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Uranium deposits at the Cebolleta project, Laguna mining district, Cibola County, New Mexico
Ted Wilton.....**1–10**

Modeled Impacts of Economics and Policy on Historic Uranium Mining Operations in New Mexico
Katie Zemlick, Bruce M. Thomson, Janie Chermak, and Vincent C. Tidwell.....**11–24**

Gallery of Geology
Virginia T. McLemore and Bonnie A. Frey.....**25–27**

Cover Image

Church Rock #1 East shaft, Church Rock-Crownpoint subdistrict, McKinley County. The mine was operated by Kerr-McKee from 1979 to 1983. Photo by O. Anderson on 3/7/79.

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Uranium in New Mexico: A Special Issue of New Mexico Geology

Virginia T. McLemore and Ted Wilton

In January 2016, a team of experts from the uranium industry and researchers from two New Mexico universities assembled at the Sevilleta National Wildlife Refuge for a three-day workshop to discuss topics associated with in situ recovery (ISR) of uranium. Part of the motivation for this workshop was the recognition that there has been little new research completed by the uranium industry or the academic community, and that much of the current uranium knowledge base consists of research, mapping and technology from the 1970s and 1980s. Researchers and industry workers today have many new technologies available to help re-evaluate exploration, mining, processing, reclamation and restoration. Furthermore, today's industry has become much more open to sharing data, in part because the strenuous permitting process has turned previously proprietary information into public record. Outcomes of the January workshop include two special editions of New Mexico Geology, including this Spring, 2017 issue. The first special issue of New Mexico Geology on uranium (v. 38, no. 4) was published in November 2016 with two articles. We hope that these editions of New Mexico Geology will provide information about current uranium-mining topics.

Another outcome of the workshop was a compilation of a list of research activities that could support renewed activity in the New Mexico uranium industry. Topics include workforce training, resource characterization, hydrogeological and geochemical modeling, updated environmental and regulatory protections, improved understanding of depositional mineralogy, microbiology and geochemistry, and the development of new recovery and restoration technology. In comparison with conventional open pit and underground mining and conventional milling, ISR exploitation of uranium deposits may provide some decided advantages to the environment, including much smaller and shorter duration of land-surface disturbances, allowing the return of the surface to traditional land uses, potentially 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 the portion of the aquifer in which the uranium deposit is situated does not, because of natural conditions, meet national drinking water standards; in other words it is naturally contaminated and it is not suitable for human consumption.

Nonetheless, it is essential that all proposed ISR operations 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:

- 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 stabilize these constituents during ISR mining and after completion of operations (post-closure).
- The geochemical characteristics of naturally-occurring groundwater that oxidized and remobilized and redeposited "trend-type" uranium deposits in the Grants Mineral Belt.
- Updated studies on the various uranium minerals in sandstone-hosted deposits as they impact the potential recovery of uranium metal from these deposits.
- Study of clay species in the mineralized zones, and their impacts not only on 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 a thorough analysis of a detailed geologic model that incorporates all data, at a detailed mine scale, relating to faults, fractures and joints that could otherwise impact the management of the fluids that are used during ISR mining.
- Proper disposal of ISR fluids used during mining.
- 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.

Virginia McLemore and Bonnie Frey volunteered to co-chair a keynote session on uranium for the April 7, 2017 spring meeting of the New Mexico Geological Society (NMGS). We hope that interested readers of these articles will join us in Socorro.

Uranium deposits at the Cebolleta project, Laguna mining district, Cibola County, New Mexico

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Abstract

The Cebolleta uranium project in northwestern New Mexico is the site of five sandstone-hosted uranium deposits contained within the Jackpile Sandstone Member of the Upper Jurassic Morrison Formation. The uranium mineralization, which has been well-delineated by numerous drill holes, two open-pit and three underground mines, is a series of tabular shaped bodies that were deposited within individual sandstone lenses of the Jackpile Sandstone. Uranium deposits in the project area exhibit characteristics of "trend," "redistributed," and "remnant" types of deposits, as described elsewhere within the Grants mineral belt. Significant uranium resources are present in the project area.

Introduction

The Cebolleta uranium project of Uranium Resources, Incorporated (URI), is located in the Laguna mining district of northeastern Cibola County, New Mexico (Fig. 1). Situated in northwestern New Mexico east of Mount Taylor, the project is approximately 72 km west of the city of Albuquerque and 16 km north-northeast of the Pueblo of Laguna. The Cebolleta project lies in an area of valleys and mesas along the southeastern margin of the San Juan Basin. Elevations within the project area range from approximately 1,798 to 1,983 m above sea level.

The project area (Fig. 2), which hosts five significant sandstone-hosted uranium deposits, is positioned near the eastern end of the so-called Grants mineral belt, which

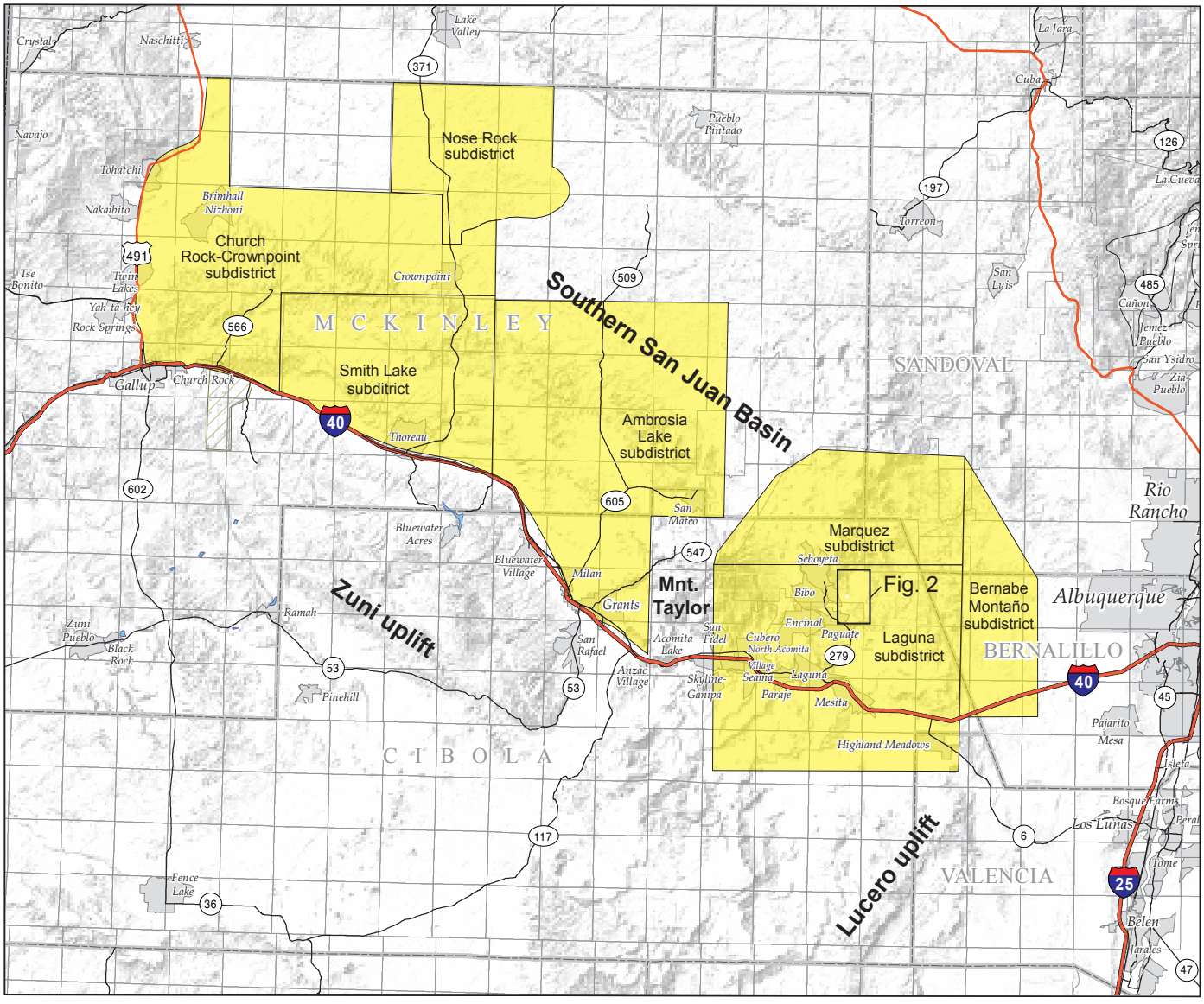
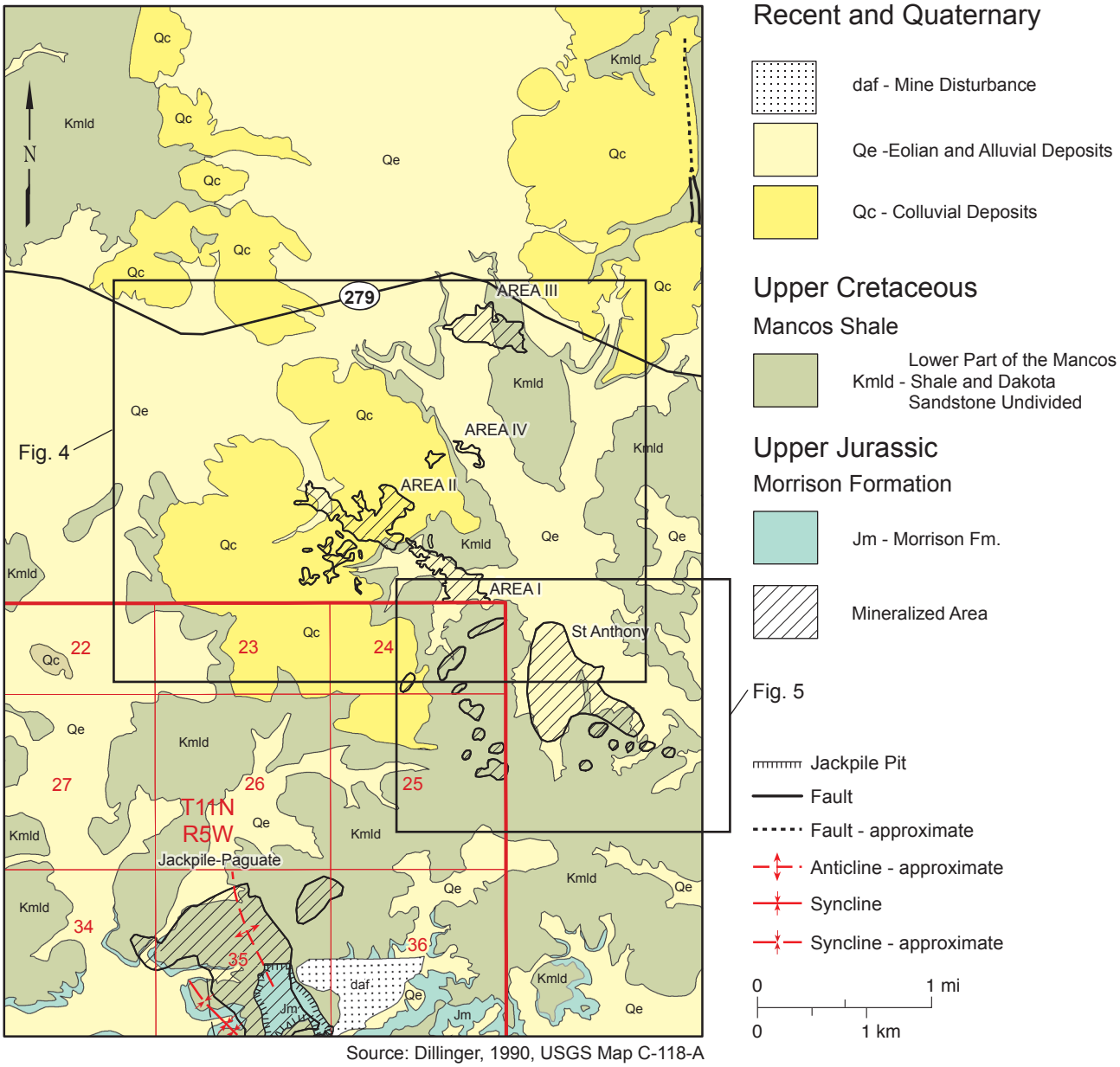


Figure 1. Map showing locations of the Cebolleta project (Fig. 2), mining districts shown in yellow, and other areas mentioned in the text.



Source: Dillinger, 1990, USGS Map C-118-A

Figure 2. Generalized geologic map of the Cebolleta project area showing outlines of uranium deposits (geology modified from Dillinger, 1990). Unsurveyed portion of map is the Cebolleta Land Grant. Locations of Figures 4 and 5 are outlined.

encompasses several mining districts in the southern part of the San Juan Basin. The Grants mineral belt is one of the largest concentrations of sandstone-hosted uranium deposits in the world. Uranium mineralization at the Cebolleta project occurs as a series of tabular bodies hosted within the Jackpile Sandstone Member of the Upper Jurassic Morrison Formation. Historical uranium production from the project area was derived from three underground and two open-pit mines, and significant uranium resources remain in the area.

Project History

The Laguna mining district has been an area of considerable interest to the U.S. uranium industry since the early 1950s, when indications of near-surface uranium mineralization were discovered by geologists and engineers of the Anaconda Copper Company in late 1951 (Beck and others, 1980). Anaconda's identification of surface exposures of uranium mineralization led to the subsequent discovery of the Jackpile-Paguate uranium deposit complex, which was later developed as the largest uranium mine in the U.S. During this time Anaconda undertook a regional exploration drilling program on the nearby Evans Ranch, northeast of the Jackpile mine, continuing this exploration effort until 1957 when they terminated their property interest. The Evans Ranch, also known as the L-Bar Ranch, along with a portion of La Merced del Pueblo de Cebolleta (Cebolleta Land Grant) is the site of the Cebolleta project. During the period of Anaconda's exploration program they completed more than 350 drill holes on the Evans Ranch, but did not advance the project beyond the exploration stage (Geo-Management, 1972, unpublished report).

The first mining in the Cebolleta project area was undertaken by Hanosh Mines, Inc., who extracted 167 tons (151 tonnes) of material that averaged 0.09% U_3O_8 (Chenoweth, 2016, personal communication; ore grades are reported as weight percent U_3O_8). Drilling by the

Climax Uranium Company during the period 1954 to 1956 resulted in the discovery of a substantial uranium deposit, which became the site of the so-called M-6 mine, in Section 30, Township 11 North, Range 4 West. Production from the M-6 mine began in July, 1957 and continued until October, 1960 (Chenoweth, 2016, personal communication). Total production from the M-6 deposit was reported to be 78,555 tons (71,264 tonnes) averaging 0.20% U_3O_8 and yielding 320,647 pounds of U_3O_8 (Chenoweth, 2016, personal communication).

At a later date United Nuclear Corporation and its subsidiary Teton Exploration Drilling Company carried out an extensive exploration program in the vicinity of the former M-6 (Climax) mine, and discovered significant and widespread uranium mineralization. In 1975 United Nuclear developed two small open pits and one underground mine on lands leased from the Cebolleta Land Grant (Baird, and others, 1980). These mines are known as the St. Anthony mines. Ore from the St. Anthony mines was processed primarily at the United Nuclear Northeast Church Rock mill near Gallup, NM. Mining was suspended at St. Anthony in 1979, and the milling of stockpiled material was completed in 1980. Total production from the St. Anthony mines was approximately 1.6 million pounds of U_3O_8 for the period 1975 through 1980 (Moran and Daviess, 2014, unpublished report).

Reserve Oil and Minerals purchased the Evans Ranch in 1968 and formed a joint venture with Sohio Western Mining to identify and develop uranium deposits on the property. Sohio operated the joint venture (then known as the L-Bar joint venture) and discovered extensive uranium mineralization on the property, leading to the development of an underground mine and construction of a uranium mill (the JJ #1 mine and L-Bar mill), which operated from late 1976 to mid-1981 and produced approximately 898,600 tons (815,000 tonnes) of material averaging 0.123% U_3O_8 and yielding 2,218,800 pounds of U_3O_8 (Boyd and others, 1984, unpublished report).

Overall, production of approximately 3.8 million pounds of U_3O_8 was derived from uranium deposits in the Cebolleta area, based on production statistics from the United Nuclear Northeast Church Rock and the L-Bar (Sohio) mills. Uranium mining and processing ceased in the project area in 1981. Neutron Energy (now a subsidiary of URI) acquired a mineral lease for the project in 2006. Since then Neutron Energy/URI have conducted technical studies on the distribution of uranium in the five deposits and have carried out environmental surveys of the project area.

Geologic Setting

The Grants mineral belt and its associated uranium deposits are located between the southern part of the San Juan Basin and the northeastern part of the Zuni uplift (Fig. 1). Sedimentary rocks exposed in this area range in age from Middle Jurassic through Late Cretaceous. Jurassic sedimentary rocks, including the economically important Morrison Formation (the predominant host for the major uranium deposits) are exposed in a narrow band that generally parallels the northwest-trending axis of the Zuni uplift. Cretaceous rocks are exposed in the northerly portion of the mineral belt and partially cover exposures of the Morrison Formation toward the south. The Mt. Taylor volcanic field covers a portion of the eastern part of the mineral belt immediately to the west of the Cebolleta project area (Moench and Schlee, 1967; Goff and others, 2015).

The belt of uranium deposits includes six major mining districts (from east to west-northwest): Laguna, Marquez (that portion of the Laguna district that contains uranium deposits hosted only in the Westwater Canyon Member of the Morrison Formation), the Ambrosia Lake-San Mateo area (north of Grants), Smith Lake, Crownpoint, and Church Rock. Collectively, the deposits of the Grants mineral belt have produced more than 340 million pounds of U_3O_8, ranking it as one of the largest uranium-producing regions in the world (McLemore and others, 2013); it is arguably the world's largest concentration of sandstone-hosted uranium deposits (Dahlkamp, 1993).

Uranium deposits of the Grants mineral belt are hosted principally in the Westwater Canyon Member, the Poison Canyon sandstone (an informal unit of economic usage), the Brushy Basin Member and the Jackpile Sandstone Member of the Morrison Formation. Limestone-hosted uranium deposits have been developed in the Middle Jurassic Todilto Formation (Moench and Schlee, 1967); however, these deposits have produced limited amounts of uranium in comparison with the Morrison Formation.

Stratigraphy

In the vicinity of the Cebolleta project the sequence of sedimentary rocks that are present near the surface range in age from Late Jurassic through Late Cretaceous (Baird et al., 1980; Jacobsen, 1980; Moench and Schlee, 1967; Schlee and Moench, 1963). The upper part of the Jurassic Morrison Formation is the host unit for uranium deposits in the project area. The Morrison Formation is unconformably overlain by the Dakota Sandstone, which in turn interfingers with and is overlain by the Mancos Shale, and is underlain by rocks of the Jurassic San Rafael Group. The stratigraphic nomenclature for the Morrison Formation and underlying San Rafael Group has evolved as correlations of Jurassic stratigraphic units across the Four Corners region continue to be worked out (e.g., Anderson and Lucas, 1995; Lucas and Anderson, 1997). The stratigraphic nomenclature in common use by mine geologists working in the Laguna mining district and Cebolleta project area is depicted in Fig. 3. The four member-rank divisions of the Morrison Formation are, in ascending order, the Recapture, Westwater Canyon, Brushy Basin and Jackpile Sandstone members (Fig. 3).

The Recapture Member is about 15 m thick in the project area (Moench and Schlee, 1967). It is composed of interbedded mudstone, siltstone, sandstone, and minor limestone. Moench and Schlee (1967) report that the unit is grayish-red on surface exposures, while fresh exposures of the various lithologies are gray (limestone), grayish-green (mudstone), or grayish-yellow (sandstone).

The Westwater Canyon Member ranges from 3 to 27 m in thickness in the project area. It consists of grayish-yellow to pale orange sandstone. The sandstones are poorly sorted, range from fine to coarse grained, and are sub-arkosic to arkosic in composition (Moench and Schlee, 1967). In the Marquez Canyon area, approximately 24 km north of the Cebolleta project, the Westwater Canyon also contains lenses of mudstone and siltstone; intercalated fine-grained intervals are less well developed in the Cebolleta area, based on available drill hole data.

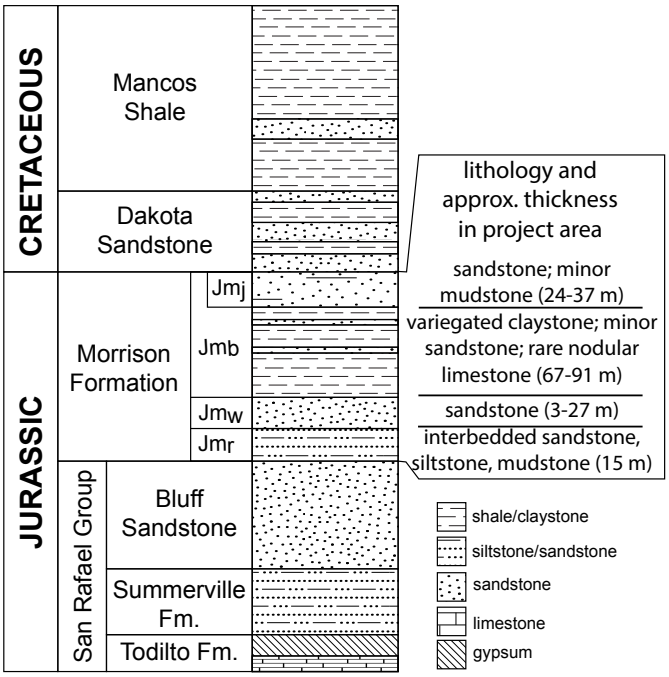


Figure 3. Stratigraphic column for the Laguna mining district, with Morrison Formation nomenclature used in this paper (modified from Rautman, 1980, inside cover). The stratigraphic divisions of the Morrison Formation discussed in historical mining reports for the study area are generally as depicted here, namely the Recapture (Jmr), Westwater Canyon (Jmw), Brushy Basin (Jmb), and Jackpile (Jmj) members.

The Brushy Basin Member ranges in thickness from 67 to 91 m in the general project area. It consists primarily of variegated mudstone and claystone with lesser sandstone beds that are hosts for uranium mineralization in some areas. Some authors (e.g., Aubrey, 1992; Santos, 1970) have noted the presence of volcanic ash beds in the Brushy Basin Member.

The Jackpile Sandstone (Owen and others, 1984; Aubrey, 1992) is a local (present in the eastern part of the Grants mineral belt, including the Laguna mining district) and distinctive unit that is the host for the major uranium deposits at the former Jackpile-Paguate, Woodrow, St. Anthony, and L-Bar mines. The Jackpile Sandstone extends in a northeasterly trending belt that may be up to 21 km wide and more than 105 km long (Jacobsen, 1980). Locally it is up to 61 m thick. In the St. Anthony mine complex the Jackpile ranges from 24 to 37 m in thickness (Baird et al., 1980), while at the adjoining L-Bar mine it is from 24 to 30 m thick (Jacobsen, 1980).

The Jackpile Sandstone was deposited in a northeasterly-flowing braided stream complex (Aubrey, 1992), and is characterized as having few persistent shale or mudstone interbeds. Instead it is dominated by fine- to medium-grained, cross-bedded, feldspathic (sub-arkosic) sands (with local zones of coarse-grained material) that often contain channel scours into underlying sandstones. It displays some variability both laterally and vertically, as demonstrated in the former JJ #1 mine, where it was subdivided into upper and lower units (FitzGerald and others, 1979, unpublished report), with the upper unit comprised primarily of quartzose sandstone with essentially no mudstone and the lower unit comprised of feldspathic to arkosic sandstone interbedded with numerous green mudstone lenses. In contrast, where exposed in the walls of the two open pits at St. Anthony, the Jackpile is white to light tan to light gray sandstone, locally exhibiting a pinkish hue where feldspar content is relatively high.

Quartz grains in the sandstone exhibit some frosting, likely due to mechanical abrasion, and are commonly coated with kaolinite. Individual sandstone lenses are cemented primarily with kaolinitic clay, and sometimes by calcite. Baird et al. (1980) reported the presence of minor amounts of pyrite in the Jackpile. Alteration within the St. Anthony portion of the project area is manifested primarily by the partial conversion of feldspar to kaolinite. Accessory minerals in the Jackpile Sandstone include trace amounts of zircon, tourmaline, garnet, and rutile. Nash (1968) noted from exposures at the Jackpile mine that biotite, amphibole, magnetite and pyroxene are absent.

Baird et al. (1980) discuss the presence of two types of carbonaceous material within the Jackpile Sandstone in the Willie P underground mine in the St. Anthony area. They reported the presence of plant material "coalified in situ" and as "sand-sized material" interstratified in cross-beds. They also report the presence of humate, occurring primarily as pore fillings between sand grains. Carbonaceous material is present in some exposures along the south wall of the St. Anthony North pit, and this material occurs as small (51 to 152 mm), vertical, rod-shaped structures, and as local accumulations of carbonaceous detritus on bedding planes. In the L-Bar area, carbonaceous material is also present as detritus and as humate accumulations. Jacobsen (1980) reports that no significant uranium mineralization occurs where carbonaceous material is absent.

Structure

The Cebolleta project and the adjoining Jackpile-Paguate group of uranium deposits lie within a feature known as the Acoma Sag (Nash, 1968), a regional syncline that is bounded on the west by the southeastern end of the Zuni uplift and on the east by the Lucero uplift. Rocks in the project area dip very gently to the north and northwest into the San Juan Basin, at less than 2 degrees. Several small-scale normal faults, generally down-dropped to the west, have been mapped on the surface several miles north of the project, and two similar structures, down-dropped to the east, have been mapped northeast and southwest of the project area (Schlee and Moench, 1963). No major faulting has been recognized in the project area. Several small-scale high-angle faults were observed in the workings of the former JJ #1 underground mine (Jacobsen, 1980), but these structures do not appear to have offset uranium mineralization, nor do they appear to have influenced the localization of mineralization.

A very small fold or structural dome was reported to be present in the southern part of the Willie P underground mine. There was an increased concentration of carbonaceous material in the north flank of this small-scale feature with a corresponding increase of uranium mineralization. A second, larger northeasterly-trending fold is present in the area of the Lobo Camp 4.8 km northeast of St. Anthony (Schlee and Moench, 1963). Overall, however, there is little in the way of deformation of rocks of the Laguna district (Moench and Schlee, 1967).

Ground Water

Throughout the Grants mineral belt sandstones of the Morrison Formation and the Dakota Sandstone are aquifers. As reported by Hatchell and Wentz (1981) and various reports concerning the former L-Bar mine, ground water discharge from the Jackpile Sandstone into the mine ranges from 113 to 454 liters/m. Water wells capable of producing between 113 and 159 liters/m were completed in the Jackpile sandstone at L-Bar, and other wells capable of producing between 159 and 227 liters/m from the Westwater Canyon Member (Geo-Management, 1972, unpublished report) were also completed in the area.

Uranium Mineralization

Nearly all of the uranium mineralization in the Grants mineral belt (which includes the Laguna mining district that encompasses the Cebolleta project) occurs as sandstone-hosted deposits in fluvial clastic rocks of the Morrison Formation. Three types of sandstone-hosted deposits have been identified in the area (Kittel et al., 1967; Granger and Santos, 1986):

- "Trend deposits," which have also been described by various workers in the district as "pre-fault" or "primary" deposits. Trend deposits are broad, undulatory layers of uranium mineralization controlled primarily by the texture or fabric of the host sandstones. Mineralization in trend deposits is localized around accumulations of humates, which acted as a reductant to precipitate dissolved uranium from ground water;

- "Redistributed deposits," which have also been described as "post-fault," "stack," or "secondary" deposits, are irregularly shaped zones of mineralization that were controlled by both the stratigraphic characteristics and the possible presence of structural features within the host rocks. Redistributed deposits are thought to be the product of destruction of trend deposits by oxidation, and have little humate associated with the mineralized zone; and

- "Remnant deposits" are, as the name implies, remnants of trend deposits that have been partially mobilized and redistributed. Remnant deposits tend to be discrete bodies of mineralization entirely enclosed within oxidized host rocks.

While the classification of sandstone-hosted deposit types is based on uranium mineralization in the Westwater Canyon Member, the classification is also applicable to Jackpile-hosted deposits with one important caveat. That is, the shapes of trend deposits in the Jackpile Sandstone do not necessarily reflect the overall geometry or architecture of individual Jackpile depositional channels, whereas in the Westwater Canyon- hosted accumulations they generally do.

Some investigators in the Grants mineral belt have discussed the presence of "roll-front" uranium deposits at various locations within the area (Clark, 1980; McCarn, 1997), and some former workers at the St. Anthony mines also suggested the presence of roll-front mineralization in the Cebolleta area. Nonetheless, geologic mapping of the Jackpile-hosted mineralization in the two St. Anthony open pits by the author and his colleagues, as well as detailed examination of several thousand gamma-ray logs from holes at Cebolleta have not revealed the presence of features that are consistent with typical roll fronts.

Individual uranium deposits in the Grants mineral belt range from a few tons to several millions of tons in size. Many of the deposits in the Westwater Canyon Member are roughly tabular, locally irregular in shape, and are elongate in a west-northwest direction, reflecting the general shape of individual channel sandstone units of the Westwater Canyon Member. Individual deposits range in size from 1 to 3 m in width and length to deposits that may be 5 to 15 m in thickness, 100 to 259 m in width, and 300 to 1,800 m in length (Fitch, 1980). Redistributed deposits hosted by the Westwater Canyon are often more irregular in their plan-view shape, and rarely conform to the geometry of their precursor trend deposits. The thicknesses of redistributed deposits may range from 1.5 to 30 m, and the deposits may have lateral extents of 61 to 610 m in length and width.

Uranium deposits hosted by the Jackpile Sandstone can also be quite large. This is demonstrated by the Jackpile-Paguate deposits, which are contiguous with the south boundary of the Cebolleta project (Fig. 2). For example, the Jackpile mine deposit is several thousand meters long and averages 609 m wide. Individual mineralized zones rarely exceed 4.5 m in thickness, but the aggregate thickness of several "stacked" layers is up to 15 m. Thus, Moench (1963) described the Jackpile mine uranium deposits as "composed of one or more semi-tabular layers". In plan view the layers range from nearly equant to strongly elongate. Viewed in vertical section, the layers are suspended within sandstone intervals; only locally do they extend to stratigraphic discontinuities such as prominent mudstone beds, diastems, or formational contacts. The distribution or architecture of mineralized zones in the St. Anthony and L-Bar deposits within the Cebolleta project area are generally similar, although the average width of mineralized zones rarely exceeds 305 m.

According to Dahlkamp (2010), the Cebolleta uranium deposits were formed by the mobilization of uranium from either granitic rocks of the ancestral Mogollon highlands, located southwest of the project area, or from the devitrification of tuffaceous rocks contained in the host sandstones and particularly in the Brushy Basin Member. In this model the uranium was mobilized and transported by alkaline ground waters. Ultimately, uranium minerals were deposited in the host sandstones, where chemical reactions associated with humic acids derived from plant material caused precipitation of dissolved uranium from the ground water (Adams and Saucier, 1981).

As currently defined (from mineral resource estimate modeling) there are five discrete uranium deposits at the Cebolleta project (see Figs. 4 and 5):

- Area I (former Sohio L-Bar);

- Area II and V (former Sohio L-Bar);

- Area III (former Sohio L-Bar);

- St. Anthony North and South pits (including the former M-6 underground deposit); and
- Willie P (St. Anthony underground).

The uranium deposits in the project area share a common set of geological characteristics:

- Essentially all of the mineralization is hosted by the Jackpile Sandstone, although minor mineralization is hosted in sandstones of the Brushy Basin Member;
- Most of the mineralization is hosted in medium to coarse-grained sandstones that exhibit large-scale tabular cross-stratification (Baird and others, 1980);
- Near the margins of the deposits the mineralization thins appreciably, although halos of low-grade mineralization surround the deposits;
- Higher grade mineralization usually occurs in the centers of the mineralized zones;
- Strong mineralization appears to be concentrated in the lowermost portions of the Jackpile, although anomalous concentrations of uranium are present throughout the entire vertical extent of the unit (Jacobsen, 1980);
- Most of the mineralization in the Cebolleta area appears to be associated with reducing redox conditions, with only isolated, discontinuous pods (primarily in the Willie P underground mine) exhibiting appreciable oxidation (Baird and others, 1980);
- Individual deposits do not show an overall preferred orientation or trend, and do not reflect the northeasterly orientation of the main Jackpile Sandstone channel trend. Indeed, current resource modeling efforts have demonstrated a NNW-SSE trending orientation for the product of grade and thickness (GT product) of mineralized zones; and
- Nearly all of the deposits are associated with carbonaceous material, although the mineralized zones exposed in the high walls of the two St. Anthony open pits are not.

The deposits range in depth from approximately 61 m at St. Anthony, to nearly 213 m in the vicinity of the Sohio Area II and Area III deposits in the central and northern (down-dip) parts of the project area. In the southern part of the project area (Fig. 5), the mineralization in the St. Anthony South pit appears to be a “remnant” deposit that has been partially depleted of uranium, which was redeposited in the nearby (down-dip) North pit area. In the northern part of the project

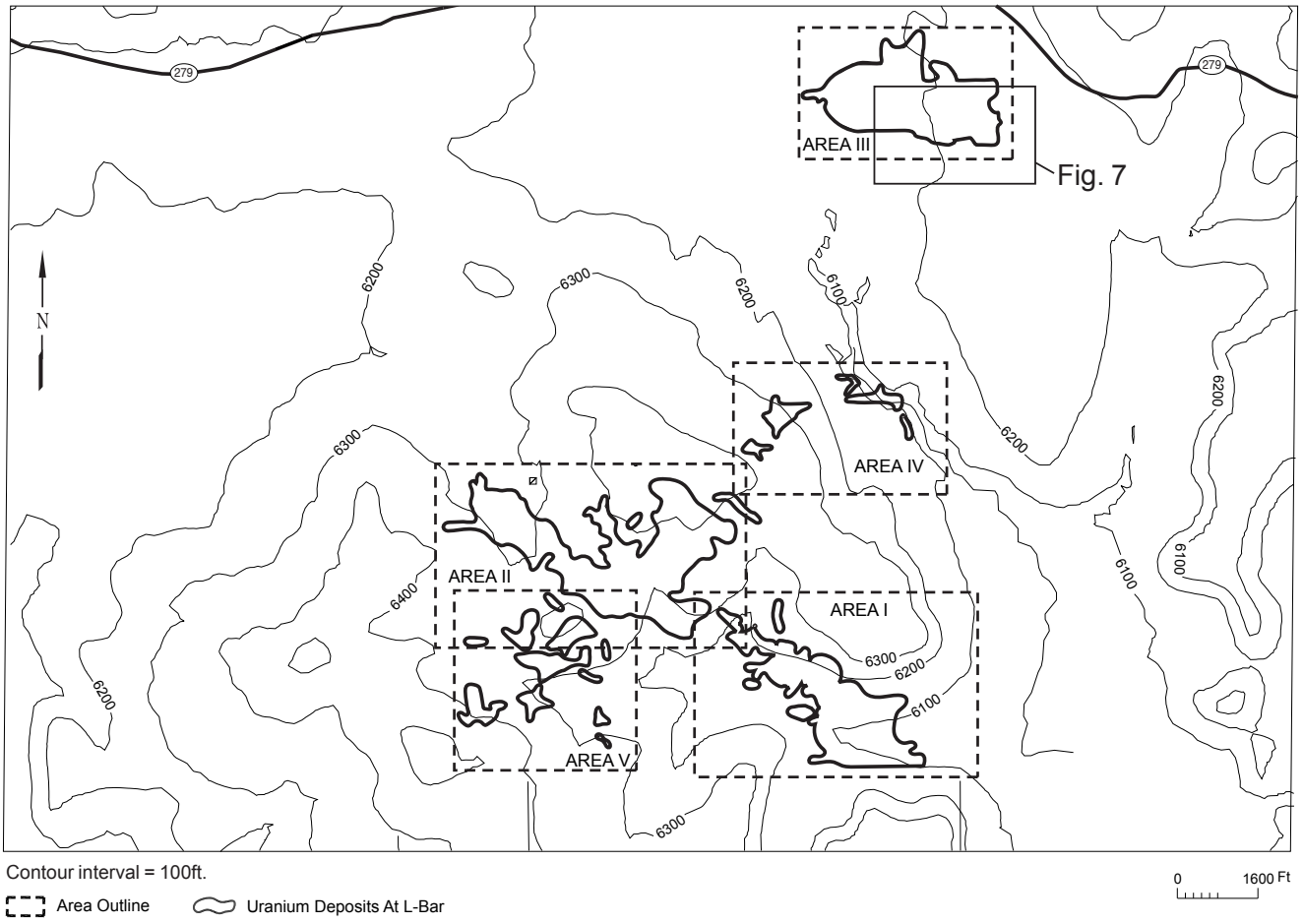


Figure 4. Index map of uranium deposits in the northern part of the Cebolleta project area (formerly referred to as the Sohio or L-Bar deposits). Location of Figure 7 is outlined.

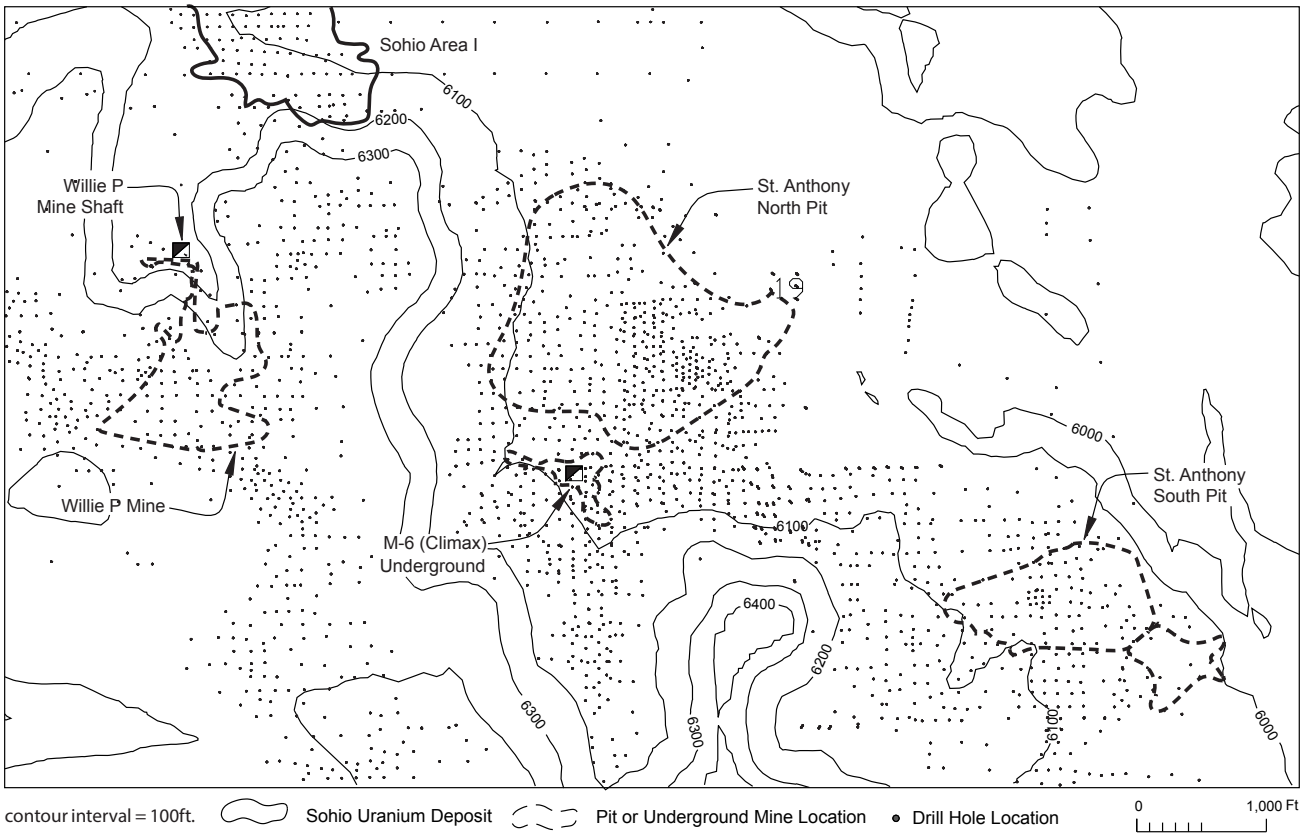


Figure 5. Index map of uranium deposits in the southern part of the Cebolleta project area (formerly referred to as the St. Anthony deposits), showing locations of historical drill holes.

area (Fig. 4), mineralization occurs in tabular bodies that may be more than 305 meters) in length and attain thicknesses of 1.8 to 3.7 m. The upper and lower boundaries of these mineralized bodies are generally quite abrupt. There is some tendency for individual deposits to develop in clusters. Locally, these clusters may be related to the coalescence of separate channel sandstone bodies. In this instance, mineralization is often thicker and of higher grade than adjoining areas.

Extensive chemical and radiometric analyses on core samples by Sohio and United Nuclear (Geo-Management, 1972, unpublished report; Olsen and Kopp, 1982, unpublished report) demonstrate that radiometric (e.g., calibrated gamma-ray measurements, or assays, denoted as "% eU_3O_8") and chemical assays generally yield comparable results in terms of ore grade (wt. % U_3O_8). Evaluation of samples from 47 core holes at St. Anthony, however, indicated that chemical analyses yielded somewhat higher estimates of grade than radiometric assays.

In summary (see figures 3, 4, 5), the northern portion of the Cebolleta project includes three distinct zones of mineralization, known as Area I, Area II-V, and Area III, with mining by Sohio limited to the II-V deposit (the JJ #1 mine). The Area I deposit, located in the southern end of the L-Bar complex (and north of the St. Anthony mines) extends south into the northern St. Anthony area, and additional uranium mineralization is present adjacent to the St. Anthony open pits and the Willie P. underground mine (McLemore and Chenoweth, 1991). Two of the former Sohio (L-Bar) uranium deposits, the Area I and Area III deposits, are described below.

Area I Deposit (part of Area I-II-V Deposit Complex)

At Area I, grade, thickness, and GT (grade times thickness) contour maps were prepared for each of the mineralized horizons. For these maps, uranium grades were calculated using data from gamma-ray logs and are denoted as weight percent "eU_3O_8" (as opposed to grade estimates based on chemical analysis). Mineralized horizons were assigned to one of four zones — "Upper," "Middle," "Lower," and "Basal" zones.

Mineralization in the Middle zone defines a broad, southeast-northwest trending body that is 183 to 244 m wide and approximately 274 m long. Drill-hole intersections of mineralized zones ("mineral intercepts") with a cut-off value of 0.5 GT indicates that the horizon averages 3.1 m thick with an average grade of 0.12% eU_3O_8. Mineralization in the Lower zone occurs as a sinuous, lenticular, southeast-northwest trending body that is 46 to 122 m wide and approximately 731 m long. A composite of mineral intercepts at a 0.5 GT cut-off averages 9.8 feet (2.98 meters) thick with an average grade of 0.153% eU_3O_8.

The mineralized zones and lenses appear to be somewhat continuous throughout the Area I deposit. However, Area I appears to have a higher frequency of thin, less continuous mineralized horizons than are observed at other deposits in the northern part of the project area. The better (higher grade) and more laterally continuous uranium deposits are in the Middle and Lower zones.

Additional mineralization at the base of the Jackpile Sandstone and in the underlying Brushy Basin Member

corresponds with the Basal zone in the Area I uranium deposits. Mineralization in the Basal zone at Area I is in several relatively small, discontinuous, lenticular pods. A composite of mineral intercepts at a 0.5 GT cut-off averages 2.13 m thick with an average grade of 0.14% eU_3O_8.

Area III Deposit

Geologic and mineralization sections were constructed across the Area III deposit utilizing the mineral intercept data from the Sohio drill-hole maps and individual gamma-ray/electric logs (Fig. 6). Mineralization is observed to be continuous from section to section in tabular or lenticular bodies of a few feet to tens of feet in thickness. Grades greater than 0.10% eU_3O_8 are commonly present, with numerous intercepts of 0.20% eU_3O_8 or better. This mineralization occurs throughout the Jackpile Sandstone, which is 24 to 30.5 m thick at Area III.

Area III mineralization, as at Area I, was assigned to four levels, designated as Upper, Middle, Lower, and Basal zones. The better and more laterally continuous mineralized bodies are in the middle to lower portion of the sandstone sequence, corresponding to the Middle and Lower zones. Mineralization is also present in the Brushy Basin Member at and immediately below the base of the Jackpile Sandstone, in the Basal zone.

Mineralization in the Middle zone occurs in an arcuate, east-west trending, elongate body that is 61 to 152 m wide and approximately 640 m long (Fig. 7). A composite of mineral intercepts at a 0.5 GT cut off averages 2.5 m in thickness with an average grade of 0.183% eU_3O_8. Mineralization in the Lower zone is represented by a continuous, lenticular, east-west trending body that is 91 to 152 m wide and approximately 670 m long. A composite of mineral intercepts at a 0.5 GT cut off averages 3.1 m thick with an average grade of 0.172% eU_3O_8.

Controls on Mineralization

Principal controls on uranium mineralization at the Cebolleta project are primary sedimentary structures in the Jackpile Sandstone (Jacobsen, 1980; Baird and others, 1980), and concentrations of carbonaceous material that served as a reductant to precipitate uranium from circulating ground water. The distribution of carbonaceous material tends to be localized, as observed in the former L-Bar mine (Jacobsen, 1980) and in the pit walls of the two St. Anthony open pits. Jacobsen (1980) notes that there are no significant accumulations of uranium without carbonaceous material; the same relation has been noted by UNC geologists (Baird and others, 1980) in the former Willie P underground mine at St. Anthony. However, the author has not observed significant accumulations of carbonaceous material associated with low-grade (0.03% to 0.06% U_3O_8) uranium mineralization in the walls of the St. Anthony North pit. This may reflect the "redistributed" type of mineralization in the St. Anthony North pit (see previous discussions), and the uranium-precipitating mechanism remains to be determined.

Baird and others (1980) noted the distinct association of substantial zones of uranium mineralization with medium to coarse-grained sandstones that exhibit large-scale tabular cross-bedding in the Willie P underground mine. Similar relationships between uranium mineralization and sedimentary structure/texture have been noted in the south high wall of the St. Anthony North pit.

While there is a strong northeasterly trend to the thickness contours of the Jackpile sandstone in the Laguna district (which includes all of the Cebolleta project area), there appears to be no consistent lateral trends in the individual uranium deposits in the Laguna district.

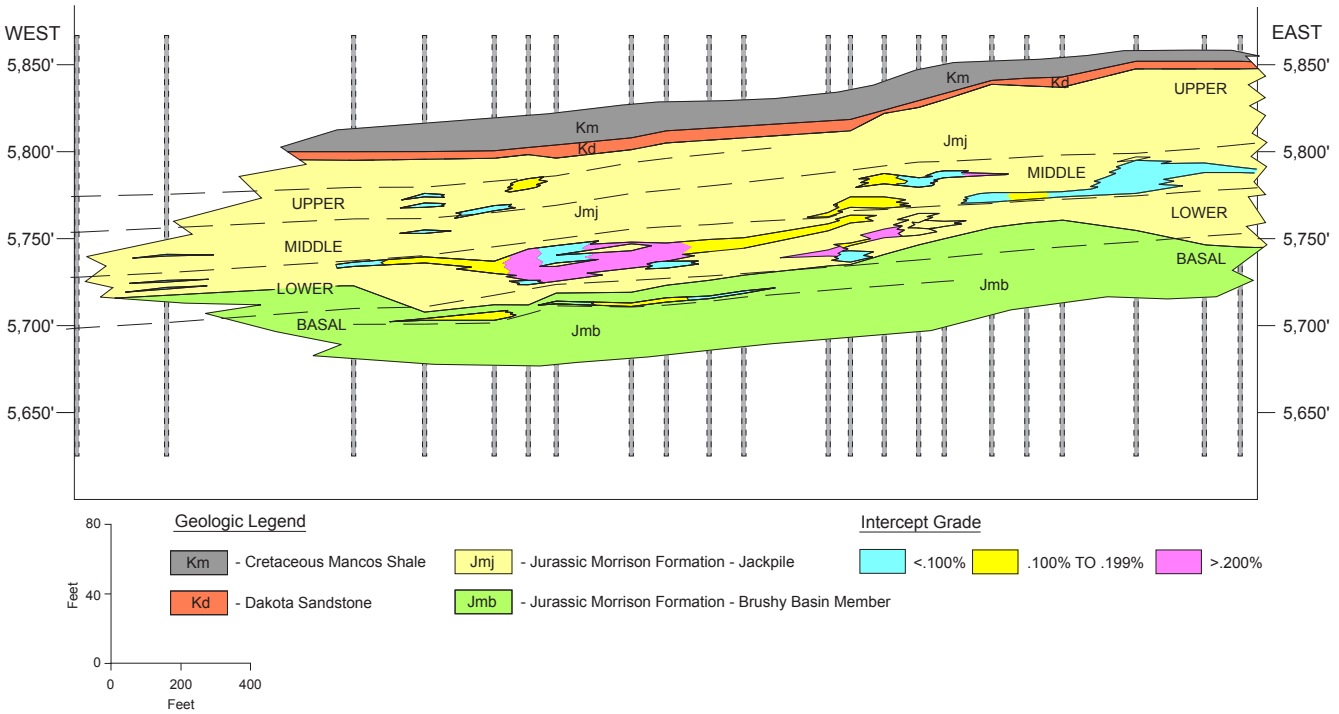


Figure 6. East-west cross section (looking north) of the Area III uranium deposit, depicting geologic units intersected by drill holes (thick vertical grey lines), as well as mineralized zones as derived from calibrated gamma-ray logs. The "Lower" mineralized zone demonstrates lateral continuity over a distance of more than 396 m at grades of 0.10% eU_3O_8 or more. Line of cross section is shown on Figure 7.

Baird and others (1980) state that there is an apparent northwest trend with respect to mineralization in the St. Anthony area. This apparent northwest trend, which was not observed by Sohio geologists at the former JJ #1 mine (Jacobsen, 1980), has perhaps been created to some extent by the erosional retreat of the Jackpile Sandstone outcrop (Baird, 1980), and the subsequent oxidation and redistribution of uranium mineralization.

Mineralogy

Uranium minerals at the Cebolleta project are reported to be coffinite [$U(SiO_4)_{1-x}(OH_{4x})$], uraninite [UO_2], organo-uranium complexes, and unidentified, oxidized uranium complexes (Robertson & Associates, 1978, unpublished report). The author is unaware of any published reports or studies regarding the mineralogy of the Cebolleta uranium deposits.

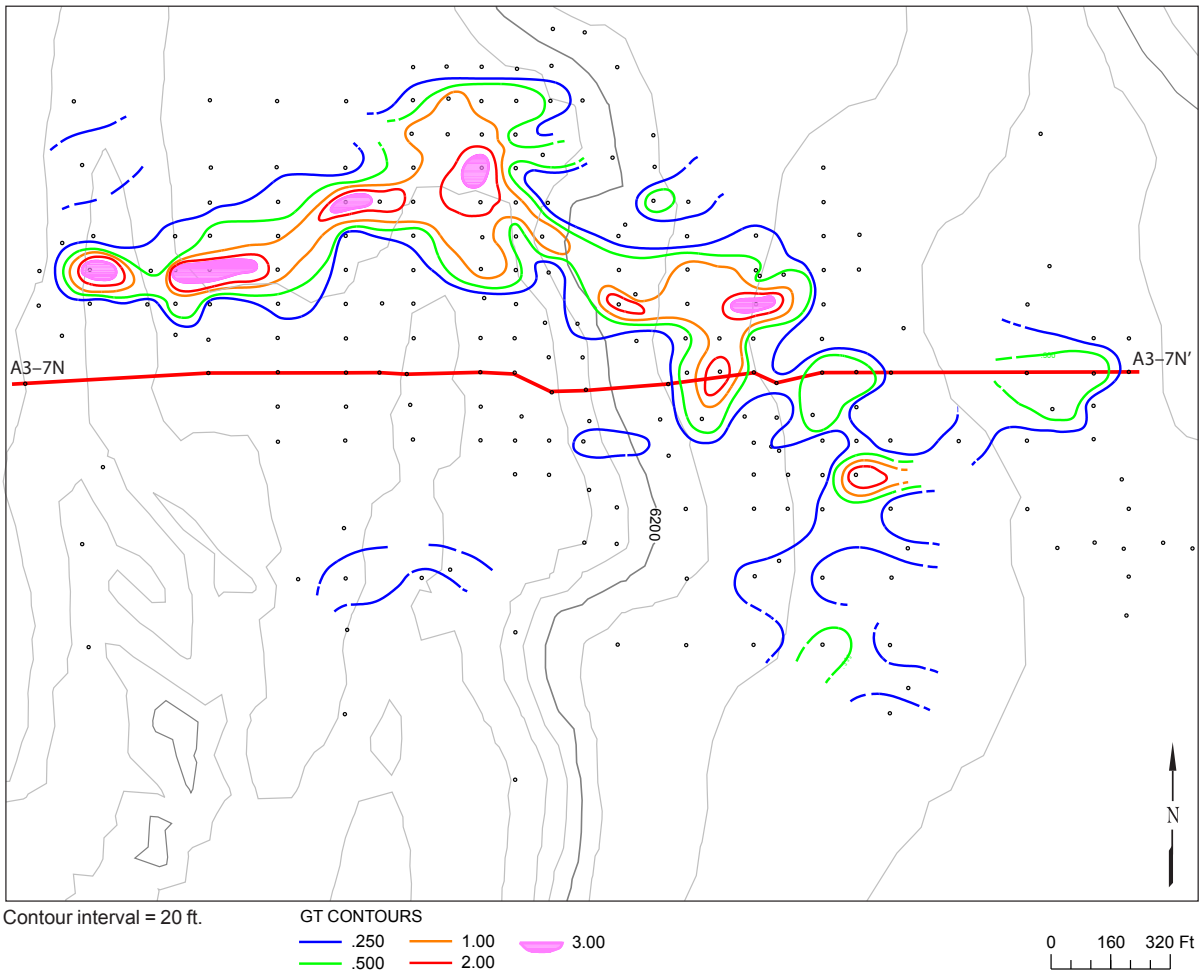


Figure 7. Grade times thickness (GT) contour map of the "Middle" mineralized zone at Area III. The location of the Fig. 6 cross section is shown. The Middle zone at Area III demonstrates good lateral continuity of mineralization in a general east-west direction at a GT cut-off of 0.50.

TABLE 1: In-Place inferred mineral resources for Cebolleta Project

Deposit	Cut-off Grade (% eU_3O_8)	Grade (% eU_3O_8)	Tons (short)	Contained Pounds eU_3O_8
Area I-II-V	0.08	0.173	4,564,000	15,748,000
Area III	0.08	0.162	998,000	3,232,000

Notes:

1. Mineral resources are not mineral reserves and do not have demonstrated economic viability;
2. Mineral resources are reported in accordance with Canadian Securities Administrators (CSA) National Instrument 43-101 (NI 43-101) and have been estimated in conformity with generally accepted Canadian Institute of Mining, Metallurgy and Petroleum (CIM) "Estimation of Mineral Resource and Mineral Reserves Best Practices" guidelines;
3. Resources are stated at a 0.08% eU_3O_8 cut-off grade; sufficient to define potentially underground mineable resources; however mineable underground shapes have not yet been defined;
4. A tonnage factor of 16.0 cubic ft per ton was used for all tonnage calculations;
5. Mineral resource tonnage and contained metal have been rounded to reflect the accuracy of the estimate, and numbers may not add due to rounding.

Mineral Resource Estimates

Mineral resources for the Cebolleta project were estimated for the former Sohio Area I, II, III, and V deposits (Moran and Daviess, 2014, unpublished report) using data from the Sohio drilling programs and a geostatistical model. The adjoining St. Anthony deposits, in and surrounding the St. Anthony open pits, have not yet been synthesized into a useable database for resource estimation. The estimates for the individual Area I, II, III, and V deposits have been combined into Areas I-II-V and Area III, and are listed in Table 1. In accordance with Canadian mining standards and guidelines (see Table 1 notes), these estimates are formally classified as "inferred resources".

Acknowledgments

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Modeled Impacts of Economics and Policy on Historic Uranium Mining Operations in New Mexico

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Abstract

New Mexico was at the forefront of the nuclear age, producing more uranium (U) than any other state in the U.S. for more than three decades until the early 1980s. The state is also unique because these historic activities have been studied and quantified over during this time, providing a unique opportunity to identify how historic uranium mining operations were influenced by economics and policy. In order to quantify these relationships, this study used a system dynamics approach to determine how these factors affected mining industry decisions and how those impacts varied based on mine size. The results of this work found that as the industry evolved over time, the influence of these factors changed and that they did not impact all mining operations equally. Results indicate that price guarantees for U concentrate and subsidies for mining and milling in the early years (1948–1964) of U mining encouraged mines of all size, although smaller mines opened and closed more quickly in response to changes in price. The economic environment created by these policies encouraged exploration and production. However, the latter led to an excess in supplies and declining prices when these incentives lapsed in the mid-1960s, which negatively impacted small- and medium-sized mines, neither of which opened after 1964. The presence of larger mines had more impact on the closing of small mines than closing of medium mines, possibly as a result of economies of scale for the medium mines or their ability to access milling resources after 1964. Lastly, medium and large mines that produced both uranium and vanadium may have had a slight historic advantage over mines that produced only uranium, as evidenced by longer delays in closing response to a unit change in average price. Quantification of these relationships assists in an improved understanding of the factors that influenced historic mining operational decisions and illustrates the complexity of the roles played by economics and policies in the boom and bust cycle manifested in the uranium industry.

Introduction

The uranium industry in New Mexico experienced rapid growth following the advent of the nuclear age. Mines and mills in the state produced more uranium (U) than any other region in the United States and were, in the mid-60s, responsible for up to 35% of U concentrate (U_3O_8) produced globally (Roskill, 1991). Between 1947 and 2002, more than 200 recorded mines and 8 mills throughout the state produced more than 340 million pounds of U_3O_8 and generated $4.7B in revenue (McLemore, 1983; McLemore et al., 2013; McLemore, in press). An integral part of uranium mining in New Mexico is the Grants uranium district. The region became known as the "Uranium Capital of the World" (Fitch, 2012) because the Grants mining district produced more than 99% of state-wide production between 1948 and 1982 (McLemore, 1983).

While the growth of the industry was rapid, it was also marked by a degree of randomness as a result of varying demand for U (used primarily for weapons by the Federal government and nuclear power generation by both the Federal government and commercial utility companies), discovery of new reserves and concerns of U scarcity, and evolving regulatory frameworks, all of which impacted both negotiated prices for long term contracts and U spot prices (Roskill, 1991). Spot price refers to an estimated value regarding transactions involving "significant quantities of natural uranium concentrates" (Roskill, 1991) that could be completed at a specific date; it is often considered to be the average price of negotiated large, long-term contracts and does not typically include smaller sales that would be included in an average price estimate (Roskill, 1991).

Roskill (1991) and Walker and Wellock (2010) describe the historic complexity of the U market. Of particular interest is how successive discoveries of new uranium reserves and uranium's practical uses increased public perception of the utilitarian value of this commodity. They also note how the rapid development of the nuclear power industry was encouraged by government subsidies and information-sharing (Walker and Wellock, 2010). "Probably the single most important difference is that the uranium industry [as compared to other mineral industries], born under a nuclear cloud, was the brainchild of the government" (Roskill, 1991).

Although the regional and national U industry thrived for nearly 30 years, it rapidly diminished in the early 1980s due to declines in prices, delays and cancellations of orders for new nuclear power plants (Roskill, 1991), and disasters, such as Three Mile Island, that altered the trajectory and credibility of the nuclear industry (Walker and Wellock, 2010). Uranium production in New Mexico ended in 2002 with the closure of the Quivira Mining Co. (formerly Kerr-McGee Corp.) mill, which at the end of its operation solely recovered U from mine water (McLemore and Chenoweth, 2003)

Nuclear energy currently supplies 19% of U.S. electric power, but nearly all of the U fuel supply is imported (US EIA, 2016). Increasing U prices and improvements in mining technologies, recognition that nuclear power is carbon free, as well as the desire for energy security and energy supply stability have resulted in renewed interest in U production in NM and elsewhere. While many factors influence mining operations, historic U.S. mining of U was driven by government-related markets, regulations, and subsidies enacted to encourage the development of the nuclear industry by ensuring a stable and reliable supply of uranium.

The objective of this study was to improve understanding of the roles that economics and policy

played in the operation of U mines in New Mexico using a system dynamics modeling (SD) framework. Because New Mexico was at the forefront of the U boom, was a leading domestic producer for nearly three decades, and because a historic record of mine production exists, this area provides a unique opportunity for evaluating how these two factors influenced past mining operations. While numerous additional factors influence the development and operation of a U mine (e.g., geologic or geographic setting), understanding the dynamics of mine opening and closing through use of historical data may provide insight into historic U mining operational decisions and a useful tool in understanding and planning for future activities associated with extractive industries

Historical Background

Uranium is a radioactive element that had been used to color glass and ceramic products in the 19th and early 20th Centuries (Roskill, 1991). The 1910 discovery of the medical application of radium, a daughter product of uranium, increased the value of what had been previously considered a relatively useless element (Roskill, 1991). The following year, one gram of radium sold for between $120,000 to $160,000 (Roskill, 1991), approximately 11–15 million dollars per gram in current dollars. However, it was the discovery of nuclear fission in 1939 that would propel U from "an element of little value to one of the most sought after commodities in the world" (Ballard and Conkling, 1955; SJBRUS, 1980). This discovery and the development of the nuclear industry, including both weapons and power generation applications, would leave an indelible mark on both New Mexico and the world.

Uranium-vanadium deposits were discovered in the eastern Carrizo Mountains in the San Juan Basin in 1918 (Chenoweth, 1997). Initially, these deposits were primarily mined for vanadium, an economically important metal used both to strengthen steel and as a catalyst for sulfuric acid production (Hilliard, 1994). The Vanadium Company of America (VCA) produced more than ten thousand pounds of ore between 1942 and 1946 (McLemore, 1983) and more than half of the vanadium produced domestically came from this and other regions within the Colorado Plateau until the mid-1980s (Hilliard, 1994). Uranium became increasingly important during the second World War, when an estimated 44,000 lbs. of U_3O_8 were recovered from the VCA's mill tailings for the Manhattan Project (McLemore, 1983; McLemore and Chenoweth, 2003).

The creation and evolution of policy and regulatory frameworks for U influenced the development of the nuclear industry and affected U mining in particular. In 1943, the Atomic Energy Act established the Atomic Energy Commission, which placed nuclear energy under the sole control of the US government and restricted its use to military applications (Walker and Wellock, 2010). In 1954, the Atomic Energy Act was revised to allow for commercial nuclear applications, encourage collaborative research and development between national laboratories and industry, and provide subsidies for energy and defense research as well as the U supply this research required (Walker and Wellock, 2010). Both Acts included specific provisions to ensure a stable supply of U: the Federal government guaranteed a minimum price ($8/lb. U_3O_8) and offered additional subsidies towards exploration, mine engineering, ore transportation, and milling costs (Roskill, 1991). In 1955, large U deposits were discovered in what is now referred to as the Ambrosia Lake subdistrict of the Grants uranium district (Fig. 1). These events sparked the uranium boom that lasted for more than three decades (McLemore and Chenoweth, 2003).

Mining Techniques and Production

Uranium production in NM historically relied on both underground and surface mining techniques (McLemore et al., 2002). The grade (concentration of uranium in the ore) and geologic position of the U deposit are the most significant factors in selection and application of mining techniques. Of the more than 1,000 uranium occurrences in the New Mexico Mines database, production activities are reported for 216 mines from 1942 until 2002 (McLemore and Chenoweth, 2003; McLemore et al., 2002). Of these, 102 were underground mines, 75 were surface or open pit mines, and 39 were characterized as both surface/open pit and underground mines. During this period of production, the grade of recovered ore ranged from 0.02–0.63% in the state (or 1 lb. of U_3O_8 from approximately 5,000 to 160 lbs. of ore respectively) (McLemore et al., 2002). Ore grade also varied by mine and date of production. For example, the Church Rock Mine recovered U ore of 0.21% grade in 1960 and 0.16% grade in 1962 (McLemore et al, 2002). The geographic distribution of uranium mines in New Mexico and their associated average annual production are shown in Figure 1.

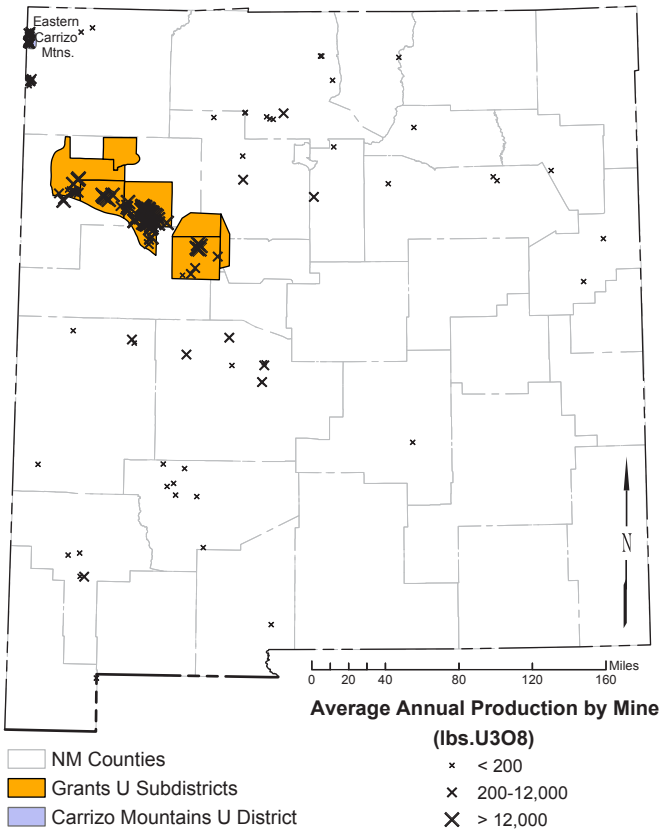

Figure 1. New Mexico uranium mines and their average annual production (1948–1985). Average production calculated as total U production divided by total operating years. Modified from McLemore et al. (2002).

Systems Dynamics Modeling

Model Approach and Development

Based on previous application to other mining operations (O'Regan and Moles, 2001, 2006), we propose that a system dynamics (SD) approach is well suited to understand and quantify the impacts of economics and changing regulatory environments on the opening and closure of historic U mines. This procedure quantifies the variability of mine openings or closings as a function of mine size, mining method, and the historic co-production of metals such as vanadium. In the context of this model, opening and closing represent the historic operational lifecycle of a mine (start and end of U production) rather than the legal and physical closing incorporated into a contemporary mine's lifecycle. This modeling technique allows for both the separation and interaction of these variables in order to understand how mine characteristics such as size and mining methods are affected by policy and economics over time. Our objective was to quantify the effect of each variable on historic mining operations. Note that the impact of these variables on one mine may have implications on other mines. The results of the model help to explain how and why mining companies decide to open a new mine or close an existing one.

This model assumes historic mining decisions were influenced by both market forces, particularly U price and competition, and government-related changes in nuclear policy. Although a poor proxy for the actual prices negotiated between producers and purchasers, we used the average price of U because no quantitative data exists for these individual transactions. In addition to market price, government policies towards the industry provided additional incentives to encourage development. For example, in 1954 the Atomic Energy Commission provided subsidies for transportation, processing facility construction, and mine engineering costs in addition to minimum price guarantees (\$8/lb. U_3O_8) for U in order to ensure a steady supply for both weapons and the developing nuclear power industry (Roskill, 1991).

One might postulate that profitability was greatly enhanced, regardless of mine size, during early U mining due to a guaranteed market for U and subsidies for production costs (resulting in profits as high as a 40% return on investment (Roskill, 1991)). Conversely, in later years a lapse in subsidies may have reversed this trend in favor of larger mines. For example, the upfront capital costs and expertise required to recover ore from deeper deposits may not have been possible for smaller mines in the absence of government incentives. Economies of scale, the principal that an increase in the scale of production decreases the unit cost of production, suggests that the size of a mine may have been an important factor in its response to changing market forces and policy environments. Therefore, government stimulation and market price of U may have affected the response (i.e. opening or closing) of historic mines in the region differently as a function of their size.

The influence of government policies, which are often the most challenging aspect of a system to model quantitatively, were treated by delineating four time periods initiated by passage of specific legislation that are described in brackets: 1) 1948–1954 [the Atomic Energy Act of 1946, which stated that all U produced must be used in government applications, guaranteed a market for ore if it was above 0.2% U_3O_8, and provided subsidies for exploration, mine engineering, ore transportation, and milling costs; note we begin with the year 1948 because that is the beginning of the average domestic U sale price record], 2) 1954–1964 [the Atomic Energy Act of 1954, which reaffirmed the government's U markets and subsidies but allowed for collaborative research on nuclear technologies between the government and private industry, resulting in increased demand for U], 3) 1964–1974 [President Johnson's mandated 25% cutback in enriched U production in 1963 and the 1964 Private Ownership of Special Nuclear Materials Act, which decreased government demand for U, allowed guaranteed prices and subsidies for U to lapse, and wholly opened the nuclear industry to the public domain (both nationally and internationally)], and 4) 1974–1985 [passage of the Energy Reorganization Act 1974, which ended government stewardship over the domestic nuclear power program (Buck, 1983)]. We chose 1985 as our ending date because by then all but one mine in the state had closed (McLemore et al., 2002). Rather than including these periods of regulatory changes as variables, the four time periods were represented as four distinct simulations within model optimization. The differences in economics and policies as a function of modeled time periods is shown in Table 1. Early years were marked by government-supported minimum prices and subsidies. In later years these economic incentives lapsed and the sales market of U concentrate broadened.

TABLE 1: Comparison of economics and policy on U markets for the four modeled time periods.

Policy Time Periods	Government Price	Subsidies	Government Usage	Public Usage	International Sales
1948–1954	X	X	X		
1954–1964	X	X	X	X	
1964–1974			X	X	X
1974–1985			X	X	X

As in any model, a number of real-life complexities hinder this model's accuracy. One, average historic prices do not reflect the entire spectrum of U commerce dynamics. These dynamics were often dominated by long-term contracts between mines, mills, and energy companies (Roskill, 1991), the terms of which are not often reported. Given data limitations, it is difficult to assess the impact on the accuracy of the model due to exclusion of long-term contracts. Two, the co-production of other metals such as vanadium (V), the price of which has been lower but more stable compared to U historically, may

have influenced the ability of a mine to weather low U price environments. Because V mining in the region was as a co- or by-product of U mining (Hilliard, 1994), we assume that trends in U prices were representative of both U and V commerce. Therefore, we ran our model first using mines that produced U only and then using mines that produced both U and V.

Our model is designed to evaluate three hypotheses that depend on several assumptions. The hypotheses are: 1) subsidies from the U.S. government for U mining both promoted and sustained smaller mines prior to 1964, 2) smaller mines responded more quickly to changes in price than did large mines, and 3) mines that produced both uranium and vanadium were more stable than mines that produced uranium only because of diversified production and the relatively stable historic price of vanadium. As mentioned earlier, we assume high U prices were a significant factor in a company's decision to open a new mine, whereas closing may have occurred as a result of low prices. We also assume mine openings and closings are a function of mine size, categorized as small, medium, or large and estimated based on total production averaged over the total duration of operation in years (see below). Economies of scale generally dictate that larger mines are able to produce a commodity at a lower per-unit cost than smaller ones, which make them more competitive in a dynamic economic environment than smaller mines. Therefore, we assume that an increase in the number of large mine operations may influence operational decisions (especially closing) for smaller mines. We describe this influence using a variable called the impact of larger mines coefficient. We believe this coefficient accounts for perceived scarcity and market flooding on competition between mines of varying sizes.

The ability of a mine to remain in operation in spite of low U prices may also have been a function of its ability to economically produce other commodities like vanadium. Of the 216 mines that produced U between 1948 and 1985, 68% also produced V. While the number of V producing mines was dominated by small and medium-sized mines (41 and 44%, respectively), large mines produced nearly three-quarters of total V produced during this period. Although historic V prices have consistently been a fraction of that for U, its price has been more stable. Between 1948 and 1980, average V price was 18% of U price with a standard deviation of 1 compared to U (SD = 8.9) (McLemore et al., 2003; USGS, 2013). Therefore, the number of openings and closings for U+V mines were compared to U-only mines in order to discern whether commodity diversity influenced operational decisions. Similar to U-only mines, real annual production data for either U or V are not available in U+V mines (instead, for both we divide total production over years of operation). Therefore, it was not possible to determine whether U+V mines were able to increase production of V in low U-price environments in order to maintain profitability or lengthen closing response time in down markets.

Model Description

In order to understand historic mine operations (i.e. opening vs. closing), mines were grouped by size and evaluated in terms of response time to changes in uranium price, policy changes, and other mining activity in the region. These were included in a Powersim Studio 9 (Powersim, 2016) optimization tool to determine the optimal value for each of these variables. This system dynamics software platform allows for rapid evaluation of dynamic interaction between multiple variables over time. The model is designed to run on an annual time step from the initial date of U price availability (1948) (McLemore and Chenoweth, 1989) until the year 1985, when all but one mine in the state had closed (McLemore et al, 2002). In order to evaluate the effects of changing policies, four time periods are included in the analysis (1948–1954, 1954–1964, 1964–1974, and 1974–1985) that reflect significant changes in policy regarding U commerce, as described in the previous section.

Optimization is a method commonly used in economic modeling to quantify the value of a series of variables that, when combined, most closely represents the real behavior of a system. The Powersim Optimization Tool uses an evolutionary search algorithm in which values of model decision variables change over time. During the optimization process, the model simulation is run many times where the best results from one simulation are used as inputs into the next simulation until a minimum difference between the number of actual and modeled mine openings and closings are achieved for each of the four policy-defined time periods. The four decision variables that potentially impact the decision to open or close a mine in the model are: 1) a coefficient response to price, 2) moving average price, 3) price time delay, and 4) impact of larger mines on smaller mine closings.

Figure 2 illustrates the conceptual process of the model and flow paths by which the decision variables (boxed) are determined from the input of real price data. Simulations are conducted separately for small, medium, and large mines. The various decision variables are defined as follows. The price coefficient indicates the number of mines that opened or closed due to a unit change in average real price of uranium, and the moving average price is the window of time over which the price is averaged. A large 'moving

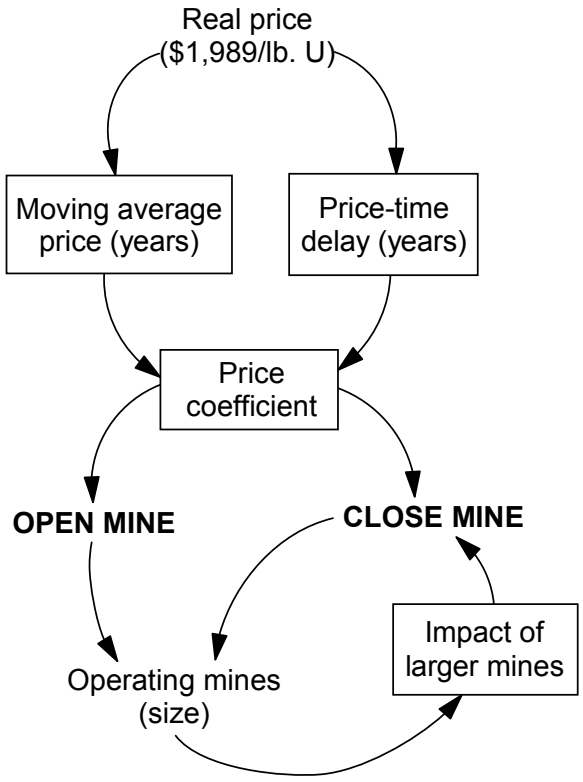

Figure 2. Conceptual model and system dynamics flow paths used in this study.

average price' implies that decisions on whether to open or close a mine depend on prices averaged over a longer term and not simply in response to short term market fluctuations. The price time delay is the length of time that passes before opening or closing occurs in response to a unit change in average price. Factors that delay construction or closing of a mine, such as the time needed to arrange for financing or evaluating trends in the market, are incorporated in the 'price time delay' variable. A large value for 'price time delay' indicates that decisions regarding mine operation are not an immediate response to changes in price. Optimal values for the moving average price and price time delay are computed directly from the real price input data using the Optimization Tool. Lastly, the impact of larger mines is a coefficient that describes the effect of larger mines on small mine closing, where a large coefficient indicates that a greater number of smaller mines closed in response to an increase in the number of larger mines operating in the region. This coefficient is also determined by iterative optimization. This coefficient was applied to the number of large mines operating during a designated time period when evaluating their impact on medium mines, and to both large and medium mines when evaluating their impact on small mines.

The first tier of optimization produces a value for the price coefficient from the moving average price and the price time delay. Using the price coefficient and the impact of larger mines coefficient, the model then predicts in a second tier of optimization how many mines open and close in a given policy-related time period from which the number of operating mines can be determined. In each iteration, the predicted number of operating mines of a given size are then compared to the actual number, and variable values are then adjusted until the difference between predicted and actual are minimized.

This process is summarized by the objective function, which shows: 1) how optimized decision variables are used to predict the number of opening (a) and closing (b) of mines, and 2) how the minimum difference between the predicted values and the actual values are calculated for each time period and then summed over the four time periods. For opening and closing, the objective of each optimization is to achieve the minimum difference between actual historic mines and modeled mines of each size for each time period (n).

Equation 1: Objective function describing the modeled opening (a) and closing (b) of historic U mines of a given size class (small, medium, large)

Where: MIN = minimum
ABS = absolute value
n = four policy-related time periods,
t_D = price time delay
t_A = moving average price
β_1= price coefficient
β_2 = impact of larger mines coefficient

It is assumed that changes in coefficients (β) and time delays (t) over the four policy-related time periods (n) will quantitatively describe the effects of changing policy and economic environments and support evaluation of the three proposed hypotheses.

$$a)\ f(n)_{MIN} = \sum_{n=1}^{4} \left(\text{Historic Mines} - (\beta_1[t_D(t_A(\text{PRICE}))])\right)$$

$$b)\ f(n)_{MIN} = \sum_{n=1}^{4} \left(\text{Historic Mines} - (\beta_1[t_D(t_A(\text{PRICE}))] + \beta_2[\text{LARGER MINES}])\right)$$

Model Input

Historic mine operations data were obtained from the New Mexico Mines Database (McLemore et al., 2002), which lists the operation and total U recovered for each mine from 1942 to 1989. More than half (128) of these mines showed a date range of production only, nearly 40% reported either a single year of production (64) or production amounts for every year in the production period (19), and five mines reported a combination of a range and annual production values (McLemore et al., 2002). Because of the disparate time scales for which production data was available, total production was divided by the time period of operation to determine estimated annual production. This value was used to classify mines as small (<200 lb/yr), medium (200–12,000 lb/yr), or large (>12,000 lb/yr). Mines were also characterized by type (surface, underground, combined) from McLemore et al. (2002) and as either U or U+V producing mines.

The real price of U (per year) is the primary economic input into the model. It is obtained by adjusting the nominal price for inflation into 1989 dollars. This adjustment allows comparison over time of real changes in value per pound of U (Figure 3). Although, there are several sources of nominal price data for uranium and vanadium (Figure 3), Roskill (1991) was used because U prices were represented in both nominal and real (1989) dollars adjusted for inflation, whereas other sources listed only nominal values.

Roskill (1991) reported U prices from two data sources: US Atomic Energy Commission (USAEC) prices (1948–1971) and the Nuclear Exchange Commission (NUEXCO) prices (1968–1990). Figure 3 also shows that vanadium prices (USGS, 2013) have historically been both lower and more stable that U prices. Comparison of nominal and real prices shows how the guaranteed minimum price for U during 1948–1964 did not result in a steady market value of U, which steadily declined between 1953 and the early 1970s. This price decrease could be due to increasing supplies of U resulting from government subsidization of the early U market or to government surpluses of U due to bans on wepons testing that decreased government demand for U.

Once historic and economic inputs were incorporated into the model and prior to optimization, a range of potential values was assigned to each variable. Price ('price coefficient') and 'impact of larger mines' each have a starting coefficient ranging from -1 to 1, with a starting value of 0.1. This allows for modeling of potentially counterintuitive results, such as increasing prices resulting in a negative response from mines. Both time variables, 'moving average price' and 'price time delay' were given a range of values from 0 to 5 with a starting value of 2.5. Using these starting values and allowed ranges, the Optimization Tool obtains temporary values for each variable during a given iteration, and then reintroduces these values as inputs until the optimal value is achieved for opening and closing mines in each size category over the four specified time periods.

Results

Historic Mining Operations Model

Data gathered from the New Mexico Mines database (McLemore et al., 2002) indicate that uranium mining in New Mexico was dominated by small and medium-sized mines from the late 1940s to the late 1950s, when the

number of these types of mines peaked (Fig. 4). Large mines began operations in the early 1950s. The number of large mines subsequently overtook the number of smaller mines and peaked in the mid-1960s concomitant with closing of smaller mines (Fig. 4).

The optimal values chosen for the decision variables minimized the differences in the number of operating mines between historical data and modeled predictions (Fig. 4). When compared to historic data, the variables included in the model accounted for 81.6% of the variability in large mine operations, 93.8% for medium mines, and 89.0% for small mines based on R-squared values (Table 2). Furthermore, the F-test reveals that these results are significant (Table 2). Generally, an F-test greater than 0.01

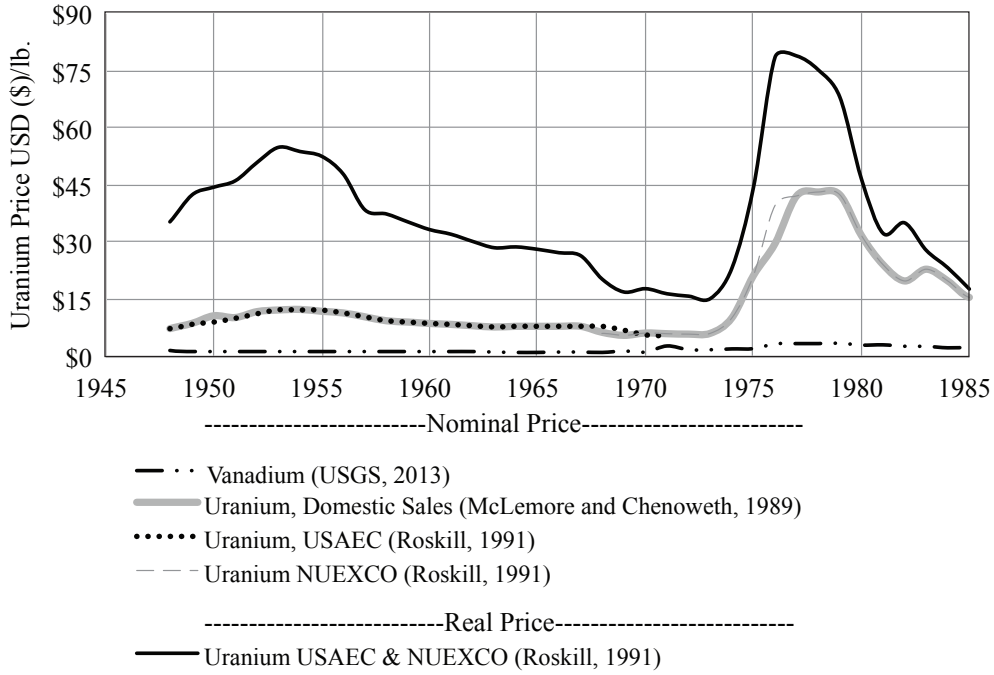

Figure 3. Comparison of reported nominal and real prices for V and U.

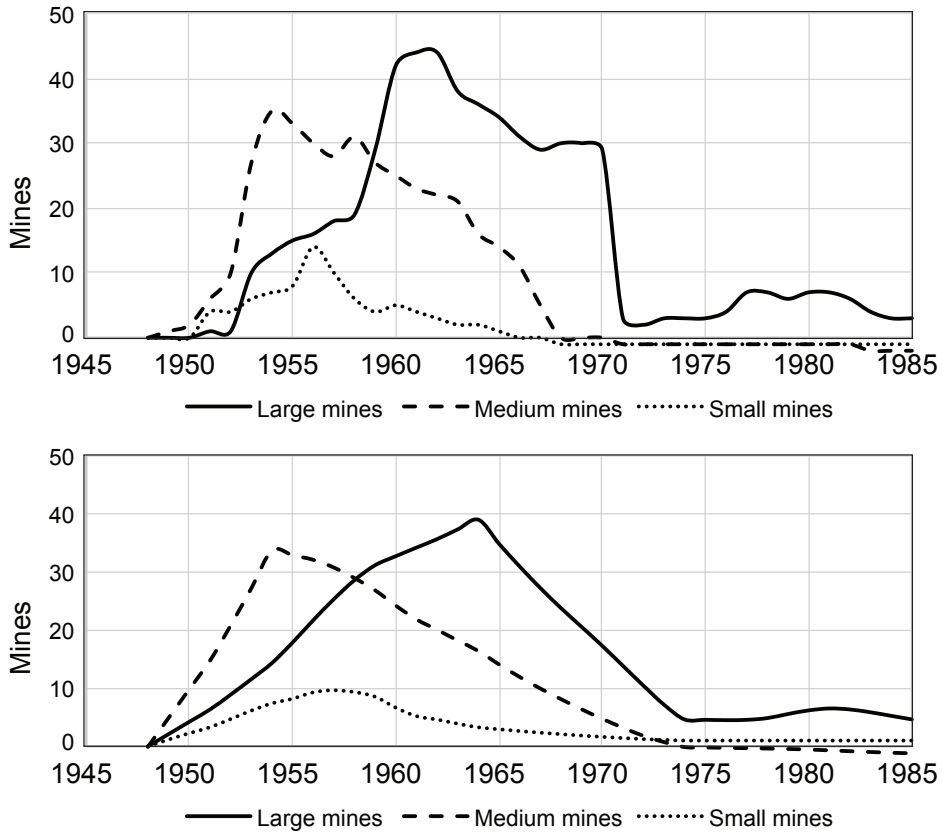

Figure 4. Number of historic mine operations (top) compared to those predicted by the model (bottom). X axis is in years.

TABLE 2: Statistical comparison of actual versus modeled mining operations.

Statistic	Mine Size		
	Small	Medium	Large
R-square	0.863	0.940	0.874
F-statistic	3.94E-17	1.40E-23	8.77E-18

indicates that results are not significant and the smaller the F-statistic in a regression output, the greater the probability modeled results are not due to chance. Model results are summarized in Tables 3a–3c. For the opening and closing of mines in each size class, optimized values for the decision variables are listed for the policy-relevant time frames. Below, we discuss the economic and policy implications that can be inferred by the modeled optimal values.

Economic Variables

The economic variables included in the model are intended to reflect how changes in price over time affected the opening and closing of mines of a given size. The decision to open or close a mine is influenced by numerous factors that include both price and competition; therefore, both the 'price time delay' and 'moving average price' are intended to capture how company decision making responded to short-term fluctuations in price stability over time.

Price coefficient

A key gauge of sensitivity to price (of a given mine type or size) is the price coefficient, which indicates the number of mines that opened or closed due to a unit change in average real price of U.

This coefficient could not be calculated for time periods when mines of a given size were not in operation (e.g., small mines in 1974–1985). Note the steady decrease in the opening price coefficient for large mines through 1948–1985, where the price coefficient decreased by more than two-thirds between 1954–1964 and 1964–1974. Such a decrease was not obvious during 1948–1964 for smaller to medium mines, except for a slight decrease in the closing price coefficient. Upon comparing small- and medium-sized U vs. U+V mines (Tables 3b and 3c), price coefficients are commonly an order of magnitude higher for U+V mines. This difference in price coefficient indicate that small to medium mines producing both U and V were more responsive (larger coefficient) to change in U price (Table 3c) than were small to medium mines that produced only U (Table 3b).

Price time delay

Figure 5 depicts the price time delay for mine opening and closing as a function of mine size. With the exception of mine closing during 1948–1954, small mines opened and closed rapidly (≤1 year). Openings for medium sized mines took ~1 year and large mines ~2 years throughout the four modeled time frames. Closing of medium to large mines took slightly longer in earlier years (4–5 years) compared to later years (3–4 years for large mines; 1.5–2.5 years for medium mines, per the model).

When mines producing U+V were compared to U-producing mines, the most noticeable difference in model results was in their price time delays. When compared to mines producing only U, medium and large U+V producing mines closed more slowly between 1954–1974 based on their higher price time delay values. Small mines producing U+V had similar price time delays for opening and closing as those producing only U.

Trends in Mine Openings and Closings

In general, there were more openings and closings of all U mines (U and U+V) in the first two periods than the last two periods (Fig. 6) and large mines dominate openings and closings after 1964, reflective of the total number of historic operating mines as a function of size (Fig. 4). Mines producing both U and V opened in greater numbers in the first two policy-related time periods as compared to U-only, but closed in much greater numbers between 1954–1964 (Fig. 7). However, U+V mines were predominantly small- and medium-sized mines, so these results could be more indicative of the role mine size played in operational (opening and closing) decisions. Between 1964 and 1985, fewer U+V mines closed as compared to U-only mines and these mines were medium or large; no U+V mines opened during this time (Fig. 7).

Discussion

Model results indicate that responses to changes in price and competition from larger mines influenced opening and closing and varied in response to national policies.

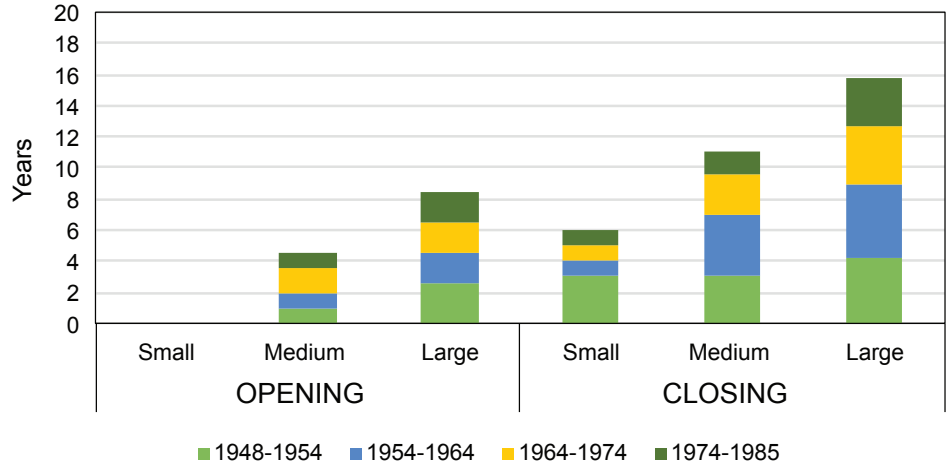

Figure 5. Comparison of modeled time delays for mine opening and closing (from Table 3a).

TABLE 3a. All Mines. Modeled regression results, includes regression results from all mines regardless of the type of commodity produced. Data are categorized according to policy-relevant time periods (in years).

Mine Size	Operation	Variable	1948–1954	1954–1964	1964–1974	1974–1985
Small Mines	**Open**	Price Coefficient	3.00E-02	3.00E-02	0.00E+00	N/A
		Moving Average Price	1.00 yr	1.00 yr	2.60 yr	N/A
		Price Time Delay	0.00 yr	0.00 yr	0.00 yr	N/A
	Close	Price Coefficient	3.00E-02	2.00E-02	1.90E-03	N/A
		Moving Average Price	2.00 yr	2.00 yr	1.00 yr	N/A
		Price Time Delay	3.00 yr	1.00 yr	1.00 yr	N/A
		Impact of Larger Mines	1.00E-02	1.00E-02	3.00E-03	N/A
Medium Mines	**Open**	Price Coefficient	1.50E-01	2.00E-02	0.00E+00	N/A
		Moving Average Price	3.00 yr	3.00 yr	1.60 yr	N/A
		Price Time Delay	1.00 yr	1.00 yr	1.60 yr	N/A
	Close	Price Coefficient	4.00E-02	3.00E-02	1.00E-02	N/A
		Moving Average Price	2.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	3.00 yr	4.00 yr	2.50 yr	N/A
		Impact of Larger Mines	5.00E-03	6.00E-03	8.50E-03	N/A
Large Mines	**Open**	Price Coefficient	5.00E-02	3.00E-02	1.00E-02	9.50E-03
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	2.00 yr
		Price Time Delay	2.50 yr	2.00 yr	2.00 yr	2.00 yr
	Close	Price Coefficient	0.00E+00	1.00E-02	6.00E-02	9.00E-03
		Moving Average Price	1.20 yr	1.117 yr	1.00 yr	3.00 yr
		Price Time Delay	4.15 yr	4.81 yr	3.70 yr	3.05 yr
		Impact of Larger Mines	N/A	N/A	N/A	N/A

TABLE 3b. U Mines only. Modeled regression results, includes results for U-producing mines only. Data are categorized according to policy-relevant time periods (in years).

Mine Size	Operation	Variable	1948–1954	1954–1964	1964–1974	1974–1985
Small Mines	**Open**	Price Coefficient	4.00E-03	9.80E-03	0.00E+00	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	0.00 yr	0.00 yr	0.00 yr	N/A
	Close	Price Coefficient	7.50E-04	4.80E-03	1.00E-03	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	1.00 yr	1.00 yr	0.00 yr	N/A
		Impact of Larger Mines	1.00E-02	1.00E-02	3.00E-03	N/A
Medium Mines	**Open**	Price Coefficient	1.00E-02	9.10E-03	1.00E-02	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	1.00 yr	1.00 yr	1.20 yr	N/A
	Close	Price Coefficient	9.00E-04	1.00E-03	3.90E-03	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	2.50 yr	1.60 yr	1.50 yr	N/A
		Impact of Larger Mines	5.00E-04	3.00E-02	3.00E-02	N/A
Large Mines	**Open**	Price Coefficient	6.50E-03	9.00E-02	4.00E-02	9.00E-03
		Moving Average Price	1.50 yr	1.50 yr	1.00 yr	0.90 yr
		Price Time Delay	1.00 yr	1.00 yr	0.73 yr	0.65 yr
	Close	Price Coefficient	1.00E-04	3.00E-02	1.30E-01	9.00E-03
		Moving Average Price	1.00 yr	0.70 yr	1.00 yr	1.32 yr
		Price Time Delay	3.20 yr	3.10 yr	2.60 yr	1.80 yr
		Impact of Larger Mines	N/A	N/A	N/A	N/A

TABLE 3c. U & V Mines. Modeled regression results, includes results from mines producing both U and V. Data are categorized according to policy-relevant time periods (in years).

Mine Size	Operation	Variable	1948–1954	1954–1964	1964–1974	1974–1985
Small Mines	**Open**	Price Coefficient	6.00E-02	1.10E-01	0.00E+00	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	0.00 yr	0.00 yr	0.00 yr	N/A
	Close	Price Coefficient	3.00E-02	1.10E-02	5.00E-03	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	1.00 yr	1.00 yr	0.00 yr	N/A
		Impact of Larger Mines	1.00E-02	1.00E-02	3.00E-03	N/A
Medium Mines	**Open**	Price Coefficient	1.60E-01	6.00E-02	0.00E+00	N/A
		Moving Average Price	1.0 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	1.00 yr	1.00 yr	1.20 yr	N/A
	Close	Price Coefficient	2.00E-02	9.00E-02	5.00E-02	N/A
		Moving Average Price	1.00 yr	1.00 yr	1.00 yr	N/A
		Price Time Delay	3.50 yr	3.00 yr	2.50 yr	N/A
		Impact of Larger Mines	5.00E-04	3.00E-02	3.00E-02	N/A
Large Mines	**Open**	Price Coefficient	5.00E-02	2.00E-02	0.00E+00	0.00E+00
		Moving Average Price	1.50 yr	1.50 yr	1.00 yr	0.90 yr
		Price Time Delay	1.00 yr	1.00 yr	0.73 yr	0.65 yr
	Close	Price Coefficient	0.00E+00	3.00E-02	3.00E-02	9.00E-04
		Moving Average Price	1.00 yr	0.70 yr	1.00 yr	1.32 yr
		Price Time Delay	4.15 yr	3.20 yr	3.00 yr	2.00 yr
		Impact of Larger Mines	N/A	N/A	N/A	N/A

We expound on these topics below, but perhaps more significant than the results of the model was the development of a modeling framework for understanding the relationships between price and policy on U mining operations that has been discussed previously (Buck, 1983; Roskill, 1991; Peach and Popp, 2008) but never quantified. This approach has utility for other commodities (such as oil and gas) in understanding the dynamic relationships between natural resource development and economics subjected to changing policy and regulatory environments.

There are several important limitations of this model. Although a production record exists of New Mexican U mines, annual production data is available for less than half of these. Furthermore, our annual production data is really an estimate using an average of total production of each mine divided by the mine's total years of operation (for both U and V) because most mines do not have year-by-year data. This introduces error and limits the number of data points available for the model. The second limitation is that the average price of U does not reflect long-term contract prices negotiated between U producers and consumers. Lastly, the role of profitability as a function of profit and fixed and variable costs are not included in this model. Although it likely influenced operational decisions, annual cost and profit data was not available for every mine or year of production. An exploration of the dynamics between actual annual production volumes of U-only mines vs. U+V mines over time as a function of changing prices warrants further study.

Trends in historic mining operations

Small and medium sized mines thrived in the state until the late 1950s (in terms of their overall number), but then declined coincidently with an increase in the number of large mines (Fig. 4). The peak in small- to medium-sized historic mining operations during 1952–1958 coincided with high real uranium prices (Figs. 3 and 4). Small- to medium-sized operations declined in conjunction with falling prices between 1958 and ~1970. Note that the number of large operations peaked in 1960–1962, after the 1952–1958 peak in price, consistent with their higher price time delay values for opening.

A possible explanation for these trends is that in early years (1948–1964) guaranteed purchase by the Federal government, regardless of quantity, encouraged production by mines of all size. In later years, (1964–1985) after the lapse of Federal purchase guarantees and subsidies which largely benefited smaller operations (Roskill, 1991), larger mines were able to produce U at lower cost due to economies of scale, where increasing production capacity generally decreases the per-unit cost of production. Below, we use our model results to explore this possibility.

Another explanation for the increase in the proportion of large mines vs. medium-small mines after 1964 may relate to mill capacity and mill contracts. Although one-quarter of total U.S. domestic mills and more than half of domestic milling capacity operated in New Mexico during this time, many of these mills were either already nearing capacity (Peach and Popp, 2008) or ore-processing suitability to mill the ore produced in the region. In the absence of government subsidies

for transportation, the added cost of moving ore from mines to mills at increasing distances would have directly impacted the profitability of existing mines. The Marquez mill was constructed in 1980 to provide additional milling capacity, but the mill owner (Bokum Resources) declared bankruptcy in 1981 and the mill was never operational (McLemore and Chenoweth, 2003). As such, larger mines may have been able to wield more market power than smaller operations, negotiating longer-term contracts at lower prices with both mills and U purchasers.

Influence of price versus governmental policies

Four policy situations were included in the model: the Atomic Energy Acts of 1946 and 1954, the Private Ownership of Special Nuclear Materials Act (1964), and the Energy Reorganization Act (1974) (Buck, 1983; Walker and Wellock, 2010). Mine openings and closings were modeled for each time period bracketed by these policy situations to understand how operational responses to changes in price varied as a result of regulatory changes. From 1948–1954, mines of all sizes opened rapidly while few mines closed (Fig. 6). The passage of the Atomic Energy Act of 1954 might have caused rapid growth of uranium mining in the second time period (reflected by mine openings), but closing rates also increased for both small and medium sized mines (Fig. 6). Declining real prices after 1954 were likely an important factor for the increase in these closing rates, perhaps influenced by the sluggish development of nuclear energy technologies (Peach and Popp, 2008). In addition, the moratorium on weapons testing signed by President Eisenhower in 1958 (Buck, 1983), combined with ample existing military stockpiles, dampened demand by the federal government for nuclear weapons.

The peak for small and medium mine closings occurred between 1954–1964 compared to the larger proportion of large mine closings which occurred in the following time period (1964–1974). The latter period coincided with a decline in domestic mining activity in general. This decline was likely due to withdrawal of the US Government's role as steward for the uranium and nuclear industries in 1974 (Buck, 1983) as well as increasing foreign U production (from South Africa, France, and Canada, which collectively surpassed US production by the early 1980s) (Roskill, 1991).

Coupled with other data, trends in price coefficients help to elucidate how government policies impact mine sensitivity. As a hypothetical example, assume that U prices were stable over two time periods of comparison, the first containing notable government subsidies and the second having no government subsidies. However, during these two time periods there was a decreasing trend in the opening price coefficient. One could interpret this scenario as indicating earlier government policies positively impacted mining operations, since fewer mines opened in the second time period. An increase in the closing price coefficients across the two hypothetical time periods would imply greater sensitivity to changes in price in the second time period, which might be due to the lack of stability provided by government subsidies provided in the earlier time period.

We argue that government subsidies affected mines of all sizes, but price change trends complicate whether smaller mines were disproportionally influenced. The high number of historic mining operations for all mine sizes during the early years (1948–1964) suggests that government subsidies for transportation, exploration, engineering, and milling costs impacted all mines. However, this comparison may also be due to relatively

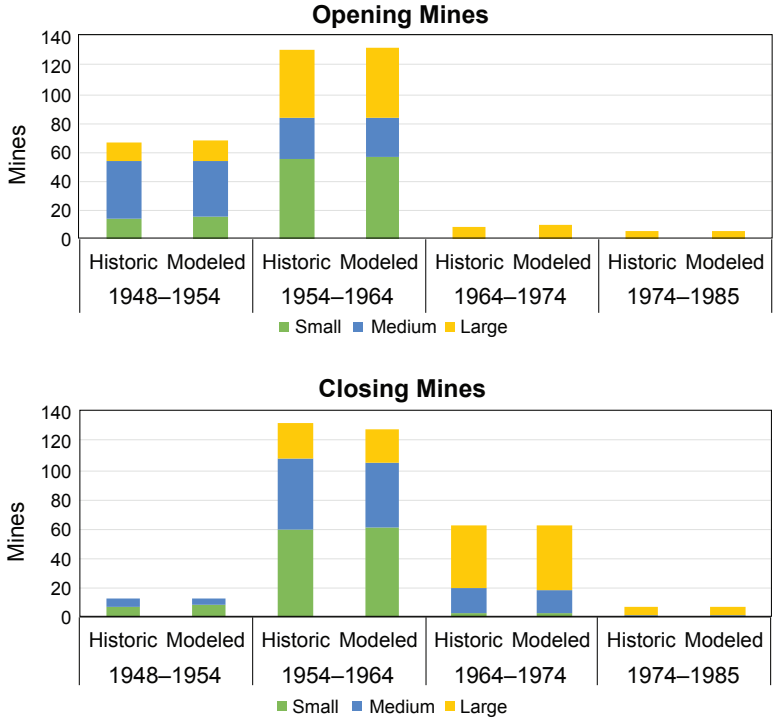

Figure 6. Total number of opening mines (left) and closing mines (right) across the four modeled time periods.

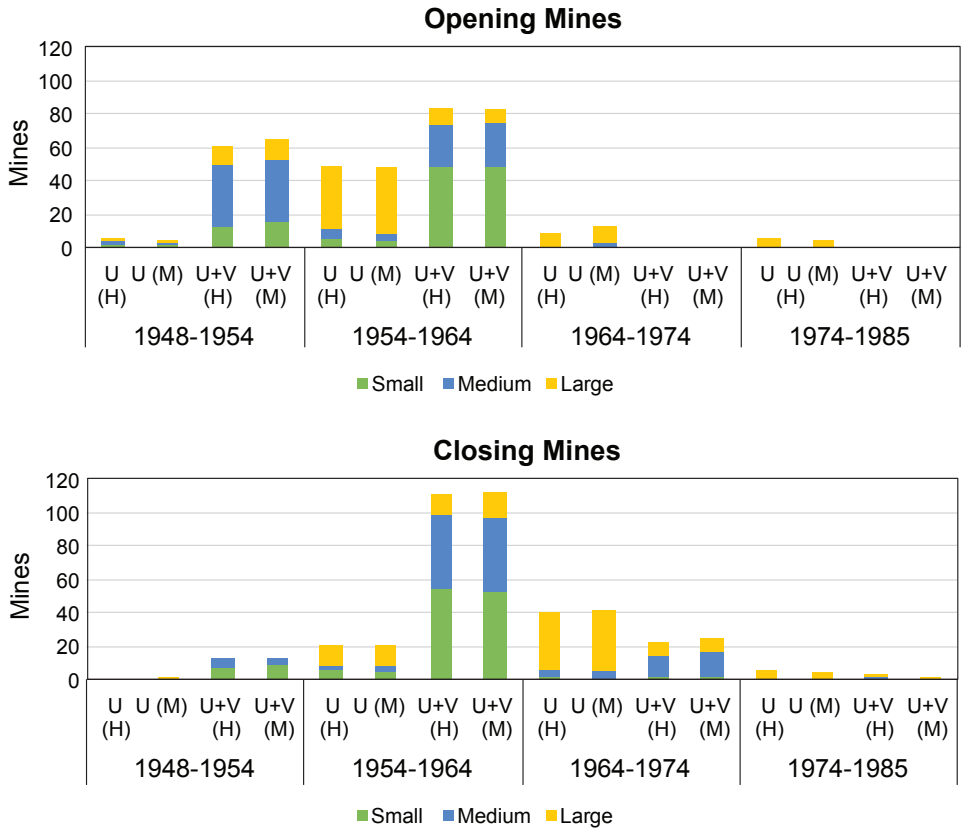

Figure 7. Comparison of the number of openings and closings for U-only mines versus U+V mines. H = historic mines and M = model-predicted mines. Data are shown for each of the four policy-related time periods.

high U prices. Mine size was the most significant indicator of whether a mine would open or close in response to price in the years following these subsidies (1964–1985). In contrast to large mines, no small or medium mines opened after 1964. Also, opening-related price coefficients for all mine sizes were greatest in earlier periods (1948–1954 and 1954–1964) and declined in later periods (Table 3a), which implies that the combination of high prices and subsidies for development encouraged mine openings prior to 1964. Although the same decreasing trend is seen for closing-related price coefficients for small and medium mines through the 1964–1974 policy time period (suggesting less sensitivity to price changes with time, even after subsidies ended), the values of closing price coefficients are greater than coeval opening price coefficients. This indicates that a decision to close rather than a decision to open had greater sensitivity to price changes following the lapse in government subsidies. Both the price coefficients and the historical data suggest that government policies prior to 1964 stimulated and sustained small and medium sized mines. Furthermore, the greatly reduced number of small- and medium-sized mines after 1964 supports our hypothesis that the loss of government subsidies, combined with the decreasing price of U, had a disproportionate impact on these size classes compared to larger mines. No clear trend is evident in the opening and closing price coefficients for large mines. Lastly, it is noteworthy that relatively few mines opened in 1974–1985 despite a large increase in real price in the early half of 1974–1985, which was actually higher than in 1952–1956 (Figs. 3–6). This paucity of openings could be attributed to the lack of government subsidies or the lack of a guaranteed market and purchaser by the government (these being more amenable to small mine operators than larger mine operators, the latter being able to better negotiate complex contracts with non-government purchasers). In summary, analysis of our data indicates that government subsidies likely impacted mines of all sizes; but due to complications posed by declining prices between 1958 and ~1970, we cannot conclusively determine that these subsidies preferentially promoted and sustained smaller mines prior to 1964.

Response times

For all four time periods, the smaller values of the price time delay coefficient for smaller and medium mines compared to larger mines supports our second hypothesis: that smaller mines respond more quickly to changes in price than large mines. The discrepancy in values suggest that the greater initial investment and fixed costs associated with larger mines may have tempered their response to changes in price (which was likely due to economies of scale for larger mines as well as higher operating costs and higher costs associated with opening and closing). On the other hand, the smaller initial investment and fixed costs associated with medium and smaller sized mines allowed them to open and close more rapidly in response to fluctuations in U prices. Grouping the time periods into 1948–1964 and 1964–1985, there is a general trend of a decrease in price time delay for a given mine size. This could be interpreted that decisions to open or close a mine occurred more quickly in the absence of subsidies.

Co-production of vanadium

We hypothesized that mines producing both U and V may have had a slight advantage, both in the speed and magnitude at which they responded to changes in price, over mines that produced U only. Because V is a co- or by-product of U production and because its price was consistently less than that of U, its production was subsidized by U production (Hilliard, 1994). Across all time periods, our modeling results showed generally higher closing and opening price coefficients for small and medium U+V mines compared to U-only mines, indicating that the U+V mines were more sensitive to changes in price which argues against our hypothesis. However, the closing price coefficients were slightly larger for U-only large mines, consistent with our hypothesis. No difference was seen in the price time delays for small mines between U-only and U+V mines, but for medium to large mines the closing price time delay was longer for U+V mines. This suggests that the co-production of vanadium stabilized mine operations for medium and large mines, even in the declining price environment prior to 1974, which supports our hypothesis.

Impacts of larger mines

Small mines were more negatively impacted by larger sized mines than were medium sized ones. This conclusion is based on the higher values of the Impact of Larger Mines coefficient for smaller mines than medium sized mines (Table 3a). In addition to competition from larger mines, exhaustion of mineable resources by smaller mines, which was not included in the model, may have affected the responsiveness of smaller mines to price.

Scarcity and Market Flooding

The U market and industry has been historically plagued by large fluctuations in price and demand. From its early discovery through the development of nuclear power, factors such as the identification of new resources, dumping of reserves, stockpiling, and fear of scarcity have affected the industry. For example, the Westinghouse Electric Company offered a guaranteed U_2O_8 price of $6/lb. for its customers who purchased their pressurized light water reactors in the early 1970s (Roskill, 1991). However, many companies were developing small modular reactors that increased demand for U, and the prices began to rise in the mid-1970s and peaked at over $40/lb. in 1978 (Roskill, 1991). Unable to buy U from existing producers or identify new resources, Westinghouse confirmed it could not meet its obligation to provide U at $6/lb. to its customers, and the market was again plagued by both real and imagined scarcity. After 1978, the supply of U outpaced its demand for nuclear power (Roskill, 1991), which constrained the market and caused spot prices to decline by more than a quarter between 1978 and 1980 and by nearly a third a year later.

Non-modeled factors influencing future mining operations

The results of this study reveal previously unquantified relationships between mining and external drivers and serves to illuminate the economic and policy considerations affecting possible renewed uranium mining in the region. It is also important to recognize that factors such as permitting and environmental regulations, tribal issues and public acceptance, and access to U mills which received little concern in the past will likely affect decisions regarding future U production.

During the historic U boom years in New Mexico, very few state and federal regulations existed which governed the environmental impacts of mining operations and waste disposal. Lack of environmental protection early on led the DOE to comment that "State and Federal controls [were] non-existent or totally inadequate," (written commun. with DOE, documented in SJBRUS, 1980). Subsequent legislation has addressed many of these shortcomings. Although passed towards the end of U production in NM, four federal laws address uranium mining and milling activities: Uranium Mill Tailings and Radiation Control Act (UMTRCA, 1978), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, 1980,1986), US Forest Service Mining Regulations and Minerals Management (1974), and BLM Mineral Land Management (1981) (Dixon, 2015). In addition, the state of New Mexico has passed important laws to address the safety of mine workers, air and water quality, and waste disposal (Dixon, 2015).

While the environmental impacts of U mining and milling operations were not often a factor historically, human impacts were even less of a consideration. In particular, the effect of these operations on Native American tribes, who own land and comprise a significant proportion of the population in the region, is an important consideration should operations resume in the future. Legacy impacts of radiation exposure to mine workers, environmental impacts of abandoned mines, and accidents like the Church Rock mill tailings pond failure (the largest radioactive spill in U.S. history) have disproportionately affected tribes in the region.

The number of U mills likely had an impact on mine operations. Between 1948 and 1982 eight mills operated in New Mexico (McLemore, 1983) whereas currently there is only one operating U mill in the U.S., the White Mesa mill in Utah (US EIA, 2016). Location of nearby mills would affect transportation costs and the marketability of U ores, an especially important fact for small U mines.

Conclusions

The objective of this study was to use systems dynamics modeling to quantify how historic uranium operations in New Mexico during 1948–1985 may have been influenced by economic and government policy factors. The number of mines operating in New Mexico during the uranium boom from 1948 to 1985 were grouped by size and classified as either U-only or U+V producing mines. To assess the impact of government policy on mining operations, four time periods were delineated that related to specific enactments of uranium-related federal legislation and policies.

We used the model to test three hypotheses: 1) subsidies from the U.S. government both promoted and sustained smaller mines prior to 1964, 2) smaller mines responded more quickly to changes in price than do large mines, 3) mines that produced both uranium and vanadium were more stable than mines that produced uranium only because of diversified production and the relatively stable historic price of vanadium.

Declining opening-related price coefficients with time is consistent with government subsidies encouraging mines of all sizes. Although closing-related price coefficients decline over time as well, their values exceed those of opening-related price coefficients after 1964 indicating that closing rather than opening had greater sensitivity to price changes following the lapse in government subsidies. Examination of historical data indicates that no small mines and only a few medium-sized mines opened after the elimination of these subsidies. Therefore, government subsidies and/or higher U prices in 1948–1963 vs. 1963–1974 may have helped promote these mine sizes prior to 1964. Economies of scale and lower milling costs for larger mines may also have contributed to the closing of all small and medium sized mines by 1974. Furthermore, the lapse of government subsidies, which were designed to encourage the development of the U industry, were likely an important factor in the relatively low amount of openings and total mines in operation during 1974–1985. This is particularly significant given that real prices were relatively high during most of this time period.

Our modeling generally supports our second and third hypotheses. Small mines opened and closed rapidly (≤1 year). Medium and large sized mines took 0.65–1.2 years to open and 2–5 years to close throughout the 37-year period model, with closing time delays of both medium and large mines being less after 1964 than prior to 1964 (Table 3a). The economic advantage of producing both vanadium and uranium was evident in longer closing times for medium and large mines, but small-medium U+V mines were more sensitive to changes in U price.

Economics, policy, and the regulatory frameworks governing the uranium industry have changed markedly since the U boom of the 1950s and 1960s, which encouraged mines of all sizes to produce U. Public perception, including awareness of legacy impacts of past mining activities and the risk of potential negative impacts on the environment and human health now plays a role in current and future U development decisions. Renewed mining activities will require consideration of all of these factors and will likely result in extensive planning, lengthy permitting times, and investment in public outreach efforts. In addition to planning and regulatory costs, future mines must have approved plans for mine closing and post-operative remediation, as well financial guarantees for the protection of cultural sites, the environment, and human health which will likely increase the unit cost of production as compared to historic costs. As a result, the high ratio of large vs. mid- to small-size mines, which began ca. 1960 is likely to persist into the future should activities resume. Consideration of these factors as well as their potential for change will undoubtedly play a role in future development decisions.

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Gallery of Geology

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Figure 1. William Chenoweth standing over a brass cap marking Milepost 16 on the New Mexico/Arizona state line. Uranium-vanadium deposits in the Salt Wash Member of the Morrison Formation were found in this area in 1918, but could not be mined since the Navajo Reservation was closed for mining at that time. *Photo by V.T. McLemore in 1983.*

Figure 2. Navajo miners leaving the King Tutt Point mine in the Salt Wash Member of the Morrison Formation on King Tutt Mesa in eastern Carrizo Mountains, San Juan County. From 1950–1953, the mine produced 429 tons of ore averaging 0.31% U_3O_8 and 2.62% V_2O_5. *Photo by K.G. Hatfield in 1953.*

Figure 3. Surface plant of Kermac's Section 22 mine, Ambrosia Lake subdistrict, McKinley County. The headframe is for a shaft that is 826 ft deep. *Photo by W.L. Chenoweth in 1961.*

Figure 4. Grade control engineer checking the grade of blasted ore with a T-probe (grade control instrument) at the Dysart No. 1 mine, Ambrosia Lake subdistrict, McKinley County. *Photo by K.G. Hatfield in the late 1950s.*

Figure 5. Grade control engineer checking grade of blasted ore with a T-probe at the Homestake-Sapin Partners Section 25 mine, Ambrosia Lake subdistrict, McKinley County. Photo by U.S. Atomic Energy Commission geologists in the 1960s.

Figure 6. Dump truck being loaded with ore at the Homestake-Sapin Partners Section 25 mine, Ambrosia Lake subdistrict, McKinley County. Photo by U.S. Atomic Energy Commission geologists in the 1960s.

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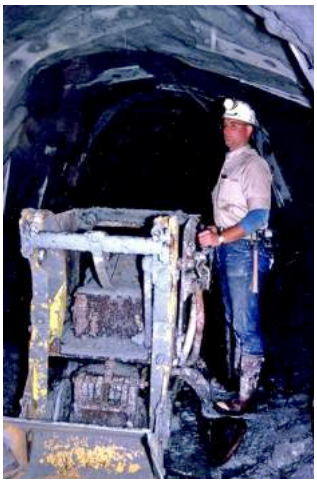

Figure 7. Mine official showing visitors how an overhead mucking machine operates at the Homestake mine, Ambrosia Lake subdistrict, McKinley County. *Photo by U.S. Atomic Energy Commission geologists in the 1960s.*

Figure 8. Headframe of Anaconda's Woodrow mine, Laguna subdistrict, Cibola County. The 230 ft deep shaft was adjacent to a collapsed ore-bearing breccia pipe in the Jackpile and Brushy Basin members of the Morrison Formation. This mine produced 5,326 tons of ore averaging 1.26% U_3O_8, 1953–1956. *Photo by W.L. Chenoweth in 1961.*

Figure 9. Bokum Resources shaft at Marquez Canyon, McKinley County. Shaft was never completed due to high water flow. *Photo by W.L. Chenoweth in 1981.*

Figure 10. Surface plant at Kermac's Rio Puerco mine, Sandoval County. *Photo by W.L. Chenoweth in 1981.*

Figure 11. Virginia McLemore standing at a stockpile of illegally mined uranium-vanadium ore from the Shadyside area of King Tutt Mesa, eastern Carrizo Mountains, San Juan County, New Mexico. In the late 1970s, the Grand Junction office of the U.S. Department of Energy received reports of some uranium mining taking place on King Tutt Mesa, but mining was terminated by the Navajo Police Department as the individuals from Farmington, New Mexico did not have the proper permits. *Photo by W.L. Chenoweth in September 1983.*

Figure 12. Navajo vanadium miners, Shadyside area, King Tutt Mesa, eastern Carrizo Mountains, San Juan County. *Photo by U.S. Geological Survey geologists in October 1942.*

Figure 13. Ambrosia Lake in a rare moment when the lake contained water, October 2014. The structure in the background is the Section 12 headframe of the Section 11/12 mine, owned by Hydro Resources. The mine has a second headframe at the west end of the mine, in Section 11. *Photo by Bonnie A. Frey.*

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Figure 14. The eastern headframe of the Section 11/12 mine, Ambrosia Lake subdistrict, McKinley County. The mine shaft is 500–520 feet deep (George Lotspeich, Hydro Resources, personal comm., 2014). Cumulative production from 1961–1963 was 211,873 pounds U_3O_8, with a production grade of 0.15% U_3O_8, likely depleting the deposit resource. The mine operated until 1980 (McLemore et al., 2013). *Photo by Bonnie A. Frey in October 2014.*

Figure 15. Sampling at the waste rock pile of Section 11/12 mine. Students from New Mexico Tech and the University of New Mexico collected samples for ongoing column and leach studies to investigate uranium transport. *Photo by Bonnie A. Frey in October 2014.*

Figure 16. Outcrop in St. Anthony mine, October 2015, which shows the Dakota Formation lying unconformably above the Jackpile Sandstone of the Morrison Formation. A white arrow indicates the contact. The white hue of the sandstone immediately below the base of the Dakota is likely due to kaolinite "dusting" on the Jackpile sand – this is a common feature of the Jackpile. Bruce Thomson is standing on lower Jackpile Sandstone beds in mine-pit floor. *Photo by Bonnie A. Frey.*

Figure 17. St. Anthony mine west pit viewed from the west–southwest. Waste piles are visible behind the pit. The cumulative production of the mine from 1953–1960 was 2.5 million pounds of U_3O_8 with a production grade of 0.17% U_3O_8. Vanadium was also recovered. The historic resource estimate was about 3.9 million tons of ore (McLemore et al., 2013). *Photo by Bonnie A. Frey in October 2015.*

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