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THE JACKPILE-PAGUATE URANIUM MINE, GRANTS URANIUM DISTRICT: CHANGES IN PERSPECTIVES FROM PRODUCTION TO SUPERFUND SITE

Virginia McLemore[1], Bonnie A. Frey[1], Eliane El Hayek[2], Eshani Hettiarachchi[3], Reid Brown[4], Olivia Chavez[5], Shaylene Paul[6], and Milton Das[3]

[1]New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, New Mexico 87801, virginia.mclemore@nmt.edu;
[2] University of New Mexico, Department of Civil, Construction and Environmental Engineering, University of New Mexico, Albuquerque, New Mexico 87131;
[3]Department of Chemistry & Biochemistry, University of California San Diego, Gilman Drive, La Jolla, Ca, 92093;
[4]Wyoming Department of Environmental Quality, Cheyenne, Wyoming 82001;
[5]Boston University, Department of Physiology and Biophysics, Boston, Massachusetts 02118; and
[6]Navajo Technical University, Crownpoint, New Mexico 87313

Abstract—Production from the Jackpile-Paguate deposit ceased in 1982, ending one of the world's largest uranium open-pit mines of the era. Jurassic Morrison Formation fluvial deposits provided suitable hosts for humate-bearing primary, redistributed and remnant sandstone uranium deposits in the area. Mining from uranium deposits in the northern Laguna Pueblo yielded more than 95.8 million lbs of U_3O_8, making it a world class uranium deposit. However, perspectives at the mine and throughout the Grants Uranium District, once the "uranium capital of the world", have changed with time from production and economic benefits for companies, miners, businessmen, and nearby communities, like the Pueblo of Laguna, to the modern focus on remediation, understanding the mobility of uranium, and mitigating the health effects for uranium mine workers and nearby residents. Thousands of miners lived and worked in the Grants District, and although health effects were beginning to be studied at that time, the long-term environmental and health effects are only now being recognized. Today, the mine's history remains relevant, as concerns about the release of elevated uranium concentrations in groundwater from the remediated area led to the Superfund designation of the site in 2013. Coincidentally, a research effort to examine the mobility, legacy and source of uranium began that same year by a team from New Mexico Institute of Mining and Technology and the University of New Mexico. Many research efforts were concentrated on the area in and around the Jackpile-Paguate Mine, resulting in numerous relevant reports that not only identify important mobility pathways for uranium, but also define biological, chemical and physical processes between uranium, workers, nearby residents and the ecosystem.

INTRODUCTION

Jackpile-Paguate Mine, located in the Laguna Subdistrict in the eastern portion of the Grants Uranium District in Cibola County (Fig. 1), developed one of the largest sandstone-hosted uranium deposits in the world (Holen and Finch, 1982; Dalkamp, 2010; McLemore, 2020a**)**. Uranium was originally used in nuclear weapons for the Cold War between the United States and Russia, but by the mid-1960's, uranium was used mostly to fuel commercial nuclear power electric plants. During uranium mining at the Jackpile-Paguate Mine, Grants was known as "the uranium capital of the world," and uranium production and exploration in the area resulted in economic benefits for nearby communities, including the Pueblo of Laguna, Grants, Gallup and other communities. Thousands of miners lived and worked in the Grants District, and health ef-

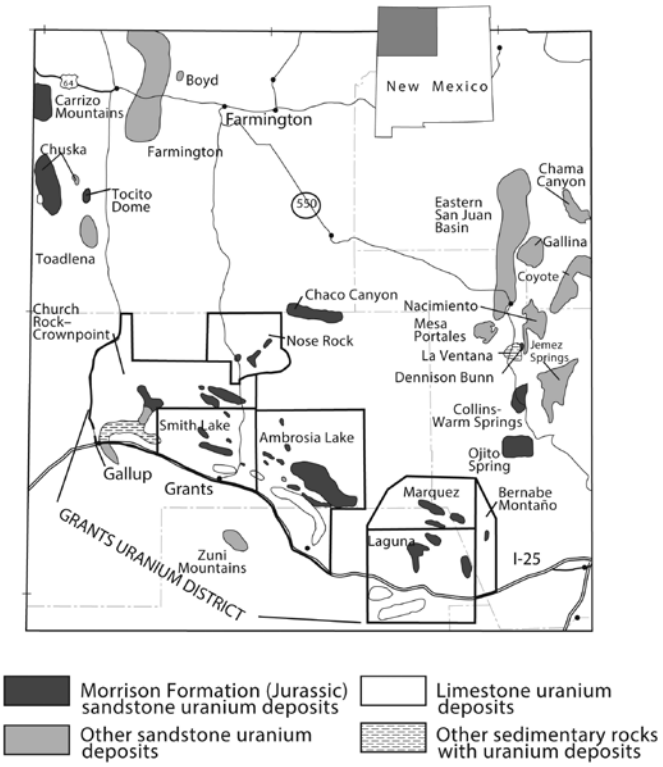

FIGURE 1. Subdistricts in the Grants Uranium District and other districts in the San Juan Basin, New Mexico with uranium deposits (McLemore and Chenoweth, 1989, 1991). Polygons outline approximate areas of known uranium deposits. See color plates on pages 89 and 90 for detailed maps.

fects were beginning to be studied at that time. Since closure in 1982, the Jackpile-Paguate Mine has been plagued with expensive environmental cleanup and serious health issues in the former workers and local population. The mine was designated a Superfund site in 2013. Today, Laguna is a Pueblo nation comprised of six villages with a population of approximately 7700, and the area has been occupied since about A.D. 1300.

The Jackpile-Paguate deposit is one of many sandstone-hosted deposits in northwestern New Mexico. Most of the economic uranium deposits in New Mexico are hosted by sandstones, and most of the uranium production in New Mexico has come from the Westwater Canyon Member of the Jurassic Morrison Formation and the Jackpile Sandstone in the Grants Uranium District in McKinley and Cibola (formerly Valencia) counties (McLemore, 1983; McLemore and Chenoweth, 1989, 1991, 2017). The Grants District represents one large area in the southern San Juan Basin, extending from east of Laguna to west of Gallup, and consists of eight subdistricts (Fig. 1; McLemore and Chenoweth, 1989, 2017). During a period of nearly three decades (1951-1980), the Grants District yielded nearly 347 million lbs of U_3O_8, almost all of New Mexico's production, and more uranium than any other district in the United States (McLemore and Chenoweth, 1989, 2017). Although there are no operating mines in the Grants District today, numerous companies have acquired uranium properties and plan to explore and develop deposits in the district in the future (McLemore et al., 2013). Meanwhile, the Jackpile-Paguate Mine is undergoing additional reclamation. The purpose of this paper is to summarize the mining/reclamation history, the geology, the mineralized deposits, and environmental studies related to this large uranium deposit.

MINING HISTORY

Uranium exploration and production in New Mexico occurred in five periods: 1) radium boom, 1918–1923; 2) vanadium production, 1926–1940's; 3) post WWII, 1948–1970; 4) uranium boom, 1970–1982; and 5) a present uranium exploration and reclamation boom, 2008–present (McLemore and Chenoweth, 2017).

The Jackpile-Paguate Mine was discovered in 1951, during the 3rd period, and production continued into the 4th period. Exploration did not resume on the Pueblo of Laguna during the 5th period; activity during this time focused on reclamation and numerous studies on environmental effects of uranium mining. Potential uranium deposits north of the Jackpile-Paguate Mine have been recently examined for future development, but no permits have been issued at the time of this publication (McLemore et al., 2013; Wilton et al., 2020).

In 1951, the Anaconda Minerals Company obtained a permit from the Pueblo of Laguna to search for uranium on Laguna lands. In November 1951, an exploration team from Anaconda investigated an airborne radioactive anomaly on a mesa informally known as "Jack's Pile" on the Laguna lands (Hough, 1955). Subsequent field investigation and drilling led to the discovery of one of the world's largest sandstone-hosted uranium deposits, the Jackpile-Paguate Mine. Anaconda obtained a mining lease from the Pueblo of Laguna in May 1952. The lease was renegotiated in 1963 and 1976 to add additional land to the mine complex.

Anaconda signed a contract with the Atomic Energy Commission (AEC) on December 27, 1951, for the production of uranium concentrate by a mill to be built near Bluewater, approximately 64 km west of Laguna that would process ores from the Jackpile-Paguate and other mines in the Grants-Laguna area. This was the first of nine mills to be built in New Mexico (Albrethsen and McGinley, 1982; McLemore, 2020b).

In June 1956, exploration drilling by Anaconda made another major discovery in the area west of the Jackpile open pit mine (Kittel, 1963). This would be developed into the Paguate open pit. The Jackpile-Paguate Mine actually consists of three open pits: Jackpile (475 acres), North (140 acres) and South Paguate (400 acres) pits (Fig. 2). At the end of mining, there were 32 waste dumps and 23 low-grade ore stockpiles that were ultimately regraded, covered, and seeded (U.S. Department of the Interior, 1985). Underground mining began in 1971 with the opening of the Alpine Test. Anaconda opened nine underground adits with more than 1076 m of underground workings (Table 1). An adit is a horizontal or near horizontal entrance to underground workings to extract ore. The mine complex was within 305 m of the village of Paguate and included part of the perennial Rio Paguate. The Rio Moquino flows into the Rio Paguate, which flows south of the Jackpile-Paguate Mine into the Rio San Jose.

Approximately 800 people worked in the mine, and most were members of the Pueblo of Laguna. Although the mine solved unemployment in the Pueblo for the 29 years that mine was in operation, once the mine closed, unemployment dramatically rose again in the Pueblo. Subsequently, many former miners experienced serious health effects (respiratory diseases, cirrhosis of the liver, and lung cancer; Boice et al., 2008; Schubauer-Berigan et al., 2009).

The Woodrow Mine (Fig. 2; Table 2), near the Jackpile-Paguate Mine, was discovered by an airborne anomaly in 1954 and was named after the pilot of the plane that discovered the anomaly (Holmquist, 1970). A drill hole was enlarged to a two-compartment, 70 m shaft with two levels that intersected the mineralized circular breccia pipe (7 to 10 m diameter).

The first attempts of *in situ* uranium recovery in the Grants District was by Anaconda at the Windwhip deposit (Fig. 2), near the Jackpile-Paguate Mine, in April 1970 (Hunkin, 1971; Holen and Hatchell, 1986; McLemore et al., 2016). During *in situ* uranium recovery, a fluid is pumped into a uranium deposit that dissolves the uranium in place. That uranium-bearing fluid is then pumped back to the surface and processed to recover the uranium. The Windwhip deposit was below the groundwater level in the lower Jackpile Sandstone at a depth of 61-73 m. A kaolinitic clay in the Dakota Formation overlies the Jackpile Sandstone at this site and shales of the Brushy Basin Member underlie the deposit, forming an ideal geologic seal for *in situ* uranium recovery. Two injection wells and 29 production wells were utilized in two separate well fields to mine the deposit. The uranium-bearing fluids, called pregnant liquor, were pumped to a surge tank then resin tanks at the

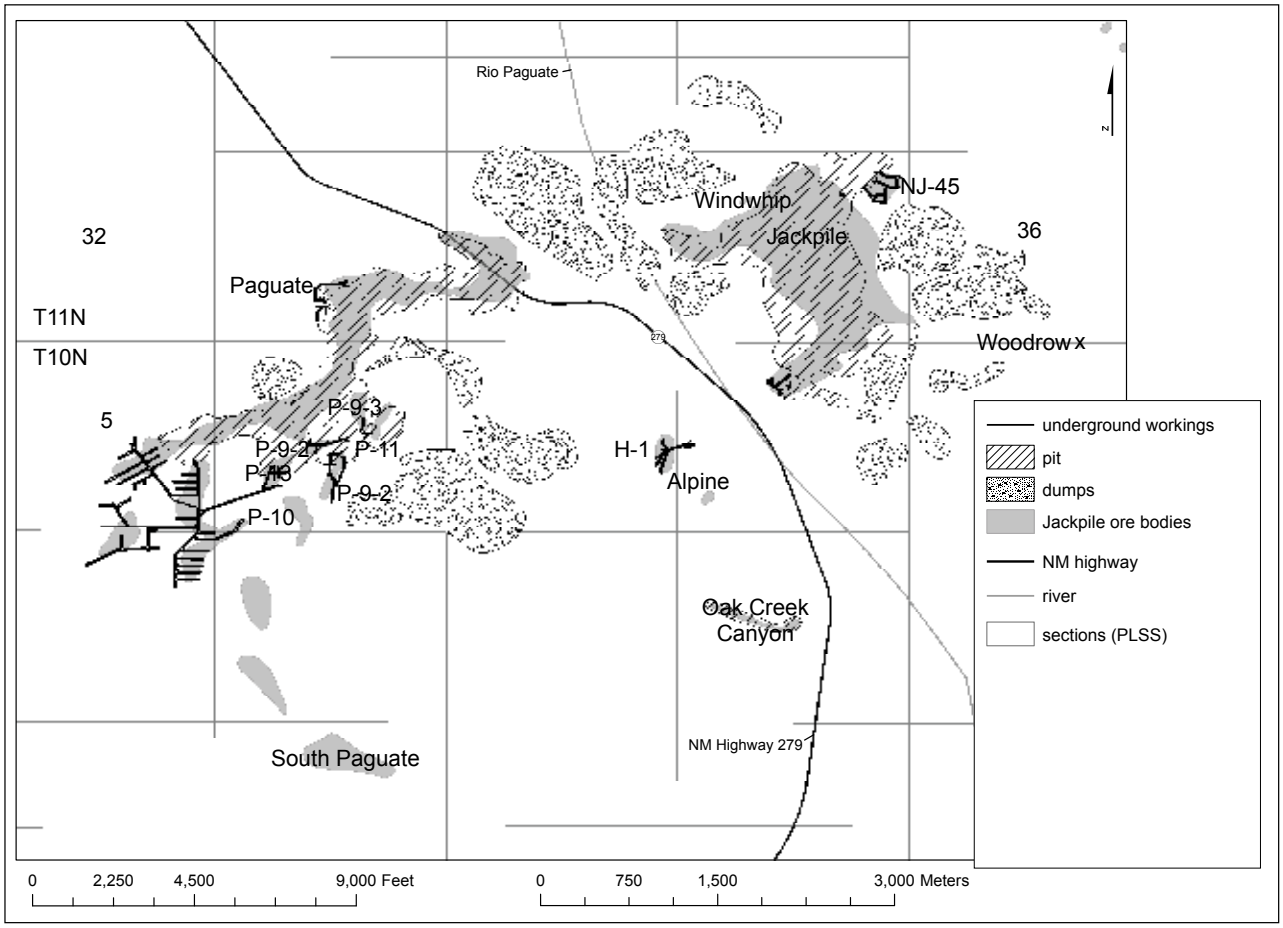

FIGURE 2. Mine map of the Jackpile-Paguate Mine, showing outlines of ore bodies and mine workings in 1982 (revised from McLemore and Chenoweth, 1991). PLSS= Public Land Survey System

TABLE 1. Summary of individual mine features (R.D. Lynn, written communication, March 13, 1982; U.S. Department of the Interior, 1985). Mine ID refers to the number of the mine feature in the New Mexico Mines Database (McLemore et al., 2005).

Mine Id	Mine	Start date	End date	Length	Depth	Comments
NMCI0018	Jackpile	5/1952	1982			pit
NMCI0035	North Paguate	6/1956				pit
NMCI0280	South Paguate					pit
NMCI0002	Alpine	9/1971	4/1973	110	70	Small operation, 2 adits, plugged
NMCI0015	H-1	7/1973	4/1975	475	140-200	Small operation, 2 adits, plugged, 3 vent holes, plugged
NMCI0030	P-9-2	3/1974	11/1976	100	140-160	Large operation, 5 adits, accessed from South Paguate pit
NMCI0031	P-9-3	11/1975	2/1976	310		
NMCI0033	P-11	11/1975	2/1976	170		
NMCI0037	PW 2/3	2/1978	8/1980	65	40-140	Small operation, 2 adits, accessed from North Paguate pit, back-filled
NMCI0034	P-13	6/1981	1/1982	150	200-600	Small operation, 2 adits, accessed from South Paguate pit, ore remains, workings flooded
NMCI0028	NJ-45	6/1981	2/1982	50	10	Small operation beneath Gavilan Mesa accessed from Jackpile pit, 3 adits, covered, only 1/3 of ore recovered
NMCI0032	P-7/10	1/1974	11/1981	2100	200-600	Large operation, workings filled with water, 2000 ft decline, covered
NMCI0281	P15/17					Operation approved but never developed, approximately 1.2 million short tons of ore remains (0.094-0.3 % U_3O_8)
NMCI0106	Woodrow	1953	1956	230		230 ft vertical shaft, backfilled
NMCI0105	Windwhip	1970	1970			Pit, *in situ* leach test

TABLE 2. Production from the Woodrow Mine (from U.S. Atomic Energy Commission, production records, NMBGMR file data; McLemore, 1983).

Year	Tons ore	Pounds U_3O_8	% U_3O_8	%V_2O_5
1953	47	1137	1.21	0.03
1954	3521	98,253	1.40	0.05
1955	553	5419	0.49	0.03
1956	1205	7712	0.32	0.03
Total	***5326***	***112,521***		

site. The uranium-bearing resin was shipped to the Anaconda Bluewater mill (Holen and Hatchell, 1986). It is unclear if the test was successful, but Anaconda did not use *in situ* recovery technology anywhere else in the Grants District.

From the initial production in 1953 to the final shipment in 1982, an estimated 26.6 million short tons of ore was produced from the Jackpile-Paguate open-pit mine, yielding 95,832,350 lbs of U_3O_8 (grade 0.39% U_3O_8; Table 3; New Mexico Bureau of Geology and Mineral Resources (NMBGMR) files; Grants Beacon, 1982; McLemore, 1983; McLemore et al., 2013, appendix 1). At the end of mining, approximately 23 million short tons of uranium material remained at the Jackpile-Paguate Mine in stock piles (21 million short tons at 0.02-0.059% U_3O_8) and known unmined resources (2 million short tons at 0.094-0.3 % U_3O_8; U.S. Department of the Interior, 1985). The total Jackpile-Paguate deposit, including production, remaining reserves, and ore estimated to have been removed by erosion, was approximately 165 million pounds of U_3O_8 (Holen and Finch, 1982). More than 400 million short tons of rock, waste rock and soil were removed from the area. The mine closed because of the depressed uranium market due to cancellations of new electric power plants, and the remaining lower grade material was not economic to mine at the time.

A Record of Decision (ROD) for the Jackpile-Paguate Uranium Mine Reclamation Project was signed between the Bureau of Land Management (BLM) and Bureau of Indian Affairs (BIA) in December 1986, and reclamation of the Jackpile-Paguate Mine began in 1989 (Olsen and Bone, 1991). Negotiations between Anaconda (now Atlantic Richfield Corporation, ARCO), BLM, BIA and Pueblo of Laguna resulted in Anaconda paying the Pueblo $45 million to reclaim the mine. The Pueblo formed the Laguna Construction Company to perform the work. The Jackpile-Paguate Mine would be the first uranium mine in the United States to be reclaimed, and there were no existing reclamation examples, guidance, laws or regulations to aid the Pueblo in the reclamation efforts (Olson and Bone, 1991). The Laguna Construction Company backfilled

TABLE 3. Uranium and vanadium production from the Jackpile-Paguate Mine, Laguna Subdistrict, Grants Uranium District. Vanadium production is unknown from 1971 to 1982. The production figures are the best data available and were obtained from published and unpublished sources (NMBGMR file data; McLemore, 1983; McLemore et al., 2013, appendix 1). Production figures are subject to change as new data are obtained.

Year of production	Quantity U_3O_8 lbs	Quantity V_2O_5 lbs
1952-1970	46,194,350	5,315,237
1971	3,822,000	
1972	4,390,000	
1973	4,650,000	
1974	4,588,000	
1975	3,880,000	
1976	5,366,000	
1977	4,860,000	
1978	6,196,000	
1979	4,290,000	
1980	3,600,000	
1981	3,328,000	
1982	668,000	
Total	***95,832,350***	***5,315,237***

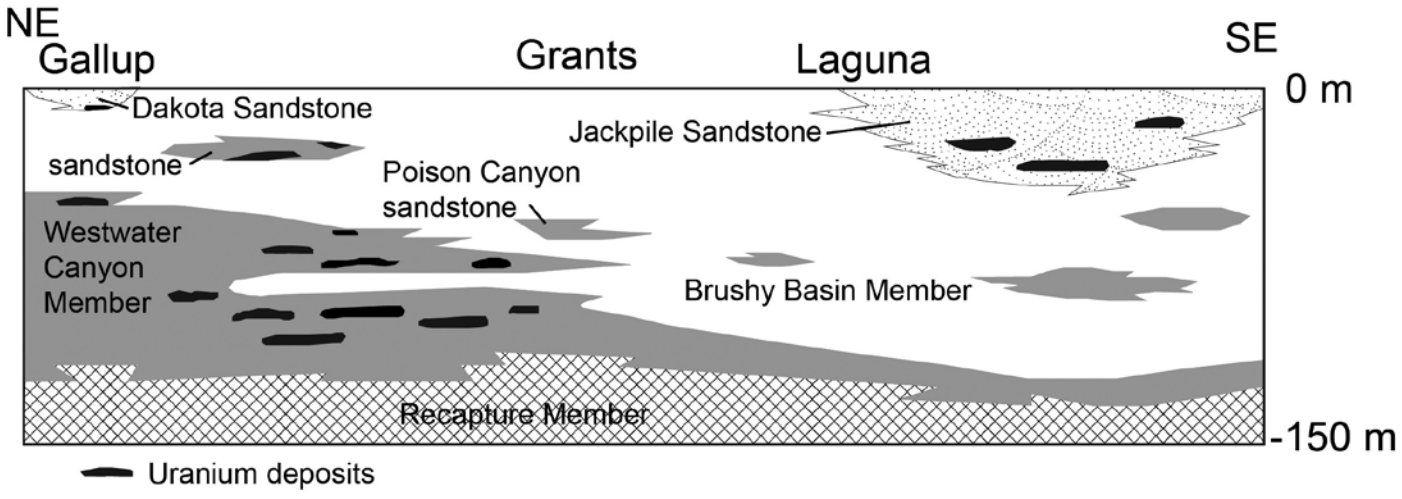

FIGURE 3. Schematic cross-section from Gallup to east of Laguna showing the relationship of the Jackpile Sandstone to the Westwater Canyon and Brushy Basin members of the Morrison Formation (modified from Hilpert, 1969).

the mines, removed uranium-bearing material near Rio Paguate, contoured and covered the remaining mine waste rock piles, and seeded the area with grasses and other plants. Reclamation was completed in 1995, and a 15-year monitoring study began. In September 2007, a ROD Compliance Assessment for the Jackpile-Paguate Mine was performed, and the results of that assessment determined that the post-reclamation was incomplete and had not met the requirements of the original ROD and Environmental Impact Statement. In response to many studies of environmental and health issues, results of monitoring studies, and local requests, the Jackpile-Paguate Mine was designated a Superfund site in 2013 and is in the Remedial Investigation and Feasibility stage (https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.Cleanup&id=0607033#bkground, accessed 7/27/2020). In 2017, EPA required that ARCO conduct the Remedial Investigation and Feasibility Study (USEPA, 2013, 2018).

GEOLOGY

Stratigraphy

The Jurassic Morrison Formation consists of three members in the Grants District (oldest to youngest): the Recapture, Westwater Canyon, and Brushy Basin members. The ore-bearing Salt Wash Member of the Morrison Formation found in the Carrizo Mountains and the Shiprock District in western New Mexico is absent in the Laguna area. The Recapture Member hosts small uranium deposits locally but was not a significant source of production in the Grants District. The Westwater Canyon Member is the predominant host for uranium in much of the Grants District, especially in the Ambrosia Lake Subdistrict, and consists of 15 to 91 m of reddish-brown or gray arkosic sandstones with interbedded gray and green to greenish-gray shales (Nash, 1968; Hilpert, 1969). The Westwater Sandstone Member is thinner in the Laguna area compared to the Ambrosia Lake area (Hilpert, 1969). Westwater Canyon sandstones exhibit features typical of a fluvial environment, whereas the siltstones and shales are typical of overbank and lacustrine environments (Turner-Peterson, 1980). Shales of the Brushy Basin Member locally interfinger with the Westwater Canyon Member. The Brushy Basin Member is 30 to 152 m thick and consists of light greenish-gray shales and mudstones and a few interbedded sandstone lenses. The Brushy Basin Member is thicker in the Laguna area compared to the Ambrosia Lake area.

Although, the Westwater Canyon Member hosts several small uranium deposits in the Laguna Subdistrict, the larger more economic deposits are in the Jackpile Sandstone (Nash, 1968; Hilpert, 1969; McLemore, 1983). The Jackpile Sandstone overlies the Brushy Basin Member (Fig. 3) and is found only in the Laguna area. The Jackpile Sandstone is truncated by a basal Cretaceous unconformity and is overlain by the Cretaceous Dakota Formation. It consists of as much as 70 m of white kaolinitic sandstone with minor interbeds or lenses of pale green shale and mudstone, and features typical of a braided-stream environment are common (Baird et al., 1980; Jacobsen, 1980; Moench and Schlee, 1967). South of Laguna, the Jackpile Sandstone is truncated due to erosion, whereas north of Laguna the sandstone splits into two or more sandstones. There is a controversy as to the age and stratigraphic position of the Jackpile Sandstone. Many geologists included the Jackpile Sandstone in the Brushy Basin Member since geologic mapping shows the Jackpile Sandstone interfingering with the upper Brushy Basin Member (Moench and Schlee, 1967; Hilpert, 1969; Baird et al., 1980). However, Aubrey (1992) was one of the first geologists to suggest that the Jackpile Sandstone is equivalent to the Lower Cretaceous Burro Canyon Formation and should not be part of the Brushy Basin Member. Recent detrital-zircon ages from the Jackpile Sandstone further support a Cretaceous age and designation as a lateral equivalent to part of the Cretaceous Burro Canyon Formation (Dickinson and Gehrels, 2010; Dickinson, 2018).

Description of the uranium deposits

The Jackpile ore body was an elongate, primary tabular deposit approximately 2.4 km long and 0.8 km wide, and the Paguate ore body was more than 3.2 km long and several hundred m wide. Individual ore deposits were up to 4.6 m thick, and stacked ore deposits were up to 15 m thick and found mostly in the lower Jackpile Sandstone (Moench, 1963). Uranium is found as replacements of detrital grains, grain coatings, pore fillings, concentrations around clay galls, irregular and diffuse masses of uranium and humates, and thin, discontinuous coal-like lenses. Detrital uranium grains were reported by Jacobsen (1980) and Baird et al. (1980). Uranium commonly was found at sandstone-shale interfaces (Moench and Schlee, 1967; Beck et al., 1980). The ore minerals were coffinite and uraninite, with minor secondary uranium and vanadium minerals that were associated with humate and other organic material. Uranium ore grades were as high as 0.9% U_3O_8 (McLemore, 1983). Fossil logs are common in the Jackpile Sandstone, but unlike the highly uranium mineralized logs in the Ambrosia Lake Subdistrict, most of the Jackpile logs do not contain uranium minerals (Moench and Schlee, 1967; Hilpert, 1969). Although trace amounts of molybdenum and selenium were found associated with Jackpile ore, concentrations were less than those found associated with Westwater Canyon ore in the Ambrosia Lake Subdistrict and Brushy Basin ore in the Smith Lake Subdistrict (McLemore, 1983). The age of the Jackpile uranium deposits is 110-115 Ma, younger than primary uranium deposits elsewhere in the Grants District (Nash and Kerr, 1966; Lee, 1976; Brookins, 1980; McLemore, 2020a).

ENVIRONMENTAL AND URANIUM TRANSPORT STUDIES

There have been numerous environmental and health studies centered around the Jackpile-Paguate Mine and the Grants District. Early studies focused mostly on water availability (Risser et al., 1984) and quality (West, 1972; Kaufmann et al., 1976; Longmire and Brookins, 1982; Popp et al., 1984; Zehner, 1985), vegetation (Kelley, 1979), and health of workers (Schubauer-Berigan et al., 2009), nearby residents, and animals (Momeni et al., 1983; Lapham et al., 1989; Gilliland et

al., 2000). More recent studies are more inclusive of the entire ecosystem affected by uranium mining, defining the processes involved. These include a wide range of topics:

- concentrations of uranium in groundwater and surface water (Blake et al., 2017),
- uranium in vegetation and soils (Gorospe, 2013; El Hayek et al., 2018),
- bioaccumulation (El Hayek et al., 2018, 2019),
- the role of dust (Brown, 2017),
- uranium mineralogy (Moench, 1962; Caldwell, 2018, Hettiarachchi et al., 2019),
- uranium mobility (De Vore, 2015; Avasarala, 2018; Velasco et al., 2019),
- and microbial communities (Chavez, 2016).

From 2013 to 2018, a joint National Science Foundation-funded team of researchers from the New Mexico Institute of Mining and Technology (NMIMT) and the University of New Mexico (UNM) investigated uranium mobility, uranium sources and environmental studies in and around the Jackpile-Paguate Mine. The purpose of these studies (part of a New Mexico EPSCoR program called Energize New Mexico, https://www.nmepscor.org/who-we-are/timeline, accessed 7/27/2020) was to generate new research on uranium mining and legacy issues using modern techniques that were not available during the mining boom. The results of this work will aid decisions regarding uranium extraction and remediation, as well as aid environmental, community and individual health near areas affected by uranium deposits and resulting mining activities. What follows is a brief description of some of these studies; some are described elsewhere in this volume in more detail (Brown and Cadol, 2020; Pearce, 2020; Wilton et al., 2020).

Uranium mobility and accumulation

The interaction between mine wastes, stream sediments, and surface water of the Rio Paguate was evaluated in a study by Blake et al. (2017) to understand uranium mobility and accumulation adjacent to the Jackpile-Paguate Mine. The mineral coffinite ($U(SiO_4)\cdot nH_2O$) was identified in this study by X-Ray diffraction analyses from mine waste solids even after exposure to oxidizing conditions (i.e., weathering) for several decades (Blake et al., 2017; Caldwell, 2018). Uranium concentrations in these solids range from 320 to 9200 mg/kg, whereas uranium concentrations in the stream bed and stream bank sediments of the Rio Paguate range from 1 to 5 mg/kg. Higher uranium concentrations (2 to 21 mg/kg) were measured in sediments from a wetland area 4.5 km downstream from the mine. These observations may be explained by the elevated organic matter in wetland sediments and uranium's affinity for sorption to organic matter. Coffinite was not observed in the stream or wetland sediments.

Surface water samples, collected and analyzed between September 2014 and August 2016, revealed higher concentrations of uranium in surface water adjacent to the mine (35.3 to 772 µg/L) compared to water from the wetland (5.77 to 110 µg/L). Uranium concentrations from water samples from the hyporheic zone below the streambed are 20 to 30 times higher than the surface water concentrations from the same location at the same time. This could be due to the proximity of the hyporheic zone samples to the mine site and depositional processes at this location. The uranium concentrations in the Rio Paguate vary with season and appear to be affected by hydrogeological and geochemical processes at different times of the year. Snowmelt from nearby mountain peaks, monsoonal rains, or dry seasons could affect the mobility of uranium in the ecosystem by means of dissolution, dilution, adsorption, chemical precipitation or other geochemical processes.

Uranium distribution among particle-size fractions

Uranium partitioning by particle-size fractions in waste rock piles from within uranium waste materials can have a significant impact on the transport of uranium to the surrounding environment. The distribution of minerals and major and trace elements in different particle size fractions is an important factor in understanding the availability of minerals for dissolution and oxidation during weathering and the mobility of the resulting mineral constituents. Unpublished results of an ongoing project to understand the geochemical distribution within different particle size fractions are summarized here (McLemore, 2012; McLemore et al., 2018).

In most geologic materials, the composition of the different size fractions is a result of the composition of the parent material and the geologic, geochemical, and pedological processes responsible for the formation of the geologic materials, as well as post-mining blasting, hauling, dumping, and emplacement into the waste rock pile (McLemore et al., 2018). The composition of various size fractions provides an insight into what chemical changes can be expected as geological materials break down to smaller particles. Weathering of minerals involves mostly surface reactions, and the rates of these reactions depend upon the available reactive surface area of the mineral. Mineral surface area is dependent upon the mineralogy, irregularities in the mineral structure (such as fractures, element impurities, and crystal structure), the extent to which the mineral is liberated from the rock matrix, particle size (especially mineral grain size), particle shape, and the surface morphology (i.e., roughness of the mineral surface). Furthermore, when mineral surfaces are covered with coatings, such as iron oxyhydroxides or humates, oxidation and dissolution of the mineral can be inhibited. Thus, particles of different sizes expose different proportions of the surfaces for chemical reaction, which plays an important role in weathering and mobility of uranium in the environment.

Samples were collected in the field from waste rock piles at the St. Anthony open pits, located north of the Jackpile-Paguate Mine and analyzed in the laboratory. The samples from the St. Anthony pits are from the Jackpile Sandstone and are similar to material mined from the Jackpile-Paguate Mine. Waste material at the Jackpile-Paguate Mine is covered with topsoil and not available for sampling. A composite sample (generally 15-20 subsamples) of rock or other material was collected using picks, shovels and hand trowels at each site, homogenized, and stored in 5-gallon buckets. Each size fraction (bulk

or not sieved, 12.5-4.76, 4.76-2, 2-0.5, 0.5-0.125, and <0.125 mm) for chemical analyses was separated using stainless steel sieves and sent to ALS laboratories in Reno, Nevada, for analyses. Laboratory methods included whole-rock geochemistry, petrographic analysis, paste pH and conductivity, particle-size analysis, acid base accounting and net acid generation.

Numerous studies of waste rock piles from base and precious metal mines have shown that the smallest size fractions (<0.125 mm) contained the largest concentrations of metals (see Morkeh and McLemore, 2012; McLemore, 2012). However, the distribution of uranium in different particle size fractions of waste rock piles from uranium mines is more complex and currently under study. The amount of uranium increased with increasing particle size or was concentrated in the middle sizes (two fractions, 4.76 to 2 mm and 2 to 0.5 mm) in the St. Anthony samples, whereas arsenic and carbon had complex variations with change in grain size (McLemore et al., 2018). Uranium and vanadium show a strong correlation, indicating that these elements are associated with each other in these deposits. The samples are heterogeneous and range in concentration from 24 to 11,050 ppm uranium. Chemical analyses indicate that uranium is correlated (R>0.6) with vanadium, carbon, zirconium, yttrium, lead, arsenic, selenium, and heavy rare earth elements (Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu). These results suggest that weathering of uranium deposits maybe more complex than weathering of metal deposits. More work is recommended to confirm and understand these complexities.

Dust Transport

In arid regions, dust transport and deposition are important processes of soil formation (Reheis et al., 1995). Natural and anthropogenic sources generate dust, which can impact soils downwind. Mining is of particular interest because a large amount of earth is moved, exposing erodible surfaces that contain ore as well as co-occurring gangue (non-economic minerals associated with the ore minerals) minerals, which can release contaminants into the surrounding area. Dust generation from active mine sites can be an important mechanism for contaminant movement. Understanding the mechanisms of dust generation as well as contaminant concentrations within the air column may be important in mine management strategies, such as where to locate exposed ore/waste rock stockpiles and how to develop remediation plans.

At the Jackpile-Paguate Mine site, dust movement and its transport of associated metals (uranium, vanadium, cobalt, chromium, manganese, and lead) were investigated (Brown, 2017). Dust samples were collected at 15 sites across the Jackpile-Paguate Mine site (Fig. 4) at 0.25 m, 0.5 m, 1.0 m and 1.5 m above the land surface. Dust collected at greater heights (1.0 and 1.5 m compared to 0.25 m) contained higher metal concentrations. Additionally, dust contained higher manganese, lead and chromium values than mine-site average soil concentration. Uranium concentrations in dust were highest at the 1.5 m collection height and were significantly elevated above average soil concentrations.

In contrast, mass flux (grams per day per meter squared) decreased with increasing sample collection height. The inverse relationship between concentration and mass flux is likely due to a positive feedback between particle-size fractionation, which occurs in the air column based on dust particle mass, and the increasing surface area of smaller dust particles. Results show that, by mass, the bulk of the sediment transport occurs in the first 25 cm above the land surface, which is consistent with results found in literature (Bagnold, 1936; Butterfield, 1999; Dong et al., 2004). However, natural processes concentrate contaminants of concern in the finer fractions of dust, which allow for suspension of contaminants and transport down wind.

Several processes were found to be important in controlling dust transport at the Jackpile-Paguate Mine site: vegetation, location (exposure to wind) and soil moisture (see Brown and Cadol, 2020). Location was the most important factor in determining dust flux. More exposed areas of the site were associated with higher dust flux, suggesting that location of waste and ore stockpiles should be based on minimizing exposure to wind.

Seasonal effects were also considered. New Mexico typically experiences a windy season in the spring and early summer. The results showed that dust flux was the greatest in the spring as expected. Unexpectedly, dust flux in the winter showed a marked decrease compared to the other three seasons despite having the highest two recorded wind gusts and a similar sustained winds profile compared to spring. The combination of elevated soil moisture and intermittent snow cover likely contributed to the observed reduction in dust flux during the winter. These results suggest that seasonal weather patterns should be incorporated into strategies that mitigate dust generation.

Bioaccumulation

Understanding the accumulation of uranium in plants is important to evaluate the transport and fate of uranium in biotic systems and to assess potential risk to humans, livestock and other organisms. A recent study at the Jackpile-Paguate Mine

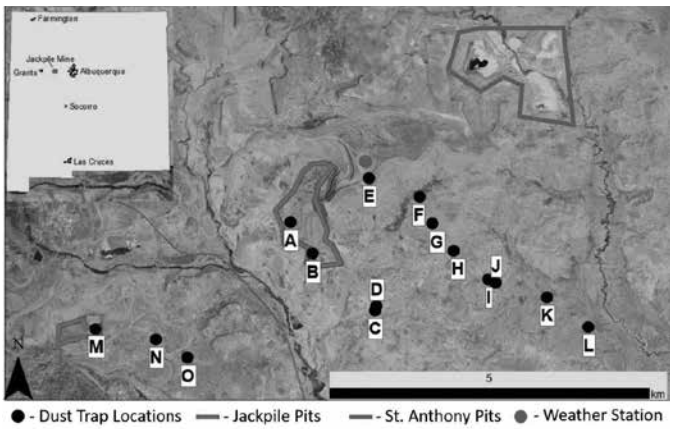

FIGURE 4. Site map of dust sampling at the Jackpile-Paguate Mine (modified from Brown, 2017). The black points represent dust trap locations. Solid lines indicate the extent of the pits. St. Anthony Mine is outlined by a dashed line. The star indicates the location of the weather station, which collects data on daily weather conditions.

measured uranium bioaccumulation in plant samples (shoots and roots) collected from the stream banks of the Rio Paguate near and within the wetland area up to 5 km downstream of the mine (El Hayek et al., 2018). Regional and abundant plants were collected (grass, willow [*Salix*], and cattail [*Typha latifolia L.*]) to assess potential human exposure at the site. The co-located sediments in the rhizosphere (the soil zone that surrounds plant roots) contained uranium concentrations up to twice the local uranium background, with the highest concentration measured in sediments collected from the rhizosphere of the wetland area (7-20 mg/kg; Blake et al., 2017). The rhizosphere of plants at these sites may also be exposed to the contaminated water of the Rio Paguate, with seasonal uranium concentrations ranging from 35 to 772 µg/L (Blake et al., 2017). Results indicated that grass roots accumulated uranium in concentrations 2 to 18 times higher (3.1-21.3 mg/kg) than willow and cattail roots. The highest uranium accumulation was detected in grass roots (21.3 mg/kg) at the wetland site, where sediment uranium concentrations were highest. The water chemistry at Rio Paguate (pH, calcium, uranium, and carbonate) suggests that aqueous ternary uranyl-carbonate complexes (Ca-U-CO_3) play an important role in uranium interaction with sediments and plant roots in the rhizosphere (Blake et al., 2017; El Hayek et al., 2018).

This research continued under lab conditions where hydroponic experiments were performed to examine the effect of calcium (0, 12 and 240 mg/L) and uranium (30, 100, 300 and 700 µg/L) concentrations in carbonate solutions at pH 7.5 (El Hayek et al., 2018, 2019). Indian mustard plant (*Brassica juncea*), a known uranium hyper-accumulator, was selected as the model organism. Scanning transmission electron microscopy and electron microprobe analyses showed that, in water free of calcium, uranium accumulated only in the cell walls at the surface of the root. No detectable accumulation of uranium was obtained at high calcium concentrations. The outcomes of these studies highlight the effect of initial uranium concentration and other co-occurring elements (such as calcium) on uranium speciation and bioavailability.

Microbiological Study at the Jackpile-Paguate Mine

Microbes can play an important role in the precipitation and dissolution of mineral components. A 2016 study aimed to characterize the microbial communities in the soil in relation to uranium concentrations and the effects of mining (Chavez, 2016). Six soil samples from areas close to the mine were taken aseptically (Fig. 4, sites A, C, D, I, K, L), and DNA was extracted and high-throughput metagenomic sequencing was performed at the National Center for Genome Resources in Santa Fe, New Mexico. The results showed a wide range of typical arid soil microbes and a strong representation from metal reducers (e.g., *Geobacter* spp.). There was also evidence that the relative abundances of some genera, including *Rhodopseudomonas, Bradyrhizobium* and *Rubrobacter,* are affected by concentrations of nickel, selenium and zinc. Uranium and background radiation did not appear to drive functional gene or phylogenetic differences among the soils sampled.

Uranium dissolution in lung fluids

Uranium is a naturally occurring element of which labile concentrations can increase due to human activities such as mining (Asic et al., 2017). This fairly abundant heavy metal is chemically toxic (LD_{50} = 14 mg/kg per body mass of an individual; LD_{50} is the lethal dose of uranium for 50% of an administered population) and can present radiological-toxicity depending on its isotopic composition and exposure route (Asic et al., 2017; Briner, 2010). During exposure to uranium, uranyl cations (UO_2^{2+}) bind to DNA in mammalian cells, combining to form a single molecular product (chemically known as a uranium-DNA adduct) that could cause mutations. The mutations trigger a range of protein synthesis errors, some of which may lead to various cancers, decrease in the antioxidative potential of lung tissues, and cause death of macrophages, the white blood cells important to the immune system (Stearns et al., 2005; Schneider et al., 2007; Periyakaruppan et al., 2007; Hsieh and Yamane, 2008; Pereira et al., 2012; Orona and Tasat, 2012). Cardiovascular and metabolic disease rates remain high among Navajo Nation residents near abandoned uranium mines in the southwestern United States.

Human exposure to uranium occurs via two major routes: 1) oral exposure via drinking water and food, and 2) inhalation of uranium-contaminated dust. Studies suggest both exposure routes play a vital role in the cardiovascular and metabolic disease rates (Harmon et al., 2017). Dust particles that are smaller than 10 µm can enter human respiratory systems and particles much smaller in size (less than 5 µm) can reach the alveolar region of human lungs, where the blood-gas exchange occurs. Particles that are not taken into the lungs continue to the gastro-intestinal tract (Kastury et al., 2017). The dust particles that reach the alveolar region of the lungs can interact with lung fluids thereby changing their chemical composition. Similarly, particles that continue to the gastro-intestinal tract can ultimately reach the stomach and interact with gastric fluids.

In the first phase of our studies (Hettiarachchi et al., 2019), dust samples collected from four different locations around the Jackpile-Paguate Mine (Fig. 4, sites A,C, E and G) and a sediment sample from St. Anthony Mine, which is five kilometers to the northeast, were investigated for their interactions in two simulated lung fluids (SLFs): 1) Artificial Lysosomal Fluid (ALF), which simulates the acidic fluid conditions inside macrophages, the white blood cells that eliminate dust particles from the alveolar region of the lungs (Stine and Brown, 1996); and 2) Gamble's Solution (GS), which simulates the pH neutral extracellular environment in the interstitium of the lungs (Guney et al., 2017; Kastury et al., 2017). The collected dust was treated with these SLFs in custom-built glass reactors for 24 hours. The system kept oxygen purged and at 37°C. The SLFs were then analyzed for their total dissolved uranium. In brief, the results show that the solid uranium in the dust dissolves in the lung fluids producing primarily UO_2^{2+} as confirmed by colorimetric measurements of uranyl-curcumin-triton-X system. The geochemical modeling studies conducted with PHREEQC 3.3.8 combined with experimental data further confirmed that the solubility of dust-uranium is controlled by the mineralogy

of the dust particles. The uranium dissolutions, modeled introducing one mineral at a time, suggested that autunite, carnotite, tyuyamunite, and uraninite were more soluble in GS than in ALF, with total dissolved uranium in GS/ALF ratios of 1.58, 16.1, 17.8, and 1.01, respectively. The uranium-bearing minerals schoepite, torbernite, coffinite, and uranophane were more soluble in ALF than in GS, with total dissolved uranium in GS/ALF ratios of 0.58, 0.26, 0.95, and 0.26, respectively. This suggests that understanding the behavior of inhaled uranium-containing dust in these mining areas, with the specific focus on site mineralogy, is vitally important in evaluating the chemical toxicity of uranium, independent of radiation studies.

In the second phase of the research, the researchers examined the fate of uranium particles in the gastro-intestinal tract. Dust was collected from three sites near Jackpile-Paguate Mine (Sites K, L and M in Fig. 4) and sediment from near St. Anthony Mine and a sample of mine waste rock from St. Anthony Mine was used. Here, the particles interacted with solutions that mimic the highly acidic gastric fluid of stomach and the slightly acidic fluid of the lower intestinal tract. The studies conducted with simulated gastro-intestinal fluids have shown higher uranium solubility compared to respiratory system simulations, also dependent on the various mineralogical components in the dust.

SUMMARY

The life cycle of the Jackpile-Paguate Mine has played an important role in U.S. and local history, supplying what has been considered a critical defense and energy material to the nation (Federal Register notice, 2018) and presenting a hazard to local communities and the environment. Today most of the high-grade uranium deposits in the Jackpile-Paguate area have been mined out. Three low-grade ore piles remain at the site and were regraded, contoured, covered, and seeded. Additional uranium resources remain in the Jackpile-Paguate area, especially in the St. Anthony Mine area (Wilton et al., 2020), but it is unknown how much uranium remains or if remaining uranium will ever be economic to recover. Additional mineral-resource studies are required before any future mining of uranium occurs. The Laguna Pueblo must agree to any further mining of uranium on Pueblo lands. Therefore, it is unlikely that any of the deposits at the Jackpile-Paguate Mine will be mined in the near future because of poor economic conditions, safety and public health concerns, community and cultural concerns, and other challenges common to uranium mining in New Mexico, as summarized by McLemore et al. (2013).

The recent hydrologic, biologic and chemical research by UNM and NMIMT workers has identified several pathways that contaminants can enter the environment, the community, and human physiology through water, soil, dust and plants. The results may help guide extraction, remediation and health care considerations for generations. Among the conclusions:

- Coffinite, a silicate with reduced uranium species, can remain in the ecosystem after several decades of exposure to oxidizing conditions.
- Seasonal variations have considerable impact on the mobilization of uranium, whether by water or wind.
- Rock and sediment grain size play an important role in the mobility of metals. Continued research will help identify the size fractions that concentrate uranium in mine sites like the Jackpile-Paguate Mine.
- Wind patterns should be considered when placing mine waste piles and other mine features.
- Uranium accumulation in plants can be affected by the water chemistry in a system (e.g., calcium in carbonate water can prevent uranium from accumulating in plants when uranium concentrations $\leq$700 µg/L).
- The soil microbes in the former mine site represent genera that are known to chemically reduce metal species.
- Mineralogy of dust particles and pH of lung and gastric fluids influence if and where uranium dissolves from inhaled dust in the body.

Although the mining of resources for weapons-grade uranium and uranium fuel at Laguna Pueblo has ceased and is unlikely to resume, the legacy of mining activities continues to provide challenges for local communities, ARCO, federal and local governments, and researchers. Perspectives toward this subject will likely continue to evolve as new remediation, energy, extraction and analytical technologies are developed.

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