

CRITICAL MINERALS IN THE LARAMIDE NORTH AMERICAN PORPHYRY COPPER MINERAL SYSTEM IN NEW MEXICO: PRELIMINARY RESULTS OF SELECTED DISTRICTS

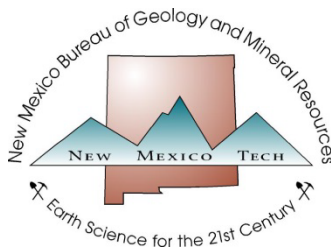
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ABSTRACT

The mineral systems approach provides a framework for expediting the identification and prioritization of potential critical minerals in the United States. Critical minerals are mineral commodities that are essential to the economic and national security of the United States and are from a supply chain that is vulnerable to global and national disruption. One of the largest and most economically important mineral systems in the world is the porphyry copper mineral system. Porphyry copper deposits are large, low-grade (<0.8% Cu) deposits that contain disseminated veinlets of copper sulfides associated with porphyritic intrusions and are associated with a variety of other mineral deposits including skarns, polymetallic veins, epithermal veins, supergene enrichment, CRD, and other types of deposits. New Mexico lies at the edge of one of the world's great metal-bearing provinces, the North American Porphyry Copper Belt, which includes adjacent parts of Arizona, Mexico, and Texas.

New $^{40}\text{Ar}/^{39}\text{Ar}$ dating and prior age determinations have constrained the North American Porphyry Copper Belt into five periods:

- 200–80 Ma Jurassic-Cretaceous (Bisbee)
- 80–70 Ma Laramide Pulse 1 (porphyry copper)
- 60–50 Ma Laramide Pulse 2 (porphyry copper)
- 45–25 Ma Paleogene Pulse 3 (Mo-W deposits, CRD, maybe porphyry copper or porphyry molybdenum)
- Ongoing supergene enrichment of porphyry copper deposits starting at ~41–2 Ma.

Many of the largest economic deposits appear to be of the Laramide Pulse 2 (60–50 Ma). Despite the large number of geologic, geochemical, and geochronological studies on the North American Porphyry Copper Belt, many questions remain on their formation, tectonic setting, and critical minerals potential. This report is just a beginning of our understanding of geochronology and critical minerals potential in the various mineral deposits forming the North American Porphyry Copper Belt.

Some of the of the porphyry copper deposits form along regional lineaments or in clusters: Resolution Ray-Castle Dome-Miami-Inspiration, Safford-Dos Pobres-San Juan-Sanchez-Sol, and Mission-Pima-Sierrita-Twin Buttes in Arizona and Chino-Hanover-Fierro-Continental, and Tyrone-Little Rock-White Signal-Malone in New Mexico. Some districts in southwestern New Mexico have more than one pulse of magmatism and mineralization: Lordsburg, Little Hatchet Mountains (Eureka and Sylvanite districts), and Peloncillo Mountains (McGhee Peak, Granite Gap, San Simon districts).

Every porphyry copper mineral system varies chemically, especially in terms of coproducts gold, silver, and molybdenum and have potential for various critical minerals, including Zn, Pb, In, Bi, Co, Ni, V, Cs, and total REE that are found as separate minerals, micro-inclusions, and/or in solid solution in sulfide minerals. Geochemical analyses of mineralized samples provide insights into critical minerals in these deposits. Some of these critical minerals are found in the skarns and polymetallic veins adjacent to the porphyry copper deposits. Most samples are low in total REE; however, a few deposits contain elevated total REE, including Santa Rita (717 ppm), Fierro-Hanover (937 ppm), Oro (Eureka, 2272 ppm) and White Signal (2684 ppm). Although, these concentrations are not economic for primary extraction, the large volumes of processed materials from porphyry copper deposits provide a feasible pathway for secondary recovery of REE and other critical minerals in these deposits.

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INTRODUCTION

Recently, there is interest in examining mineral deposits for their critical minerals potential and possible extraction of critical minerals. *Critical minerals* are mineral commodities that are essential to the economic and national security of the United States and are from a supply chain that is vulnerable to global and national disruption (Fig. 1; McLemore and Gysi, 2023). Most critical minerals are imported into the United States (U.S. Geological Survey, 2026). In the United States mining industry, the term *mineral* refers to any rock, mineral or other naturally occurring material of economic value (U.S. Bureau of Land Management, 2026). Therefore, the term mineral includes metals, industrial minerals, critical minerals, energy minerals (oil, natural gas, and coal), gemstones, aggregates, synthetic materials sold as commodities and some inorganic substances.

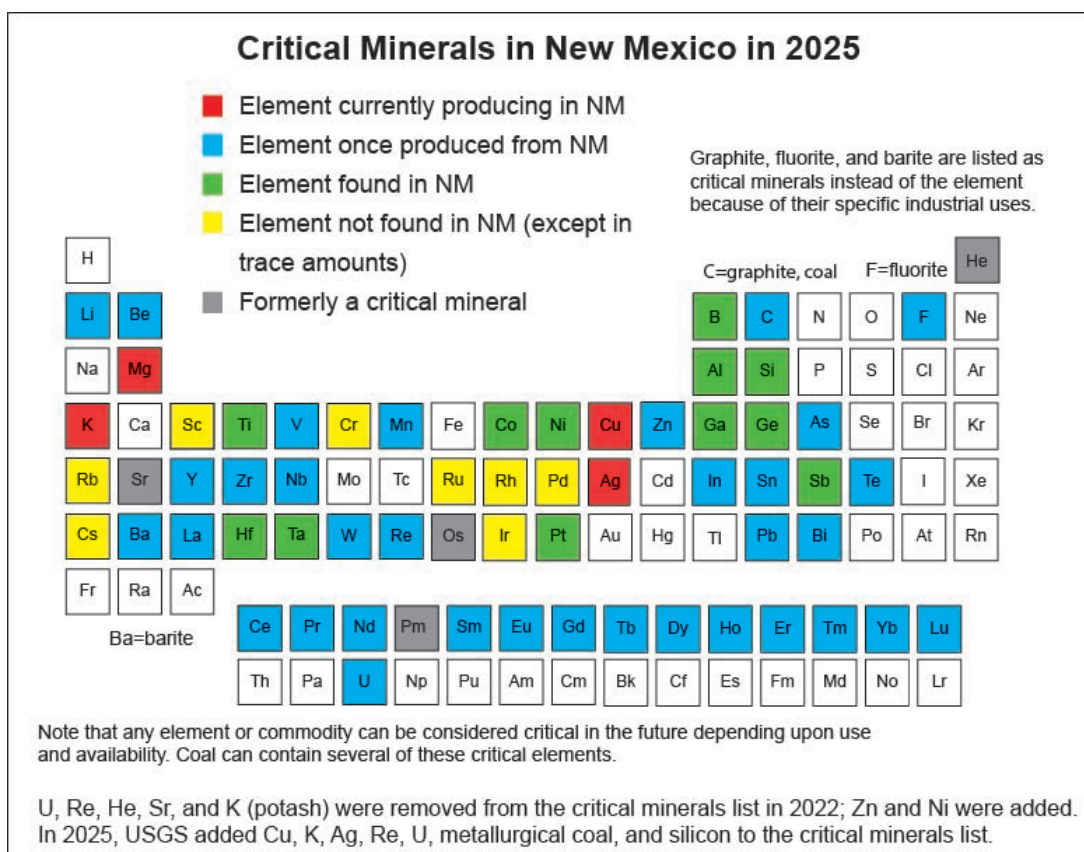


FIGURE 1. Critical minerals in New Mexico, color coded according to past production or occurrence in the state (modified from McLemore and Gysi, 2023).

The U.S. Geological Survey (USGS) Earth MRI (Minerals Resources Initiative) program is using the mineral systems approach to expediate the identification and prioritization of potential critical minerals (Hammarstrom, and Dicken, 2019, 2020, 2022; Hofstra and Kreiner, 2020). Mineral systems are large geological frameworks or models, at province or district scales that relates all geologic processes that form and preserves an economic mineral deposit: energy source (tectonic setting, heat, gravity, etc.), metal source (fertility, magmas, host rocks), fluid

pathways (fluid migration, plumbing, structures, stratigraphy), deposition sites (temperature, chemical and physical traps), and post-mineralization preservation of the mineral deposits (Fig. 2). Mineral systems organize cogenetic alteration zoning and mineral deposit types with specific tectonic settings and geologic processes during a specific time span (McCuiag et al., 2010; McCuiag and Hronsky, 2014; Huston et al., 2016; Hofstra and Kreiner, 2020; Groves et al., 2022). Mineral systems are based upon current theories of how mineral deposits form and relate them to the broader geologic, geodynamic, and tectonic history of the mineralized region. These frameworks are larger in scale than mineral deposits and have aided in revising and redefining mineral deposit models to enable more efficient exploration for critical minerals on a district or regional scale.

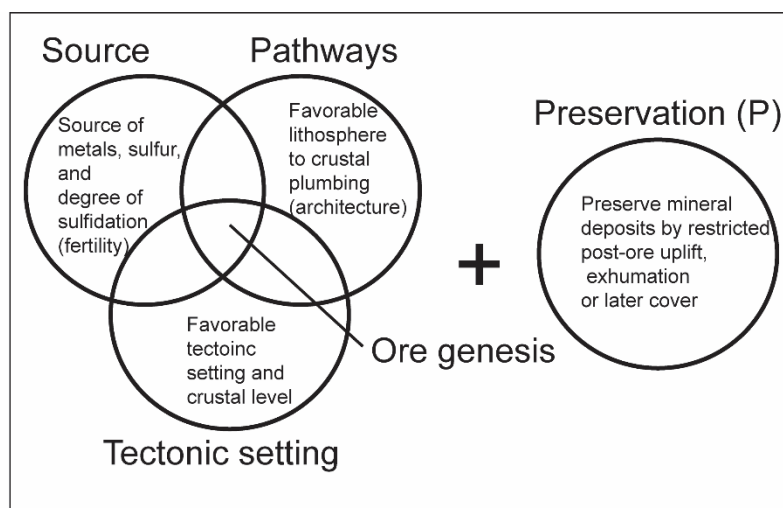


FIGURE 2. The basic components of a mineral system (modified from McCuiag and Hronsky, 2014; Groves et al., 2022). The formation of mineral deposits must include a source of elements (fertility), favorable pathways (architecture), favorable tectonic setting (geodynamics) and preservation of the deposit. These components are generally regional in scale and form the basis of mineral systems.

Porphyry copper deposits are part of a mineral system that has the potential for a variety of critical minerals because of their large size (millions to billions of tons of material), long mine life (decades), and diversity of associated mineral deposits (Fig. 3). Porphyry copper deposits are large, low-grade (<0.8% Cu) mineral deposits that contain disseminated sulfides, breccias, and stockwork veinlets of copper and molybdenum sulfides associated with porphyritic intrusions. The term porphyry or porphyritic is a descriptive term describing a high-level crustal intrusive rock with a texture of coarse-grained phenocrysts (or crystals) dispersed in a fine-grained matrix or groundmass. Other types of associated mineral deposits are found within this mineral system (skarns, polymetallic veins, epithermal veins, supergene enrichment deposits, CRD; Fig. 3) that formed at or near the time of emplacement of the porphyry copper deposit and, in many cases, were mined as part of the porphyry copper mine (Hofstra and Kreiner, 2020). The metal content of porphyry deposits is diverse, but the focus of this paper are porphyry copper deposits (Sinclair, 2007). In addition to these critical minerals, high sulfidation zones and lithocaps have potential for Ag, Al, Ga and K (Hofstra and Kreiner, 2020).

Not all porphyritic plutons are mineralized, but they provide the heat and the source of metals to the system. Although, these concentrations are not economic for primary extraction, the large volumes of processed materials from porphyry copper deposits provide a feasible pathway for secondary recovery of REE and other critical minerals in these deposits (John and Taylor, 2016). In past mining, the critical minerals weren't always recovered because of low concentrations, low prices, and lack of technologies to recover them (Eggert et al. 2008; Sillitoe, 2010; Vikre et al., 2023). Barren plutons were often ignored when modelling porphyry deposits, despite being intimately related in age and formation to the other associated mineral deposit types (i.e skarns, polymetallic veins) within the mineral system. Current research is examining these porphyry-related deposits for their critical minerals content (Asadi et al., 2014; Park et al., 2019; Hammarstrom, and Dicken, 2019, 2020, 2022).

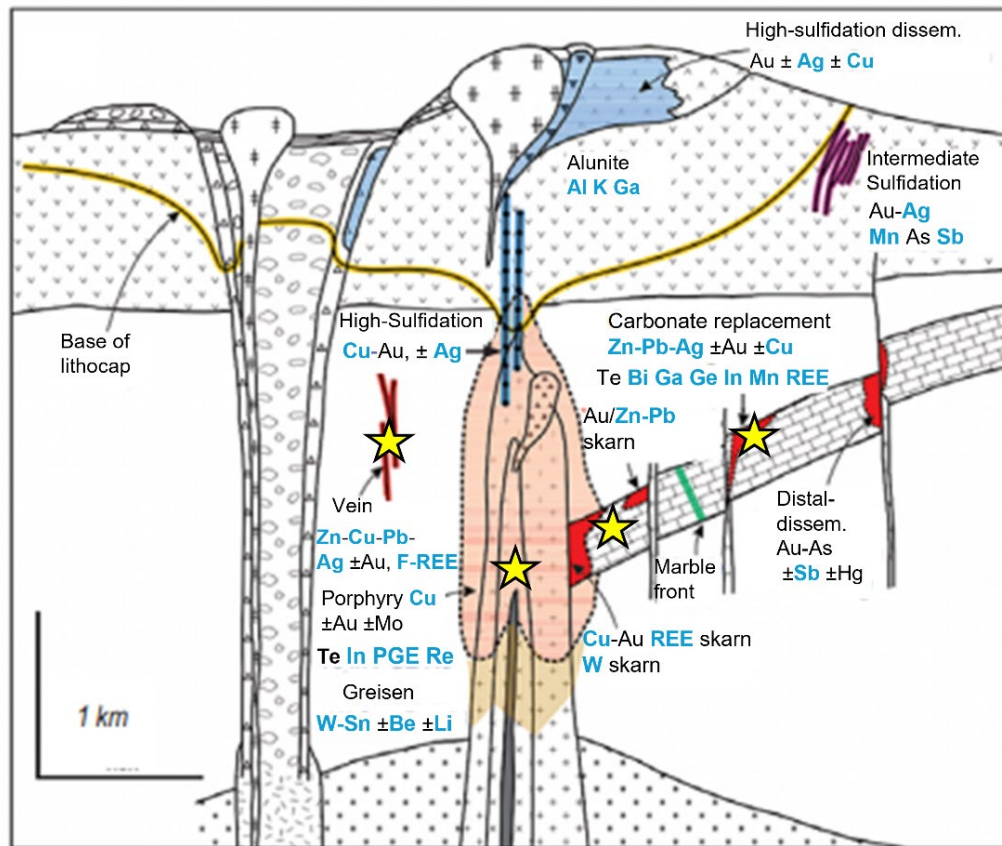


FIGURE 3. Schematic model of porphyry copper mineral system with related deposit types (yellow stars) and associated critical minerals in blue. Modified from Sillitoe (2010), John et al. (2010), Hofstra and Kreiner (2020) and Vikre et al. (2023).

One of the largest and most studied porphyry copper provinces in the world is the North American Porphyry Copper Belt in southwestern United States (Arizona, New Mexico, Texas) and northern Mexico (Fig. 4), and exploration for additional resources is ongoing throughout the area. The North American Porphyry Copper Belt formed as a result of the Farallon plate, composed of oceanic crust and mantle lithosphere, being subducted beneath the North American crustal plate (Fig. 5). Changing the angle of subduction from shallow- to flat-slab subduction of

the Farallon plate allowed the mineral belt to extend hundreds of kilometers inland from the subducting trench, resulting in numerous porphyry copper and associated mineral deposits (Fig. 4; Barton, 1996; Leveille and Stegen, 2012; Richards, 2021). Despite the large number of geological studies of this province, the geochronology and trace-element composition, especially the critical minerals potential of many of these deposits is still unknown. The mineral systems approach is important because not all plutons within this belt have known mineral deposits associated with them and some of these could indicate that mineralized deposits could be at depth.

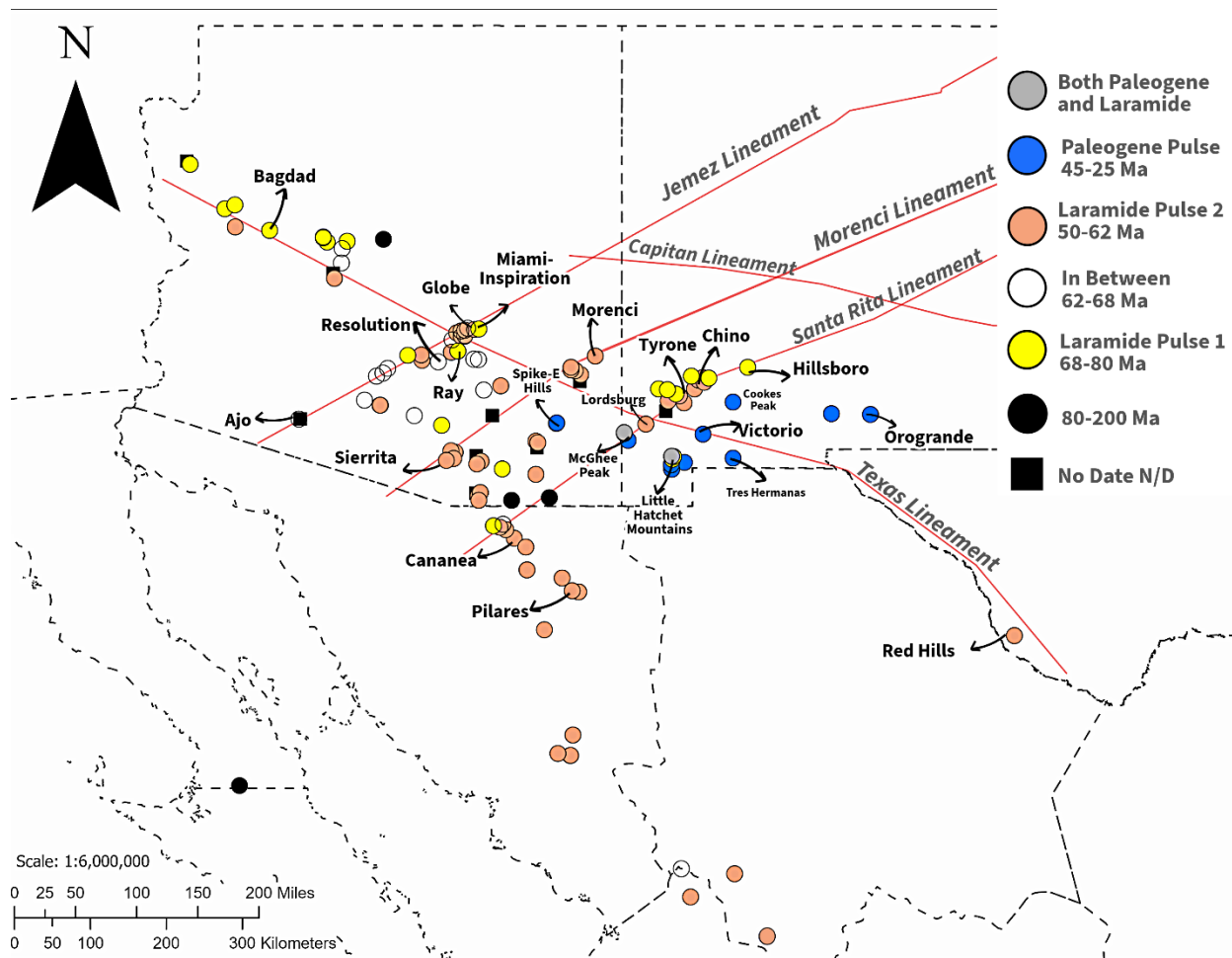


FIGURE 4. North American Porphyry Copper Belt in southwestern U.S. and Mexico (modified by Moses, in preparation, from McLemore, 2008). Deposits are summarized in Appendix 1. Both refers to ages that are Laramide and Paleocene.

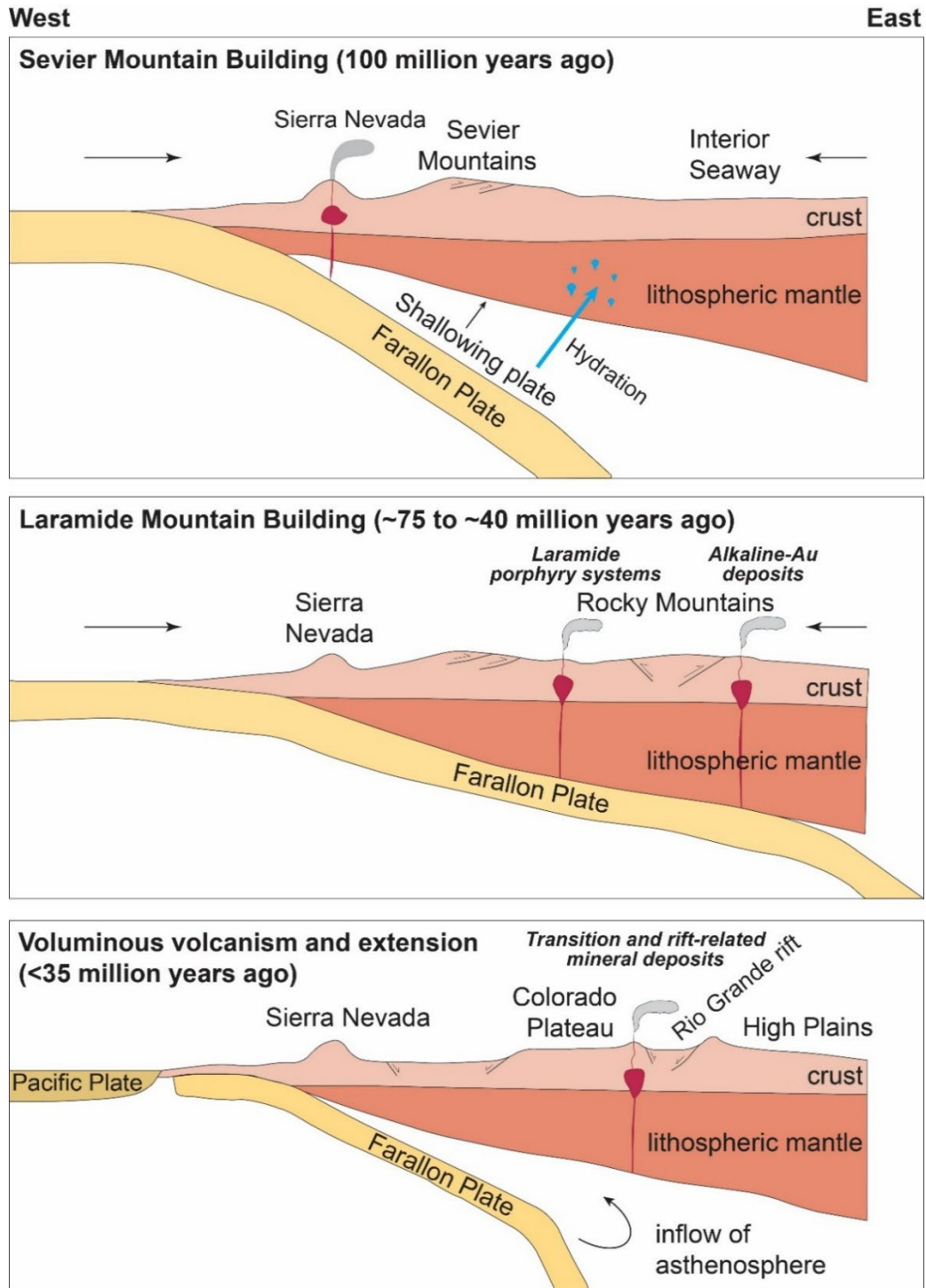


FIGURE 5. Schematic tectonic model of subducting slabs forming porphyry copper mineral systems from Eocene–early Oligocene subduction and compression (Laramide, 80–40 Ma) and mid-Tertiary extension (45–25 Ma; modified from Richards, 2005; John et al., 2010; Price, 2010; McLemore et al., 2025).

The North American Porphyry Copper Belt formed during the Laramide orogeny. The term Laramide is used to describe a specific time period (Late Cretaceous to Paleogene), a structural style (basement involved deformation and uplift associated with major faults), and a type of orogenesis associated with subduction (Weil and Yonkee, 2023; Chapman et al., 2025). The most widely accepted theory of the formation of the Laramide orogeny in the United States is shallow to flat-slab subduction of an oceanic plateau (Coney, and Reynolds, 1977; Saleeby, 2003; Humphreys et al., 2015; Liu and Currie, 2016; Schwartz et al., 2023). However, some studies have challenged this model (McMillan, 2004; Hildebrand, 2009; Jones et al., 2011; Sigloch and Mihalynuk, 2017; Carrapa et al., 2019; Lawton et al., 2020; Glazner, 2022).

The purpose of this report is to: 1) summarize the geology, geochronology, mineral production, and mineral reserves of selected deposits found in the New Mexico portion of the Laramide North American Porphyry Copper Belt, 2) provide a rigorous compilation of geochemical analyses (both new and legacy data) with an emphasis on which specific mineral deposits have elevated concentrations of critical minerals; and 3) develop a better understanding of the distribution of critical minerals within the mineralizing and alteration haloes of porphyry systems. This report focuses on the mineral deposits formed during the Laramide orogeny (80–40 Ma) in New Mexico. Mineral deposits formed during the younger Paleocene to Eocene (45–25 Ma) including porphyry Mo-W, skarn, and CRD (McLemore and Lueth, 2017) are not included in this report but will be in a future publication. This report includes updated interpretations building upon previous compilations describing the North American Porphyry Copper Belt, (Singer et al., 2008; John et al., 2010; McLemore, 2008; Leveille and Stegen, 2012; Vikre et al., 2023; Lamont et al., 2024) based on new geochronological and geochemical data collected in this study. This report is not intended to provide endowments or estimates of critical minerals that can be recovered from porphyry copper deposits, but instead is to provide geochemical and mineralogical analyses of samples from various types of deposits to focus and prioritize future research and resource evaluations. This report is preliminary because not all prospective areas in New Mexico have been sampled and the results of some samples that have been submitted for chemical analyses have not been completed. A future report is planned to evaluate the critical minerals potential of the Arizona, Texas, and Mexico portions of the belt.

Further details about critical minerals occurrences, geology, geochemistry, geochronology, and economic potential are summarized in McLemore et al. (2025) for alkaline-igneous and carbonatites deposits in the North American Alkaline-Igneous Belt, which spans southern Colorado, New Mexico, Texas and Mexico that is located east of the North American Porphyry Copper Belt. The North American alkaline-igneous deposits in central New Mexico (McLemore et al., 2025) and most CRD in southwestern New Mexico (McLemore, 2017) are younger (40–25 Ma) than the North American Porphyry Copper Belt and related deposits (80–40 Ma).

THE PORPHYRY COPPER MINERAL SYSTEM

The mineral deposits found in porphyry copper mineral systems have potential for various critical minerals, including Cu, Zn, Bi, Co, Ni, rare earth elements (REE), Te, Ga, Ge, In, Re, U, and W (John et al., 2010; Vikre et al., 2023) that are found as 1) primary minerals, 2) essential minor constituents in associated minerals, 3) inclusions of crystals within other minerals, 4) substitutions in minerals, 5) crystal defects (regions where the regular atomic structure is disrupted), 6) interstitial sites (void spaces within a crystal structure where atoms usually do not reside and absorbed onto surfaces), 7) intergrown indicating complex hydrothermal processes, and 8) alteration of a primary mineral (McLemore et al., 2026). New and previously published mineralogical and geochemical analyses of ores, mineralized and altered rocks, host rocks, and mine wastes provide insights into the potential of critical minerals in these deposits (Granitto et al., 2020; Vikre et al., 2023).

A variety of mineral deposits are associated with porphyry copper deposits in New Mexico (Fig. 3; McLemore, 2017), many could be at depth beneath known mineral deposits. Deep drilling in districts such as Resolution (Hehnke et al., 2012), Ray (Briggs, 2024), and Red Mountain (Chaffee, 2020) in Arizona have demonstrated porphyry copper deposits are beneath mineralized areas found near the surface. Resolution contains an inferred resource of 1.787 billion metric tonnes of 1.54% Cu and 0.037% Mo, with potential rhenium, tellurium, indium, arsenic, and bismuth at approximately 4500-7000 ft depth (U.S. Forest Service, 2025). Reserves at the Ray mine are estimated as 417.6 million short tons of mill ore (proven and probable) of 0.531% Cu at approximately 1500 ft and 80.8 million short tons of dump leach ore at 0.384% Cu (Briggs, 2024). Additional exploration is needed in most districts in New Mexico to identify any potential at depth.

Note that the use of sericite ($\text{KAl}_2(\text{AlSi}_3\text{O}_{10})(\text{OH})_2$ a phyllosilicate), is controversial with some economic geologists. It is an official mineral recognized by the International Mineralogical Association (Aras and Karaduman, 2025) and is also used as a descriptive term used to describe the replacement of primary minerals or matrix with very fine, ragged grains and aggregates of white to colorless phyllosilicate (typically muscovite, illite, or paragonite) forming a turbid appearance of the original mineral grains (typically feldspars). Sericite is a characteristic alteration in epithermal veins and porphyry copper deposits. The metasomatic process of altering a mineral or rock to sericite is sericitization. Sericitization forms over a wide temperature range and is characterized by replacement of feldspars primarily by fine-grained phyllosilicate mineral, typically mica, with local quartz, hematite, chlorite, and pyrite. This term is used in this report to describe a well-known alteration process and texture.

Porphyry copper deposits

Porphyry copper deposits typically are found in and around relatively small porphyritic diorite, granodiorite, monzonite, and quartz monzonite plutons that were intruded at relatively shallow crustal levels, commonly within 1-6 km of the surface, and are surrounded by crudely concentric zones of hydrothermal alteration (Lowell and Guilbert, 1970; Sillitoe, 2005; 2010; Seedorff et al., 2005; Heinrich, 2024). Mineralizing fluids and other volatiles, build up within the magma and ultimately there is enough pressure to fracture the solidified intrusive porphyry and adjacent host rocks above the magma chamber. Hydrothermal solutions are released through these fractures and react with the host rocks, altering them in a characteristic, concentric zonation

(Lowell and Guilbert, 1970; Sillitoe, 2005; 2010; Richards, 2013; Hurtig et al., 2021). The outer hydrothermal zone (referred to as propylitic alteration) is typically characterized by epidote-chlorite-pyrite mineral assemblages. A quartz-sericite-pyrite (QSP) mineral assemblage alteration zone typically is found closer to the center and can overprint other zones. A central potassic zone of biotite-orthoclase-chalcopyrite mineral assemblage is commonly associated with most of the ore. This hydrothermal alteration can include numerous additional types of mineral assemblages that commonly overlap (Seedorff et al., 2005). In some deposits, the concentric zoning is destroyed and replaced by younger quartz-sericite alteration, such as at the Chino deposit in New Mexico. Alteration zoning is important because it increases the footprint of the mineral deposit. Thus, these alteration zones are excellent indicators of nearby deposits.

Copper minerals are deposited as a part of this interaction between magmatic-hydrothermal solutions along fractures in solid rock. Copper minerals are found as disseminations along thin fractures, zones of brecciation, and within larger stockwork veins. Copper grade varies from less than 0.10 to 1.5% copper, with 2–5% pyrite and varying amounts of gold (0.1–1.5 g/ton), silver, molybdenum, uranium, and other metals and nonmetals, including critical minerals. It is important to note that early production of many porphyry copper deposits was from adjacent, associated base-metal skarn and polymetallic vein deposits. Porphyry copper deposits were generally not mined until 1906 after the development of large-scale, bulk tonnage, open-pit methods of mining at Bingham Canyon mine in Utah, which also coincided with the introduction of steam shovels, the introduction of the railroad in the western states, and improved mineral processing techniques of low-grade copper ores.

Breccia deposits

In many areas mineralized magmatic-hydrothermal breccia pipes are found in or adjacent to the porphyry copper deposits. These magmatic-hydrothermal breccia pipes are different from fault and volcanic breccias in that breccia pipes are not related to faults. Volcanic breccias are layered volcanic rocks that consist of angular rock fragments produced during volcanic eruptions. Breccia pipes are formed above, within or adjacent to some porphyritic intrusions associated with porphyry copper deposits as a result of the sudden, violent release of high-pressure magmatic-hydrothermal fluids that break through the surrounding country rocks (Sillitoe, 1985; Ollier, 20017). Repeated injections of magma and magma degassing can also cause brecciation of the country rock (Sinclair, 2007). This hydraulic fracturing creates near-vertical, permeable conduits (locally termed breccia pipes) focusing volatiles and fluid flow from the magma body towards the surface (Gruen et al., 2012; Almada-Gutiérrez et al., 2024). Not all breccia pipes reach the surface. The breccia pipes consist of broken fragments of the surrounding country rock cemented together by crystallized magma or precipitation of minerals from the magmatic-hydrothermal fluids and minerals are precipitated within veinlets in the matrix or as thin coatings in fractures. The sudden decrease in pressure allows for precipitation of high-grade copper and other metals derived from the nearby magma or leached from the country rocks. Supergene deposits overlie the porphyry deposits.

Skarn deposits

Skarn deposits are found at or near the contacts of the porphyry copper deposits where hot magma intruded into dolomite, limestone, and other carbonate-bearing rocks. Skarn is

Swedish for filth or waste and is a term used for rocks that can have diverse origins, but with similar mineralogy, typically calcium-bearing varieties of garnet and pyroxene (Einaudi et al., 1981; Einaudi and Burt, 1982). Whereas skarns can form in many geological environments, they are common in the southwestern United States in contact metamorphic aureoles, where hot, magmas or magmatic-hydrothermal fluids have intruded calcareous host rocks, and many skarns are associated with porphyry copper deposits and are mineralized by hydrothermal fluids escaping the porphyry magma chamber (Einaudi, 1982). Magnetite, hematite and manganese oxides are common, especially in magnesian (dolomitic) host rocks. Although, chalcopyrite (CuFeS_2) and sphalerite (ZnS) are typically found in relatively minor amounts, they are important ore minerals in this type of deposit.

Skarns can be classified as exoskarn (sedimentary protolith) or endoskarn (igneous protolith). Magnesian and calcic skarns describe the composition of the predominant gangue minerals. Skarns also can be described by their predominant economic minerals as iron (magnetite, hematite), gold, copper, tungsten, molybdenum, and lead-zinc. In most systems, garnet and pyroxene are proximal grading outwards from the igneous source to distal pyroxene and idocrase, depending upon the composition of the host rocks. Marble and/or recrystallized limestone is common. Skarns can be magnesium dominant, and these deposits should be re-evaluated as magnesium is a critical mineral that is essential for making rechargeable magnesium-ion batteries.

Laramide skarn deposits in New Mexico are contact-metasomatic deposits that formed in predominantly Paleozoic dolomites, dolomitic limestones, and limestones adjacent to calc-alkaline plutonic rocks emplaced during the Laramide compressional event (McLemore and Lueth, 1996). Three types of Laramide skarns occur in the North American Porphyry Copper Belt. The first type is composed of copper, typically adjacent to porphyry copper deposits (Einaudi et al., 1981; Einaudi, 1982; Lueth, 1984). The second type, lead-zinc is proximal and includes vein-type deposits (Einaudi et al., 1981; Meinert, 1987; Turner and Bowman, 1993; Lueth, 1996). The third type includes iron skarns (Einaudi et al., 1981; Lueth, 1984, 1996). These skarns, except the iron type, are either copper- or zinc-rich with lead and silver produced as by-products. The largest lead-zinc skarns in New Mexico are in the Fierro-Hanover and Pinos Altos districts.

Copper skarns are intimately associated with many Laramide plutons (e.g. Santa Rita, Pinos Altos), whereas the lead-zinc skarns are typically distal from igneous rocks (Fig. 6). Some lead-zinc skarns occur along faults distal from intrusive rocks (e.g., Groundhog, southwestern deposits at Pinos Altos, Eureka). Most deposits probably formed from mixing of meteoric and magmatic fluids (Ahmad and Rose, 1980; Abramson, 1981; Lueth, 1984; Turner and Bowman, 1993). Grades and tonnages vary (McLemore and Lueth, 1996, 2017). District-scale zoning of metals is common in many areas with iron (magnetite), copper and gold adjacent to the intrusive rocks grading outwards to iron (hematite) and manganese or zinc-lead, lead-zinc, lead-silver, and locally, lead-silver-manganese (Meinert, 1987; McLemore and Lueth, 1996, 2017). Some areas grade into CRD. Iron skarns are common in the North American Porphyry Copper Belt and many were productive, but these deposits are overlooked today because iron is produced elsewhere.

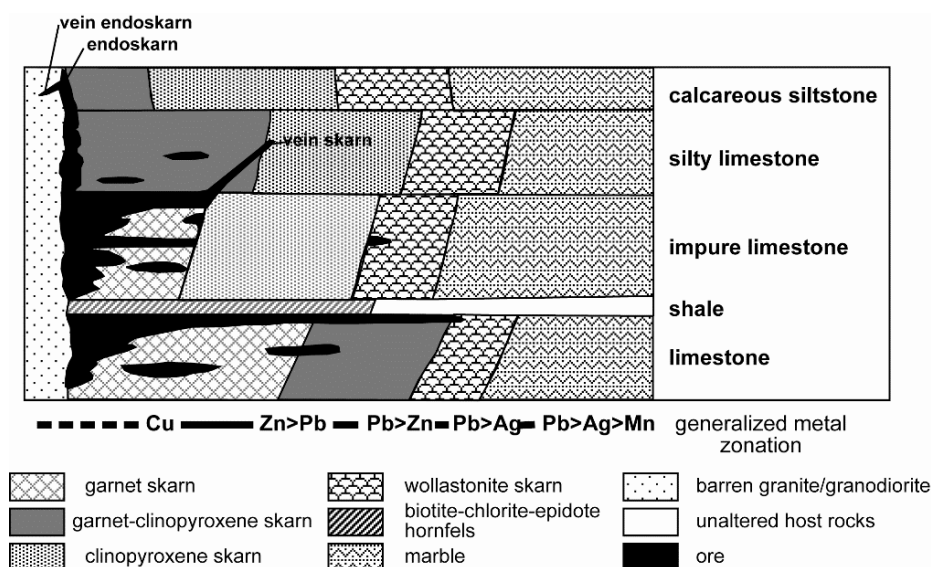


FIGURE 6. Generalized diagrammatic sketch showing mineralization and alteration patterns in Laramide skarns in southwestern New Mexico (from Lueth, 1984, 1996; McLemore and Lueth, 1996, 2017). Garnet forms nearest the stock in the purer limestones. Garnet-clinopyroxene forms adjacent to the stock in the argillaceous carbonate rocks. Hornfels typically forms at the parting shale, and wollastonite and marble form the outer zones. Chalcopyrite occurs in the garnet zone and sphalerite occurs in the clinopyroxene zone and at the contact between the skarn and marble.

Polymetallic vein deposits

Polymetallic vein deposits of probable Laramide age exhibit variations in textures and mineralogy but are similar in age. In some districts with Laramide polymetallic vein deposits, skarns are locally present and economically important. Lindgren (1933) classified these veins as polymetallic veins and Cox and Singer (1986) classified them as mesothermal veins. The term Cordillera veins also has been used. The most important districts in southwestern New Mexico are Malone, Hillsboro, Pinos Altos, Bayard, and Lordsburg.

The deposits at Hillsboro provide a model showing the relationship of Laramide polymetallic vein deposits associated with porphyry copper deposits. Polymetallic veins (Cu, Au, Ag, Pb, Zn, Sb, As, Bi) are hosted in latite dikes intruding andesite, extend radially outward from the Copper Flat porphyry copper deposit at Hillsboro (Fig. 7). Distal CRD containing Ag, Pb, Mn, V, Mo, Zn are found in the southern and northern parts of the Hillsboro district. Geological, geochronological, and geochemical evidence suggests that the mineral deposits found in the Hillsboro district are spatially related and were formed by large, convective magmatic-hydrothermal systems related to the Copper Flat volcanic/intrusive complex (McLemore et al, 1999, 2000b, Geedipally et al., 2012). Two barren porphyritic plutons intruded the volcanic rocks near the mineralized Copper Flat deposit.

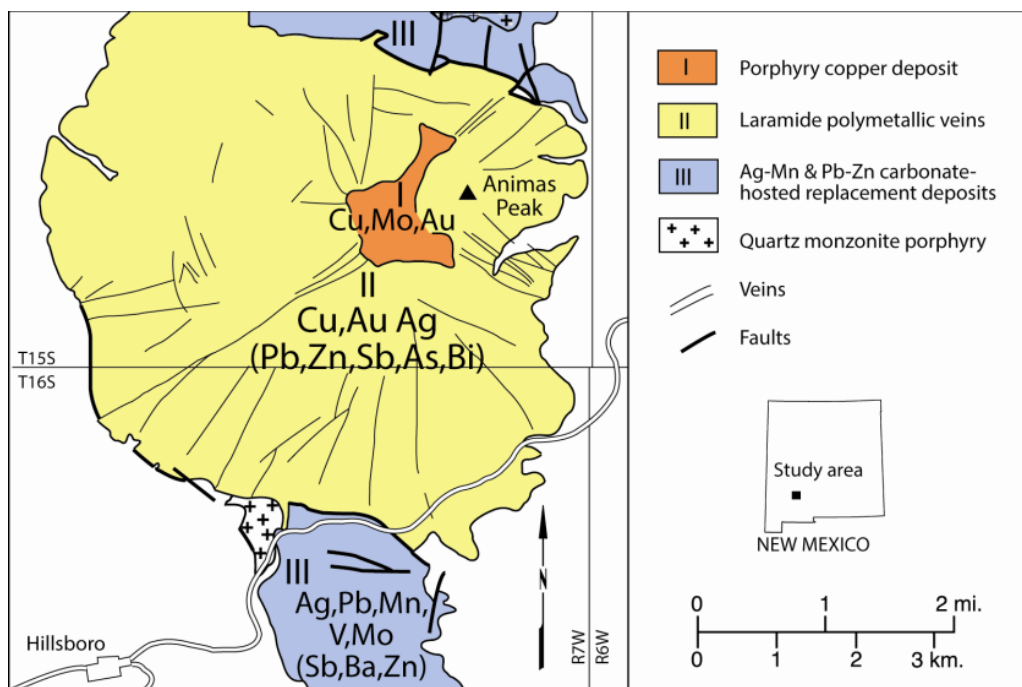


FIGURE 7. Characteristic porphyry-style metal zoning in the Hillsboro district (from McLemore, 1999, 2000b; McLemore and Lueth, 2017). The mineralized breccia pipe is surrounded by polymetallic veins. CRD are found peripheral.

Many of these veins display multiple episodes of veining. Proterozoic rocks are a common host rock (Burro Mountains, Telegraph district), although Cretaceous volcanic and plutonic rocks also are host rocks in some districts (i.e. Lordsburg, Hillsboro). Paleozoic and Cretaceous sedimentary rocks host the veins in the Central district. Laramide polymetallic veins were typically worked for both base and precious metals and locally contain U, W, Te, and Be. Mineral and metal associations are diverse, even within a district.

CRD (carbonate replacement or carbonate-hosted deposits)

Carbonate replacement or carbonate-hosted deposits (CRD) occur throughout southwestern New Mexico and southeastern Arizona; but the ages of most CRD in New Mexico are uncertain (McLemore, 2017; McLemore and Lueth, 2017) and can be as old as 75 Ma (Hillsboro), and young as 20 Ma (McLemore and Lueth, 1996). Some CRD deposits in New Mexico are not related to porphyry copper deposits, but are found near Oligocene calderas (Magdalena, Kingston, Lake Valley; Chapin et al., 2004; McLemore and Lueth, 1996, 2017). CRD include replacements in carbonate rocks with little or no calc-silicate minerals, minor skarns with few calc-silicate minerals, and minor veins in carbonate rocks near intrusive rocks. There are three predominant types in New Mexico: lead-zinc ($\pm$ copper, silver), silver-manganese (lead, iron), and molybdenum-tungsten. Some districts have no known associated pluton or igneous intrusion in the immediate vicinity. Carbonate replacement deposits are found in the Hillsboro and other districts (Victorio Mountains, Apache Hills, Fremont, etc.), but their relationship to intrusions is not always clear.

Distal disseminated gold-silver deposits

Distal disseminated gold-silver deposits are low-grade, disseminated gold-silver with local manganese deposits that form in sedimentary rocks distal from any potential magmatic source. They can be associated with CRD or Carlin-type gold deposits (Henry et al., 2023; Huff et al., 2025) and are controlled by structures and stratigraphy. Although distal disseminated gold-silver deposits (including Carlin-type deposits) have not been identified in New Mexico, at least one exploration company is examining southwestern New Mexico for similar deposits. One example in Nevada is the Battle Mountain district (Theodore, 1998).

Epithermal gold-silver veins (low/intermediate sulfidation)

Lindgren (1933) defined the term *epithermal* to include a broad range of deposits that formed by ascending hydrothermal waters at shallow to moderate depths (<4500 ft), low to moderate temperatures (50–200° C), and which are typically associated with intrusive and/or volcanic rocks. It is now generally accepted that epithermal deposits were formed at slightly higher temperatures (50–300° C) and relatively low pressures (a few hundred bars) based on fluid inclusion and isotopic data. White (1955, 1981) established the now-recognized association between epithermal mineral deposits and active geothermal or hot springs systems (Chapman et al., 2018). Subsequent work by Henley (1985) and associates (Henley and Brown, 1985) in New Zealand, and many other researchers elsewhere, confirmed this association. However, there are many small hot spring systems with no known associated gold or base metals. The difficulty remains in identifying paleo-geothermal systems that contain economic concentrations of gold and/or base metals. Most epithermal vein deposits in New Mexico are associated with Oligocene to Miocene volcanic fields and calderas (Cox and Singer, 1986; McLemore and Lueth, 2017), however epithermal veins are found in some districts that could be Laramide in age and possibly associated with porphyry copper mineral systems at depth. These epithermal veins differ from the Laramide polymetallic veins by being more gold and silver rich and formed closer at the surface by cooler meteoric fluids.

High-sulfidation epithermal gold deposits

High-sulfidation epithermal gold deposits are shallow, disseminated gold deposits associated with acid-sulfate (i.e., advanced argillic; Fig. 8) altered rocks found in many districts in the world (John et al., 2018), such as Round Mountain, Nevada (Tingley and Berger, 1985); Red Mountain and Summitville, Colorado (Rye et al., 1992; John et al., 2018); and El Indio (John et al., 2018). Not all of these deposits are associated with porphyry copper systems; many in New Mexico and elsewhere are associated with calderas and hot spring systems (McLemore, 1993; McLemore and Lueth, 2017). They form by hot, sulfuric, highly acidic fluids derived from deeper magmas (volcanic sources) that rise to the surface and interact with the host rock, locally forming hot springs and geysers. These deposits are characterized by gold, pyrite, and enargite in vuggy silica, veinlets, stockworks, and breccias in zones of acid-pH altered rocks. Bonanza veins can form, but deposits of fine-grained gold disseminated in the host rock also are common (White and Hedenquist, 1990). High-sulfidation epithermal gold deposits are similar to lithocap and supergene copper deposits because of the similar styles of alteration but differ in alteration zoning. The altered areas in high-sulfidation epithermal gold deposits can be differentiated into three zones on the basis of mineralogy, texture, and inferred temperatures (Fig. 8, 9; White and

Hedenquist, 1990; McLemore, 1993) as 1) clay zone (argillic to advance argillic), 2) silicified zone (characterized by vuggy silica and high temperature clay), and 3) massive alunite and silica/chert zone. Boundaries between the zones are typically gradational and are distinguished by quartz content and texture. Critical minerals found in these deposits include silver, copper, gallium, potassium, and alunite (source of aluminum).

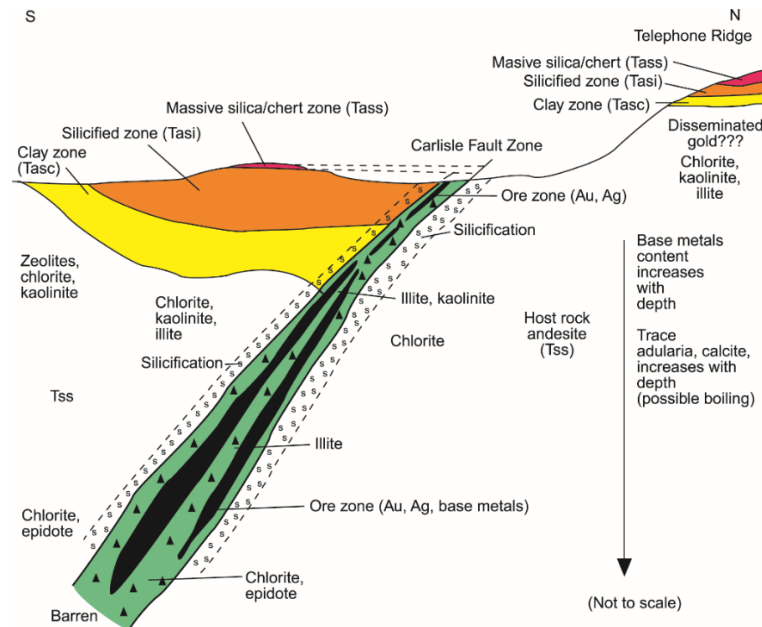


FIGURE 8. Schematic relationship between alteration and vein deposits along the Carlisle fault in the Steeple Rock district (from McLemore, 1993). Tss = Oligocene andesitic volcanic rocks.



FIGURE 9. High-sulfidation epithermal (gold) deposits in the Goat Hills and Saddleback Mountain (skyline) in the Steeple Rock district, New Mexico (V.T. McLemore photograph, looking north).

Lithocap deposits

Lithocap deposits are laterally and vertically extensive, stratabound zones of clay alteration (advanced argillic alteration) and silicification (vuggy silica) that form at the surface by magmatic-hydrothermal fluids from an underlying magma, generally a porphyry copper deposit (Cooke et al., 2017). Most lithocaps are barren or have low-grade copper oxides disseminations above the porphyritic ore zone. Lithocaps form due to volcanic gases such as H₂S, SO₂ and HCl mixing with meteoric waters, where they oxidize and dissociate, forming highly acidic fluids that drive leaching and alteration, leaving behind a porous, silica-rich cap. Advanced argillic alteration is typically surrounded by argillic and propylitic alteration assemblages. Rapid uplift and erosion may result in the lithocaps overprinting the core of the porphyry deposit, producing deposits with overlapping alteration and ore zones (Sillitoe, 1995; Sillitoe and Hedenquist, 2025). Uplift and erosion rates result in the lithocap and related high-sulfidation mineralization forming several hundred meters or more above the porphyry deposit. Lithocaps are highly altered, high-crustal level surface targets which can be used for exploration and indicators of potential porphyry bodies at depth. Critical minerals include gallium, potassium, and aluminum found in the mineral alunite and other Al-sulfate minerals (halotrichite).

Supergene copper deposits

Supergene or oxide copper deposits are near-surface, low-temperature, secondary-enriched mineral deposits formed by near-surface oxidization of hypogene sulfide minerals by meteoric water (rainwater or groundwater) circulating in the upper portions of a fractured copper sulfide deposit (Blancard, 1968; Chavez, 2000). The circulating water within fractures leaches or oxidizes copper from the hypogene copper sulfide minerals, transports the copper downward along fractures, and reprecipitates copper (as secondary sulfate minerals, chalcocite, malachite) at the groundwater table, which acts as a reducing boundary (called the supergene-hypogene boundary). The descending oxidizing waters forms a distinct vertical zonation (Chavez, 2000) from the upper gossan cap (Fe-oxides and hydroxides), leached zone (silicified zone), oxidized zone (malachite, azurite, native copper and cuprite), water table, enriched zone, to the lower primary hypogene zone (chalcopyrite and bornite). Fluctuating water tables can overprint these alteration zones. Supergene processes can increase the copper content of a deposit. Supergene copper deposits are amenable to relatively inexpensive heap leaching and SX/EW methods, but only copper is recovered leaving any critical minerals in the heap-leach pile. Supergene enrichment zones can overprint the hypogene mineralization of the porphyry deposits.

TECTONIC SETTING

Prior to the Late Cretaceous, southwestern New Mexico had not experienced significant volcanism since Grenville rift-related magmatism at 1.3–1.0 Ma (Karlstrom et al., 2004; Chapin et al., 2004; Bright et al., 2011). The Jurassic-Lower Cretaceous Mexican Borderlands rift did affect southern New Mexico from the Little Hatchet Mountains southward as evidenced by minor basalt flows in the Broken Jug Formation (Lawton and McMillan, 1999; Lawton, 2004; Leveille and Stegen, 2012; Lawton et al., 2020). The Bisbee and Cochise porphyry copper deposits in southern Arizona are Jurassic in age (200 Ma; Leveille and Stegen, 2012; Lewis, 2021; Lamont et al., 2024) and part of this Jurassic rift system (Lewis, 2021). However, by Late Cretaceous times, things changed significantly in New Mexico.

The North American Porphyry Copper Belt is generally attributed to Laramide (80–40 Ma; Barton, 1996; Keith and Swan, 1996) magmatism and compressional deformation resulting from the subduction of the Fallon plate beneath the North American plate (Fig. 4, 10; Sillitoe, 1972; Seedorff et al., 2005). Since Late Cretaceous time, western North America has undergone almost constant tectonic and volcanic activity related to this subduction zone and subsequent thrust faulting, folding, uplifts, and basin and range extension (Keith and Wilt, 1986; Seager, 2004; McMillan, 2004). Laramide deformation and magmatic activity extended eastward as far as the Copper Flat igneous complex and porphyry copper deposit near Hillsboro (McLemore et al., 1999, 2000b) and as far southeastward as the Red Hills intrusion in Trans-Pecos Texas (Gilmer et al., 2003; Frelinger, 2013). Bagdad in western Arizona is the western-most producing deposit in the belt; and Big Sandy and Mineral Park are the most western of the known deposits. The structural style of Laramide compressional deformation and magmatism is typically attributed to the low-angle subduction and subsequent breakup of the Farallon plate, which resulted in the locus of magmatic activity shifting eastward with time (Fig. 4; Coney and Reynolds, 1977; Damon et al., 1983; McMillan et al., 2000; McLemore et al., 2025). Flattening, roll-back, and slab tearing resulted in slab melting, the formation of oxidized melts conducive to porphyry mineralization and different geochemical signatures of the porphyry copper deposits (Rosenbaum et al., 2008; Cooke et al., 2014; Lamont et al., 2024). The magmatism was localized by deep-seated Proterozoic basement structures that channeled crustal melts, resulting in the Laramide intrusions found in the North American Porphyry Copper Belt.

The entire North American Porphyry Copper Belt was subsequently affected by younger Basin and Range extension with horst- and graben-type faulting, locally tilting and offsetting some porphyry copper deposits, especially in Arizona. Some deposits in Arizona were affected by formation of the Arizona metamorphic core complexes and detachment faulting. Many of New Mexico Laramide deposits such as in the Little Hatchet Mountains and McGhee Peak, also experienced block faulting and tilting during younger events. Starting at 46–35 Ma and persisting until at least 18 Ma, extensive intermediate to silicic calc-alkaline to alkaline volcanism and associated plutonism occurred throughout much of New Mexico and Arizona as the tectonic style of deformation changed from compressional to extensional.

Numerous widespread silicic calderas and andesitic to basaltic volcanic centers erupted in this interval yet represent only part of a regional late Eocene-Oligocene volcanic province that extends from Southern Colorado to the Sierra Madre Occidental of Mexico (Fig. 10; McDowell and Clabaugh, 1979; McIntosh et al., 1991, 1992; McIntosh and Bryan, 2000). Within southwestern New Mexico and Arizona, silicic caldera volcanism is informally divided into the northern Mogollon-Datil volcanic field and the southern Boot Heel volcanic field. Approximately 15

calderas have been identified in the Mogollon-Datil field and approximately ten calderas in the Boot Heel field (Fig. 9; McIntosh and Bryan, 2000), and regional ignimbrites (ash-flow tuffs) linked to most of the calderas have been recognized (Elston, 1984; Ratté et al., 1984; McIntosh et al., 1991, 1992; McIntosh and Bryan, 2000). Caldera volcanism in these two volcanic fields occurred in two temporally distinct pulses: 36–32 Ma, and 29–24 Ma. In central and eastern New Mexico, alkaline to subalkaline igneous rocks (46–19 Ma) are found along a north-south belt, roughly coinciding with the Great Plains physiographic margin with the Basin and Range (Rio Grande rift) and Rocky Mountains physiographic provinces (McLemore et al., 2025). The Mogollon-Datil volcanic field lies to the north of the North American Porphyry Copper Belt and porphyry copper deposits could be buried by the Mogollon volcanics. The Sierra Madre Occidental caldera field lies in eastern Mexico and could also overlie older porphyry deposits. Most of the deposits in the North American Porphyry Copper Belt lies west of the Rio Grande Rift, except for Organ, Orogrande, Cave Peak, and Red Hills (Fig. 10).

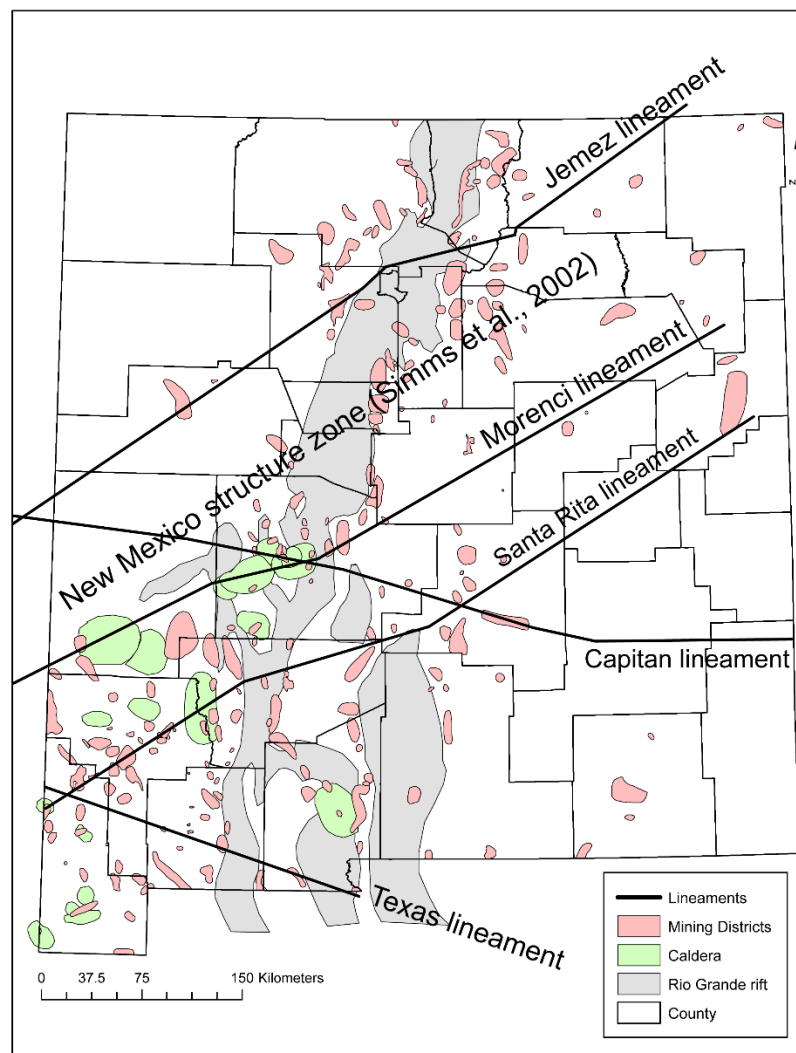


FIGURE 10. Mining districts in New Mexico in relationship to calderas and lineaments.

Newly compiled magnetic and gravity maps have resulted in refined interpretations of the tectonic setting of New Mexico and adjacent areas. Linear geophysical features, lineaments, appear to correlate with the alignment of magmas and mineral deposits in western U.S. (Fig. 3; Hildenbrand et al., 2000; Kucks et al., 2001; Sims et al., 2002). A lineament is an extensive regional linear feature that is believed to reflect deep crustal structure (Neuendorf et al., 2005; McLemore and Zimmerer, 2009). Sims et al. (2002) define the New Mexico structure zone as a northeast-trending zone that is 250 km wide and roughly parallels the Colorado mineral belt, one of the more famous mineral belts. The Colorado mineral belt is an alignment of alkaline igneous plutons and associated, relatively large alkali epithermal gold deposits forming the northeast-trending gold-silver belt in central Colorado (Chapin, 2012). Sims et al. (2002) showed that north-east trending magnetic anomalies are aligned along the northeast-trending New Mexico structural zone, which is most likely controlled by Proterozoic basement structures (Muehlberger, 1980; Goff and Kelley, 2021). Note that New Mexico-Arizona lineaments are not controlled by single faults or structures but are defined by several geologic factors including multiple subparallel fault zones, volcanic and intrusive rocks, geophysical anomalies, high heat flow resulting in geothermal centers, and mineral deposits (Muehlberger, 1980; Goff and Kelley, 2021). Local offsets occur (Muehlberger, 1980; Goff and Kelley, 2021).

The relationship between lineaments and mineral deposits, especially porphyry copper deposits is not a new concept and many of these lineaments are commonly interpreted as Proterozoic accretionary suture zones (Richards, 2000; Sims et al., 2002; McLemore and Zimmerer, 2009; Chapin, 2012). The Jemez lineament in New Mexico is a northeast-trending, long-lived intracontinental lithospheric conduit for Miocene to Holocene magmatism that appears to predate mineral deposits in the Old and New Placers, Cerrillos, Elizabethtown-Baldy and Laughlin Peak districts that are found along it (Fig. 10; Nereson et al. 2013, Goff and Kelley 2021; McLemore et al., 2025). Miami, Resolution, Pinto Valley, Ajo and many more porphyry copper deposits are along the Jemez lineament (Fig. 3). The Morenci lineament is defined primarily by the Morenci, Safford, and other porphyry copper deposits (Fig. 3; Chapin, 2012; McLemore and Zimmerer, 2009). Chino (Santa Rita), Tyrone, Malone, Lordsburg, McGee Peak, Bisbee and other porphyry copper deposits lie along the Santa Rita lineament (Fig. 3; Chapin, 2012; McLemore and Zimmerer, 2009). The Capitan lineament is defined by the east-trending alignment of Railroad Mountain dike near Roswell, Capitan Mountains pluton, and Jones Camp dike (McLemore et al., 2025). The modern Socorro magma body also lies along the western portion of the Capitan lineament, but no known porphyry copper deposits are found on this lineament. Perhaps this is an exploration target? These hypotheses dovetail nicely with the views of Titley (2001), suggesting that metals in the porphyry copper deposits are derived from Proterozoic basement sources moving along regional fracture zones.

METHODS OF STUDY

A methodology was designed to systematically evaluate critical minerals potential and mineralogical associations. Figure 11 provides a summary diagram of the methodology.

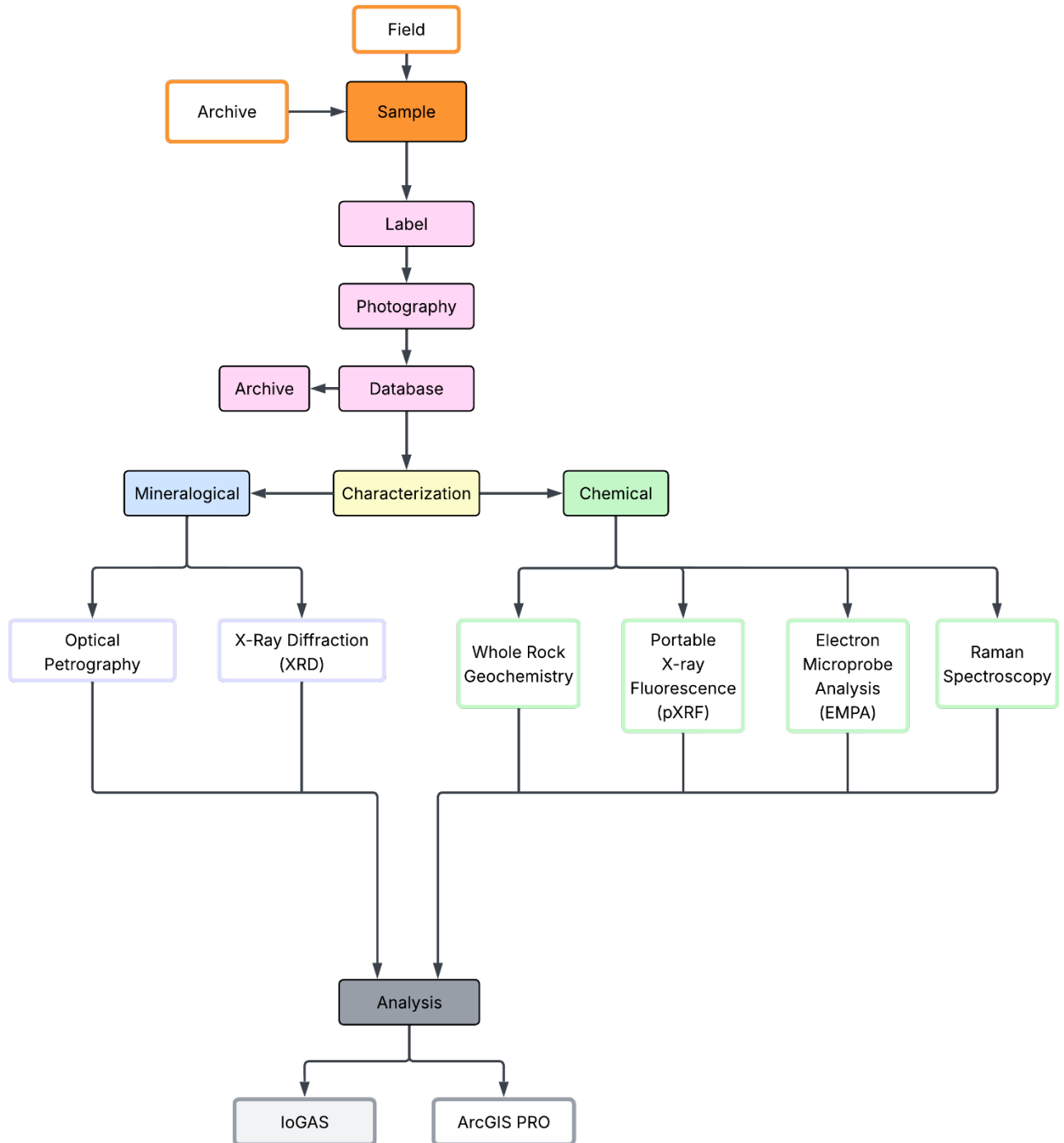


FIGURE 11. Research methodology diagram.

Previous data

An important step in this study is to compile all published and unpublished data from existing mines and prospects within southwestern New Mexico, including historical accounts from newspaper articles, older geologic reports, and other precompetitive data (Jowitt and Fisher, 2025). Jowitt and Fisher (2025) identified several types of data that are considered precompetitive, including geochemistry, mapping, county reports, and mineral reports that are accessible to stakeholders on the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) web page. Mineral databases were examined, including the Mineral Resource Data System (MRDS) of the USGS (Mason and Arndt, 1996), the Minerals Industry Location System (MILS) of the U.S. Bureau of Mines (USBM), U.S. Forest Service Abandoned and Inactive Mines database, AMLIS (U.S. Bureau of Land Management, BLM) and the mine features from topographic maps database (Horton and San Juan, 2025). Published and unpublished reports and files at the NMBGMR were also examined. Using these data, mineral occurrences, deposits, mines, prospects, resources, and mills were identified, plotted, and entered in the NMBGMR New Mexico Mines Database (McLemore et al., 2005a, b). Mines, prospects, and quarries in the area are identified by the unique mine identification number (NMGRxxxx, New Mexico Mines Database) throughout the report to avoid confusion between different mines with the same name.

Appendix 1 provides a summary of the porphyry copper and associated deposits in New Mexico, including geochronology and known critical minerals. Most of the deposits are not currently being produced but are potential exploration targets. Some of the plutons are barren and do not have a known productive porphyry copper deposit, but many have significant skarns or veins associated with the plutons. Production and reserve data are compiled in Appendix 2.

Project databases

Databases were developed for this project. Initially, data were collected and stored in MS Access databases. Data collected were migrated to a MS SQL Server (SQLS) database, and the Access front-end forms were reworked to connect to the database server to increase reliability, efficiency, and security. Location, descriptions of samples, and other information from photographs taken in the field and thin sections are recorded in the SQL database. SOPs (Standard Operating Procedures) were developed for the project and provided in McLemore and Trivitt (2026, appendix 3).

Drill core

NMBGMR retains drill core of mineral deposits from locations throughout the North American Porphyry Copper Belt. Specific drill holes were selected for logging, sampling, and photographing based on location (mining district), completeness of the core, core description, presence of mineralized zones and availability of data on the core. Drill core was logged describing the lithology, color, mineralogy, phenocryst size and shape, alteration, fracture intensity, and hardness. Grain size cards were used to determine phenocryst shape and rounding, and tables were used to determine alteration and fracture intensity. Drill core was photographed with hole, box, and depth information and then replaced in the original position. Samples were collected of mineralized and altered zones and unaltered host rocks. Drill core samples were split in half using a drill core splitter or saw. One half of the core was returned to the box to preserve

the core. The other half was split into sufficient sizes for thin section preparation and chips for chemical analysis. Sampled intervals are indicated in the core box by a note denoting sampler, date, purpose, project, hole, box, and depth. Photographs of the core are found at <https://photoarchive.nmt.edu/>.

Sampling

Samples from outcrops, mine waste rock piles, mine workings, drill core, and rarely subcrop or float were collected by project personnel, analyzed, and used to supplement published and unpublished precompetitive data. Generally, three types of samples were collected (unaltered igneous intrusions or country rock (classified as host), mineralized, and altered samples, also classified as host) for geochronological, mineralogical, and geochemical analyses. Mine wastes from dumps and tailings and other mine wastes were collected separately for characterization of mine wastes (McLemore et al., 2025, 2026). Appendix 3 contains chemical analyses of samples. Appendix 4 contains mineral chemistries, and Appendix 5 contains summary statistics of geochemical analyses in Appendix 3. Mineralized and altered areas that were previously sampled and analyzed before this project are included (precompetitive or legacy data). These geochemical data were combined and used in the chemical interpretations. Since very few of these legacy samples were available for petrographic analyses, some sites were resampled for this study. Location, type of sample, and other descriptive data were entered into the project database. Most samples were composite samples (i.e. combination of individual samples over an outcrop, generally 0.3-1 m in diameter), although select (high-grade or highly mineralized) or chip (i.e. combination of individual samples over a specified length) samples of mineralized and altered areas were collected for specific analyses. Samples were slabbed and scanned. Samples (slabbed samples, thin sections, hand samples, mineral separates, probe samples) are archived at NMBGMR for future examination.

Characterization methods

Petrography and mineralogy

A variety of nomenclatures for the igneous rocks in these districts have been used in previous studies; the rocks typically are porphyritic in a fine-grained matrix and include both shallow intrusions and deeper plutonic rocks. The nomenclature of intrusive igneous rocks in this report mostly conforms to the international classification (Le Maître, 2002), where the primary classification of igneous rocks is based upon mineralogy, or by plotting whole-rock geochemical analyses on a TAS diagram for fine-grained rocks (Irvine and Baragar, 1971) and R1–R2 (De la Roche et al., 1980) diagrams.

Petrographic analyses were performed using standard petrographic techniques (hand lens, binocular microscope, polarizing microscope and reflective light microscope). These analyses were supplemented by thin-section petrography, X-ray diffraction (XRD), handheld portable X-ray fluorescence (pXRF), and whole-rock chemical analyses. Hand sample descriptions, including mineralogy and texture of samples, slabbed samples, epoxy mounts, and thin sections, were entered into the project database. Polished thin sections of selected samples of the host, altered, and mineralized rocks were made by commercial laboratories. Thin sections were scanned in plane and plane-polarized light, and selected photomicrographs were taken. The

mineralogy of selected samples was determined by visual, petrographic, and XRD methods. Modal mineralogy was estimated using standard comparison abundance charts. Mineral concentrations and phase percentages, grain size, roundness, and sorting were estimated visually using standard charts (Carpenter and Keane, 2016). Bulk mineral identification can identify minerals in quantities greater than approximately 3%. Estimates of primary and secondary minerals were determined, cementation and alteration described, and mineralogy and lithology were described (Folk, 1974; Carpenter and Keane, 2016). Any special features were noted. Mineralogy of selected samples was determined using XRD, Raman spectroscopy, and electron microprobe analyses (EMPA). Detailed petrographic analyses are in theses associated with this project (Stafford, 2024; Sanchez, 2025; Newcomer, 2025; Appah, 2026; Moses, in preparation).

X-ray diffraction (XRD) analysis

Whole rock and mineral separates were powdered to perform XRD analysis using the Panalytical X'Pert Pro Diffractometer at the NMBGMR XRD laboratory. Analyses were conducted using 45 kV X-ray beam tension and 40 mA X-ray beam current. A diffractogram is produced. X'Pert HighScore Plus software was used to interpret the XRD data by comparing measured X-ray peak intensities and matching the patterns to a Powder Diffraction File database that correspond to specific mineral structures.

Raman spectroscopy

Raman spectroscopy was performed on mineral grains, hand samples, epoxy mounts and thin sections at the Raman Spectroscopy laboratory at NMBGMR to identify mineralogy. Raman spectra of selected mineral phases were measured on a Horiba LabRAM HR Evolution confocal Raman Microscope utilizing a 532 nm laser and a 1800 or 600 grooves/mm grating. The Raman microscope is equipped with an automated XYZ stage. Standardization and calibration were carried out using a Horiba SPRCO standard objective at 1000 cm^{-1} and validated against a silica waver at 520 cm^{-1} . Measurements were carried out using the x50 LWD Olympus objective variable laser intensity set to between 1% and 10% with average acquisition times of 10 s and 3–5 acquisitions per analysis. Spatial resolution for the Raman spectrometer is 1 μm , and the precision of the instrument was $\pm 0.25 \text{ cm}^{-1}$ using the 1800 grooves/mm grating and $\pm 0.8 \text{ cm}^{-1}$ using the 600 grooves/mm grating. Measured Raman spectra were corrected for background and compared to standards from the RRUFF database (Laetsch and Downs, 2006) for mineral identification.

Geochemical analyses

Geochemical data are an essential part of evaluating critical minerals resources. Sample preparation and geochemical analyses of solid samples collected for this study were performed by USGS laboratories (Appendix 3). Analytical methods are described in the spreadsheet with the geochemical analyses (Appendix 3). Duplicate samples and reference standards were analyzed (Appendix 3); the uncertainty of most analyses is generally <5%. Chemical compositions of igneous rocks and mineral deposits in the North American Porphyry Copper Belt from various sources also are in Appendix 3. Note that these geochemical analyses may not be representative of the individual copper deposits because of the low number of analyses and

were generally randomly collected (Appendix 3). Samples were collected to determine the presence of critical minerals, not to calculate grades and tonnages. Analytical methods, methods of analyses, detection limits, and analytical errors are described in the various cited reports. Mineralized areas were examined and sampled during 1980-2026 by the authors.

Chemical plots were created using ioGAS-64 ([ioGAS™ - REFLEX \(reflexnow.com\)](https://www.reflexnow.com)). REE plots are typically normalized to a standard, such as chondrite in order to remove the systematic zig-zag patterns due to the Oddo-Harkins effect. Normalization produces a smoother curve that is easier to interpret. Box and whisker plots are similar to histograms and provides visual representations of data distribution, illustrating the minimum and maximum ranges as whiskers along with the median value and quartile ranges as boxes of a given dataset. Box and whisker plots were used to represent the range and distribution of elements over certain districts and types of mineral deposits. Other plots and descriptive statistics can be created using ioGAS-64 and are used in this report. Correlation diagrams plot one element versus another element. In some cases, the elements do show a correlation, in other cases, the elements show no correlation between them. Downhole vertical plots show the distribution of elements vertically down a drill hole, with 0 ft representing the surface and the depths indicated.

Electron microprobe studies (EMPA)

Samples with high or suspected critical minerals were selected and analyzed for major and minor element compositions of specific minerals (Appendix 4). All preparation work was completed at the NMBGMR electron microprobe lab. Rock samples were cut to billet size, set in plastic ring molds, backfilled with Spurr 4-part epoxy, and cured at 80°C for four hours. A subset of the picked grains were analyzed on the electron microprobe. These samples were mounted in leucite 4-hole mounts, backfilled with Spurr 4-part epoxy and cured. All cured samples were polished using diamond polishing wheels (168 µm, 63 µm and 30 µm) and finished with diamond polishing powder slurry on Buehler polishing cloth (15 µm, 6 µm) down to 1 µm and coated with approximately 20 nm of carbon.

Prepared samples were analyzed using the Cameca SX-100 electron microprobe with four wavelength dispersive spectrometers (WDS) located at the NMBGMR. Backscattered electron (BSE) images were used to observe textures, identify phases with high mean atomic number, and assess REE phase abundance. WDS qualitative element scans and WDS X-ray maps were used to identify the mineral phases. Major, minor, and trace element concentrations were collected on specific mineral phases using a 20 nA beam current and an accelerating voltage of 15 kV. Eudialyte, bastnäsite, monazite, and feldspars were analyzed with a 10 µm beam diameter, and 5 µm for calciocatapleiite due to their small size in most samples. All other mineral phases were analyzed with a point beam (~1 µm). Microprobe analytical conditions, standards and secondary standards can be found in Appendix 4.

⁴⁰Ar/³⁹Ar Geochronology

Biotite, hornblende, amphibole, mica, K-feldspar, and groundmass concentrates were prepared using conventional techniques at the New Mexico Geochronology Research Laboratory (NMGR). Samples were crushed using a jaw crusher and disk mill crusher. The crushed samples were sieved into three size fractions using 1.41 and 0.420 mm (14 and 40 mesh) sieves and the 14-40 mesh size fraction was washed in deionized water. Crushed materials were

sonicated in hydrochloric acid, rinsed and then sonicated in hydrofluoric acid depending on the condition of the mineral grains intended to be picked. Cleaning samples in an ultrasonic bath enables the mineral grains to be broken apart and as well as remove fines between those clusters. Cleaned samples were magnetically separated using a Frantz Isodynamic Magnetic Separator. If needed, separated samples were separated by density using heavy liquids (LMT) to concentrate and sink biotite and amphiboles, or to float feldspar from quartz grains. Altered mineral grains were removed and clean mica or amphiboles were picked using a binocular microscope. In samples that lacked either phase, mostly homogeneous groundmass grains were picked to remove the non-potassium bearing crystals. Picked phases were analyzed using SEM-EDS or XRD to better assess their potassium content and mineral phase, respectively.

Picked samples were loaded into 8-hole aluminum disks to be irradiated. Irradiation NM-316 contained five samples for this project and was conducted at the USGS TRIGA reactor in Denver, Colorado. They were irradiated for 16 hours and returned to NMGR. Irradiations NM-322 and NM-324 contained nine and twelve samples, respectively and were irradiated for 24 and 21 hours at the Oregon State University TRIGA reactor in Corvallis, Oregon. Samples were co-irradiated with flux monitor FC-2 sanidine crystals using the age 28.201 Ma (Kuiper et al, 2008) and the decay constant of $5.463 \times 10^{-10}/\text{yr}$ (Min et al., 2000).

Following irradiation, feldspar monitors were loaded into 421 stainless steel laser trays and degassed as single-crystal fusions by a 55-watt CO₂-laser and analyzed on a high-sensitivity ARGUS VI multi-collector mass spectrometer. Samples were loaded into 37-hole stainless steel trays, placed under vacuum, and step heated with ten steps using a Photon Machines 810 nm diode laser at NMGR. The samples were then analyzed using the Helix MC Plus multi-collector mass spectrometer. Atmospheric air ($^{40}\text{Ar}/^{36}\text{Ar} = 295.5$, Neir, 1950), blank air, cocktail (internal reference gas with a $^{40}\text{Ar}/^{39}\text{Ar}$ ratio of 6.71), and blank cocktail measurements were taken between each sample to aid in calibration and assist in data reduction. Data was reduced using PyChron software version 20.1.1 (Ross, 2014) and ages were assigned by either step-heating spectral analysis or inverse-isochron. The preferred age was a plateau age as defined by Fleck et al. (1977). If no plateau was available, the inverse isochron or integrated spectrum age was selected as the preferred age.

Additional information on analytical procedures, age calculations and instrumentation can be found in the various theses associated with this project (Stafford, 2024; Sanchez, 2025; Moses, in preparation). All published $^{40}\text{Ar}/^{39}\text{Ar}$ ages are recalculated using FC-2 Fish Canyon Tuff sanidine age of 28.201 Ma after Kuiper et al. (2008).

Quality control (QA) and quality assurance (QC)

The samples and field data (including field observations and measurements) are the basic component of the data collection and interpretation, which ultimately leads to the project conclusions. Therefore, it is important to understand the spatial and geological context and to describe the types of samples collected, sample preparation, and sample analyses. The purpose of this section is to describe the QA/QC procedures to support the accuracy and precision for the entire project and the geochemical (Appendix 3) and mineralogical analyses obtained by NMBGMR. The data were obtained from the various laboratories and at least 10% of the data were validated or checked by an additional staff member to assure the data were entered into the database properly. If during validation, data were found to be entered incorrectly, the error was immediately corrected. This section only describes the sample collection and preparation of

samples collected during the project. The QA/QC procedures for the electron microprobe laboratory at NMIMT are explained at <http://geoinfo.nmt.edu/labs/microprobe/home.html>.

The determination of total error or uncertainty of a measurement depends upon several parameters, including the sample error and analytical error (Rollinson, 1993; Schreuder et al., 2004). The sample error is the error that results from studying the collected sample instead of the entire population and depends upon completeness, comparability, and representativeness, as defined below:

- *Completeness*—the comparison between the amount of valid, or usable, data originally planned to collect, versus how much was collected.
- *Comparability*—the extent to which data can be compared between sample locations or periods of time within a project, or between projects.
- *Representativeness*—the extent to which samples depict the true condition or population being evaluated.

Sample heterogeneity is the error caused by observing a single sample instead of the whole population and typically is dependent upon the sample-to-sample variation that is controlled by collecting a sample of suitable size relative to the heterogeneity of the sampled material, as well as sampling enough material to characterize the population (Wellmer, 1989).

All analytical measurements are incorrect at some level and are measured against an agreed upon standard of analysis. It is just a question of how large the errors are compared to an agreed upon standard of accuracy, but if those errors are acceptable. These are typically defined in the original sampling plan. Analytical error is the error that results from laboratory analysis, is typically reported by the laboratory, and is defined by precision and accuracy.

Precision is the degree of agreement among repeated measurements of the same characteristic and is monitored by multiple analyses of many sample duplicates and internal standards. It can be determined by calculating the standard deviation, or relative percent difference, among samples taken from the same place at the same time (i.e. duplicates and triplicates, Fig. 8). *Accuracy* measures how close the results are to a true or accepted value and can be determined by analyzing certified reference standards as unknown samples and comparing with known certified values (Fig. 12).

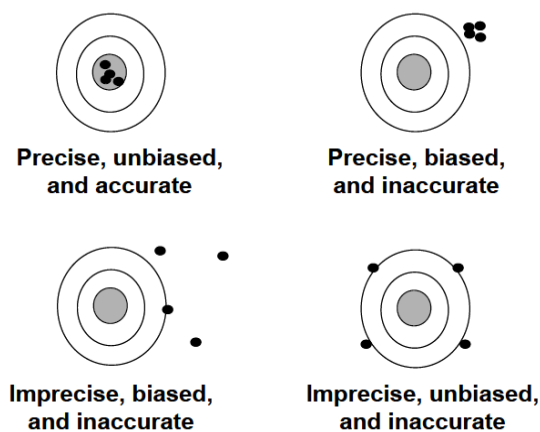


FIGURE 12. Diagram illustrating the difference between precision, bias, and accuracy (from McLemore et al., 2026).

Two types of standards, certified standards and internal, were used. Laboratories used certified standards, which are commercial standards with certified values as determined by round robin analyses at numerous certified laboratories. The certified standards are expensive, so internal standards also were submitted with each batch. The internal standards are samples collected and analyzed by different methods and over several years' time. Numerous duplicates and triplicates were submitted blind to the laboratory and analyzed with each sample batch to compare and assess analytical precision, accuracy, and representativeness. Duplicate samples were also sent to different laboratories. Detection limits can vary between laboratories and even samples. Uncertainty of analyses is generally <5% of duplicate samples and standards that were analyzed.

The sum of major oxides should total between 98 and 101% (Appendix 3), however, many samples have lower or higher totals. Extreme totals are found mostly in mineralized samples, especially samples with high F, Ba, Pb, S, or Cu. The precision of analyses is acceptable (within 10%) for samples where multiple analyses of the same sample were obtained for this report. For every 10 samples submitted, a duplicate sample was analyzed; most of these analyses compared within 10%.

There are numerous reasons why duplicate samples and standards do not always reproduce precisely. Some samples, such as rhyolite and basalt, grind into a powder more easily than other samples, such as stream-sediment samples and nepheline syenites. Fusion techniques required for XRF analyses vary from lab to lab and can differ between different personnel that could result in variations between sample pairs. Analytical error is higher for analyses with concentrations close to the detection limit. In addition, dump samples and alluvium are very heterogeneous and difficult to completely homogenize. Most variations between duplicate samples are probably a result of sample inhomogeneities and analytical errors related to low concentrations of trace elements.

Accuracy of the data is how close the measured value is to the true or accepted value. Analyzing certified standards as unknown samples and comparing these values with certified values can monitor accuracy. Each laboratory is responsible for the accuracy of the data they produce, and the laboratory's QA/QC protocols are available upon request from the project manager. In general, analyses obtained from the laboratories agree with certified values of certified standards and precision is excellent between multiple analyses (see Appendix 3).

Differences between certified standards and duplicate pairs do exist. Generally, no corrective procedures could be applied to solid samples. Variation in preparation of the glass disk used in the XRF analysis is a major cause of these differences. Nugget effects can account for variations in Cu, Fe, Pb, S, Zn, and Zr, observed in some pairs of samples. An example of the nugget effect is where a small grain of native gold or other mineral occurs in one split and not the other split and thus produces a higher concentration. Another variation between certified values and the results provided by the laboratories is a result of different analytical techniques. ICP requires acid digestion and analysis of a liquid-based solution. In some cases, not all of the solid will be completely digested and can result in a lower value than that obtained by certified values generated using XRF or instrumental neutron activation analysis (INAA).

Samples were collected, prepared, and analyzed according to standard methods for each specific laboratory analysis. 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). Effective sampling and analysis help plan the field program and the control of

accuracy and precision. This 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 PI were performed to ensure that procedures were followed.

Most legacy samples were analyzed by NMBGMR, ALS Global, Skyline, USGS, New Mexico State University or USBM laboratories in the past, where the uncertainty of analyses was reported as generally <5%. Most chemical analyses by the exploration and mining companies were performed at the same commercial laboratories used by NMBGMR with similar QA/QC. Some REE analyses were deleted from interpretations in this report because the REE analyses were below detection limits or only a few REE were determined.

MINIMUM CONCENTRATIONS OF CRITICAL MINERALS FOR EXPLORATION: HOW GOOD IS GOOD ENOUGH?

This section proposes a practical way to decide whether early exploration results for critical minerals are “good enough” to justify advancing an exploration project. Critical minerals are produced from primary ore deposits as well as secondary sources (e.g. cobalt from battery recycling, platinum group metals from catalytic converters). They also can be extracted as byproducts or recovered from unconventional sources, such as coal and coal combustion products (e.g., fly ash). However, as critical minerals continue to face increasing global demand, mineral exploration for new deposits becomes an important tool in ensuring long-term supply security. To determine whether the concentration of critical minerals in a deposit can justify spending further resources on an exploration target, it is necessary to evaluate and understand established cut-off grades of actively operating mines and exploration sites (Otoo et al., 2025a, b). These cut-off grades provide a benchmark for assessing whether exploration targets contain sufficiently high concentrations for economic consideration.

In exploration, the preliminary cut-off grade acts as an early filter to guide resource allocation toward promising targets. Cut-off grade is dynamic and shaped by multiple factors including, logistical, geological, economic, and processing techniques. Larger deposits depend upon high grades and tonnages and include lower cut-off grades because economies of scale. Whereas smaller deposits typically require higher grades to remain viable. Mining and processing methods also play a significant role. For instance, brine evaporation in lithium extraction generally allows for lower cut-off thresholds compared to more expensive hard-rock mining techniques with higher cut-off grades. Additionally, the recovery of valuable byproducts or coproducts such as niobium or uranium can offset production costs and effectively lower the required cut-off grade of the primary mineral.

A study by Otoo et al., (2025a, b) reviewed active mines and exploration sites across different deposit types to establish concentration thresholds for exploration targets. Exploration thresholds are set at approximately 70% of the lowest cut-off grade used in comparable active mining or exploration operations. For example, Greenbushes mine in Australia, which is one of the largest and highest-grade pegmatite lithium deposits, reports cut-off grades between 0.5 and 0.7% Li_2O (SEC, 2023). Similar projects with cut-off grades around 0.4% Li_2O could still be considered attractive for further exploration, depending on deposit size, mining and processing methods, and other economic factors. This approach helps align exploration with realistic economic standards and reduces the risk of pursuing sub-economic deposits.

Tonnages and cut-off grades of economic deposits vary with the commodity and type of deposits (Table 1). For example, what is economic for REE in carbonatites (10–15% total REE) differs from potentially economic values in coal deposits (500 ppm total REE). It also is important to compare chemical compositions to crustal abundance (Otoo et al., 2025a, b).

TABLE 1. Concentration of trace elements (ppm, except where noted) within the upper continental crust and recommended exploration values. *DOE recommended value. **recommended by Dai and Finkelman (2018). ppm—parts per million.

Element (ppm, unless noted)	Shaw et al. (1967, 1976)	Gao et al. (1998)	Taylor and McLennan (1985, 1995)	Wedepohl (1995)	Rudnick and Gao (2003)	Hu and Gao (2008)	Recommended crustal abundance values (ppm)	Cut-off grades for various economic deposits (ppm or stated)	Recommended exploration value (ppm)
Li	22	20	20		21	41	41	320 (brine), 4000 (pegmatite)	224 (brine), 2800 (pegmatite)
Co	12	17	17		17.3	15	15	0.14%	980
Ni	19	38	44		47	34	34	0.6%	0.42%
Cu	14	32	25		28	27	27	0.2%	0.14%
Zn	52	70	71		67	75	75	2.2%	1.5%
As		4.4	1.5	2	4.8	5.7	5.7		100
Cd	0.075	0.079	0.098	0.102	0.09	0.06	0.06		100
Se		0.15	0.05	0.083	0.09		0.09		100
Y	21	17.4	22		21		21	300**	210
Ag		55	50	55	53		53		100
Ga	14	18	17		17.5	18.6	18.6		100
Ge		1.34	1.6	1.4	1.4	1.3	1.3		100
Ce	65.6	66.4	64		63		63		500
Sc								100*	70
Total REE								2.4%	500*
Hg	0.096	0.0123		0.056	0.05		0.05		100
Ti	0.524	1.55	0.75	0.75	0.9	0.55	0.55		0.1%
Be	1.3	1.95	3	3.1	2.1	1.9	1.9	300	210
Zr	237	188	190		193		193	2000**	1400
Nb	26	12	12		12	11.6	11.6	300**	210
Sb		0.3	0.2	0.31	0.4	0.075	0.075	1000	700
Ta	5.7	0.74	1	1.5	0.9	0.92	0.92		100
W		0.91	2	1.4	1.9	1.4	1.4	1500	1050
Pb	17	18	17	17	17		17	1.5%	1.05%
Th	10.3	8.95	10.7		10.5		10.5		1000
V	53	98	107	53	97	106	106	3000	2100
U	2.45	1.55	2.8		2.7	2.6	2.6	1300	910

EXPLORATION AND MINERAL PRODUCTION IN NEW MEXICO

New Mexico's mineral wealth is among the richest endowments of any state in the U.S. New Mexico is home to 243 mining districts (McLemore, 2017) and most of them contain critical minerals. The mining history of most of the mining districts associated with porphyry copper mineral systems is summarized by Anderson (1955), Northrop (1996), Bartsch-Winkler (1997), and McLemore et al. (1996). Most of New Mexico's energy and mineral production currently comes from oil, gas, coal, copper, potash, industrial minerals, geothermal, and aggregates; past uranium production also was significant (McLemore and Lueth 2017; McLemore, 2017; McLemore and Trivitt, 2026). Mining in the North American Porphyry Copper Belt, found in southwestern New Mexico, has been an important economic industry with copper currently produced at Chino (along with gold and silver) and Tyrone. Although copper production elsewhere in New Mexico hasn't occurred since the 1990s, active exploration is ongoing, especially for critical minerals (Fig. 13). Production and reserves from mineral deposits in the New Mexico portion of the North American Porphyry Copper Belt is in Appendix 2.

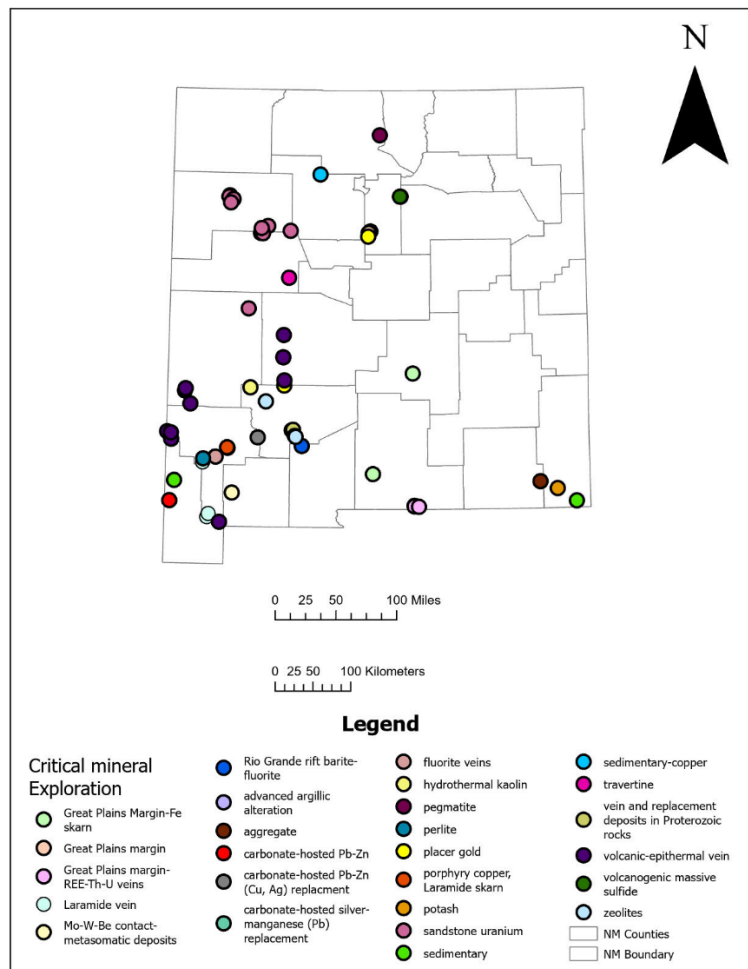


FIGURE 13. Exploration projects in New Mexico in 2025–2026.

Energy and mineral extractive industries are vital to the economy of New Mexico and to the maintenance of public education and services. These industries provide important minerals needed to maintain technology-dependent lifestyles that are heavily dependent upon mining to manufacture components needed for our lifestyles. The minerals industries provide property and corporate income taxes, while their ~100,000 direct employees (including oil, gas, and mining) contributed millions of dollars of personal income taxes (New Mexico Energy, Minerals and Natural Resources Department, 2025). The multiplier effect of dispersal of these wages through local economies increases their impact many fold. Furthermore, additional production of copper and other critical minerals is required for the transition to carbon-free energy sources.

This study has additional benefits. Several mining companies working in these districts are interested in understanding the potential for critical minerals on their properties (i.e., Donegan Resources, Inc. in the Victorio district; Standard Silver Corp. in Steeple Rock and Black Hawk districts). Residents of several small communities in rural southwestern U.S. are concerned about the mineral resources near their communities and this project will aid in their understanding of these resources in these areas. These data will increase our understanding of ore formation, mineral-resource potential, consumption, disposal, and how minerals and mineral extraction interact with the environment. State and Federal government decision makers, mining companies, and the public require this information for land use decisions, remediation prioritization, and to determine if some of these deposits can be mined.

Despite the interest in critical minerals, the number of mines and value of produced minerals has remained relatively stable in recent years (Fig. 14, 15). However, numerous complex and interrelated factors affect the current and future production; some of the more important factors include declining or fluctuating commodity prices, declining quality of ore (for example lower grades and more difficult ore to process), competition from throughout the world (i.e. a global market), and a shift in using alternative energy sources besides oil, gas and coal for generating electricity. Other factors have hampered new mines from opening in the state. These challenges include water rights issues, availability of water, public perceptions, and public opposition to mining, along with the complexity and length of time for the entire regulatory process to occur in the U.S. at local, state, and federal levels. All these factors add to the cost of mining, not only in New Mexico, but throughout the world.

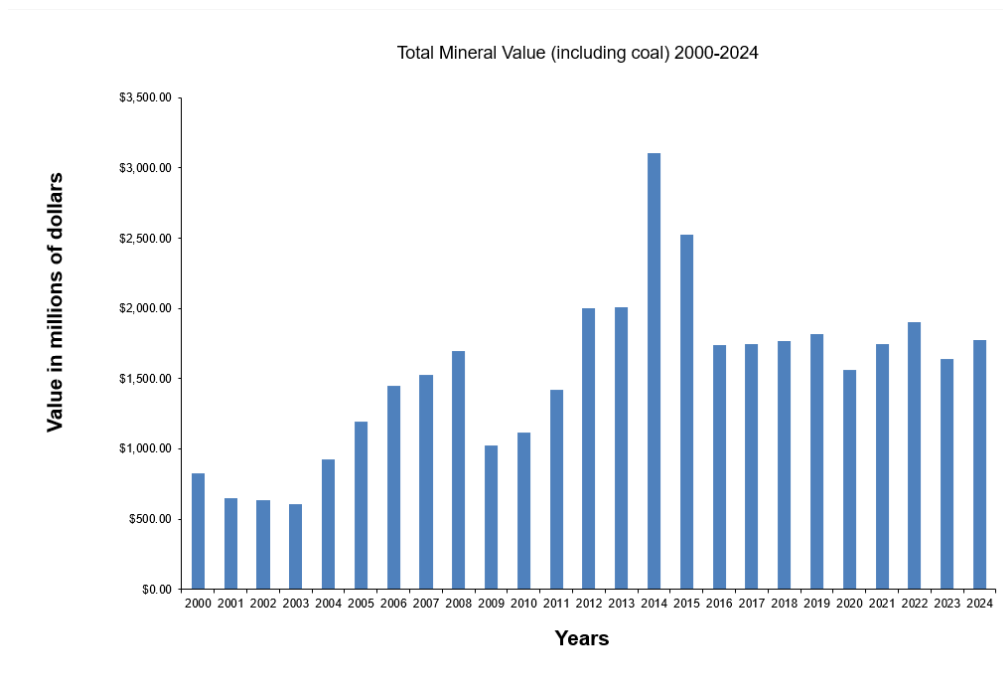


FIGURE 14. Production of minerals (total value excluding oil and gas production) from New Mexico (data from New Mexico Energy, Minerals and Natural Resources Department, 2000–2025).

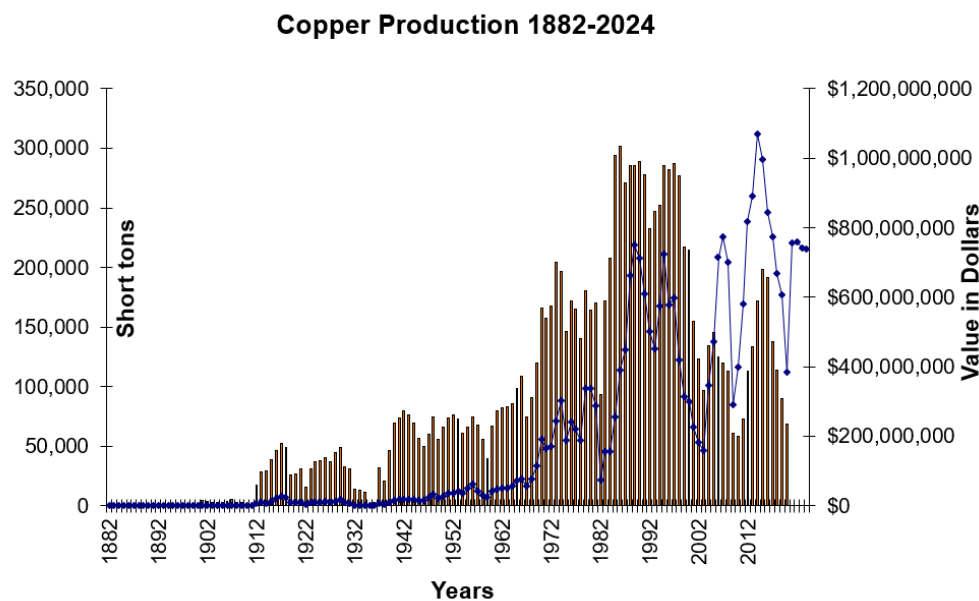


FIGURE 15. Copper production from New Mexico (data from Lindgren et al., 1910; U.S. Geological Survey, 1902–1927; U.S. Bureau of Mines, 1927–1990; New Mexico Energy, Minerals and Natural Resources Department, 1989–2025). The bars are production in short tons and the blue line is the value in dollars.

DESCRIPTIONS OF SELECTED MINERAL DISTRICTS ASSOCIATED WITH THE LARAMIDE NORTH AMERICAN PORPHYRY COPPER MINERAL SYSTEM

Introduction

Brief descriptions of many of the porphyry copper and related mining districts in the North American Porphyry Copper Belt in New Mexico are below. Appendix 1 summarizes the districts in the belt. Production and reserves from mineral deposits in the New Mexico portion of the North American Porphyry Copper Belt are summarized in Appendix 2. Chemical analyses are in Appendix 3. Detailed petrographic, mineral chemistry, and geochronology data are in the various theses associated with this project (Geedipally et al., 2012; Stafford, 2024; Sanchez, 2025; Newcomer, 2025; Appah, 2026; Moses, in preparation). Mines, prospects, and quarries in the area are identified by the unique mine identification number (NMGRxxxx, New Mexico Mines Database) throughout the deposit descriptions.

Hillsboro district (Copper Flat porphyry copper deposit)

The Hillsboro mining district in the Animas Mountains, central New Mexico is one of the oldest Laramide mineral deposits in New Mexico and includes the Copper Flat porphyry copper deposit (NMSI0610). Early discovery in 1877 resulted in production of the Laramide polymetallic vein and placer gold deposits and production continued through the 20th century (Table 2). The porphyry Cu-Mo-Au deposit was discovered in the 1970s, with Quintana Minerals briefly operating the open pit for several months in 1982 (Fig. 16). The Rattlesnake mine (NMSI1671) was in operation until around 1992, but production was small. Between 1877 and 1992, the district's total estimated production reached approximately 8,100,000 pounds of copper, 160,000 ounces of lode gold, 120,000 ounces of placer gold, 134,000 ounces of silver, and 154,000 pounds of lead (Table 2). Zinc production was small and not available. Zinc was not always recovered in the past because of low zinc prices, lack of demand, and difficulties in recovering zinc. Proven reserves at Copper Flat porphyry copper deposit are estimated at 78.9 million short tons with a grade of 0.32% Cu (504,685,000 pounds), 0.010% Mo (15,717,000 pounds), 0.003 ounces/ton Au (237,000 ounces), and 0.07 ounces/ton Ag (5,520,000 ounces), while probable reserves amount to 34.1 million short ton with 0.25% Cu (675,820,000 pounds), 0.007% Mo (20,563,000 pounds), 0.003 ounces/short ton Au (340,000 ounces), and 0.04 ounces/short ton Ag (6,889,000 ounces) (Zimmerman et al., 2020).



FIGURE 16. Copper Flat open pit, looking north (V.T. McLemore photograph).

TABLE 2. Metals production from the Hillsboro district, Sierra County (U.S. Geological Survey, 1902–1927; U.S. Bureau of Mines, 1927–1990; Harley, 1934; M3 Engineering and Technology Corporation, 2012; McLemore et al., 1999; Geedipally et al., 2012). *Includes production from Tierra Blanca district in 1939 and from the Caballo district in 1957. Production from 1902–1932 is estimated from unpublished records. Some zinc was produced from the Hillsboro district but was not reported.

Year	Ore (short tons)	Copper (pounds)	Lode gold (ounces)	Placer gold (ounces)	Silver (ounces)	Lead (pounds)	Value (\$)
1877–1904	—	—	134,000	104,000	—	—	6,750,000
1891	—	—	—	—	—	—	253,000
1892	—	—	—	—	—	—	354,424
1893	—	—	—	—	—	—	458,388
1894	26,225	310,000	16,785	—	112,500	—	432,680
1902	1428	3400	988	—	1,508	80,000	20,500
1903	8	—	6	—	—	—	1
1904	1,000	16,000	2,400	—	8,001	—	52,000
1905	3,464	35,984	552	—	3,644	—	12,800
1906	3,200	5,000	684	—	3,733	—	15,500
1907	602	4,255	236	—	1,311	—	5,000
1908	827	7,124	551	—	12,157	73	17,000
1909	194	15,523	401	—	1,755	860	8,900
1910	5,530	1,747	94	—	1,585	296	1,880
1911	2,570	4,555	92	—	1,005	422	1,840
1912	90	2,918	90	—	510	94	1,800
1913	4	352	13	—	34	—	280
1914	6	939	11	—	43	—	220
1915	10	1,442	32	—	197	129	640
1916	56	5,621	71	—	889	246	1,400

Year	Ore (short tons)	Copper (pounds)	Lode gold (ounces)	Placer gold (ounces)	Silver (ounces)	Lead (pounds)	Value (\$)
1917	38	5,377	63	—	3,835	4,616	4,300
1918	14	3,693	—	—	4	—	700
1919	58	3,044	160	—	524	5,945	3,700
1920	688	17,278	428	—	2,500	—	11,000
1921	9	73	30	—	1	—	600
1922	38	4,939	111	—	688	—	2,300
1923	53	2,845	210	—	415	725	4,200
1925	61	5,210	79	—	830	—	1,600
1926	52	5,878	143	—	1,354	2500	3,000
1927	656	13,658	436	—	1,306	4333	8,800
1928	34	2,000	123	—	306	—	2,500
1929	41	3,222	79	—	50	—	1,600
1930	109	7,302	159	—	563	—	3,300
1931	469	4,100	4,278	—	525	7700	85,600
1932	497	9,000	342	—	1,204	16000	7,100
1933	272	3,000	239	221	1,277	600	10,177
1934	761	14,100	462	1,139	4,647	700	60,109
1935	666	22,000	1,098	1,761	2,561	18,400	104,481
1936	983	34,980	1,638	1,620	4,571	—	120,788
1937	469	17,400	357	1,234	2,587	—	70,309
1938	268	13,900	425	2,073	2,104	—	90,138
1939*	1,160	29,900	868	2,271	3,427	100	115,306
1940	1,084	25,000	684	1,688	2,219	3,300	87,588
1941	4,581	20,000	432	989	1,562	1,100	53,269
1942	11	—	16	582	79	—	20,811
1943	—	—	—	4	—	—	70
1944	—	—	—	8	—	—	175
1946	12	400	7	—	83	—	377
1947	4	—	1	—	3	—	20
1948	6	—	4	—	65	—	199
1949	11	1,000	35	—	338	—	1,728
1950	111	3,600	121	—	491	—	5,428
1951	1,214	—	289	—	52	—	0,162
1952	563	—	125	—	30	—	4,402
1953	1,230	—	265	—	51	—	9,426
1955	10	400	2	3	11	—	2,259
1957*	304	3,300	4	58	4	—	1,138
1961	16	118	12	—	17	63	350
1982	1,200,000	7,400,000	2,289	—	55,996	—	5,000,000
Total 1877-1992	1,261,767	8,091,577	173,032	117,651	245,152	148,202	14,287,101
Estimated total 1877-1992		8,100,000	160,000	120,000	134,000	154,000	14,500,000

A summary of the igneous and mineralizing events is in Table 3. The Hillsboro district is dominated by Cretaceous andesite flows (75.4 ± 3.5 Ma), breccias, and volcanoclastic rocks that erupted from a volcano (Fig. 17). The mineralized Copper Flat quartz-monzonite porphyry (CFQM, 73.97 ± 0.66 Ma) intruded the vent of the volcano (Fig. 18). The unmineralized Warm Springs quartz monzonite (74.4 ± 2.6 Ma) and a third altered, unmineralized quartz monzonite intruded along fracture zones on the flanks of the volcano. Younger latite and quartz latite dikes

intruded the andesite and CFQM and radiate outwards from the CFQM; the polymetallic vein deposits are associated with these dikes. Alteration of the igneous rocks consists of locally intense silicification, biotite, potassic, phyllic, and argillic alteration. Large jasperoid bodies have replaced the El Paso Formation, Fusselman Dolomite, Lake Valley Limestone, and Percha Shale in the southern part of the district. Re/Os dating for molybdenite yielded an age of 76.2 ± 0.5 Ma (Stafford, 2024).

The igneous rocks are part of a differentiated comagmatic suite. The andesites are metaluminous and alkaline; the quartz monzonites and latites are peraluminous and alkaline to subalkaline. The linear variation in Nb/Zr, Zr/TiO₂, V/TiO₂, and various major elements suggests that the igneous rocks are comagmatic (McLemore et al., 1999, 2000b). The igneous rocks are classified as Within-Plate Granite by Pearce et al. (1984; McLemore et al., 1999, 2000b). These data are consistent with a subduction-related back-arc extension setting.

TABLE 3. Sequence of major geologic events in the Hillsboro mining district. Deposition of the Copper Flat porphyry copper and vein deposits and formation of jasperoids most likely overlapped in time. From McLemore et al. (2000b).

Geologic Event	Age (McLemore et al., 2000b)	Mineralization And Alteration
Eruption of alkali basalt	4 Ma	None
Uplift of the Copper Flat volcanic/intrusive complex followed by erosion	21–22 Ma to present	Minor supergene enrichment of porphyry copper deposit, Placer gold deposits
Eruption of Sugarlump and Kneeling Nun Tuffs (Emory caldera)	35–34 Ma	None in the Hillsboro district
Burial? or possibly minor erosion?	75 M–35 Ma	Minor supergene enrichment of porphyry copper deposit?
Formation of jasperoids	75–35 Ma	Followed by deposition of carbonate-hosted replacement Ag-Mn and Pb-Zn deposits
Latite and quartz latite dikes	75–70 Ma	Vein (Au, Ag, Cu) deposits, type 4, 5, and 6 alteration (McLemore et al., 2000b)
Intrusion of quartz monzonite porphyry and formation of breccia pipe deposit	75 Ma	Porphyry copper deposits (Cu, Au, Ag, Mo), type 1, 2 and 3 alteration, formation of skarn and marble in limestone
Eruption of andesite volcano	75 Ma	None, possible early deuteric alteration

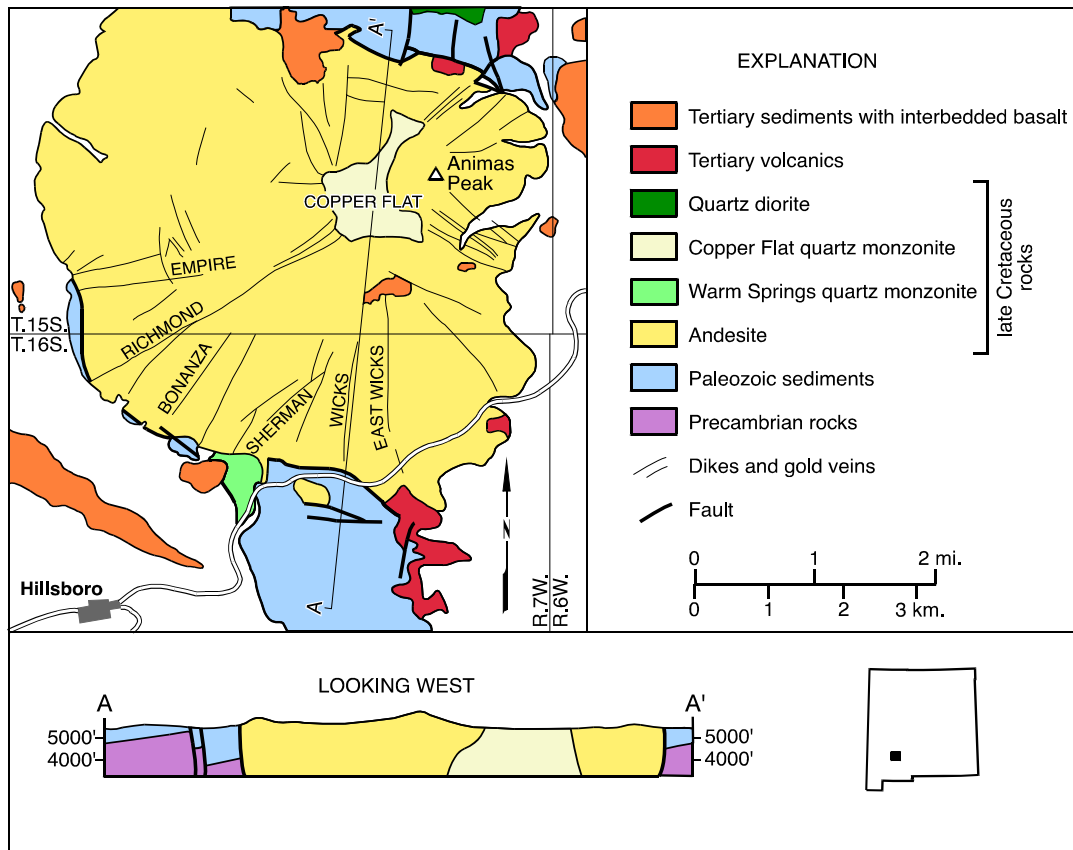


FIGURE 17. Simplified geologic map of Hillsboro district (modified from Hedlund, 1977a, b, 1985a, b; Jochems et al., 2014).



FIGURE 18. Copper Flat quartz monzonite porphyry, near the pit lake (photo by V.T. McLemore).

Many workers in the district have recognized district-wide zoning (Fig. 7; Harley, 1934; Reeves, 1963; Fowler, 1982; McLemore et al., 1999, 2000b; Geedipally et al., 2012). Trending radially from the CFQM are Laramide Au-Ag-Cu veins (Fig. 17). CRD (Ag, Pb, Mn, V, Mo, Zn) are located in the southern and northern parts of the district, distal from the center. The Copper Flat quartz-monzonite porphyry stock (CFQM) intruded the vent facies of an andesitic volcanic/intrusive complex and hosts porphyry copper mineralization. Polymetallic veins are associated with latite/quartz latite dikes and both radiate outwards from the CFQM and are flanked by distal carbonate-hosted Pb-Zn and Ag-Mn replacement deposits to the south and north. Miocene-Holocene placer gold deposits occur in arroyos draining the CFQM and vein deposits.

The Copper Flat porphyry copper deposit is a low sulfur (<7%) system with little supergene enrichment compared to many of the larger porphyry copper deposits in the North American Porphyry Copper Belt. The Copper Flat deposit consists of copper, gold, silver, and molybdenum disseminated in a quartz-monzonite stock and in stockwork quartz veins (Dunn, 1982, 1984; Hedlund, 1985b; McLemore et al., 1999, 2000b). Much of the ore is concentrated within a breccia pipe (Fig. 19) that is 1,300 ft long, 600 ft wide, and has a vertical extent of almost 1,000 ft with veins of pegmatitic material to 1,700 ft (Castellano et al., 1977; Dunn, 1982; Wallace, 2016). Predominant minerals include pyrite, chalcocite, chalcopyrite, azurite, malachite, and cuprite and minor amounts of molybdenite, galena, bornite, tetrahedrite, vanadinite, willemite, wulfenite, and sphalerite also are present (Northrop, 1996; McLemore et al., 2000b; Stanszak, 2006). Chalcopyrite is the predominant copper mineral. Gold and silver occur as electrum. Molybdenite is the predominant molybdenum mineral. Thin veinlets containing quartz, chalcopyrite, pyrite, bornite, biotite, and epidote cut the porphyry. Oxidation is restricted to the upper 18-25 ft of the sulfide zone (Castellano et al., 1977). Overburden ranges from 0 to 20 ft.



FIGURE 19. Veinlets of chalcopyrite and pyrite in the Copper Flat quartz monzonite porphyry stock. From drill hole CF11-013 at depth of 320 ft.

Fluid inclusion data indicates that the mineralizing fluids had temperatures of 179–359°C and contained 7.7–34.4 eq. wt.% NaCl (Norman et al., 1989). The composition of the inclusions in the fluids from the vein and the porphyry-type deposits are similar, suggesting that the mineralizing fluids forming the two deposit types were from a common source. Norman et al. (1989) concluded that depositional processes, not differences in fluid composition, controlled mineral precipitation.

The polymetallic veins are along latite/quartz latite dikes and consist of quartz, pyrite, clay, iron oxides, barite, malachite, pseudomalachite, chrysocolla, chalcopyrite, bornite, free gold, galena, and several additional minor minerals (Harley, 1934; Hedlund, 1985b). Some veins are as much as 1500 m long and 0.8–3 m wide. They are typically en echelon and pinch and swell. The polymetallic veins locally grade along strike into an alteration zone of sericite and pyrite with little or no metals concentrations. The polymetallic veins vary in chemical composition, but are typically enriched in Au, Ag, Cu, As, Bi, Pb, Zn, Sb, and depleted in Mo relative to the porphyry copper and carbonate-hosted replacement deposits in the district (McLemore et. al., 1999, 2000b).

The paragenetic sequence of the minerals within the polymetallic veins is complex. Typically, quartz and pyrite precipitated first followed by chalcopyrite and pyrite. Some of the pyrite contain inclusions of chalcopyrite. A later stage of pyrite surrounds bornite, indicating that bornite is locally a primary mineral. Locally, galena rims pyrite crystals or contains small inclusions of pyrite. Cuprite, digenite, and arsenopyrite are locally present in small amounts, likely as low temperature overprinting or weathering by meteoric water infiltration and supergene overprinting. Late veins of hematite with a central core of malachite are found in some areas and may suggest a change in fluid chemistry to more oxidizing fluids.

Ag-Mn and Pb-Zn CRD consist of small pods of Ag-Mn and Pb-Zn replacements (North and McLemore, 1986; McLemore, 2001), small Pb-Zn skarns, and polymetallic veins in Paleozoic limestones and dolostones, of the El Paso Formation, Fusselman Dolomite and Lake Valley Limestone. The replacement deposits are enriched in Pb, Zn, Ba, V, Ag, Mn, Mo, Sb, and depleted in Au and Cu relative to the vein and porphyry copper deposits (McLemore et. al., 1999). Two styles of mineralization occur: 1) fissure vein deposits along fracture zones and faults (irregular, steeply dipping deposits that cut across bedding planes), and 2) tabular bedded replacement deposits (adjacent to the mineralized fault zones, replacing limestone). These deposits are irregular in shape and grade into the fissure replacement bodies. The fissure deposits are most likely the feeder zones for the bedded deposits.

Two distinct types of CRD are recognized in the Hillsboro district: 1) Pb-Zn and 2) Ag-Mn. Breccia fragments of jasperoid within the deposits indicate that early deposition of jasperoid replacement preceded metals deposition in both types of CRD deposits. Typically, in the Pb-Zn CRD, sphalerite, quartz, calcite, and dolomite precipitated next and cement the jasperoid breccia fragments. Locally, sphalerite contains inclusions of galena, pyrite, and iron-oxide minerals. Cerussite and locally anglesite typically occur as rims surrounding galena and filling fractures within the galena. Smithsonite and willemite, when present, typically surround or replace sphalerite grains. Locally, well-crystallized cerussite grains contains pyromorphite inclusions (Munroe, 1999). Garnet and wollastonite are locally present in small amounts. Wulfenite, vanadinite, pyromorphite, hemimorphite, hydrozincite, mottramite, plumbojarosite, argentojarosite, rhodochrosite, cuprite, malachite, azurite, linarite, descloisite, endlicheite, franklinite, and mimetite are also late-stage oxidation minerals (Lovering and Heyl, 1989; Munroe, 1999; observations by the authors). Psilomelane and pyrolusite are present in some

deposits. Samples of wulfenite, vanadinite, endlicheite, melanotekite, and calcite from the district are in the Smithsonian Institute collection (Kimbler, 1981).

In the CRD Ag-Mn replacement deposits, early deposition of unidentified silver minerals in association with quartz, siderite, and calcite was followed by a manganese-rich stage. Manganese-oxide minerals, typically psilomelane, pyrolusite, and coronadite occur with manganese-rich calcite, hematite, and siderite. Smectite and mixed-layered clay minerals surround some manganese-oxide minerals in places and are attributed to formation by surface weathering (Munroe, 1999).

Poorly developed, unmineralized skarn deposits occur in limestone north and south of the andesite volcanic/intrusive complex. The skarns are typically small replacement pods consisting of garnet, epidote, and magnetite with fine-grained hornfels and thin beds of white to gray marble adjacent to barren limestone or sandstone. Pyrite is rare, although locally as much as 3% pyrite is present, typically as thin quartz-pyrite veinlets. Precious and base metals concentrations are typically low (<0.2 ppm Au, <2 ppm Ag, and <50 ppm Cu, Appendix 3). The skarns generally occur within less than a kilometer of the intrusive contacts and are thought to be genetically related to the quartz monzonite intrusions. White marble occurs sporadically adjacent to and within the skarns and locally contains disseminations of pyrite, garnet, and epidote. Recrystallized limestone is also common adjacent to skarns and jasperoids. Iron oxide minerals are common in the recrystallized limestone.

Placer gold deposits are found in many arroyos draining the Hillsboro district. The placer gold deposits in the Hillsboro district are the second-most productive of placer gold districts in New Mexico (McLemore, 1994). The best deposits were found in drainages and gulches radiating from the Copper Flat area. Total production from placer deposits is estimated as 120,000 ounces Au and accounts for most of the gold production from the district (Segerstrom and Antweiler, 1975; Lovering and Heyl, 1989; McLemore, 2001). The absence of abundant water has hampered production. The deposits are small and amenable to small-scale placer operations.

An extensive set of chemical analyses exists from the Hillsboro district (Fig. 20; Appendix 3), including a USBM study (Korzeb and Kness, 1994; Korzeb et al., 1995), additional sampling by the senior author (McLemore et al., 1999, 2000b; Geedipally et al., 2012), sampling of mine wastes (McLemore et al., 2025), and additional sampling for this report. Three types of samples, unaltered igneous intrusions (country rock, classified as host), mineralized, and altered samples (also classified as host) were collected for geochemical analyses. Mineralized samples were generally classified according to the type of deposit. Copper, gold, silver, and molybdenum are the economic minerals that will be recovered (Fig. 21). Proven reserves at Copper Flat include 0.32% Cu and 0.07 ounces/ton Ag (Zimmerman et al., 2020). Additional critical minerals are elevated relative to crustal abundance and exploration cut-off grades (see methods section) include arsenic (8,560 ppm), bismuth (12,900 ppm), antimony (82.8 ppm), tellurium (130 ppm), tungsten (7,590 ppm), and zinc (205,890 ppm) (Table 4). Strong correlation exists between zinc and cadmium and lead and antimony, suggesting the critical minerals are found in sphalerite and galena (Sanchez, 2025). REE are relatively flat-lying patterns and low, typical of porphyry copper deposits (Fig. 22).

TABLE 4. Summary statistics of selected critical and other minerals in samples from the Hillsboro district. Chemical analyses are in Appendix 3. Average crustal abundance and exploration threshold values from Table 1 (Otoo et al., 2025a, b).

	Ag ppm	Bi ppm	Cd ppm	Cu ppm	Te ppm	V ppm	W ppm	Total REE
Count	306	306	306	339	229	325	260	46
Minimum	0.05	0.005	0.05	1	0.005	1	0.25	11
Maximum	494	12,900	386	123,000	130	2000	7590	237
Mean	15	196	7	3022	3	70	60	153
Median	1	12	0.05	594	0.005	42	8	162
Standard Deviation	49	919	36	8780	16	127	492	58
Average crustal abundance	53		0.06	27		106	1.4	
Exploration threshold	100	100	100	1400	10	2100	1050	500

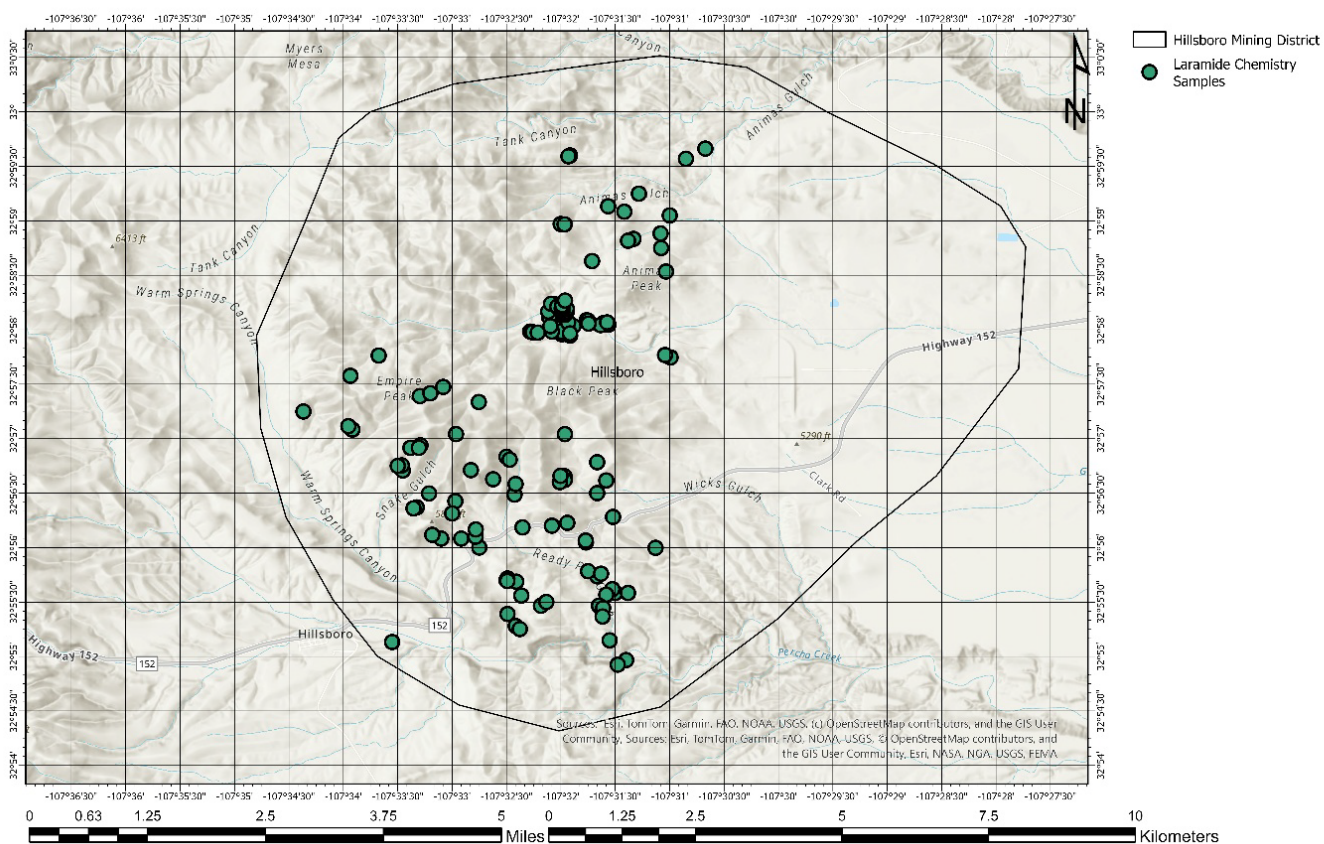


FIGURE 20. Sample location map for Hillsboro district.

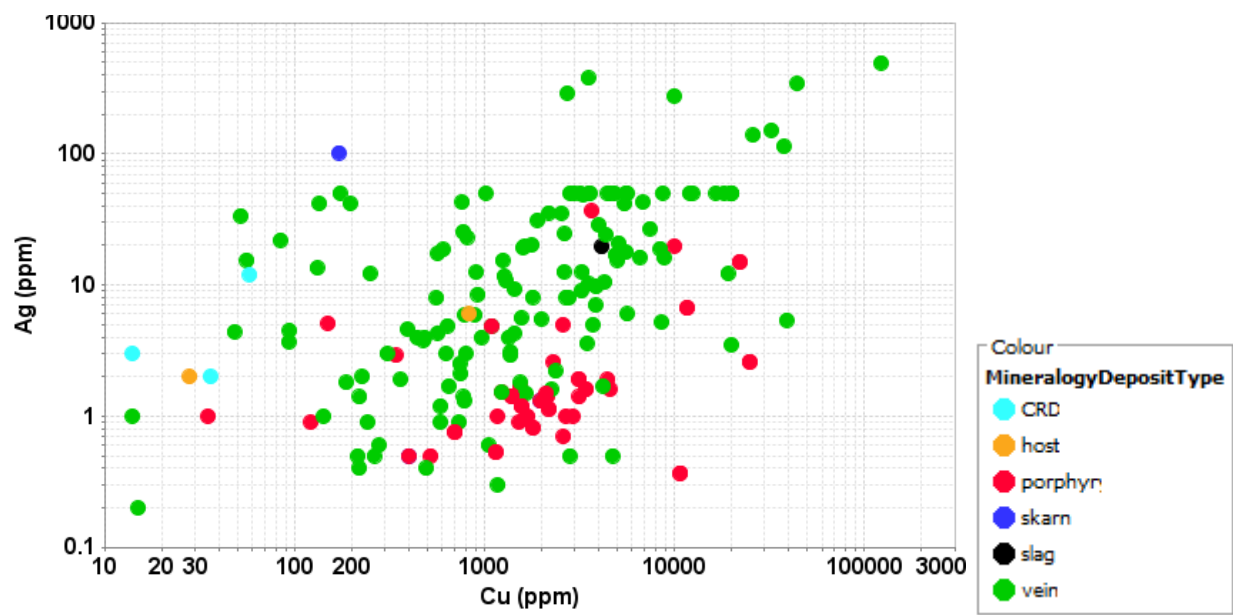


FIGURE 21. Silver vs. copper of samples from the Hillsboro district. Chemical analyses are in Appendix 3. Silver and copper concentrations are elevated, especially in the tailings and polymetallic veins, but there is no correlation, suggesting that silver and copper are in distinct minerals.

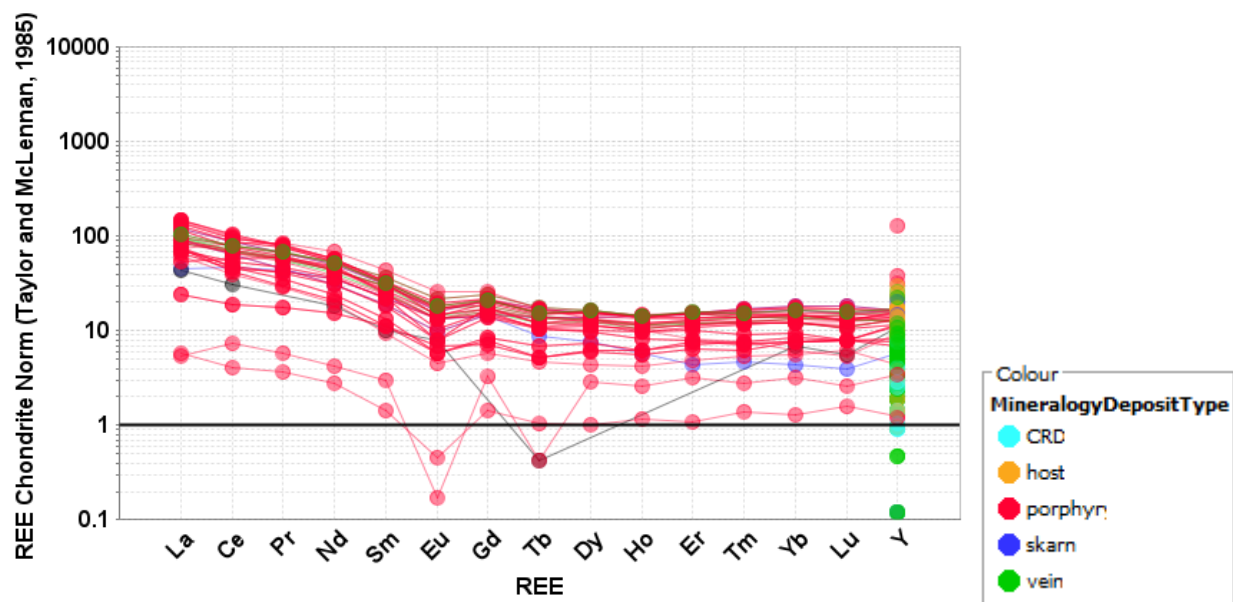


FIGURE 22. Chondrite-normalized REE plot of samples from the Hillsboro district. Chondrite values from Taylor and McLennan (1985). REE are relatively flat-lying patterns and low, typical of porphyry copper deposits.

Pinos Altos district

The Pinos Altos mining district is in the Pinos Altos Mountains approximately 8 mi northeast of Silver City. Historical records found in Chihuahua, Mexico archives suggest that

gold was first found in the Pinos Altos area by General Pedro Almendaris about 1837 when the first shipments from San Domingo Creek were sent to Santa Rita (Watson, 1987). Placer gold was re-discovered in 1860 in Bear Creek by three prospectors: Birch, Snively, and Hicks. By September 1860, several hundred men were working the area (Watson, 1987). Later that same year, the Pacific vein was the first lode discovered in the district. Within two years, 30 mines were being worked by more than 300 men (Lindgren et al., 1910). Mining continued as disruptions, such as the Civil War and plundering by Apaches, would allow.

During World War I, Pinos Altos yielded a considerable tonnage of zinc ore containing sphalerite, chalcopyrite, and galena (Waldschmidt and Lloyd, 1949). The Pacific mine (NMGR0658) was one of the largest producers in the area having a total production to 1905 of over \$1 million (Lindgren et al., 1910). By 1940, roughly 7.5 to 12% of the area's past production value was accounted for by placer gold, and the district had yielded over \$8 million worth of gold, silver, copper, lead, and zinc (Wells and Wootton, 1940).

The U.S. Mining, Smelting, and Refining Co discovered the Cyprus Pinos Altos skarn (NMGR0644) in 1948. Exxon Minerals Corp. drilled 213 holes in the early 1970s, and Boliden Minerals Corp. drilled 135 more holes and drove 7,950 ft of underground drifts in 1982, estimating reserves at 1,015,979 short tons of 4.96% Cu, 2.54% Zn, 3.482 ounces/short ton Ag, and 0.024 ounces/short ton Au. Cyprus Metals took over in 1987 and began operation of the mine in a joint venture with St. Cloud Mining Co (Osterberg and Muller, 1994). The joint venture ended in 1989, and Cyprus continued until closure in 1995. Production to 1994, shortly before closure of the mine, is 661,238 short tons of ore, containing 56,886,468 pounds Cu, 18,515 ounces Au, 1,805,180 ounces Ag, and 31,210 pounds Zn. Production from the entire district is estimated as 59.5 million pounds Cu, 169,000 ounces Au, 2.6 million ounces Ag, 6 million pounds Pb and 64 million pounds Zn (Table 5). Some iron ore was also produced.

TABLE 5. Metals production from the Pinos Altos district, Grant County, New Mexico (U.S. Geological Survey, 1902–1927; U.S. Bureau of Mines, 1927–1990; Osterberg and Muller, 1994).
^c estimated.

Year	Ore (short tons)	Copper (pounds)	Gold lode (ounces)	Gold placer (ounces)	Silver (ounces)	Lead (pounds)	Zinc (pounds)	Total Value (\$)
1860-1904	—	—	—	—	—	—	—	^c 4,700,000
1904	4,718	104,068	2,403	375	37,228	2,653	—	92,587
1905	6,348	103,468	1,522	528	39,585	—	160,778	82,442
1906	14,074	328,788	4,338	111	83,566	—	—	211,409
1907	14,841	322,195	3,808	183	65,862	—	—	190,413
1908	1,451	34,514	414	72	8,941	3,953	—	21,528
1909	38	6,200	101	173	1,377	418	—	7,207
1910	20	269	66	121	233	2,226	—	4,119
1911	355	3,232	68	196	5,616	4,063	16,773	9,968
1912	6,169	96,507	386	123	15,864	50,289	929,176	102,581
1913	3,643	100,555	1,411	80	28,276	83,067	366,056	87,626
1914	3,686	129,587	5,524	1,047	23,256	29,994	48,840	169,497
1915	7,024	377,463	1,540	96	19,856	130,638	454,710	172,463
1916	46,471	122,716	570	97	17,816	152,696	6,741,925	967,621
1917	45,993	49,945	374	153	10,803	80,989	5,556,892	607,189
1918	28,983	12,227	95	33	2,243	40,028	3,013,802	284,324
1919	2,912	14,452	244	52	2,524	20,906	267,671	32,281
1920	1,444	2,456	151	27	2,000	40,325	43,247	13,083

Year	Ore (short tons)	Copper (pounds)	Gold lode (ounces)	Gold placer (ounces)	Silver (ounces)	Lead (pounds)	Zinc (pounds)	Total Value (\$)
1921	—	—	—	115	37	—	—	2,405
1922	7,880	26,193	926	101	55,820	673,847	—	117,639
1923	2,968	68,129	628	63	17,404	90,471	44,000	47,899
1924	388	4,320	105	50	1,979	62,135	—	10,069
1925	407	430	5	26	2,287	96,550	—	10,672
1926	3,488	8,400	268	31	4,578	152,800	170,000	35,178
1927	5,219	12,206	258	34	4,591	142,492	130,000	27,524
1928	1,229	1,000	41	45	812	27,466	18,000	5,089
1929	234	4,557	85	24	2,180	8,047	—	4,722
1930-1931	—	—	—	—	—	—	—	0
1932	—	13,100	654	—	3,280	13,400	—	15,688
1933	1,462	18,000	223	327	4,755	57,000	67,000	19,118
1934	3,183	28,600	1,047	99	11,583	134,400	—	54,808
1935	3,860	37,450	1,895	131	14,258	94,400	—	88,052
1936	1,437	18,500	729	58	6,425	37,900	24,000	37,188
1937	6,482	33,200	706	71	10,157	94,900	672,000	88,347
1938	1,834	11,900	626	76	7,195	81,800	—	34,185
1939	2,465	15,700	807	167	11,107	119,700	147,000	56,532
1940	4,122	24,400	1,058	470	8,952	117,700	410,000	94,318
1941	9,811	10,500	725	444	4,683	62,100	1,089,000	130,699
1942	720	11,000	178	165	2,420	31,000	79,400	24,518
1943	10,391	72,800	73	26	19,108	81,400	1,337,000	177,075
1944	7,649	26,200	—	221	18,585	304,300	1,015,400	164,588
1945	4,815	14,400	90	2	10,426	116,000	595,000	91,002
1946	652	4,300	265	1	2,729	29,100	161,000	35,026
1947	9,057	32,600	157	6	26,506	399,100	1,447,000	269,144
1948	16,519	61,000	133	—	30,573	756,000	2,111,000	461,649
1949	3,812	15,000	66	28	5,888	186,000	486,000	101,226
1950	2,407	6,200	4	6	4,656	132,800	287,100	64,550
1951	12,109	90,800	533	4	16,104	148,300	426,700	158,610
1952	8,409	60,000	—	396	11,816	101,000	220,000	91,855
1953	4	500	—	—	142	—	—	272
1954	1,005	11,000	111	4	1,643	2,000	—	9,031
1955	53	300	2	23	30	200	200	1,069
1956	—	—	—	2	—	—	—	70
1957	578	100	—	13	1,525	31,500	50,700	12,250
TOTAL 1904-1952	322,819	2,551,427	35,413	6,696	689,280	5,028,053	28,587,370	5,598,405
TOTAL 1987-1994	661,238	56,866,468	18,515	—	1,805,180	—	31,210,434	—
ESTIMAT ED TOTAL 1890-1994	—	59,500,000	169,000 (lode and placer)	—	2,600,000	6,000,000	64,000,000	>10,300,000

In the district, Late Cretaceous andesitic volcanic rocks rest unconformably on Cretaceous clastic rocks of the Beartooth Quartzite and Colorado Formation or Paleozoic carbonate rocks of the Magdalena Group. The sedimentary and volcanic rocks have been intruded by Pinos Altos stock, a medium- to coarse-grained, multi-phase quartz monzonite (Fig. 23). The stock is part of the Pinos Altos intrusive complex, dated at 78.55–72 Ma (Laramide Pulse 1; Stafford, 2024), which consists of the porphyry stock and a variety of mafic to

intermediate intrusions peripheral to the pluton (McKnight and Fellows, 1978). The mineral deposits in the area lie within the Pinos Altos stock or in the sedimentary and volcanic rocks in close proximity to the stock. The sedimentary units are carbonate rich at the base and siliciclastic at the top (Osterberg and Muller, 1994).



FIGURE 23. Pinos Altos stock (K. Stafford photograph).

The braided structural pattern of the northwest- and northeast-trending faults is characteristic of porphyry systems (McKnight and Fellows, 1978). Northeast-trending dikes and fissure veins indicate northwest-southeast extension. Fissure veins are a subset of veins that form when a pre-existing fissure or fracture is filled with minerals and they are generally much larger in length and depth than width. Many of the fissure veins are mineralized and are exposed in the stock and the host rocks. East-west trending faults cross the northeast-trending normal faults and divide the district into several structural blocks (Osterberg and Muller, 1994).

Gold placer deposits covered an area of about 1.5 mi² in Bear Creek, Rich, Whiskey, and Santo Domingo Gulches. The gold was derived from eroded outcrops of oxidized base metal-

gold-silver veins and replacements in the area. Placer mining was hampered by an intermittent water supply as most production was on a small scale by individuals using pans, rockers, and sluices. In 1935 and from 1939 to 1942, Bear Creek and Santo Domingo Gulches were dredged (Wells and Wootton, 1940). Assays of placer gravels contained as much as 40% heavy mineral sands containing 83% magnetite, 3% garnet, 8% hematite, and \$9.30 in Au per ton (at \$20.67 per ounces Au).

The primary mineral deposits in the district consist of polymetallic veins in intrusive rocks and lead-zinc skarns with a lesser amount of copper skarns in the limestones. Replacement and skarn deposits in Magdalena Group limestones were responsible for most of the district's past production (McKnight and Fellows, 1978). The most prolific mine in the district, for example, was the Cleveland mine (NMGR0643), which produced zinc, lead, copper, silver, and gold from a polymetallic replacement deposit, west of Pinos Altos stock.

Chavez (1991) described the paragenetic sequences of mineral deposition of base-metal and precious-metal vein and replacement deposits in the district. Early pyrite and pyrite-marcasite were followed by the initial episodes of copper deposition as chalcopyrite. Zinc was deposited as sphalerite succeeding the chalcopyrite. A later episode of copper mineralization as chalcocite, bornite, and chalcopyrite was accompanied by silver and bismuth deposition as possibly stromeyerite and native silver.

Skarns (Fig. 24) at the Cyprus Pinos Altos mine occur in altered Lake Valley, Oswaldo, and Syrena Formations and in Beartooth Quartzite, all overlain by the Colorado Formation and capped by Cretaceous-Tertiary andesites and andesitic epiclastic breccias. The intrusive body is quartz monzonite and diorite. The central portion of the mine is occupied by a breccia body with diffuse and poorly defined margins, the central portion containing an intrusive matrix of diorite. Quartz monzonite fragments are not found in the breccia, but quartz monzonite dikes and sills cut the breccia and its silica-pyrite alteration. Economic mineralization is predominantly chalcopyrite and bornite with minor chalcocite, covellite, native copper, wittichenite, sphalerite, galena, arsenopyrite, native silver, and others. Gangue minerals include quartz, kaolinite-sericite, calcite, magnetite, hematite, goethite, and limonite (Osterberg and Muller, 1994).

Alteration and mineralization were a continuous process consisting of thermal-metamorphic, metasomatic, and retrograde stages. During the thermal metamorphism stage, the alteration depended on the composition of the original host rocks (McKnight and Fellows, 1978). The pure limestones and dolomites were simply recrystallized. If silica was available, wollastonite formed. In argillaceous and silty limestones, a variety of calc-silicate skarn minerals formed. Siltstones, mudstones, and shales were altered to a variety of hornfels. The metasomatic stage produced a lesser variety of skarn minerals. Andradite, quartz, and calcite make up most of the rock. Magnetite, pyrite, specularite, diopside, and base-metal sulfides occur in lesser amounts. Garnet replaces limestone beds in mass. Sulfides occur sporadically throughout the garnetized zones, and some sphalerite occurs in marble outside the skarn. Minerals produced during the retrograde stage of alteration are usually hydrous phases such as chlorite, clay, actinolite, talc, and sericite. The paragenetic sequence for the Cyprus Pinos Altos deposit shows that calc-silicate minerals formed early followed by iron oxides and a variety of copper, zinc, silver, lead, and bismuth sulfides.



FIGURE 24. Mineralized skarn deposits showing chalcopyrite and magnetite mineralized zones in drill core from the Pinos Altos district, hole PAPD2, interval (ft) 367–376, box 42 (K. Stafford photograph).

At the Lady Katherine mine (NMGR0650), north of the Cleveland mine (NMGR0523), fissure veins containing chalcopyrite and minor sphalerite occur with pyrite in Magdalena Group limestone that has been altered to the skarn-assemblage minerals garnet, diopside, actinolite, and calcite (McKnight and Fellows, 1978). Northeast of the Lady Katherine mine, the Exxon prospect is another skarn deposit associated with Pinos Altos stock. McKnight and Fellows (1978) describes results of exploration at the Exxon prospect where drilling located copper-zinc-silver sulfide mineralization in altered Magdalena Group, Lake Valley Limestone, and in Lower Paleozoic formations.

The Pacific mine is an example of one of the area's polymetallic fissure-vein deposits. The fissure veins cut fine-grained diorite porphyry and extend for over 4,000 ft trending at N60°E. On average, vein width is about 2.5 ft but may reach 10–12 ft. The vein consists of quartz, with calcite, barite and rhodochrosite with lesser amounts of pyrite, chalcopyrite, galena, and sphalerite. Pyrite and chalcopyrite are generally more abundant than galena and sphalerite. The diorite porphyry wall rocks are altered to mostly chlorite and sericite for 1–2 inches away from the vein. Gold is associated with the pyrite, but the galena is not typically argentiferous.

Between Sycamore and Bear Creeks in the Pinos Altos Mountains oolitic hematite deposits in Bliss Sandstone are exposed for a length of over 8,000 ft. The basal, oolitic-hematite-bearing part of the Bliss Sandstone in Sycamore Canyon contained 12 beds total in approximately 45 ft thick (Harrer and Kelly, 1963).

Chemical analyses of samples in the district were obtained from the literature and drill core at the NMBGMR (Fig. 25). Four types of samples, unaltered igneous intrusions (country rock, host), mineralized, altered samples (also classified as host), and tailings were collected for geochemical analyses. Mineralized samples were generally classified according to the type of deposit. The data show that the district has elevated concentrations of critical minerals, including copper (up to 256,000 ppm in drill core samples), lead (up to 1,550 ppm), silver (up to 200 ppm), and zinc (>300,000 ppm in drill core), compared to the average crustal abundances. Summary

statistics are in Table 6. Strong correlation exists between copper and silver (Fig. 26), suggesting silver and copper minerals occur together or are in the same copper minerals (Sanchez, 2025). REE are relatively flat-lying patterns and low, typical of porphyry copper deposits (Fig. 27).

Chemical composition of minerals using electron microprobe analyses provides insights to the host minerals for some of the critical minerals (Appendix 4). Copper is found in chalcopyrite (CuFeS_2), pyrite (FeS_2), arsenopyrite (FeAsS), bornite (Cu_5FeS_4), and wittichenite (Cu_3BiS_3). Cobalt is found in glaucodot ($(\text{Co,Fe})\text{AsS}$). Silver is found in wittichenite (Cu_3BiS_3), bornite (Cu_5FeS_4), and galena (PbS) (Fig. 28).

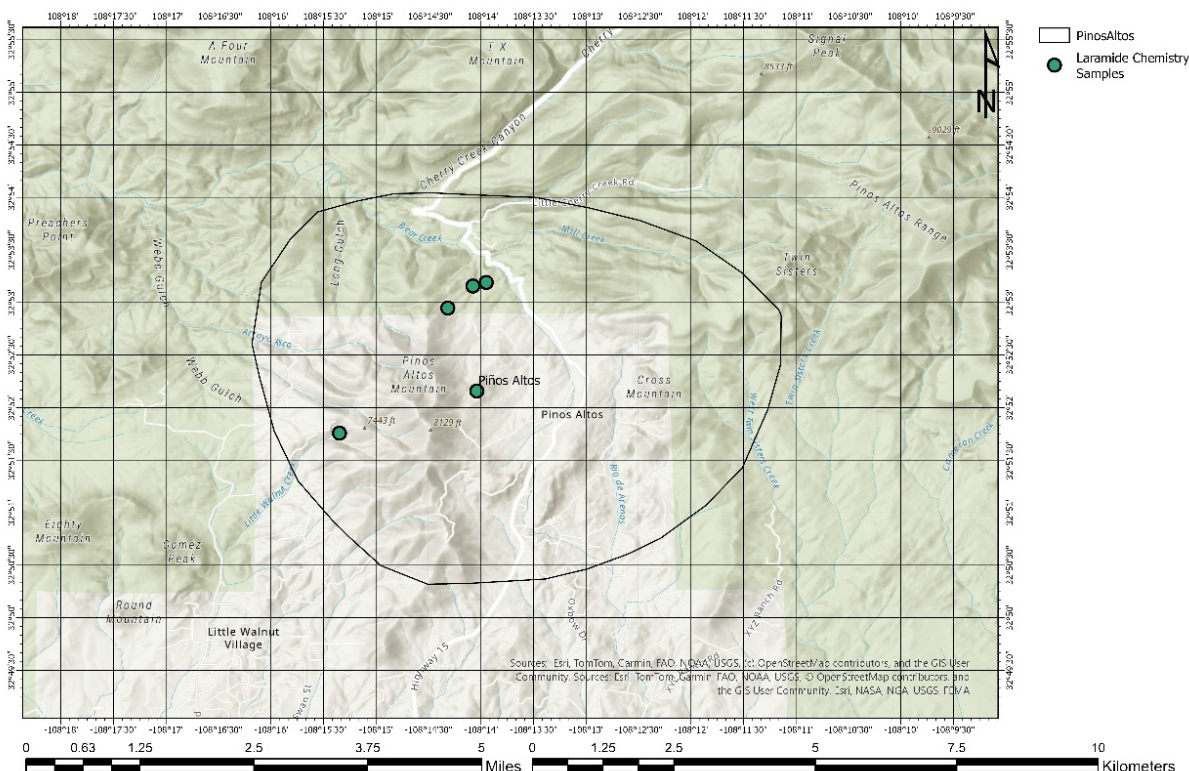


FIGURE 25. Sample location map of the Pinos Altos district.

TABLE 6. Summary statistics of selected critical and other minerals in samples from the Pinos Altos district. Chemical analyses are in Appendix 3. Average crustal abundance and exploration threshold values from Table 1 (Otoo et al., 2025a, b).

	Ag ppm	Bi ppm	Cd ppm	Cu ppm	In ppm	Te ppm	Total REE
Count	16	16	16	18	16	16	14
Minimum	0.05	0.005	0.05	1	0.005	0.005	56
Maximum	200	1000	1000	256,200	54.5	13	664
Mean	25	72	90	29,377	9	1	187
Median	1	0.45	0.8	326	0.6	0.06	138
Standard Deviation	56	249	248	76,290	17	3.5	170
Average crustal abundance	53		0.06	27			
Exploration threshold	100	100	100	1400	10	10	500

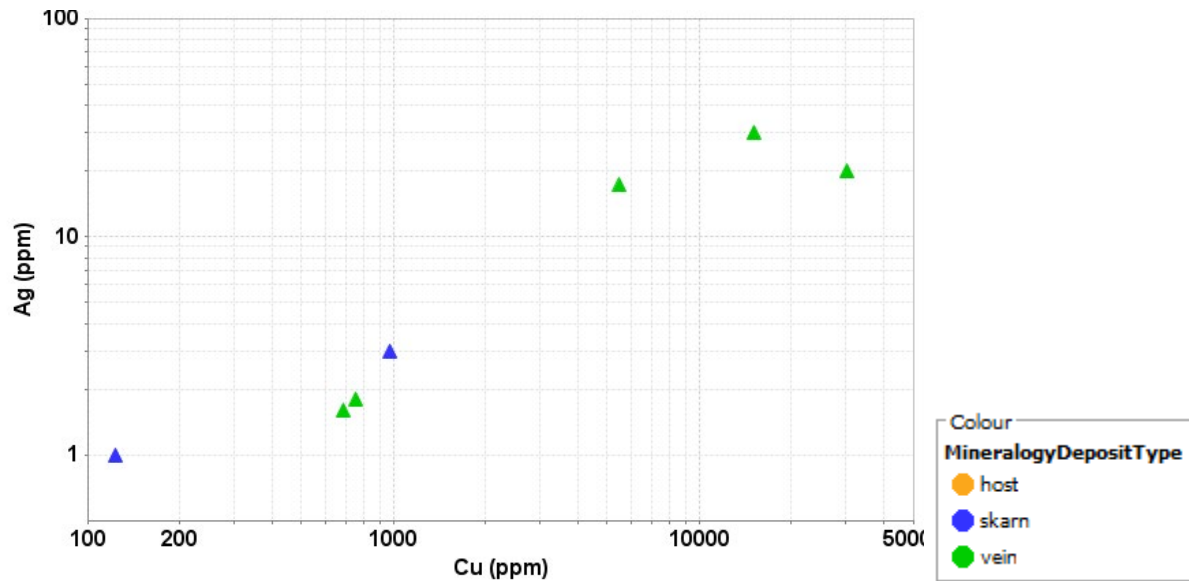


FIGURE 26. Silver vs. copper of samples from the Pinos Altos district. Chemical analyses are in Appendix 3. Note the linear correlation, which suggest silver and copper minerals occur together or are in the same copper minerals.

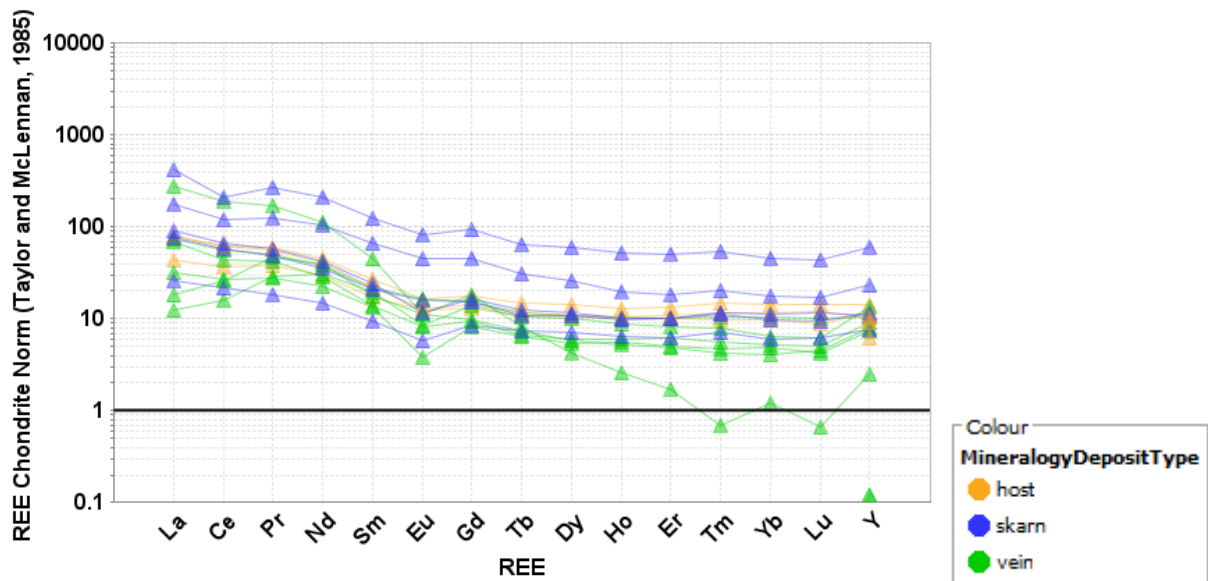


FIGURE 27. Chondrite-normalized REE plot of samples from the Pinos Altos district. Chondrite values from Taylor and McLennan (1985). REE are relatively flat-lying patterns and low, typical of porphyry copper deposits.

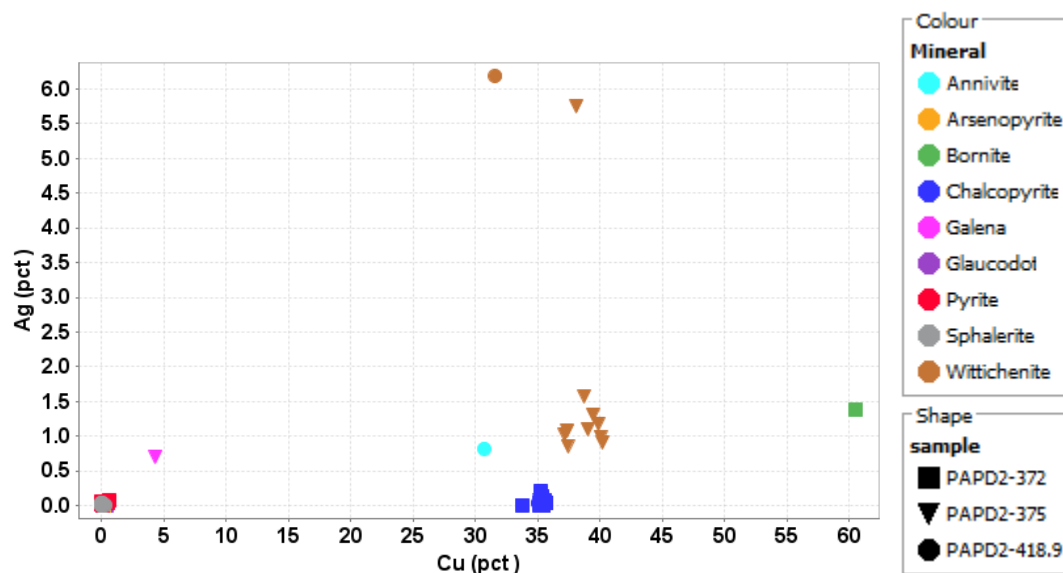


FIGURE 28. Plot of Ag and Cu in specific minerals from the Pinos Altos district determined by electron microprobe. Analyses are in Appendix 4.

Fierro Hanover district

The Fierro-Hanover mining district was discovered in 1850. Iron deposits in the Fierro-Hanover district were identified in the early years of copper development in the area. Early accounts of mining in the area mention lodestone cliffs and high-grade magnetite outcrops. During the 1880s and 1890s, iron ores from the Fierro and Hanover areas were used for smelter fluxes.

Climax Molybdenum Co. began production at the Continental mine (Fig. 38; now Cobre mine, NMGR0033, NMGR0373) in 1918 and ceased production in 1974. AMAX Inc. reopened the mine in 1993. From 1967 to 1994, the Continental copper mine produced over 22,000,000 short tons of ore containing 1.00–1.16% Cu and 0.41% Pb. Drilling in the 1970s and 1990s delineated 80 million short tons of resources of 0.38% copper at Hanover Mountain, northeast of the Continental mine (Hillesland et al., 1994, 1995). The merger of AMAX Inc. with Cyprus Minerals Company to form Cyprus Amax Minerals Company in 1993. Phelps Dodge Corporation acquired Cyprus Amax in 1999. Phelps Dodge became part of Freeport-McMoRan in 2007, making the Continental mine a Freeport McMoRan, Inc. subsidiary, who renamed it Cobre (Fig. 29). Freeport McMoRan is mining at Hanover Mountain and the Cobre mine and transporting the ore to the heap leach and mill at the Chino mine. Leaching reserves at Cobre were estimated as 73 million short tons of 0.39% copper in 2013 (Freeport-McMoRan, Inc., 2013). Contained copper in the Hanover Mountain and Cobre areas is estimated as 1.09 million metric tonnes of copper and 0.33183 million ounces of silver (Leveille and Stegen, 2012).



FIGURE 29. Continental (Cobre) pit (NMGR0373, V.T. McLemore, photograph, 2018).

The district is centered around the Hanover-Fierro pluton that consists of light gray, fine- to coarse-grain granodiorite porphyry. The sedimentary country rocks are intruded by the pluton and by quartz diorite sills, granodiorite and quartz monzonite dikes, and post-ore latite dikes. Age dates of intrusive rocks in the Fierro-Hanover district range from 70.4–57.1 Ma (K-Ar, McDowell, 1971). A granodiorite porphyry sample collected from the Continental pit (Cobre) was dated more precisely as 56.59 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$, McLemore et al., 1995).

The iron deposits are along the sides of the pluton generally at the contact or a short distance from it. The ore bodies are lenticular masses having an average thickness of approximately 30 ft, but ranging in thickness from a few feet to over 200 ft. They range in length from 100 ft to 1,000 ft. The ore bodies may be solid masses or contain zones of waste composed of limestone or wollastonite. Ore bodies are known to form in various stratigraphic positions from Bliss Sandstone to Fusselman Dolomite, but most of the higher-grade iron deposits are in El Paso limestone (Kelley, 1949). This appears to be because of the proximity of the intrusive to the limestone, less silicification of the limestone beds, and greater susceptibility of the El Paso limestone to replacement by iron-bearing fluids. In several places, Bliss Sandstone lies between the pluton and El Paso Limestone, but the more siliceous sandstone was not as readily replaced as the limestone.

The minerals in the iron deposits include predominant magnetite, subordinate specularite, and minor chalcocite, pyrite, chalcopyrite, sphalerite, and sporadic molybdenite. Magnetite is altered to martite at or near the surface. Gangue minerals include unaltered host rock, serpentine, and apatite (Hernon, 1949). Normal unoxidized iron ores contain about 0.6% Cu, and at some sites leaching and redeposition of copper has occurred at the contact between the iron ore and the intrusion.

The Pewabic mine (NMGR0361), on the eastern part of the Hanover-Fierro pluton,

exploits pod-like sphalerite ore bodies, with little or no lead or copper, that were localized by the intersection of a thrust fault with nearly vertical post-silicate northeast fault zones (Schmitt, 1939). They are as much as 40 ft in diameter and 600 ft long. At the Empire Zinc mine (NMGR0344), around the southwest margin of the Hanover-Fierro stock, blankets as thick as 135 ft and upright tabular bodies as large as 1,000 x 120 x 30 ft replace Lake Valley limestone along granodiorite dikes (Spencer and Paige, 1935). Ore from 1905 to 1969 averaged 8.75% Zn. At the Shingle Canyon mines (NMGR0802), Zn-Pb skarn occurs in limey mudstone and limestone-pebble conglomerate of the Permian Abo Formation in the footwall of the Barringer Fault, northeast of the stock (Anderson, 1957; Hernon et al., 1964).

The Lost Treasure and Gold Quartz groups ((NMGR0337) are the major source of manganese in the district. The deposit consists of replacement manganese bodies and lenticular fissure fillings in gently dipping Pennsylvanian Magdalena Group limestones along two subparallel faults about 1,000 ft apart striking NS-60° E. The Lost Treasure No. 2 vein ranges in width from 2 to 5 ft and can be traced along strike for 800 ft. In places, ore minerals have replaced the gently dipping limestone beds adjacent to the vein. The mineralized beds range from 2 to 3 ft thick and extend outward about 3 ft into the hanging wall of the vein. The Gold Quartz vein is traceable for 2,000 ft and varies from 2 to 6 ft in width. Pyrolusite and manganese wad are the chief manganese minerals. Gangue minerals are abundant iron oxides, manganiferous calcite, and quartz (Farnham, 1961).

The Hamlett claims (NMGR0346) contain a small iron-manganese skarn deposit where limestone of the Magdalena Group has experienced contact metamorphism. Manganiferous iron ore consisting of magnetite, hematite, and manganese oxides occurs in various-size lenses along fractures and in irregular masses scattered over an area several hundred feet square (Farnham, 1961). The larger masses are several feet wide and a few tens of feet long. Epidote, garnet, and pyroxene are alteration products.

Mineral deposits consist of porphyry-copper and related skarns (Fig. 30), including iron (magnetite) and zinc-lead skarns, and polymetallic veins and replacements. Classic alteration associated with porphyry copper deposits is poorly developed at the Continental mine (Hillesland, 1995). The Hanover Mountain deposit (NMGR0208) is a complex supergene blanket in the Colorado Formation near the Continental skarn deposits, near Hanover and Hermosa Mountains (Hillesland et al., 1994, 1995). The tabular zones contain fine-grained chalcocite along fractures within the Colorado Formation (Cretaceous) and are 50–500 ft thick. Iron skarns cut by copper skarns formed adjacent to the granodiorite.

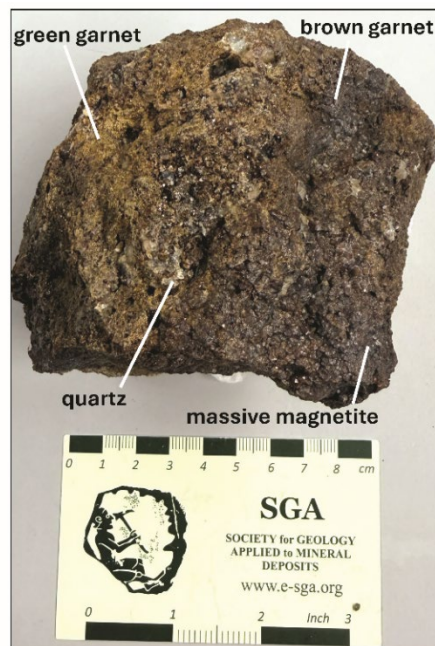


FIGURE 30. Skarn from Hanover pit (N. Hurtig photograph).

Only 25 samples have been analyzed from this district (Fig. 31); summary statistics are in Table 7. Silver and copper concentrations are elevated (Fig. 32). REE patterns are relatively flat-lying and low, typical of porphyry copper deposits (Fig. 33).

TABLE 7. Summary statistics of selected critical and other minerals in samples from the Fierro-Hanover district. Chemical analyses are in Appendix 3. Average crustal abundance and exploration threshold values from Table 1 (Otoo et al., 2025a, b).

	Ag ppm	Bi ppm	Cd ppm	Cu ppm	In ppm	W ppm	Total REE
Count Numeric	23	23	23	23	23	23	7
Minimum	1	0.005	0.05	676	0.005	0.25	30
Maximum	140	1062	1370	31738	140	220	938
Mean	32	224	162	7294	8	47	220
Median	32	197	3.5	4231	0.005	10	135
Standard Deviation	34	272	387	8187	30	66	320
Average crustal abundance	53		0.06	27		1.4	
Exploration thresholds	100	100	100	1400	10	1050	500

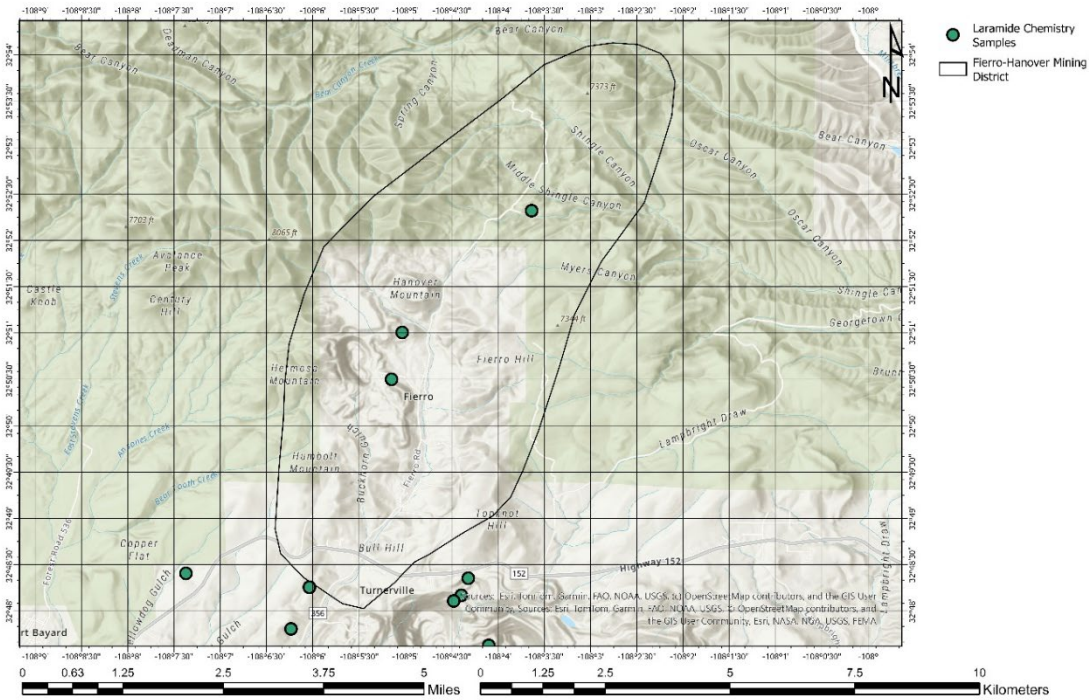


FIGURE 31. Sample location map for the Fierro-Hanover mining district.

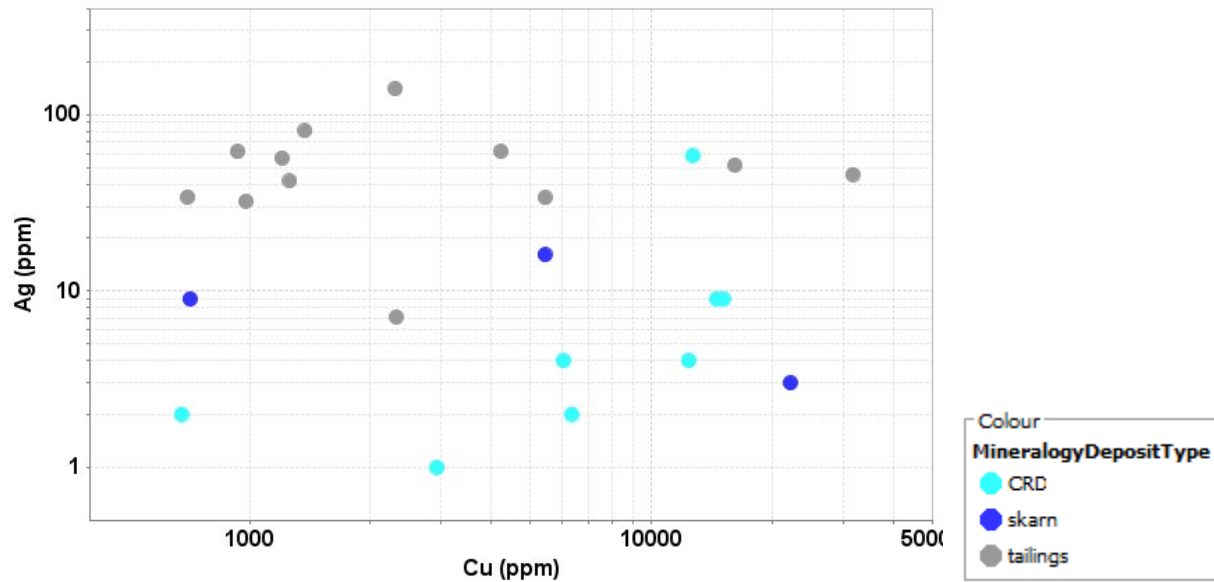


FIGURE 32. Silver vs copper plot of samples from the Fierro-Hanover district. Chemical analyses are in Appendix 3. Silver and copper concentrations are elevated, but there is no correlation, suggesting that silver and copper are distinct minerals.

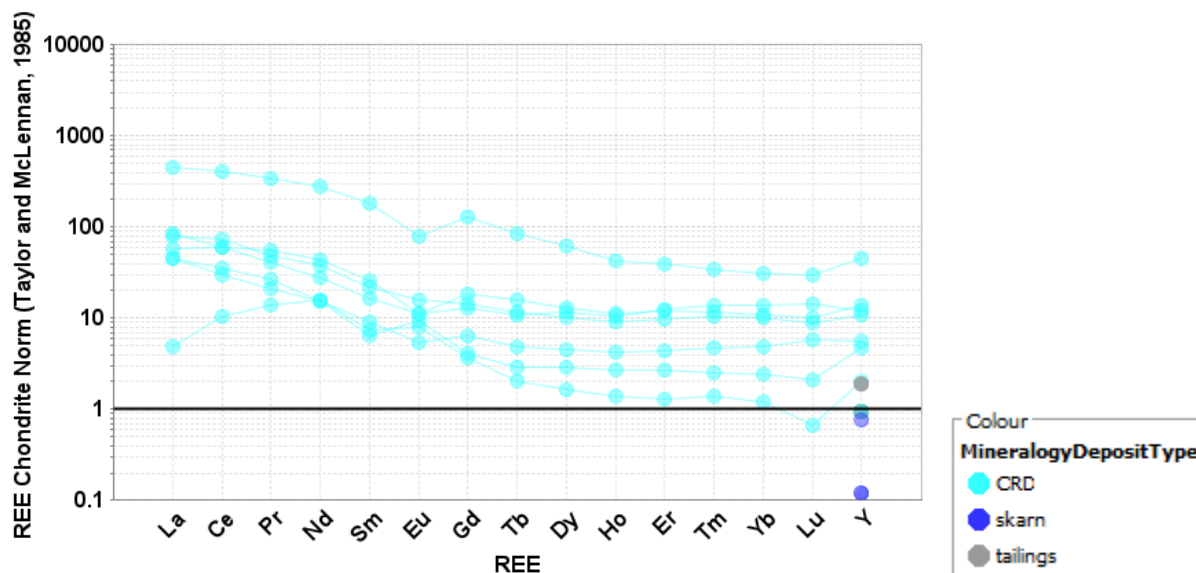


FIGURE 33. Chondrite-normalized REE plot of samples from the Fierro-Hanover district. Chondrite values from Taylor and McLennan (1985). REE patterns are relatively flat-lying and low, typical of porphyry copper deposits.

Chino mine (Santa Rita district)

The Chino open pit mine (NMGR0029) at Santa Rita is the largest porphyry copper deposit in New Mexico and has been in operation since 1910. Copper sulfides (chalcocite, chalcopyrite) along with chrysocolla and azurite are found in the upper, fractured granodiorite and adjacent mineralized skarns. The copper deposits in the Santa Rita district were first discovered by Native Americans who used it for implements and weapons (Lueth et al, 2009). Mining by the Spanish soon occurred but did not amount to much until ca. 1798, when an Apache Indian told Col. Manuel Carrasco, a Spanish officer, about the copper deposit in the area. Carrasco and another Spanish soldier, Francisco Manuel Elguea, formed a partnership, and they were issued a land grant, the Santa Rita del Cobre Grant. By 1804 Elguea bought out Carrasco and began mining copper at Santa Rita. Elguea found a ready market for copper in Mexico City. Ore was shipped by mule to Mexico City. Actual production records are lacking, but Christiansen (1974) estimates 200 mule trains were sent annually, amounting to approximately 6,000,000 pounds (3000 short tons) of copper per year. Mining at Santa Rita diminished after 1809 because of increasing costs, difficult transportation, Apache uprisings, declining copper demands in Mexico, and finally, the Mexican War of Independence in 1810. The records are conflicting as to who owned and operated the mines after 1809 until the mines finally closed in 1834. Lindgren et al. (1910) estimates total production from 1804 to 1879 as 15,000 short tons of copper.

In 1881, a stamp mill and a smelter were built to process the low-grade sulfide ore. In 1899, the Santa Rita Mining Co. bought the property, but did not produce much ore. In 1904, John M. Sully arrived at Santa Rita and recognized the similarity of ore at Santa Rita to that mined at Bingham Canyon, Utah. Sully thoroughly explored the area and attempted to obtain backers (Sully, 1908). In 1908, the Chino Copper Co. was formed and took over the Santa Rita Mining Co. Finally, in 1909 Sully obtained additional financial backing and in 1910 production began. The first concentrator mill was erected in Hurley in 1911. Flotation concentration was added in 1914 (Hodges, 1931). The Hurley smelter (NMGR0550) was commissioned in 1939 at

Hurley and was closed in 2005. Phelps Dodge Corp. acquired the mine in 1986 and built the Ivanhoe concentrator (NMGR0531) at Hurley. In 2003, Phelps Dodge became the sole owner of Chino mine when it bought the remaining third of the company that had been controlled by Heisei Minerals Corp. (a subsidiary of Mitsubishi Materials Corporation). In 2007, the Chino mine became part of Freeport McMoRan, Inc.

The Chino operation includes three open pits (Fig. 34), a 150 million pound/year solvent extraction/electrowinning (SX/EW) plant that produces copper cathode from solution generated by run-of-mine (ROM) leaching (Fig. 35) and a 36,000 metric ton/day concentrator (mill) that produces copper and in the past molybdenum concentrates. Gold and silver also are recovered. The Chino operation encompasses approximately 118,600 acres. In 2025, Freeport-McMoRan, Inc. produced 150 million pounds of copper from Chino, up from the 133 million pounds of copper produced from Chino in 2025 (Freeport-McMoRan, Inc., 2025). Current mill proven and probable reserves are reported as 275 million metric tons of ore at 0.51% Cu, 0.05 g/t Au, and 0.95 g/t Ag (Freeport McMoRan, Inc., 2025). ROM (run of mine) leachable proven and probable reserves are reported as 46 million metric tons at 0.25% Cu (Freeport McMoRan, Inc., 2025). Freeport McMoRan continued reclamation of the inactive areas of the Chino mine. The Chino mine has produced nearly 9 billion pounds copper, 500,000 ounces gold, and 5.36 million ounces silver plus some molybdenum and iron ore (Table 8; Leveille and Stegen, 2012; McLemore and Lueth, 2017; McLemore, 2017). Low concentrations of silver and gold are recovered as by-products through conventional milling techniques. Production is in Table 8 and reserves are in Appendix 2. Precious metals, including platinum group elements (PGEs), can be recovered from the anode slimes remaining after copper is refined at a refinery. They occur as particles of native species and as solid solutions or exsolved species in sulfide minerals.



FIGURE 34. Chino mine looking south (V.T. McLemore photograph, looking south).



FIGURE 35. Heap leach pad at Chino mine (V.T. McLemore photograph).

TABLE 8. Production from the Chino mine, Santa Rita district, Grant County (U.S. Geological Survey, 1902–1927; U. S. Bureau of Mines, 1927–1990; Phelps Dodge Annual Reports; Freeport McMoRan, Inc. 2004–2024, 2025). In addition, >500,000 ounces Au, >5.36 million ounces Ag, and some Mo have been produced. w=production withheld

Year	Copper (pounds)
1804-1879	15,000
1931	53,130,000
1932	23,146,500
1933	22,166,000
1934	19,470,000
1935-1936	w
1937	55,204,000
1938	32,950,000
1939	76,993,000
1940	117,319,889
1941	117,779,582
1942	125,407,629
1943	116,540,246
1944-1975	w
1976	114,404,000
1977	114,526,000
1978-1982	w
1983	212,520,000
1984	193,600,000

Year	Copper (pounds)
1985-1986	w
1987	244,200,000
1988	146,000,000
1989	175,400,000
1990	295,800,000
1991	314,800,000
1992	304,400,000
1993	319,000,000
1994	320,000,000
1998	315,800,000
1999	260,200,000
2000	271,200,000
2001	156,400,000
2002	107,600,000
2003	79,800,000
2004	183,000,000
2005	210,000,000
2006	186,000,000
2007	190,000,000
2008	155,000,000
2009	36,000,000
2010	34,000,000
2011	69,000,000
2012	144,000,000
2013	171,000,000
2014	250,000,000
2015	314,000,000
2016	308,000,000
2017	215,000,000
2018	173,000,000
2019	175,000,000
2020	92,000,000
2021	124,000,000
2022	130,000,000
2023	141,000,000
2024	133,000,000
2025	150,000,000
Total 1804-2025	8,288,771,846

Sedimentary rocks in the district include Paleozoic and Upper Cretaceous sandstone, limestone, dolomite, and shale. A summary of the intrusive events in the Santa Rita, Central, Copper Flat, and Fierro-Hanover districts is in Table 9. Igneous activity at Chino began about 60–59 Ma with the intrusion of pre-mineralization dioritic to quartz diorite sills into Proterozoic and younger sedimentary rocks. The intrusion of multiple stages of quartz-monzodiorite to granodiorite dikes and stocks with porphyritic textures followed (Rose and Baltosser, 1966; Reynolds and Beane, 1985; Audétat and Pettke, 2006). The Santa Rita stock represents an oxidizing magma enriched in sulfur (Audétat and Pettke, 2006). New high-precision zircon U-Pb geochronology (Abrasion-Isotope Dilution-Thermal Ionization Mass Spectrometry, CA-ID-TIMS) indicates the Santa Rita pluton was emplaced over 2 Ma (59.905 ± 0.028 – 57.744 ± 0.035 Ma).

Ma) by multiple discrete individual batches of magmas. Most of the mineralization is predominantly chalcopyrite and molybdenite veinlets formed shortly after intrusion of the dikes and stock along the stock margins (Fig. 36, 37) and in skarns and breccia bodies. Polymetallic veins and mantos formed distal to the stocks. Potassic, phyllic, argillic, and propylitic alteration zones are present, but are not everywhere concentric (Nielsen, 1968, 1970). Several periods of supergene enrichment have further concentrated the ore (Cook, 1994; Cook and Porter, 2005).

Supergene deposits have been one of several ore types at Chino (Fig. 37). Prior to mining, supergene deposits were present as three northwest trending zones of relatively thick, high grade chalcocite ore: along the northeast and southwest margins of the Santa Rita Stock, straddling the contacts and hosted by both granodiorite porphyry and siliciclastic rocks, and a broad central zone over the core of the main stock. The dominant sulfide is chalcocite, with minor covellite, native copper, chrysocolla, cuprite, malachite and azurite. Both sooty and steel-glance chalcocite are present.

Adjacent copper skarns are becoming increasingly more important economically, with chalcopyrite as the main ore mineral and major amounts of magnetite, pyrite, quartz and calc-silicate minerals. Skarn alteration outcrops to the north of the open pit and extends below the surface on the eastern and western margins of the stock. Chalcopyrite occurs in veinlets and as disseminated grains with magnetite, quartz, pyrite, garnet, epidote, chlorite, pyroxenes and amphiboles. Sphalerite and minor galena are found in limestones near the outer margins of the copper zone.

Several breccias are found in the Santa Rita area containing copper minerals and generally comprising fragments of granodiorite porphyry, quartz diorite and/or sediments in a matrix of fine rock replaced by quartz, orthoclase, biotite and magnetite, with some sulfides. The breccias generally only contain clasts of the intruded lithology (Rose and Baltosser, 1966).

TABLE 9. Events at Santa Rita, Copper Flat, Central, and Fierro-Hanover districts (Mizer et al., 2015; Gaynor et al., 2024).

Geologic event	Age (Mizer et al., 2015; Gaynor et al., 2024)	Mineralization and alteration
Weathering and supergene alteration	41–1 Ma	Supergene deposits (Cook, 1994)
North Star is a biotite-hornblende monzonite plug (northwest of Hanover Mountain)	46.6±0.9 Ma	Non known mineral deposits
Copper Flat (Grant County) is a biotite-hornblende granodiorite porphyry stock	57.5±0.7 Ma	Cu±Fe breccia and skarn
Felsic dikes (cut earlier intrusions) hornblende-biotite quartz diorite porphyry biotite granite porphyry biotite hornblende granodiorite porphyry	58.5±0.7 Ma 58.3±0.8 Ma 59.0±0.7 Ma	Zn±Cu skarn and replacement mineralization (Empire, Pewabic, Groundhog, and Bullfrog mines)
Hanover-Fierro stock is a biotite-hornblende granodiorite/ quartz monzodiorite	58.5±0.9 Ma	Hanover Mountain porphyry copper and magnetite skarn and replacement bodies (Fe±Cu; Continental mine, Jim Fair pit)
Santa Rita stock is a biotite-hornblende granite and granodiorite pluton	59.905±0.028–57.744±0.035 Ma (Gaynor et al., 2024)	Chino porphyry copper deposit
Hornblende-biotite granodiorite and quartz monzodiorite sills	60.5±1.3 Ma	None



FIGURE 36. Typical gray porphyry copper-molybdenum veinlets at Chino, Santa Rita district (V.T. McLemore photograph).

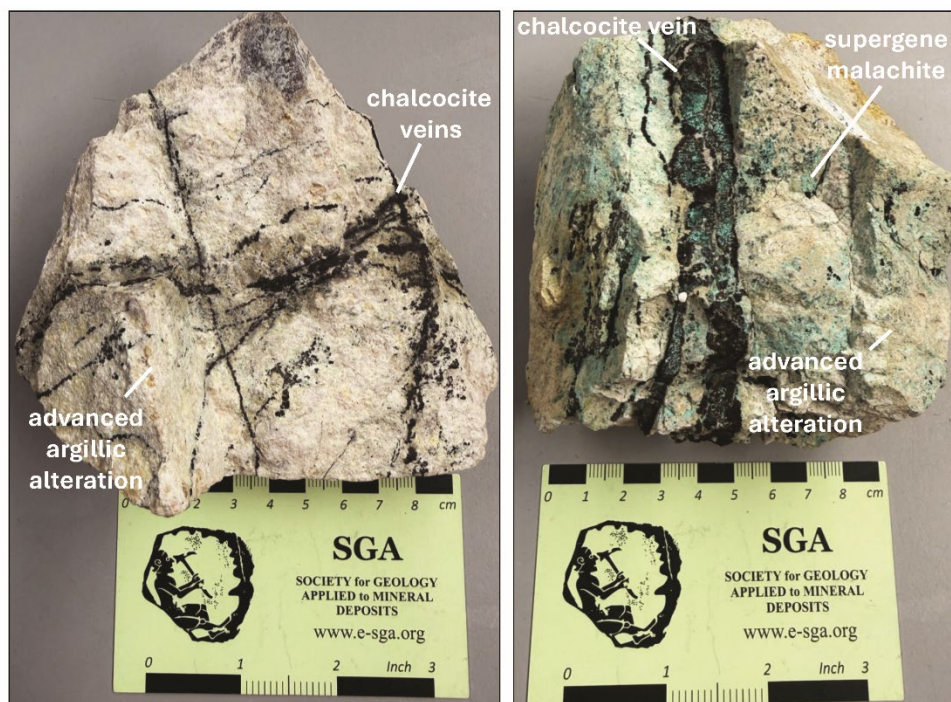


FIGURE 37. Supergene copper veins from Chino mine, Santa Rita district (N. Hurtig photograph).

The decrease of copper grade through time is apparent. In 1912, the grade was over 2% copper; in 1925, it was averaging 1.5%; in 1948 the grade was less than 1% (Gibson and Trujillo, 1966; Wunder and Trujillo, 1987); in 1980 the copper grade was just 0.81%. Today the grade is only 0.5%.

Sample locations from the Chino mine (Santa Rita district) are in Figure 38 and summary statistics are in Table 10. A TAS (total alkali, $\text{Na}_2\text{O}+\text{K}_2\text{O}$ vs silica, SiO_2) diagram for host rock samples from the Chino mine; most of the samples plot as granite to quartz (Fig. 39). Silver, cobalt and copper are elevated (Fig. 40). REE are relatively flat-lying patterns and low, typical of porphyry copper deposits (Fig. 41). Additional sampling is required.

TABLE 10. Summary statistics of selected critical and other minerals in samples from the Chino mine. Chemical analyses are in Appendix 3. Average crustal abundance and exploration threshold values from Table 1 (Otoo et al., 2025a, b).

	Ag (ppm)	Co (ppm)	Cu (ppm)	Mo (ppm)	Pb (ppm)	TREE
Count	19	19	41	33	41	27
Minimum	0.05	2	2	0.5	0.05	18
Maximum	497	581	50,000	4590	297,000	717
Mean	38	90	3914	151	11874	168
Median	1	41	310	4	12	162.2
Standard Deviation	114	145	9127	797	54,005	140
Average crustal abundance	53	15	27		17	2.4%
Exploration threshold	210	980	0.14%		1.05%	500

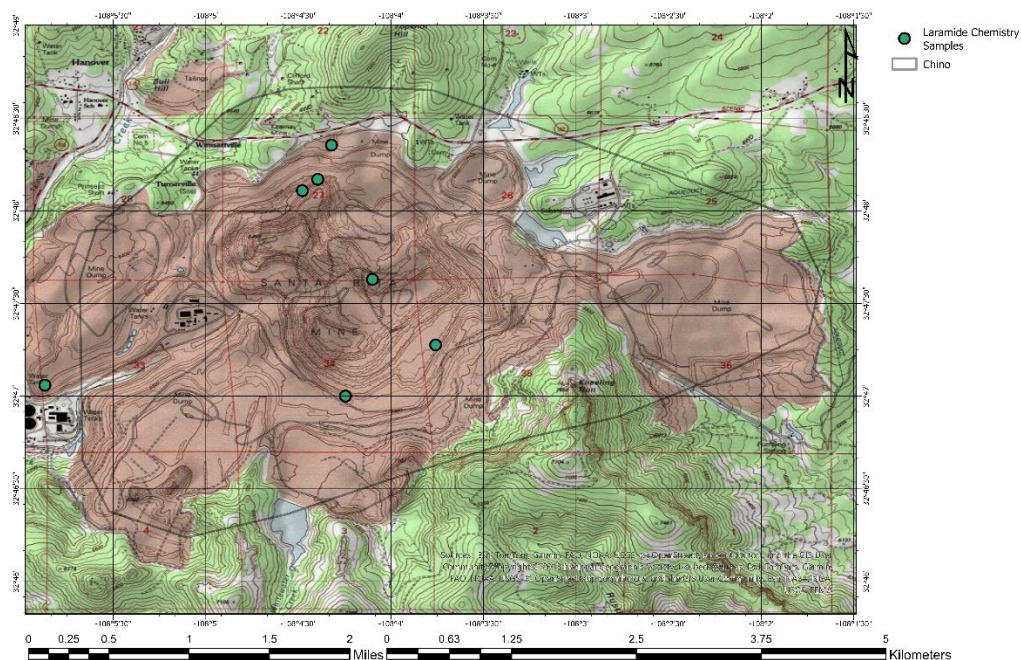


FIGURE 38. Location of samples in the Chino mine, Santa Rita district.

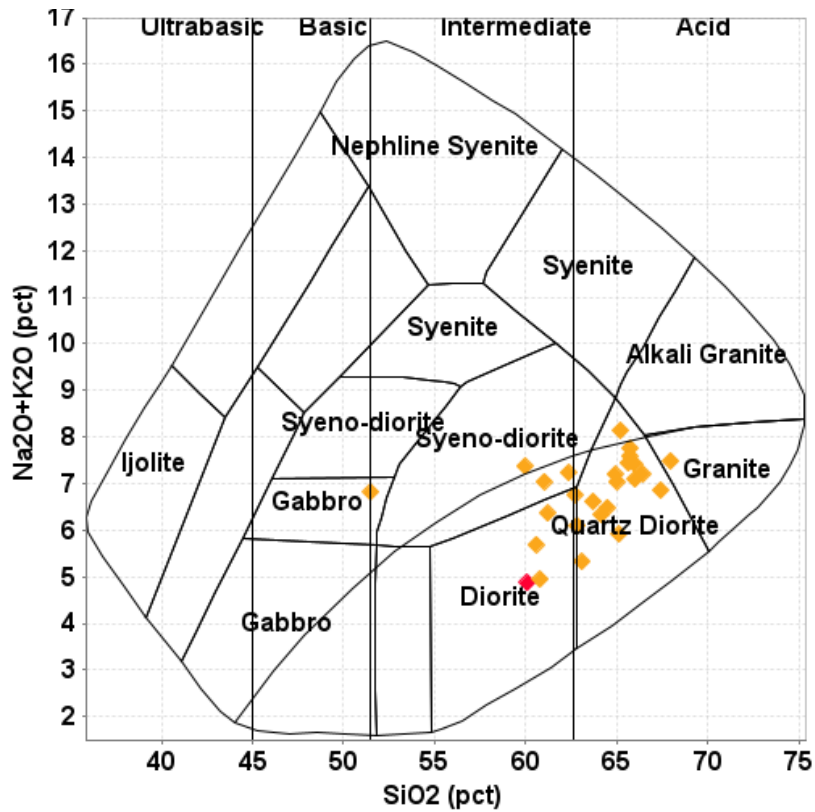


FIGURE 39. TAS (total alkali, $\text{Na}_2\text{O}+\text{K}_2\text{O}$ vs silica, SiO_2) diagram for samples from the Chino mine, Santa Rita district (Cox et al., 1979). Most of the samples plot as granite to quartz diorite. The curved solid line subdivides the alkaline (above curve) from subalkaline rocks (below curve; from Irvine and Baragar, 1971).

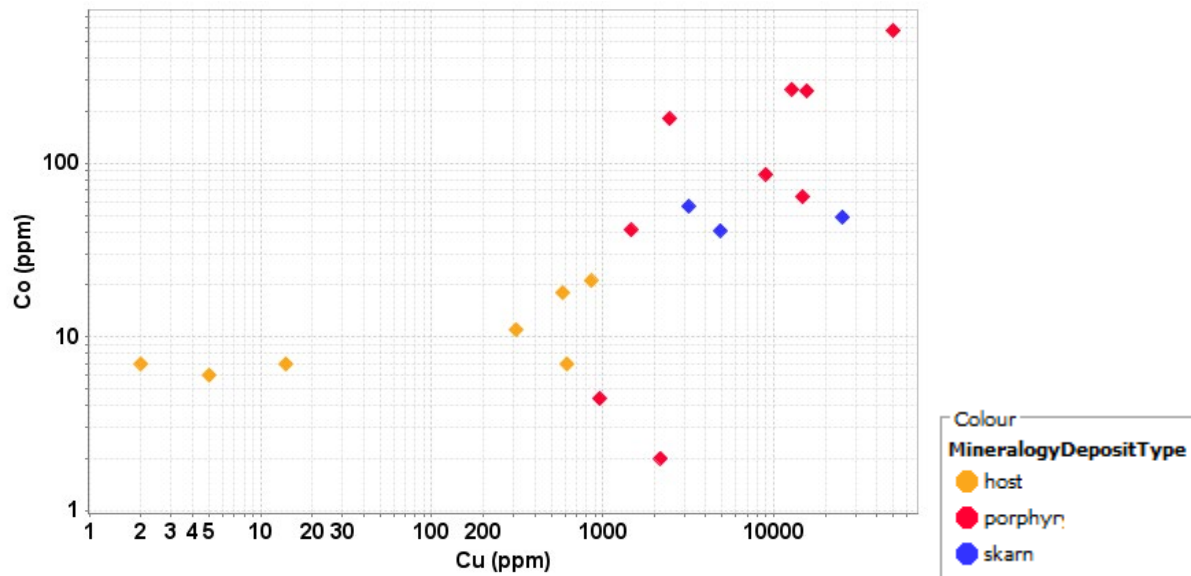


FIGURE 40. Copper vs. cobalt for samples from the Chino mine, Santa Rita district.

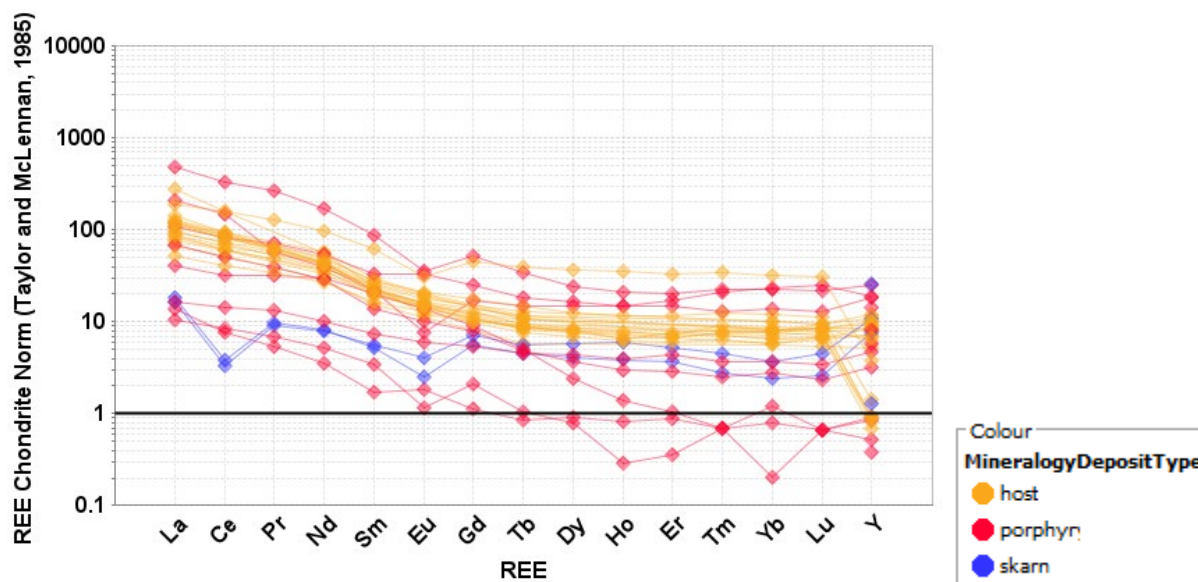


FIGURE 41. Chondrite-normalized REE plot of samples from the Chino mine, Santa Rita district. Chondrite values from Taylor and McLennan (1985). REE patterns are relatively flat-lying and low, typical of porphyry copper deposits. Chemical analyses are in Appendix 3.

Tyrone mine and vicinity, Burro Mountains district

The Tyrone mine (NMGR0084) on the northeast side of the Mangas Valley in the Burro Mountains district is the second largest porphyry copper deposit in New Mexico and is operated by Freeport McMoRan, Inc. (formerly Phelps Dodge Corp.). Copper minerals were first discovered in the Burro Mountains about 600 AD when the Native American Indians mined turquoise for jewelry and trade, but it was not until the early 1860s that the first mining claims were filed. In 1880–1881, prospecting in western Grant County resulted in the discovery of numerous gold, silver, lead, and copper deposits and mining began shortly after, until 1885.

The Tyrone ore body was mined by numerous small underground operations until 1909 when Phelps Dodge Mining Co. consolidated 150 mining companies that operated in the area at the time and began mining in 1916. It was not until 1921 that underground mining ceased, after several high-grade areas averaging 2–3% Cu were mined out. From 1948 to the 1950s, a drilling program defined the Tyrone ore body. Overburden stripping began in 1967, and open pit mining commenced in 1968. In its history, mining at Tyrone has gone from underground to open pit, and from sulfide concentration by mill to heap leaching by SX/EW. Approximately 300 million short tons of ore grading 0.81% copper were processed by the concentrator (mill) at Tyrone from 1969 to 1992. Approximately 425 million short tons of ore grading 0.35% Cu have been leached (SX/EW). Silver and gold were recovered from 1903 to 1992, and the Tyrone mine has produced more than 5.3 billion pounds Cu, 500,000 ounces Au, and 5.36 million ounces Ag, plus some molybdenum and iron ore from 1911 to 2006 (Long, 1995; McLemore et al., 1996; McLemore, 2008). Gold and silver were recovered only from the concentrate at the mill. Production has continued since from numerous open pits, some of which have been backfilled.

Today, the copper processing facilities consist of a SX/EW operation (commissioned in 1984) with a maximum capacity of approximately 100 million pounds of copper cathodes per year. Approximately 300 million short tons of ore grading 0.81% Cu were processed by the

concentrator at Tyrone from 1969 to 1992. Approximately 425 million short tons of ore grading 0.35% Cu have been leached. The mine has produced more than 5.3 billion tons Cu, 500,000 ounces Au, and 5.36 million ounces Ag plus some molybdenum and iron ore from 1911 to 2006 (Table 11; Long, 1995; McLemore, et al., 1996, McLemore, 2008). Total copper production from the Tyrone mine from 1911 to 2025 exceeds 6.6 billion pounds (Table 11). In 2025, proven and probable ROM leaching reserves (recoverable copper) are estimated as 59 million tons of 0.19% copper (Freeport McMoRan, Inc., 2025). The Tyrone mine is among the lowest grade porphyry copper deposit in the world.

TABLE 11. Production from the Tyrone mine, Burro Mountains district, Grant County (Phelps Dodge Annual Reports; Long, 1995; McLemore, 2008; Freeport McMoRan, Inc. 2006–2024, 2025). In addition, the mine produced 500,000 ounces Au, and 5.36 million ounces Ag plus some molybdenum and iron ore from 1911–2006.

Year	Copper (pounds)
1911–2006	5,300,000,000
2006	64,000,000
2007	50,000,000
2008	76,000,000
2009	86,000,000
2010	82,000,000
2011	76,000,000
2012	83,000,000
2013	96,000,000
2014	94,000,000
2015	84,000,000
2016	76,000,000
2017	61,000,000
2018	55,000,000
2019	48,000,000
2020	45,000,000
2021	55,000,000
2022	59,000,000
2023	51,000,000
2024	43,000,000
2025	32,000,000
Total 1922–2025	6,616,000,000

The Little Rock deposit (Ohio mine, NMGR0160) was a historic open pit mine near the Tyrone mine that was mined and leached in the late 1960s and early 1970s. In 1970–1972, U.S. Natural Resources, Inc. removed and stockpiled approximately 1 million tons of leach material. Phelps Dodge Mining Corp. obtained the Little Rock properties in 1990 and began mining operations soon after, shipping ore to the Tyrone leaching facilities. Freeport McMoRan, Inc. began mining ore and leaching copper in 2010 as part of the Tyrone operation.

While Tyrone is the largest producer, it is not the only producing mine in the district (McLemore et al., 1996). Numerous additional mines were developed and mined throughout the district. Turquoise has been produced (Zalinski, 1907) as well as 172,539 short tons of fluorite and 30 pounds U_3O_8 .

The Tyrone mine is in the Little Burro Mountains and trend northwest along a northeast tilted fault block along the west side of the northwest-trending Mangas fault. This area consists

of Proterozoic granite and Cretaceous sedimentary rocks intruded by andesitic and rhyolitic rocks and overlain by Tertiary volcanic flows (Kolesaar, 1970, 1982; DuHamel et al., 1995). The supergene ore of the Tyrone deposit continues into the adjacent Big Burro Mountains and is hosted by Proterozoic granite (Burro Mountain granite), which is emplaced into a series of schists, amphibolites, and quartzites of the Bullard Peak metamorphic rocks. The granite has been intruded by Proterozoic diabase dikes and contains rhyolite dikes and plugs, and dikes and plugs of various rock types and the Tyrone stock, a quartz monzodiorite porphyry laccolith (Fig. 42). The age of the Tyrone stock is 55.2 Ma (DuHamel et al., 1995; McLemore, 2008; Safford, 2024). Gila Conglomerate and Recent sands gravels fill Mangas Valley.



FIGURE 42. Intrusive breccia in the Tyrone pit (V.T. McLemore photograph).

The Burro Mountain granite is the major component of the Big Burro Mountains. It is typically a medium- to coarse-grained equigranular granite with locally porphyritic texture. The color, texture, mineral and chemical composition, fracturing and jointing, and degree of weathering and alteration are quite variable (Gillerman, 1970).

Tyrone stock and smaller plugs and dikes of varying texture, composition, and age intruded the Burro Mountain granite. The largest part of Tyrone stock is a medium light-gray, medium-grained massive quartz monzodiorite (Hedlund, 1978a, b, 1985a, b). The remainder of the stock is mostly very light-gray to light brownish-gray quartz monzonite porphyry, pinkish-gray aplite, and very light-gray porphyritic quartz monzonite dikes as much as 35 m wide. Paleozoic strata and Mesozoic rocks are largely absent, except for some minor Mesozoic units in the Little Burro Mountains (Hedlund, 1985a, b)

By far the most important deposit in the district is the Tyrone porphyry copper deposit. The Tyrone ore body is a chalcocite blanket developed over the Tyrone stock (Kolesaar, 1970, 1982; Hedlund, 1985a, b; DuHamel et al., 1995). At the Tyrone mine, most of the stock is a porphyritic quartz monzodiorite with abundant quartz, oligoclase, and sporadic chloritized biotite (Kolesaar, 1970, 1982), with the mineralized portion exhibiting pronounced potassic

metasomatism and sericitic alteration. Fine-grained quartz monzonite dikes intrude the stock and the surrounding Proterozoic granite. The main ore body consists of a supergene blanket containing erratic chalcocite mineralization varying from a few feet to over 300 ft thick. The ore contains predominantly chalcocite, chrysocolla (varying from sky blue to black), chalcopyrite and pyrite with minor amounts of gold and silver, especially in the enriched zones. Other ore minerals, such as malachite, azurite, cuprite, tenorite, native copper, turquoise, minor torbernite, and autunite, occur in kaolinized areas. Most of the minerals occur as disseminations and fracture fillings in the stock, and to a limited extent in the Proterozoic granite (Hedlund, 1985a, b). Trace molybdenite and bornite, with pyrite, chalcopyrite, sphalerite, and galena are hypogene minerals that have been mostly mined out. Fluorite is found locally, and alunite is common in white veinlets. Overall, the ore is low grade, but within the mined area were several high-grade areas that averaged 2–3% Cu.

Within the ore body, breccia ore bodies occur that were described as intrusive breccias by Paige (1922) and hydrothermal breccias by DuHamel et al. (1995). They consist of fragments of granite and quartz monzonite porphyry and are 200–400 ft in diameter. The matrix of the breccia was finer-grained breccia, and the breccia was itself fractured, with some ore minerals as partial matrix to fragments. The breccias are low in grade, but contain excellent supergene mineralization (DuHamel et al., 1995). Breccia pipes are found within the Tyrone stock and within the granite country rock (Hedlund, 1985b). At least three cycles of supergene enrichment have concentrated the ore at 35.7–31.6 Ma, 19.4–16.2 Ma and 8.7–4.6 Ma (Cook, 1994; Mach, 2004).

The Emma deposit (NMGR0293) is another historical deposit that was produced for copper and is currently being permitted by Freeport McMoRan, Inc. as an extension of the Tyrone mine. The deposit consists of malachite, cuprite, and chalcocite in Proterozoic granite (Fig. 43).



FIGURE 43. Copper oxides at the Emma deposit (sample VTM2407, V.T. McLemore photograph).

Only 19 samples have been collected from the Tyrone mine (Fig. 44). A TAS (total alkali, $\text{Na}_2\text{O}+\text{K}_2\text{O}$ vs silica, SiO_2) diagram for samples from the Tyrone mine showed that most of the samples plot as granite to alkali granite (Fig. 45). REE are relatively flat-lying patterns and low, typical of porphyry copper deposits (Fig. 46). Critical minerals are primary copper, but additional sampling is required.

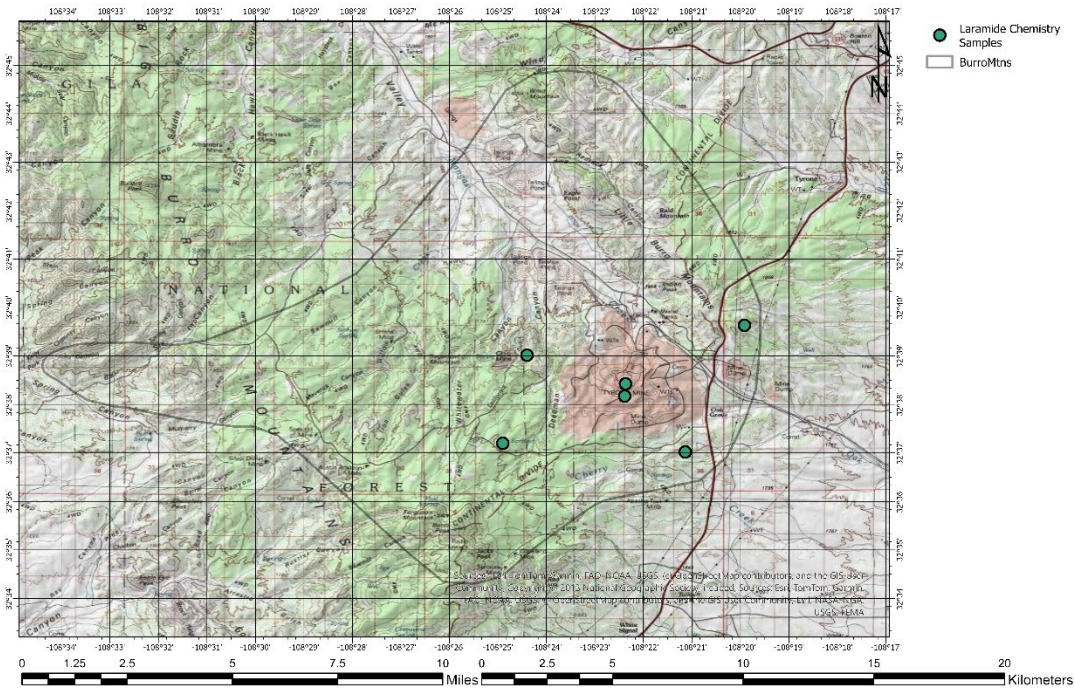


FIGURE 44. Location of samples in the Tyrone and Emma mines, Burro Mountains district.

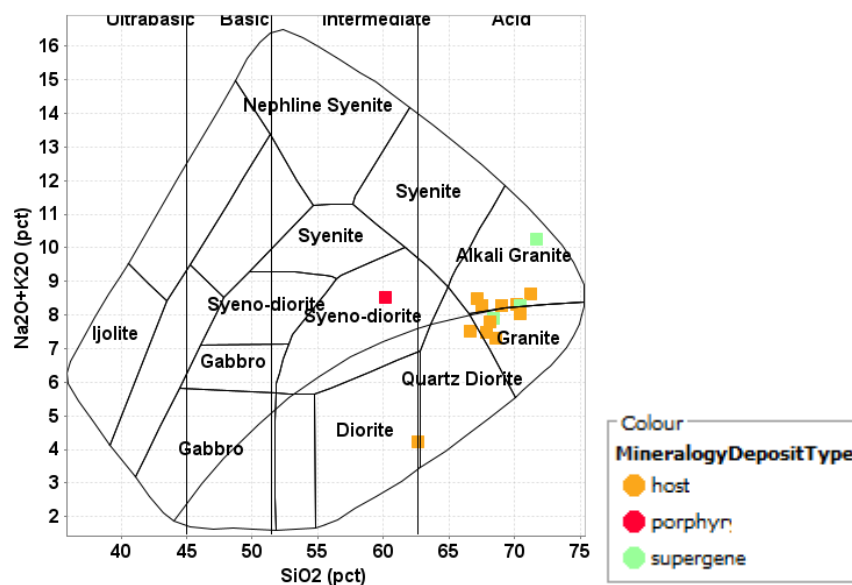


FIGURE 45. TAS diagram for samples from Tyrone and Emma mines (Cox et al., 1979). Most of the samples plot as granite to alkali granite. Chemical analyses are in Appendix 3. The curved solid line subdivides the alkaline (above curve) from subalkaline rocks (below curve; from Irvine and Baragar, 1971).

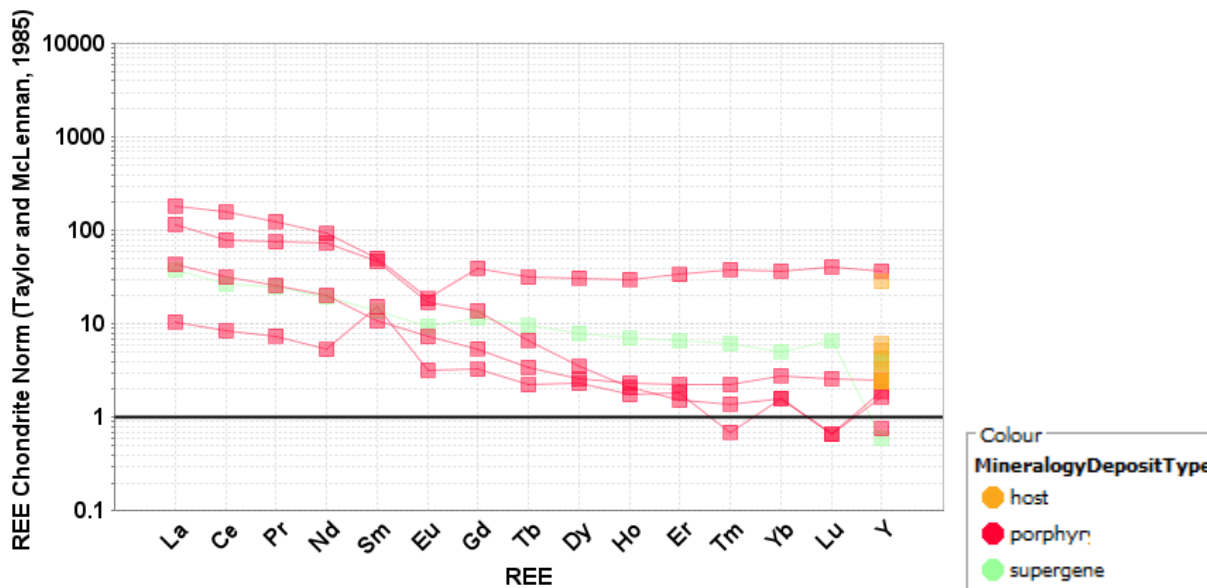


FIGURE 46. Chondrite-normalized REE plot of samples from the Tyrone and Emma mines. Chondrite values from Taylor and McLennan (1985). Chemical analyses are in Appendix 3.

Eureka (Oro) and Sylvanite (Little Hatchet Mountains) districts

The Eureka mining district occurs in the northern part of the Little Hatchet Mountains and Sylvanite district is to the south (Fig. 47). Mining activities in the Little Hatchet Mountains began in 1871. However, stone tools found in old turquoise pits are evidence of much earlier activity. Legend has it that the district was named "Eureka" when these old Native American mining tools were found. The American (Fig. 48; NMGR0680), Hornet (NMGR0692), and King (NMGR0732) mines in the district were located in 1877–1878 at the same time when the Sylvanite district in the southern part of the mountains was prospected. The Eureka and Sylvanite mining districts were originally subdistricts of the Hachita district, which is no longer in use.

The earliest mining was at the Hornet mine; but Apache Indians were hostile to mining and prospecting and made things difficult. By late 1878, when the U.S. Army visited the district, only 20 people resided there. Protection afforded by the army allowed the miners to return, and in 1881, ore shipments from the American mine were being recorded. In the early 1880s, smelters were built at both the American and Hornet mines, but neither smelter operated for very long due to technical difficulties. In 1885, a drop in the price of silver caused mining activities to subside until 1902, when the railroad connected the smelter towns of Douglas, Arizona, and El Paso, Texas, and stimulated production. The total value of ore produced to 1906 was not more than \$500,000 (Lindgren et al., 1910). Total estimated production from the Laramide veins is approximately \$1.59 million, including 2.9 million pounds Pb, 1.7 million pounds Zn, 500,000 pounds Cu, 5,000 ounces Au, and 450,000 ounces Ag (Table 12).

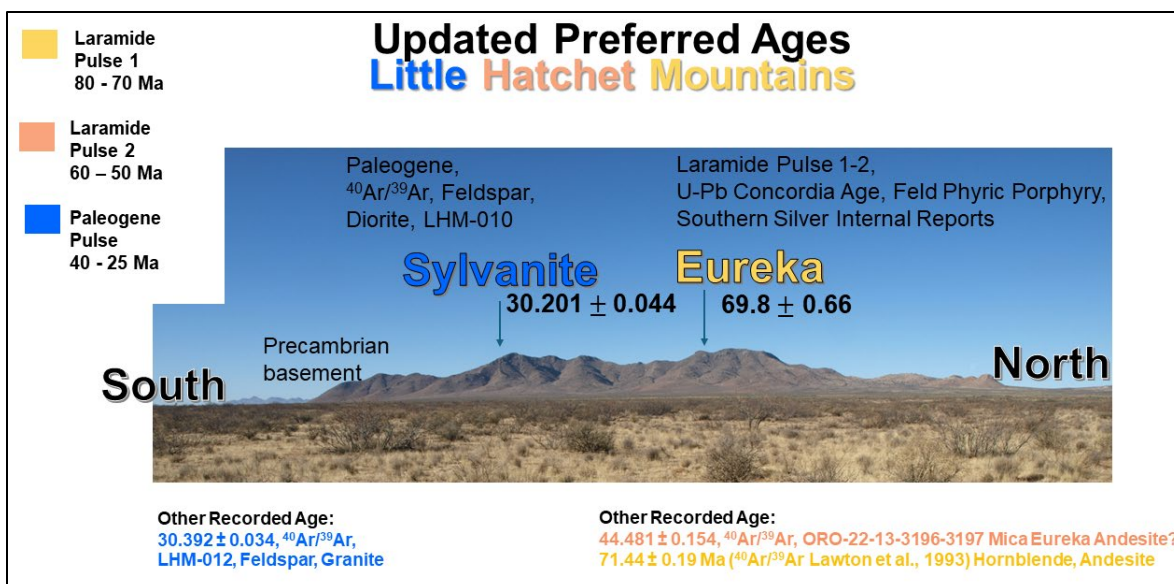


FIGURE 47. Preferred ages of the Little Hatchet Mountains range of igneous rocks within the Sylvanite and Eureka districts. Photo of mountain range, looking west, (from Moses, in preparation using V.T. McLemore photograph).

TABLE 12. Metals production from the Eureka district, Grant County, New Mexico (U.S. Geological Survey, 1902–1927; U. S. Bureau of Mines, 1927–1990).

Year	Ore (short tons)	Copper (pounds)	Gold (ounces)	Silver (ounces)	Lead (pounds)	Zinc (pounds)	Total Value (\$)
1934	10	100	0.09	161	400		\$130
1935-1939	Production not reported						
1940	98	300	1.00	1,163	4,400		\$1,116
1941	28		2.00	1,156	9,200		\$1,416
1942	48	200		1,194	12,300		\$1,697
1943	298	800	1.00	3,057	25,800	19,000	\$6,300
1944	260	600		2,385	31,700	25,000	\$7,163
1948	4,093	4,000	6.00	17,998	225,000	208,000	\$85,306
1949	12,017	6,000	7.00	19,493	341,000	276,000	\$107,171
1950	6,036	4,600	4.00	15,514	262,000	281,700	\$90,591
1951	6,031	5,800	25.00	19,526	353,400	402,700	\$154,380
1952	6,150	3,000	16.00	10,964	203,000	206,000	\$78,088
1953	450	100	1.00	650	14,600	6,200	\$3,278
1954	Production not reported						
1955	888	600	5.00	3,107	52,600	53,400	\$17,616
1956	900	700	4.00	2,601	47,700	71,400	\$20,063
1957	1,500	300	18.00	4,257	130,800	35,600	\$27,408
Reported Total 1934-1957	38,807	27,100	90.09	103,226	1,713,900	1,585,000	\$601,723
Estimated total 1880-1961	-	500,000	5,000	450,000	2,900,000	1,700,000	\$1,590,000



FIGURE 48. Open stopes along a skarn in the American mine, Eureka district, Little Hatchet Mountains (V.T. McLemore photograph, looking southeast).

Three back-arc rift basins formed in southern New Mexico and northern Mexico, including the Little Hatchet Mountains, during the Late Jurassic to middle Cretaceous (Lawton et al., 2020). Basalt flows range in age from 161 to 104 Ma in the Little Hatchet Mountains and in Sonora. The Bisbee and Cochise porphyry copper deposits in southern Arizona are Jurassic in age (200 Ma; Leveille and Stegen, 2012; Lewis, 2021; Lamont et al., 2024) and part of this Jurassic rift system (Lewis, 2021).

In the Little Hatchet Mountains, Cretaceous sedimentary and early Tertiary volcanic rocks were intruded by Tertiary stocks, dikes, and sills. The oldest rocks in the district are Cretaceous sedimentary rocks consisting of thin bedded limestone, dolomite, and shale. Between Howells Ridge and Old Hachita, the Hidalgo Volcanics of early Tertiary age crop out. These rocks consist of altered andesite and andesite breccia with a few sedimentary units consisting of andesite detrital sediments. A hornblende andesite (Fig. 49) near the base of the section has an age date of 70.53 ± 0.19 Ma ($^{40}\text{Ar}/^{39}\text{Ar}$, hornblende; Lawton et al., 1993). South and west of Old Hachita, the Hidalgo Volcanics have been intruded by the Sylvanite quartz monzonite stock and diorite (Fig. 48). In the Little Hatchet Mountains, several Laramide stocks, dikes, and sills have intruded the Cretaceous sedimentary rocks, and the most highly mineralized areas are associated with these intrusive rocks. The quartz monzonite and monzonite in the Sylvanite and Eureka districts is called the Sylvanite quartz monzonite stock (Zeller, 1970; Young, 1996), but detailed studies are needed to determine if there is more than one intrusive phase. Table 13 is a summary of geologic events in the Little Hatchet Mountains. Additional mapping, geochemistry, and geochronology is needed for the Eureka and Sylvanite districts in the Little Hatchet Mountains.



FIGURE 49. Monzonite (LHM002, top left), andesite (LHM001, top right) and quartz monzonite (ORO22-12-2738, bottom) from the Little Hatchet Mountains (I. Sanchez photographs).

TABLE 13. Sequence of major geologic events in the Little Hatchet mountains (from Channell et al., 2000; Clinkscales and Lawton, 2017; Moses, in preparation).

Geologic Event	Age	Mineralization And Alteration
Peak of Post-Laramide Extension Mid-Tertiary (Ignimbrite Flare-up) Eruption of volcanics (Andesite) Extensive ash-flow tuffs, rhyolites, and basaltic andesites. -Ignimbrite tuff -Granite -Quartz monzonite	25–35 Ma	Paleogene magmatism. Carbonate replacement deposits, Pb-Zn skarns, garnet, scheelite, molybdenite etc. Hydrothermal Alteration potassic and phyllic alteration (25–45 Ma).
Hydrothermal Alteration.	25–45 Ma	Potassic and Phyllic alteration.
Magmatic quiescence	40–55 Ma	

Geologic Event	Age	Mineralization And Alteration
Laramide Pulse 2 -Granite intrusions -Rhyolite dikes	55–60 Ma	
Sylvanite Intrusive Complex. -Quartz monzonite -Diorite	65–69 Ma	
Laramide orogeny	50–70 Ma	Chalcopyrite, Galena, copper skarns, polymetallic veins and potential mineralized porphyry plutons emplaced at depth under cover.
Hidalgo Uplift & Ringbone Basin Laramide Pulse 1 -Ringbone -Skunk Ranch -Hidalgo volcanics	70–80 Ma	
Mid-Cretaceous Quiescence	80–100 Ma	
Cretaceous foreland basin. -Mancos Shale -Mojado Formation -U Bar Formation -Hell to Finish Formation	80–160 Ma 80–95 Ma 100–105 Ma 100–125 Ma 120–145 Ma	
Late Jurassic rifting. Border rift system. -Broken Jug Formation. -Jurassic basalt flows. -Sedimentary rocks.	145–160 Ma	
Paleozoic Marine Sequences, shallow seas.	250–540	Sedimentation & lithification.
Precambrian Granite, basement rocks.	1.1 Ga	

Mineral deposits in the Eureka district consist of Laramide veins in limestone and monzonite, Laramide skarns and replacements in metamorphosed limestone along the edge of the intrusive rocks, turquoise deposits, and disseminated quartz-specularite deposits (Table 14). Lasky (1947) divides the mineral deposits into seven types based on mineralogy: 1) disseminated pyrite in Tertiary intrusive rocks, 2) quartz-specularite deposits (sec. 2, 11, T28S, R16W), 3) lead-zinc skarns and replacements (Hornet), 4) arsenopyrite-lead-zinc veins (Fig. 50; American, Miss Pickel), 5) manganosiderite-galena veins, 6) manganosiderite-tetrahedrite-galena veins (King 400, Silver King, Howard), and 7) quartz-pyrite-chalcopyrite veins (Copper King, Stiles).

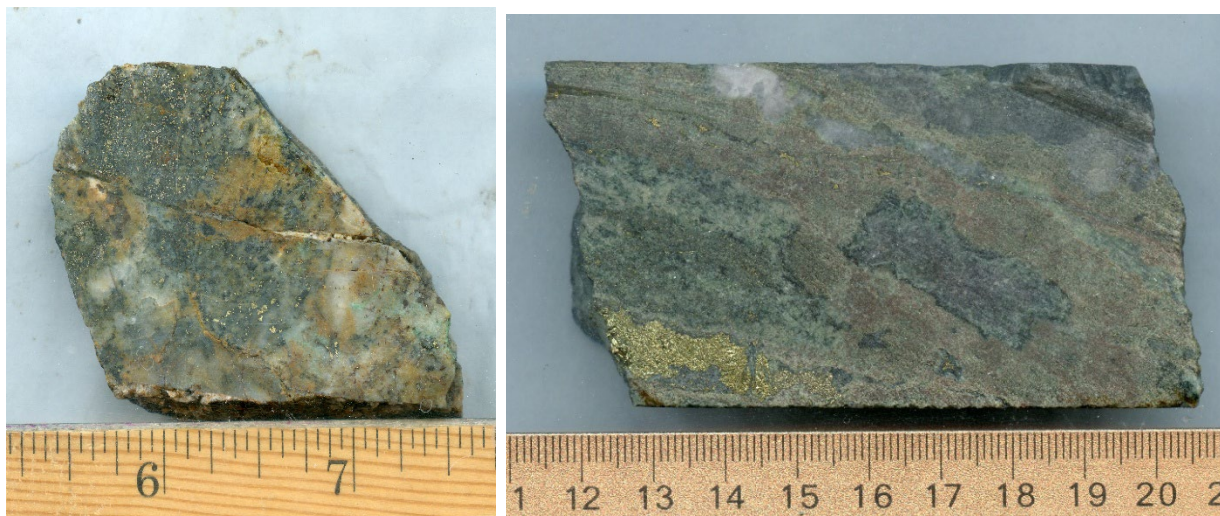


FIGURE 50. Polymetallic vein with 130 ppm Ag (LHM009) from the Little Hatchet Mountains (I. Sanchez photographs).

Ore deposits at the American mine occur along a vein in metamorphosed limestone near the contact with a monzonite stock (Fig. 48; Lasky, 1947). The limestone has been metamorphosed to marble and garnet. The vein strikes N50° E and dips 58° to 75° NW and can be traced in outcrop for about 1,000 ft before either end plunges beneath arroyo gravels. In the mine, the vein varies from 2 to 20 ft wide. Mineralized vein material contains galena, sphalerite, pyrite, arsenopyrite, chalcopyrite, and cubanite (Fig. 51). Gangue material includes manganosiderite, calcite, and sericite.

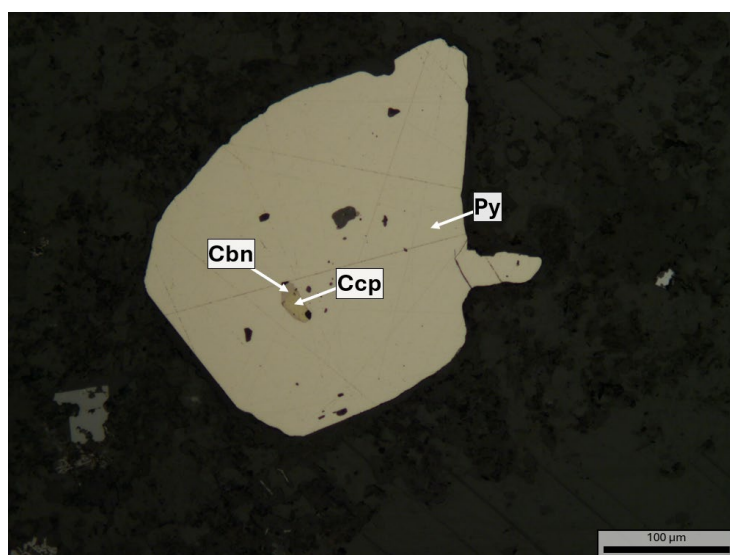


FIGURE 51. Transmitted light photomicrograph of LHM-008 sample, showing pyrite (Py) with cubanite (Cbn) and chalcopyrite (Ccp) inclusion (from Sanchez, 2025).

One example of an ore deposit that formed in the district without developing calc-silicate, skarn-type mineralization occurs at the Hornet mine. The Hornet mine was one of the earliest mining locations in the Little Hatchet Mountains and for a while it was the site of the greatest

mining activity in the mountain range until 1958. The host rocks at the mine include limestone, Hidalgo Volcanics, and an irregular diorite sill that intrudes the contact between the limestone and the volcanic rocks. Ore at the mine consisted of three types: 1) lead carbonate ore stained black by manganese oxides and averaging 25 ounces/short ton Ag; 2) galena ore that was even richer in silver; and 3) zinc carbonate ore also rich in silver. The grade of material shipped between 1905 and 1927 was approximately 22 ounces/short ton Ag, 3.5% Zn, less than 1% Pb, and 0.05% Cu. Gangue was almost entirely coarse-grained calcite; pyrite occurred in unoxidized material.

Turquoise deposits were rediscovered about 1885 and worked intermittently for 25 years or more. Total production is unknown. Blue and green turquoise is found in veins in altered trachyte, andesite, and ash-flow tuff (Fig. 46, 47). Some bands were up to 7 ft wide (Sterrett, 1911); but most are smaller. Impurities include jarosite, sericite, iron oxides, pyrite, and clay (Lasky, 1947; McLemore, 2017). Zones of disseminated pyrite occur in the monzonite in the district. The monzonite is altered to and replaced by jarosite, iron oxides, and pyrite.

A zone of disseminated quartz-specularite occurs in sec. 2 and 11, T28S, R16W in the anticline of diorite and andesite breccia (Lasky, 1947). Iron was produced and used in the Hornet and American smelters. The rock is locally completely sericitized and replaced by quartz, sericite, and specularite.

Figure 52 shows a working understanding of the geological events across the Little Hatchet Mountains. Recent drilling, exploration activities and critical mineral studies discovered a potential unexposed large-scale porphyry center in the northern Little Hatchet Mountains (Oro project, Southern Silver Exploration Corp, 2022).

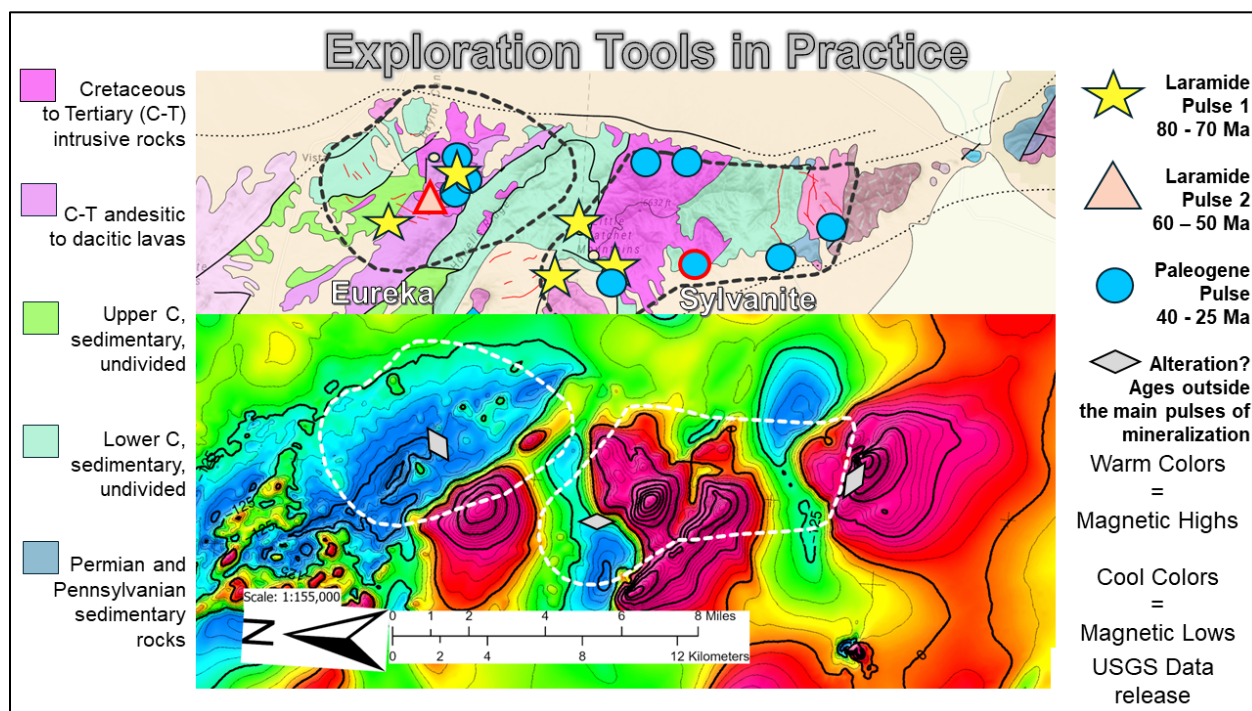


FIGURE 52. Working understanding of utilizing magnetics, geology and geochronology in order to create a more coherent timeline of magmatism in the Little Hatchet Mountains, see Table 14 (from Moses, in preparation).

The Eureka district exhibited a greater diversity of critical minerals than the Sylvanite district, with the presence of arsenic as a substitute in tetrahedrite ($\text{Cu}_{12}\text{Sb}_4\text{S}_{13}$), bismuth as matildite (AgBiS_2), arsenic and antimony in ruby silvers (proustite (Ag_3AsS_3) or pyrargyrite (Ag_3SbS_3)) and indium probably associated with chalcopyrite or sphalerite. Additionally, exploration drilling from the Oro project by Southern Silver Exploration indicates elevated molybdenum and rhenium values at depth, as deep quartz-molybdenite mineralization associated with a buried porphyry system (Appendix 3; Sanchez, 2024).

Sample locations from the Little Hatchet Mountains are in Figure 53 and summary statistics are in Table 14. A TAS (total alkali, $\text{Na}_2\text{O}+\text{K}_2\text{O}$ vs silica, SiO_2) diagram for host rock samples from the Little Hatchet Mountains; most of the samples plot as syeno-diorite to gabbro (Fig. 54). Silver, cobalt and copper are elevated (Fig. 55). REE are relatively flat-lying patterns and low, typical of porphyry copper deposits (Fig. 56).

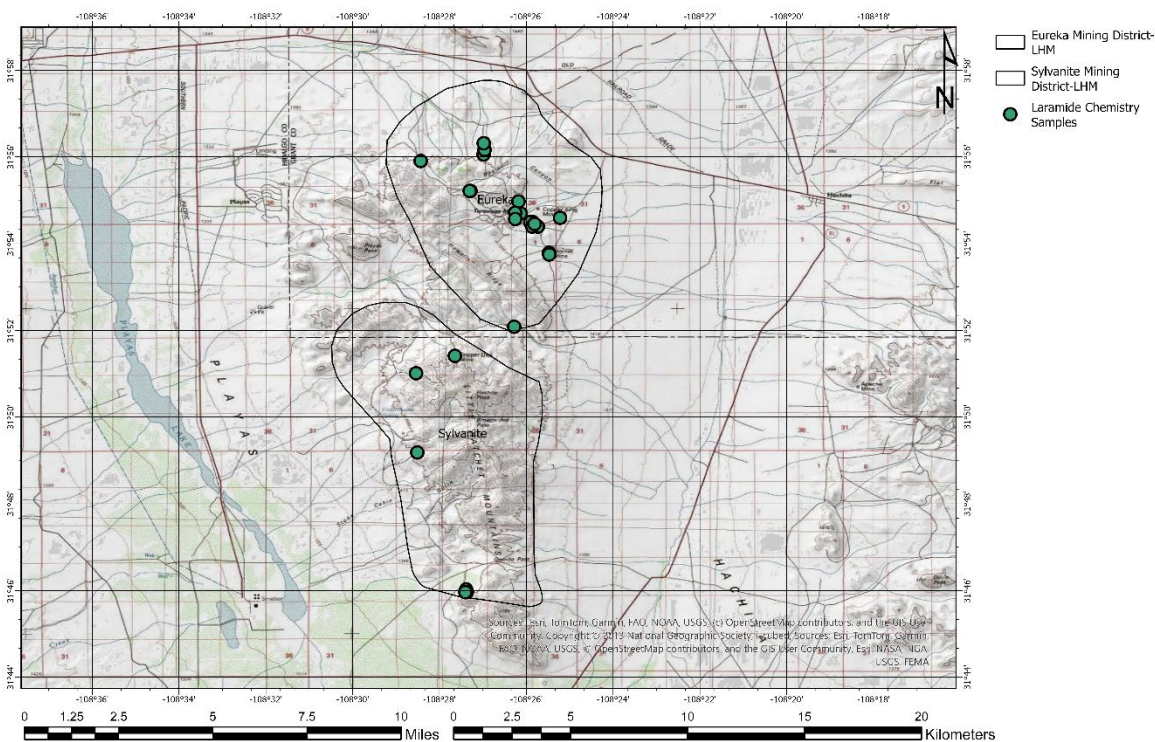


FIGURE 53. Location of samples in the Eureka and Sylvanite districts, Little Hatchet Mountains.

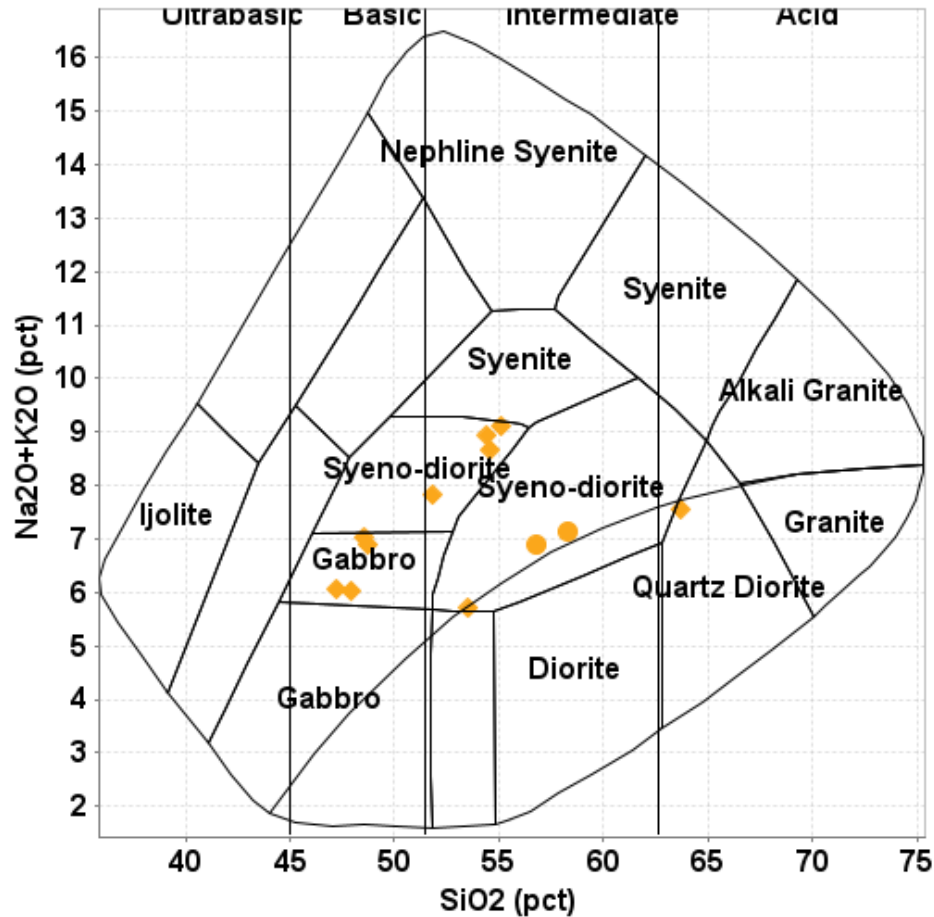


FIGURE 54. TAS diagram of samples from the Eureka (diamonds) and Sylvanite (circles) districts, Little Hatchet Mountains (Cox et al., 1979). Most of the samples plot as syeno-diorite to gabbro. Chemical analyses are in Appendix 3. The curved solid line subdivides the alkaline (above curve) from subalkaline rocks (below curve; from Irvine and Baragar, 1971).

TABLE 14. Summary statistics of selected critical and other minerals in samples from the Eureka and Sylvanite districts, Little Hatchet Mountains. Chemical analyses are in Appendix 3. Average crustal abundance and exploration threshold values from Table 1 (Otoo et al., 2025a, b).

	Ag ppm	Bi ppm	Cd ppm	Cu ppm	In ppm	Mo ppm	Te ppm	W ppm	Total REE
Count	134	106	106	166	106	109	105	134	101
Minimum	0.03	0.005	0.05	0.9	0.005	0.5	0.005	0.1	39
Maximum	631	250	3430	171,000	30	9820	36	219,000	3236
Mean	14	7	46	2363	1	151	0.5	1792	550
Median	0.3	0.2	0.2	503	0.09	15	0.01	1	292
Standard Deviation	63	33	346	13582	4	941	4	18928	630
Average crustal abundance	53		0.06	27				1.4	
Exploration threshold	100	100	100	1400	10	1000	10	1050	500

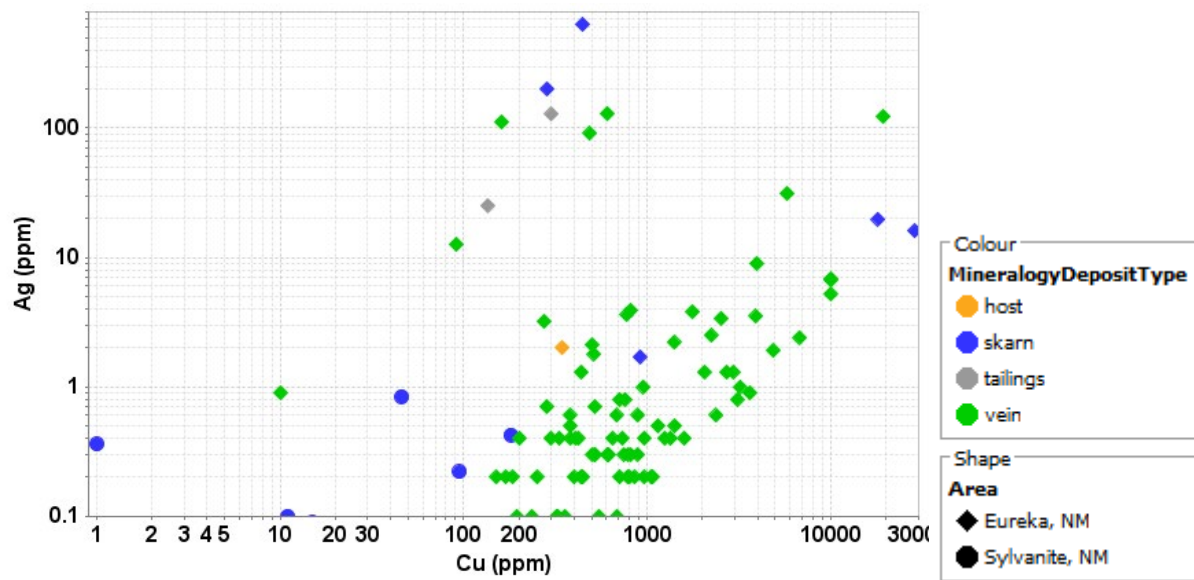


FIGURE 55. Silver vs. copper from samples from the Eureka and Sylvanite districts, Little Hatched Mountains. Chemical analyses in Appendix 3.

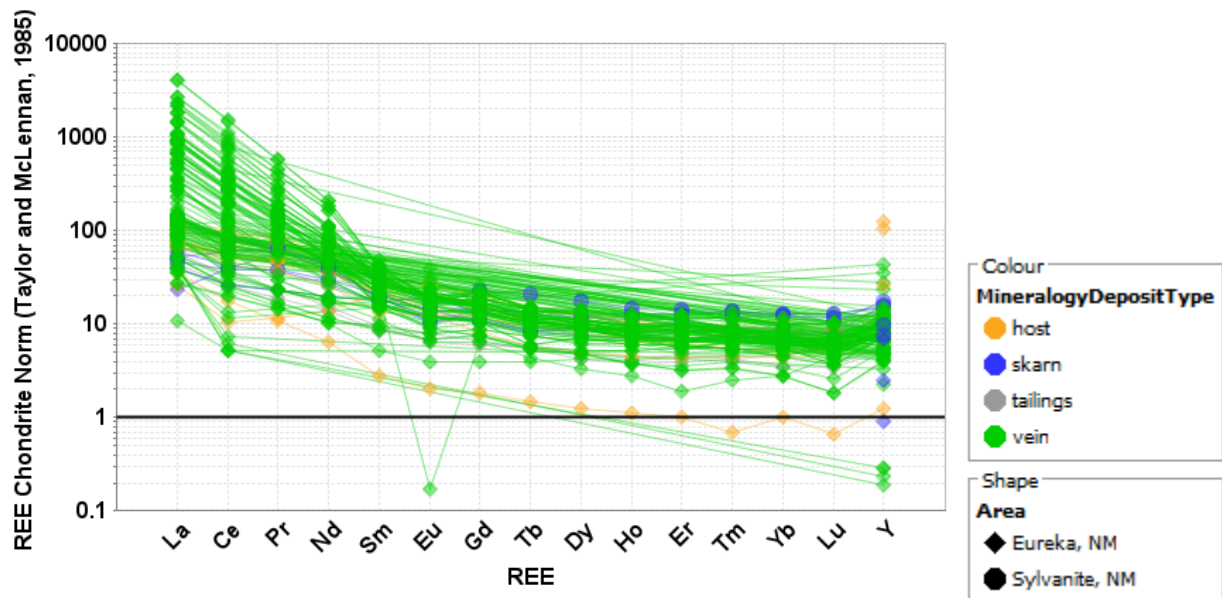


FIGURE 56. Chondrite-normalized plot of samples from the Eureka and Sylvanite districts, Little Hatched Mountains. REE are relatively flat-lying patterns and low, typical of porphyry copper deposits Chondrite values from Taylor and McLennan (1985).

Lone Mountain district

The Lone Mountain mining district consists of a series of low hills approximately 7 mi southeast of Silver City. Mineral deposits in the district consist of carbonate-hosted Ag-Mn and Cu-Pb-Zn skarn deposits. The district was discovered in 1871 by Frank Bisbee and Jack Frost. Once rich silver ore was identified, a mill was erected and mining and milling continued for two

or three years until the ore ran out and the mines closed (Lindgren et al., 1910; Pratt, 1967). Except for a small amount of manganiferous iron production during World War I, the area was dormant until 1920, when other silver discoveries were made. In 1921 to 1923 mining was again active. It was during this period, that lead was produced along with silver. These later discoveries continued to be worked sporadically in the late 1930s to 1950 (Table 15; Pratt, 1967). Since then, no additional silver has been produced. In 1942, 30 short tons of manganese ore averaging 39.5% Mn were produced (Farnham, 1961). From 1950 to 1955, another 800 short tons of sorted ore averaging 29.1% Mn was shipped to the government-purchasing depot in Deming. As of 1967, the silver and manganese deposits were mostly mined out and nearly all shafts are caved or unsafe (Pratt, 1967). Total metal production for the Lone Mountain mining district is shown in Table 15. Some of the deposits were mined for silver before turning to manganese production.

TABLE 15. Metals production from the Lone Mountain mining district, Grant County, New Mexico (U.S. Bureau of Mines, 1927-1950).

Year	Ore (Short Tons)	Copper (Pounds)	Gold (Ounces)	Silver (Ounces)	Lead (Pounds)	Total Value (\$)
1936	12	—	1	452	—	385
1938	1	—	—	68	—	44
1939	1	—	—	19	—	13
1948	2,509	—	3	13,356	—	12,193
1950	2,819	2,800	14	14,683	1,000	14,496
TOTAL 1936-1950	5,342	2,800	18	28,578	1,000	27,131
ESTIMATED TOTAL 1871-1950	—	5,000	<1,000	>100,000	5,000	>30,000

In 1975–1977, Bear Creek Mining Co. in joint venture with Leonard Resources Co. drilled along a positive aeromagnetic high located beneath Quaternary gravels, northwest of the known silver-manganese carbonate-hosted deposits. In 1979–1982, Dave Lowell with Coastal Mining Co. and Getty Oil Co. acquired the property and deepen several of the holes previously drilled and drilled two new holes. In 1982, Chevron joined the venture, deepen several of the holes, and drilled a new hole. Bear Creek drilled two additional holes in 1985. The Lone Mountain Mining Co. drilled holes in 1989 and 1997. In 2004, Galoway Resources, Ltd. acquired the property and drilled seven holes. Continent Resources Inc. acquired the property in 2008 and drilled additional holes. Copper One (USA), Inc. received a permit for additional exploration in 2013. Cornerstone Metals Inc. acquired the property in August 2013. A potential estimate of resources (not 43–101 compliant) from the prior drilling amounts to 110–160 million tons at 0.2–0.29% Cu (Ray and Pawlowski, 2009).

Lone Mountain consists of northeast-dipping Paleozoic, and Mesozoic sedimentary rocks, primarily limestone and dolomite, that were uplifted along a fault on the southwest (Lindgren et al., 1910). Rocks in the area range from Proterozoic to Recent. Proterozoic granite crops out at the western base of Lone Mountain (Pratt, 1967). The granite is overlain by about 4,000 ft of sedimentary rocks. From bottom to top, the sedimentary formations are the Bliss Sandstone, El Paso Dolomite, Montoya Group, Fusselman Dolomite, Percha Shale, Lake Valley Limestone, Magdalena Group, Abo (?) Formation, Beartooth Quartzite, and Colorado Formation. On the eastern flank of Lone Mountain, the Cameron Creek laccolith, an upper Cretaceous to Lower Tertiary biotite-quartz latite, was probably the intrusion suggested by Lindgren et al. (1910) as being related to the mineralization in the area. A Cretaceous-Tertiary-age Laramide intrusive suite that comprises the quartz monzonitic-granodioritic-latite Lone Mountain Intrusive

Complex (51.5–50.6 Ma, P.B. Hubbard and P.G. Dunn, unpubl. report, 1983; Moore and Moran, 2006) intrudes the sedimentary package. This complex includes the subcircular, 1 km-diameter Lone Mountain Stock, as well as a small satellite stock and related phases of sills and dikes, some of which occur as swarms. Most dikes and sills are only a few feet wide, but a few have an inferred length of as much as 3/4 mi. Most of the dikes filled already existing fractures or created new ones as they were emplaced.

Three distinctive types of mineral deposits are found at Lone Mountain: porphyry copper, supergene copper, and skarn deposits with minor CRD. The intrusive stock contains low-grade disseminated copper mineralization and would most likely be classified as a porphyry pyrite deposit instead of a porphyry copper deposit. Pyrite with minor chalcopyrite occurs as disseminations and thin veinlets. A near-surface supergene deposit was defined by drilling and grades up to 0.9% Cu (Ray and Palawski, 2009). Copper mineralization in the supergene deposit includes chrysocolla, malachite, azurite, chalcocite and Cu-Mn oxides.

Most of the silver and manganese deposits are CRD and skarns that occur along main crosscutting fractures in carbonate rocks (Pratt, 1967). Some brecciation occurs along the fractures, and limestone has been locally silicified (Lindgren et al., 1910). The deposits did not indicate the strict stratigraphic control found in many silver deposits in the region. In the Lone Mountain area, the silver deposits are scattered throughout the Fusselman Dolomite, and one vein reaches down into the Upham Dolomite and Aleman Formation.

Cerargyrite was the most common ore mineral, but curved bundles of native silver wire were the richest ore (Lindgren et al., 1910). Argentite was reported as a primary ore mineral, and native copper was reported (Pratt, 1967). Limonite was plentiful as an oxidation product of pyrite. Other minerals seen in fractures or on the mine dumps include quartz, calcite, dolomite, and small amounts of anglesite, cerussite, willemite, and malachite (Pratt, 1967). The mineralized veins were a narrow 2 to 5 ft with ore veins nearly 8 ft thick. The veins were not very persistent, but the ore they did contain was rich in silver (Lindgren et al., 1910).

Manganese deposits occur as irregular disconnected pod-like bodies along fracture zones that cut beds and replace Lake Valley Limestone just beneath the basal shale member of the Oswaldo Limestone of Magdalena Group (Farnham, 1961). The fractures are almost vertical and strike north. The ore bodies range to as much as 60 ft long and 1 to 6 ft wide. Some fractures contained two or more ore bodies separated by tens of feet of unmineralized or sparsely mineralized material. Most of the ore runs along the fractures, but in some places the adjacent limestone beds have been replaced. The chief ore minerals are pyrolusite and wad. Iron oxides, jasper, and black and white calcite are the principal gangue minerals.

The manganese deposits could be utilized a low-grade iron resource. The deposits are described as irregular masses of mangiferous hematite in shattered limestone on the flanks of Lone Mountain. The ore consists of hematite and pyrolusite with some wad, magnetite, calcite, and jasper. Ore from the Mineral Mountain group contained about 35% Fe and 15% Mn (Harrer and Kelly, 1963).

Drilling in 1975–1989 and in 2006–2007 northwest of the carbonate-hosted silver deposits at Lone Mountain delineated a weakly mineralized quartz latite to quartz monzonite stock surrounded by an upper copper oxide zone and two deeper, stratiform, copper and lead-zinc skarn bodies, ranging in depth from 100 to 3000 ft (Moore and Moran, 2006). Copper oxide zones are approximately 100 ft thick with grades of 0.1 % to 0.2 % copper, and rare intercepts to 0.6 %. Skarn grades in the Lake Valley Formation, while variable, are typically 1.5 to 3.0 % copper, 3 to 5 % zinc, 1.0 to 2.0 % lead, 0.01 to 0.02 ounces/short ton gold, and 1.0 to 3.0

ounces/short ton silver. Drilling indicates that skarn deposits surround the intrusive stock or plug and potential resources in the Lake Valley and Percha Shale are estimated as 7.5 million tons grading 2–3% Cu, 1–2% Pb, 4–5% Zn, 0.01–0.02 ounces/short ton Au, and 2–3 ounces/short ton Ag (NMBMMR file data unpublished report, November 1989).

Three drill holes were logged and handheld XRF measurements were obtained (Table 16, Fig. 57). Some critical minerals (Cu, Co, Ni, Pb, Zn) are above the exploration threshold, but these concentrations need to be confirmed by laboratory analyses and additional samples.

TABLE 16. Summary statistics of selected critical and other minerals in samples from the Lone Mountain district. Chemical analyses are from handheld XRF instrument and should be considered as estimates until verified by chemical analyses. Average crustal abundance and exploration threshold values from Table 1 (Otoo et al., 2025).

	Ag ppm	As ppm	Bi ppm	Cd ppm	Co ppm	Cu ppm	Mn ppm	Mo ppm
Count	460	460	460	460	460	460	460	460
Minimum	1	1	1	3	11	135	19	1
Maximum	49	1214	272	111	1696	236,761	27,399	4172
Mean	3	7	5	6	24	14,260	1001	44
Median	2	1	2	3	11	5330	139	10
Standard Deviation	4	57	14	9	95	24,074	3198	264
Average crustal abundance	53			0.06	15	27		
Exploration threshold	100	100	100	100	980	1400		1000

	Ni ppm	Pb ppm	S ppm	Sb ppm	U ppm	V ppm	W ppm	Zn ppm
Count	460	460	460	460	460	460	460	460
Minimum	10	2	22	4	2	3	10	4
Maximum	562	5613	78,259	325	73	1976	330	11,046
Mean	64	35	1284	23	3	53	51	598
Median	59	2	290	23	2	28	10	143
Standard Deviation	57	270	5437	23	5	114	64	1175
Average crustal abundance	34	17		0.075	2.6	106	1.4	75
Exploration threshold	4200	10500		700	910	2100	1050	15000

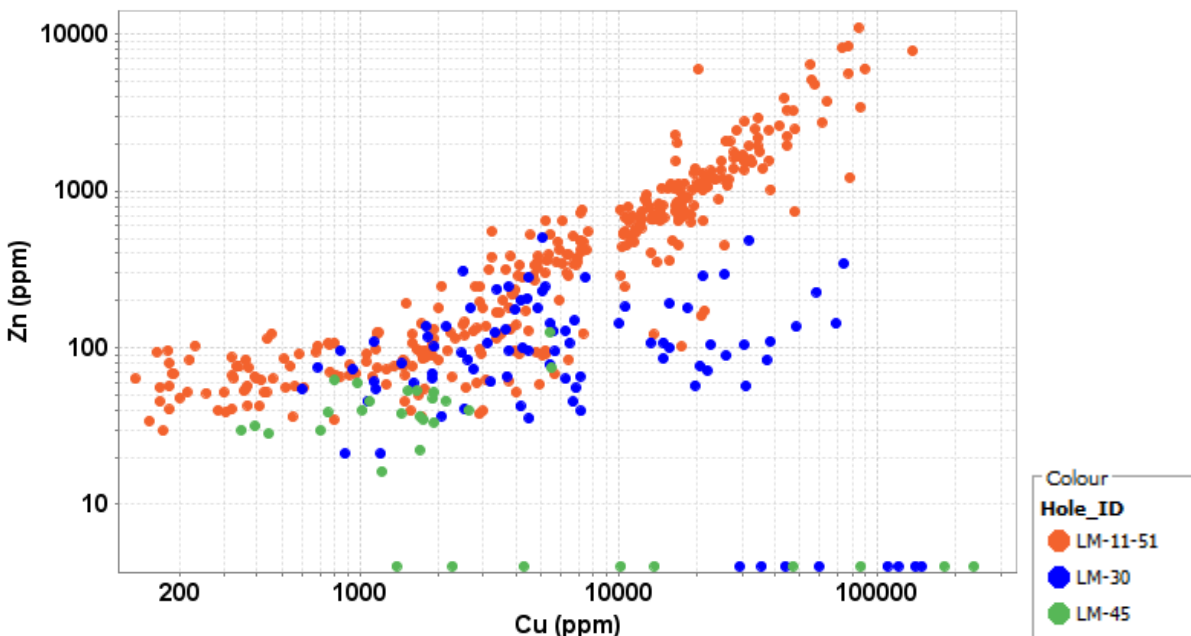


FIGURE 57. Scatter plot of copper versus zinc analyzed by handheld XRF instrument for three drill holes at Lone Mountain, New Mexico. Drill core is stored at the NMBGMR.

Gold Lake (White Signal district)

The Gold Lake copper-molybdenum ($\pm$ gold) porphyry deposit (NMGR0478) is in the White Signal district, Burro Mountains, Grant County. Mining began in the 1870s or 1880s. Fluorspar, uranium, radium, gold, silver, lead, bismuth, turquoise, and garnet have been produced from the district. The veins were mined to shallow depths (300 ft deep). Turquoise was mined from the Chapman (NMGR0028) and Red Hill mines. Exploration for uranium in the district occurred into the 1970s (Gillerman, 1968, 1970). Kerr McGee drilled 5 holes in 1960s and found brannerite in disseminated porphyry copper deposit. Cotter Corp drilled six holes exploring for uranium in 1970–1980. Other companies, including Cities Service Mineral Corp, Rocky Mountain Energy Corp. And S.E.A. Inc explored in the district. However, very little examination of the copper and molybdenum potential occurred until High Desert Gold Corp. Drilling by High Desert Gold Corp. in 2008 identified a porphyry copper-gold-molybdenum deposit (Katsura, 2009). Surface geochemistry, alteration, and turquoise supports that interpretation. Total production from 1880 to 1968 amounts to 26,000 pounds Cu, 2500 ounces Ag and 2200 pounds Pb, worth approximately \$80,000. In addition, 1700 ounces Au and 10 pounds of garnet have been produced from placer deposits (Table 17).

TABLE 17. Metals production from the White Signal mining district, Grant County, New Mexico (U.S. Bureau of Mines, 1927–1950).

Year	Ore (short tons)	Gold lode (ounces)	Gold placer (ounces)	Silver (ounces)	Copper (pounds)	Lead (pounds)	Total Value (\$)
1933	10		11.42	15.14	3		\$550
1934	23			138.17	187	200	\$4,957
1935				48.46	8		\$1,702
1936			0.40	4.66	2		\$179
1937				30.40	5		\$1,068
1938				98.40	12		\$3,452
1939	14	100	13.00	14.00	7		\$960
1940	30		31.00	2.00	90		\$1,219
1941	68	5,400	25.00	4.00	346		\$1,898
1942	140	10,100	10.00		169		\$1,692
1943	26	1,500			7		\$200
1946	19	700	17.00		151	1,900	\$1,037
1954	1	100			2		\$31
1957	39	100			43	100	\$83
Reported total 1933-1957	370	18,000	107.82	355.23	1,032	2,200	\$19,028
Estimated total 1880-1968	2,000	1,700		2,500.00	26,000	2,200	\$80,000

The Burro Mountains is a structural high composed mostly of Proterozoic granite and metamorphic rocks that were intruded by Late Cretaceous and Early Tertiary quartz monzonite and rhyolite intrusions. Quartz monzonite intrudes rhyolite plug in the Signal Mountain area. Tilting of the White Signal block is approximately 10 degrees northeast. Quartz monzonite and rhyolite have intruded Proterozoic rocks and are associated with porphyry-style alteration and veins (Klemmick, 2006; Katsura, 2009). Numerous, small, historic mine workings are found within this area, mostly prospects for copper, uranium, and gold. Rock chip sampling by High Desert Gold Corporation (formerly General Minerals Corporation) indicated anomalous copper (up to 11.5%), molybdenum (up to 0.17%), silver (up to 385 ppm), and bismuth (up to 2300 ppm) (Klemmick, 2006). Six drill holes, drilled in 2008, confirm the presence of porphyry copper mineralization and associated alteration. Additional drilling is needed to confirm and delineate any economic potential in the White Signal district.

Sample locations from the White Signal district are in Figure 58 and summary statistics are in Table 18. A TAS (total alkali, $\text{Na}_2\text{O} + \text{K}_2\text{O}$ vs silica, SiO_2) diagram for host rock samples from the White Signal district; most of the samples plot as granite (Fig. 59). Silver, copper, zinc, and uranium are elevated (Fig. 60). REE are relatively flat-lying patterns and low, typical of porphyry copper deposits (Fig. 61).

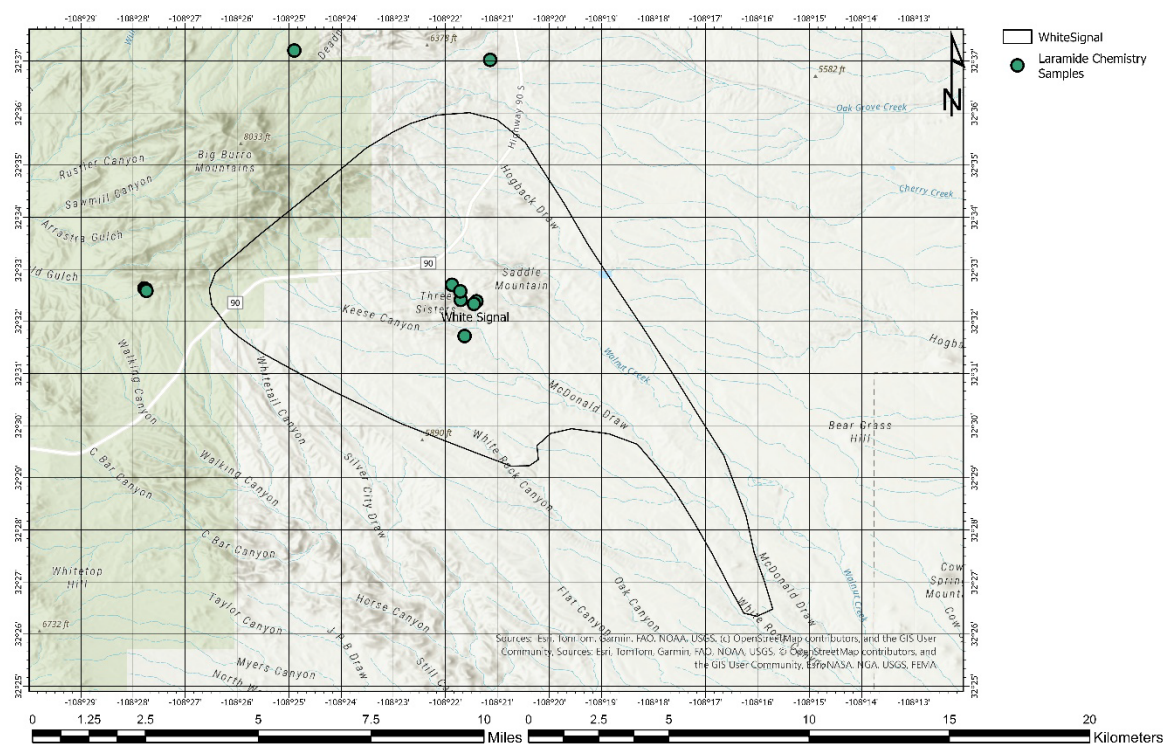


FIGURE 58. Location of samples in the White Signal districts, Burro Mountains.

TABLE 18. Summary statistics of selected critical minerals in samples from the White Signal district.

	Ag (ppm)	Bi (ppm)	Cu (ppm)	U (ppm)	TREE
Count	14	14	14	14	14
Minimum	0.05	0.2	14	2	40
Maximum	128	222	70,700	721	2684
Mean	13	27	5447	76	491
Median	3	3	129	8	273
Standard Deviation	34	59	18,798	189	712

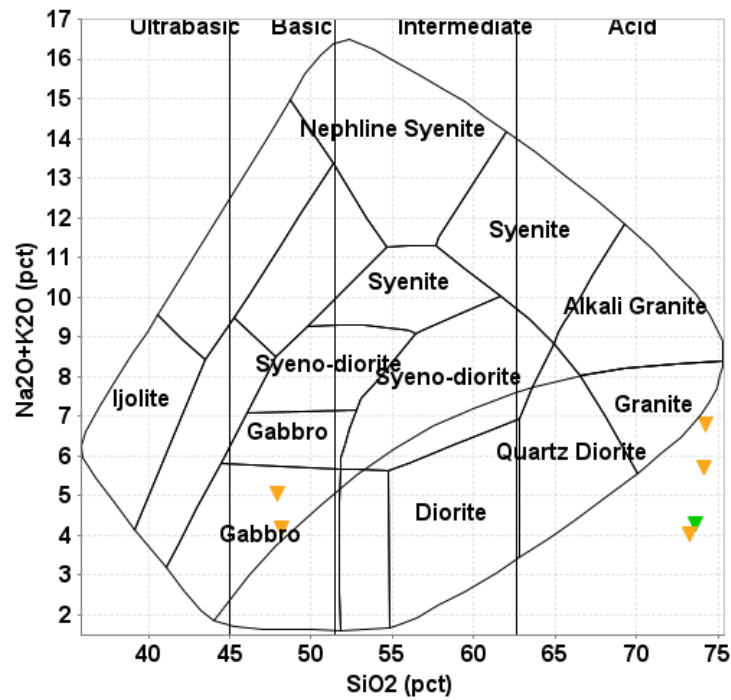
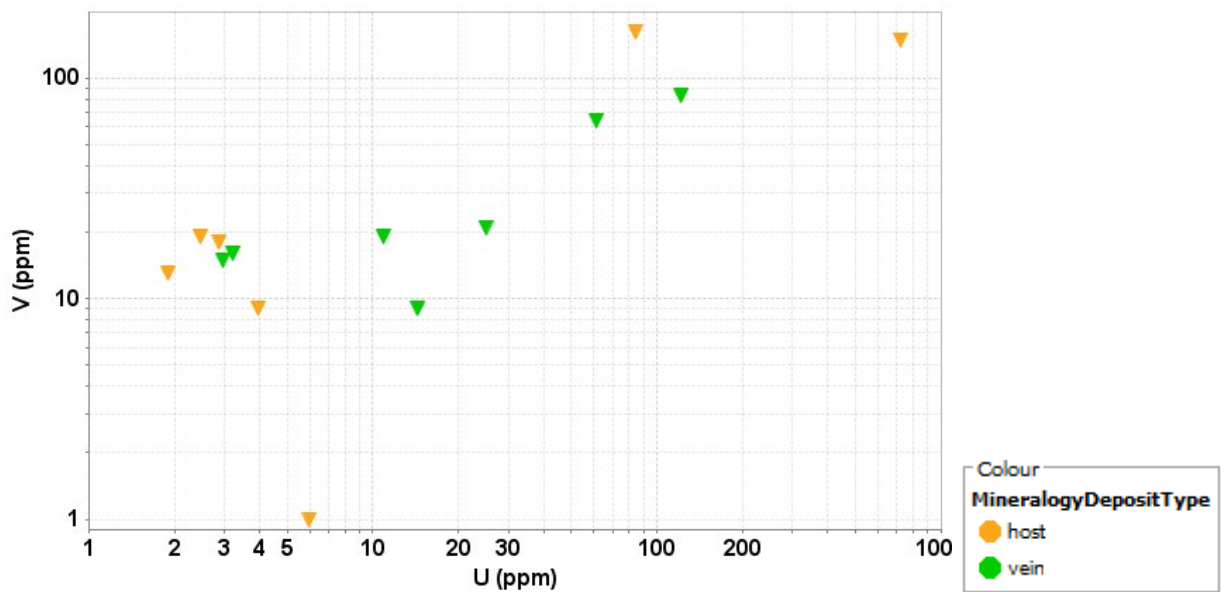


FIGURE 59. TAS diagram of samples from the White Signal district (Cox et al., 1979). Most of the samples plot as granite. Chemical analyses are in Appendix 3. The curved solid line subdivides the alkaline (above curve) from subalkaline rocks (below curve; from Irvine and Baragar, 1971).



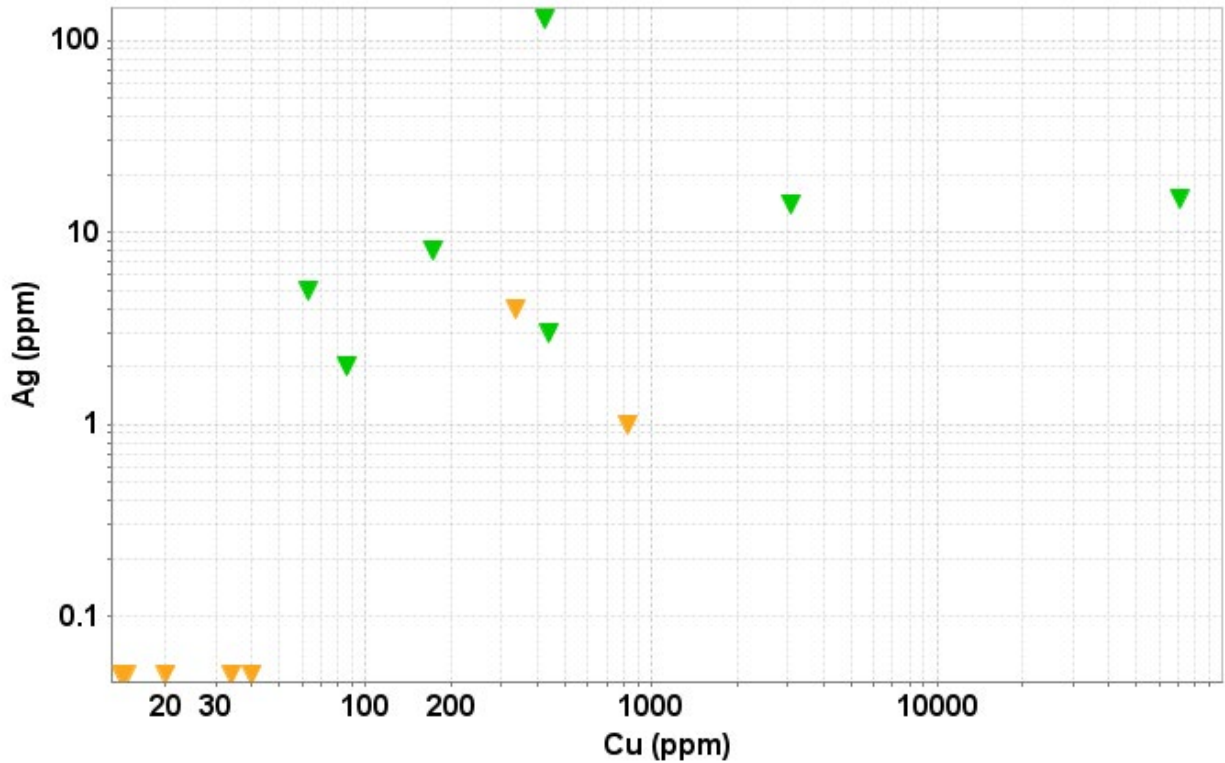


FIGURE 60. Vanadium vs. uranium and silver vs. copper for samples from the White Signal district, Burro Mountains.

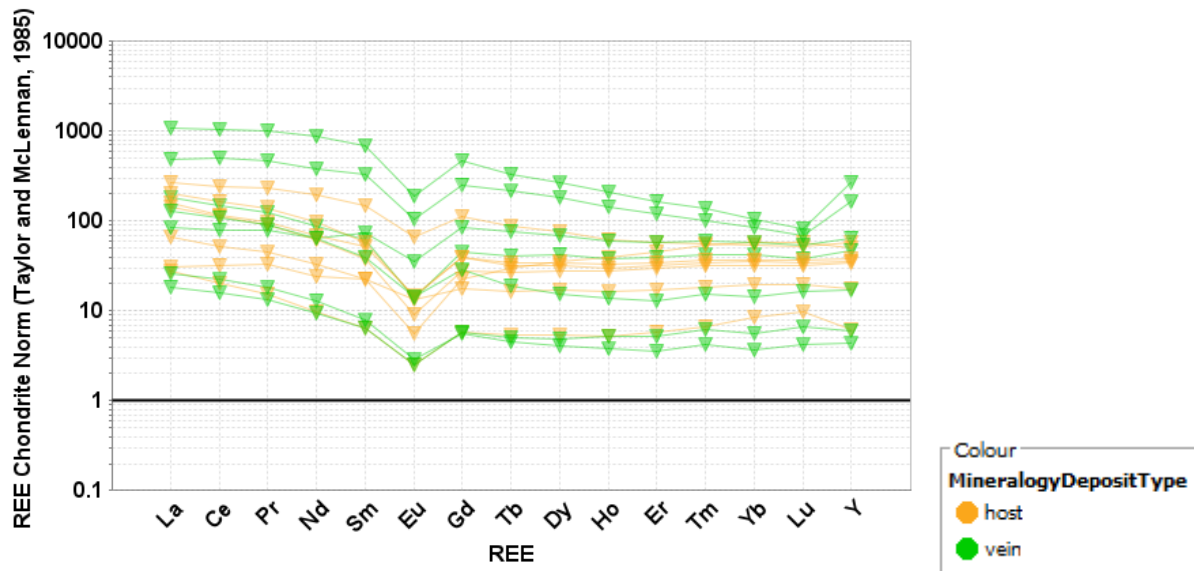


FIGURE 61. Chondrite-normalized plot of samples from the White Signal district. Chondrite values from Taylor and McLennan (1985).

Malone district

The Malone mining district lies in the southwestern part of the Burro Mountains along the Malone fault. John B. Malone discovered gold in the area in 1884 after years of placer gold

mining in nearby Gold Gulch and Thompson Canyon (Gillerman, 1964). Production prior to 1925 amounted to approximately \$250,000 in gold and a little silver, most before 1900. In 1904, while gravels in many of the local gulches were being worked for placer gold, additional gold-silver veins were discovered just west of the Malone mine. Total production after 1925 amounted to no more than \$50,000. In the 1930s, renewed interest in the area led to new mining ventures and extensions to some older workings. From the 1940s, until at least 1964, mining has been intermittent. In 1961, Albert A. Leach owned 13 unpatented claims covering most of the district (Gillerman, 1964). Total production from 1880 to 1985 from Laramide veins and placer gold deposits in the district amounts to approximately 12,000 ounces Au, more than 10,000 ounces Ag, and minor amounts of copper, lead, and zinc (Table 19). Several mining companies have explored the Malone district, including Santa Fe Gold Corp., Evolving Gold Corp., and Newmont Corporation. In 2021, Bronco Creek Exploration Co. was exploring the district.

TABLE 19. Production from the Malone district (Richter et al., 1983; North and McLemore, 1986; McLemore, 2017).

Period of production	Ore (short tons)	Copper (pounds)	Gold (troy ounces)	Silver (troy ounces)	Lead (pounds)	Zinc (pounds)	Estimated metals value
1880-1925							\$250,000
1949	388.992		92.707	1494.61			\$4,272
1985	222.718	702	14.04	1450.1			\$8,648
Estimated total 1884-1985	—	W	12,000	>10,000	W	W	\$300,000

Placer gold deposits and quartz-pyrite veins are hosted in a half-graben consisting of Proterozoic Burro Mountain granite and related to Cretaceous (?) quartz monzonite and rhyolite dikes and small plutons are found in the Malone district (Fahey, 2019; Mizer, 2022). Proterozoic granite and metamorphic rocks are unconformably overlain by titled, unaltered volcanic rocks ranging in age from 36.2 ± 0.6 to 32.6 ± 0.4 Ma (Amato et al., 2025). A rhyolite dike that intruded the Proterozoic granite has been dated as 58.6 ± 0.7 Ma by Amato et al. (2025) (Appendix 1). The Malone fault strikes N20°W and dips 70°NE and marks the western edge of zones of numerous fractures that cut the granite adjacent to the fault, but the Malone fault is not mineralized (Gillerman, 1964). Although the age of the Malone mineral deposits is uncertain, the absence of hydrothermal alteration and mineralized veins in the volcanic rocks suggests that the Malone mineralization is older than the volcanic rocks that range in age from 36.2 ± 0.4 to 32.6 ± 0.4 Ma (Amato et al., 2025) but is associated with the faulting and the rhyolite dike (Gillerman 1964; Ray, 2007; Fahey, 2019).

Sheeted and stockwork quartz-pyrite veins with Au-Pb-Zn-Cu minerals and pervasive, weak to moderate quartz-sericite-pyrite alteration are characteristic of porphyry copper alteration (Fahey, 2019). Fractures cutting the Burro Mountain granite adjacent to the Malone fault are mineralized up to 1,000 ft away. The fractures are filled with gold-bearing quartz and pyrite veins with minor chalcopyrite, argentiferous galena, and sphalerite (Gillerman, 1964). The gold is extremely fine grained and can only be detected by chemical analysis. Mineralization appears to be shallow, as none of the mines in the area are greater than 100 ft deep. The granite hosting the veins shows evidence of sericitic, kaolinitic, and hematitic alteration. Overlying sedimentary and volcanic rocks are unaltered.

The fractures trend mostly N45–85°W, except for the Patanka vein, which strikes N35°E and dips steeply to the southeast. This complex faulting suggests that the area has been tilted 50–70°E (Hedlund, 1985a, b; Fahey, 2019). Structural reconstruction by Fahey (2019) and Favorito and Seedorf (2024) suggests the Malone district could be a western extension of the Tyrone porphyry copper deposit.

Critical minerals are present in the Malone district. Silver was produced (Table 19). Reported sampling (Ray, 2007) indicated high concentrations of Au (17.7 ppm), Ag (695 ppm), As (148 ppm), Bi (112 ppm), Hg (0.87 ppm), Sb (62 ppm) and Zn (1.59%). Only two vein samples are from the Malone district. Additional chemical analyses are pending. REE are relatively flat-lying patterns and low, typical of porphyry copper deposits (Fig. 62).

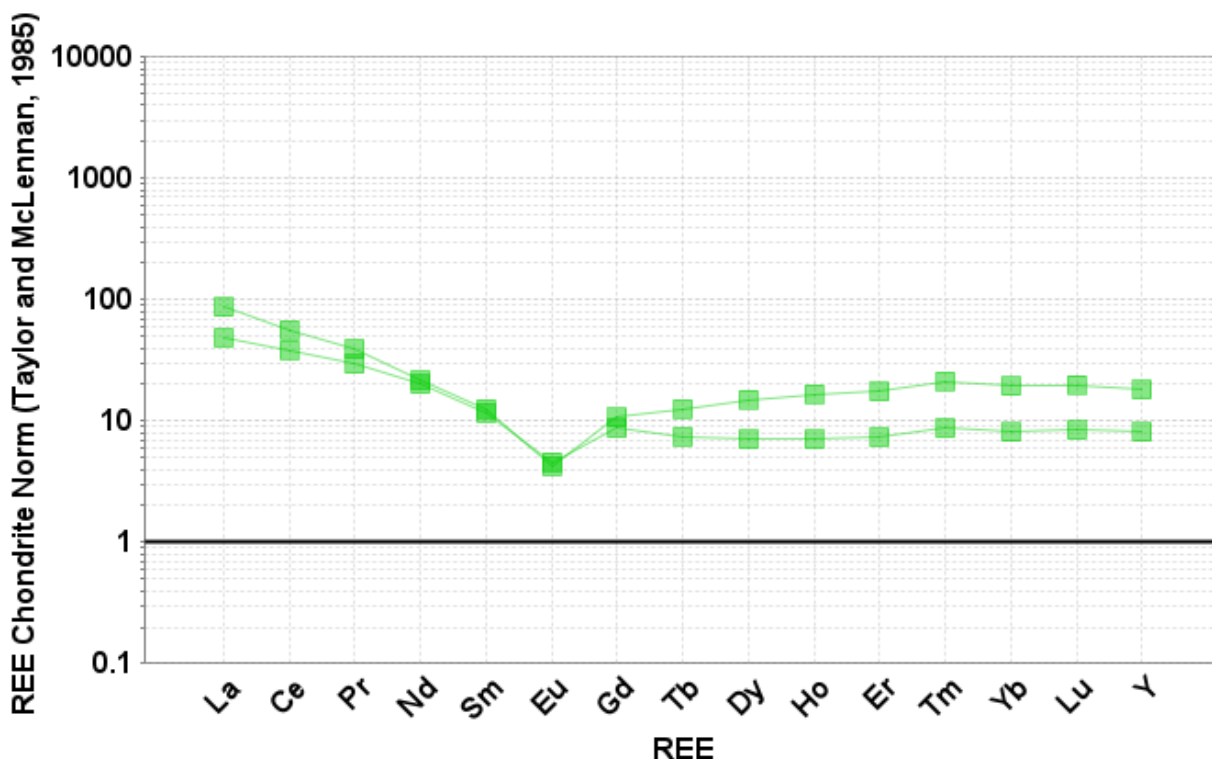


FIGURE 62. Chondrite-normalized plot of samples from the Malone district. Chondrite values from Taylor and McLennan (1985).

Lordsburg district

The Lordsburg district is in the northern part of the Pyramid Mountains and is divided into two subdistricts, the northern Virginia (Ralston, Shakespeare) and southern Pyramid (Leitendorf) subdistricts. The Lordsburg mining district is one of the few districts in New Mexico that contain Laramide polymetallic veins without any porphyry copper deposits exposed at the surface (North and McLemore, 1986; McLemore, 2017). Exploration for porphyry copper deposits in the district has occurred during the last 30–40 yrs and has located three centers of porphyry copper mineralization in the subsurface (Mine Mappers, LLC, 2022). Lasky (1938) and Flege (1959) provided an extensive geologic report of the district. Elston (1965), Clark (1970) and Agezo (1995) also describe the mineral deposits.

Although, the first mining claims were located in the Pyramid subdistrict in 1870, polymetallic veins were known as early as 1854. Some early attempts were made to ship silver ore from the silver-gold-copper vein deposits, but it was not until the Southern Pacific Railroad reached Lordsburg in 1880 that mining began. The district has seen numerous booms and busts; the last mine closed in 1999. Significant production occurred from 1904 to 1951 (Table 20). Federal Resources Corp. operated the Banner, Bonney (NMHI0063), Little Annie, and Eighty-five (NMHI0072) mines. Phelps Dodge and joint ventures explored the district in 1970-1975. A tri-venture was formed in 1983 between Federal Resources, Phelps Dodge, and Westar, Inc. to develop the North Atwood open pit for smelter flux. Westar assumed full control of the operation in the mid-1980's and constructed a cyanide heap leach facility west of the Banner mill site but soon went bankrupt (White, 2000). Federal Resources regained control of the properties in 1990, and later joined the Lordsburg Mining Company (LMC) joint venture, which developed the underground North Atwood mine and closed in 1994 (White, 2000). LMC produced barren aggregate from the district during the 1990s as part of reclamation of old mine and mill sites. The largest producing mines were on the Bonney and Emerald veins at the Eighty-five mine. In 2007, Entrée Gold Inc. announced the discovery of a porphyry copper deposit in the Lordsburg district; drilling in 2008–2009 indicated as much as 0.33% copper and 0.26 ppm gold from the deposit. Santa Fe Gold Company conducted exploration in 2011. Later in 2012, historic reserves were estimated as 72,268 tons of ore at 3.58% Cu, 0.012 grams/tonne Au and 0.63 gram/tonne Ag (Table 21; Rogers, 2012). Waterton Global Resource Management studied the area in 2016 and 2020 (Mine Mappers, LLC, 2022). American Copper Development Co. (formerly Cirrus Gold Corp) acquired the property in 2022. Total production from the district from 1885 to 1999 is estimated as 229,577,000 pounds Cu, 11,000,000 pounds Pb, 4,200,000 pounds Zn, 8,067,741 ounces Ag, and 286,275 ounces Au (Table; McLemore, 2017). Placer gold has been reported (Table 20; McLemore, 2017) and 3527 short tons of fluorite were also produced.

TABLE 20. Production from the Lordsburg district (USGS, 1902–1927; USBM, 1927–1990; Lasky, 1938; Lasky and Wootton, 1933; Fledge, 1959; McLemore and Elston, 2000; White, 2000; McLemore, 2017).

Year	Ore (short tons)	Copper (pounds)	Gold (ounces)	Silver (ounces)	Lead (pounds)	Zinc (pounds)	Total value (\$)
1882–1903							\$45,000
1904	250	18,200	58.44	2,580	12,000		\$5,550
1905	366	48,000	0.50	7,584			\$12,124
1906	1,743	212,601	250.00	27,261			\$64,737
1907	5,645	463,335	423.85	31,303	10,522		\$122,646
1908	7,532	259,079	513.60	9,889	11,363		\$50,534
1909	10,690	589,969	1,257.04	50,154	8,862		\$129,140
1910	29,220	1,627,591	2,892.73	130,324	19,662		\$337,742
1911	46,139	2,455,336	5,160.00	182,448	2,157		\$510,359
1912	55,340	3,155,585	7,008.00	275,251	4,562		\$835,015
1913	31,284	1,601,461	2,672.00	154,779	14,572		\$397,588
1914	38,964	2,614,674	4,890.00	232,647	30,049		\$578,658
1915	92,093	3,890,365	10,781.00	374,325	28,723		\$1,094,795
1916	118,966	4,755,179	12,924.00	373,074	30,478		\$1,684,508

Year	Ore (short tons)	Copper (pounds)	Gold (ounces)	Silver (ounces)	Lead (pounds)	Zinc (pounds)	Total value (\$)
1917	99,532	4,261,956	11,882.00	295,443	41,442		\$1,656,130
1918	55,015	2,214,996	6,331.00	153,236	17,831		\$832,464
1919	77,002	3,516,457	8,467.00	242,733	53,264		\$1,103,753
1920	55,307	2,695,674	7,424.00	182,000	98,312		\$855,710
1921	11,593	579,295	1,112.00	35,119	13,134		\$133,426
1922	61,291	3,216,585	5,559.00	107,511	102,291		\$662,287
1923	96,587	4,314,122	10,477.00	141,538	46,185		\$970,024
1924	88,472	4,927,878	9,299.00	113,591	40,412		\$917,094
1925	108,219	5,064,140	10,780.00	126,781	69,700		\$1,035,981
1926	97,420	4,762,750	11,706.00	126,909	73,400		\$993,802
1927	93,406	3,933,496	9,547.00	77,155	46,381		\$759,290
1928	91,289	4,625,347	10,525.00	104,653	19,638		\$945,959
1929	83,091	4,248,193	10,612.00	159,163	59,080		\$1,055,597
1930	102,317	4,857,300	14,021.00	189,070	88,300		\$998,479
1931	96,032	3,991,700	11,288.00	137,731	96,700		\$640,080
1932	Production not reported						
1933	256	21,000	105.41	1,820	19,000		\$4,863
1934	773	27,950	243.89	2,998	19,200		\$13,408
1935	1,658	78,000	439.97	11,370	28,100		\$31,169
1936	21,279	816,150	1,306.20	28,612	52,900		\$145,396
1937	74,752	3,807,890	2,143.40	75,196	53,200		\$597,077
1938	112,157	6,346,300	3,402.40	134,849	113,200		\$833,403
1939	116,331	6,367,900	4,230.00	131,471	6,000		\$899,835
1940	126,670	6,555,300	2,225.00	76,770	77,900		\$877,111
1941	121,145	7,467,300	1,270.00	63,886	48,000	12,000	\$974,657
1942	123,397	6,715,100	1,257.00	90,803	224,400	113,600	\$946,693
1943	110,963	4,991,900	1,440.00	82,350	113,800	41,500	\$770,924
1944	132,707	4,717,400	2,316.00	113,739	292,800	78,000	\$831,106
1945	84,773	2,292,800	1,411.00	90,336	337,200		\$452,151
1946	54,729	2,392,000	1,582.00	100,963	215,000		\$547,887
1947	70,893	3,539,300	1,845.00	185,561	530,400		\$1,052,139
1948	68,481	3,415,000	1,683.00	165,256	158,000	138,000	\$996,161
1949	81,640	3,868,000	1,981.00	149,312	683,000	51,000	\$1,080,704
1950	73,349	4,122,100	714.00	92,816	171,100	8,000	\$990,624
1951	72,107	3,041,000	755.00	89,610	287,300	31,000	\$898,794
1952	60,524	2,950,000	820.00	70,911	105,000	4,000	\$824,347
1953	84,324	3,975,000	1,205.00	100,844	124,000		\$1,290,513
1954	100,861	4,419,000	367.00	73,098	45,900		\$1,388,895

Year	Ore (short tons)	Copper (pounds)	Gold (ounces)	Silver (ounces)	Lead (pounds)	Zinc (pounds)	Total value (\$)
1955	122,992	4,509,800	684.00	83,751	17,500	2,000	\$1,784,748
1956	88,142	4,240,500	543.00	60,699	37,400		\$1,882,625
1957	83,887	3,432,100	495.00	30,685	7,500	1,500	\$1,079,405
Reported total 1904–1957	3,643,595	174,010,114	222,325.43	6,151,958	4,816,820	468,600	\$40,623,107
Estimated total 1885–1999	4,337,495	229,577,000	286,275	8,067,741	11,000,000	4,200,000	>\$60,000,000

TABLE 21. Historic resources (not NI43–101 compliant) reported by Federal Resources, May 1970 (Rogers, 2012). Although these resources are not NI43–101 compliant or significantly large tonnages, they do indicate a potential remining resource.

	Proven tons	%Cu	Au ounces/ton	Ag ounces/ton	Probable Tons	%Cu	Au ounces/ton	Ag ounces/ton	Possible Tons	%Cu	Au ounces/ton	Ag ounces/ton
Bonney 1600-2100 level	55,694	3.51	0.008	0.065	230,621	2.93	0.011	0.66	118,444	2.89	0.01	0.66
Eighty-five 1500-1950 level	23,968	3.74	0.062	0.59	61,084	4.22	0.034	0.66	57,569	2.34	0.009	0.31
Total	79,662	3.58	0.012	0.63	291,705	3.2	0.016	0.66	176,013	2.71	0.01	0.5

Host rocks in the district consist of Lower Cretaceous andesite to basalt flows at least 2000 ft thick, which were intruded by plugs of basalt and rhyolite breccias (Table 22; Thorman and Drewes, 1978; McLemore, 2000). The volcanic rocks have been intruded by a granodiorite porphyry stock and related granodiorite porphyry, aplite dikes and plugs (Fig. 2). Plugs and dikes of dacite cut the granodiorite. The granodiorite phases are medium to coarse grained, porphyritic (Fig. 3).

The age results record three chronologically discrete events in the region (Appendix 1; McLemore et al., 2000a). The ~67 Ma andesites in the Lordsburg district may correlate to the upper Hidalgo Formation in the Little Hatchet Mountains or alternatively, they represent a separate volcanic event. The second pulse is the 57.3–58.8 Ma intrusion of the granodiorite and associated rocks (Appendix 1). The third age grouping is recorded by the zircon fission-track data, the total gas age from Lord 11 biotite, and the young part of Lord 22 plagioclase ~54 Ma (Appendix 1). This time period may represent a discrete pulse of igneous activity or a time of cooling below ~200–250°C in the area. The polymetallic veins are 57–54 Ma, since they cut the granodiorite and are intruded by the dacite dikes. Lordsburg is along the Santa Rita Lineament and almost near the intersection of the Texas Lineament.

TABLE 22. Summary of age determinations in the northern Lordsburg district (McLemore et al., 2000a).

Sample	$^{40}\text{Ar}/^{39}\text{Ar}$ (NMBMMR; McLemore et al., 2000a)	Fission track ages (Ma, zircon, Thorman and Drewes, 1978)	Lithologic unit (Thorman and Drewes, 1978)
Lord 11 (biotite)	54.53±0.56 (total gas age)	52.7±2.7	Dacite porphyry dikes (Tl)
Lord 12 (biotite)	41.9±1.1 (total gas age)		Dacite porphyry dikes (Tl)
Lord 18 (biotite)	57.25±0.12		Aplite (Tap)
Lord 5 (biotite)	56.58±0.30	58.5±2.0	Granodiorite (Tgd)
Lord 14 (biotite)	56.84±0.36		Granodiorite (Tgd)
Lord 20 (biotite)	58.06±0.10		Granodiorite (Tgd)
Lord 17 (groundmass)	66.3±0.4	54.9±2.7	Andesite flows of Animas Road (Taa)
Lord 22 (plagioclase)	67.94±0.57 (high-temperature plateau age) 54.7±0.1 (low-temperature plateau age)	67.3±7.1	Andesite of Gore Canyon (Kag)

Mineral deposits in the district are polymetallic, fissure-filling veins in fault and fracture zones that transect the contact zone of the granodiorite porphyry stock (Thorman and Drewes, 1978; McLemore and Elston, 2000). Clark (1970) defined the surface and vertical district zoning as a central core of chalcopyrite with tourmaline and specularite, grading into an outer zone of less copper and more lead, zinc, silver, and barite, centered around Eighty-five Hill. The polymetallic veins are 57–54 Ma, since they cut the granodiorite and are intruded by the dacite dikes. The primary ore mineral is chalcopyrite occurring in steeply dipping quartz veins hosted by Tertiary andesite and granodiorite. Other minerals associated with the mineralization include clays, chlorite, pyrite, calcite, and minor sphalerite, galena, and local specularite, tourmaline, fluorite and barite.

Various surface and subsurface (drill core) evidence indicate that the district is underlain by three porphyry copper systems: 1) alteration patterns (Rogers, 2012; Mine Mappers LLC, 2022), 2) district zoning (Clark 1970), 3) predominance of copper in the veins, increasing at depth in the deepest mines, 4) geophysical data shows major magnetic highs in the district (Rogers, 2012; Mine Mappers LLC, 2022; Bultman, 2024), and 5) presence of breccia pipes (Mine Mappers LLC, 2022). It is likely that three porphyry copper deposits underlie the veins beneath the Eighty-five mine, south of the Misers Chest, and in the northeastern portion of the district (Fig. 3).

Critical minerals that were produced include Ag, Cu, Pb, Zn, and F (Appendix 2) and these elements are present in economic grades (Table 22; Clark, 1970; Rogers, 2012; Mine Mappers, LLC, 2022). The data set in Appendix 3 include analyses by Juhas (2013). Sample locations from the Lordsburg district are in Figure 63 and summary statistics are in Table 23. Other critical minerals that are elevated include (Appendix 3) Bi (up to 373 ppm) and In (up to 9 ppm). Silver, copper, zinc, and uranium are elevated (Fig. 64). REE are relatively flat-lying patterns and low, typical of porphyry copper deposits (Fig. 65).

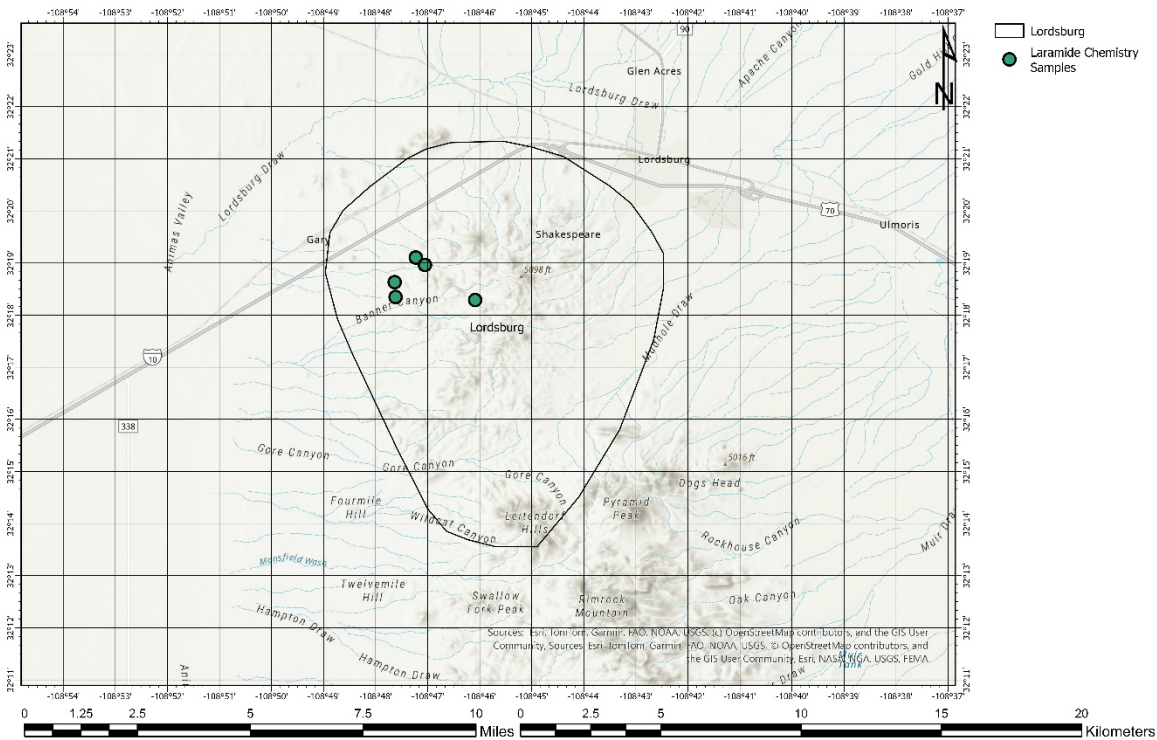


FIGURE 63. Location of samples in the Lordsburg districts, Animas Mountains.

TABLE 23. Summary statistics of selected critical and other minerals in samples from the Lordsburg district. Average crustal abundance and exploration threshold values from Table 1 (Otoo et al., 2025a, b). Chemical analyses are by Juhas (2013) and samples collected for this report (Appendix 3).

	Ag (ppm)	Bi (ppm)	Cu (ppm)	Pb (ppm)
Count Numeric	15	15	29	30
Minimum	0.05	0.03	5	1.9
Maximum	328	595	180,000	13,200
Mean	47	66	9794	1331
Median	10	1	136	35
Standard Deviation	89	175	33851	3308
Average crustal abundance	53		27	
Exploration threshold	100		1400	10

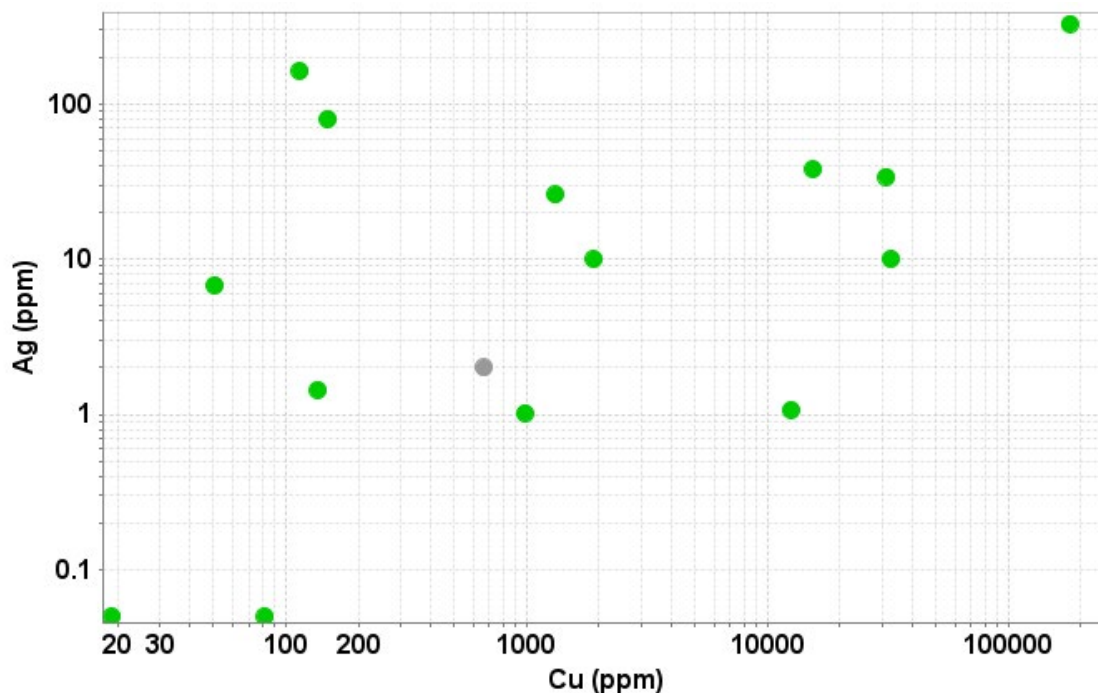


FIGURE 64. Silver vs. copper for polymetallic vein samples from the Lordsburg district. Chemical analyses are by Juhas (2013) and samples collected for this report (Appendix 3).

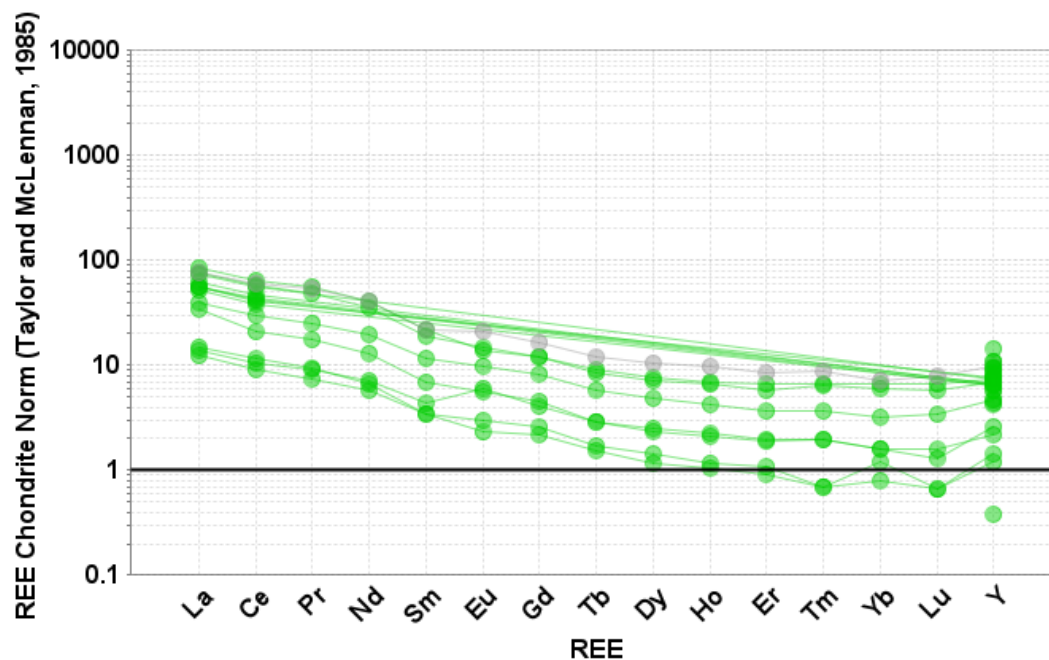


FIGURE 65. Chondrite-normalized plot of polymetallic vein samples from the Lordsburg district. Chondrite values from Taylor and McLennan (1985). Chemical analyses are by Juhas (2013) and samples collected for this report (Appendix 3).

DISCUSSION

Geochronology

The geochronology of the plutons in the New Mexico portion of the North American Porphyry Copper Belt is summarized in Appendix 1 and Figures 66 and 67. New dates are from various theses associated with this project (Stafford, 2024; Sanchez, 2025; Moses, in preparation) as well as previous dating efforts reported in the literature (Appendix 1). These new $^{40}\text{Ar}/^{39}\text{Ar}$ dates and prior $^{40}\text{Ar}/^{39}\text{Ar}$ and U/Pb age determinations have constrained the North American Porphyry Copper Belt into five pulses:

- Jurassic (Bisbee, Az, 200 Ma)
- 80–70 Ma Laramide Pulse 1 (porphyry copper)
- 60–50 Ma Laramide Pulse 2 (porphyry copper)
- 45–25 Ma Paleogene Pulse 3 (Mo-W deposits, CRD, maybe porphyry copper)
- Supergene enrichment followed igneous activity in many porphyry copper districts starting at ~41 Ma and lasting until ~2 Ma or even younger locally (Mach, 2004; Cook and Porter, 2005; Leveille and Stegen, 2012).

Magmatic activity associated with mineral deposits in southwest New Mexico occurred in only three pulses. Two pulses, 80–70 Ma and 60–50 Ma, are associated with the Laramide orogeny, with an additional younger pulse from 45–25 Ma associated with Paleocene extension (Fig. 67). Supergene enrichment occurred in many districts 41–2 Ma. There is no distinct spatial pattern of the distribution of the plutons with age (Fig. 66). Several districts have more than one pulse of magmatism that could have resulted in mineralization.

Critical Minerals

Most hosts to porphyry copper deposits in New Mexico are calc-alkaline to alkaline (Fig. 68; Stafford, 2024). Calc-alkaline magmas generally have a greater affinity for forming fertile porphyry copper deposits (Titley, 1982; Keith and Wilt, 1986; Keith, 1986; Richards, 2005, 2013, 2021), but other magma compositions, especially alkaline, are possible (Richards, 2021; Park et al., 2021). The differentiation of magmas to more alkaline affinities and tears in the subducted slab allowing asthenospheric material accounts for the local variations in chemistry, style of intrusions, and associated mineralization (Richards, 2005; McMillan 2004).

Elevated copper and silver are found in most mining districts in southwestern New Mexico. Range of selected critical minerals by type of mineral deposit are in Figure 69 and by mining district in Figure 70. Districts with high molybdenum (Hillsboro have elevated rhenium. Uranium is elevated in some samples from the White Signal district. Vein deposits tend to be higher in total REE than other types of deposits (Fig. 69, 71), but the total REE are relatively low for most samples. However, a few deposits contain elevated total REE (Table 24; Fig. 71), including Santa Rita (717 ppm), Fierro-Hanover (937 ppm), and Oro (Eureka, 2272 ppm). Although, these values are not normally economic, the large volumes of porphyry copper deposits mined enhance the economics of REE and critical minerals in these deposits.

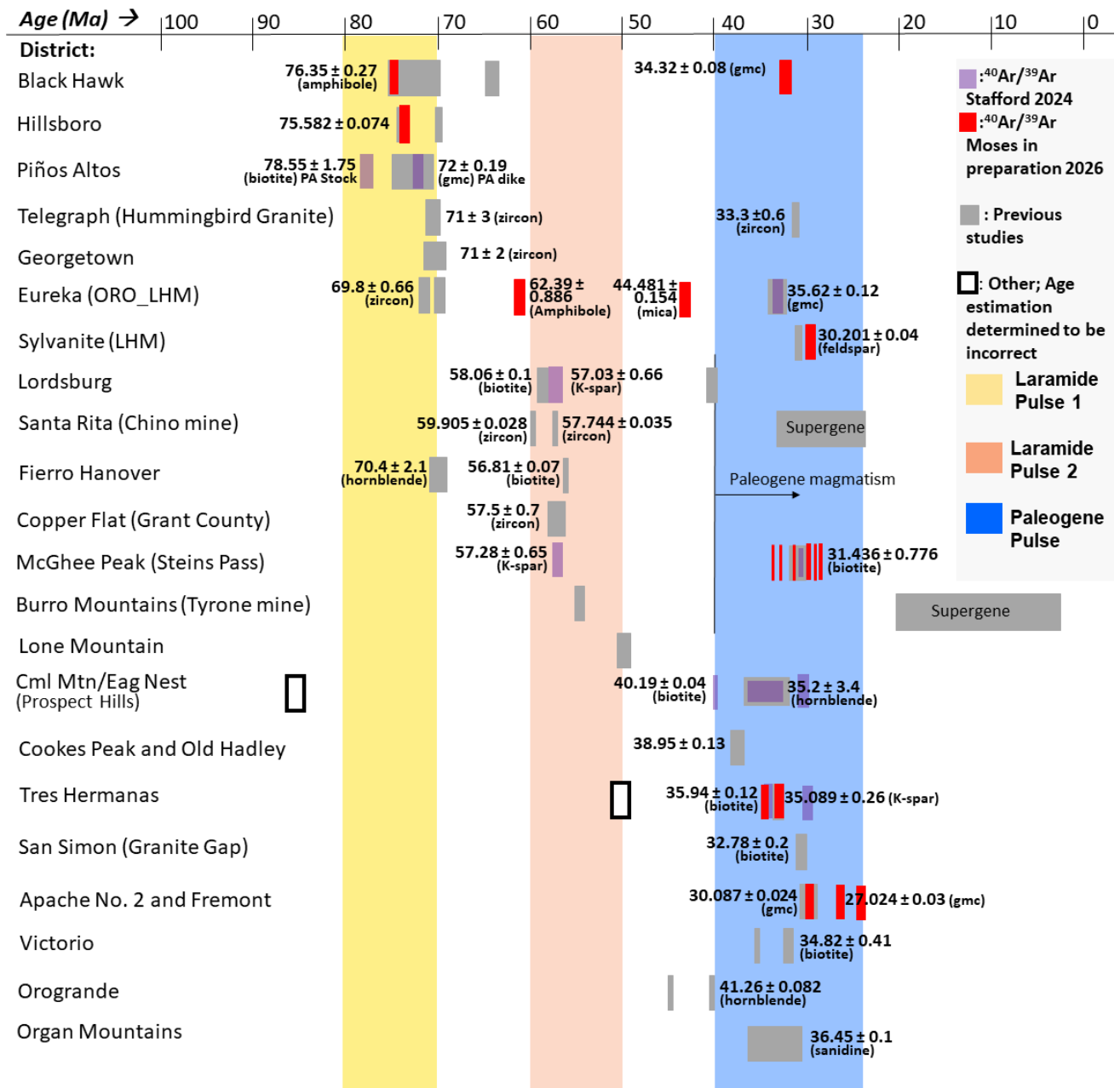


FIGURE 66. Updated geochronology for Laramide and Paleocene deposits in the North American Porphyry Copper Belt in southwestern New Mexico (from Moses, in preparation modified from Stafford, 2023). Ages, methods of age determinations and references are in Appendix 1. All older published $^{40}\text{Ar}/^{39}\text{Ar}$ ages are recalculated using FC-2 Fish Canyon Tuff sanidine age of 28.201 Ma after Kuiper et al. (2008).

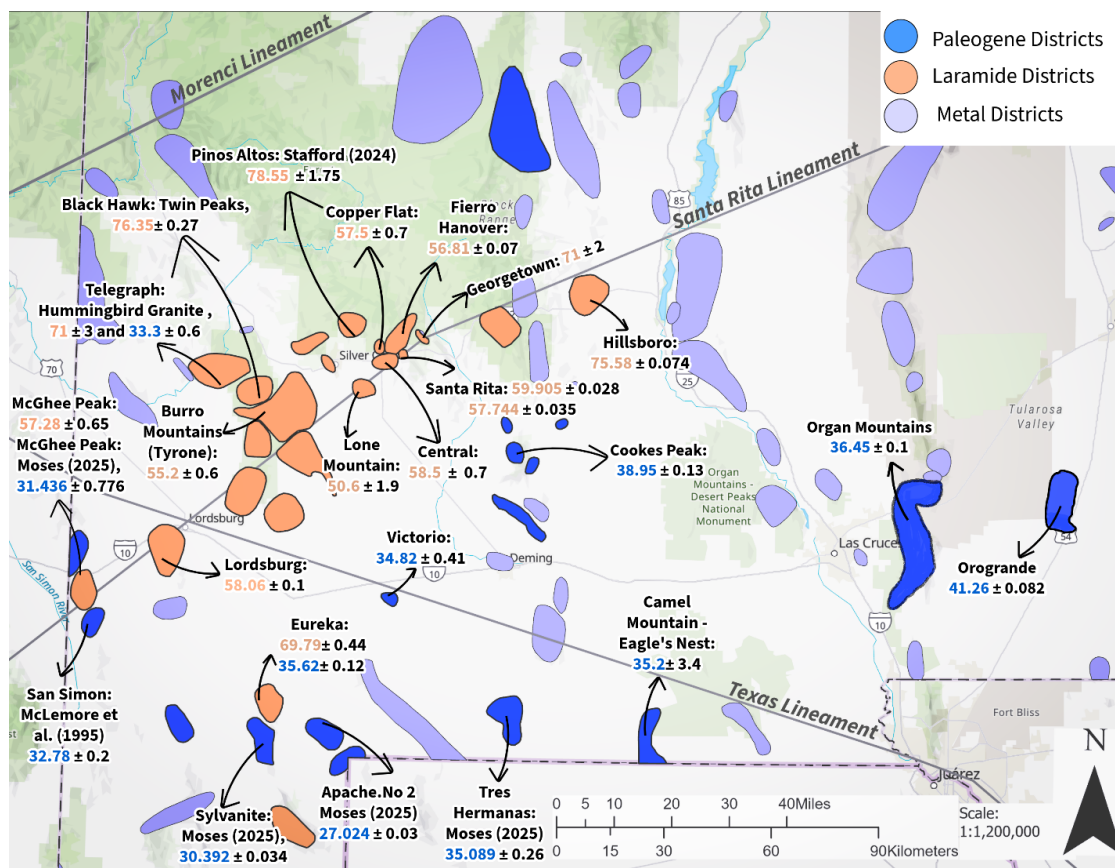


FIGURE 67. Preferred ages for mining districts in the North American Porphyry Copper Belt in southwestern New Mexico (from Moses, in preparation modified from Stafford, 2023). Paleogene Mo-W ages are blue polygons, whilst the Laramide 80-40 Ma ages are orange/tan color. Ages, methods of age determinations and references are in Appendix 1. All older published $^{40}\text{Ar}/^{39}\text{Ar}$ ages are recalculated using FC-2 Fish Canyon Tuff sanidine age of 28.201 Ma after Kuiper et al. (2008).

TABLE 24. Summary statistics of selected critical minerals in samples from selected Laramide deposits in southwestern New Mexico. Chemical analyses are in Appendix 3. Complete summary statistics are in Appendix 4. Exploration values from Table 1 (Otoo et al., 2025a, b).

	Ag (ppm)	Bi (ppm)	Cd (ppm)	Cu (ppm)	In (ppm)	Te (ppm)	W (ppm)	U (ppm)	TREE
Count	580	552	552	703	292	433	534	624	256
Minimum	0.03	0.005	0.02	0.9	0.005	0.005	0.1	0.025	10
Maximum	14,500	12,900	3430	256,200	146	130	219,000	721	3236
Mean	46	137	44	4245	3	2	495	7	325
Median	1	5	0.065	516.5	0.04	0.005	5	4	160
Standard Deviation	605	703	225	17,739	14	13	9491	31	480
Average crustal abundance	53		0.06	27			1.4	2.6	
Exploration threshold	100	100	100	0.14%	10	10	1050	910	500

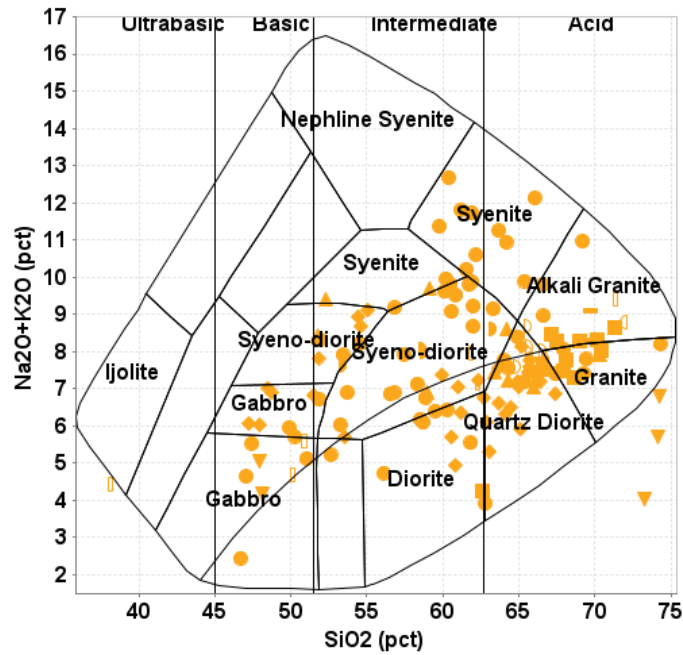
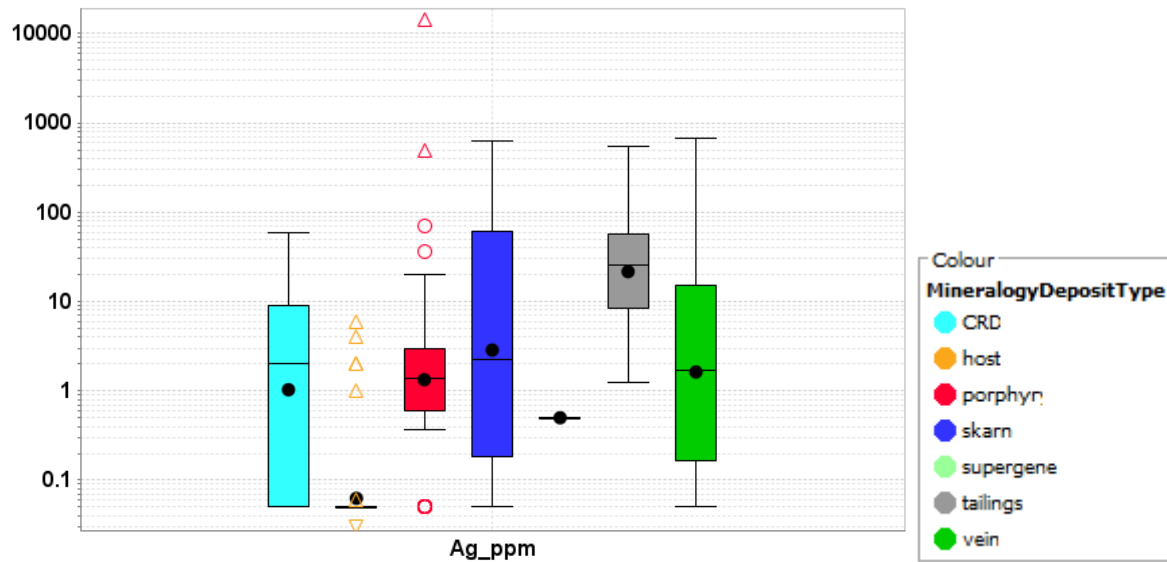


FIGURE 68. TAS diagram of samples from the North American Porphyry Copper Belt in southwestern New Mexico (Cox et al., 1979). Most of the samples plot as granite. Chemical analyses are in Appendix 3. The curved solid line subdivides the alkaline (above curve) from subalkaline rocks (below curve; from Irvine and Baragar, 1971).



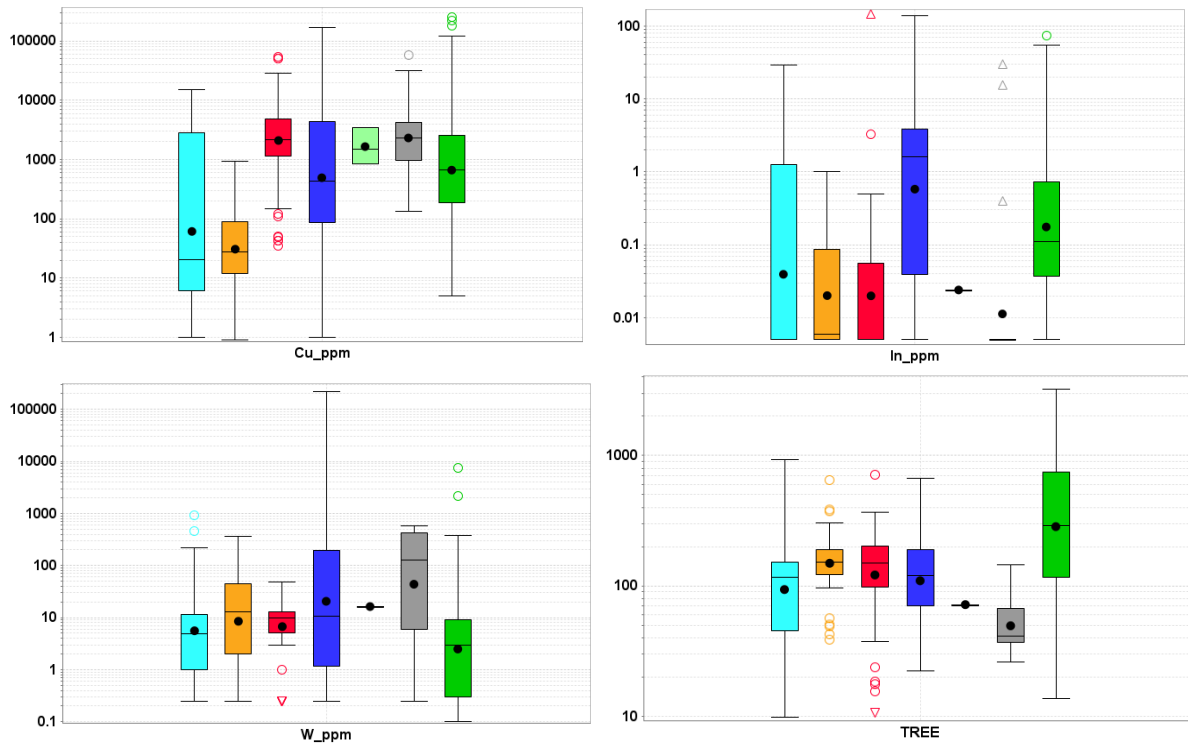
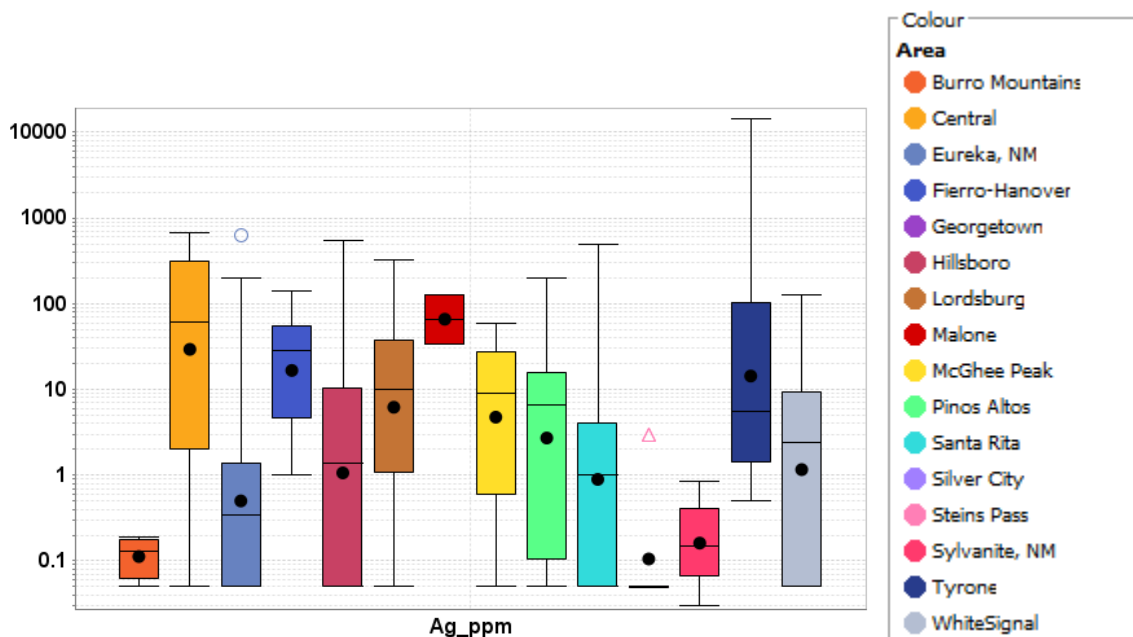


FIGURE 69. Box and whisker plots of critical minerals for selected Laramide deposits in southwestern New Mexico, by type of mineral deposit. Box and whisker plots are similar to histograms and provides visual representations of data distribution, illustrating the minimum and maximum ranges as whiskers along with the median value and quartile ranges as boxes of a given dataset. Box and whisker plots were used to represent the range and distribution of elements over certain types of mineral deposits. See Table 24 for number of samples.



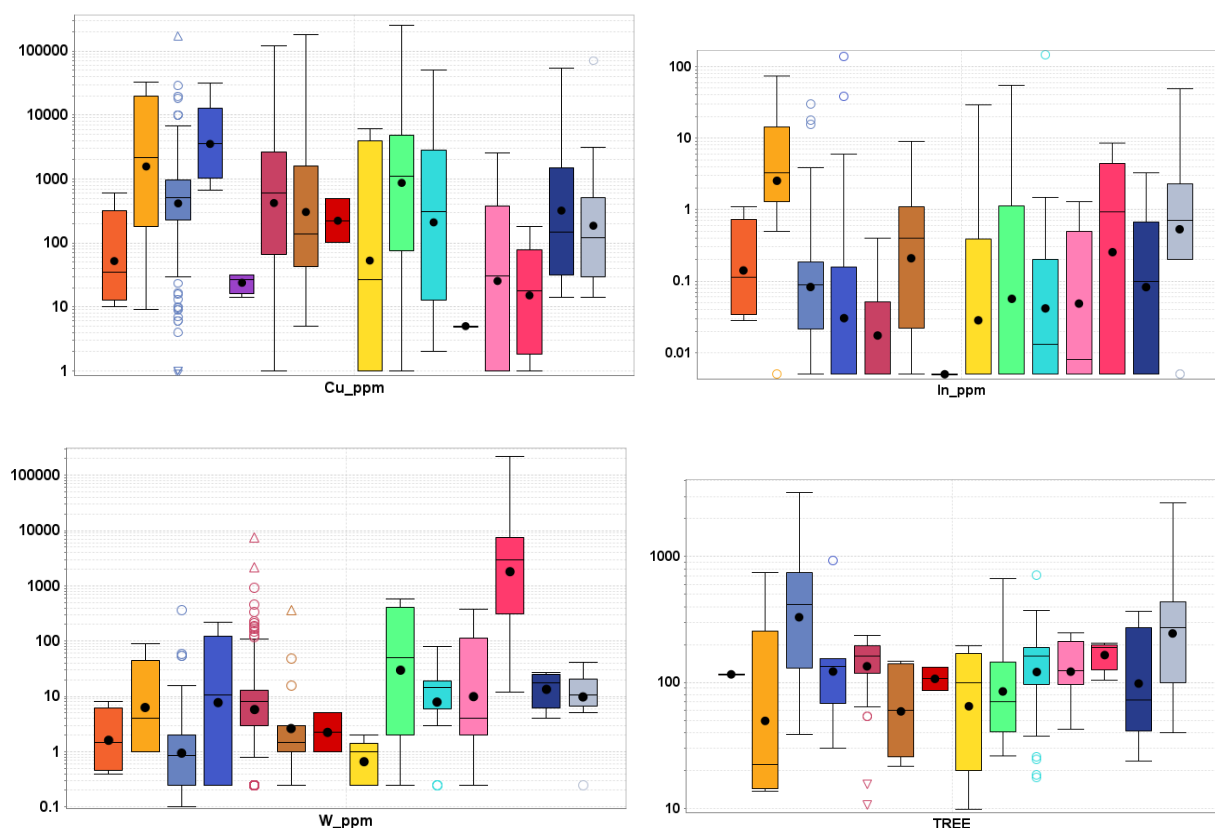


FIGURE 70. Box and whisker plots of critical minerals for selected Laramide deposits in southwestern New Mexico, by mining district. Box and whisker plots were used to represent the range and distribution of elements over mining districts. See descriptive summaries for number of deposits (Table 24). TREE=total REE.

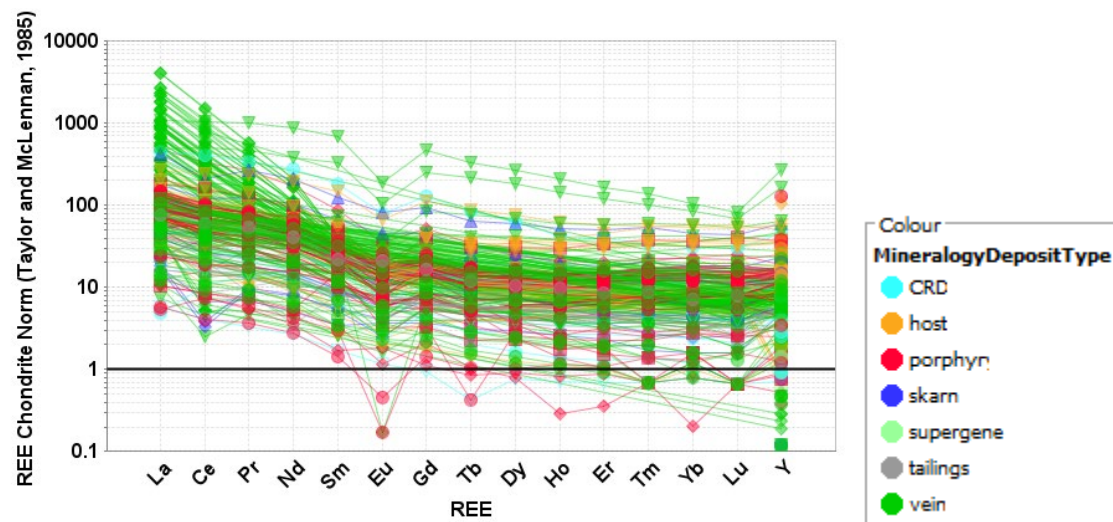


FIGURE 71. Chondrite-normalized REE plot of Laramide deposits in southwestern New Mexico, by type of mineral deposit. Chondrite values from Taylor and McLennan (1985). Vein deposits are higher in REE than other deposits.

PRELIMINARY CONCLUSIONS

Plutons associated with mineralization in New Mexico occurred in three pulses. Two pulses 80–70 Ma and 60–50 Ma are associated with the Laramide orogeny, with an additional younger pulse from 45–25 Ma associated with Paleocene extension. The largest economic deposits appear to be of the Laramide Pulse 2 (60–50 Ma). Despite the large number of geologic, geochemical, and geochronological studies on the North American Porphyry Copper Belt, many questions remain on their formation, tectonic setting, geochronology, and critical minerals potential. This report is just a beginning of our understanding of geochronology and critical minerals potential in the mineral deposits forming the North American Porphyry Copper Belt. Some preliminary conclusions are:

- Many of the porphyry copper deposits occur in clusters and trend along and around lineaments that are interpreted as pre-existing basement structures: Resolution Ray-Castle Dome-Miami-Inspiration, Safford-Dos Pobres-San Juan-Sanchez-Sol, and Mission-Pima-Sierrita Twin Buttes in Arizona and Chino-Hanover-Fierro-Continental, Tyrone-Little Rock-White Signal-Malone and Steins Pass-McGhee Peak-San Simon in New Mexico.
- New $^{40}\text{Ar}/^{39}\text{Ar}$ dating and prior age determinations have constrained the North American Porphyry Copper Belt into five periods:
 - Jurassic (Bisbee, 200 Ma)
 - 80–70 Ma Laramide Pulse 1 (porphyry copper)
 - 60–50 Ma Laramide Pulse 2 (porphyry copper)
 - 45–25 Ma Paleogene Pulse 3 (Mo–W deposits, CRD, maybe porphyry copper or porphyry molybdenum)
 - Supergene enrichment followed igneous activity in many porphyry copper districts starting at ~41 Ma and lasting until ~2 Ma or even younger locally (Leveille and Stegen, 2012).
- Some districts in southwestern New Mexico have more than one pulse of magmatism and mineralization: Lordsburg, Little Hatchet Mountains (Eureka and Sylvanite districts), and Peloncillo Mountains (McGhee Peak, Granite Gap, San Simon).
- In most districts, episodic igneous activity spanned for millions of years (15–10 Ma; Seedorff et al., 2005), but the individual mineralized plutons (Chino-Hanover-Fierro, Lordsburg, Eureka, Morenci, Cananea, La Caridad, and Bagdad) have much shorter life spans (2–8 Ma; Appendix 1; Mizer et al., 2015; Gaynor et al., 2024).
- Each porphyry system is chemically distinct, especially in terms of coproducts gold, silver, and molybdenum (Appendix 2, 3). One hypothesis for this is changes in magma chemistry, perhaps by introduction of asthenospheric material through tears in the subducted slab.
- Chemical analyses indicate elevated critical minerals in many types of deposits, especially Cu, Ag, Zn, Pb, In, Bi, Co, Ni, V, Cs, and total REE.
- Most samples are low in total REE; however, a few deposits contain elevated total REE, including Santa Rita (717 ppm), Fierro-Hanover (937 ppm), Oro (Eureka, 2272 ppm), and White Signal (2684 ppm). Although, these values are not normally economic, the large volumes of porphyry copper deposits mined enhance the economics of REE and critical minerals in these deposits.
- Southwestern North American porphyry copper deposits do not have large concentrations of platinum group metals (John and Taylor, 2016).

- Reserves of copper, gold, silver, and molybdenum have been calculated for some districts (Appendix 2).
- Many porphyry copper deposits are producing copper only by SX/EW, leaving other critical minerals in the heap leach. These mine wastes should be characterized for potential recovery of critical minerals in the future.
- It is unlikely that the plutons in the North American Porphyry Copper Belt formed from a single upper crustal source because the 80–40 Ma span in ages is a large timeframe for porphyry copper formation and the chemical composition of the plutons and mineral deposits varies from one porphyry copper deposit to another. Laramide deposits have different geochemical characteristics than younger Paleocene deposits (Stafford, 2024). It is likely that these differences are from tearing of the subducted slab that allowed athenospheric material to form some of the magmas.
- The diversity between critical minerals distribution in porphyry copper deposits spatially and with time must be accounted for in any geologic modeling and understanding of the geophysical anomalies of these complex mineral systems.
- Chemical composition of minerals using electron microprobe analyses provides insights to the host minerals for some of the critical minerals (Appendix 4). Copper is found in chalcopyrite (CuFeS_2), pyrite (FeS_2), arsenopyrite (FeAsS), bornite (Cu_5FeS_4), and wittichenite (Cu_3BiS_3). Cobalt is found in glaucodot ($((\text{Co},\text{Fe})\text{AsS})$). Silver is found in wittichenite (Cu_3BiS_3), bornite (Cu_5FeS_4), and galena (PbS) (Fig. 28).

FUTURE STUDIES

- Samples need to be collected and analyzed for chemical, mineralogical, and geochronology for districts not well studied in this report, including Central, Georgetown, Lordsburg, Malone, etc.
- Additional mapping, geochemistry, and geochronology is needed for the Eureka and Sylvanite districts in the Little Hatchet Mountains and the Lordsburg district.
- More mineral chemistry (electron probe, Raman spectroscopy) is needed to understand where critical minerals reside.
- Several areas (Eureka-Sylvanite, Lordsburg, McGhee Peak-San Simon) require more detailed study, including mapping and U-Pb dating of igneous intrusions to understand emplacement ages of the porphyry bodies and their relationships to the thermochronological events previously reported. Resolving overlapping age relationships in porphyry systems requires a multi-method geochronological approach and is especially essential to understanding this Laramide North American Porphyry Copper Belt.
- How do we explore for these deposits deeper under cover in this region?
- What is the future minerals resource potential of critical minerals in the North American Porphyry Copper Belt, including critical minerals potential of the Paleocene Mo-W, CRD, and volcanic-epithermal deposits?
- The geochemical analyses in Appendix 3 may not be representative of the individual copper deposits because of the low number of analyses, which were generally randomly collected. Therefore, detailed sampling of many porphyry copper deposits is needed to fully understand the spatial and temporal distribution of critical minerals, especially within associated mineral deposit types.
- How do CRD and volcanic epithermal (<30 Ma) deposits relate to the Laramide North American Porphyry Copper Belt (different ages, distal from magmatic source)?
- Why are some porphyry deposits barren of mineralization? Are there mineral deposits associated with them at depth or could they have been eroded away?
- Need to determine best technologies for extraction and processing of critical minerals. How many mills (current or needed to be built) in New Mexico are capable of future production demands?
- Does the Jurassic rift and the lack of volcanism from Proterozoic through Late Cretaceous in southwestern New Mexico explain the geochronology and chemical differences in the Laramide North American Porphyry Copper Belt compared to other porphyry copper mineral systems?

**APPENDIX 1. SUMMARY OF THE COPPER AND ASSOCIATED DEPOSITS IN THE
NEW MEXICO PORTION OF THE LARAMIDE NORTH AMERICAN PORPHYRY
COPPER BELT WITH LOCATION AND AGES**

See supplemental excel spreadsheet.

**APPENDIX 2. PRODUCTION AND RESERVES FROM COPPER AND ASSOCIATED
DEPOSITS IN THE NEW MEXICO PORTION OF THE LARAMIDE NORTH
AMERICAN PORPHYRY COPPER BELT**

See supplemental excel spreadsheet.

**APPENDIX 3. CHEMICAL COMPOSITIONS OF IGNEOUS ROCKS AND MINERAL
DEPOSITS IN THE NEW MEXICO PORTION OF THE NORTH AMERICAN
PORPHYRY COPPER BELT**

See supplemental excel spreadsheet.

**APPENDIX 4. MINERAL CHEMISTRIES OF SELECTED SAMPLES FROM MINERAL
DEPOSITS IN THE NEW MEXICO PORTION OF THE NORTH AMERICAN
PORPHYRY COPPER BELT**

See supplemental excel spreadsheet.

**APPENDIX 5. SUMMARY STATISTICS OF GEOCHEMICAL ANALYSES OF
SAMPLES FROM THE NEW MEXICO PORTION OF THE NORTH AMERICAN
PORPHYRY COPPER BELT (APPENDIX 3)**

See supplemental excel spreadsheet.

APPENDIX 6. ACRONYMS, CONVERSIONS, AND GLOSSARY

Acronyms

BLM	U.S. Bureau of Land Management
BSE	Backscattered electron imaging
CRD	Carbonate replacement deposits
Earth MRI	Earth Mineral Resources Initiative
EO	Presidential Executive Order
ICP-MS	Inductively coupled plasma mass spectrometry
MRDS	Mineral Resource Data System
MILS	Minerals Industry Location System
SQLS	MS SQL Server
NMBGMR	New Mexico Bureau of Geology and Mineral Resources
NMGRL	New Mexico Geochronology Research Laboratory
NMGS	New Mexico Geological Society
NMT	New Mexico Tech (New Mexico Institute of Mining and Technology)
QA/QC	Quality assurance and quality control
REE	Rare earth elements
ROM	Run of mine
SX/SW	Solvent extraction/electrowinning
USBM	U.S. Bureau of Mines
USGS	U.S. Geological Survey
VAG	Volcanic arc granite
WAG	Within plate granite
WDS	Wavelength dispersive spectroscopy
XRD	X-ray diffraction
XRF	X-ray fluorescence

Conversions

1 ounce (troy)	= 31.1034768 grams.	
1 troy ounce per short ton	= 34.2857 ppm	= 34.2857 grams per metric tonne
1 gram per metric tonne	= 0.0292 troy ounces per short ton	
1 kilogram (kg)	= 32.151 ounces (troy)	= 2.205 pounds
1 ounce (avoirdupois)	= 28.3495 grams	
1 inch (in)	= 2.54 centimeters	
1 foot (ft)	= 0.3048 meters	
1 cubic foot (cu ft)	= 0.028 cubic meters	
1 yard (yd)	= 91.44 centimeters	= 0.9144 meters
1 meter (m)	= 39.370 inches	= 3.28083 feet = 1.094 yards
1 mile (mi)	= 1.6093 kilometers	= 1609.3 meters
1 kilometer (km)	= 0.621371 miles	= 3280 feet = 1000 meter
1 acre (ac)	= 0.4047 hectares	
1 hectare (ha)	= 2.471 acres	= 10,000 square meters = 0.00386 square miles

1 square kilometer (sq km) = 247.1 acres = 100 hectares = 0.3861 square miles
 1 square mile (sq mi) = 640 acres = 258.99 hectares = 2.59 square kilometers
 1 liter (l) = 0.220 gallons = 0.880 quarts
 1 liter (l) = 1000 cubic centimeters = 61.025 cubic inches
 1 kilogram (kg) = 2.2045855 pounds
 1 metric ton (1000 kg) = 0.9842 long tons = 1.102311 short tons = 2204.622 pounds
 1 long ton (l t) = 1.01605 tonne = 2240 pounds (lb)
 1 short ton (s t) = 0.90718474 tonne = 2000 pounds (lb)
 1 pound (lb) = 0.45359237 kilograms
 Degrees Fahrenheit (°F) - 32x5/9 = Degrees Celsius (°C)

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