt Wash and Recapture Members of the Morrison Formation are restricted to the east Carrizo (including the King Tutt Mesa area) and Chuska Mountains subdistricts of the Shiprock district, western San Juan Basin, where historical production totals 493,510 lbs of U_3O_8 (Table 2). The Salt Wash Member is the basal member of the Morrison Formation in this part of the Colorado Plateau and is overlain by the Brushy Basin Member (Anderson and Lucas, 1992, 1995). It unconformably overlies the Bluff-Summerville Formation, using older stratigraphic nomenclature (Anderson and Lucas, 1992), or the Wanakah Formation as proposed by Condon and Peterson (1986). The Salt Wash Member consists of 190–220 ft of interbedded fluvial sandstones and floodplain mudstones, shales, and siltstones. The mudstone and siltstone make up approximately 5–45% of the total thickness of the unit (Masters et al., 1955; Chenoweth, 1993).

The tabular uranium deposits of the Salt Wash Member are generally elongated parallel to paleostream channels and are associated with carbonized fossil plant material. A cluster of small uranium deposits along a channel trend could contain as much as 4,000 short tons of ore averaging 0.23% U_3O_8 (Hilpert, 1969; McLemore and Chenoweth, 1989, 2017). The deposits tend to form subhorizontal clusters that are elongated and blanket-like. Ore bodies in the King Tutt Mesa area are small and irregular and only a few ore bodies have yielded more than 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). The deposits are typically concordant to bedding, although discordant lenses of uranium-vanadium minerals cross-cut bedding planes locally. The ore bodies typically float in the sandstone; locally, they occur at the interface between sandstone and less permeable shale or siltstone. However, unlike uranium deposits in the Grants district, the deposits at King Tutt Mesa are high in vanadium. The U:V ratio averages 1:10 and ranges 1:1 to 1:16.

It is unlikely that the Salt Wash deposits in New Mexico are amenable for ISR, because most of them are situated above the water table, have low permeability (calcite and gypsum cement and abundant clay minerals), and contain abundant organic material and vanadium that makes recovery difficult. These high carbon ores, which have complex mineralogy (including appreciable vanadium content), are known to be difficult to recover by conventional milling techniques and will provide challenges to ISR operations (Holen and Hatchell, 1986). Furthermore, the lenticular nature of the mineralized sandstone channels will make ISR challenging. However, no pilot studies have been released to determine the solubility or recovery of these deposits.

Other Sandstone Uranium Deposits

Redistributed uranium deposits in the Dakota Sandstone (Cretaceous)

A total of 501,169 lbs of U_3O_8 has been produced from redistributed uranium deposits in the Dakota Sandstone in the southern part of the San Juan Basin (Table 2; Chenoweth, 1989). These deposits are similar to redistributed uranium deposits in the Morrison Formation and are found near primary and redistributed deposits in the Morrison Formation. Deposits in the Dakota Sandstone are typically tabular masses that range in size from thin pods a few feet long and wide to masses as much as 2,500 ft long and 1,000 ft wide. The largest known 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, 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 (Chenoweth, 1989). These deposits are amenable for ISR.

Roll-front sandstone uranium deposits

Roll-front sandstone uranium deposits are found in the Crevasse Canyon-Baca Formations (Hook Ranch-Riley district), Tesuque Formation (San Jose district) and Ojo Alamo Sandstone (Farmington, Mesa Portales districts) areas in northern New Mexico, where production totals 60 lbs of U_3O_8 (Table 2; McLemore and Chenoweth, 1989). Roll-front uranium deposits typically are found in permeable fluvial channel sandstones and are associated with carbonaceous material, clay galls, sandstone-shale interfaces, and pyrite at an oxidation-reduction interface. Although only a few minor and unverified uranium occurrences have been reported at Mesa Portales (McLemore, 1983); radiometric anomalies are detected by water, stream-sediment, drill logs, and aerial-radiometric studies. Past drilling at Mesa Portales (Fig. 1) indicated that low-grade uranium is found in blanket-like bodies in several horizons. The known mineralization pattern from drill logs suggests that these deposits are modified roll-type ore bodies. These deposits are low grade, but the deeper deposits that are below the water table could be amenable for ISR.

Sedimentary sandstone uranium deposits

Sedimentary sandstone uranium deposits are stratabound deposits associated with syngenic organic material or iron oxides, or both, such as at the Boyd deposit (Fruitland Formation) near Farmington and deposits in the Chinle Formation throughout northern New Mexico. Uranium contents vary, but average grades of shipments from these deposits rarely exceeded 0.1% U_3O_8. These deposits tend to be small, containing only a few tons of ore, and the potential for future production is low. More information is needed to determine if these deposits have ISR potential.

Sedimentary-copper deposits

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

History of in situ recovery operations in New Mexico

Several ISR tests and pilot studies have been conducted in New Mexico (Table 3). In addition, more than 9.6 million pounds of U_3O_8 was produced by mine water recovery from 1963 through 2002 (Table 1), mostly from the Ambrosia Lake, Church Rock, and Smith Lake areas (Table 4). Native groundwater, without any additional additives, was circulated throughout the surface or underground workings and collected for processing.

Environmental issues

ISR exploitation of uranium deposits provides decided advantages to the environment, in comparison to conventional open pit and underground mining and conventional milling. These advantages include much smaller surface disturbances and shorter duration (allowing the timely return of the surface to traditional land uses), significant reductions of the introduction of radionuclides into the surface environment, and other reduced impacts to local ecosystems. In evaluating the possibilities of developing an ISR mine, it is important to recognize that in the portion of the aquifer in which the uranium deposit is situated, the groundwater prior to ISR operations is not potable because the concentrations of uranium and/or uranium progeny such as ^{226}Ra and ^{222}Rn exceed acceptable drinking water standards by a large margin (Pelizza 2014); in other words it is naturally contaminated.

The aforementioned notwithstanding, it is essential that all proposed ISR operations consider certain geological processes as well as undergo rigorous and detailed pre-mining aquifer characterization studies, careful and detailed mineralogical and geochemical studies of the uranium mineralized zones, and comprehensive modeling of the entire hydrologic regime that is based on physical testing and subsequent modeling. Of particular importance are:

TABLE 3. Past pilot and small-scale ISR operations in New Mexico (updated from Holen and Hatchell, 1986). Mine identification number is from the New Mexico Mines Database (McLemore et al., 2005a, b).

Mine Identification Number	Project	Company	Location (latitude, longitude in degrees)[1]	Approximate depth to deposit (feet)	Comments
NMMK0040	Crownpoint ISR—South Trend	Mobil/TVA	35.706678 108.22052	2,000	commercial wellfield that was drilled but never commissioned
NMMK0038	Crownpoint—Section 9	Mobil/TVA	35.71751 108.226809	2,000	1979, successful recovery and ground water restoration
NMMK0109	Monument	Mobil/TVA	35.676444 108.118645	2,000	no information available, may have been a lab test
NMMK0124	Section 13 (Push-pull)	UNC-Teton	35.61626 108.589759	1,300	1980
NMMK0209	Leach Site No. 1 (Section 23)	Grace Nuclear	35.608667 108.602083	500	1975
NMSA0076	Leach Site No. 2 (Section 13)	Grace Nuclear	35.273278 107.205778	380	1975
NMSO0098	Hook Ranch	Grace Nuclear	34.306972 107.424611	50?	Unsuccessful test
NMCI0105	Windwhip	Anaconda	35.142548 107.339932	200–240	1970

[1] Latitudinal, longitudinal in NAD27.

- Mobilization of uranium is part of a broader geochemical process that also mobilizes other elements such as molybdenum and radium, and operational procedures are required to control these constituents during ISR mining and to mitigate their presence after completion of operations (post-closure).

- Study of clay species in the mineralized zones, and their impacts, not only upon porosity and permeability characteristics during uranium extraction, but their geochemical interactions with various elements and compounds during and after groundwater restoration (post-closure).

- Development of detailed hydrological models of the aquifer, relying not only on the results of rigorous aquifer tests, but also thorough incorporation of a detailed geologic model that incorporates all data relating to faults, fractures and joints that could otherwise impact the management of lixiviants during mining.

- During ISR operations, slightly higher production rates are maintained within the wellfields to help ensure none of the lixiviant migrates from the mining area. Proper disposal of this "bleed water" during mining and the larger quantity of water that is produced during the restoration process.

- Thorough and honest communication with the public and regulators.

While the environmental, technological and operational applications of ISR mining of uranium have advanced appreciably since the time of ISR pilot test programs in New Mexico, these important environmental issues continue to require the attention of mine operators and regulators alike.

The mineralogical, chemical, hydrological, and physical parameters of the aquifer are characterized well before ISR, but these parameters are also important to characterize during and even after ISR is completed. The process dissolves not only uranium, but other minerals, which could alter the geochemistry of the aquifer, and affect recovery of the lixiviant as well as the composition of groundwater. Precipitation of minerals such as gypsum and calcite can occur during the process that could seal the well bore, affect recoveries and potentially impact future use of the aquifer. Complex reactions with clay minerals also can lead to changes in aquifer conditions. Changes in mineralogy of the host sandstone during and after ISR should be monitored using the most advanced geochemical techniques that are available.

In the Grants district, structural discontinuities (faults, folds, pinch-outs of beds) are visible during open-pit and underground mining that are not observed on the surface or by exploration drilling. These structural discontinuities are encountered in ISR, but the effects of these discontinuities may be difficult to plan for in during ISR wellfield development because in the U.S., most exploration drilling is conducted at 100-ft centers, which typically detects and characterizes many, but not all of these features. For this reason, during ISR wellfield development, delineation drilling is conducted in advance of well installation where drill spacing is generally reduced to 50 ft or less. It is important that the project wellfield development geological staff pay particularly close attention to structural and stratigraphic changes that may not have become apparent during the wider spaced exploration drilling program to assure the best wellfield design and optimal ISR performance.

Most ISR operations are relatively shallow, less than 500 ft deep, but many of the Grants uranium deposits are deeper than 1,000 ft, with some deposits as much as 4,000 ft deep. Depending on uranium market prices, some of the remaining Grants deposits may be too deep for commercially viable ISR operations because of well construction costs and irregular surface topography. Despite these difficulties, ISR could be a viable alternative to the conventional mining of uranium and can be used in the Grants district with proper advanced geological and aquifer characterization and monitoring by the ISL companies, all which are evaluated during the permitting process by state and federal regulatory agencies. Every location should be evaluated, tested and reviewed by regulators on a case by case basis.

Summary

Sandstone-hosted uranium deposits in New Mexico have played a major role in global historical uranium

TABLE 4. Mine water recovery from stope leaching (modified from Holen and Hatchell, 1986). Mine identification number is from the New Mexico Mines Database (McLemore et al., 2005a, b).

Project	Company	Mine (Mine Id)
Ambrosia Lake	United Nuclear	Section 27 (NMMK0226), Ann Lee (NMMK0003), Sandstone (NMMK0149)
Church Rock	United Nuclear	Northeast Church Rock (NMMK0117), Old Church Rock (NMMK0034)
Ambrosia Lake	Kerr-McGee (Quivira)	Sections 17, 19, 22, 24, 30, 30 West, 33, 35 (NMMK0191, NMMK0199, NMMK0206, NMMK0213, NMMK0237, NMMK0236, NMMK0250)
Church Rock	Kerr-McGee (Quivira)	NE Church Rock 1 (NMMK0112)
Ambrosia Lake	United Nuclear-Homestake Partners (later Homestake, now Quivira)	Sections 15, 23, 25, 32 (NMMK0183, NMMK0208, NMMK0216, NMMK0244)
Smith Lake	Gulf	Mariano Lake (NMMK0102)
San Mateo	Gulf (Chevron)	Mount Taylor (NMCI0027)
Seboyeta	Sohio-Western	L Bar (NMCI0019)

production. Although some other types of uranium deposits in the world are higher in grade and larger in tonnage, the Grants uranium district could become a significant source of uranium because as ISR technologies improve, production costs decrease. However, several challenges need to be addressed by companies before uranium could be produced once again from the Grants uranium district, especially by ISR, and these can be planned for during the permitting process:

- Permitting for new ISR and especially for conventional mines and mills will take years to complete at significant up-front costs.
- Geological and technical issues need to be resolved on a deposit by deposit basis.
- In the United States, closure plans, including reclamation, are developed during the permitting process, prior to the commencement of mining or ISR activities. Modern regulatory costs will add to the cost of producing uranium in the U.S.
- Some communities, especially the Navajo Nation communities, do not view development of uranium properties as favorable. The Navajo Nation has declared that no uranium production will occur on Navajo lands.
- High-grade, low-cost uranium deposits in Canada and Australia are sufficient to meet a portion of today's demands; however, additional resources, possibly including those in New Mexico, will be required to meet long-term future requirements.

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