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POTENTIAL FOR LARAMIDE PORPHYRY COPPER DEPOSITS IN SOUTHWESTERN NEW MEXICO

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Abstract — New Mexico lies at the eastern edge of one of the world's great metal-bearing provinces, where there are eight known Laramide porphyry copper deposits in New Mexico: Santa Rita, Tyrone (Burro Mountains district), Little Rock (Burro Mountains district), Copper Flat (Hillsboro district), Hanover-Hermosa Mountain (Fierro-Hanover district), Lone Mountain, Gold Lake (White Signal district), and McGhee Peak (Peloncillo Mountains). Additional Laramide skarn and polymetalic vein deposits in New Mexico formed in Paleozoic limestones and dolomitic limestones adjacent to calc-alkaline plutonic rocks emplaced during the Laramide compressional event; most of these areas have potential for additional porphyry copper deposits.

INTRODUCTION

New Mexico lies at the eastern edge of one of the world's great metal-bearing provinces. Copper is particularly important with large, and in some cases, world-class deposits in Arizona, New Mexico, Utah, Nevada, and Sonora (Fig. 1). Gold and silver deposits are abundant in Nevada, and to a lesser extent, throughout the Southwest. Some of the largest molybdenum deposits in the world occur in central Colorado and northern New Mexico. Numerous geologists have examined the geology and mineral resource potential of these porphyry deposits over the last 50 years or more (Titley, 1982, 1997, 2001). Copper production from New Mexico has been significant (Table 1). However, most of the recent published reports emphasize the potential in Arizona only, or were not written in context of today's current increase in demand for copper, as reflected by the recent increase in copper price and production (Table 1). Several porphyry copper deposits and other areas in New Mexico are currently being examined by mining and exploration companies for potential development. Additional potential exists in other districts in New Mexico.

The purpose of this paper is to provide an updated framework for exploration for porphyry copper deposits in southwestern New Mexico by identifying 1) the geologic criteria favorable for porphyry deposits, 2) areas of Laramide plutons in New Mexico, 3) known porphyry copper deposits in New Mexico, and 4) other mining districts with Laramide-age mineral deposits. This paper focuses on the Laramide-age rocks (40-80 Ma in age; Barton, 1996) in New Mexico and not on the younger mid-Tertiary deposits in central and northern New Mexico that also include some smaller porphyry copper deposits (although not all of the deposits discussed here have been dated). This paper is an update of the work by North and McLemore (1986) and McLemore (2001), who summarize the various gold and silver mineral deposits, including porphyry copper deposits in the state.

WHAT ARE PORPHYRY COPPER DEPOSITS?

Porphyry copper (molybdenum, gold) deposits are large, low-grade (<0.8% Cu) deposits that contain disseminated, breccias and stockwork veinlets of copper and molybdenum sulfides associated with porphyritic intrusions (Schmitt, 1966; Lowell and Guilbert, 1970; Kesler, 1973; Lowell, 1974; Titley and Beane, 1981; Cox and Singer, 1986; Seedorff et al., 2005). These copper deposits typically are found in and around relatively small porphyritic diorite, granodiorite, monzonite, and quartz monzonite plutons that were intruded at relatively high crustal levels, commonly within 1-6 km of the surface, and are surrounded by crudely concentric zones of hydrothermal alteration (Lowell and Guilbert, 1970; Seedorff et al., 2005). Volatiles, primarily steam and other gases, 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. 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). However, in some deposits, the concen-

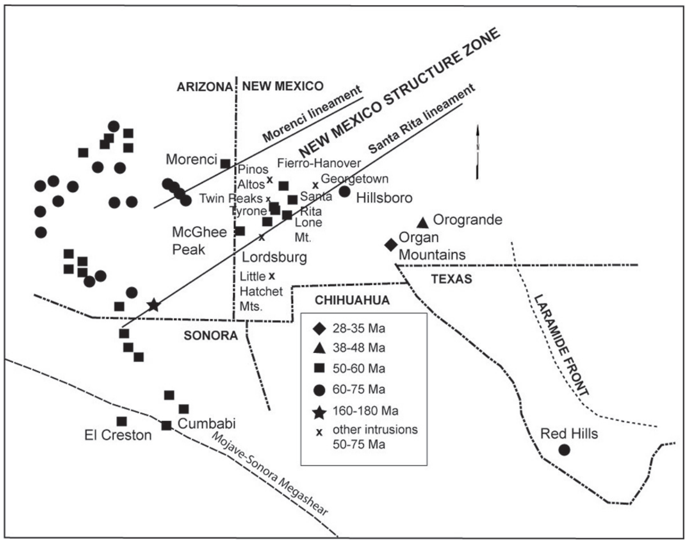

FIGURE 1. Laramide porphyry copper deposits in southwestern United States and northern Mexico.

TABLE 1—Estimated copper production from New Mexico, 1804-2006 (yearly production data compiled from Lindgren et al., 1910; U.S. Geological Survey, 1902-1927; U.S Bureau of Mines Mineral Yearbooks, 1927-1994; Energy, Minerals and Natural Resources Department, 1986-2007).

Years of Production	Copper (short tons)	Value ($)
1804-1880	15,003	6,001,205
1881-1903	23,554	6,831,500
1904-1920	338,425	138,857,559
1921-1940	601,346	151,850,186
1941-1960	1,316,268	613,905,615
1961-1980	2,686,467	3,186,423,120
1981-1994	3,379,866	6,031,137,421
1995-2006	2,594,823	5,612,299,176
TOTAL 1804-2006	8,360,929	10,135,006,606

tric zoning is destroyed and replaced by younger quartz-sericite alteration, such as at the Chino deposit.

Copper minerals, to varying degrees, are deposited as a part of this interaction between hydrothermal solutions along fractures in solid rock. The copper minerals are found as disseminations along thin fractures, zones of brecciation, and within larger veins, called stockwork veins. Typically, these deposits are very large, some in excess of a billion tons of mineralized rock. Copper grade varies from less than 0.10% copper to over 1% copper, with 2-5% pyrite and varying amounts of gold, silver, molybdenum, uranium, and other metals and nonmetals. The important deposits in New Mexico at Chino and Tyrone had relatively low copper grade after this initial mineralization, but the grade was enhanced through supergene enrichment. Low concentrations of silver and gold are present in most deposits and can be recovered as by-products by conventional milling techniques. Skarns and epithermal-vein deposits locally are spatially associated with porphyry copper deposits. A variety of different types of porphyry copper deposits are found as defined by the predominant metal content and composition of the porphyritic intrusions (Cox and Singer, 1986, 1992; Seedorff et al., 2005).

Supergene enrichment is a weathering process that occurs when rocks with high pyrite content come into contact with water in an oxidizing environment (Anderson, 1982; Chávez, 2000; Sillitoe, 2005). During this process, water, oxygen, and pyrite react to form sulfuric acid. This acid naturally leaches copper from chalcopyrite ($CuFeS_2$) and other copper-bearing minerals, putting copper into solution. Copper will stay in solution as long as the solution is acidic and oxidized. However, when the acidic solution is neutralized or evolves to reducing conditions, there is no longer free oxygen in the solution and copper is no longer soluble. In natural systems, conditions typically will become reducing just beneath the water table. When this happens, the copper in solution easily combines with reduced sulfur. This reduced sulfur is available in pyrite and the copper in solution will replace first chalcopyrite and then pyrite (FeS_2) with chalcocite (Cu_2S). This process preserves copper through chemical dissolution and subsequent enrichment rather than the loss of the metal through the erosion of copper-bearing rock by mechanical means. Without this process, deposits such as Tyrone would never have been economic, and the ore zone at Chino would be much smaller.

Skarn deposits of copper and other metals can form near the contact between hot magma intruded into limestone and other carbonate-bearing rocks. Skarn is a term 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 these types of deposits can form in a number of geological environments, they are most common in the southwestern U.S. in contact metamorphic aureoles, where hot, igneous rocks have intruded calcareous host rocks (Einaudi, 1982). Hydrothermal fluids exsolved from the igneous rocks metasomatize the calcareous wall rocks, converting them to garnet and pyroxene. Magnetite commonly also is present, especially in magnesian (dolomitic) host rocks. Although, chalcopyrite ($CuFeS_2$) and sphalerite (ZnS) are found in relatively small amounts, they are important ore minerals in this type of deposit. Polymetallic veins also are associated with some porphyry copper deposits, such as the Copper Flat deposit, Hillsboro district.

GEOLOGIC CRITERIA FOR EXPLORATION OF PORPHYRY COPPER DEPOSITS

Tectonic Setting

Porphyry copper deposits are found along the margins of volcanic arcs in subduction zones (Sillitoe, 1972; Seedorff et al., 2005). Since Late Cretaceous time, southwestern United States and northern Mexico have undergone almost constant tectonic and volcanic activity related to motions of the lithospheric plates off the coast of present California. Laramide compressional deformation from Late Cretaceous to early Tertiary formed a series of northeast- to northwest-trending uplifts and broad shallow basins in southern New Mexico and Arizona (Drewes, 1991; Seager et al., 1997). The southwestern U.S. porphyry copper belt (Fig. 1) is generally attributed to Laramide (40-80 Ma in age; Barton, 1996; Keith and Swan, 1996) magmatism and compressional deformation, which extended as far eastward as south-central New Mexico, as evidenced by the Copper Flat igneous complex and porphyry copper deposit near Hillsboro (McLemore et al., 1999, 2000b) and volcanic-clast conglomerates in the McRae and Love Ranch Formations in the Jornada del Muerto near Truth or Consequences (Chapman-Fahey, 1996; Seager et al. 1997). Laramide deformation and magmatic activity extended as far southeast as the Red Hills intrusion in Trans-Pecos Texas (Fig. 1; Gilmer et al., 2003). The structural style of Laramide compressional deformation and magmatism is typically attributed to the low-angle subduction of the Farallon plate, which resulted in the locus of magmatic activity shifting eastward with time (Coney and Reynolds, 1977; Damon et al., 1983; McMillan et al., 2000). However, Duecker et al. (2001) suggests from teleseimic images of the upper mantle that movement of the North American plate sliding over the mantle could produce convection in the asthenosphere. The convection was localized by deep-seated Proterozoic basement structures and formed crustal melts, resulting in the Laramide intrusions common in the southwestern U. S.

Newly compiled magnetic and gravity maps have resulted in new interpretations of the tectonic setting of New Mexico and adjacent areas. Linear geophysical features appear to correlate with the alignment of mineral deposits in western U.S. (Hildenbrand et al., 2000; Kucks et al., 2001; Sims et al., 2002). 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. Although, most of the mineral deposits within this zone are mid-Tertiary in age, Sims et al. (2002) recognize that the southern Santa Rita zone is dominated by Late Cretaceous porphyry copper deposits in New Mexico and Arizona. Furthermore, 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. These hypotheses dovetail nicely with the views of Titley (2001), suggesting that metals in the porphyry copper deposits are derived from Proterozoic basement sources.

Composition of Associated Plutons

Compositions of the Laramide intrusive rocks vary regionally and with time from early mafic and silica-poor diorites and monzonites to more siliceous and felsic monzogranites, quartz diorites, and monzogranites (Keith, 1986). They are typically calc-alkaline to mildly alkaline. Laramide volcanic rocks in New Mexico have arc-like chemical characteristics (Chapman-Fahey, 1996; Young, 1996; McLemore et al., 1999) and are consistent with generation by subduction processes triggered by dehydration of the subducted Farallon plate.

McMillan et al. (2000) documents a shift in magma source regions about the end of the Laramide from a subcontinental lithosphere source with contamination from distinct upper- and lower-crustal sources during the Laramide (at about 45 Ma) to an asthenosphere source with insignificant additions from the continental crust (late Tertiary). Lead isotopic data from the Copper Flat deposit at Hillsboro indicates that the Copper Flat igneous system is derived from a similar source as the other porphyry copper deposits in New Mexico and the source is distinctly different from the younger mid-Tertiary mineral deposits (Stacey and Hedlund, 1983). The lead is relatively nonradiogenic, suggesting a lower crust or upper mantle source, which is consistent with the geochemical composition of the Copper Flat igneous rocks (McLemore et al., 1999, 2000b).

KNOWN DEPOSITS IN NEW MEXICO

Porphyry copper, copper-molybdenum (± gold) deposits

There are eight known Laramide porphyry copper deposits in New Mexico (Fig. 1; Table 2): Santa Rita, Tyrone (Burro Mountains district), Little Rock (Burro Mountains district), Copper Flat (Hillsboro district), Hanover-Hermosa Mountain (Fierro-Hanover district), Lone Mountain, Gold Lake (White Signal district), and McGhee Peak (Peloncillo Mountains). Many other areas in the state have potential for porphyry copper deposits, as discussed below.

The largest porphyry copper deposit in New Mexico is the Chino deposit in the Santa Rita district, where copper sulfides occur in the upper part of a highly fractured quartz-monzodiorite to granodiorite and adjacent metamorphosed sedimentary rocks. Igneous activity at Chino began about 60-59 Ma with the intrusion of dioritic to quartz diorite sills into the Precambrian basement. The intrusion of multiple stages of the quartz-monzodiorite to granodiorite dikes and stocks followed (Rose and Baltoser, 1966; Audétat and Pettke, 2006). Reported ages of the stock range from 64.6 to 59.7 Ma (K-Ar, biotite; Schwartz, 1959; McDowell, 1971), but unpublished $^{40}Ar/^{39}Ar$ data by NMBGMR indicates the age of the stock is slightly younger, at 58.6 Ma (Table 2). The stock had a high oxygen fugacity and was enriched in sulfur (Audétat and Pettke, 2006). Most of the mineralization occurred shortly after intrusion of the dikes and stock. 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). Adjacent copper skarns are becoming increasingly more important economically. The mine has produced more than 5.9 million tons Cu, 500,000 oz Au, and 5.36 million oz Ag plus some molybdenum and iron ore from 1911 to 2006 (Long, 1995; McLemore et al., 1996; V.T. McLemore, this guidebook). Estimated milling reserves at the Chino mine in December 2006 are 53.9 million tons of 0.68% copper and 0.03% molybdenum, and estimated leaching reserves are 120.5 million tons of 0.43% Cu (Phelps Dodge Corporation, 2007). Accordingly, the Chino mine in the Santa Rita district is the largest copper and gold district in New Mexico and ranked ninth in silver production in terms of total metal production.

The Tyrone porphyry copper deposit in the Burro Mountains district occurs within a quartz-monzonite laccolith and adjacent Proterozoic rocks (Kolessar, 1970, 1982). The ore contains minor amounts of gold and silver, especially in the enriched zones. The age of the Tyrone stock is 54.5 Ma (NMBGMR unpublished data). At least two cycles of supergene enrichment have concentrated the ore at 16.2-19.4 Ma and 4.6-8.7 Ma (Cook, 1994; Mach, 2004). Approximately 300 million short tons of ore grading 0.81% Cu were processed by the concentrator at Tyrone from 1969 to1992. Approximately 425 million short tons of ore grading 0.35% Cu have been leached. In addition, silver and gold were recovered from 1903 to 1992. The mine has produced more than 5.3 million tons Cu, 500,000 oz Au, and 5.36 million oz Ag, plus some molybdenum and iron ore from 1911 to 2006 (Long, 1995; McLemore et al., 1996; V.T. McLemore, this guidebook).

The Little Rock deposit (Ohio mine) is 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. If it goes into production, Freeport McMoRan Inc. will extract copper from the existing open pit and leach piles.

The Copper Flat deposit in the Hillsboro district consists of copper, gold, and silver disseminated in a quartz-monzonite stock and in quartz veins (Kuellmer, 1955; Dunn, 1982, 1984; Hedlund, 1985b; McLemore et al., 1999, 2000b). Unlike the Santa Rita and Tyrone deposits, there is no significant supergene enrichment

TABLE 2. Laramide porphyry copper deposits in southwestern New Mexico. References for age determinations are in Table 3. * reported reserves are recoverable copper reserves as reported by the company (not always 43-101 compliant). ** skarn or carbonate-hosted replacement deposits also present. Mine identification number is from the New Mexico Mines Database (McLemore et al., 2005a, b).

Mine Identification Number	Porphyry Deposits	District	County	Latitude (decimal degrees)	Longitude (decimal degrees)	Year of Discovery
NMGR0029	Chino**	Santa Rita	Grant	32.791667	108.06667	1909
NMGR0084	Tyrone	Burro Mountains	Grant	32.643889	108.36722	1903
NMSI0610	Copper Flat**	Hillsboro	Sierra	32.806667	108.12222	1970s
NMGR0478	Gold Lake	White Signal	Grant	32.55270	108.32957	1970s
NMGR0208	Hanover Mountain	Fierro-Hanover	Grant	32.833	108.083	1970s
NMGR0409	Lone Mountain**	Lone Mountain	Grant	32.718056	108.17667	1970s
NMGR0160	Little Rock (Ohio)	Burro Mountains	Grant	32.646698	108.40675	1070s
NMHI0327	Steins	McGhee Peak	Hidalgo	32.186111	109.020833	1970s

zone at Copper Flat. The Copper Flat porphyry is dated at 75 Ma (McLemore et al., 1999, 2000b). Approximately 7 million pounds of copper was produced in 1982 prior to closure of the mine. Reserves are estimated at 56.5 million tons of ore at grades of 0.432% Cu, 0.004 oz/ton Au, 0.064 oz/ton Ag, and 0.014% Mo (Alta Gold Co., Form 10K, December 13, 1997).

Supergene-enriched copper zones are found near the Continental (Cobre) skarn deposits, at Hanover and Hermosa Mountains in the Fierro-Hanover district (Hillesland et al., 1994, 1995). The tabular zones contain fine-grained chalcocite along fractures within the Colorado Formation (Cretaceous) and are 15-152 m thick. Age dates of intrusive rocks in the Fierro-Hanover district range from 70.4 to 57.1 Ma (K-Ar, McDowell, 1971). A granodiorite porphyry sample collected from the Continental pit was dated more precisely as 57.55 Ma (^{40}Ar/^{39}Ar, McLemore et al., 1995). Drilling in the 1970s and 1990s has delineated 80 million short tons of geologic resources of 0.38% Cu at Hanover Mountain, northeast of the Continental mine (Hillesland et al., 1994, 1995). The deposit at Hermosa Mountain, southwest of the Continental mine, has not been characterized.

Drilling in 1975-1989 and in 2006-2007 northwest of the carbonate-hosted silver deposits in 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 30 to 915 m (Moore and Moran, 2006). Copper oxide horizons are approximately 30 m thick at grades of 0.1 % to 0.2 % Cu, with rare intercepts to 0.6 %. Skarn grades in the Lake Valley horizon, while variable, typically assay 1.5 to 3.0 % Cu., 3 to 5 % Zn, 1.0 to 2.0 % Pb, 0.01 to 0.02 oz/ton Au, and 1.0 to 3.0 oz/ton Ag. The intrusions have been dated at 51.5-50.6 Ma (P. B. Hubbard and P. G. Dunn, unpublished report, 1983; Moore and Moran, 2006).

The Gold Lake deposit is in the White Signal district, where quartz monzonite and rhyolite have intruded the Proterozoic rocks and are associated with porphyry-style alteration and veins (Klemmick, 2006). Numerous, small, historic mine workings are found within this area, mostly exploiting and prospecting for copper, uranium, and gold. Rock chip samples collected from the area contain anomalous copper (up to 11.5%), molybdenum (up to 0.17%), silver (up to 385 ppm), and bismuth (up to 2300 ppm) (Klemmick, 2006). Additional drilling is needed to confirm and delineate any economic potential.

Drilling in the early 1970s and 1990s encountered a porphyry copper deposit at 30 m depth in the northwestern part of the McGhee Peak district (McLemore et al., 1996; NMBMMR file data). Cyprus Minerals Corp. filed claims in sec. 30 and 31, T24S, R21W in the early 1990s. Pyritization and argillic alteration were found in most drill holes and phyllic alteration is exposed in a small outcrop near the drill sites (Hudson, 1984). The age of the drilled porphyry copper deposit is unknown. The granite exposed at Granite Gap in the Peloncillo Mountains is 33.20 ± 0.20 Ma (^{40}Ar/^{39}Ar, McLemore et al., 1995). Quartz-latite porphyry dikes in the Peloncillo Mountains were emplaced 26-27 Ma (K/Ar, Armstrong et al., 1978). A pegmatite collected south of Granite Gap was dated as 55-70 Ma (K/Ar, Armstrong et al., 1978). Mid-Tertiary intrusions are found in the Peloncillo Mountains, but it is uncertain what the age of the drilled porphyry copper deposit is.

Laramide copper and lead/zinc skarn deposits

Laramide skarn deposits in New Mexico are contact-metasomatic deposits that formed in Paleozoic limestones and dolomitic limestones adjacent to calc-alkaline plutonic rocks emplaced during the Laramide compressional event (McLemore and Lueth, 1996). Three types of Laramide skarns occur in southern New Mexico: copper (typically associated with porphyry copper deposits; Einaudi et al., 1981; Einaudi, 1982; Lueth, 1984), lead-zinc (proximal and vein-type deposits; Einaudi et al., 1981; Meinert, 1987; Turner and Bowman, 1993; Lueth, 1996), and 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 are in the Fierro-Hanover and Piños Altos districts. Laramide iron skarns are found throughout southwestern New Mexico (Fig. 2, Table 3).

Copper skarns are intimately associated with Laramide plutons (e.g. Santa Rita, Piños Altos), whereas the lead-zinc skarns are typically distal from igneous rocks. Some lead-zinc skarns occur

TABLE 2. continued.

Porphyry Deposits	Commodities	Estimated Copper Production (pounds)	Reported Estimated Reserves	References
Chino	Cu, Au, Ag, Mo	9,080,000,000	53.9 million tons of 0.68% Cu and 0.03% Mo and estimated leaching reserves are 120.5 million tons of 0.43% Cu *	Phelps Dodge Corp. (2007)
Tyrone	Cu, Au, Ag, U, F	5,240,000,000	230.2 million tons 0.35% Cu (leachable)*	McDowell (1971), Hedlund (1985a), McLemore et al. (1996)
Copper Flat	Au, Ag, Pb, Zn, Cu, V	7 million pounds	60 million tons 0.42% Cu, 0.012% Mo (mineable)	McLemore et al. (1999, 2000b)
Gold Lake	Cu, Au, Ag, Bi, U, Mo	None	unknown/exploration underway	
Hanover Mountain	Au, Ag, Cu, Zn, Pb, Fe, F, Mn, Bi	None	80 million tons 0.38% Cu (geolgic reserves)	McLemore et al. (1996)
Lone Mountain	Cu, Au, Ag	None	unknown/exploration underway	P.B. Hubbard (written report, 1983)
Little Rock	Cu, Au, Ag	Unknown	unknown/exploration underway	P.B. Hubbard (written report, 1983)
Steins	Au, Ag, Pb, Cu, Zn	None	unknown/exploration underway	McLemore et al. (1996)

along faults distal from intrusive rocks (e.g., Groundhog, southwestern deposits at Piños Altos, Eureka). The Laramide skarns in New Mexico formed from variable, but higher temperature and saline fluids compared to carbonate-hosted lead-zinc replacement deposits in New Mexico (McLemore and Lueth, 1996). 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). District-scale zoning of metals is common in most areas with copper adjacent to the intrusive rocks grading outwards to zinc-lead, lead-zinc, lead-silver, and locally, lead-silver-manganese (Meinert, 1987; McLemore and Lueth, 1996).

Polymetallic vein deposits

Polymetallic vein deposits of probable Laramide age (Late Cretaceous-early Eocene, 75-40 Ma) occur in a number of districts in New Mexico (Table 3, Fig. 2). These vein deposits exhibit variations in textures and mineralogy, but are similar in form and age. In some districts with Laramide polymetallic vein deposits, Laramide 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 most important districts in New Mexico are Hillsboro, Piños Altos, Bayard, and Lordsburg.

The deposits at Hillsboro provide a good model for the description of Laramide vein deposits that are associated with porphyry copper deposits. Polymetallic veins, many of which are hosted by latite dikes, extend radially outward from the Copper Flat porphyry copper deposit. Distal carbonate-hosted replacement deposits containing Ag, Pb, Mn, V, Mo, Zn are found in the southern and northern parts of the district. Geological, geochronological, and geochemical evidence suggests that the mineral deposits found in the Hillsboro district are zonally related and were formed by large, convective magmatic-hydrothermal

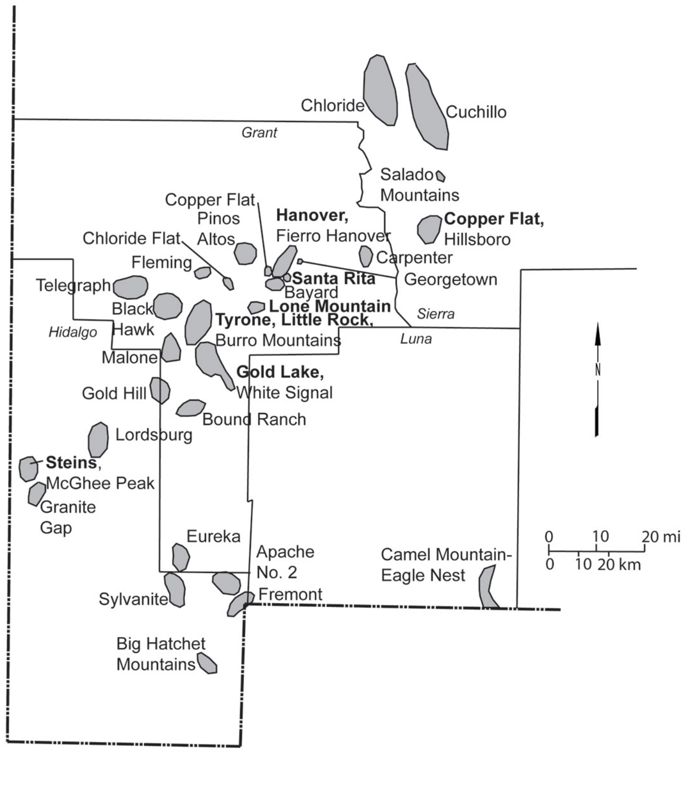

FIGURE 2. Laramide mineral deposits and plutons in southwestern New Mexico.

TABLE 3. Late Cretaceous-early Tertiary mineral deposits in southwestern New Mexico. District number is from the New Mexico Mines Database (McLemore et al., 2005a, b). Names of mining districts are after File and Nothrop (1966) wherever practical, but many districts have been combined and added. Estimated value of production is in original cumulative dollars and includes all commodities in the district. Production data complied from Lindgren et al. (1910), Anderson (1957), U.S. Geological Survey (1902-1927), U.S Bureau of Mines Mineral Yearbooks (1927-1994), Energy, Minerals and Natural Resources Department (1986-2007). Types of deposits are after North and McLemore (1986) and McLemore (2001).

District number, District	Year of Discovery	Estimated Cumulative Production	Type of deposits	Pluton and age in million years (dating method)	Reference for isotopic ages
DIS043 Bayard	1858	$60,000,000	Laramide vein, placer Au		
DIS044 Black Hawk	1881	$1,000,000	Laramide vein, placer W	Twin Peaks monzonite, 72.5 (K/Ar)	Hedlund (1978)
DIS045 Bound Ranch		$97,000	Laramide vein, fluorite veins		
DIS046 Burro Mountains	1871	$2,000,000,000	Laramide vein, placer Au, W veins, porphyry Cu	Tyrone stock, 54.5 ($^{40}Ar/^{39}Ar$)	NMBGMR unpublished data
DIS049 Carpenter	1891	$1,360,000	Cu-Pb-Zn skarn, carbonate-hosted Pb-Zn (Cu, Ag) replacement		
DIS050 Chloride Flat	1870	$13,000,000	Carbonate-hosted Ag-Mn(Pb) replacement		
DIS051 Copper Flat	1890	$120,000	Cu-Pb-Zn skarn, carbonate-hosted Ag-Mn (Pb) replacement	Copper Flat stock, 55.4 (K/Ar)	NMBGMR unpublished data
DIS053 Eureka	1871	$1,590,000	Laramide vein, Cu-Pb-Zn skarn, placer Au	Hidalgo Formation (basaltic andesite), 71.4 ($^{40}Ar/^{39}Ar$)	Lawton et al. (1993)
DIS054 Fierro-Hanover	1850	$2,000,000,000	Porphyry Cu, Cu-Pb-Zn skarn, Laramide vein	Hanover-Fierro (Hermosa) stock, 57.55 ($^{40}Ar/^{39}Ar$)	McLemore et al. (1996)
DIS055 Fleming	1882	$320,000	Laramide vein, fluorite veins		
DIS056 Georgetown	1866	$3,500,000	Carbonate-hosted Ag-Mn(Pb) replacement	Granodiorite porphyry dikes, 71 ($^{40}Ar/^{39}Ar$)	McLemore (1998)
DIS058 Gold Hill	1884	$200,000	Laramide vein, placer Au		
DIS059 Lone Mountain	1871	$30,000	Laramide skarn, carbonate-hosted Ag-Mn (Pb) replacement, porphyry Cu	Lone Mountain stock, 51.5 (K/Ar)	P. B. Hubbard and P. G. Dunn, unpublished report, 1983
DIS060 Malone	1884	$300,000	Laramide vein, fluorite veins, placer Au		
DIS062 Piños Altos	1800	$11,000,000	Laramide vein, Cu-Pb-Zn skarn, placer Au	Pinos Altos stock, 74.4 (K/Ar)	McDowell (1971)
DIS065 Santa Rita	1800	$2,000,000,000	Porphyry Cu, Laramide skarn	Santa Rita stock, 58.3 ($^{40}Ar/^{39}Ar$)	NMBGMR unpublished data
DIS067 Telegraph	1881	$482,000	Laramide vein		
DIS068 White Signal	1880	$165,000	Laramide vein, placer Au		
DIS075 Apache No. 2	1879	$107,000	Laramide vein, carbonate-hosted Pb-Zn (Cu, Ag) replacement, Cu-Pb-Zn skarn		
DIS076 Big Hatchet Mountains	1917	$2,000	Carbonate-hosted Pb-Zn (Cu, Ag) replacement		
DIS078 Fremont	1860	$17,000	Carbonate-hosted Pb-Zn (Cu, Ag) replacement		
DIS080 Granite Gap	1875	$1,950,000	Carbonate-hosted Pb-Zn (Cu, Ag) replacement, Cu-Pb-Zn skarn, W skarns		
DIS082 Lordsburg	1854	$60,000,000	Laramide vein, placer Au	Granodiorite, 58.5 ($^{40}Ar/^{39}Ar$)	McLemore et al. (2000a)
DIS083 McGhee Peak	1894	$1,171,500	Porphyry Cu, Laramide vein, Cu-Pb-Zn skarn		

TABLE 3. Continued.

District number, District	Year of Discovery	Estimated Cumulative Production	Type of Deposits	Pluton and age in million years (dating method)	Reference for isotopic dating
DIS088 Sylvanite	1871	$315,000	Laramide vein, Cu-Pb-Zn skarn, placer Au	Hidalgo Formation (basaltic andesite), 71.4 ($^{40}Ar/^{39}Ar$)	Lawton et al. (1993)
DIS102 Camel Mountain - Eagle Nest		None	Carbonate-hosted Pb-Zn (Cu, Ag) replacement, Cu-Pb-Zn skarn	Diorite, 86.3 ($^{40}Ar/^{39}Ar$)	McLemore et al. (2001)
DIS191 Chloride	1879	$20,000,000	Laramide skarn, placer Au		
DIS192 Cuchillo	1879	$205,000	Cu-Pb-Zn skarn		
DIS197 Hillsboro	1877	$8,500,000	Porphyry Cu, Laramide skarn, Laramide veins	Copper Flat, 75 ($^{40}Ar/^{39}Ar$)	McLemore et al. (1999, 2000b)
DIS254 Salado Mountains	1970	None	Fluorite veins	nepheline monzodiorite, 59.9±2.4 Ma (K–Ar, nepheline)	Lamarre (1974)

systems related to the Copper Flat volcanic/intrusive complex (McLemore et al, 1999, 2000b).

Many of these veins display multiple episodes of opening and mineralization. Proterozoic rocks are a common host rock, 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 Bayard district. Laramide 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. Despite these differences, these deposits are grouped together because of similar form, association with Laramide intrusive rocks, and perceived origin at moderate to high temperatures and moderate depths.

SUMMARY OF MINERAL RESOURCE POTENTIAL FOR PORPHYRY COPPER DEPOSITS IN NEW MEXICO

Many areas in New Mexico have potential for porphyry copper deposits, but more exploration is needed to verify their occurrence. Development of these deposits will depend upon the copper market. Exploration has occurred north of the Lordsburg and Eureka districts for porphyry copper deposits, but the results are unknown. Both districts are known for Laramide vein deposits as well as alteration suggestive of porphyry copper mineralization. The potential for discovering additional skarns in the districts in southwestern New Mexico is excellent. Cobre Mining Co. reported reserves at the Continental mine in the Fierro-Hanover district of over 10 million short tons of 0.92% Cu (Hillesland et al., 1994, 1995). Significant copper skarns also are mined at the Chino mine in the Santa Rita district (Nielsen, 1968, 1970; McLemore, 1996). The ores from Laramide veins have potential for siliceous flux for copper smelters. Nearly two million tons of mineralized siliceous flux have been shipped from veins in the Lordsburg district. Early exploration is occurring in several other districts in southwestern New Mexico. Some of the more favorable areas are associated with Laramide vein and Laramide skarn deposits (Table 3).

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REFERENCES

Abramson, B.S., 1981, The mineralizing fluids responsible for skarn and ore formation at the Continental mine, Fierro, New Mexico, in light of REE analyses and fluid inclusion studies (M.S. thesis): Socorro, New Mexico Institute of Mining and Technology, 143 p.

Ahmad, S.N. and Rose, A.W., 1980, Fluid inclusions in porphyry and skarn ore at Santa Rita, New Mexcio: Economic Geology, v. 75, p. 229-250.

Anderson, E.C., 1957, The metal resources of New Mexico and their economic feature through 1954: New Mexico Bureau of Mines and Mineral Resources, Bulletin 39, 183 p.

Anderson, J.A., 1982, Characteristics of leached capping and techniques of appraisal, *in* Titley, S. R., ed., Advances in Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, University of Arizona Press, p. 275-295.

Armstrong, A.K., Silberman, M.L.; Todd, V.R., Hoggatt, W.C., and Carten, R.B., 1978, Geology of the central Peloncillo Mountains, Hidalgo County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 158, 19 p.

Audétat, A. and Pettke, T., 2006, Evolution of a porphyry-Cu mineralized magma system at Santa Rita, New Mexico (USA): Journal of Petrology, v. 47, p. 2021-2046.

Barton, M.D., 1996, Granitic magmatism and metallogeny of southwestern North American: Transactions of the Royal Society of Edinburgh, Earth Sciences, v. 87, p. 261-280.

Chapman-Fahey, J., 1996, Petrology of an Upper Cretaceous volcanic complex as recorded in clasts of the McRae and Love Ranch Formations, Jornada del Muerto basin, south central New Mexico (M.S. thesis): Las Cruces, New Mexico State University, 106 p.

Chávez, W.X., Jr., 2000, Supergene oxidation of copper deposits: Zoning and distribution of copper oxide minerals: SEG Newsletter, no. 41, p. 1, 10-21.

Coney, P.J. and Reynolds, S.J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403-406.

Cook, S.S., 1994, The geologic history of supergene enrichment in the porphyry copper deposits of southwestern North America (PhD. Dissertation): Tucson, University of Arizona, 163 p.

Cook, S.S., and Porter, T.M., 2005, The geologic history of oxidation and supergene enrichment in the porphyry copper deposits of southwestern North America, *in* Porter, T. M., ed., Super Porphyry Copper and Gold Deposits: A Global Perspective: Linden Park, South Australia, PGC Publishing, p. 207-242.

Cox, D.P., and Singer, D.A., eds., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

Cox, D.P., and Singer, D.A., eds., 1992, Distribution of gold in porphyry copper deposits: U.S. Geological Survey Bulletin 1877, p. C1–C14.

Damon, P.E., Shafiqullah, M., and Clark, K.F., 1983, Geochronology of the porphyry copper deposits and related mineralization of Mexico: Canadian Journal of Earth Sciences, v. 20, p. 1052-1071.

Drewes, H., 1991, Description and developement of the Cordilleran orogenic belt in the southwestern United States: U. S. Geological Survey Professional Paper 1512, 92 p.

Duecker, K., Yuan, H., and Zurek, B., 2001. Thick-structured Proterozoic lithosphere of the Rocky Mountain region: GSA Today v. 11(12), p. 4-9.

Dunn, P.G., 1982. Geology of the Copper Flat porphyry copper deposit, Hillsboro, Sierra County, New Mexico *in* Titley, S.R., ed., Advances in Geology of the Porphyry Copper Deposits, Southwestern North America: Tuscon, University of Arizona Press, p. 313–326.

Dunn, P.G., 1984. Geologic studies during the development of the Copper Flat porphyry deposit: Mining Engineering, v. 36, p. 151–160.

Einaudi, M.T., 1982, Skarns associated with porphyry copper deposits: description of deposits; I Southwestern North America, II General features and origin *in* Titley, S. R., ed., Advances in the geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 139-183.

Einaudi, M.T. and Burt, D.M., 1982, Introduction--Terminology, classification, and composition of skarn deposits: Economic Geology, v. 77, p. 745-754.

Einaudi, M.T., Meinert, L.D., and Newberry, R.J., 1981, Skarn deposits *in* Skinner, B.J., ed., Economic Geology 75th Anniversary Volume: Economic Geology, p. 317-391.

Energy, Minerals and Natural Resources Department, 1986-2007, Annual Resources Report: New Mexico Energy, Minerals and Natural Resources Department, Santa Fe, various paginated.

File, L. and Northrop, S.A., 1966, County, township, and range locations of New Mexico's Mining Districts: New Mexico Bureau of Mines and Mineral Resources, Circular 84, 66 p.

Gilmer, A.K., Kyle, J.R., Connelly, J.N., Mathur, R.D., and Henry, C.D., 2003, Extension of Laramide magmatism in southwestern North America into Trans-Pecos Texas: Geology, v. 31, p. 447-450.

Hedlund, D.C., 1978, Geologic map of the Wind Mountain Quadrangle, Grant County, New Mexico: U.S. Geological Survey, Miscellaneous Field Studies Map MF- 1031, scale 1:24,000.

Hedlund, D.C., 1985a, Geology, mines, and prospects of the Tyrone stock and vicinity, Grant County, New Mexico: U.S. Geological Survey, Open-file Report 85-232, 32 p.

Hedlund, D.C., 1985b, Economic geology of some selected mines in the Hillsboro and San Lorenzo quadrangles, Grant and Sierra Counties, New Mexico: U.S. Geological Survey, Open-file Report 85-456, 76 p.

Hildenbrand, T.G., Berger, B., Jachens, R.C., and Ludington, S., 2000, Regional crustal structures and their relationship to the distribution of ore deposits in the western United States, based on magnetic and gravity data: Economic Geology, v. 95, p. 1583-1603.

Hillesland, L.L., Worthington, W.T., and Hawkins, R.B., 1994, General geology of the Continental mine, Grant County, New Mexico; in Trip 10 and 13; Tyrone, Piños Altos, Chino, Continental, Central district, New Mexico *in* Bootprints along the Cordillera: Arizona Geological Society, Field Guide, 22 p.

Hillesland, L.L., Hawkins, R.B., and Worthington, W.T., 1995, The geology and mineralization of the Continental mine area, Grant County, New Mexico *in* Pierce, F. W. and Bolm, J. G., eds., Porphyry copper deposits of the American Cordillera: Arizona Geological Society Digest 20, p. 473-483.

Hudson, J.S., 1984, Geology and hydrothermal alteration of the San Simon mining district south of Steins Pass, Peloncillo Mountains, Hidalgo County, New Mexico (M.S. thesis): Albuquerque, University of New Mexico, 125 p.

Keith, S.B., 1986, Petrochemical variations in Laramide magmatism and their relationship to Laramide tectonic and metallogenic evolution in Arizona and adjacent regions *in* Beatty, B. and Wilkinson, P.A.K., eds., Frontiers in geology and ore deposits of Arizona and the southwest: Arizona Geological Society Digest, v. 16, p. 89-101.

Keith, S.B., and Swan, M.M., 1996. The great Laramide porphyry copper cluster of Arizona, Sonora, and New Mexico: The tectonic setting, petrology, and genesis of a world class porphyry metal cluster' *in* Coyner, A.R. and Fahey, P.L., eds., Geology and Ore Deposits of the American Cordillera: Reno-Sparks, Nevada, Geological Society of Nevada Symposium Proceedings, April 1995, p. 1667–1747.

Kesler, S.E., 1973, Copper, molybdenum, and gold abundance in porphyry copper deposits: Economic Geology, v. 68, p. 106-112.

Klemmick, G.F., 2006, Report on Gold Lake property, Grant County, New Mexico: unpublished report, General Minerals Corp., 60 p.

Kolessar, J., 1970, Geology and copper deposits of the Tyrone district *in* Tyrone-Big Hatchet Mountains-Florida Mountains region: N. M. Geological Society, 21st Field Conference Guidebook, p. 127-132.

Kolessar, J., 1982, The Tyrone copper deposits, Grant County, New Mexico *in* Titley, S. R., ed., Advances in Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, University of Arizona Press, p. 327-333.

Kucks, R.P., Hill, P.L., and Heywood, C.E., 2001, New Mexico aeromagnetic and gravity maps and data: A web site for distribution of data: U.S. Geological Survey Open-file Report 01-0061 http://pubs.usgs.gov.of/2001/ofr-01-0061/html/newmex.htm, (accessed 1/3/08)

Kuellmer, F.J., 1955, Geology of a disseminated copper deposit near Hillsboro, Sierra County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Circular 34, 46 p.

Lamarre, A.L., 1974, Fluorite in jasperoid of the Salado Mountains, Sierra County, New Mexico: Significance to metallogeny of the western United States (M. S. thesis): London, Canada, University of Western Ontario, 134 p.

Lawton, T.F., Basbilvazo, G.T., Hodgson, S.A., Wilson, D.A., Mack, G.H., McIntosh, W.C., Lucas, S.G., and Kietzke, K.K., 1993, Laramide stratigraphy of the Little Hatchet Mountains, southwestern New Mexico: New Mexico Geology, v. 15, no. 1, p. 9-15.

Lindgren, W., 1933, Mineral deposits, 4th edition: New York, McGraw-Hill, 930 p.

Lindgren, W., Graton, L.C., and Gordon, C.H., 1910, The ore deposits of New Mexico: U.S. Geological Survey, Professional Paper 68, 361 p.

Long, K.R., 1995, Production and reserves of Cordilleran (Alaska to Chile) porphyry copper deposits *in* Pierce, F. W. and Bolm, J.G., eds., Porphyry Copper Deposits of the American Cordillera: Arizona Geological Society Digest 20, p. 35-68.

Lowell, J.D., 1974, Regional characteristics of porphyry copper deposits of the southwest: Economic Geology, v. 69, p. 601-617.

Lowell, J.D., and Guilbert, J.M., 1970, Lateral and vertical alteration mineralization zoning in porphyry ore deposits: Economic Geology, v. 65, p. 373-408.

Lueth, V.W., 1984, Comparison of copper skarn deposits in the Silver City mining region, southwestern New Mexico (M.S. thesis): El Paso Texas, University of Texas at El Paso, 179 p.

Lueth, V.W., 1996, Garnet resource potential in southern New Mexico *in* Austin, G.S., Barker, J.M., Hoffman, G., Gilson, N., and Zidec, J., eds., Proceedings of the 31st Forum on the Geology of Industrial Minerals, Boderland Forum: New Mexico Bureau of Mines and Mineral Resources, Bulletin 154, p. 137-146.

Mach, C.J., 2004, Tectonic controls, timing, and geochemistry of supergene enrichment of the Tyrone porphyry copper deposit, Grant County, New Mexico (abs.): Geological Society of America, Abstracts with Programs, v. 36, no. 4, p. 4.

McDowell, F.W., 1971, K-Ar ages of igneous rocks from the western United States: Isochron/West, no. 2, p. 1-16.

McLemore, V.T., 1996, Copper in New Mexico: New Mexico Geology, v. 18, p. 25-36.

McLemore, V.T., 1998, Insights into origin of carbonate-hosted Ag and Pb-Zn replacement deposits in the Black Range, Sierra and Grant Counties, New Mexico (abs.): New Mexico Geological Society, Spring Meeting Program; New Mexico Geology, v. 20, p. 49.

McLemore, V.T., 2001, Silver and gold resources in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Resource Map 21, 60 p.

McLemore, V.T., McIntosh, W.C., and Pease, T.C., 1995, $^{40}Ar/^{39}Ar$ age determinations of four plutons associated with mineral deposits in southwestern New Mexico: New Mexico Bureau of Mines and Mineral Resource, Open-file Report 410, 34 p.

McLemore, V.T. and Lueth, V.W., 1996, Lead-zinc deposits in carbonate rocks in New Mexico, *in* D. F. Sangster, ed., Carbonate-Hosted Lead-Zinc Deposits: Society of Economic Geologists, Special Publication 4, p. 264-279.

McLemore, V.T., Sutphin, D.M., Hack, D.R., and Pease, T.C., 1996, Mining history and mineral resources of the Mimbres Resource Area, Doña Ana, Luna, Hidalgo, and Grant Counties, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open-file Report OF-424, 254 p.

McLemore, V.T., Munroe, E.A., Heizler, M.T., and McKee, C., 1999, Geochemistry of the Copper Flat porphyry and associated deposits in the Hillsboro mining district, Sierra County, New Mexico, USA: Journal of Geochemical Exploration, v. 67, p. 167-189.

McLemore, V. T., Peters, L. and Heizler, M. T., 2000a, $^{40}Ar/^{39}Ar$ geochronology of igneous rocks in the Lordsburg district, northern Pyramid Mountains, Hidalgo County, New Mexico: N. M. Geological Society, 51st Field Conference Guidebook, p. 6-8.

McLemore, V. T., Munroe, E. A., Heizler, M. T. and McKee, C., 2000b, Geology and evolution of the Copper Flat Porphyry Copper and associated mineral deposits in the Hillsboro mining district, Sierra County, New Mexico; *in* Cluer, J. K., Price, J. G., Struhsacker, E. M., Hardyman, R. F. and Morris, C. L. eds., Geology and Ore Deposits 2000, The Great Basin and Beyond: Geological Society of Nevada, Symposium Proceedings, p. 643-659.

McLemore, V. T., Donahue, K., Breese, M., Jackson, M. L., Arbuckle, J., and, Jones, G., 2001, Mineral-resource assessment of Luna County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open file Report 459, 153 pp., CD-ROM.

McLemore, V.T., Hoffman, G., Smith, M, Mansell, M., and Wilks, M., 2005a, Mining districts of New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Report 494, CD-ROM.

McLemore, V.T., Krueger, C. B., Johnson, P., Raugust, J.S., Jones, G.E., Hoffman, G.K. and Wilks, M., 2005b, New Mexico Mines Database: Society of Mining, Exploration, and Metallurgy, Mining Engineering, February, p. 42-47.

McMillan, N.J., Dickin, A.P., and Haag, D., 2000, Evolution of magma source regions in the Rio Grande rift, southern New Mexico: Geological Society of America Bulletin, v. 112, p. 1582-1593.

Meinert, L.D., 1987, Skarn zonation and fluid evolution in the Groundhog mine, Central mining district, New Mexico: Economic Geology, v. 82, p. 523-545.

Moore, S.W. and Moran, A.V., 2006, Lone Mountain Copper exploration property, Grant County, New Mexico: National Instrument 43-101 Technical Report, Galway Resources Ltd., www.sedar.com, 102 p.

Nielsen, R.L., 1968, Hypogene texture and mineral zoning in a copper-bearing granodiorite porphyry stock, Santa Rita, New Mexico: Economic Geology, v. 63, p. 37-50.

Nielsen, R.L., 1970, Mineralization and alteration in calcareous rocks near the Santa Rita stock, New Mexico, *in* Woodward, L.A., ed., Guidebook of the Tyrone-Big Hatchet Mountains-Florida Mountains region: N. M. Geological Society, 21st Field Conference Guidebook, p. 133-139.

North, R.M., and McLemore, V.T., 1986, Silver and gold occurrences in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Resource Map 15, 32 p., 1 map.

Phelps Dodge Corporation, 2007, Annual report: http://library.corporate-ir.net/library/95/953/95336/items/192481/2005AR.pdf (accessed on December 7, 2007).

Rose, A.W. and Baltosser, W.W., 1966, The porphyry copper deposit at Santa Rita, New Mexico *in* Tiley, S.R. and Hicks, C.L., eds., Geology of the porphyry copper deposits in southwestern North America: Tucson, Arizona, University of Arizona, p. 205-220.

Schmitt, H.A., 1966, The porphyry copper deposits in their regional setting, *in* Titley, S. R. and Hicks, C. L., eds., Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Arizona, The University of Arizona Press, p. 17-33.

Schwartz, G.M., 1959, Hydrothermal alteration: Economic Geology, v. 54, p. 161-183.

Seager, W.R., Mack, G.H., and Lawton, T.F., 1997, Structural kinematics and depositional history of a Laramide uplift-basin pair in southern New Mexico: Implications for development of intraforeland basins: Geological Society of America Bulletin, v. 109, p. 1389–1401.

Seedorff, E., Dilles. J.H., Proffett, Jr., J.M., Einaudi, M.T., Zurcher, L., Stavast, W.J.A., Johnson, D.A., and Barton, M.D., 2005, Porphyry deposits: Characteristics and origin of hypogene features *in* Hedenquist, J. W., Thompson, J. F. H., Goldfarb, R. J., and Richards, J. P., eds., Economic Geology 100th Anniversary Volume: Economic Geology, p. 251-298.

Sillitoe, R.H., 1972, A plate tectonic model for the origin of porphyry copper deposits: Economic Geology, v. 67, p. 184–197.

Sillitoe, R.H., 2005, Supergene oxidized and enriched porphyry copper and related deposits *in* Hedenquist, J. W., Thompson, J. F. H., Goldfarb, R. J., and Richards, J. P., eds., Economic Geology 100th Anniversary Volume: Economic Geology, p. 723-768.

Sims, P.K., Stein, H.J., and Finn, C.A., 2002, New Mexico structural zone—an analogue of the Colorado mineral belt: Ore Geology Reviews, v. 21, p. 211-225.

Stacey, J.S. and Hedlund, D.C., 1983, Lead–isotopic compositions of diverse igneous rocks and ore deposits from southwestern New Mexico and their implications for early Proterozoic crustal evolution in western United States: Geological Society of America Bulletin, v. 94, p. 43–57.

Titley, S.R., 1982, Geologic setting of porphyry copper deposits, southeastern Arizona *in* Titley, S.R., ed., Advances in the Geology of the Porphyry Copper Deposits in the Southwestern North America: Tucson, University of Arizona Press, p. 37-58.

Titley, S.R., 1997, 1997 Jackling Lecture: Porphyry copper geology: A late century view: Mining Engineering, v. 49, no. 7, p. 57-63.

Titley, S.R., 2001, Crustal affinities of metallogenesis in the American Southwest: Economic Geology, v. 96, p. 1323– 1342.

Titley, S.R. and Beane, R.E., 1981, Porphyry copper deposits, Part I. Geologic settings, petrology, and tectogenesis, *in* Skinner, B.J., ed., Economic Geology 75th Anniversary Volume, p. 214-235.

Turner, D.R. and Bowman, J.R., 1993, Origin and evolution of skarn fluids, Empire zinc skarns, Central mining district, New Mexico, U.S.A.: Applied Geochemistry, v. 8, p. 9-36.

U.S. Bureau of Mines, 1927-1994, Minerals yearbook: Washington, D.C., U.S. Government Printing Office, variously paginated.

U.S. Geological Survey, 1902-1927, Mineral resources of the United States (1901-1923): Washington, D.C., U.S. Government Printing Office, variously paginated.

Young, J.R., 1996, Volcanology and geochemistry of the Upper Cretaceous–lower Tertiary Hidalgo Formation: Remnant of a Laramide volcanic center, southwestern New Mexico (M.S. thesis): Las Cruces, New Mexico State University, 95 p.