

A STUDY OF ABANDONED MINE LANDS IN NEW MEXICO

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ABSTRACT

Abandoned mines (AML) are lands that were mined and left unreclaimed where no individual or company has reclamation responsibility and there is no closure plan in effect. These may consist of excavations, either caved in or sealed, that have been deserted and where future mining is not intended. The New Mexico Bureau of Geology and Mineral Resources (NMBGMR) and the Mineral Engineering Department at New Mexico Tech is conducting research to develop a better procedure to inventory and characterize legacy, inactive, or abandoned mine features in New Mexico. The object of this study was to inventory a number of abandoned mine features in the North Magdalena District in Socorro County, New Mexico and the Jicarilla District and Gallinas District in Lincoln County, New Mexico. This inventory was conducted by means of recording field observations according to the procedure already used by the program, soil petrography of composite dump samples, and paste pH analysis of said samples. This work served to identify environmental hazards in the two districts, which contributed to the goals of the AML program.

INTRODUCTION

Legacy issues of past mining activities forms negative public perceptions of mining, and inhibits future minerals production in the state. Some legacy mines have the potential to contaminate the environment; the Gold King uncontrolled release into the Animas River is a recent example. At the time the General Mining Law of 1872 was written, there was no recognition of the environmental consequences of discharge of mine and mill wastes or the impact on drinking water and riparian and aquatic habitats. Miners operating on federal lands had little or no requirement for environmental protection until the 1960s-1970s, although the dumping of mine wastes and mill tailings directly into rivers was halted by an Executive Order in 1935. It is important to recognize that these early miners were not breaking any laws, because there were no laws to break, but legacy issues still exist and should be remediated.

The New Mexico Bureau of Geology and Mineral Resources (NMBGMR) has been examining environmental effects of mine waste rock piles and tailings throughout New Mexico since the early 1990s (<http://geoinfo.nmt.edu/staff/mclemore/projects/environment/home.html>). There are tens of thousands of inactive or abandoned mine features in 274 mining districts in New Mexico (McLemore, 2017; including coal, uranium, metals, and industrial minerals districts), and many more in Colorado. However many of these inactive or abandoned mines have not been inventoried or identified as needing reclamation. The New Mexico Abandoned Mine Lands (AML) Bureau of the New Mexico Mining and Minerals Division (NMMMD) estimates that there are more than 15,000 abandoned mine features in the state (<http://www.emnrd.state.nm.us/MMD/AML/amlmain.html>). The New Mexico AML Program has safe guarded over 2,300 mine openings since inception in 1981 in about 250 separate construction projects (some of which were focused on coal gob reclamation and not safe guarding). The U.S. Bureau of Land Management (BLM) recently estimated that more than 10,000 mine features are on BLM lands in New Mexico and only 936 sites have been reclaimed

(<https://www.blm.gov/programs/public-safety-and-fire/abandoned-mine-lands/blm-aml-inventory>). The U.S. Park Service has identified 71 mine features in seven parks in New Mexico, of which 12 have been mitigated and 34 require mitigation (https://www.nps.gov/subjects/abandonedminerallands/upload/NPS_A_MLInv-2013-1231-2.pdf). Additional sites have been reclaimed by the responsible mining companies or the Superfund program (CERCLA). Data in the NMBGMR mining archives suggest that these numbers are minimal conservative estimates of the actual number of un-reclaimed mine features in the state.

The NMBGMR has collected published and unpublished data on the districts, mines, deposits, occurrences, and mills since it was created in 1927 and is slowly converting this historical data into a relational database, the New Mexico Mines Database (McLemore et al., 2005a, b). More than 8,000 mines are recorded in the New Mexico Mines Database and more than 7,700 are inactive or abandoned. These mines often include two or more actual mine features. Most of these mine features do not pose any physical or environmental hazard. Some of these inactive or abandoned mine features can pose serious health, safety and/or environmental hazards, such as open shafts and adits (some concealed by deterioration or vegetative growth), tunnels and drifts that contain deadly gases, radon, highwalls, encounters with wild animals, and metal-laden waters, locally acidic. Other sites have the potential to contaminate surface water, groundwater and air quality. Heavy metals in mine waste piles, tailings and acid mine drainage can potentially impact water quality and human health.

Many state and federal agencies and mining companies have mitigated many of the physical safety hazards by closing some of these mine features, but very few of these reclamation efforts have examined the long-term environmental effects. There is still potential for environmental effects long after remediation of the physical hazards, as found in several areas in New Mexico (for example Terrero, Jackpile, and Questa mines). Understanding these effects involves petrographic studies and some of these observations only come from detailed geochemical and electron microprobe studies that are not part of a remediation effort.

The NMBGMR in cooperation with the Mineral Engineering Department at New Mexico Tech and the AML program is conducting research on legacy mine features in New Mexico. The objective of our research is to develop a better procedure to inventory and characterize legacy, inactive or abandoned mine features in New Mexico. This project will inventory, characterize, and prioritize for remediation the mine features in several mining districts in New Mexico. The project involves field examination of the mines features and collecting data on the mine features (Bureau of Land Management, 2014). Samples are collected to determine total whole rock geochemistry, mineralogical, physical, and engineering properties, acid-base accounting, hydrologic conditions, particle size analyses, soil classification, shear strength testing for stability analysis, and prioritization for remediation, including hazard ranking. Not only are samples collected for geochemical and geotechnical characterization, but the mine features are mapped, evaluated for future mineral-resource potential, and evaluated for slope

stability. The results of this study will prioritize the mine features in selected mining districts in New Mexico for remediation.

DEFINITION OF ABANDONED MINE LANDS

A mine (or mine feature) is any opening or excavation in the ground for extracting minerals, even if no actual mineral production occurred. Abandoned mine lands (AML) are lands that were excavated, left un-reclaimed, where no individual or company has reclamation responsibility, and there is no closure plan in effect. These may consist of excavations, either caved in or sealed, that have been deserted and where further mining is not intended in the near future. AML includes mines and mine features left un-reclaimed on land administered by Federal, State, private, and Native Americans because the current owner was not legally responsible for reclamation at the time the mine was created. These mine features also are called inactive, legacy, and orphaned mines. In the NMBGMR AML project we are examining mines that are not technically AMLs and may have responsible owners that are in the process or have remediated the mine, mostly in order to these mines with AMLs.

Note that other agencies have slightly different definitions of AML. The Surface Mining and Reclamation Act (SMARA) defines abandoned surface mined areas as mined lands that meet all of the following requirements (Section 2796 (b)(2)(A)(ii)):

- Mining operations have ceased for a period of one year or more.
- There are no approved financial assurances that are adequate to perform reclamation in accordance with this chapter.
- The mined lands are adversely affected by past mineral mining, other than mining for coal, oil, and gas, and mineral material mining.

California defines abandoned mine as the location of any mineral extraction, exploration or borrow operation that may include, but is not limited to, shafts and adits, buildings and workings, open pits, stockpiles, roads, processing areas, waste disposal areas, or tailing piles and ponds, and which meet all of the following conditions:

- Mining operations have ceased for a period of one year or more.
- There is no interim management plan in effect.

The National Orphaned and Abandoned Mines Initiative (NOAMI) in Canada defines orphaned or abandoned mines as those mines for which the owner cannot be found or for which the current owner is financially unable to carry out cleanup (<http://www.abandoned-mines.org/en/>).

METHODS

Field Inventory

Published and unpublished data on existing mines and mills within five districts in New Mexico (Fig. 1) were inventoried and compiled in the New Mexico Mines Database (McLemore et al., 2005a, b; McLemore, 2017). Mines in the Silverton area were inventoried by Church et al. (2007). Names of types of mineral deposits (i.e. volcanoc-epithermal veins, sandstone uranium deposits, etc.) are from Cox and Singer (1986), North and McLemore (1986, 1988), McLemore (1996, 2001, 2017), McLemore and Chenoweth (1989, 2017), and McLemore and Lueth (2017). Locations of mines were obtained from published reports, files at the NMBGMR, and patented mining claims files.

Known mines and mineralized areas were examined and mapped. Mining was by surface and/or underground methods (pits, shafts and/or adits) and waste rock piles are located around or near the openings of most of these features. Waste rock piles were mapped using a handheld GPS and/or measuring tape. Some mines were located and described in the literature or mines records, but could not be found during the field investigation; these features were included in the database and identified as not found.

A field inventory form was designed to collect data on all mine features during the field examination, which were later entered into the New Mexico Mines Database. Inventory procedures employed are described in Bureau of Land Management (2014). Photographs and sketch maps are included. Depths of shafts were rarely determined by

a tape measure; generally depths of shafts were estimated by visual, if safe, or by pitching a rock into the opening and estimating the depth. Buildings, trash dumps, water wells, springs, and other archaeological and water features also were inventoried.

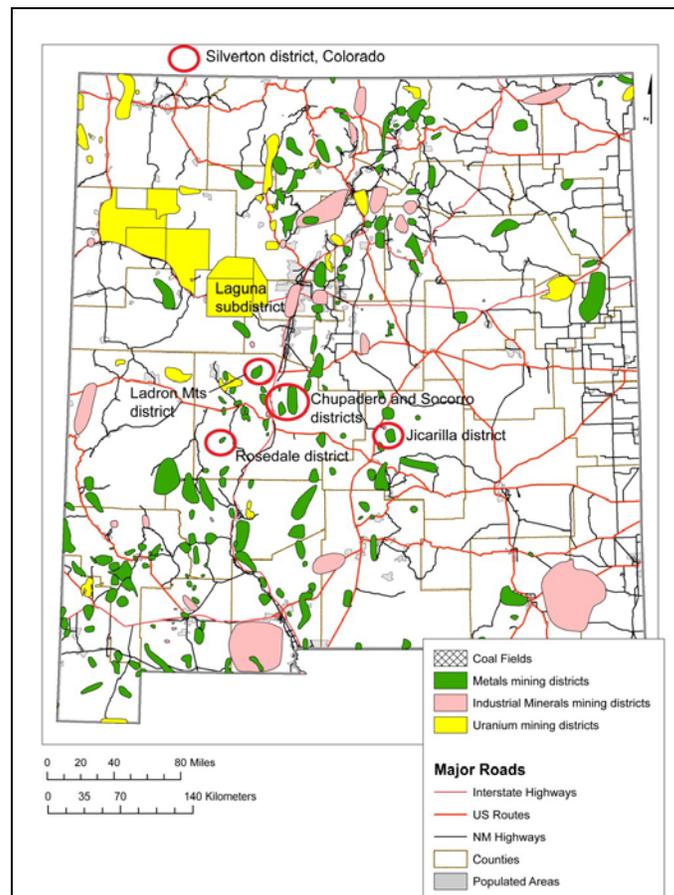


Figure 1. Location of mining districts examined during this study (McLemore, 2017).

Sample collection

In order to evaluate AML sites, a variety of field sampling methods of solid, water, and biological media are required, if present. Sampling and laboratory analyses are important to:

- Determine the mineralogy/chemistry of the mineral deposit and waste rock, especially sulfide minerals, in order to determine if the rock is potentially acid generating.
- Understand weathering processes, both at the surface and within the waste rock and tailings piles, in order to understand the effect of weathering on the acid drainage potential and the long-term physical stability of the rock piles, tailings, and other mine features.
- Identify water quality problems caused by drainage and related activities from legacy mines.
- Determine how reactive pyrite and carbonate minerals are in order to evaluate acid drainage potential and other water quality issues.
- Determine the suitability of existing waste rock piles for backfill material.

A sample is a representative portion, subset, or fraction of a body of material representing a defined population (Koch and Link, 1971; Wellmer, 1989; Davis, 1998; Neuendorf et al., 2005; Downing, 2008; McLemore et al., 2014). A sample is that portion of the population that is actually studied and used to characterize the population. Collecting a representative sample of waste rock-pile material can be difficult because of the compositional, spatial, and size heterogeneity of the material. It is necessary to define the particle-size fraction of the

sample required and analyzed, because of the immense size heterogeneity in many waste rock piles (Smith et al., 2000).

Composite samples of waste rock piles were collected, using procedures developed by Munroe (1999) and the U.S. Geological Survey (Smith et al., 2000; Smith, 2007; McLemore et al., 2014). Evenly spaced metal flagging pegs were positioned across an entire rock pile at each site marking a subsample location. Subsamples are collected with a small stainless steel hand trowel or shovel and sieved using 0.5 mm mesh into a 5-gallon bucket. Approximately two shovels of material were collected from each marked location on the waste pile. Subsamples are then mixed thoroughly and stored in buckets or large plastic bags. Sampling equipment is cleaned after sampling each waste pile. A subsample of the homogenized, composite sample was split for petrographic, mineralogical, geochemical and geotechnical analyses. Figure 2 is a flow chart describing the steps in collecting samples and the laboratory analyses performed on selected samples.

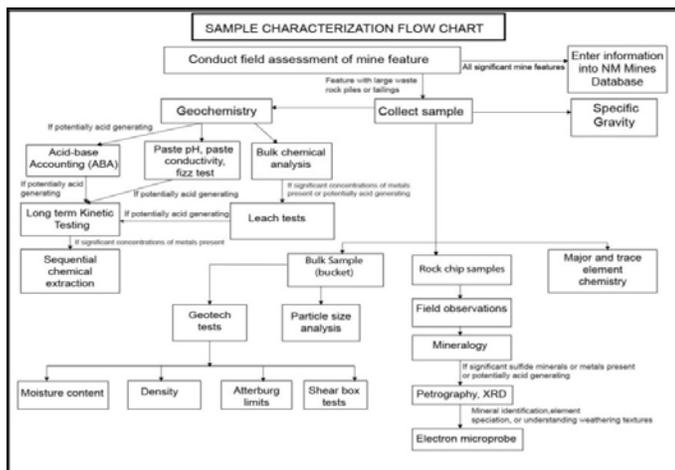


Figure 2. Sample characterization flow chart.

LABORATORY ANALYSES

Sample preparation

Laboratory analyses were performed on selected samples based upon a combination of criteria including the size of the mine waste rock pile (i.e. larger piles in the district) and mineral composition (i.e. presence of pyrite and/or jarosite and other sulfide/sulfate minerals). Selected rock chips and fragments from the waste rock piles or from outcrops were collected in order to determine the mineralogical and chemical composition. Sample preparation for different laboratory analyses is summarized in Table 1.

Petrographic descriptions and mineralogy

Petrographic analyses were performed using standard petrographic techniques (hand lens and binocular microscope); these analyses were supplemented by thin section petrography, electron microprobe analyses, X-ray diffraction (XRD) analyses, and whole-rock chemical analyses. Modal mineralogy was estimated using standard comparison abundance charts. Mineral concentrations and phase percentages, grain size, roundness, and sorting were estimated using standard charts (Carpenter and Keane, 2016). Data will be presented in future reports.

Bulk mineral identification can be used to identify minerals present in quantities greater than approximately 3%. Estimates of both primary and secondary minerals were determined, cementation and alteration described, and mineralogy and lithology identified (Folk, 1974; Carpenter and Keane, 2016). Any special features were noted. Altered, unaltered, and mineralized samples, including select samples of cement, are powdered and analyzed by X-ray diffraction (XRD). Weathered mine waste rock piles typically contain some amount of amorphous material that cannot be identified by XRD (Smith et al., 2000), but by integrating electron microprobe and geochemical data this material are characterized. This amorphous material typically contains metals that can be released into the water and also may form

clay minerals. This amorphous material in some cases acts as a cement.

Table 1. Summary of sample preparation for different laboratory analyses. XRF–X-ray fluorescence analyses. XRD–X-ray diffraction analysis. ICP–Induced-coupled plasma spectrographic analysis.

Laboratory analysis	Type of sample	Sample Preparation	Method of obtaining accuracy and precision
Petrographic analyses	Collected in the field, used split from chemistry sample	Uncrushed, typically smaller than gravel size material used, thin sections made of selected rock fragments	Not applicable
Paste pH and paste conductivity	Collected in the field, used split from chemistry sample	Uncrushed, typically smaller than gravel size material used	Use duplicates, compare to mineralogical analysis
Laboratory analysis	Type of sample	Sample Preparation	Method of obtaining accuracy and precision
Whole-rock chemical analysis (XRF, ICP, S/SO ₄)	Collected in the field in separate bag, analysis performed on powdered sample	Crushed and pulverized	Use reference standards and duplicates
Chemical analyses of water samples	Collected in the field in bottles	Refrigerated until analyzed	Use reference standards and duplicates
X-ray diffraction (XRD) analyses	Used select split from chemistry sample	Crushed	Compared to detailed analysis by electron microprobe
Electron microprobe analyses	Collected in the field or split from chemistry sample	Uncrushed, generally rock fragments or soil matrix	Use reference standards

Paste pH and conductivity

Paste pH and paste conductivity were determined to predict geochemical behavior of mine waste rock materials subjected to weathering under field conditions and to estimate or predict the pH and conductivity of the pore water resulting from dissolution of secondary mineral phases on the surface of oxidized rock particles. The paste conductivity values were converted to total dissolve solids (TDS) using standard procedures (<http://www.chemiasoft.com/chem/TDS>). Data for selected samples will be presented in future reports.

Geochemistry of solid samples

Samples underwent multiple analyses such as X-Ray Fluorescence (XRF), inductively coupled plasma atomic emission spectroscopy (ICP-AES), and inductively coupled plasma mass spectrometry (ICP-MS) at the ALS Laboratory Group in Reno, Nevada for evaluation of major and trace elements (CCP-PKG03 and Au-ICP21;

<https://www.alsglobal.com/myals/downloads?keywords=Geochemistry+Fee+Schedule&category=b5b5208b58bc4609bd2fa20f32d820f8>.

Samples were dried, crushed, split and pulverized according to standard ALS Laboratory Group preparation methods PREP-31; <https://www.alsglobal.com/myals/downloads?keywords=Geochemistry+Fee+Schedule&category=b5b5208b58bc4609bd2fa20f32d820f8>).

This package combines the whole rock package ME-ICP06 plus carbon and sulfur by combustion furnace (ME-IR08) to quantify the major elements in a sample. Trace elements, including the full rare earth elements (REE) suites, are performed after three acid digestions with either ICP-AES or ICP-MS finish: 1) a lithium borate fusion for the resistive elements (ME-MS81), 2) a four acid digestion for the base metals (ME-4ACD81) and 3) an aqua regia digestion (ME-MS42). Gold was analyzed separately (Au-ICP21). Chemical analyses will be reported in future reports.

On-going control and duplicate samples were submitted with each batch of samples submitted. Certified standards are commercial standards with certified values as determined by round robin analyses at numerous certified laboratories. Certified standards are expensive, so on-going control samples were analyzed instead. The on-going control samples are standards collected by NMBGMR personnel and

analyzed by different methods over several years of analyses by different laboratories. A summary of the quality assurance and quality control (QA/QC) is in McLemore and Frey (2009).

X-ray Diffraction (XRD)

X-ray diffraction (XRD) analysis was conducted on selected portions of composite mine waste rock samples to determine the mineralogy. Samples were ground into a well-homogenized material with a mortar and pestle, forming a fine powder (~75µ/0029 mesh). This was poured into an aluminum sample holder and mounted with the silicon standard in the XRD instrument. A five-minute absolute scan analysis was run. Sample analyses were performed using an appropriate software program. More details are found at NMBGMR website (<https://geoinfo.nmt.edu/labs/x-ray/home.html>).

Electron Microprobe Mineralogical Analyses

Samples were examined using a Cameca SX100 electron microprobe with three wavelength-dispersive spectrometers at New Mexico Institute of Mining and Technology (NMIMT) to characterize compositional, chemical and textural characteristics. Samples chosen for microprobe analysis were selected based on presence of pyrite or other sulfide minerals. Samples cut to an appropriate size were placed in 1 inch round sample mounting cups, set in epoxy, and cured overnight at around 80°C. Once cured, samples were first polished using coarse diamond grinding wheels and finely polished with diamond powder suspended in distilled water. Polished sample surfaces were then cleaned using petroleum ether and carbon coated to a 200 angstrom thickness.

Different types of analyses are performed. The initial observations of the samples are made using backscattered electron imaging (BSE), which allowed observation of sample textures, and location of high mean atomic number (Z) phases. BSE observations are coupled with acquisition of rapid X-ray maps and/or qualitative geochemical scans, which allow for qualitative assessment of the elements present in a given mineral phase. Peaks that appeared on the scans were identified using Cameca software. The elements shown by the peaks and their relative abundance, based on peak height, were used to identify the mineral phases. Qualitative scans were carried out using an accelerating voltage of 15 kV and a probe current of 20 nA. For more information on the electron microprobe laboratory see <http://geoinfo.nmt.edu/labs/microprobe/home.html> (accessed 6/1/16).

Quality Control Procedures and Sample Security

Samples were collected, prepared, and analyzed according to standard methods for each specific laboratory analysis. Samples were collected in the field and kept under direct control of the authors to avoid contamination. Samples are archived at the NMBGMR. Samples collected are complete, comparable, and representative of the defined population at the defined scale. Precision and accuracy are measured differently for each field and laboratory analysis (parameter), and are explained in McLemore and Frey (2009). Most geochemical laboratory analyses depend upon certified or on-going reference standards and duplicate analyses. The sampling and analysis plans for each segment of the field and drilling program as well as the control of accuracy and precision as defined here, provides a large high-quality set of observations and measurements that are adequate to support the interpretations and conclusions of this report. Field and laboratory audits by the senior author were performed to ensure that standard operating procedures were followed.

PRELIMINARY RESULTS

Petrography and mineralogy

Most rock samples from mine waste rock piles exhibit iron-oxide alteration, mostly as pyrite replacements by hematite. Pyrite has weathered to jarosite in the Silverton and Jicarilla districts. Gangue minerals associated with many samples include quartz, potassium feldspar, biotite and kaolinite. Quartz and potassium feldspar are major constituents of the groundmass, whereas quartz forms the matrix of the sample. Calcite is abundant in only a few districts studied. The destruction and replacement of biotite by hematite and quartz in some portions of the samples were observed along fractures. For samples from Gallinas, fluorite and chrysocolla were present.

Geochemistry of solid samples

Average pH values of the mine features from North Magdalena and Jicarilla ranges between 4.9 and 6.6. For Gallinas, pH values range from 5.85 to 8.00. The pH results from the first two districts indicate moderately alkaline to acidic waste rock piles, while those for Gallinas indicate slightly acidic to highly alkaline waste rock piles. Total dissolved solids (TDS) values calculated were between 5.9 and 40 mg/L and these results provide an indication of the level of dissolved solids in the stream or lakes closer to the waste rock piles. TDS values of 1 to 500 mg/L are typical of lakes and streams.

Potential for acid rock drainage

Acid rock drainage is formed when sulfide minerals are exposed to oxidizing conditions such as weathering. Field characteristics of potential ARD in mine waste rock piles include identification of pyrite and/or jarosite and low pH. The rate of sulfide oxidation depends on reactive surface area of sulfide, oxygen concentration and solution pH. ARD can be determined by Acid Base Accounting (ABA) and Net Acid Generation (NAG) Tests. The ABA procedure consists of two separate tests; the acid potential (AP) test and the neutralization potential (NP) test. ABA was calculated and plotted on the ARD classification plot for waste rock pile samples from the various mines (Sobeck et al., 1978). Results of ABA tests are presented in Figure 2. The assumption is that all C in the samples are as CaCO₃ (no organic carbon) and also the NAG pH is equals the measured paste pH of the sample. Below are the formula used:

$$\begin{aligned} \text{AP (kg CaCO}_3\text{/tonnes)} &= 31.25 \times \text{S (\%)} \\ \text{NP (total C)} &= 83.3 \times \text{C (\%)} \\ \text{NNP} &= \text{NP} - \text{AP} \\ \text{NPR} &= \text{NP/AP} \end{aligned}$$

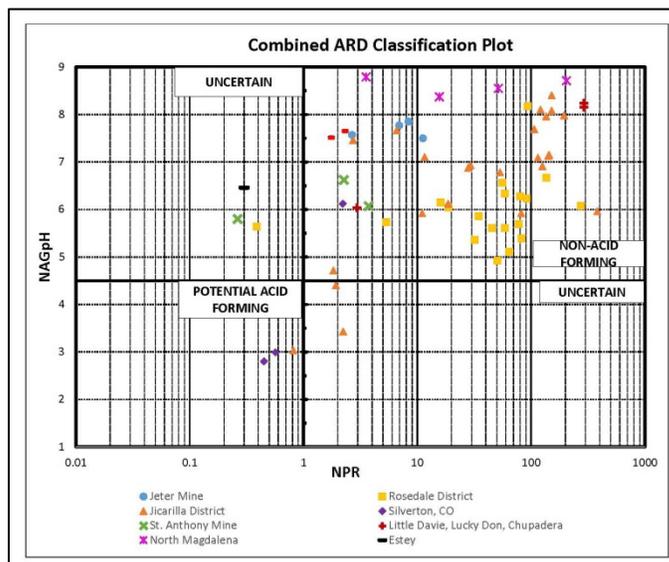


Figure 3. Acid Rock Drainage (ARD) plot of waste rock pile at mines examined during the NMBGMR AML project. The results for the waste rock piles from the Little Davie, Lucky Don, Chupadera, and Jeter uranium mines (Socorro County), St. Anthony uranium mine (Cibola County), Rosedale and Jicarilla gold mines (Socorro and Lincoln Counties) and Silverton gold-silver mines (Colorado) are shown for comparison (unpublished work in progress). Results of these mines will be published in future reports.

Samples that plot in the uncertain and potential acid forming fields are not suitable for backfill material and need to be handled with care during reclamation. Locations of mining districts is in Figure 1.

PRELIMINARY CONCLUSIONS

Samples that have higher concentrations of pyrite are more likely to have a higher acid generation capacity. Generally, Acid Potential (AP) depends on the amount of pyrite and other sulfide minerals and Neutralizing Potential (NP) depends upon the amount of calcite and

other acid- neutralizing minerals. But, no single component controls the ABA and NAG tests.

A few mine sites examined have potential to generate acid drainage and additional mine sites are physically dangerous and require proper safe guarding.

Most of the waste rock piles surrounding the mine features are suitable for backfill material. Sulfide oxidation can be slow in some areas and metal release can be low, but other areas are the opposite—characterization of mine wastes is important.

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