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SANDSTONE-HOSTED URANIUM DEPOSITS AT THE CEBOLLETA LAND GRANT, CIBOLA COUNTY, NEW MEXICO

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ABSTRACT—The Cebolleta Land Grant of west-central New Mexico is the site of five sandstone-hosted uranium deposits that represent the northeastern extension of the prolific Jackpile–Paguate uranium mineralized zone and the northern part of the Laguna mining district. The uranium mineralization at Cebolleta, which is hosted in the Jackpile Sandstone Member of the Upper Jurassic Morrison Formation, has been extensively delineated by more than 1,000 drill holes, two open pit mines, and three underground mines. The mineralization occurs as a series of generally tabular-shaped bodies that were deposited within various lenses of the Jackpile Sandstone. Individual uranium deposits at the land grant exhibit many of the characteristics of *primary*, *redistributed*, and *remnant* types of uranium deposits that are hosted in the Westwater Canyon Member of the Morrison Formation elsewhere within the Grants Mineral Belt. Coffinite and minor uraninite are the principal primary uranium minerals in the deposits. Secondary uranium minerals, which are the result of post-mining oxidation of the primary coffinite and uraninite-rich zones, are exposed in the two former St. Anthony open pits. Significant unmined uranium mineralization is present in the area of the former mines, between and adjoining the now inactive St. Anthony and JJ#1 mines, and extending to the northeast of the former mines.

INTRODUCTION

The Cebolleta Land Grant (La Merced del Pueblo de Cebolleta) is a former Spanish land grant that is located in northeastern Cibola County, New Mexico, 45 mi (72 km) west of the city of Albuquerque and 10 mi (16 km) north of the Pueblo of Laguna (Fig. 1). Situated southeast of Mount Taylor, the land grant lies in an area of mesas and valleys along the southeastern margin of the San Juan Basin.

The land grant, which hosts five significant sandstone-hosted uranium deposits (St. Anthony, Area I, Area II, Area III and Area V) in the northern part of the Laguna mining district (Fig. 2), is positioned near the southeastern end of the prolific Grants Mineral Belt, one of the largest concentrations of sandstone-hosted uranium deposits in the world, and has been the single largest source of uranium production for the United States (Turner-Peterson et al., 1986; Dahlkamp, 1993; Cuney and Kyser, 2008). The mineral belt encompasses five uranium mining districts in the southern part of the San Juan Basin, from the Laguna area, near its southeastern end, northwesterly for a distance of nearly 100 mi (160 km) to the vicinity of the town of Gallup. Collectively, mines in the mineral belt have produced in excess of 340 million pounds of U_3O_8 (McLemore, 2010) between 1948 and 2002. Readers will note that our use of the term "Grants Mineral

Belt" (i.e., Brookins, 1975, 1979; Fitch, 1979; Saucier, 1976) to describe the regional concentration of sandstone-hosted uranium deposits in the area between Gallup on the northwest and Laguna on the southeast is not universally applied. Various other researchers have utilized the terms "Grants Uranium Region" (i.e., Kelley, 1963; Rautman, 1979; Dahlkamp, 2010) or
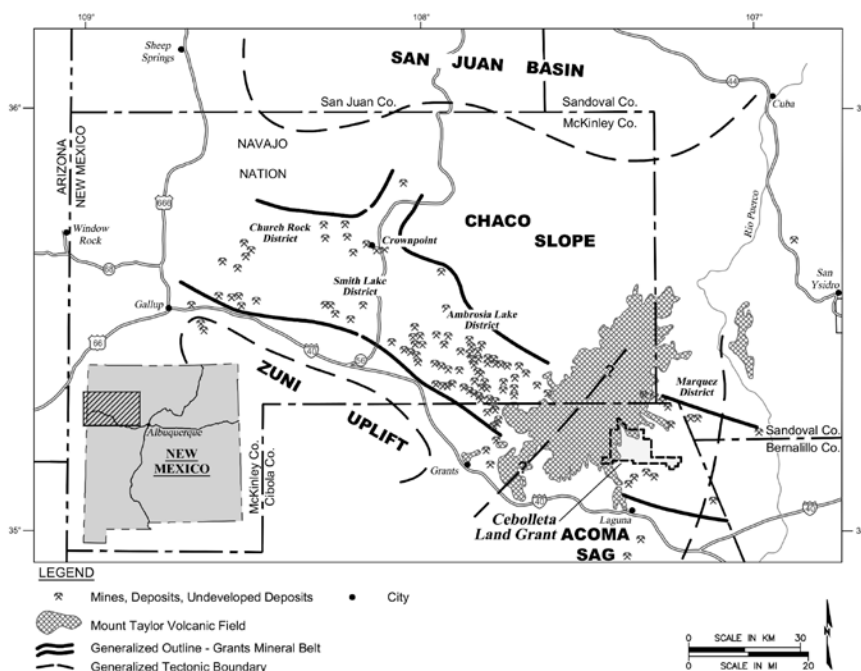

FIGURE 1. West-central New Mexico map. Cebolleta Land Grant situated at the southeast end of the Grants Mineral Belt. Map depicts tectonic features of the region. See section about geologic setting for more details.
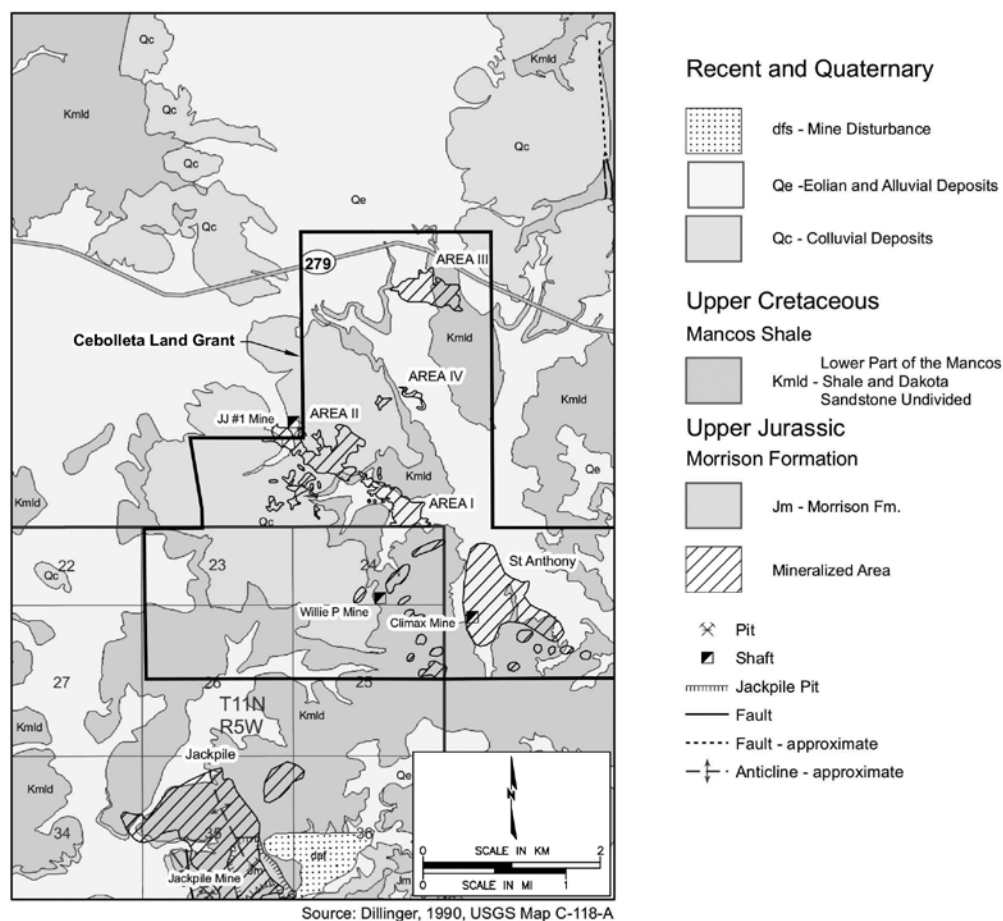
FIGURE 2. Generalized geologic map of the Cebolleta Grant and adjoining part of the Laguna Mining District. Uranium deposits outlined in hachures (geology modified from Dillinger, 1990b).

"Grants Uranium District" (i.e., McLemore, 2010; McLemore and Chenoweth, 1991; McLemore, et al., 2013) to describe this mineralized region. The same holds true for the more localized concentrations of uranium deposits within the Grants Mineral Belt, such as the Laguna Mining District, where the term "mining district" has been used by many authors (i.e., Moench and Schlee, 1967; Adams et al., 1978; Baird et al., 1979; Jacobsen, 1979), while others have applied the term "subdistrict" for the more localized concentrations of uranium deposits (i.e., McLemore, 2010; McLemore and Chenoweth, 1991). We use the term "Grants Mineral Belt" to delineate the regional concentration of uranium deposits in the southern part of the San Juan Basin.

Uranium mineralization at the Cebolleta Land Grant occurs as a series of tabular bodies hosted within the Jackpile Sandstone Member of the Upper Jurassic Morrison Formation. Historical uranium production from the land grant was derived from three underground and two open-pit mines, and significant uranium resources remain in the area.

MINING HISTORY

Exploration for uranium deposits in the Laguna mining district, which includes a portion of the Cebolleta Land Grant,

commenced in 1951, when surface exposures of high-grade uranium mineralization were discovered by the Anaconda Copper Co. (Beck et al., 1980) on a portion of the Laguna Pueblo lands contiguous with the southern boundary of the Cebolleta Land Grant. Anaconda's identification of mineralized outcrops led to the discovery of the Jackpile and Paguate uranium deposits, which were subsequently developed into the largest uranium mine complex in the United States. Concurrent with the development of the Jackpile open pit mine, Anaconda conducted a regional exploration drilling program on the nearby Evans Ranch, 3 mi (5 km) northeast of the Jackpile deposit, culminating in the initial discovery of uranium mineralization in the Jackpile Sandstone that was to ultimately become the L-Bar uranium project. The Anaconda exploration program included more than 350 drill holes on the Evans Ranch, but did not advance beyond the exploration stage (Geo-Management, unpubl. report for Sohio Western Mining Co., 1972). In the late 1990s, ownership of the western part of the Evans Ranch (also known as the L-Bar Ranch) was conveyed to its former traditional property owners, the Cebolleta Land Grant.

There has been considerable uranium exploration and production on the Cebolleta Land Grant immediately northeast of the Jackpile–Paguate Mine. The first recorded commercial production of uranium on the Cebolleta Land grant was in 1951 by Hanosh Mines, Inc., who extracted 167 short tons (151 tonnes) of material that averaged 0.09% U_3O_8 (W.L. Chenoweth, pers. commun., 2016) from a small underground mine. Drilling by the Climax Uranium Co. from 1954 to 1956 resulted in the discovery of an important deposit in Section 30, T11N, R4W. Production from the resulting M-6 Mine began in July 1957 and continued until October 1960, yielding 78,555 tons (71,264 tonnes) that averaged 0.20% U_3O_8 and contained 320,647 lbs (145,443 kg) of U_3O_8 (Chenoweth, pers. commun., 2016).

In the 1970s, the United Nuclear Corp. (UNC) and its subsidiary Teton Exploration Drilling Co. carried out an extensive exploration program in the vicinity of the former Climax Mine and discovered significant and widespread uranium mineralization in the Jackpile Sandstone on lands leased from the Cebolleta Land Grant. UNC developed two small open pits and one

underground mine, known as the St. Anthony Mine Complex (Baird et al., 1980). Mining was completed at St. Anthony in late 1979, and the milling of stockpiled material continued into 1980. Total production from the St. Anthony Mines amounted to approximately 1.6 million lbs (725,747 kg) of U_3O_8 for the period 1975 through 1980 (Moran and Daviess, 2014).

Reserve Oil and Minerals acquired the adjoining Evans/L-Bar Ranch in 1968 and formed a joint venture with Sohio Western Mining. Sohio operated the joint venture and re-discovered extensive uranium mineralization on the property that was initially discovered by Anaconda in the early 1950s, leading to the development of the large-scale JJ #1 Underground Mine and a uranium mill (L-Bar project), which operated from late 1976 to mid-1981. During the life of the L-Bar project, the JJ #1 Mine produced approximately 898,600 short tons (815,000 tonnes) of material averaging 0.123% U_3O_8, yielding 2,218,800 lbs (1,006,492 kg) of U_3O_8 (Boyd et al., 1984, unpubl. report for Sohio Western Mining Co.).

Collectively, approximately 3.8 million lbs (1,723,649 kg) of U_3O_8 have been produced from uranium deposits on the Cebolleta Land Grant. Although uranium mining and processing ceased on the land grant in 1981, considerable uranium resources remain on land grant properties. Encore Energy, Inc., currently holds a mining lease from the Cebolleta Land Grant on the lands that encompass the former St. Anthony and L-Bar mines.

GEOLOGIC SETTING

The Cebolleta Land Grant is situated near the southeastern end of the Grants Mineral Belt, a northwest-southeast oriented zone of uranium deposits that are primarily hosted in various members of the Upper Jurassic Morrison Formation. The mineral belt, which is approximately 100 mi (160 km) long and up to approximately 25 mi (40 km) wide, is positioned on the Chaco Slope (Kelley, 1955) between the southern part of the San Juan Basin and the northeastern flank of the Zuni uplift and within the adjoining Acoma Sag (Fig. 1). Sedimentary rocks exposed along the trend of the mineral belt range in age from Upper Triassic through Late Cretaceous (Dillinger, 1990a, b). Jurassic sedimentary rocks of continental origin, including the economically important Morrison Formation, are exposed in a narrow band that generally parallels the northwest-trending axis of the Zuni Uplift. Cretaceous rocks, principally shales and sandstones, are exposed in the northeasterly portion of the mineral belt and unconformably overlie the Morrison Formation. Pliocene-Pleistocene volcanic rocks of the Mt. Taylor volcanic field obscure a portion of the southeastern part of the mineral belt, immediately to the west of the Cebolleta Land Grant (Moench and Schlee, 1967; Goff et al., 2015, Dillinger, 2009 b).

The Grants Mineral Belt encompasses five major mining districts (listed from southeast to northwest): Laguna, Marquez (which lies to the north of the Laguna district and contains uranium deposits hosted only in the Westwater Canyon Member of the Morrison Formation), Ambrosia Lake, Smith Lake, and Church Rock. The Grants Mineral Belt has produced more than 340 million lbs (154,221,280 kg) of U_3O_8, ranking it as one of the largest uranium-producing regions in the world (McLemore et al., 2013) and 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 (Jmw), the Poison Canyon sandstone (an informal unit of economic usage), the Brushy Basin Member (Jmb) and the Jackpile Sandstone Member (Jmj) of the Morrison Formation. Additional uranium deposits, with less significant production, are hosted on limestones of the Middle Jurassic Todilto Formation.

STRATIGRAPHY

Sedimentary rocks exposed within the Cebolleta Land Grant (Fig. 2) range in age from Late Jurassic through Late Cretaceous (Baird et al., 1980; Jacobsen, 1980; Moench and Schlee, 1967; Schlee and Moench, 1967). The Upper Jurassic Morrison Formation (Jm), is the principal host formation for uranium deposits throughout the Grants Mineral Belt. The Morrison Formation overlies rocks of the Jurassic San Rafael Group and is, in turn, unconformably overlain by the Cretaceous Dakota Sandstone (Kd), which in turn interfingers with and is overlain by the Mancos Shale (Km). The stratigraphic relationships of the various members of the Morrison Formation and underlying San Rafael Group have evolved as studies of Jurassic stratigraphic units throughout the Colorado Plateau region continue to be studied (e.g., Lucas and Anderson, 1997; Dickinson and Gehrels, 2010; Cather, et al., 2013). The stratigraphic nomenclature in general use by mine geologists working in the Laguna district and at the Cebolleta Land Grant uranium deposits is depicted in Figure 3 and is the convention used in this paper.
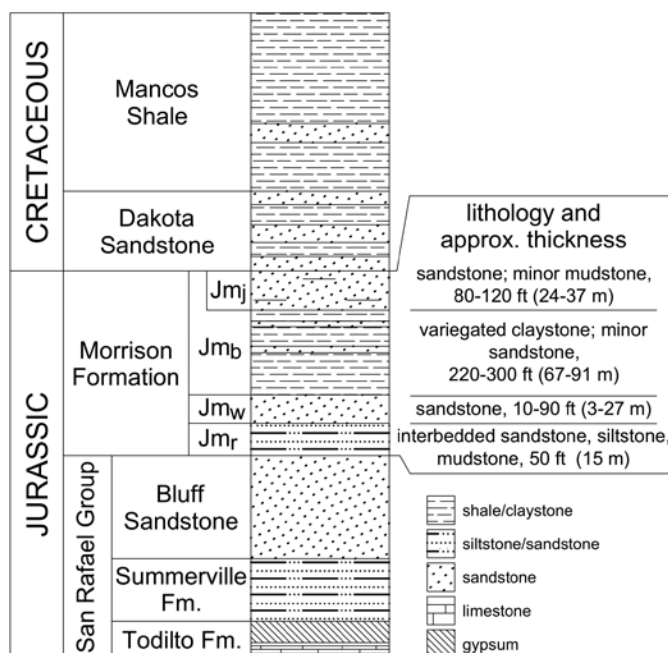

FIGURE 3. Stratigraphic column for the Cebolleta Land Grant with Morrison Formation nomenclature used in this paper (modified from Rautman, 1980).

The Morrison Formation is comprised of four distinct members in the area of the Cebolleta Land Grant (in ascending order): Recapture (Jmr), Westwater Canyon (Jmw), Brushy Basin (Jmb) and Jackpile Sandstone Members (Jmj). The basal unit of the Morrison Formation is the Recapture Member, which is approximately 50 ft (15 m) in thickness in the Laguna area (Moench and Schlee, 1967). Moench and Schlee (1967) describe it as a sequence of interbedded mudstone, siltstone, sandstone and minor limestone, grayish-red on weathered exposures, while fresh exposures of the various lithologies are gray (limestone), grayish-green (mudstone), and grayish-yellow (sandstone). The Recapture Member is not exposed on the Cebolleta Land Grant.

Overlying the Recapture member is the Westwater Canyon Member, which is the principal host for sandstone-hosted uranium deposits throughout much of the Grants Mineral Belt. In the area of the Cebolleta Land Grant, it ranges in thickness from 10 to 90 ft (3 to 27 m) and is comprised principally of grayish-yellow to pale orange sandstones, with a thin (3 ft) interval of greyish-red siltstone dividing it into upper and lower units. The Westwater Canyon sandstones are generally poorly sorted, range from fine to coarse grained, and are sub-arkosic to arkosic in composition (Moench and Schlee, 1967).

Overlying the Westwater Canyon is the Brushy Basin Member, which ranges in thickness from 220 to approximately 300 ft (67 to 91 m). The Brushy Basin is a visually distinctive unit comprised dominantly of variegated mudstone, claystone and shale, with lesser sandstone beds near the base that are hosts for uranium mineralization in the Ambrosia Lake, Smith Lake and Church Rock mining districts.

Overlying the Brushy Basin is the uppermost member of the Morrison, the Jackpile Sandstone Member (Owen et al., 1984; Aubrey, 1992). The Jackpile Sandstone is a light gray to white sandstone that forms vertical exposures. Within the Cebolleta Land Grant, exposures of the Jackpile Sandstone are limited to narrow bands along the base of Gavilan Mesa, south of the St. Anthony Mine, and in Arroyo Pedro Padilla, east of the St. Anthony Mines. It is a visually distinctive sandstone unit that is the host for the major uranium deposits at the former Jackpile–Paguate, Woodrow, St. Anthony, and L-Bar mines. Overall, the thickness of the Jackpile Sandstone ranges from approximately 80 to 120 ft (24 to 37 m) as determined from exploration drill holes and from exposures in the Willie P Underground Mine (Baird et al., 1980) and the JJ#1 Mine (Jacobsen, 1980).

The contact between the Brushy Basin and the Jackpile members is gradational to scoured in some locations (Owen et al., 1984). The Jackpile Sandstone interfingers with the uppermost part of the Brushy Basin Member in the Willie P Mine (Baird et al., 1980) and at the head of Oak Canyon (SW1/4 sec.10, T10N, R5W), about 2 mi southeast of the village of Paguate (Schlee and Moench, 1963b). The areal extent of the Jackpile is limited to the southeastern-most end of the Grants Mineral Belt and the southeastern part of the San Juan Basin and the Chama Basin (Owen et al., 1984).

At the Cebolleta Land Grant, the Jackpile Sandstone ranges from subarkosic to arkosic in composition (Moench and Schlee, 1967, Owen et al., 1984), with minor lenses of quartzose sand-

stone in the upper portion of the unit in the St. Anthony south pit (Caldwell, 2019). Individual sandstone lenses are generally dominated by fine- to medium-grained, pervasively cross-bedded, sub-arkosic sands, with local lenses of coarse-grained sands. Correlation of individual sandstone lenses throughout the Jackpile Sandstone is difficult, due to abundant channel features that routinely cut into underlying sandstones or lateral sandstone lenses. As such, the Jackpile Sandstone displays a high degree of variability, both laterally and vertically, as demonstrated in the former JJ #1 Mine and the St. Anthony south pit. In the JJ#1 Mine, the Jackpile has been subdivided into upper and lower units (FitzGerald et al., unpubl. report for Sohio Western Mining Co., 1979), with the upper unit comprised primarily of quartzose sandstone with essentially no mudstone lenses, and the lower unit comprised of subarkosic 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 dominantly sandstone with few mudstone lenses. The Jackpile Sandstone was deposited in a braided-stream environment (Owen et al., 1984).

Overall, the Jackpile is a white to light gray/light tan sandstone, locally exhibiting a pinkish hue where feldspar content is relatively high. The white to light gray coloration is a distinctive characteristic of Jackpile Sandstone exposures throughout the Laguna district, including exposures in the St. Anthony north pit. In contrast, exposures in the St. Anthony south pit, which is approximately 2500 ft (760 m) southeast of the north pit, are tan to light gray to pale orange in color, due to post-depositional oxidation. Minor zones of hematite and limonite staining impart slight red to orange casts in the vicinities of some mineralized zones in both open pits.

Individual sandstone lenses are cemented primarily with kaolinitic clay in the middle and upper parts of the unit, and to a lesser extent by quartz and calcite, primarily in the lowermost part of the unit (Moench and Schlee, 1967). Alteration of the sandstones is manifested primarily by the partial conversion of feldspar to kaolinite. Accessory minerals include trace amounts of pyrite (Baird et al., 1980; Caldwell, 2019), zircon, tourmaline, garnet, and rutile. Nash (1968) noted, from exposures at the Jackpile Mine, that biotite, amphibole, magnetite and pyroxene are generally absent.

Baird et al. (1980) discuss two types of carbonaceous material within the Jackpile Sandstone in the Willie P Underground Mine. They reported the presence of carbonaceous material "coalified *in-situ*" and as "sand-sized material" interstratified in cross-beds. They also reported the presence of humate, occurring primarily as pore fillings between sand grains. Carbonaceous material (humate) is present in limited exposures along the south wall of the St Anthony north pit and locally in the south pit, primarily in proximity to zones of uranium mineralization. This material occurs as small (2 to 6 in, 51 to 152 mm), sparse, poorly developed, sub-vertical rod-shaped features, as amorphous masses, and as local accumulations of carbonaceous detritus on bedding planes near the bases of individual sandstone lenses. An anonymous report (1977) describes lithologies intersected by an exploration shaft at the St. Anthony north pit as similar vertical "carbon rods" in one mineral-

ized zone. The overall content of carbonaceous material in the open pit mines, either in the form of plant debris or as humate, is very low when compared to descriptions from the Willie P and JJ#1 mines, thereby providing support that the uranium mineralization in these areas is remnant in nature (south pit) and redistributed (north pit). In the JJ#1 Mine, carbonaceous material is present as plant detritus and humate accumulations. In contrast, Jacobsen (1980) reported that for the trend-type deposit at the JJ#1 Mine no significant uranium mineralization occurred where carbonaceous material was absent.

The Cretaceous Dakota Sandstone unconformably overlies the Jackpile Sandstone and is a light grey to pale tan quartzose sandstone with lenses of black carbonaceous shale. Exposures of the Dakota in the north and south pits range from 6 to about 10 ft (1.8 to 3 m) in thickness.

STRUCTURE

The Cebolleta Land Grant and the adjoining Jackpile–Paguate Mine lie within the Acoma Sag (Kelley, 1955; Nash, 1968), near the southeastern end of the Chaco Shelf. The Acoma Sag is 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 (Kelley, 1955). Structure within the sag is relatively simple, with rocks displaying shallow dips and small folds that generally trend to the northwest (Woodward, 1982).

Rocks on the Cebolleta Land Grant dip gently to the north and northwest toward the San Juan Basin, at less than 2 degrees. Faults with significant offset have not been recognized in the project area, although several small-scale, high-angle faults were observed in the workings of the former JJ #1 Underground Mine (Jacobsen, 1980) and minor north-trending normal faults were mapped in the Lobo Mountain area (Schlee and Moench, 1963 b). The faults observed in the JJ#1 Mine do not appear to have offset uranium mineralization, nor do they appear to have influenced the localization of mineralization (Jacobsen, 1980).

A very small fold, or structural dome, was identified in the southern part of the Willie P Underground Mine. A second, larger northeasterly-trending fold is present in the area of the Lobo Camp 3 mi (4.8 km) northeast of St. Anthony (Schlee and Moench, 1963 a). Overall, however, there is little in the way of deformation of rocks of the Laguna district (Moench and Schlee, 1967).

URANIUM MINERALIZATION

Nearly all of the uranium deposits in the Grants Mineral Belt (which includes the Cebolleta Land Grant) occur as sandstone-hosted deposits in fluvial clastic rocks of the Upper Jurassic-age Morrison Formation. Three general types of sandstone-hosted deposits have been recognized by workers in the mineral belt (Kittel et al., 1967; Granger and Santos, 1986):

- Primary deposits, which have also been described as trend or pre-fault deposits. They are broad, undulatory layers of uranium mineralization controlled primarily by the texture or fabric of the host sandstones.

Mineralization in primary deposits is localized around accumulations of humate and carbonaceous plant debris that served as reductants to precipitate dissolved uranium from ground water;
- Redistributed deposits, which are also referred to as post-fault, stack, or secondary deposits, are irregularly shaped bodies of mineralization that were controlled by both the stratigraphic characteristics of the host rocks and faults, fractures and/or joints. Redistributed deposits result from oxidation and remobilization of uranium derived from primary deposits. Redistributed deposits have little or no humate associated with the mineralization; and
- Remnant deposits are, as the name implies, remnants of primary deposits that have been partially to nearly totally mobilized and redistributed. Remnant deposits tend to be discrete bodies of mineralization entirely enclosed within otherwise oxidized host rocks. Mineralization is often localized by small accumulations of carbonaceous material.

While this classification of sandstone-hosted deposits is based on the characteristics of uranium mineralization in the Westwater Canyon Member of the Morrison Formation, it applies to Jackpile Sandstone-hosted deposits with two important caveats: 1) the geometry of primary deposits in the Jackpile Sandstone do not necessarily reflect the overall geometry or architecture of individual Jackpile Sandstone channel sands or individual lenses, whereas 2) primary deposits hosted in the Westwater Canyon commonly reflect the overall orientation
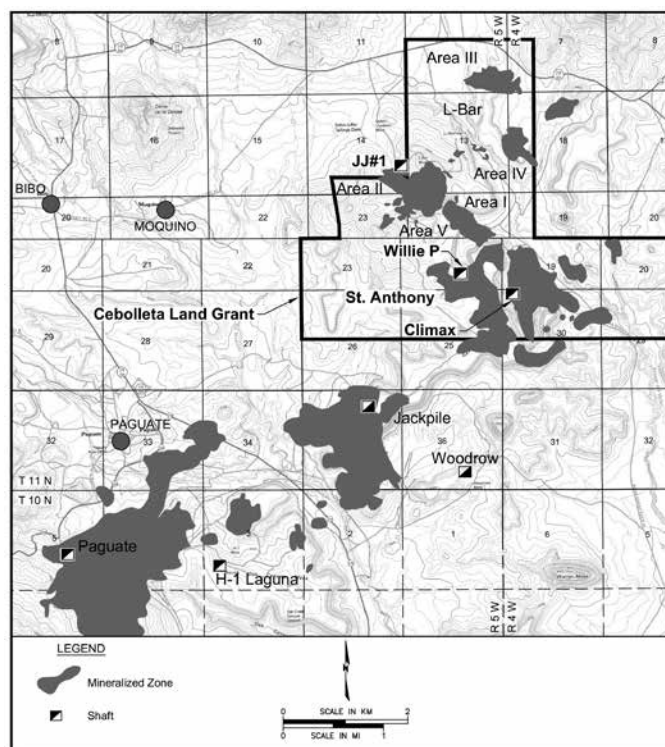

FIGURE 4. Uranium deposits of the Cebolleta Land Grant and adjoining areas of the Laguna Mining District. Areas depicted in gray are uranium deposits.

of the sandstone bodies (Jacobsen, 1980; Wilton, 2017). In addition, redistributed deposits in the Jackpile Sandstone at the Cebolleta Land Grant area are not localized along faults or fractures as is the case with Westwater Canyon-hosted redistributed deposits.

Uranium deposits in the Jackpile Sandstone range from moderate to large size, as demonstrated by the Jackpile and Paguate deposits, which are contiguous with the south boundary of the Cebolleta Land Grant (Fig. 4). The Jackpile deposit is more than 10,000 ft (3 km) long and averages 2000 ft (609 m) wide. Individual mineralized lenses rarely exceed 15 ft (4.5 m) in thickness, but the aggregate thickness of several "stacked" layers range up to 50 ft (15 m). Moench (1963) described the Jackpile Mine uranium deposits as "composed of one or more semi-tabular layers." In plan view, individual mineralized lenses range from nearly equant to strongly elongate. Viewed in vertical section, the mineralized intervals are suspended within sandstone intervals; only locally do they extend to stratigraphic discontinuities such as prominent mudstone beds, diastems, or formational contacts. The overall characteristics of mineralized zones in the St. Anthony and L-Bar deposits on the Cebolleta Land Grant are similar to the Jackpile and Paguate deposits, although the sizes of individual deposits are less, ranging from 500 to 1000 ft (152 to 305m) in width and from 2000 to 3000 ft (610 to 910 m) in length.

While Dahlkamp (2010) attributes the source of uranium in the Laguna mining district and Cebolleta Land Grant to the mobilization of uranium from either granitic rocks of the ancestral Mogollon highlands (southwest of the Cebolleta Land Grant) or from the devitrification of tuffaceous rocks contained in the host sandstones and particularly in the Brushy Basin Member, it is our opinion that deriving uranium from the underlying Brushy Basin Member is unlikely. However, there has been long-lived debate among uranium geologists as to the source(s) of uranium in sandstone-hosted deposits, and definitive proof of the source of the metal has yet to be established. Ultimately, uranium minerals were deposited in the host sandstones, where chemical reactions (reduction) associated with humic acids derived from plant material caused precipitation of dissolved uranium from the groundwater (Adams and Saucier, 1981).

As currently defined, there are five significant uranium deposits at the Cebolleta Land Grant (Fig. 4):

1. Area I and its southeastern extension,
2. Area II and V (including the former JJ#1 L-Bar Mine),
3. Area III,
4. St. Anthony north and south pits, and
5. Willie P (St. Anthony underground).

The uranium deposits on the Cebolleta Land Grant share a common set of geological characteristics:

- Economically significant mineralization is hosted by the Jackpile Sandstone, although minor mineralization is hosted in sandstones of the Brushy Basin Member and the Dakota Sandstone;
- Most of the mineralization is hosted in medium- to coarse-grained sandstones that exhibit large-scale tabular cross-stratification (Baird et al., 1980);
- Near the margins of the deposits, the mineralization

thins appreciably, although halos of low-grade mineralization may surround deposits;
- Higher grade mineralization usually occurs in the centers of the mineralized zones;
- Although mineralization is present throughout the entire stratigraphic sequence of the Jackpile Sandstone, the strongest mineralization is concentrated in the lower part of the unit (Jacobsen, 1980; Wilton, 2017);
- Individual deposits do not show an overall preferred orientation or trend and do not reflect the regional northeasterly orientation of the main Jackpile Sandstone channel trend; and
- The primary deposits are associated with amorphous carbonaceous material and humate (Nash, 1966; Piette, 1970; Baird et al., 1980; Jacobsen, 1980; Caldwell, 2019). At the JJ#1 Mine, no meaningful concentrations of uranium mineralization occur without associated carbonaceous material (Jacobsen, 1980). It should be noted, however, that the remnant and redistributed deposits, as exposed in the two St. Anthony open pits, do not have appreciable amounts of carbonaceous material associated with them.

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. Mineralization in the north pit is more pervasive in individual sandstone lenses, is associated with minor concentrations of humate and other carbonaceous plant debris and is redistributed mineralization. In the JJ#1 Mine and Area I and Area III, trend-type uranium deposits occur as tabular bodies that may be more than 1,000 ft (305 m) in length and attain thicknesses of 6 to 12 ft (1.8 to 3.7 m). The upper and lower boundaries of these mineralized bodies are generally abrupt. There is a tendency for individual deposits to develop in clusters. Locally, these clusters are 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 former mine operators (Geo-Management, unpubl. report for Sohio Western Mining Company, 1972; Olsen and Kopp, unpubl. report for Sohio Western Mining Company, 1982) demonstrate that radiometric and chemical assay methods generally yield comparable results (Wilton, 2017). Evaluation of samples from 47 core holes at St. Anthony, however, indicated that chemical analyses yielded somewhat higher grades than radiometric assays indicate. As such, the mineralization at the Cebolleta Land Grant is considered to be in radiometric to chemical equilibrium.

Exploration drilling north of the St. Anthony Mines delimited four substantial uranium deposits, the Area I, Area II and V, and Area III deposits. Mining by Sohio was restricted to parts of the II and V deposits (JJ #1 Mine). The Area I deposit, located in the southern end of the L-Bar complex, 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. Two of the former Sohio (L-Bar) uranium deposits, the Area I and Area III deposits, which host

substantial mineral resources and are excellent examples of trend-type mineralization are described below.

Area I Deposit

At the Area I deposit, grade, thickness, and GT (grade times thickness) contour maps were prepared for each of the mineralized horizons. Uranium grades were calculated from gamma-ray logs (down-hole geophysical logging) with grades denoted as weight percent "eU_3O_8" (where "e" denotes "equivalent" U_3O_8 as determined from radiometric assays rather than chemical assaying methods). Four distinct and separate mineralized horizons were identified in the Area I deposit – "upper", "middle", "lower", and "basal" zones.

Mineralization in the middle zone is a broad, southeast-northwest trending body that is 600 to 800 ft (183 to 244 m) wide and approximately 900 ft (274 m) long. Drill-hole intersections of mineralized zones, using a GT cut-off value of 0.5, indicate that the horizon averages 10.2 ft (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 150 to 400 ft (46 to 122 m) wide and approximately 2400 ft (731 m) long. This mineralized interval at a 0.5 GT cut-off averages 9.8 ft (2.98 m) thick with an average grade of 0.153% eU_3O_8.

The mineralized zones appear continuous throughout the Area I deposit. As well, the Area I deposit has a higher frequency of thin, less continuous mineralized horizons than are observed at other deposits. The higher average grades and more laterally continuous uranium mineralization are hosted in the middle and lower zones at the Area I deposit.
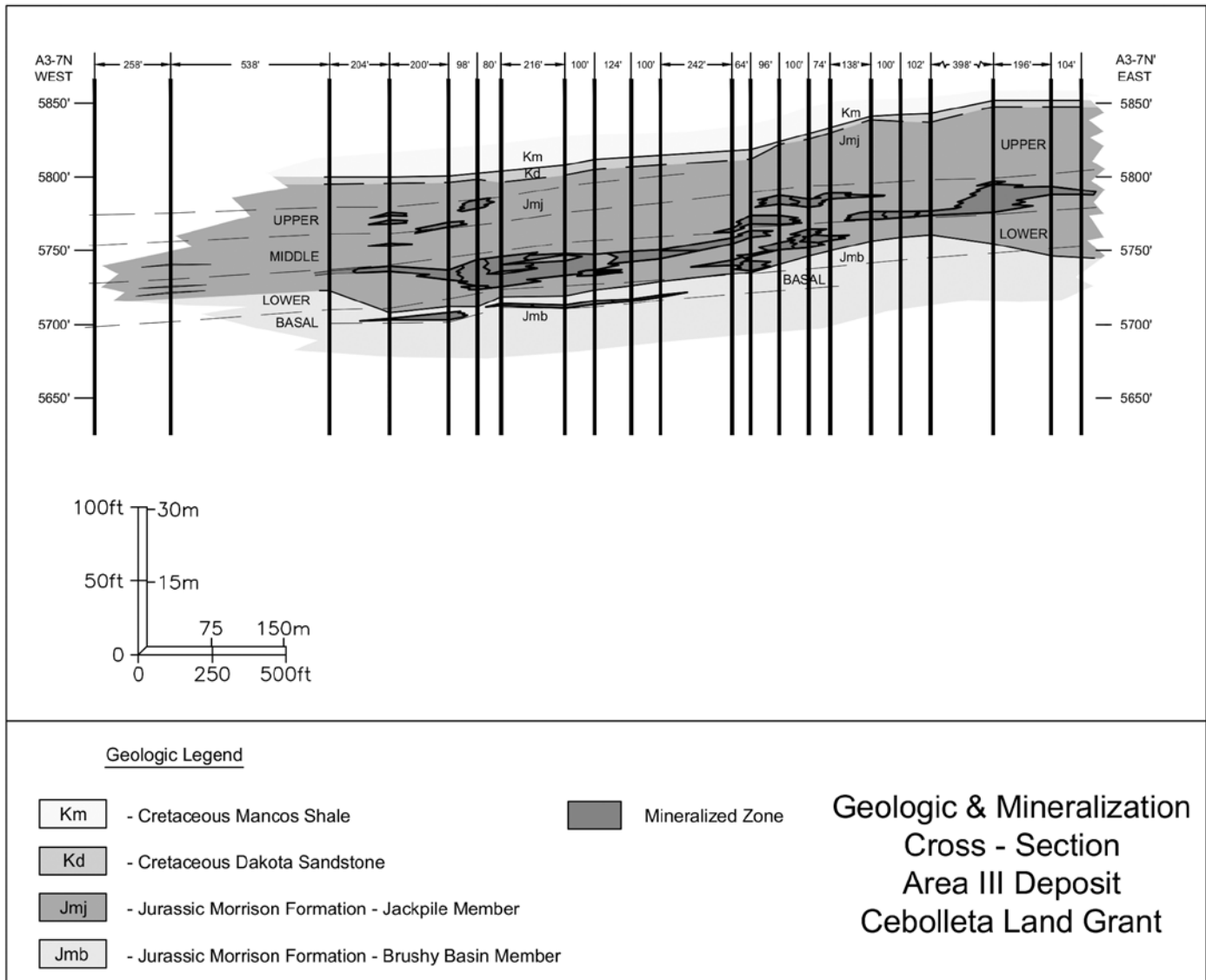

FIGURE 5. East-west cross section (looking north) of the Area III Uranium Deposit. Geologic units and mineralized intervals identified from drill-hole gamma-ray/self-potential and resistivity logs. The "lower" mineralized zone demonstrates lateral continuity over a distance of more than 1,300 ft (396 m) at grades of 0.10% eU_3O_8 or greater (The "e" in eU_3O_8 denotes "equivalent" U_3O_8 as determined from radiometric assays rather than chemical assaying methods).
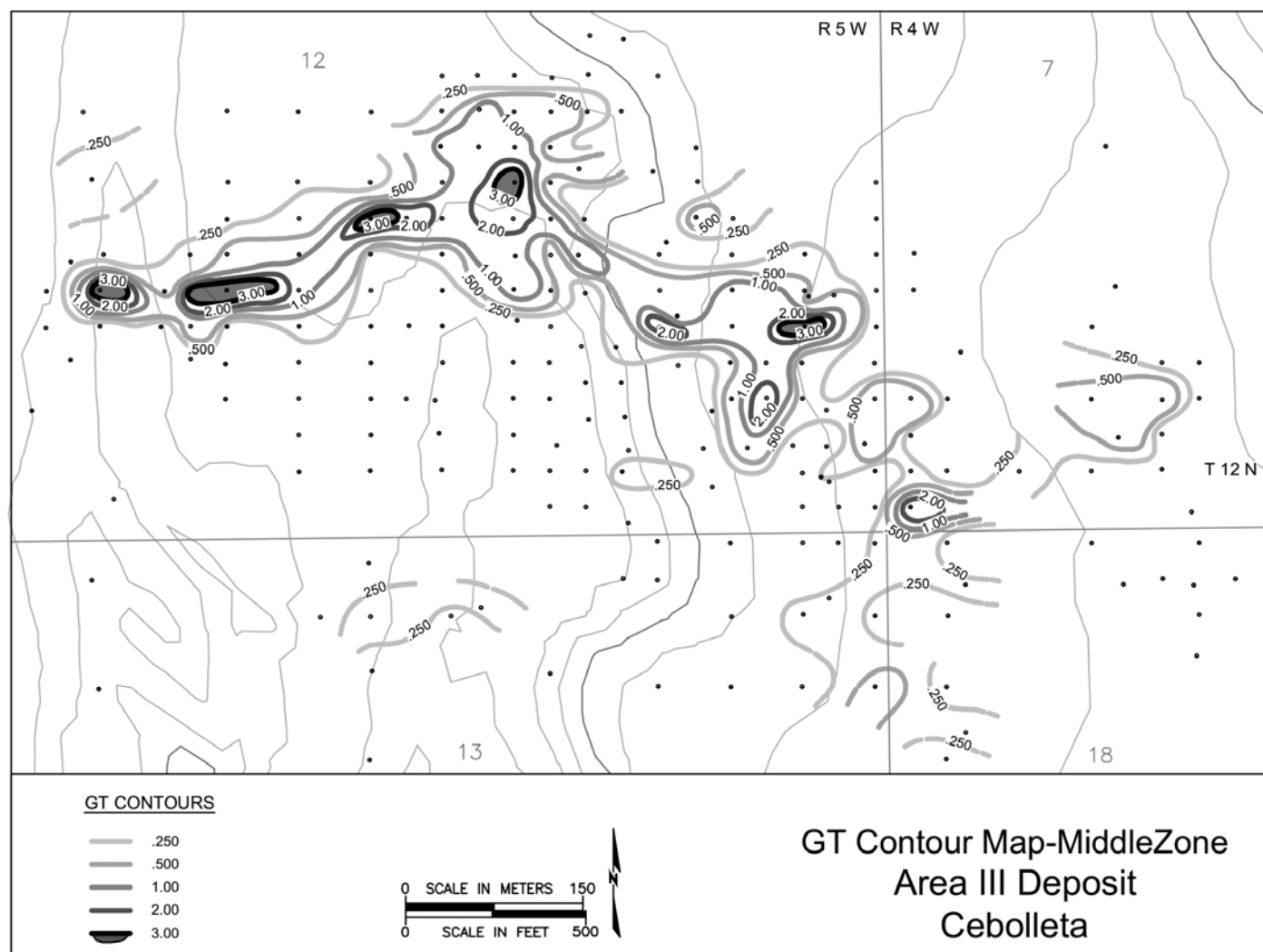
FIGURE 6. Grade times thickness (GT) contour map of the "middle" mineralized zone, Area III deposit. The "middle zone" at Area III demonstrates good lateral continuity of mineralization in a general east-west direction at a GT cut-off of 0.50 (ft-% eU$_3$O$_8$).

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 geophysical logs (Fig. 5). Mineralization is continuous in tabular or lenticular bodies 2 ft (0.6 m) to more than 30 ft (9 m) in thickness. Grades greater than 0.10 % eU$_3$O$_8$ are commonly present, with numerous intercepts of 0.20% eU$_3$O$_8$ or greater. This mineralization occurs throughout the entirety of the Jackpile Sandstone, which is 80 to 100 ft (24 to 30 m) thick.

Area III mineralization, as at Area I, was assigned to four intervals, again designated as the upper, middle, lower, and basal zones (Fig. 5). The better and more laterally continuous mineralized bodies are in the middle and lower zones in the Jackpile Sandstone. Mineralization is also present in the Brushy Basin Member at and immediately beneath the lower contact of the Jackpile Sandstone, in the basal zone.

Mineralization in the middle zone (Fig. 6) occurs in an arcuate, east-west trending, elongate body that is 200 to 500 ft

(61 to 152 m) wide and approximately 2100 ft (640 m) long (Fig. 6). A composite of mineral intercepts at a 0.5 GT cut off averages 8.3 ft (2.5 m) in thickness at an average grade of 0.183% eU$_3$O$_8$. Mineralization in the lower zone is represented by a continuous, lenticular, east-west trending body that is 300 to 500 ft (91 to 152 m) wide and approximately 2,200 ft (670 m) long. A composite of mineral intercepts at a 0.5 GT cut off averages 10.2 ft (3.1 m) thick with an average grade of 0.172% eU$_3$O$_8$.

The Area I and Area III deposits display certain similar geologic characteristics, including four mineralized horizons and similar lengths, widths and thicknesses. Grade variations between the middle zone in the two deposits is appreciable, as is the sinuous nature of the lower mineralized zone in the Area I deposit. The continuity of mineralization the lower zone of the Area III deposit is in marked contrast to that of the Area I deposit and the mineralization in the St. Anthony area. As such, it is an excellent example of the mode of occurrence of trend-type mineralization in the Cebolleta area.

Controls on Mineralization

Principal controls on uranium mineralization on the Cebolleta Land Grant are primary sedimentary structures, including channel fills, bars and cross-bedding in the Jackpile Sandstone (Jacobsen, 1980; Baird et al., 1980). In the primary deposits, concentrations of carbonaceous material (humate and/or carbonaceous plant debris) served as reductants that precipitated uranium from circulating ground water. The distribution of carbonaceous material tends to be localized, as observed in the former JJ#1 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 et al., 1980) in the former Willie P Mine. However, this relationship is not well developed in low grade (0.03% to 0.06% U_3O_8) mineralized areas currently exposed in the St. Anthony north and south pits. This reflects the remnant nature of mineralization in the south pit and the redistributed nature of mineralization in the north pit. As such, the uranium-precipitating mechanism for this part of the Cebolleta Land Grant remains to be determined.

Baird et al. (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 Mine. Similar relationships between uranium mineralization and sedimentary features 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 the Cebolleta Land Grant), there is no similar trend to individual uranium deposits. Baird et al. (1980) state that there is an apparent northwest trend with respect to mineralization in the St. Anthony area. This northwest trend, which was not observed by Sohio geologists at the former JJ #1 Mine (Jacobsen, 1980), may have resulted from the erosional retreat of the Jackpile Sandstone outcrop (Baird et al., 1980) and the subsequent oxidation and redistribution of uranium mineralization closer to the outcrop. Additional analyses of drill-hole data and contouring of grade-thickness products for the un-mined uranium deposits in the L-Bar portion of the Cebolleta Land Grant do not indicate any discernable regional trend to mineralization, but deposit-scale trends were observed from this work.

MINERALOGY

Coffinite [$U(SiO_4)_{1-x}(OH_{4x})$] and uraninite (UO_2) are the principal uranium minerals in the primary and redistributed mineralized zones at the St. Anthony deposits (Moench and Schlee, 1978; Robertson and Associates, unpubl. report for Sohio Western Mining Company, 1978; Adams et al., 1978). Organo-uranium complexes have also been reported from St. Anthony (Baird et al., 1980), although these mineralized zones may also contain weakly crystalline coffinite as the principal uranium mineral. Several samples collected from the St. Anthony north and south pits, including a high-grade pod of remnant mineralization in the north highwall of the south pit, yielded samples containing fine-grained and weakly crystalline coffinite as the principal uranium mineral, with minor uraninite overgrowths (Caldwell, 2019), as identified by polished section and XRD analysis (Caldwell, 2019).

Post-Mine Stability of Uranium Minerals

Assessment of uranium minerals hosted in Jurassic-age continental arkosic sandstones of the Jackpile Sandstone Member, exposed in former open-pit mine subcrops of the St. Anthony north and south pits, shows that post-mine, weathering-derived replacement of reduced uranium minerals has locally modified such minerals to a series of variably-hydrated, highly-oxidized derivatives (Caldwell, 2019).

Because uranium minerals, especially carbonates and sulfates, are soluble under weakly- to low-pH conditions (Brugger et al., 2015), the development of such minerals identified in this study and that of Caldwell (2019) at St. Anthony, following open pit mining, indicates that hydrated sulfate and carbonate minerals were engendered through reaction of reduced uranium minerals with oxidizing, near-neutral pH regional groundwaters. The presence of kaolinite and illite suggest that these minerals are likely part of the original uranium-mineralization suite, as each of these minerals represent at least weakly-acidic solution compositions (e.g., Anderson, 1982).

Reduced Uranium Minerals

X-Ray diffraction analyses of surface and near-surface mineralized samples (see next paragraph) indicate that "coffinite" [generally $U(SiO_4)_{1-x}(OH)_{4x}$] and poorly-crystalline "uraninite" are present locally as geochemically residual reduced uranium minerals. Pyrite is identified in trace amounts, and only locally. These reduced minerals are considered to represent original uranium distribution at St. Anthony in our assessment of post-mining geochemical reactions.

St. Anthony Post-Mining Uranium Minerals

To assess the effects of post-mining oxidation on the reduced and partially oxidized ore minerals in the St. Anthony mine, surface and very near-surface samples were collected from former open pit mine exposures; samples generally comprised crusty to efflorescent patches of gaudy cream-yellow to greenish-amber minerals that displayed anomalous radioactive signatures. Some grey, interstitial mineralization was also sampled so as to represent likely reduced uranium occurrence. No woody or obviously organic material was observed in our sample traverses at St. Anthony.

Although it is acknowledged that uranium dissolution and mobility is enhanced in groundwaters characterized by near-neutral pH and elevated carbonate activity (e.g., see Eröss, et al., 2018; uranium mobile as UO_2^{++}(aq); vanadium mobile as vanadate oxyanion VO_4^{+3}(aq) (e.g., see Gustaffson, 2019)), St. Anthony mineral assemblages, which include patchy to interstitial gypsum (Caldwell, 2019), suggest that Ca^{++}(aq) activity was likely too great to permit spatially-significant uranium mi-

gration; instead, we suggest that reduced and partially-oxidized uranium minerals were oxidized and variably hydrated *in-situ* with nominal lateral uranium transport. We also acknowledge that this apparent lack of lateral migration may be a function of time such that geographically-significant post-mining uranium re-distribution is not as yet evident.

Post-mining uranium minerals comprise sulfates and carbonates, with scant phosphates. The most volumetrically-important St. Anthony post-mining uranium minerals as determined by Caldwell (2019) are the sulfates zippeite $[K_3(UO_2)_4(SO_4)_2O_3(OH)•3H_2O]$ and natrozippeite $[Na_5(UO_2)_8(SO_4)_4O_5(OH)_3•12H_2O]$, with minor jachymovite $[(UO_2)_8(SO_4)(OH)_{14}•13(H_2O)]$; these sulfates are associated with ubiquitous gypsum. The St. Anthony Mine host rocks, via weathering-related oxidative destruction of widespread but volumetrically minor pyrite, apparently provided the locally-derived, weakly-acidic solutions (Garrels and Christ, 1968) necessary for the development of these sulfate minerals. The occurrence of Na-zippeite, and associated uranyl Na-carbonate minerals noted below, indicates that groundwaters are characterized by high $aNa^+(aq)$ and, as indicated by widespread gypsum, high $aCa^{++}(aq)$.

Carbonate-hosted uranium minerals comprise andersonite $[Na_2Ca(UO_2)(CO_3)•6H_2O]$, cejkaite $[Na_4(UO_2)(CO_3)_3]$, and trace oswaldpeetersite $[(UO_2)_2(CO_3)(OH)_2•4H_2O]$ as efflorescent coatings and crusts on fractures along mine highwalls. Scant but widespread calcite is observed with these carbonate minerals. The occurrence of these uranyl carbonates represent the modification of reduced uranium minerals by high $aNa^+(aq)$, near-neutral pH groundwaters (e.g., see figure 1 in Xie et al., 2019; Garrels and Christ, 1968); this observation is consistent with andersonite occurrences in the Ambrosia Lake district (Section 31 Mine, Wiesenburger and Chávez, 1979) and supports the assessment that the recent groundwater modification of Cebolleta Land Grant uranium ores was provoked by near-neutral, oxidizing solutions.

Phosphate-hosted uranium comprises a series of local and volumetrically scant minerals consisting of sabugalite $[HAl(UO_2)_4(PO_4)_4•16(H_2O)]$, autunite $[Ca(UO_2)_2(PO_4)_2•10-12H_2O]$, meta-autunite $[Ca(UO_2)_2(PO_4)_2•2-6(H_2O)]$, and trace chernikovite $[(H_3O)_2(UO_2)_2(PO_4)_2•6(H_2O)]$ (Caldwell, 2019). Uranium phosphate minerals display generally limited solubility (Munasinghe et al., 2020) and represent moderately- to weakly-acidic pH weathering environments; their presence therefore suggests that locally lower-pH conditions existed during St. Anthony Mine phosphate-mineral genesis. Given the generally arkosic nature of the Jurassic-age host rocks, it is likely that St. Anthony Mine phosphate is sourced from the weathering of residual apatite.

We conclude that recent, weakly-acidic to near-neutral groundwaters characterized by geochemically high activities of $Na^+(aq)$ and $Ca^{++}(aq)$ are responsible for post-mining modification of reduced uranium ore minerals of the St. Anthony mine. Local low-pH environments were likely engendered by oxidative destruction of pyrite, permitting the development of uranyl phosphate minerals and serving as a source of sulfate. The apparent limited spatial mobility of the observed post-min-

ing sulfate, carbonate, and phosphate uranium minerals is a function of the general but time-dependent stability of these minerals in the current oxidizing open pit mine environment and the limited time since these minerals were developed upon cessation of mining.

SUMMARY

Sandstone-hosted uranium deposits on the Cebolleta Land Grant are present as *trend*, *redistributed, and remnant* type deposits throughout the 80 to 120 ft (24 to 27 m) thickness of the Jackpile Sandstone. *Trend*-type mineralization displays a strong affinity to carbonaceous material, in particular humate, while carbonaceous material is generally absent in *redistributed* and *remnant* mineralization. Coffinite and uraninite are the principal uranium minerals (Caldwell, 2019) in the deposits, whereas post-mining oxidation of mineralization has resulted on the formation of uranium-bearing sulfate and carbonate minerals.

ACKNOWLEDGMENTS

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