Energy and Mineral Resources of New Mexico

Metallic Mineral Deposits

Virginia T. McLemore and Virgil W. Lueth

VOLUME D

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NEW MEXICO BUREAU OF GEOLOGY AND MINERAL RESOURCES

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CONTENTS

Tables Preface

Tables

Figure 1. Geography of New Mexico, showing highways and major cities.

PREFACE

Virginia T. McLemore, Ronald F. Broadhead, Gretchen K. Hoffman, and Fraser Goff

New Mexico is called the Land of Enchantment, in part because of the diverse geologic formations of the state, which give rise to spectacular landscapes of mountains, valleys, mesas, canyons, rivers, deserts, and plains. Major cities are concentrated along the Rio Grande, including Albuquerque, Las Cruces, Rio Rancho, and Santa Fe, with smaller population centers in the southeast, eastern plains, and northwest, such as Roswell, Hobbs, Alamogordo, Carlsbad, Clovis, and Farmington (Fig. 1). New Mexico is the 5th largest state in terms of land area in the lower United States and contains five major physiographic provinces (Fig. 2): Great Plains, Basin and Range, Transition Zone, Colorado Plateau, and Southern Rocky Mountains. The rocks, which date back nearly two billion years, have undergone multiple major tectonic events that were accompanied by faulting and igneous activity (Figs. 3, 4). This rich geologic history has yielded a diversity of valuable energy and mineral deposits, which occur in all of the physiographic provinces in New Mexico, and in a variety of tectonic and geologic settings (Fig. 3). For more information on the geology of New Mexico, see Mack (1997), Mack and Giles (2004), and Price (2010). In addition, mining districts and prospect areas are shown and briefly described in McLemore (2017).

Rock collecting (or rock hounding), prospecting, and non-commercial gold panning are considered a casual use of public lands under most circumstances. **However, it is up to each individual to know the laws and land ownership.** For more information on mining claims and mineral leasing in New Mexico see McLemore (2017), BLM website (http://www.blm.gov/lr2000/), and New Mexico Mining and Minerals Division website (http://www.emnrd.state.nm.us/MMD/MARP/marpmainpage.html).

Importance of Energy and Minerals in New Mexico

New Mexico's mineral wealth is among the richest of any state in the United States. Oil and gas are the most important extractive industries in New Mexico in terms of production value (McLemore, 2017). In 2015, New Mexico ranked 6th in oil production, 8th in gas production, 10th in coal production, and 15th in non-fuel minerals production. Most of the state's mineral production comes from oil, gas, coal, copper, potash, industrial minerals and aggregates (Tables 1, 2). Other important commodities include a variety of industrial minerals (perlite, cement, zeolites, etc.), sulfuric acid, molybdenum, gold, uranium, and silver. New Mexico is fortunate to have geothermal resources in many locations. In December 2013, the Dale Burgett Geothermal Plant in the Animas Valley of southwest New Mexico started delivering up to 2 MW of electricity to the Public Service Company of New Mexico. Development of the Lightning Dock No. 2 project is underway with an additional 6 MW of generation planned.

A healthy energy and mineral industry is vitally important to the economy of New Mexico and to maintenance of public education and services (Table 2). The minerals industries provide property and corporate income taxes, while their ~35,000 direct employees contributed millions of dollars of personal
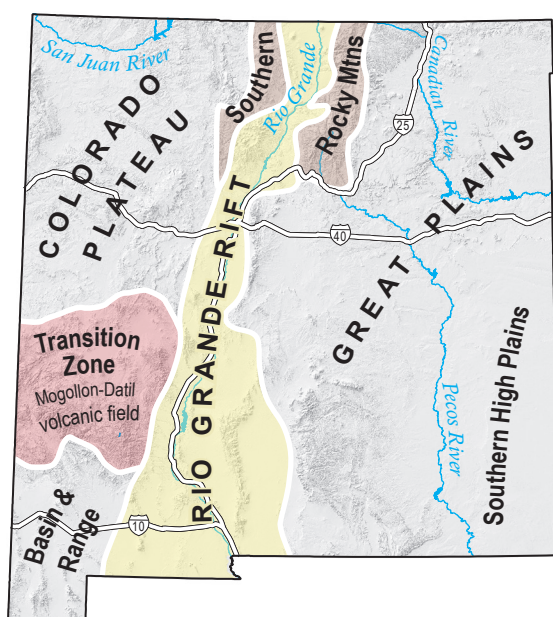
Figure 2. Physiographic provinces of New Mexico.
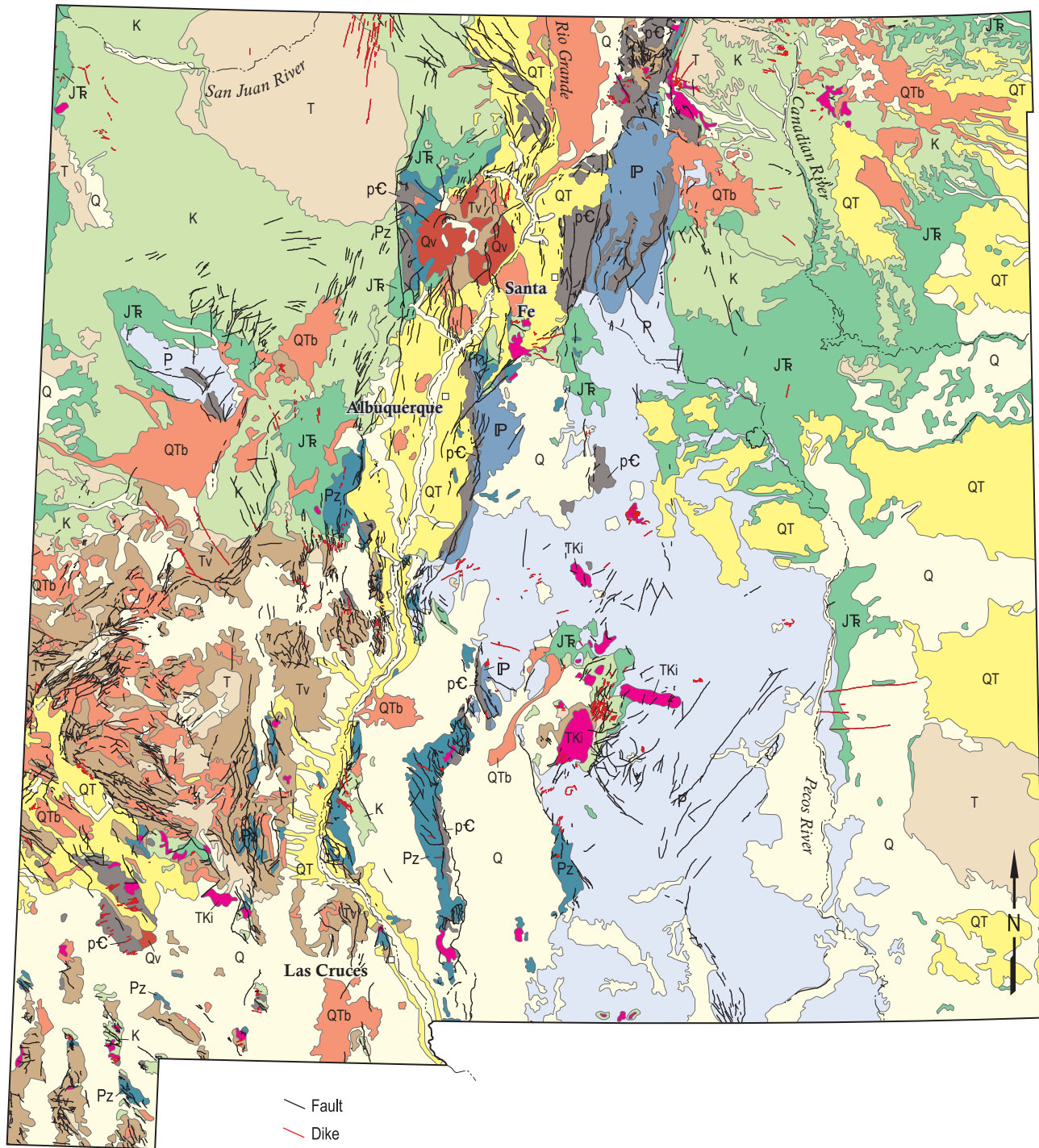
Geologic unit

Q	Quaternary sediments		TKi	Tertiary-Cretaceous intrusives
QT	Quaternary - Tertiary sediments		K	Cretaceous sediments
Qv	Quaternary rhyolites, tuffs		JⱯ	Jurassic-Triassic
QTb	Quaternary - Tertiary basalts, andesites		P	Permian
T	Tertiary sediments		ℙ	Pennsylvanian
Tv	Tertiary volcanics		Pz	Paleozoic undifferentiated
			pⱰ	Precambrian

Fault

Dike

Figure 3. Simplified geologic map of New Mexico.

income taxes (New Mexico Energy and Minerals Division, 2016). The number of mines and actual tonnage of produced minerals has declined in recent years (McLemore, 2017). This decline is a result of numerous complex and interrelated factors. Some of the more important factors include declining profits in mineral operations, decreased quality of ore (for example, lower grades and more difficult ore to process), competition from the global market, and a shift from coal-generated electricity to alternative energy sources.

Table 1. Estimated total production of major commodities in New Mexico, in order of estimated cumulative value (data from USGS, 1902–1927; USBM, 1927–1990; Kelley, 1949; Harrer, 1965; USGS, 1965; Howard, 1967; Harben et al., 2008; Energy Information Administration, 2015; New Mexico Energy, Minerals and Natural Resources Department, 1986–2016). Figures are subject to change as more data are obtained. Estimated cumulative value is in real, historic dollars at the time of production and is not adjusted for inflation.

Commodity	Years of production	Estimated quantity of production	Estimated cumulative value ($)
Natural Gas	1921–2015	>75 trillion cubic feet	$169 billion
Oil	1922–2015	>6.4 billion barrels	$119 billion
Coal	1882–2015	>1.46 billion short tons	>$21.7 billion
Copper	1804–2015	>11.7 million tons	>$21.6 billion
Potash	1951–2015	>113 million short tons	>$15.6 billion
Uranium	1948–2002	>347 million pounds	>$4.8 billion
Industrial minerals**	1997–2015	>41 million short tons	>$2.7 billion
Aggregates***	1951–2015	>674 short tons	>$2.6 billion
Molybdenum	1931–2013	>176 million pounds	>$852 million
Carbon dioxide	1931–2015	>3.3 trillion cubic feet	>$726 million
Gold	1948–2015	>3.3 million troy ounces	>$486 million
Zinc	1903–1991	>1.51 million tons	>$337 million
Silver	1848–2015	>119 million troy ounces	>$280 million
Lead	1883–1992	>367,000 tons	>$56.7 million
Iron	1888–2015	>6.7 million long tons	>$23 million
Fluorspar	1909–1978	>721,000 tons	$12 million
Manganese	1883–1963	>1.7 million tons	$5 million
Barite	1918–1965	>37,500 tons	>$400,000
Tungsten	1940–1958	113.8 tons (>60% WO$_3$)	na
Niobium-tantalum	1953–1965	34,000 pounds of concentrates	na
TOTAL	**1804–2015**	—	**>$359 billion**

*Oil and gas values are estimated from production data provided by https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Reporting/Production/ProductionInjectionSummaryReport.aspx (New Mexico Oil Conservation Division Natural Gas and Oil Production, continuously updated, accessed 2/1/16) and estimated average commodity price. Minerals data are from New Mexico Energy, Minerals and Natural Resources Department (2016). **Industrial minerals include the combined total of several industrial minerals (e.g., perlite, cement, decorative stone, pumice, zeolites, etc.), but excluding potash and aggregates. ***Aggregates include only sand and gravel from 1951–1997, after 1997 aggregates include crushed stone and scoria. na–not available.

Table 2. Summary of mineral production in New Mexico in 2015, including oil and natural gas (New Mexico Energy, Minerals and Natural Resources Department, 2016, https://wwwapps.emnrd.state.nm.us/ocd/ocdpermitting/Reporting/Production/ProductionInjectionSummaryReport.aspx; Gould, 2015). na—not available.

Mineral	Production in 2015	Production rank in the U.S. in 2015	Production value in NM in 2015	Employment in NM (# full time jobs)	Reclamation employment in NM (# full time jobs)	State revenue generated from extractive industries	Federal revenue generated from extractive industries
Oil	147 million bbls oil	6	~$7,143,000,000	~30,000*	na	~$1,600,000,000*	na
Gas	1.23 trillion ft^3 gas	8	~$6,470,000,000	—	na	—	na
Copper	397,441,145 lbs	2	$996,838,033	1,878	4	$8,086,903	—
Coal	19,676,277 short tons	12	$691,047,434	1,341	118	$17,656,313	$10,243,850
Gold	20,438 troy oz	—	$23,708,980	—	—	$191,947	—
Industrial minerals	1,411,731 short tons	—	$87,305,356	413	11	$269,261	$213,816
Aggregates	8,169,753 short tons	—	$62,625,896	837	53	$3,092,285	—
Other metals (iron, manganese)	18,358 short tons	—	$165,223	18	—	$761,027	—
Potash	1,433,245 short tons	1	$659,505,518	1,194	12	$6,542,580	$8,133,012
Silver	56,983 troy oz	—	$895,610	—	—	$9,737	—
Uranium	none	—	—	11	11	—	—
Carbon dioxide	106 billion ft^3	—	$112,000,000	—	—	—	na
Total	—	**15 (excluding oil, gas, and coal)**	**~$16,247,000,000**	**~35,000**	**209**	**~$1,636,000,000**	**$18,590,678**

*Estimate includes oil, gas, and carbon dioxide.

Era	Period/Epoch			Geologic units in New Mexico	Millions of years ago
Cenozoic	Quaternary	Holocene		Bandelier Tuff	0.01
		Pleistocene			2.8
	Tertiary	Pliocene	volcanics	Late Teritary volcanics / Rio Grande rifting	5.3
		Miocene		Zuni-Bandera volcanics	23
		Oligocene		Mid-Tertiary volcanism	33.9
		Eocene		San Jose Formation	55.8
		Paleocene		Nacimiento Formation / Laramide orogeny	65.5
Mesozoic	Cretaceous	Upper		Kirtland Formation / Fruitland Formation / Pictured Cliffs Sandstone / Mesaverde Group / Mancos Shale / Dakota Sandstone	
		Lower			145.5
	Jurassic	Upper		Morrison Formation / Bluff Sandstone / Summerville Formation / Todilto Formation / Entrada Sandstone	
		Middle			
		Lower			199.6
	Triassic	Upper		Chinle Group / Santa Rosa Formation / Moenkopi Formation	
		Middle			
		Lower			251
Paleozoic	Permian			Artesia Group / Yeso Formation / Glorieta Sandstone / San Andres Formation	
					299
	Pennsylvanian			Ancestral Rocky Mtn. orogeny (320–290) / Madera Limestone	
					318.1
	Mississippian				359.2
	Devonian				416
	Silurian			Strata of this age not exposed in Northern New Mexico (present only in the subsurface)	443.7
	Ordovician				488.3
	Cambrian				542
Precambrian/Proterozoic	Late			Sandia granite / Grenville orogeny / Mazatzal orogeny	
					900
	Middle			Proterozoic rock of the Sangre de Cristo Mtns. / Oldest rock in New Mexico	1,600
	Early				2,500

Figure 4. Geologic time scale. "Tertiary" is often used in these chapters to describe timing of events in the Paleogene and Neogene geologic periods.

New mines and petroleum drilling face a multitude of challenges, including water availability, water rights issues, public perceptions, a complex regulatory process and public opposition to petroleum drilling and mining.

Minerals and Society

The minerals industries (including oil and gas) play a vital role in the world economy by filling a persistent demand for the raw materials that are the foundation of our civilization. Our modern lifestyles are heavily dependent upon mining commodities that Americans use on a daily basis (Table 3). For example, petroleum, metals, and industrial minerals are used in every sector of construction and manufacturing. Coal, oil, gas, and uranium provide electricity and fuels. They are used in urban and industrial applications. Geothermal resources also provide electricity and heating (Table 3). Agriculture depends upon minerals for fertilizers and pesticides.

Mineral production in New Mexico and the world has increased dramatically in the last 100 years (Fig. 5, Wagner, 2002). Most industries no longer follow the casual mining and safety practices of the past. "*One of the greatest challenges facing the world today is integrating economic activity with environmental*

Table 3. Selected uses of commodities found in New Mexico.

Commodity	Selected Uses
Oil	Fuel, electricity generation, pesticides, fertilizers, chemicals, plastics
Gas	Fuel, electricity generation
Copper	Electrical wire, pipe, plumbing, motors, machinery, computers
Coal	Electricity generation, steel production, manufacture of cement, liquid fuel, chemical and pharmaceutical industries
Aggregates	Manufacture concrete and cement, road construction, railroad ballast
Molybdenum	Stainless and structural steel, superalloys, chemicals, cast iron
Potash	Agricultural fertilizers
Silver	Currency, jewelry, electronics, photography, silverware, mirrors
Gold	Currency, jewelry, electronics, computers, dentistry, glass
Uranium	Fuel for nuclear reactors, projectiles, shielding of radioactive materials
Perlite	Building construction materials, soil amendment, filter aid
Zeolites	Water purification, animal feed, sorbents
Rare earth elements	Catalyst, glass, polishing, re-chargeable batteries, magnets, lasers, glass, TV color phosphors
Geothermal resources	Electricity generation, space heating, greenhouse heating, aquaculture (fish farms), spas, and bath houses
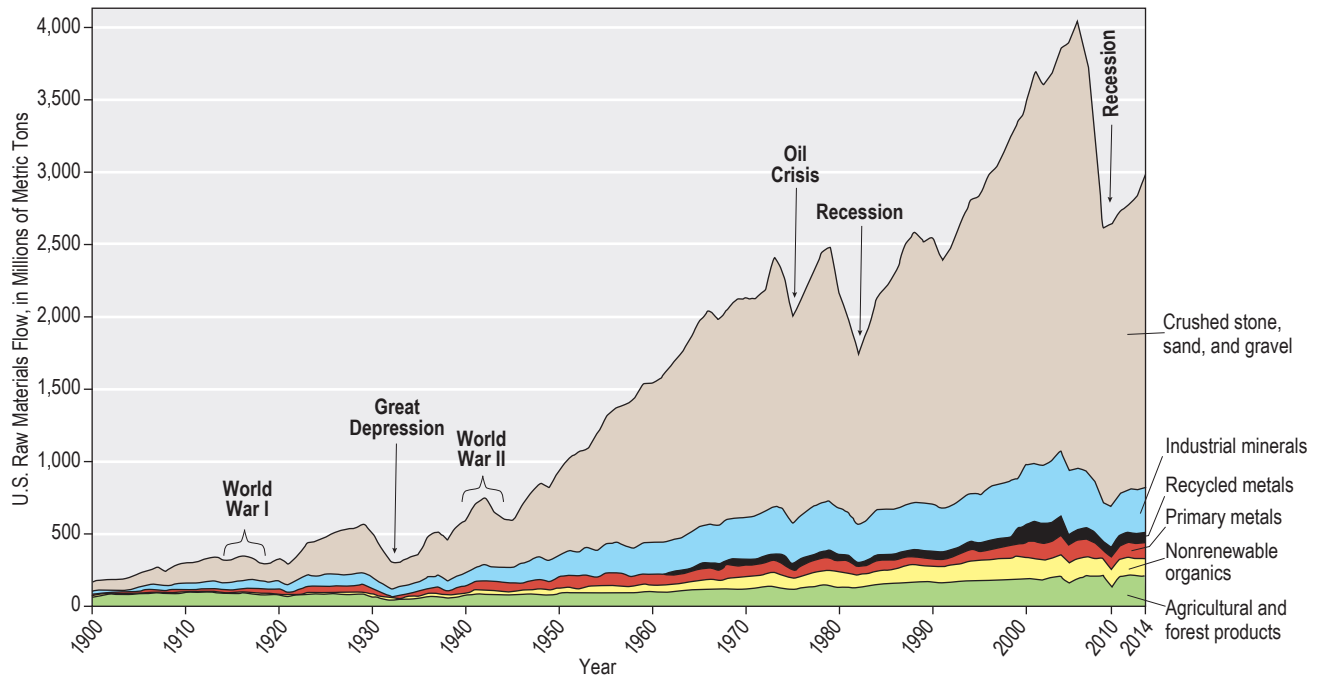
Figure 5. United States flow of raw materials by weight from 1900–2014. The use of raw materials increased dramatically during the last 100 years (modified from Wagner, 2002).

integrity and social concerns… The fulfillment of 'needs' is central to the definition of sustainable development" (IIED, 2002). The permitting process applied to most extractive industries includes archeological surveys, identification of rare and endangered species, and environmental monitoring during and after production. Today, another important aspect of mine planning in a modern regulatory setting is the philosophy, and often the requirement, that new mines and mine expansions must have plans and designs for closure. This philosophy is relatively new. It attempts to prevent environmental accidents common in the past and has increased the cost of mining.

Organization of this Series

This Memoir/Special Publication is the first modern summary of New Mexico's energy and mineral resources since work by the U.S. Geological Survey (USGS, 1965) and Howard (1967). This series of volumes is a joint publication of the New Mexico Bureau of Geology and Mineral Resources and the New Mexico Geological Society. This publication consists of six individual volumes under the theme of Energy and Mineral Resources of New Mexico.

Energy and Mineral Resources of New Mexico,
New Mexico Bureau of Geology and Mineral Resources, Memoir 50
New Mexico Geological Society, Special Publication 13

- **Petroleum Geology**
  by Ronald F. Broadhead, *Volume A*

- **Coal Resources**
  by Gretchen K. Hoffman, *Volume B*

- **Uranium Resources**
  by Virginia T. McLemore and William L. Chenoweth, *Volume C*

- **Metallic Mineral Deposits**
  by Virginia T. McLemore and Virgil W. Lueth, *Volume D*

- **Industrial Minerals and Rocks**
  by Virginia T. McLemore and George S. Austin, *Volume E*

- **Overview of the Valles Caldera (Baca) Geothermal System**
  by Fraser Goff and Cathy J. Goff, *Volume F*

SUMMARY

All metallic mineral deposits in New Mexico, including silver and gold, base metals, molybdenum, manganese, and rare earth elements (REE), can be divided into six major geologic periods of metallogenesis: 1) Proterozoic, 2) Paleozoic to Mesozoic, 3) Laramide, 4) Transition stage, 5) Extensional, and 6) Pliocene-recent. There are more than 32 distinct types of deposits that are found in more than 230 metallic mining districts or mineralized areas in New Mexico, with at least $21 billion worth of metals produced from deposits in New Mexico since the early 1800s. The most important types of deposits in the state, in terms of production, size, and future mining potential, are the Laramide porphyry copper, Laramide polymetallic vein, and Oligocene-Miocene volcanic-epithermal vein deposits. Changing technologies and economics suggest that other types of deposits, currently unrealized, may exist in the state. Known deposits of REE occurrences also could become important in the future, along with other critical and strategic minerals such as selenium, cadmium, gallium, and tellurium. Other metal commodities currently not considered could become important in the future as technology evolves. Many of these types of elements are typically found associated with other types of mineral deposits, especially precious and base metals deposits, and represent potential deposits in known mining areas.

The Chino mine (*Chino* is Spanish for Chinaman), is an open-pit copper mine located east of Silver City (NMGR0029). *Photo by Virginia T. McLemore.*

I. INTRODUCTION

The earliest mining in New Mexico was by Native Americans, who recovered obsidian, chert, basalt, turquoise, malachite, azurite, and possibly fluorite for ornaments and stone tools. They also collected hematite, clay, and other mineral pigments for decoration and pottery. Native American houses were made of stone, adobe, and clay. Soon after settling, Native Americans also began collecting native copper from porphyry copper deposits along with the associated turquoise. Later, the Spanish entered New Mexico in 1534 with dreams of gold and silver, however, very little mining was actually accomplished. Early Spanish mining was centered around the Cerrillos and Old Placers district, mostly for turquoise, copper, and gold. Copper, as well as gold and silver, were mined for coinage during the Mexican period. Gold was discovered in the Ortiz Mountains in 1828. The arrival of the Anglos after New Mexico became part of the United States in 1848 began the great metal mining period of New Mexico history, with the

production of more than $21 billion worth of metals since the early 1800s (Table 1). Today, mining is still an important part of the economy of New Mexico, although to a lesser extent than during the late 1800s and early 1900s.

A *mineral deposit* is any occurrence of a valuable commodity or mineral that is of sufficient size and grade (concentration) for potential economic development under past, present, or future favorable conditions. An *ore deposit* is a well-defined mineral deposit that has been tested and found to be of sufficient size, grade, and accessibility to be extracted and processed at a profit over a specific time. Mineral deposits are not found just anywhere in the world. Instead, they are relatively rare and their formation and distribution depends upon specific natural geologic conditions or processes to form. Mineral deposits require a source of constituent elements, transport and concentration mechanisms, and preservation from geochemical and mechanical

Table 1. Estimated total production of major commodities in New Mexico, in order of estimated cumulative value (from USGS, 1902–1927; USBM, 1927–1990; Kelley, 1949; Northrop, 1959, 1996; Harrer, 1965; USGS, 1965; Howard, 1967; Harben et al., 2008; New Mexico Energy, Minerals and Natural Resources Department, 1990–2015). Figures are subjected to change as more data are obtained (these are conservative estimates).

Commodity	Years of production	Estimated quantity of production	Estimated cumulative value ($)	Quantity of production in 2015	Value in 2015 ($)	Ranking in U.S. in 2015
Copper	1804–2015	>11.7 million tons	>21.6 billion	na	na	2
Molybdenum	1931–2013	>176 million pounds	>852 million	na	na	na
Gold	1848–2015	>3.2 million troy ounces	>463 million	20,438 troy ounces	$23,708,980	9
Zinc	1903–1991	>1.51 million tons	>337 million	none	$0	
Silver	1848–2015	>118.7 million troy ounces	>279 million	56,983 troy ounces	$895,610	7
Lead	1883–1992	>367,000 tons	>56.7 million	none	$0	
Iron	1888–2015	>6.7 million long tons	>23 million	na	na	
Fluorspar	1909–1978	>721,000 tons	12 million	none	$0	
Manganese	1883–1963	>1.9 million tons	5 million	none	$0	
Barite	1918–1965	>37,500 tons	>400,000	none	$0	
Tungsten	1940–1958	113.8 tons (>60% WO_3)	na	none	$0	
Niobium-tantalum	1953–1965	34,000 pounds of concentrates	na	none	$0	
TOTAL (excluding coal)	**1804–2015**	—	**>23 billion**	—	—	**15**

Beryllium, tin, antimony, arsenic, vanadium, selenium, tellurium, thorium, REE, titanium, bismuth also have been produced. Na–not available.

destruction. The requirement that an ore deposit must be extracted at a profit makes them even rarer. Mineral deposits also form through a combination of geological processes that are closely related in geologic time. Thus, mineral deposits are commonly clustered in geological provinces (i.e., mineral or mining districts) in terms of both location and time.

Classification of Mineral Deposits

Numerous classifications have been applied to metallic mineral deposits to aid in exploration and evaluation of metallic resources (Lindgren et al., 1910; Lindgren, 1933; Eckstrand, 1984; Guilbert and Park, 1986; Cox and Singer, 1986; Roberts and Sheahan, 1988; Sheahan and Cherry, 1993). Early classifications were based on the form of the deposit or a combination of form and perceived chemical conditions of formation, such as Lindgren's (1933) classification of mineral deposits associated with igneous rocks into epithermal, mesothermal, and hydrothermal. In the 1960s and 1970s, wide acceptance of plate tectonic theories led to the recognition that similar mineral deposits occur in areas of similar tectonic settings and resulted in classifications of mineral deposits according to tectonic settings (Sillitoe, 1972, 1981; Guilbert and Park, 1986). In the 1980s, mineral deposit models became popular, incorporating tectonic setting and physical and chemical characteristics of the deposits (Cox and Singer, 1986; Roberts and Sheahan, 1988; Sheahan and Cherry, 1993). In New Mexico, North

and McLemore (1986, 1988) and McLemore (2001) classified the silver and gold deposits of New Mexico according to age, mineral assemblages, form, alteration, tectonic setting, and perceived origin. This classification, based upon Guilbert and Park (1986) and Cox and Singer (1986), with some modifications and additions, is retained in this volume (Table 2).

Metallogenesis

Geologists have long recognized that certain types of deposits have formed during particular time periods and under specific tectonic conditions. Accordingly, the major types of metallic mineral deposits in New Mexico (Fig. 1) can be divided into six major periods of metallogenesis (Figs. 2, 3; North and McLemore, 1986, 1988; North, 1989; McLemore, 2001): 1) Proterozoic (Mazatzal, Late granitic plutonism, pre-Grenville extension, Grenville), 2) Ancestral Rocky Mountains (Paleozoic to Mesozoic), 3) Laramide, 4) Transition stage, 5) Extensional, and 6) Pliocene-Recent. Many mining districts exhibit multiple periods of metallic mineralization and recent geochronological studies indicate that the ages of most metallic mineral deposits in New Mexico fall within one of these six periods. More than $23 billion worth of metals have been produced from New Mexico since the early 1800s (Table 1). There are 36 distinct types of deposits found in more than 230 metallic mining districts or mineralized areas in New Mexico (Table 2; McLemore, 2001; McLemore et al., 2002, 2005a, b).

Table 2. Types of mineral deposits in New Mexico, in order of perceived age, excluding coal and many industrial minerals deposits (modified from North and McLemore, 1986, 1988; Cox and Singer, 1986; McLemore and Lueth, 1996; McLemore, 1996a, 1996b, 2001). USGS (U.S. Geological Survey) classification from Cox and Singer (1986). PGE=platinum group metals. REE=rare earth elements. *Not described in this chapter but by McLemore and Chenoweth (2016).

NMBGMR classification	USGS classification (USGS model number)	Commodities	Perceived age of deposit in NM
Volcanogenic massive sulfide (VMS)	Volcanogenic massive sulfide (24a,b, 28a)	Au, Ag, Cu, Pb, Zn	1,650–1,600 Ma
Pegmatites	Pegmatite (13a–h)	Be, Li, U, TH, REE, Nb, Ta, W Sn, Zr, Hf	Probably 1,450–1,400 Ma, 1,100–1,200? Ma, some Tertiary
Vein and replacement deposits in Proterozoic rocks (formerly Precambrian veins and replacements)	Polymetallic veins, fluorite veins (22c, 26b)	Au, Ag, Cu, Pb, Zn, Mn, F, Ba	Proterozoic to Tertiary
Proterozoic iron formation	Volcanic hosted magnetite (25i)	Fe, Au	Proterozoic
Syenite/gabbro-hosted Cu-Ag-PGE	Gabbroid-associated Ni-Cu (7a)	Cu, Ag, PGE	Probably 1,450–1,400 Ma, could be older
Disseminated Y-Zr deposits in alkaline rocks	Alkaline complex associated zircon (11c)	Y, Zr, REE, U. Th, Hf	1,100–1,200 Ma
Carbonatites	Carbonatite (10)	REE, U, Th, Nb, Ta, Zr, Hf, Fe, Ti, V, Cu, apatite, barite	400–600 Ma, one about 22 Ma

Table 2. Continued

NMBGMR classification	USGS classification (USGS model number)	Commodities	Perceived age of deposit in NM
Episyenites and REE-Th-U veins	Th-REE veins (10b, 11d)	REE, U, Th, Nb, Ta	400–600 Ma
Sedimentary iron deposits	Oolitic iron (34f)	Fe	Cambrian-Ordovician
Sedimentary-copper deposits	Sediment-hosted copper (30b)	Cu, Ag, Pb, Zn, U, V	Pennsylvanian-Permian, Triassic
Uraniferous collapse-breccia pipe (including clastic plug deposits)	Solution-collapse breccia pipe U deposits (32e)	Cu, Ag, U, Co, Se, REE?	Triassic, Jurassic
Limestone uranium deposits*	None	U, V, Se, Mo	Jurassic
Sandstone uranium deposits*	Sandstone uranium (30c)	U, V, Se, Mo, REE?	Pennsylvanian-Permian-Miocene
Beach-placer sandstone deposits	Shoreline placer Ti (39c)	Th, REE, Zr, Hf, Ti, U, Fe, Nb, Ta	Cretaceous
Replacement-iron	Iron skarn (18d)	Fe	Cretaceous-Miocene (75–50 Ma)
Porphyry Cu, Cu-Mo (±Au)	Porphyry copper (17, 20c, 21a)	Cu, Mo, Au, Ag	75–50 Ma
Laramide, Cu, Pb, Zn, Fe skarn	Skarn (18a, 18c, 19a)	Au, Ag, Cu, Pb, Zn	75–40 Ma
Laramide, Polymetallic vein	Polymetallic veins (22c)	Au, Ag, Cu, Pb, Zn	75–40 Ma
Porphyry Mo (±Cu, W)	Porphyry Mo-W (16, 21b)	Mo, W, Au, Ag, Be, Cu	Probably 35–25 Ma
Carbonate-hosted W-Be replacement and skarn (Mo-W-Be, F-Be, Fe-Mn)	W-Be skarns (14a)	Mo, W, Be, Pb, Zn, Cu, F, Mn	Probably 35–25 Ma
Carbonate-hosted Pb-Zn (Cu, Ag) replacement	Polymetallic replacement (19a)	Pb, Zn, Cu, Ag	75–25 Ma
Carbonate-hosted Ag-Mn (Pb) replacement	Polymetallic replacement, replacement manganese (19a, b)	Ag, Mn, Pb, Zn	75–25 Ma
Great Plains Margin (GPM or alkaline-related) deposits (including veins; gold-bearing breccias and quartz veins; porphyry Cu-Mo-Au; Cu, Pb/Zn, and Au skarns and carbonate-hosted replacement deposits; Fe skarns and replacement bodies; Th-REE-fluorite (with U and Nb) epithermal veins, carbonatites)	Porphyry copper, polymetallic veins, copper skarns, iron skarns, placer gold (17, 22c, 18a,b, 18d, 39a), Th-REE veins (10b, 11d)	Au, Ag, Cu, Pb, Zn, Mo, Mn, Fe, F, Ba, Te, REE, Nb, Zr, U, Th	47–25 Ma
Volcanic-epithermal veins	Quartz-adularia, quartz-alunite, epithermal manganese (25b,c,d,e,g, 26b, 35a)	Au, Ag, Cu, Pb, Zn, Mn, F, Ba	35–16 Ma or younger
Rhyolite/granite-hosted tin (topaz rhyolites)	Rhyolite-hosted tin (25h)	Sn, Be, REE	28 Ma
Tin skarns	Tin skarns (15c, 14b, 14c)	Sn	
Volcanogenic Be (volcanic-hosted replacement, volcanic-epithermal, Spor Mountain Be-F-U deposits)	Volcanogenic Be deposits	Be, F, U	Miocene-Pliocene
Carbonate-hosted Mn replacement	Replacement Mn (19b)	Mn	Miocene-Pliocene
Rio Grande Rift Copper-silver (±U) vein deposits	Polymetallic veins (22c)	Cu, Ag, U	Miocene-Pliocene
Mississippi Valley-type (MVT) (here restricted to Permian Basin)	Mississippi Valley-type (MVT) (32a-d)	Cu, Pb, Ag, Zn, Ba, F	Oligocene-Pliocene
Surficial uranium deposits*		U	Miocene-Recent
Rio Grande Rift (RGR) Epithermal Mn	Epithermal Mn (25g)	Mn	Miocene-Recent
Rio Grande Rift (RGR)barite-fluorite-galena	Fluorite and barite veins, polymetallic replacement (IM26b, c, 27e, 19a)	Ba, F, Pb, Ag, U	12 Ma-Recent
Placer tungsten	None	W	Pliocene-Recent
Placer tin	Stream placer tin (39e)	Sn	Pliocene-Recent
Placer gold	Placer gold-PGE (39a)	Au, Ag	Pliocene–Recent

The purpose of this chapter is to summarize the types of metallic mineral resources of New Mexico in terms of metallogenesis and geologic history (Figs. 2, 3). Metallic mineral deposits, considered herein, include precious and base metals, molybdenum, manganese, REE, and similar commodities as described in Table 2, even though some of these commodities are considered nonmetallic or industrial minerals (McLemore and Austin, 2017). Uranium deposits and some industrial minerals, such as fluorite, manganese, barite, and REE are included in this chapter because

they are associated with metallic mineral deposits. The mineral deposits are described in order of their determined or perceived age (oldest to youngest), although some deposit types formed over one or more time period. Coal, uranium, industrial minerals and geothermal deposits are described in other chapters associated with this volume (Broadhead, 2017; Hoffman, 2017; McLemore and Austin, 2017; McLemore and Chenoweth, 2017; Goff and Goff, 2017).

Data used in this report have been compiled from literature reviews, field examinations, and unpublished
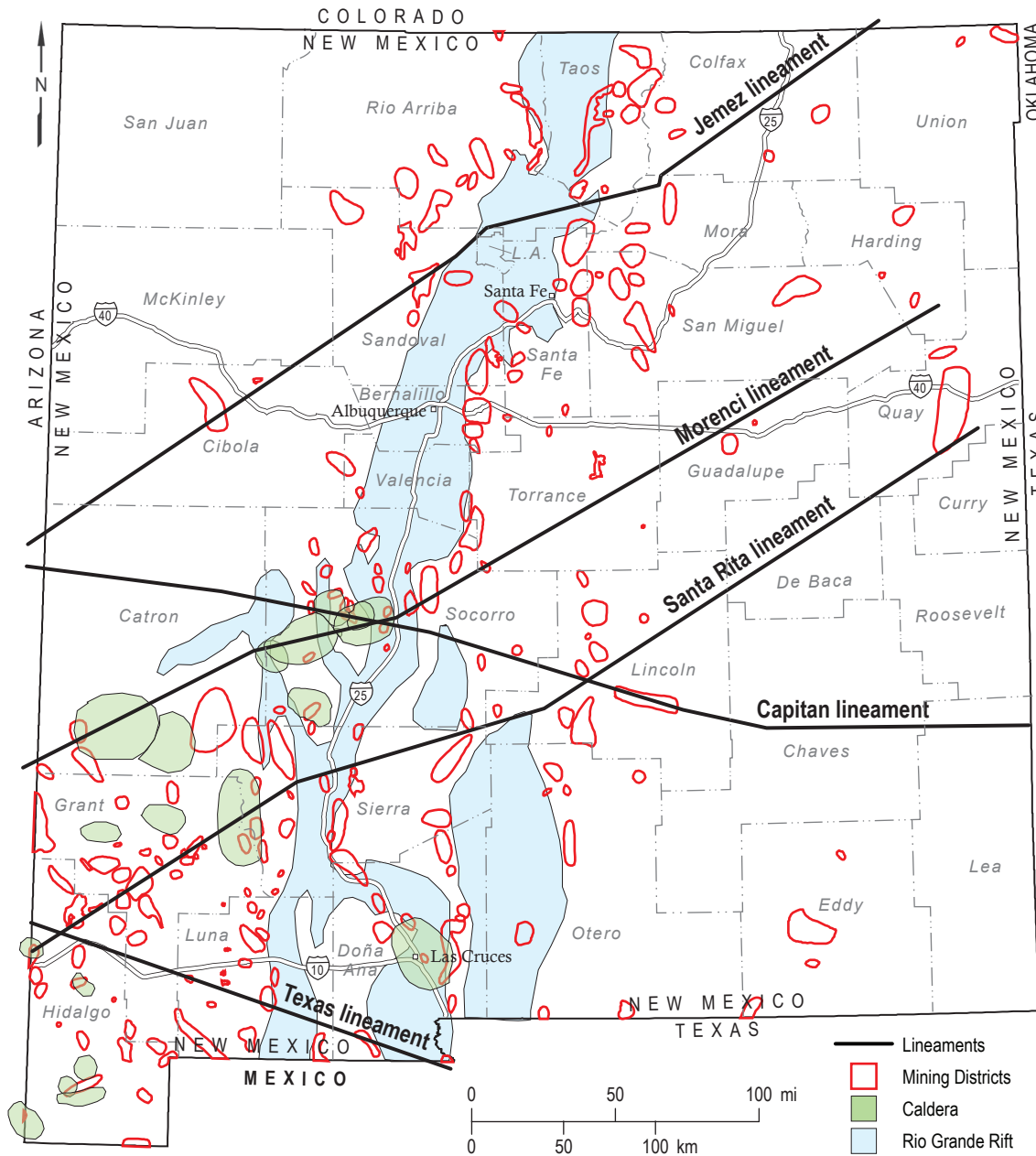
Figure 1. Metallic mining districts, lineaments, calderas, and the Rio Grande rift in New Mexico (Chapin et al., 1978, 2004; McLemore, 2001; Sims et al., 2002; McLemore et al., 2005a; McLemore and Zimmerer, 2009). Brief summaries of districts found in McLemore (2017).
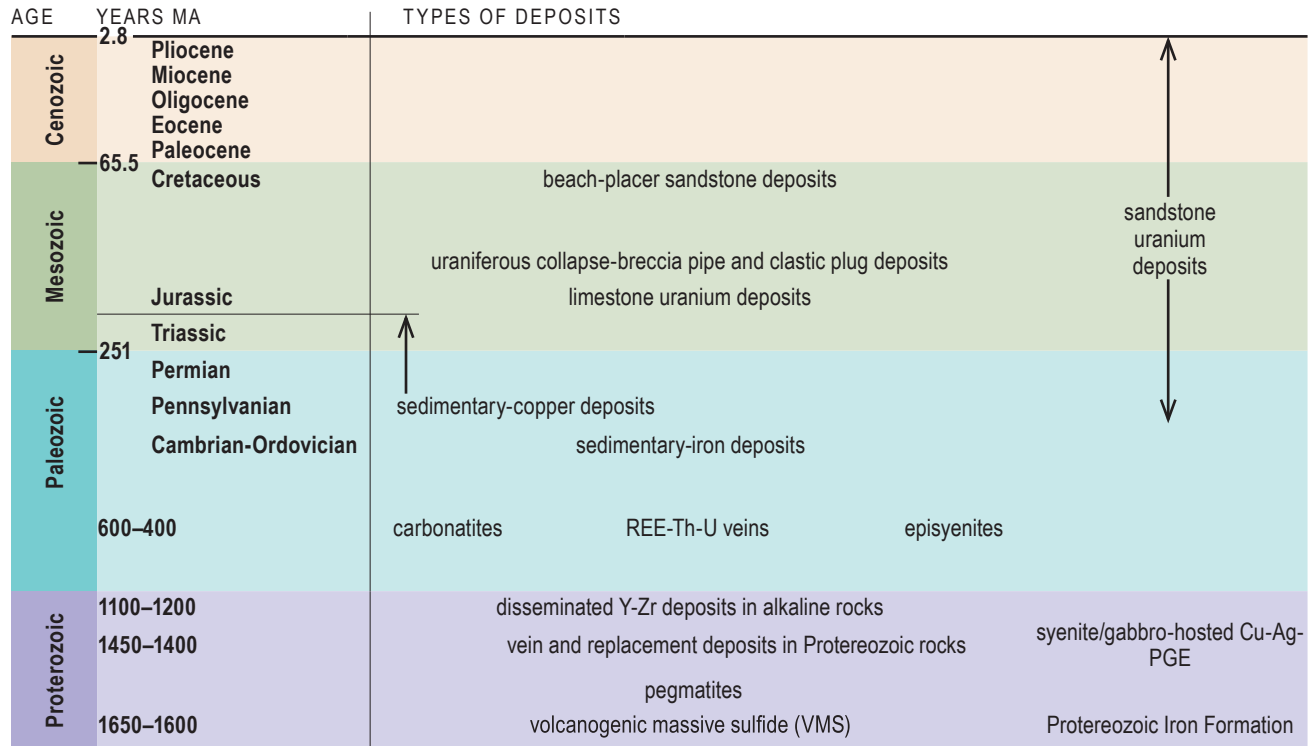
Figure 2. Distribution of Proterozoic-Mesozoic metallic mineral and uranium deposits in New Mexico through time. Arrows delineate the time period sedimentary-copper and sandstone uranium deposits span.
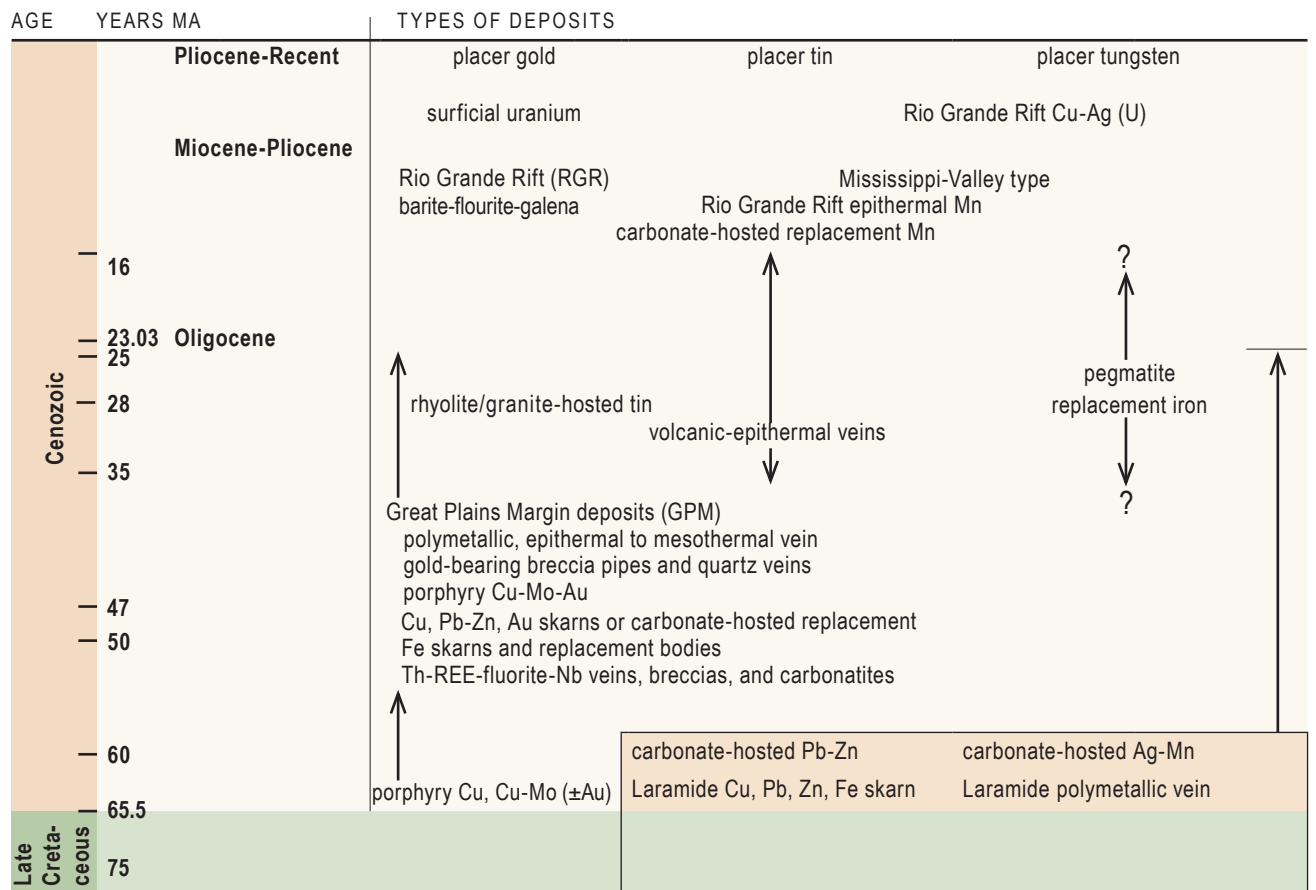
Figure 3. Distribution of Late Cretaceous to Cenozoic metallic mineral and uranium deposits in New Mexico through time.

data by the authors. Several general reports describing the mineral resources of New Mexico, some including more detailed descriptions of many of the mining districts, can be found in Lindgren et al. (1910), Anderson (1957), Howard (1967), North and McLemore (1986), McLemore and Chenoweth (1989), McLemore (2001), Bartsch-Winkler and Donatich (1995), McLemore et al. (1996a, b), Ludington (1996), Bartsch-Winkler (1997), McLemore (2017)and numerous other reports. Names of mining districts are generally from File and Northrop (1966), McLemore and Chenoweth (1989), McLemore (2017), and McLemore et al. (2002). Many of the mines and prospects in this report are described in the New Mexico Mines Database (McLemore et al., 2002, 2005a, b) and are identified by a unique mine identification number (Mine ID), beginning with NMOt (for example NMOt0054). Districts are identified by a unique number beginning with DIS (for example DIS001). This information is provided in order to properly locate the deposits; the New Mexico Mines Database is constantly being updated and locations

of mines not in McLemore et al. (2002a) can be obtained by request using the Mine ID number.

Mineral production by commodity is in Table 1, however, mining and production records are generally poor, particularly for earliest mining activities, and many early records are conflicting. Nonetheless, these production figures are the best data available and were obtained from published and unpublished sources (USGS, 1902–1927; USBM, 1927–1990; New Mexico Energy, Minerals and Natural Resources Department, 1990–2013; NMBGMR unpubl. data). However, historic production figures are subject to change as new data are obtained. Any resource or reserve data presented here are historical data and are provided for information purposes only and do not conform to Canadian National Instrument NI 43-101 requirements, unless otherwise specified (Chapter 5, Rules and Polices; http://web.cim.org/standards/documents/Block484_Doc111.pdf, accessed 1/29/16). Historic and recent production and reserve/resource data are reported in metric or English units according to the original publication to avoid conversion errors.

II. PROTEROZOIC MINERAL DEPOSITS

Proterozoic age deposits are found in many of the mountain ranges of New Mexico (Fig. 4) and represent a variety of tectonic settings and depositional environments. Four major periods of plutonism characterize the Proterozoic in New Mexico, including the 1) Mazatzal orogeny, 1,700–1,600 Ma (Karlstrom and Bowring, 1988; 1993; Karlstrom et al., 1990), 2) Late Proterozoic granitic plutonism,
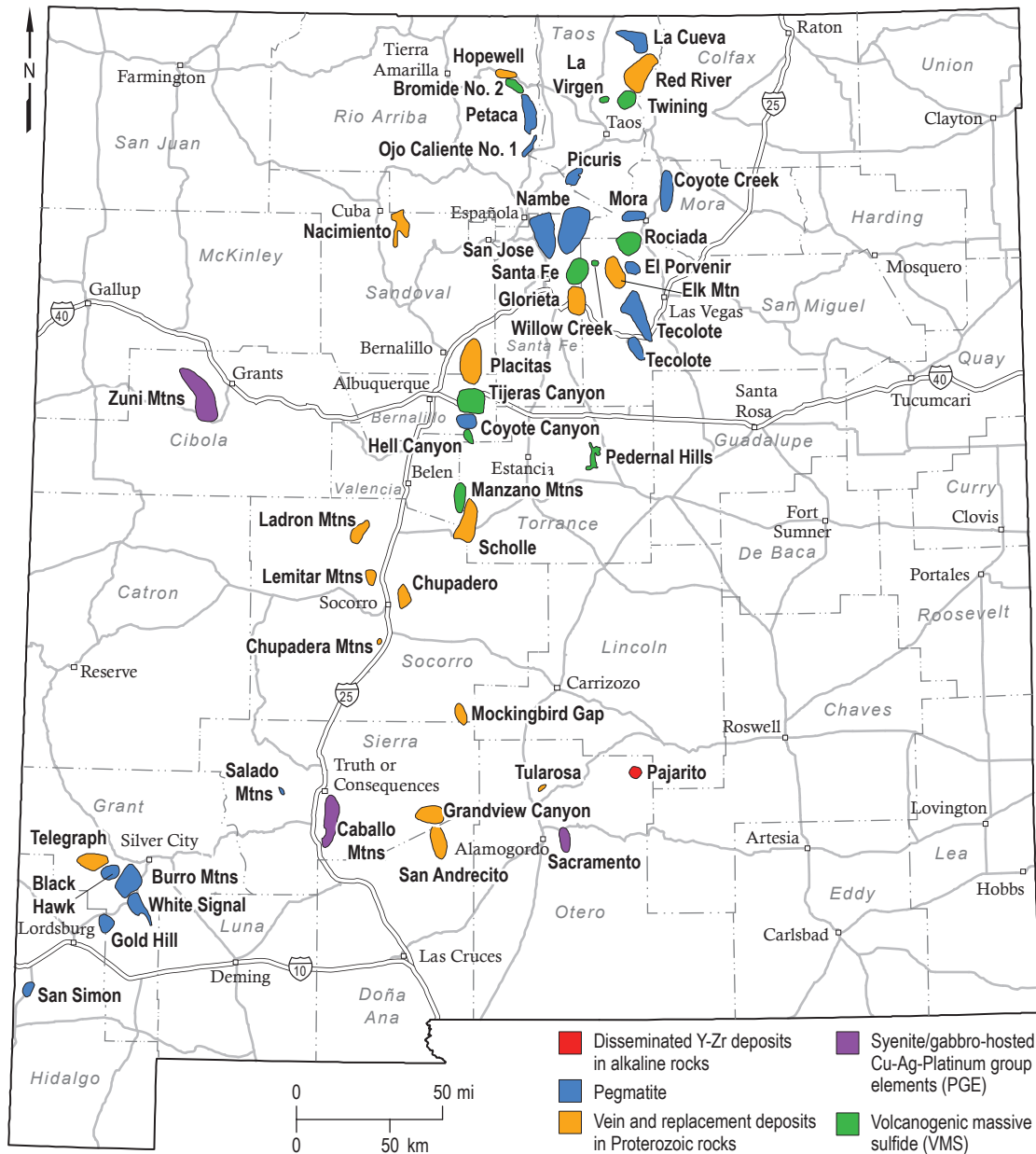
Figure 4. Proterozoic age mineral deposits in New Mexico. Some districts contain more than one type of deposit. Iron formation deposits are found in two districts, Hopewell and Bromide No. 2, in northern New Mexico.

1,450–1,350 Ma (Karlstrom and Bowring, 1988; 1993; Adams and Keller, 1996; Karlstrom et al., 1997; Karlstrom and Humphreys, 1998), 3) pre-Grenville extension and formation of continental margin at 1300-1200 Ma (Adams and Keller, 1994, 1996; Karlstrom et al., 1997; Karlstrom and Humphreys, 1998; Barnes et al., 1999), and 4) Grenville orogeny and extension during 1200-1000 Ma (Adams and Keller, 1996; Smith et al., 1997; Mosher, 1998; Barnes et al., 1999; Reese et al., 2000; McLemore et al., 2000a; Bickford et al., 2000). Six types of metallic deposits are found in Proterozoic age rocks in the state: 1) volcanogenic massive sulfide (VMS), 2) pegmatite, 3) vein and replacement, 4) iron formation, 5) syenite/gabbro-hosted Cu-Ag-PGE (platinum group elements) and 6) disseminated Y-Zr deposits hosted by alkaline rocks. The VMS, iron formation, and pegmatites are associated with the Mazatzal Orogeny and Late Proterozoic granitic plutonism, whereas, the vein and replacement and syenite/gabbro-hosted Cu-Ag-PGE deposits are associated with the Late Proterozoic granitic plutonism. Disseminated Y-Zr deposits in alkaline rocks, found only at Pajarito Mountain (NMOt0095), were formed during the Grenville Orogeny. Very few of these Proterozoic age deposits have been significantly productive in New Mexico; the largest and most economic deposit was the Pecos VMS deposit (NMSM0137) in the Willow Creek district (Riesmeyer and Robertson, 1979).

Volcanogenic Massive Sulfide Deposits

Volcanogenic massive sulfide (VMS) systems are hosted in volcanic rocks comprising of polymetallic, strata bound deposits formed contemporaneously with submarine volcanism by hot saline brines and consist of at least 50% sulfides, generally copper, lead, and zinc with some precious metals (Sangster and Scott, 1976; Franklin et al., 1981; 2005). Modern analogies to this type of mineralization include the "smoker" deposits at ocean rifts (Ames et al., 1993). Subsequent metamorphism, hydrothermal, and/or tectonic activity associated with younger granitic intrusions or younger tectonic events have locally redistributed and reconcentrated the mineralization (Fig. 5). In New Mexico, VMS deposits contain varying amounts of base and precious metals, and are associated with Proterozoic age greenstone terranes best assigned to the Mazatzal Orogeny (1,700–1,600 Ma) or even older. Greenstone terranes consist of dark-green altered or metamorphosed rocks, typically mafic igneous rocks, containing chlorite, epidote or
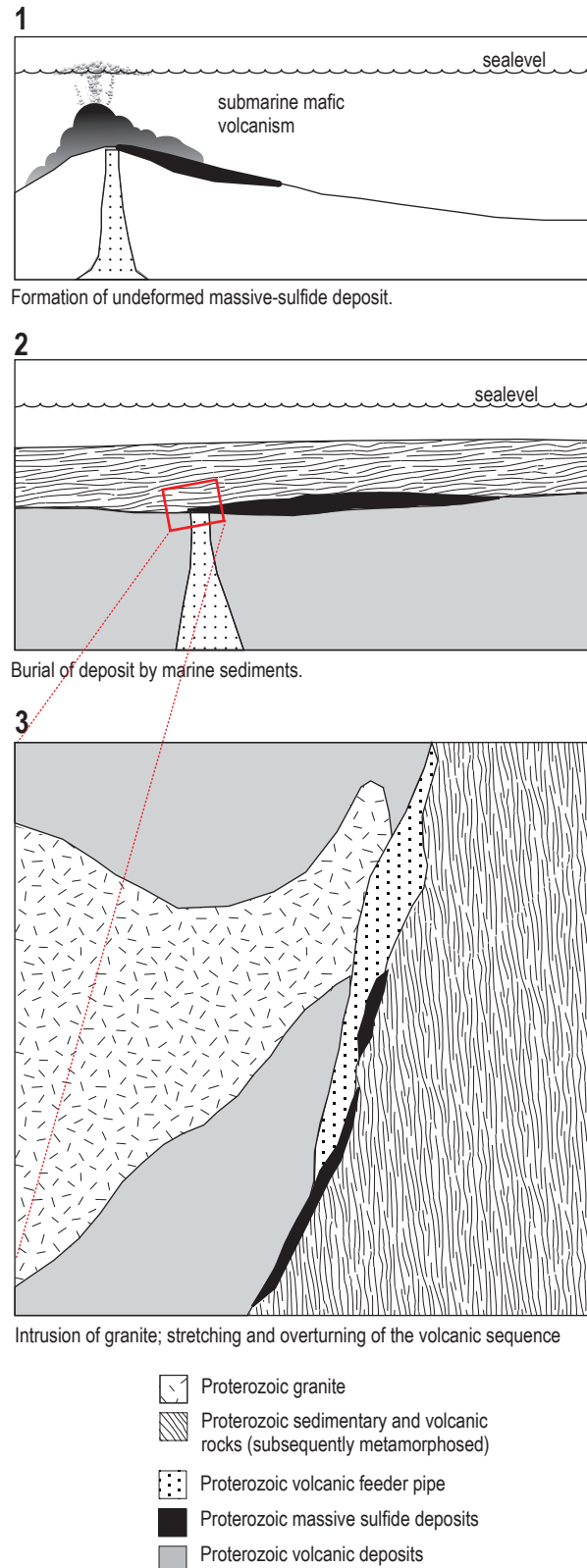
Figure 5. Schematic cross section showing geologic history of Jones Hill VMS deposit (NMSF0095, NMSF0148), Santa Fe and San Miguel Counties (modified by V. T. McLemore from NMBGMR unpubl. data). Eruption of submarine volcanism (1) followed by burial of marine sediments (2). The entire sequence was tilted, metamorphosed and faulted (3).

other green amphiboles. The VMS mineral deposits typically consist of several stratabound lensoid bodies that are conformable with layering and metamorphic fabric (Robertson et al., 1986), and contain pyrite and pyrrhotite in varying amounts with chalcopyrite, sphalerite, magnetite, hematite, and galena. Silver and gold are associated with sulfides, usually in economically minor, but significant concentrations. Chloritization, silicification, and argillization occur adjacent to most deposits, but widespread alteration is absent. Only 10 districts in New Mexico contain known VMS deposits (Fig. 4; Willow Creek, DIS167; Bromide No. 2, DIS139; Santa Fe, DIS189 ; Rociada, DIS164; La Virgen, DIS233; Hell Canyon, DIS250; Manzano Mountains, DIS244; Pedernal Hills, DIS245; Twinning, DIS240; Tijeras Canyon, DIS004), and only the Pecos mine in the Willow Creek district has yielded any significant production. The Pecos and Jones Hill (NMSF0095, NMSF0148) deposits are approximately 1720 Ma (Slack et al., 2009). Although primary sedimentary structures are rarely preserved (Riesmeyer and Robertson, 1979), the majority of New Mexico VMS deposits are metamorphosed. Production from the Pecos mine amounted to 2,302,753 short tons of ore containing 18,687,426 lbs copper, 178,858 oz gold, 5,477,760 oz silver, 133,942,500 lbs lead, and 42,154,00 lbs zinc (Harley, 1940; Robertson et al., 1986; McLemore, 2001). The Pecos mine was the largest lead and zinc producer in New Mexico from 1927 to 1939 and is one of the top 10 lead and zinc producers in New Mexico. Estimates from drill data suggest that the Jones Hill VMS deposit contains more than 5 million short tons

of massive and disseminated sulfide ore composed of 0.89% copper, 1.98% zinc, 0.21% lead, 20 ppm silver, and 2 ppm gold (historic resource; Dixon and Seay, 1979; McLemore, 2001).

VMS deposits may occur in several additional districts in New Mexico that have similar geologic characteristics (Sangster and Scott, 1976; Franklin et al., 1981; Robertson et al., 1986; McLemore, 2011). The mineralized metamorphosed volcaniclastic rocks of the Moppin Metavolcanic Complex in the Hopewell and Bromide No. 2 districts are suggestive of VMS deposits (Robertson et al., 1986; McLemore, 2011). However, many of the VMS deposits occur within or near wilderness areas and probably will not be developed in the foreseeable future.

Pegmatites

Pegmatites are coarse-grained granitic dikes, lenses, or veins and represent the last and most hydrous phase of crystallizing magmas. Most of the pegmatites in New Mexico are associated with the Late Proterozoic granite plutonism of 1450–1330 Ma (Gaston et al., 2014). The pegmatites in New Mexico vary in size, but in map view are typically several hundred feet long and several tens of feet wide. Simple pegmatites consist of feldspar, quartz, and mica, whereas complex pegmatites are mineralogically and texturally zoned and consist of a variety of rare minerals (Fig. 6). Quartz veins commonly grade into the pegmatites and consist of white to colorless quartz with minor amounts of muscovite and feldspar, although these

I. Border zone
II. Wall zone
III. Outer intermediate zone
IV. Inner intermediate zone
V. Core
VI. Partial zone pseudomorph
VII. Fracture filling
VIII. Fracture-controlled replacement body

Zones (early units)

Other (later units)

25-40
General plunge of pegmatite body

0   50 ft
0   10 m

Figure 6. Idealized pegmatite body (modified from Jahns, 1946).

quartz veins generally lack economic mineralization. Several commodities have been produced from complex pegmatites in New Mexico, including mica, beryl, lithium, uranium, thorium, REE, feldspar, niobium, tantalum, tungsten, and gemstones (see McLemore and Austin, 2017). Additional commodities occur in pegmatites that could be recovered, including quartz, antimony, strontium, rubidium, and molybdenum (Jahns, 1946; Lesure, 1965; McLemore et al., 1988a, b; McLemore and Chenoweth, 1989). Although many pegmatites are zoned (Fig. 6), typically, minerals containing these rare commodities are scattered discontinuously throughout the pegmatite, thereby hampering mechanized recovery. Nearly all of the pegmatites in New Mexico intruded metamorphic and granitic rocks of Proterozoic age, although mid-Tertiary-age pegmatites are found in the Organ Mountains and Black Range (Carpenter district, DIS049). Most pegmatites in New Mexico are not economically viable because of low grade, small size, and the expensive hand-sorting techniques required in order to recover any of the commodities.

The Harding pegmatite (NMTA0015) in the Picuris district is the most important pegmatite in New Mexico and was discovered about 1910. Mining for lepidolite began in 1919 and was the first of three mining periods at the pegmatite (the Lepidolite period, 1919–1930; Jahns and Ewing, 1977). Lepidolite, a lithium-bearing mica, is used to manufacture glass. From 1920 to 1930, approximately 12,000 short tons of lepidolite-spodumene ore, averaging 3.5% LiO_2, were produced (Schilling, 1960).
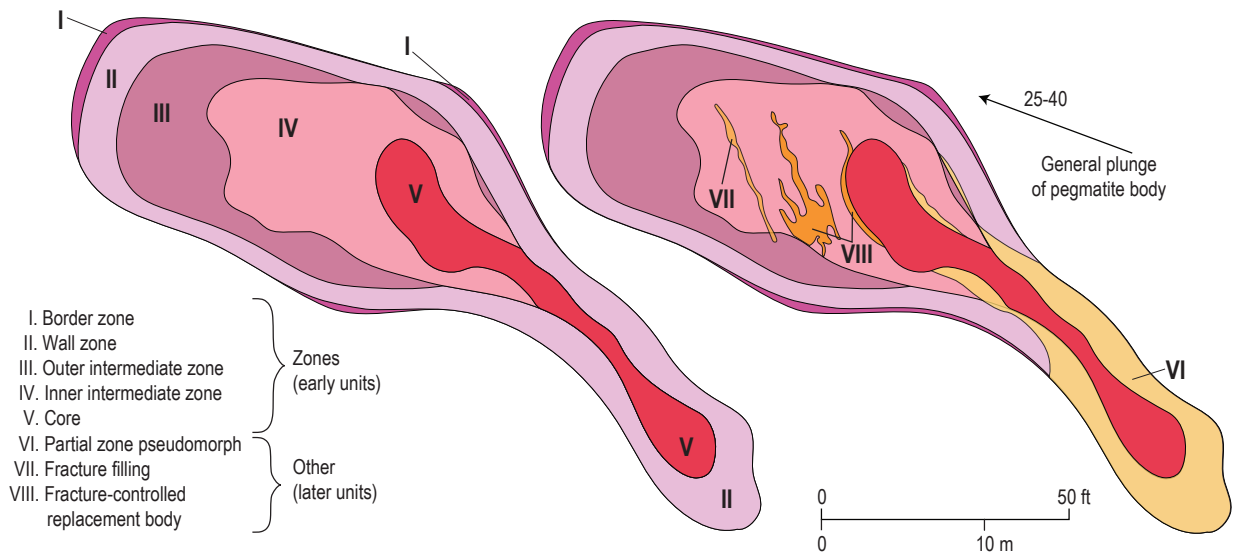
The second period of mining, the Microlite period (1942–1947), began in 1942 when Arthur Montgomery began mining microlite, a tantalum-niobium mineral. The Harding pegmatite is one of the few mines in the world to produce microlite. From 1942 to 1947, more than 22,000 lbs of tantalum concentrates, averaging 68% Ta_2O_5 and 7% Nb_2O_5, were produced (Jahns and Ewing, 1977). Reportedly, 41 short tons of spodumene and 558 short tons of lepidolite were produced during this period. In addition, 464 lbs of placer tantalite and columbite averaging 43% Ta_2O_5 and 36% Nb_2O_5 were produced nearby.

The third mining period, the Beryl period, occurred between 1950 and 1959. From 1950 to 1959, 848.3 short tons of beryl that averaged 10% BeO were produced from the Harding pegmatite, and from 1950 to 1955, the pegmatite accounted for nearly 20% of the beryl production in the United States (Schilling, 1960). An additional 806 short tons of lepidolite and 249 short tons of spodumene were

produced. After mining ceased in 1959, the Harding mine was leased to several companies for exploration of additional resources. In 1978, the mine was donated to the University of New Mexico to preserve one of the State's unusual natural assets and to provide access for educational purposes (The Harding Pegmatite Mine - New Mexico; http://epswww.unm.edu/harding-mine/, accessed 1/5/16).

Vein and Replacement Deposits in Proterozoic Rocks

Vein and replacement deposits containing base and precious metals occur sporadically throughout most of the Proterozoic age terranes in New Mexico. Gold, silver, and copper occur in lenticular quartz veins along shear zones in Proterozoic greenstones in the Hell Canyon (DIS250) and Tijeras Canyon (DIS004) districts. Silver deposits with minor quantities of gold and copper occur in quartz veins along shear zones in granite and metamorphic rocks in the Zuni Mountains district (DIS017; McLemore, 1989, 2013). Free gold occurs with quartz and calcite in several districts, most notably the Hopewell district (DIS145; McLemore, 2011). Copper minerals with gold and silver concentrations occur in shear zones and as disseminations in granitic and mafic rocks in many districts (i.e., Zuni Mountains, Pedernal Hills, Lemitar Mountains, DIS219). Veins and small replacement bodies containing copper, gold, silver, tungsten, and bismuth occur along faults, fractures, shear zones, and contact zones within granitic and metamorphic rocks in the Grandview Canyon district (DIS195; McLemore, 1994b). Production of metals from most deposits has been limited, although evidence suggests that Proterozoic deposits may be a significant metals and sulfur source for younger deposits, such as sedimentary-copper sandstone deposits of late Paleozoic and Mesozoic ages (LaPoint, 1976, 1979, 1989; Fulp and Woodward, 1990).

The age of mineralization is uncertain in most districts, although many of these deposits are structurally controlled, coincident with schistosity or shear zones of Proterozoic age and are, therefore, syn- or post-metamorphic (i.e., Zuni Mountains, Grandview Canyon; McLemore, 1989, 1994b, 2013). However, some of these deposits show evidence of metamorphism (Fig. 7; Williams and Bauer, 1995). A syn- to late-metamorphic age of the Copper Hill deposits (NMTA0014) in the Picuris district is indicated by crosscutting relationships, local replacements of kyanite and staurolite by sulfide minerals, and evidence
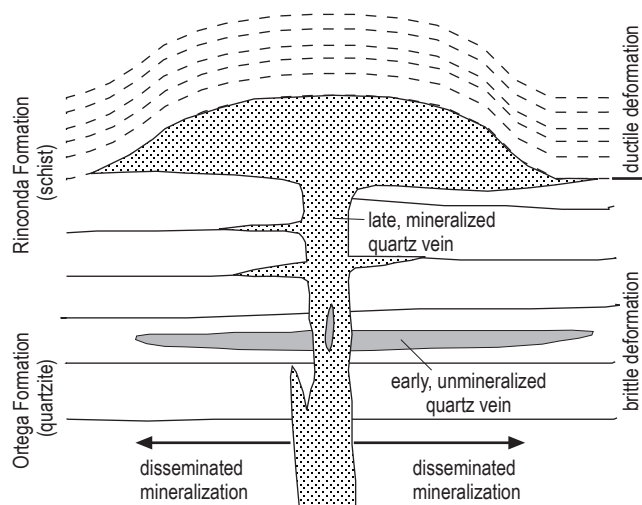
Figure 7. Schematic model of retrograde mineralization in the Copper Hill deposit (NMTA0014), Picuris district (simplified from Williams and Bauer, 1995). Early, unmineralized quartz veins were emplaced during regional retrograde metamorphism of the Ortega Group. Cu-Sb-Ag-quartz veins were emplaced after early quartz veins emplacement, but before the final recrystallization of the Ortega quartzite and late quartz veins.

for post-mineralization annealing of vein quartz and quartzite (Williams and Bauer, 1995). Historic resources at Copper Hill are estimated at 46,500,000 short tons of 0.42% copper (McLemore, 2001). In many districts, there is a strong spatial association of precious-metal veins with diabase or mafic dikes of presumed late Proterozoic age (i.e., Glorieta, DIS183; Grandview Canyon, DIS195; Dunham, 1935; McLemore, 1994b; McLemore et al., 1996). Fulp and Woodward (1990) presented evidence suggesting that deposits in the Hell Canyon district are, in part, hot-springs epithermal deposits remobilized from Proterozoic volcanic-exhalative deposits. Thus, these deposits would most likely be mid-Tertiary age and associated with the formation of the Rio Grande rift. Hence, although the age of mineralization is uncertain in most of these districts, it is apparent that multiple periods of mineralization probably occurred, and detailed geologic and geochronologic studies are needed to constrain the timing of mineralization. Most of the precious-metal deposits in Proterozoic terranes are small, low grade and uneconomic.

Proterozoic Iron Formation

Proterozoic iron formations are stratigraphic units composed of layered rocks that contain 15% or more iron, occurring with quartz, chert, and/or carbonate. Worldwide, these systems are among the largest iron

ore deposits mined for steel manufacturing in the world (Bekker et al., 2010), although those in New Mexico are quite small in comparison (McLemore, 2011). Proterozoic banded iron formations are found in the Moppin Metavolcanic Complex at the Iron Mountain mine (NMRA0181) in the northern Hopewell district and also in the Bromide No. 2 district (Fig. 4; McLemore, 2011). However, there has not been any iron production in either locality. The iron ore deposits found at the Bromide No. 2 district are large enough to be economically interesting, but the grade and size are well below what would be economically feasible today. Beneficiation tests should be performed though to see if it can be upgraded to ~50% Fe, as material of this grade is currently being mined in Utah.

Syenite/Gabbro-Hosted Copper-Silver-Platinum Group Elements

Platinum group elements (PGE, including platinum [Pt], palladium [Pl], osmium [Os], ruthenium [Ru], iridium [Ir], and rhodium [Rh]) typically occur in economic concentrations in ultramafic and associated mafic rocks (Eckstrand, 1984; Cox and Singer, 1986; Macdonald, 1988). Many of the PGE ore deposits in the world are in Archean rocks. Combined PGE content of most ore deposits ranges from 1–20 ppm (Eckstrand, 1984). Typical host rocks include diorite, peridotite, pyroxenite, anorthosite, gabbro, norite, and syenite (Eckstrand, 1984; Mutschler et al., 1985; Cox and Singer, 1986; Macdonald, 1988). PGE ore deposits occur as conformable layers or lenses near the base of layered ultramafic and mafic complexes, thin stratiform layers within ultramafic and mafic intrusions, and irregular pipe-like bodies with ultramafic and mafic intrusions. PGE values also have been obtained from sulfide ores associated with alkaline rocks (Finch et al., 1983; Mutschler et al., 1985, 1991).

No proven PGE ore deposits are currently known in New Mexico that contain concentrations rich enough and/or large enough to be mined economically (McLemore et al., 1989). In the Zuni Mountains, PGEs are found in Proterozoic syenite and amphibolite bodies in a shear zone (McLemore, 2013). A PGE-bearing mineral (stibiopalladinite, PdSb) and gold have recently been identified in these mafic units and commercial assay results have been confirmed by electron microprobe and petrographic examination of the ore at the New Mexico Bureau of Geology and Mineral Resources. Further mineralogical and chemical work is needed.

Several additional Proterozoic terranes associated with the 1,450–1,400 Ma event in New Mexico (Fig. 4; Sacramento and Caballo Mountains) contain mafic and, rarely, ultramafic rocks that have limited potential for occurrence of PGE. A sample of Proterozoic age gabbro from the Sacramento Mountains contained 1 ppb platinum and 66 ppb palladium (New Mexico Bureau of Mines and Mineral Resources et al., 1998) and similar samples of Proterozoic age gabbro from the Caballo Mountains contained 1–3 ppb Pt and 1–2 ppb Pd (V.T. McLemore, unpubl. data).

Disseminated Yttrium-Zirconium Deposits in Alkaline Rocks

Disseminated yttrium-zirconium deposits in alkaline rocks are found at Pajarito Mountain, in the northeastern part of the Mescalero Apache Indian Reservation, south of Ruidoso in Otero County (Sherer, 1990; McLemore, 1990, 1991, 2012a) and dating by Kelley (1968) and the U.S. Geological Survey (Moore et al., 1988) indicate a Proterozoic age of about 1,100–1,200 Ma. This deposit is associated with a regional period of mafic volcanic and A-type granite intrusions coincident with the Grenville orogeny. If not for unfavorable economic conditions in the 1980s, the undeveloped Pajarito Mountain deposit would have been the first and only deposit in the world mined solely for yttrium and zirconium, which are typically produced as co-products or by-products of mining other commodities.

The Pajarito Mountain complex consists of an unusual lithologic assemblage for Proterozoic rocks in New Mexico because the complex is predominantly alkaline. Several varieties of syenite, quartz syenite, alkali granite, and gabbro are exposed at Pajarito Mountain and are intruded by pegmatite and gabbroic dikes (Kelley, 1968; Condie and Budding, 1979; Moore et al., 1988; Sherer, 1990). Such rocks, although present locally, are not the predominant lithologies in most Proterozoic terranes in New Mexico. Molycorp, Inc. (a former subsidiary of Unocal Corp.) began exploration in the area in 1984 and announced the discovery of a yttrium and zirconium deposit at Pajarito Mountain on May 31, 1989 (McLemore, 1990, 1991; Sherer, 1990). A joint leasing-operating agreement was reached between Molycorp, Inc. and the Mescalero Apache Tribe and a recoverable historic resource of 2.7 million short tons grading 0.18% Y_2O_3 and 1.2% ZrO_2 as disseminated eudialyte was reported (Sherer, 1990). However, before mine planning began, market prices decreased for yttrium and zirconium and Molycorp dropped the project. Eudialyte ($(Na,Ca)_5(Zr,Fe,Mn)$ $(Si_6O_{17})(O,OH,Cl)$), the major ore mineral at Pajarito Mountain, is disseminated throughout syenite, quartz syenite, and alkali granite, containing yttrium, and is generally amenable to heap-leach recovery after crushing, similar to the process used in recovering gold and silver. Unpublished chemical analyses (V.T. McLemore) indicate these alkaline Proterozoic age rocks are anomalously high in light-REE (lanthanum as high as 1,500 ppm, cerium as high as 3,910 ppm) and niobium (200 ppm). The Bureau of Indian Affairs drilled six holes in June 2014 to evaluate the mineral resource potential of the Pajarito Mountain deposit; results are pending. Development of this resource is dependent upon the ever-changing market and demand for yttrium, zirconium, and REE market and demand for yttrium, zirconium, and REE (McLemore, 2012a).

III. CAMBRIAN–ORDOVICAN MINERAL DEPOSITS

A minor episode of alkaline and carbonatite magmatism occurred during Cambrian to early Ordovician time in parts of New Mexico and southern Colorado that resulted in episyenites, REE-Th-U veins and carbonatite deposits (McLemore, 1986, 1987; McLemore et al., 1999a; McMillan et al., 2000; McMillan and McLemore, 2004). The remainder of Cambrian-Ordovician time was a period of sedimentary deposition as beach sands and marine limestones were deposited throughout New Mexico.

Carbonatites

Carbonatites are carbonate-rich rocks of apparent magmatic derivation and typically contain disseminated REE, uranium, thorium, niobium, tantalum, zirconium, hafnium, iron, titanium, vanadium, copper, apatite, vermiculite, and barite. Carbonatites are commonly associated with REE-Th-U veins and alkali-metasomatism, known as fenitization (LeBas, 2008) and (Fig. 8). In New Mexico, Cambrian-Ordovician

carbonatites occur as dikes and associated veins and stockworks in four areas: Lemitar (506 Ma, V.T. McLemore, unpubl. $^{40}Ar/^{39}Ar$ data on phlogopite), Chupadera Mountains, Lobo Hill, and the Monte Largo area in the Sandia Mountains (Fig. 9). A fifth Oligocene carbonatite locality in New Mexico occurs at Laughlin Peak in the Chico Hills, Colfax County (see Great Plains Margin, GPM, deposit type). Carbonatites could be in the subsurface in the Gallinas Mountains as suggested by alteration, geochemistry, and previous drilling, but no samples have been obtained for precise determination of the lithology (McLemore, 2010b; Vance, 2013). The Cambrian-Ordovician dikes are typically 3–5 ft
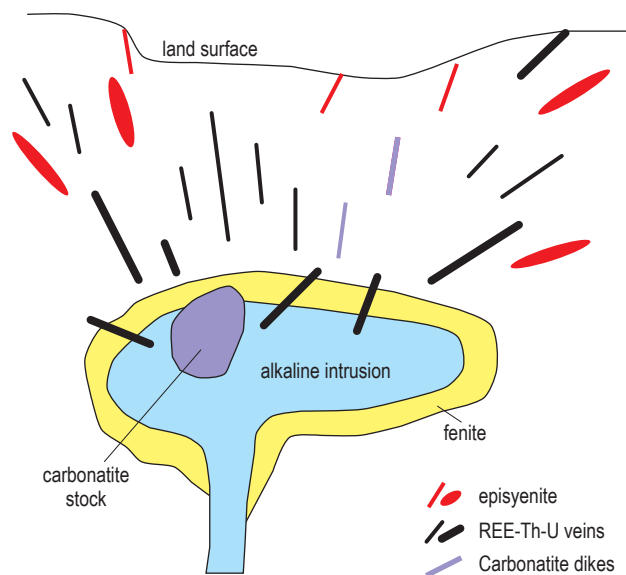
Figure 8. Relationship of REE-Th-U veins, fenites, and episyenites to alkaline rocks and carbonatites. Fenite is an alkali metasomatic alteration that surrounds the alkaline and carbonatite intrusions.
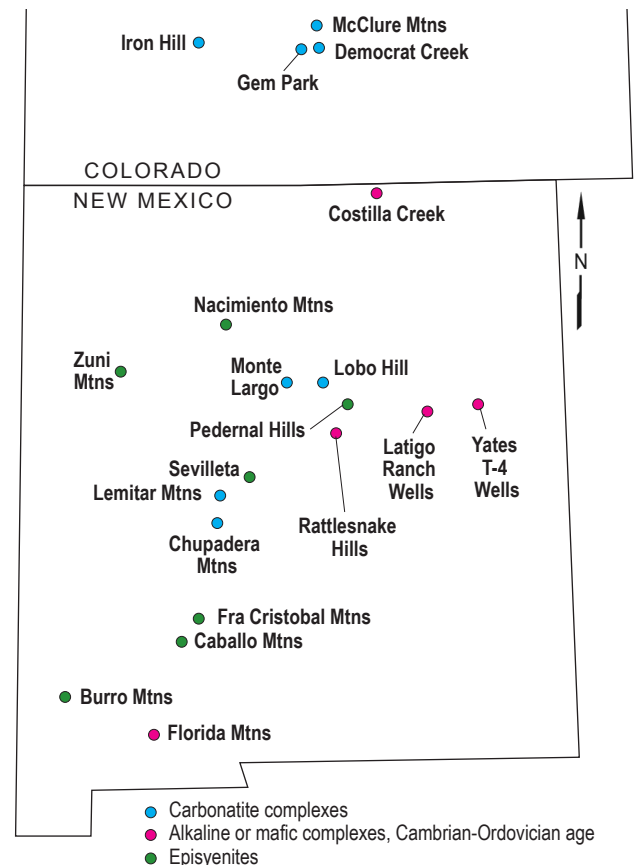
Figure 9. Cambrian-Ordovician carbonatite, alkaline and mafic igneous rocks, and episyenites in New Mexico and Colorado that contain anomalous rare earth elements (REE) concentrations.

wide and up to 1,500 ft long (Fig. 10; McLemore, 1987). There has been no significant mineral production from any of the carbonatites in New Mexico, although barite was mined from the Lemitar carbonatites in the late 1970s.

Episyenites and REE-Th-U Veins

Episyenites and REE-Th-U veins are commonly associated with carbonatites and alkaline igneous rocks and also are found in New Mexico without any direct association with carbonatites or alkaline rocks (Fig. 8). Episyenites containing anomalous REE concentrations are found in the Caballo, Burro, Zuni, and Nacimiento Mountains, Pedernal Hills, Lobo Hill, and Fra Cristobal Mountains and on the Sevilleta National Wildlife Refuge (Fig. 9). Episyenites are brick-red, K-feldspar-rich rocks that were desilicated and metasomatized by alkali-rich fluids, possibly related to alkaline or carbonatite magmas (Fig. 11). Field relationships and ^{40}Ar/^{39}Ar dating indicates that New Mexico episyenites are ~500 Ma (Cambrian-Ordovician age) or older (McLemore et al., 1999a; Riggins, 2014). The New

Mexico episyenites contain as much as 16% K_2O and have greater concentrations of REE (as much as 3,167 ppm total REE), Th (as much as 9,721 ppm), and U (as much as 2,329 ppm) than most igneous rocks and exhibit textures consistent with a metasomatic origin. Some episyenites contain high concentrations of heavy REE (as much as 133 ppm Yb and 179 ppm Dy). K-feldspar, hematite, and REE-bearing minerals have replaced the protolith granites and metamorphic gneisses. Recent electron microprobe studies on episyenites from the Caballo Mountains have identified synchysite (Ca(Ce,La)(CO$_3$)$_2$F), aeschynite ((Y,Ca,Fe,Th)(Ti,Nb)$_2$(O,OH)$_6$), xenotime (YPO$_4$), thorite ((Th,U)SiO$_4$), uranophane (Ca(UO$_2$)$_2$SiO$_3$(OH)$_2$•5(H$_2$O)), and apatite (Ca$_5$(PO$_4$)$_3$(F,Cl,OH) (Riggins, 2014). Bastnaesite was reported previously (McLemore, 1986). These episyenites may be representative of alkaline or carbonatite plutons at depth and are possibly related to the widespread Cambrian–Ordovician magmatic event that occurred throughout New Mexico and southern Colorado (Fig. 9). See McLemore and Austin (2017) for more information. Younger REE-Th-U veins are found in Great Plains Margin deposits as described in volume E.

Figure 10. Cambrian-Ordovician carbonatite dike intruding Lemitar diorite, Lemitar Mountains (NMGR0016). *Photo by Virginia T. McLemore.*

Figure 11. Red episyenites in Proterozoic granite north of Palomas Gap, Caballo Mountains (NMSI1744). *Photo by Virginia T. McLemore.*

IV. PALEOZOIC TO MESOZOIC SEDIMENTARY MINERAL DEPOSITS

Paleozoic to Mesozoic time in New Mexico is dominated by extensive sedimentation and relatively little tectonism. Most Paleozoic tectonic events were occuring west of New Mexico (e.g. Antler orogeny). Accordingly, most mineral deposits formed during this period in New Mexico were sedimentary-related deposits (Fig. 12). However, during the Pennsylvanian age, crustal shortening in the region lead to the formation of broad basins and basement uplifts bounded by reverse faults. Known as the "Ancestral Rocky Mountains," these uplifts were the source for large deposits of clastic rocks that graded into marine strata. Within these clastics, sedimentary-copper, uranium (McLemore and Chenoweth, 2017), and other sedimentary-hosted deposits were formed. Alternating terrestrial and marine sedimentation persisted into the late Mesozoic. The San Juan and Permian basins formed during this time, and contain substantial petroleum (Broadhead, 2017), coal (Hoffman, 2017), potash, and other commodities (McLemore and Austin, 2017). Metallic mineral deposits formed during Paleozoic to Mesozoic time in New Mexico are shown in Figure 12.

Sedimentary-Iron Deposits

Sedimentary-iron deposits are found in a few localities in New Mexico (Fig. 12), with the largest deposits in the Caballo Mountains. Oölitic hematite is abundant in two zones in sandstones belonging to the Cambrian–Ordovician Bliss Formation on the western slopes of the Caballo Mountains. Hematite was mined from the Oölite, Little Helen, and Ida Belle (also known as the Sharpshooter and Sierrite claims) mines by the Sierrite Mineral Corp. from 1937 to 1939 for use in pigment (Kelley, 1949). The Bliss Formation is 138 ft thick at the mines and consists predominantly of limestone with thin interbeds of sandstone and conglomerate. The lower mineralized bed is 16 ft above the unconformity with the Proterozoic granite, assays 24% Fe, and is 1.5–6 ft thick; the upper, main mineralized bed is 4 ft above the lower ore bed, assays 39.2% Fe, and is 4–7 ft thick (Kelley, 1949; Harrer and Kelly, 1963). The sedimentary iron deposits contain oölitic hematite that is associated with quartz, calcite, and glauconite. These iron deposits are not economic at present because they are thin (maximum thickness of 12 ft), low grade (<40% Fe), and contain high concentrations of phosphorus and silica.

Sedimentary-Copper Deposits

Stratabound sedimentary-copper deposits containing copper, silver, and locally lead, zinc, uranium, vanadium, and molybdenum occur throughout New Mexico (Fig. 12). These deposits have also been called *red-bed* or *sandstone copper* deposits by previous workers (Soulé, 1956; Phillips, 1960; Cox and Singer, 1986). These deposits typically occur in bleached gray, pink, green, or tan sandstones, siltstones, shales, and limestones within or marginal to typical thick red-bed sequences. The red, brown, purple, or yellow sedimentary host rocks were deposited in fluvial, deltaic or marginal-marine environments of Pennsylvanian, Permian, or Triassic age. The majority of sedimentary-copper deposits in New Mexico occur at or near the base of individual sedimentary layers within these sediments; some deposits such as some in the Zuni Mountains (DIS017) and Nacimiento (DIS176) districts (Figs. 12, 13), are in sedimentary rocks that unconformably overlie mineralized Proterozoic granitic rocks (McLemore, 2013).

The mineralized bodies typically occur as lenses or blankets of disseminated and/or fracture coatings of copper minerals, predominantly chalcopyrite, chalcocite, digenite, malachite, and azurite with local uranium minerals, galena, sphalerite, and barite. Ore minerals in these sedimentary-copper deposits are typically associated with organic debris and other carbonaceous material. Local sedimentary features such as bedding, crossbedding, paleochannels, and intraformational slumping also appear to control mineralization. Local structures in some areas are also

important mineralization controls, such as anticlinal folds in the Tecolote district (DIS166) and a shallow synclinal fold or structural depression at the Stauber deposit (NMGU0013) in the Pastura district (DIS069). The deposits in New Mexico vary in thickness from 3–60 ft and are as much as several thousand feet long. Some deposits contain up to 40–50 % Cu in local lenses. Silver averages approximately 0.5 oz/short ton (17 ppm) and typically increases with growing copper concentrations. Gold is rare in these deposits. Some deposits in the Sacramento district (DIS131) are predominantly lead bearing with subordinate copper and silver. Other deposits,

such as some in the Tularosa (DIS133) and Sabinoso (DIS165) districts, are predominantly uranium and vanadium bearing.

Copper and other metals were probably transported in low-temperature brine solutions through permeable sediments, along bedding planes and faults shortly after burial. Replacement textures and diagenetic features of the organic material indicate mineralization occurred during or after diagenesis. Oxidizing waters could have leached copper and other metals from at least three sources; 1) Proterozoic rocks enriched in these metals, 2) Proterozoic base-metal deposits, and 3) clay minerals and detrital grains
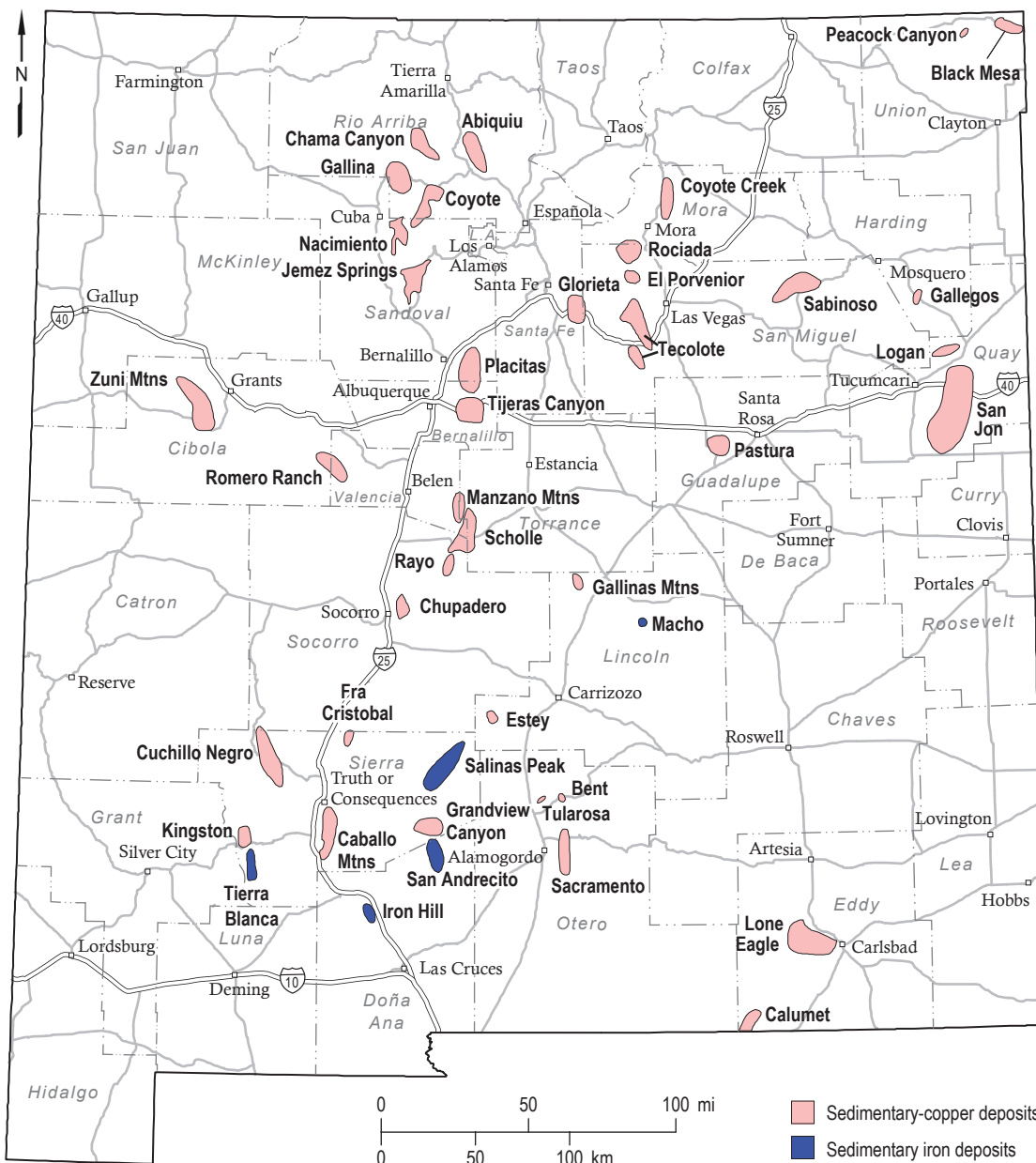
Figure 12. Metallic mineral deposits formed during Paleozoic to Mesozoic time in New Mexico.
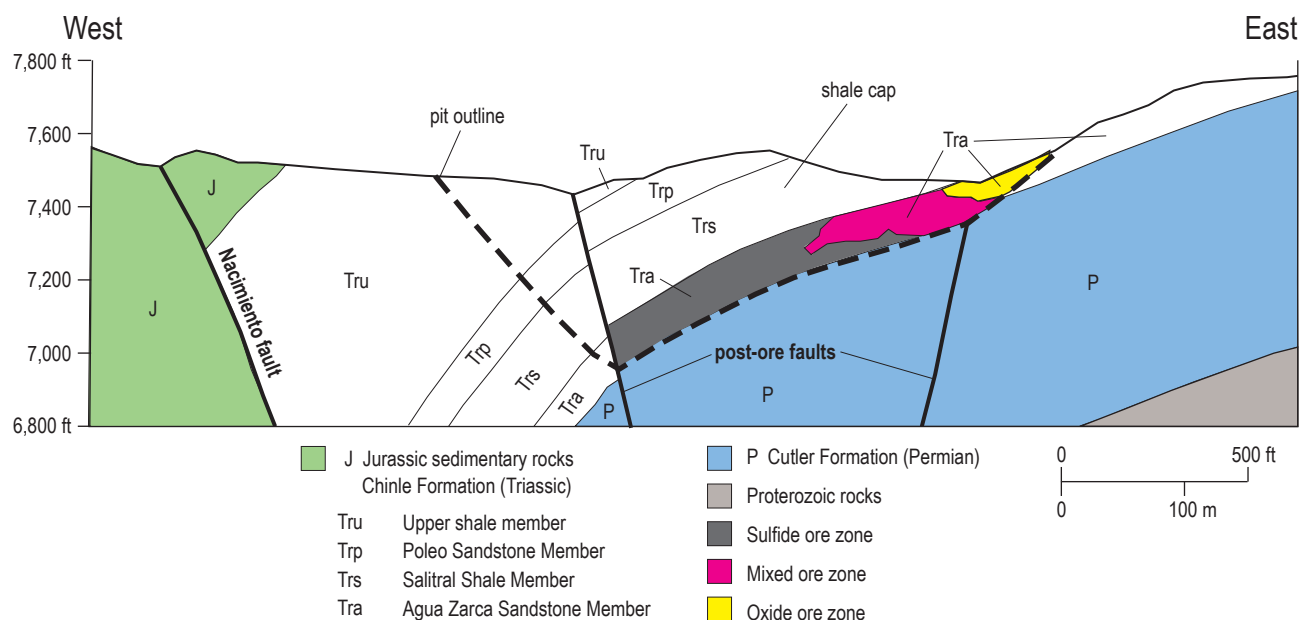
Figure 13. Cross section through Nacimiento open pit mine (NMSA0064), Nacimiento district, exposing a sedimentary-copper deposit (modified from Talbot, 1974).

within the red-bed sequences (La Point, 1976, 1979, 1989; Brown, 1984). Sources for chloride and carbonate needed to form soluble cuprous-chloride or cuprous-carbonate and other metal complexes (Rose, 1976) occur in older Paleozoic evaporite and carbonate sequences. Transport of metal-bearing waters occurred laterally through the aquifers from Proterozoic highlands or, in some cases, by circulating, ascending fluids (Brown, 1984). Geologic, mineralogic, and isotopic studies of similar deposits elsewhere in the United States suggest that these waters are in approximate chemical equilibrium with quartz, feldspar, hematite, and mica at temperatures less than 75°C (Rose, 1976). Precipitation occurred at favorable oxidation-reduction interfaces in the presence of organic material or H_2S-rich waters. Geologic membrane processes have been proposed as a possible concentration mechanism in these deposits, but the role of this process in deposition is still a matter of debate (Lueth and Whitworth, 2001; 2009). Subsequent geologic processes, such as groundwater movement and dissolution, igneous intrusions (such as at Sacramento), and/or structural events could have modified, altered, or even destroyed some deposits (La Point, 1979).

Most sedimentary-copper deposits are low grade, low tonnage, and far from existing copper mills for current development for copper. They are generally low in silica and are not suitable as silica flux material. However, an increase in copper and silver prices has renewed interest in some of the larger deposits.

Historic reserves are reported for the Nacimiento mine (NMSA0064) amounting to 5.4 million metric tons of ore at a grade of 0.56% copper and an additional 11.8 million metric tons of ore at a grade of 0.48% copper as of May 2, 1980 (NMBGMR unpubl. data). An in situ leaching project was proposed for this deposit, but poor recovery, low permeability, and environmental concerns have hampered this project.

Beach-Placer Sandstone Deposits

Heavy mineral, beach-placer sandstone deposits (thorium, REE, zirconium, titanium, uranium, iron, niobium, tantalium) are accumulations of heavy, resistant minerals (i.e., high specific gravity) that form on upper regions of beaches or in long-shore bars in a marginal-marine environment (Fig. 14). They form by mechanical concentration (i.e., settling) of heavy minerals by the action of waves, currents, and winds (Bryan et al., 2007; Van Gosen et al., 2014). Modern examples are found along the Atlantic Coast, United States (Koch, 1986; Carpenter and Carpenter, 1991), southeastern Australia (Roy, 1999), and Andhra Pradesh, India. Many beach-placer sandstone deposits contain high concentrations of thorium, REE, zirconium, titanium, uranium, niobium, tantalum, and iron. Detrital heavy minerals comprise approximately 50–60 % of the sandstones and typically consist of titanite, zircon, magnetite, ilmenite, monazite, apatite,
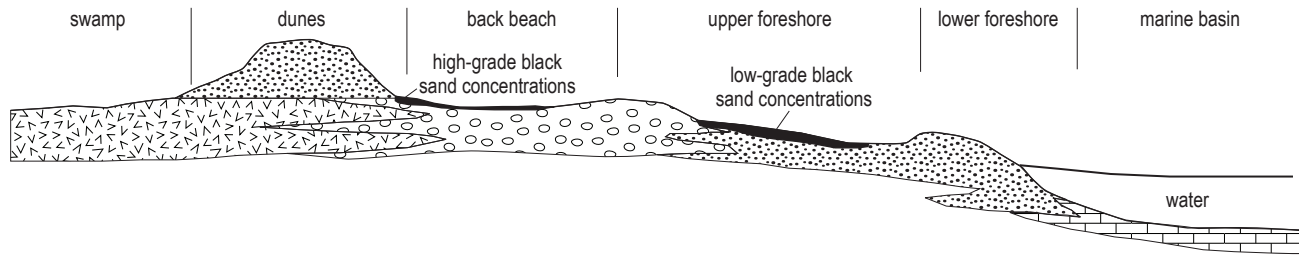
Figure 14. Idealized cross-section of formation of beach-placer sandstone deposits (Houston and Murphy, 1970, 1977). Most of the New Mexico deposits are in the upper foreshore zone, but small high-grade deposits in the back beach are locally found.

and allanite, among others. Although beach-placer sandstone deposits are found in strata of all ages throughout the world, the deposits in the San Juan Basin in New Mexico (Fig. 15) are restricted to Late Cretaceous rocks belonging to the Gallup, Dalton, Point Lookout, and Pictured Cliffs Sandstones (Chenoweth, 1957; Houston and Murphy, 1970, 1977; McLemore, 2010a). The beach-placer sandstones are black, dark gray to olive-brown, resistant to erosion, and radioactive due to zircon, monazite, apatite, and thorium minerals. They rarely exceed several hundred feet long, tens of feet wide, and 3–5 ft thick (Fig. 16).

Anomalously high concentrations of titanium, iron, niobium, thorium, uranium, zirconium, scandium, yittrium, and REE are characteristic of these deposits. Collectively, the known deposits in the San Juan Basin (Fig. 15) contain an estimated resource of 4,751,200 short tons of material containing 12.8% TiO_2, 2.1% Zr, 15.5% Fe and less than 0.10% ThO_2 (Dow and Batty, 1961; McLemore, 2010a). Force (2000) estimated the titanium ore resource of the Sanostee deposit (NMSJ0088) at 700,000 metric tons and does not consider any other deposit in New Mexico to have any titanium resource potential because of small size and low grade. However, drilling of these deposits is needed to fully evaluate their potential, considering today's economic market. Drilling of the Apache Mesa deposit (NMRA0001) on the Jicarilla Apache Reservation occurred in August 2015 and results will appear in a future report.

Reliable estimates of tonnage are hampered by the fact that many of the heavy mineral lenses are discontinuous and the degree of alteration, which tends to increase the TiO_2 content, is highly variable among the deposits (Bingler, 1965). Many of these elements, especially titanium and REE, including yttrium and scandium, are increasingly becoming more important as they are used in many of our electronic devices such as cell phones, computer monitors, televisions,

and wind turbines. It is unlikely that any of the heavy mineral, beach-placer sandstone deposits in the San Juan Basin will be mined in the near future because of several factors: small tonnage, low grades, high degree of cementation through lithification, high iron content, and distance to processing plants and markets. However, as the demand for some of these elements increases due to increased demand and short supplies, the dollar value per ton of ore may rise, enhancing deposit economics, especially if most of the deposits in the San Juan Basin could be developed at the same time.
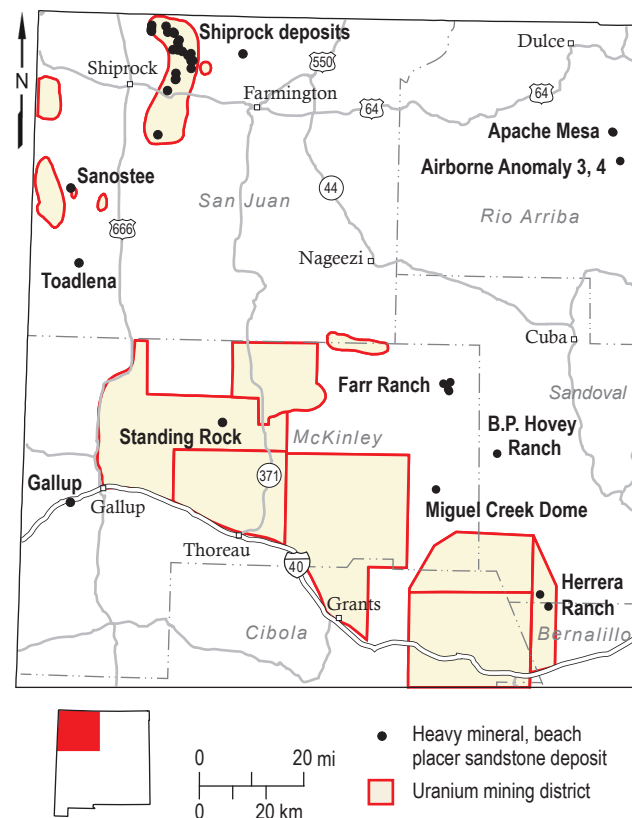
Figure 15. Location of Late Cretaceous heavy mineral, beach-placer sandstone deposits in the north-central San Juan Basin, New Mexico. More detailed location of the deposits are in McLemore (2010a).

Figure 16. Dark-brown beach placer sandstone capping ridge at Sanostee, San Juan County (NMSJ0088). *Photo by Virginia T. McLemore.*

Preliminary examination of the NURE (National Uranium Resource Evaluation) stream-sediment data reveals numerous single-element geochemical anomalies of zirconium, titanium, REE, scandium, and thorium scattered throughout the San Juan Basin; these areas need to be examined and sampled (McLemore, 2010a). Chenoweth (1957) identified three wells drilled for oil or gas with gamma anomalies in Cretaceous-age sandstones, suggesting that these could be buried heavy mineral, beach-placer sandstone deposits; detailed examination of other geophysical logs of wells could locate additional deposits. Chamberlin (2009) noted from NURE stream survey anomalies that monazite placer deposits may also be hosted in the Sierra Larga area within the Permian Glorieta Sandstone in Socorro County.

Rig drilling blast holes on a bench at the Tyrone Mine, 1999 (NMGR0084). *Photo by Virginia T. McLemore.*

V. LARAMIDE OROGENY MINERAL DEPOSITS

Since Late Cretaceous times, southwestern United States and northern Mexico have undergone almost constant tectonic and volcanic activity related to motions of subducted lithospheric plates. Laramide compressional deformation as a result of low-angle subduction of the Farallon plate from Late Cretaceous to early Tertiary time formed a series of northeast- to northwest-trending uplifts and broad shallow basins in southern New Mexico and Arizona (Seager et al., 1986; Drewes, 1991). Arc magmatism migrated eastward as subduction of the Farallon plate beneath North America continued (Coney and Reynolds, 1977; Dickinson, 1981), resulting in eruption of intermediate, calc-alkaline intrusive and extrusive rocks about 50–75 Ma, and formation of numerous Laramide porphyry copper, skarn, and polymetallic vein deposits in Arizona, New Mexico, and Mexico (Fig. 17). Most of the skarn and polymetallic vein deposits could be related to buried porphyry copper systems (McLemore, 2008a).

Replacement-Iron Deposits

Replacement-iron deposits are typically small and consist of hematite and magnetite as lenses or irregular bodies in tabular or pod-shaped deposits in limestone or dolomite and as veins filling fractures, faults, and along bedding planes, in limestone and dolomite. Calc-silicate minerals are rare. Most deposits in New Mexico are typically less than a few feet thick and less than several hundred feet long, but some ore shoots are reported to be larger. Most deposits in New Mexico are typically low grade, small, and uneconomic.

Porphyry Copper, Copper–Molybdenum (±Gold) Deposits

Porphyry copper and copper-molybdenum (±gold) deposits are large, low-grade (<0.8% copper) deposits that contain disseminated copper minerals, breccias, and stockwork veinlets of copper and molybdenum sulfides associated with porphyritic intrusions

(Schmitt, 1966; Lowell and Guilbert, 1970; Kesler, 1973; Lowell, 1974; Cox and Singer, 1986; Seedorff et al., 2005; Sillitoe, 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 0.6–3.7 mi of the surface, and are surrounded by crudely concentric zones of hydrothermal alteration (Lowell and Guilbert, 1970; Seedorff et al., 2005; Sillitoe, 2005). Hydrothermal solutions are released through these fractures and react with the host rocks, altering them in a characteristic, concentric zonation. The
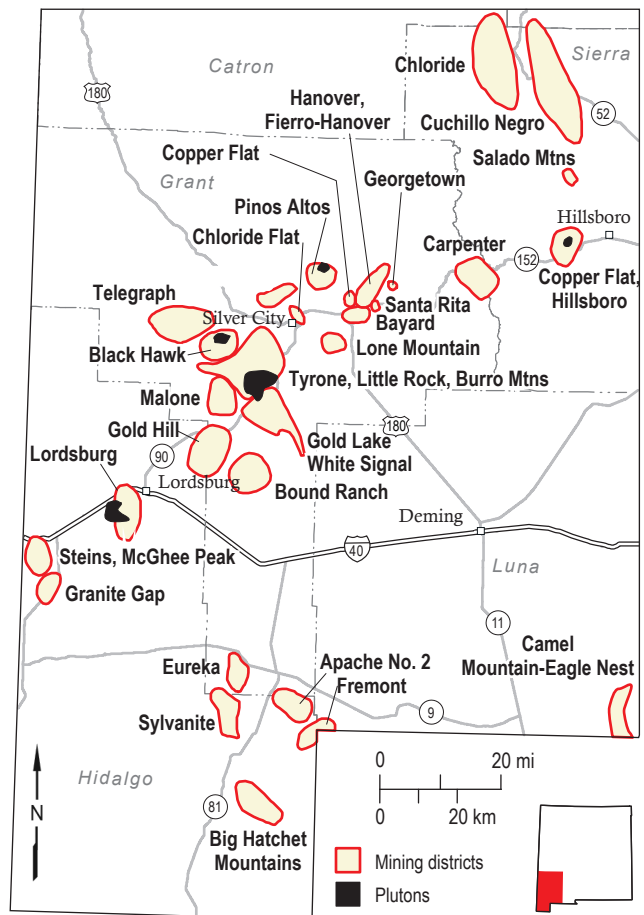
Figure 17. Districts with Laramide copper porphyry, polymetallic veins and skarn deposits (yellow) and plutons (black) in southwestern New Mexico (McLemore, 2008a).

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 activity can include numerous additional types of mineral assemblages that commonly overlap (Fig. 18; Seedorff et al., 2005). Other types of deposits are commonly found near porphyry copper deposits, including skarns, polymetallic veins, and carbonate-hosted deposits (Fig. 18). Low concentrations of silver and gold are present in most deposits and can be recovered as by-products by conventional milling techniques. Precious (gold, silver) and rare metals, including PGEs (McLemore et al., 1989), tellurium, indium, germanium, and gallium can be recovered from the anode slimes remaining after copper is refined. They occur as particles of native species and as solid solutions or exsolved species in sulfide minerals.

There are nine known Laramide porphyry copper deposits in New Mexico (Table 3; Fig. 19; McLemore, 2008a), although many other areas have potential for porphyry copper deposits, there are no reported reserves or production. The largest Laramide porphyry copper deposit in New Mexico is the
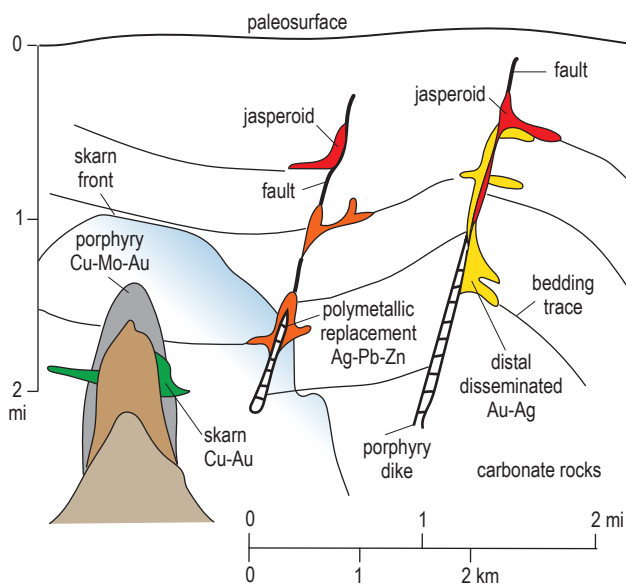
Figure 18. Simplified settings of porphyry copper and associated deposit types (modified from John, 2010). Distal disseminated Au-Ag deposits have not been found associated with porphyry copper deposits in New Mexico and are shown here as potential future exploration targets.

Chino mine (NMGR0029) in the Santa Rita district, where copper sulfides occur in the upper part of a highly fractured granodiorite and adjacent sedimentary rocks.

Igneous activity at Chino began about 60–59 Ma with the intrusion of dioritic to quartz diorite sills into Proterozoic basement, followed with intrusion of multiple stages of quartz-monzodiorite to granodiorite dikes and stocks with porphyritic textures (Rose and Baltosser, 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 (McLemore, 2008a). The Santa Rita stock represents an oxidizing magma enriched in sulfur (Audétat and Pettke, 2006). Most of the mineralization is predominantly chalcopyrite and molybdenite formed shortly after intrusion of the dikes and stock along the stock margins 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). Adjacent copper skarns are becoming increasingly more important economically.

The first mining of the deposit was by Native Americans prior to 1798. In 1798, an Apache Indian led Colonel Manuel Carrasco, a Spanish officer, to these copper deposits, and by 1804, copper was being mined at Santa Rita and transported 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 lbs (3,000 short tons) of copper per year. Mining at Santa Rita diminished after 1809 as a result of increasing costs, difficult transportation, Indian 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.

Production from the modern open pit began in 1910 and the original concentrator was commissioned in 1911 and replaced in 1982. A smelter was commissioned in 1939 at Hurley and was closed in 2005. The Chino mine has produced more than 9 billion lbs copper, 500,000 oz gold, and 5.36 million oz silver plus some molybdenum and iron ore (Table
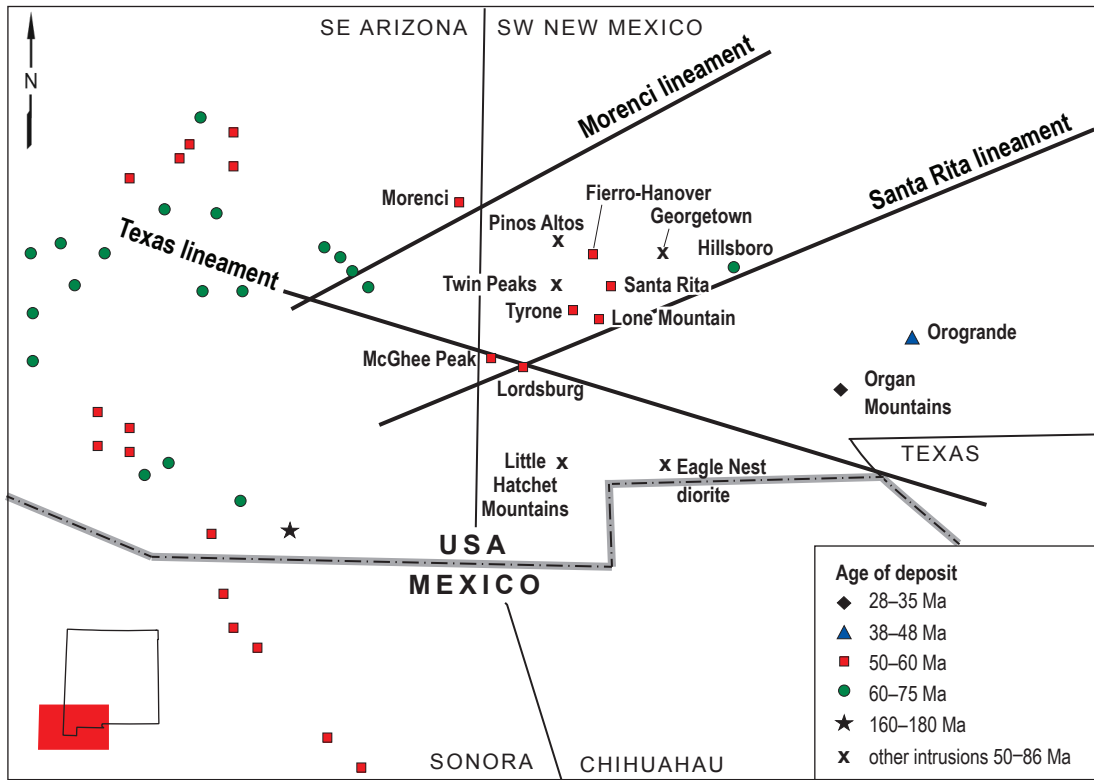
Figure 19. Laramide porphyry copper deposits in southwestern United States and northern Mexico. The Copper Flat porphyry copper deposit is in the Hillsboro district.

3; Long, 1995; McLemore, 2008a). Today, the Chino operation consists of open pits (Fig. 20), a 36,000 metric ton-per-day concentrator that produces copper and molybdenum concentrates, and a 150 million lb/yr SX/EW (solvent extraction/electrowinnowing) plant that produces copper cathode from solution generated by ROM (run of mine) leaching. Published proven and probable leachable reserves in 2016 at Chino are 91 million metric tons of 0.28% copper; estimated proven and probable millable reserves are 135 million metric tons of 0.59% copper, 0.04 grams/ metric ton gold, 0.50 g/metric ton silver, and 0.01% molybdenum (Freeport-McMoRan Copper and Gold Inc., 2017). Accordingly, the Chino mine is the largest copper and gold district in New Mexico and ranked 9th in New Mexico in silver production.

The Tyrone porphyry copper deposit (NMGR0084) in the Burro Mountains district occurs within a porphyritic quartz monzonite to monzonite to granodiorite laccolith and adjacent Proterozoic rocks (Kolessar, 1970, 1982). The ore contains predominantly chalcopyrite and pyrite with minor amounts of gold and silver, especially in the enriched zones. The age of the Tyrone stock is 54.5 Ma (McLemore, 2008a). 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). Native Americans mined turquoise from the area prior to 1860. Phelps Dodge Corporation (now Freeport-McMoRan) acquired the mine in 1909 and began underground mining in 1916 through1921. Only minor production occurred until open pit mining started in 1967. Approximately 300 million short tons of ore grading 0.81% copper were processed by the concentrator at Tyrone from 1969 to 1992. Approximately 425 million short tons of ore grading

Figure 20. Chino mine. *Photo by S. Timmons.*

Table 3. Laramide porphyry copper deposits in southwestern New Mexico (McLemore, 2008a). References for age determinations are in McLemore (2008a).

Mine identification	Porphyry deposits	District	County	Latitude (decimal degrees)	Longitude (decimal degrees)	Year of discovery	Commodities	Estimated copper production (pounds)	Reported estimated reserves	Estimated metal endowment (production + reserves + resources)	References
NMGR0029	Chino**	Santa Rita	Grant	32.791667	108.06667	1909	Cu, Au, Ag, Mo	9,080,000,000	Estimated mill reserves (2016) of 135 million tons of 0.59% Cu, 0.04 g/t Au, 0.50 g/t Ag and 0.01% Mo and estimated leaching reserves of 91 million tons of 0.28% Cu*	11,398,000 tons Cu 197,900 tons Mo 1,047,600 oz Au 5,236,700 oz Ag	Leveille and Stegen (2012), Freeport-McMoRan Copper and Gold Inc. (2014)
NMGR0084	Tyrone	Burro Mountains	Grant	32.643889	108.36722	1903	Cu, Au, Ag, U, F	5,240,000,000	6 million tons leaching reserves of 0.50% Cu (2016)*	7,419,000 tons Cu 148,000 tons Mo 500,000 oz Au 5,360,000 million oz Ag	McDowell (1971), Hedlund (1985a), McLemore et al. (1996), Leveille and Stegen (2012), Freeport-McMoRan Copper and Gold Inc. (2014)
NMGR0033	Cobre	Fierro-Hanover	Grant	32.845	108.091667	1900s	Cu	Unknown	73 million tons leaching reserves of 0.30% Cu (2017)*	1,201,500 tons Cu	Leveille and Stegen (2012), Freeport-McMoRan Copper and Gold Inc. (2014)
NMGR0160	Little Rock	Burro Mountains	Grant	32.646698	108.40675	1970s	Cu, Au, Ag	Unknown	Unknown (included with Tyrone)		P.B. Hubbard (written report, 1983)
NMSI0610	Copper Flat**	Hillsboro	Sierra	32.806667	108.12222	1970s	Au, Ag, Pb, Zn, Cu, V	7 million	113 million short tons at 0.39% Cu, 0.009% Mo, 0.096 g/t Au, and 1.93 g/t Ag*	595,000 tons Cu 16,800 tons Mo 404,700 oz Au 10,647,700 oz Ag	Hedlund (1985b), McLemore et al. (1999b, 2000b); Geedipally et al. (2012), Leveille and Stegen (2012)
NMGR0478	Gold Lake	White Signal	Grant	32.55270	108.32957	1970s	Cu, Au, Ag, Bi, U, Mo	None	unknown/ exploration underway		McLemore (2008a)
NMGR0208	Hanover Mountain	Fierro-Hanover	Grant	32.833	108.083	1970s	Au, Ag, Cu, Zn, Pb, Fe, F, Mn, Bi	None	80 million tons 0.38% Cu (historic reserves)*		McLemore et al. (1996)
NMGR0409	Lone Mountain**	Lone Mountain	Grant	32.718056	108.17667	1970s	Cu, Au, Ag	None	unknown/ project on hold		P.B. Hubbard (written report, 1983)
NMHI0327	Steins	McGhee Peak	Hidalgo	32.186111	109.020833	1970s	Au, Ag, Pb, Cu, Zn	None	unknown/ project on hold		McLemore et al. (1996)

* Skarn or carbonate-hosted replacement deposits also present. Mine identification number is from the New Mexico Mines Database (McLemore et al., 2005a, b). Reserves for Copper Flat are 43-101 reserves (reserves, location and history; http://themacre-sourcesgroup.com/copper_flat_mine, accessed 1/29/16). ** Reported reserves are recoverable copper reserves as reported by the company (most are historic resources and not all are 43-101 compliant, see introduction).

0.35% copper have been leached. Silver and gold were recovered from 1903 to 1992 and the Tyrone mine has produced more than 5.2 billion lbs copper, 500,000 oz gold, and 5.36 million oz silver, plus some molybdenum and iron ore (Table 3; Long, 1995; McLemore et al., 1996; McLemore, 2008a). Gold and silver were recovered only from the concentrate. Today, the copper processing facilities consist of a SX/EW operation (commissioned in 1984) with a maximum capacity of approximately 100 million lbs of copper cathodes per year. In 2016, proven leaching reserves (recoverable copper) are estimated as 6 million short tons of 0.50% copper (Freeport-McMoRan Copper and Gold Inc., 2017). These reserves are expected to be produced through 2018. The Tyrone mine is among the lowest grade porphyry copper ore deposits in the world.

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 short tons of leach material. Freeport McMoRan began mining ore and leaching copper in 2010 as part of the Tyrone operation.

Supergene-enriched copper zones are found near the Cobre (Continental, NMGR0033) skarn deposits, near 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 50–500 ft thick. 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 Cobre (Continental) pit was dated more precisely as 57.55 Ma (^{40}Ar/^{39}Ar, McLemore et al., 1995). Leaching reserves at Cobre are estimated as 73 million short tons of 0.30% copper (Freeport-McMoRan Copper and Gold Inc., 2017). Drilling in the 1970s and 1990s delineated 80 million short tons of geologic resources of 0.38% copper at Hanover Mountain, northeast of the Cobre mine (Hillesland et al., 1994, 1995). Iron skarns cut by copper skarns formed adjacent to the granodiorite. The deposit at Hermosa Mountain, southwest of the Cobre mine, has not been characterized.

The Copper Flat deposit (NMGR0336) in the Hillsboro district consists of copper, gold, silver, and molybdenum disseminated in a quartz-monzonite stock and in polymetallic quartz veins radiating from the stock (Fig. 21; Kuellmer, 1955; Dunn, 1982, 1984; Hedlund, 1985b; McLemore et al., 1999b, 2000b; McLemore, 2008a; M3 Engineering and Technology

Corporation, 2012; Geedipally et al., 2012). Unlike the Santa Rita and Tyrone deposits, there is no significant supergene enrichment zone at Copper Flat, because ongoing uplift of the Black Range resulted in an erosional rate that exceeded that of geochemical weathering and supergene development. The Copper Flat porphyry is dated at 75 Ma (McLemore et al., 1999b, 2000b). Approximately 7 million lbs of copper were produced in 1982 prior to closure of the mine, with proven and probable reserves of 113 million short tons at 0.39% copper, 0.009% molybdenum, 0.096 g/t gold, and 1.93 g/t silver, and measured and indicated resources of 305 million short tons of ore at a reported grade of 0.23% copper, 0.007% molybdenum, 0.078 g/t gold and 1.55 g/t silver (location and history; http://themacresourcesgroup.com/copper_flat_mine, accessed 5/1/17). New Mexico Copper Corporation (owned by Themac Resources) is in the process of permitting for re-opening the mine.
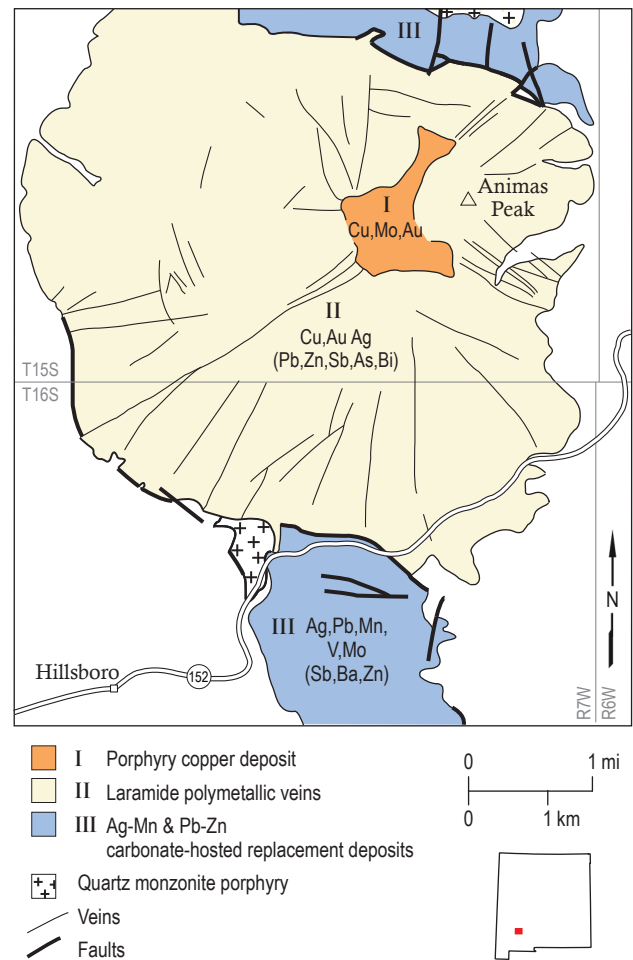

Figure 21. Metal zoning surrounding the Copper Flat porphyry copper deposit in the Hillsboro district (McLemore et al., 1999b).

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 100 to 3,000 ft (51.5–50.6 Ma, P.B. Hubbard and P.G. Dunn, unpubl. report, 1983; 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 oz/short ton gold, and 1.0 to 3.0 oz/short ton silver. Lone Mountain Mining Co. explored the property in the late 1990s and Copper One (USA), Inc. received a permit for additional exploration in 2013. Cornerstone Metals Inc. acquired the property in August 2013. The project is currently on hold.

The Gold Lake copper-molybdenum (±gold) porphyry deposit (NMGR0478) is in the White Signal district, Grant County, where 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 2,300 ppm) (Klemmick, 2006). Six drill holes, drilled in 2008, confirm the presence of porphyry copper mineralization. Additional drilling is needed to confirm and delineate any economic potential in the White Signal district.

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 0.21 ppm gold from the deposit (Lordsburg (Cu-Au); http://www.entree-gold.com/projects/lordsburg-property/default.aspx, accessed 1/29/16). Andesites in the Lordsburg area have been dated at 67 Ma and the granodiorite and associated rocks have been dated at 57.3–58.8 Ma (McLemore et al., 2000d). Additional drilling is needed to confirm and delineate any economic potential at Lordsburg.

Other areas in New Mexico have potential for porphyry copper deposits, especially where Laramide polymetallic vein and skarn deposits are found (Fig. 17). Exploration has occurred north of the Lordsburg district, in the Mimbres Mountains and Eureka districts, but the results are unknown. The Lordsburg and Eureka districts are known for Laramide vein deposits as well as alteration suggestive of porphyry copper mineralization (McLemore and Elston, 2000).

Laramide Copper and Lead-Zinc Skarn Deposits

Laramide skarn deposits in New Mexico are contact-metasomatic deposits that formed in Paleozoic limestone and dolomitic limestone adjacent to calc-alkaline intrusive rocks emplaced during the Laramide compressional event (Figs. 17, 18; McLemore and Lueth, 1996). Three types of Laramide skarns occur in southern New Mexico: copper skarns, which are typically associated with porphyry copper deposits (Einaudi et al., 1981; Einaudi, 1982; Lueth, 1984, 1996), lead-zinc skarns, which are proximal and vein-type deposits (Meinert, 1987; Turner and Bowman, 1993; Lueth, 1996), and iron skarns (Lueth, 1984, 1996). Except for the iron type, these skarns are either copper- or zinc-rich with lead and silver produced as by-products. The largest lead-zinc skarns are in the Fierro-Hanover (DIS054) and Piños Altos (DIS062) districts. Laramide iron skarns are found in the Fierro-Hanover and Santa Rita (DIS065) districts.

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 (Figs. 18, 22). Some lead-zinc skarns occur along faults distal from intrusive rocks (e.g. Groundhog and Southwestern deposits at Piños Altos, Eureka). The Laramide skarns in New Mexico are formed from variable composition, but from higher temperature and higher salinity fluids as compared to carbonate-hosted lead-zinc replacement deposits in New Mexico. Most deposits probably formed from mixing of meteoric and magmatic fluids (Abramson, 1981; Ahmad and Rose, 1980; Lueth, 1984; Turner and Bowman, 1993; McLemore and Lueth, 1996). District zoning is common with copper adjacent to the intrusive rocks grading outwards to zinc>lead, lead>zinc, lead>silver, and locally, lead-silver-manganese (Fig. 22; Meinert, 1987; McLemore and Lueth, 1996).

The potential for discovering additional skarns in these districts is excellent. Cobre Mining Company reports reserves at the Continental mine (NMGR0373) in the Fierro-Hanover district of over
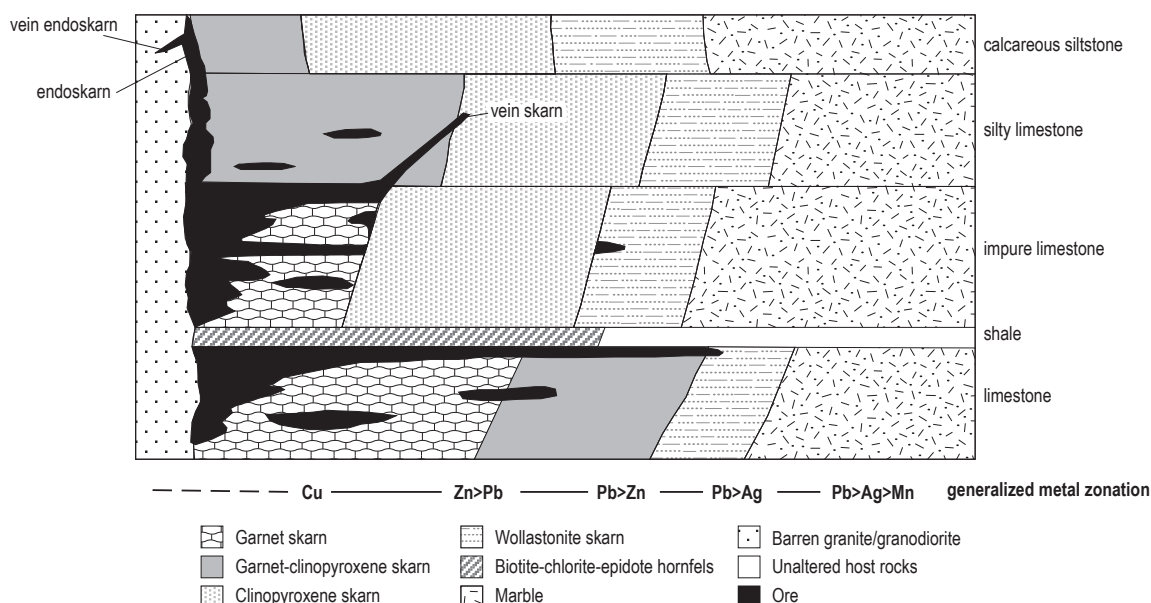
Figure 22. Diagrammatic sketch showing mineralization and alteration patterns in Laramide skarns in southern New Mexico (modified from Lueth, 1984, 1996; McLemore and Lueth, 1996). Garnet forms nearest the stock in the limestone of the Lake Valley Limestone and Oswaldo Formations. Garnet-clinopyroxene forms adjacent to the stock in the argillaceous carbonate rocks. Hornfels typically forms at the parting shale in the Oswaldo Formation, 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.

10 million short tons of 0.92% copper (Hillesland et al., 1994, 1995). Significant copper skarns are also mined at the Chino mine in the Santa Rita district (Nielson, 1968, 1970; McLemore, 1996c).

Laramide Polymetallic Vein Deposits

Laramide polymetallic vein deposits of probable Laramide age (Late Cretaceous-early Eocene, 75–40 Ma) occur in a number of districts (Fig. 17; McLemore, 2008a). These deposits exhibit different textures and mineralogies, but are similar in form and age. Laramide skarns are locally important in some districts that also host Laramide polymetallic vein deposits. Lindgren (1933) classified these veins in New Mexico as polymetallic veins, and Cox and Singer (1986) classified them as mesothermal veins. The most important districts in New Mexico are Hillsboro (Fig. 21, DIS197), Piños Altos (DIS062), Central (DIS043), and Lordsburg (DIS082).

Vein deposits at Hillsboro provide a good example of New Mexican Laramide vein deposits and other associated deposits (Fig. 21). Polymetallic veins along latite dikes propagate radially outward from the Copper Flat porphyry copper deposits. Distal carbonate-hosted replacement deposits (silver, lead, manganese,

vanadium, molybdenum, and zinc) are found in the southern and northern parts of the Hillsboro district (Fig. 21). Geologic, geochronological, and geochemical evidence suggests that these mineral deposits were formed by large, convective, magmatic-hydrothermal systems related to the Copper Flat volcanic/intrusive complex (McLemore et al., 1999b, 2000b).

Although Proterozoic rocks are common host rocks in many districts, there are Cretaceous volcanic and plutonic host rocks in some districts (e.g., Lordsburg, Hillsboro). Paleozoic and Cretaceous sedimentary rocks host the veins in the Central district. Laramide veins were typically worked for both base and precious metals and locally contain uranium, tungsten, tellurium, and beryllium. Mineralogies 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.

The ores from some Laramide veins have potential for siliceous (silica-rich) flux used in copper smelters. Nearly two million short tons of mineralized siliceous flux have been shipped from veins in the Lordsburg district. Past production indicates that Laramide vein deposits are small to medium tonnage.

"Old Abe" headframe at the White Oaks District, 1990s (NMLI0343). *Photo by Virginia T. McLemore.*

VI. "TRANSITION" STAGE MINERAL DEPOSITS

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 (McDowell and Claubaugh, 1979; McIntosh et al., 1992a, b; McIntosh and Bryan, 2000). Within southwestern New Mexico and Arizona, silicic caldera volcanism is informally divided into the Mogollon-Datil volcanic field to the north and the Boot Heel volcanic field to the south. No formal dividing line between the two volcanic fields has been proposed, but most published maps suggest a boundary near Interstate 10. Approximately 15 calderas have been identified in the Mogollon-Datil field and 6–10 in the Boot Heel field (Fig. 1; McIntosh and Bryan, 2000), and regional ignimbrites (ash flow tuffs) linked to most of the calderas have been recognized (Elston, 1984; Rattè at al., 1984; McIntosh et al., 1992a, b; McIntosh and Bryan, 2000). Caldera volcanism in these two volcanic fields occurred in two temporally distinct pulses: 36–32 Ma, and 30–24 Ma. Most of the metal deposits in New Mexico appear to be associated with magmatic and/or hydrothermal activity during this time, although in many cases precise ages of the mineral deposits are lacking and only estimates are determined. In 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. Associated deposits are called Great Plains Margin (GPM) deposits in this report.

Porphyry Molybdenum (±Tungsten) Deposits

Porphyry molybdenum (±tungsten) deposits are large, low-grade deposits that contain disseminated and stockwork veinlets of molybdenum sulfides with little if any copper and are associated with porphyritic intrusions. They occur in three areas in New Mexico (Fig. 23): Questa (NMTA0017, Fig. 24), Rialto stock (NMLI0121) in the Nogal district, and the Victorio Mountains (NMLU0468, Fig. 25), with the largest deposits at Questa in Taos County (Meyer, 1990). R and S Molybdenum Mining Company began production at Questa in 1918, reorganized as the Molybdenum Corporation of America in 1921, eventually becoming Molycorp, Inc. High-grade vein ore was mined underground from 1919 to 1958, with a production of 0.375 million short tons of >4% MoS_2 (McLemore, 2009). Exploration continued from 1953 to 1964, when open-pit mining commenced. The current mill was built in 1964, and the company mined approximately 81 million short tons of ore from their open pit at a grade of 0.191% MoS_2 between 1965 until 1982. The Questa mine was shut down from 1986 to 1989 and again in 1992 to 1995 before being purchased by Chevron Mining Inc. in 2005. Production from the Goat Hill orebody from 1983 to 2000 amounted to 21.11 million short tons of 0.31% MoS_2. Recent production since 2001 was from the adjacent D-orebody with a grade of 0.338% MoS_2. Chevron Mining Inc. closed the Questa mine in June 2014. The Questa deposits are ~24.2 Ma and consist of thin veinlets, fracture coatings, and disseminations in granitic host rock. Ore minerals include molybdenite, powellite, scheelite, beryl, helvite, bismuthinite, and wolframite (Ross et al., 2002, McLemore, 2009; Rowe, 2012). The deposits are similar in form to the porphyry copper deposits described in the Laramide (above), but are younger (35-25 Ma) and exhibit only minor supergene alteration. Additional porphyry molybdenum deposits are found in the Questa-Red River area (McLemore, 2009).

The porphyry molybdenum deposit in the Victorio district was found by drilling a geophysical anomaly and has not been mined (McLemore et al., 2000c). Measured and indicated resources are estimated as 39,400,550 short tons of 0.11% molybdenum and 0.11% tungsten ($35/ton cutoff; http://galwaymetalsinc.com/s/Victorio.asp, accessed 10/16/14). Past metals production was from

surrounding carbonate-hosted lead-zinc replacement and tungsten-beryllium-molybdenum skarn/vein/tactite deposits (Fig. 25; McLemore et al., 2000c).

Carbonate-Hosted Tungsten-Beryllium Replacement and Skarn (Molybdenum-Tungsten-Beryllium, Iron-Beryllium, Iron-Manganese) Deposits

Molybdenum-tungsten-beryllium contact metasomatic deposits occur as small veins and replacement

lenses as well as poorly developed skarns within limestones and dolostones in the vicinity of granitic or rhyolitic intrusions, such as in the Victorio district (Fig. 25). Ore minerals include helvite, wolframite, scheelite-powellite solid solution, molybdenite, galena, sphalerite, and beryl in a gangue of pyrite, quartz, calcite, and iron oxides, with local grossular, tremolite, pyroxene, idocrase, and phlogopite (Warner et al., 1959; McLemore et al., 2000c). These deposits are most similar to copper and lead-zinc skarn deposits found at intrusive contacts with gross features similar to those deposits described in
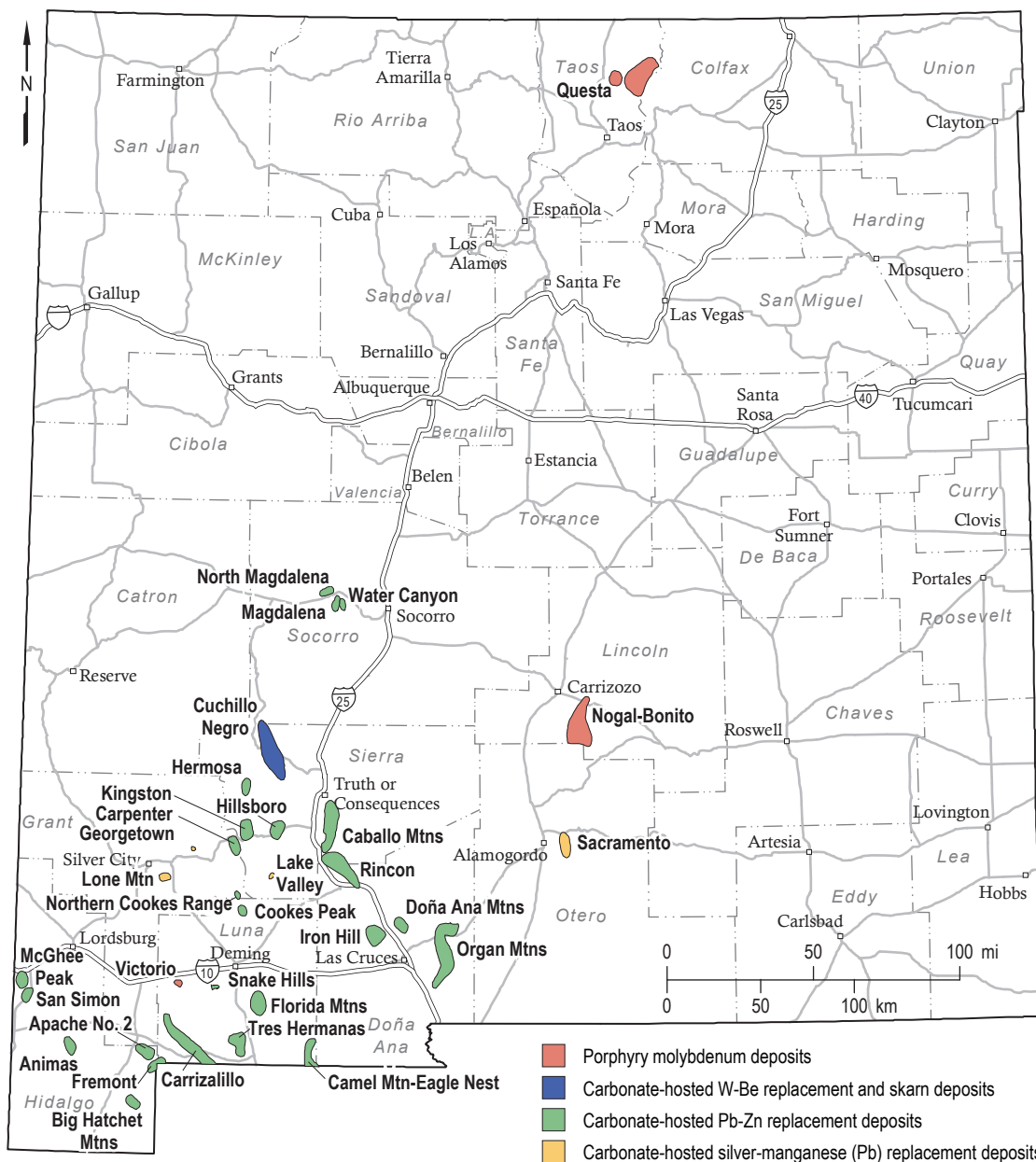
Figure 23. Porphyry molybdenum, carbonate-hosted W-Be replacement and skarn and carbonate-hosted lead-zinc replacement deposits in New Mexico.

the Laramide. The most important deposits are in the Victorio district (McLemore et al., 2000c) and at Iron Mountain in the Cuchillo Negro district (DIS192; Fig. 23; Jahns, 1944).

Carbonate-Hosted Lead-Zinc (Copper, Silver) Replacement Deposits

Carbonate-hosted lead-zinc replacement deposits occur in Southwestern New Mexico (Fig. 23) and were emplaced over an apparently long time span,

approximately 50–20 Ma (McLemore and Lueth, 1996). The deposits include replacements in carbonate rocks with little or no calc-silicate minerals, minor skarns with calc-silicate minerals, and minor veins in carbonate rocks adjacent to intrusive rocks (Figs. 18, 25). They are typically lead-zinc dominant, with a by-product of copper, silver, and gold, consisting predominantly of galena and sphalerite with lesser amounts of chalcopyrite. Many deposits in New Mexico are oxidized near-surface and contain cerussite, anglesite, and smithsonite. Recognizable silver and gold minerals are rare. These oxidized zones
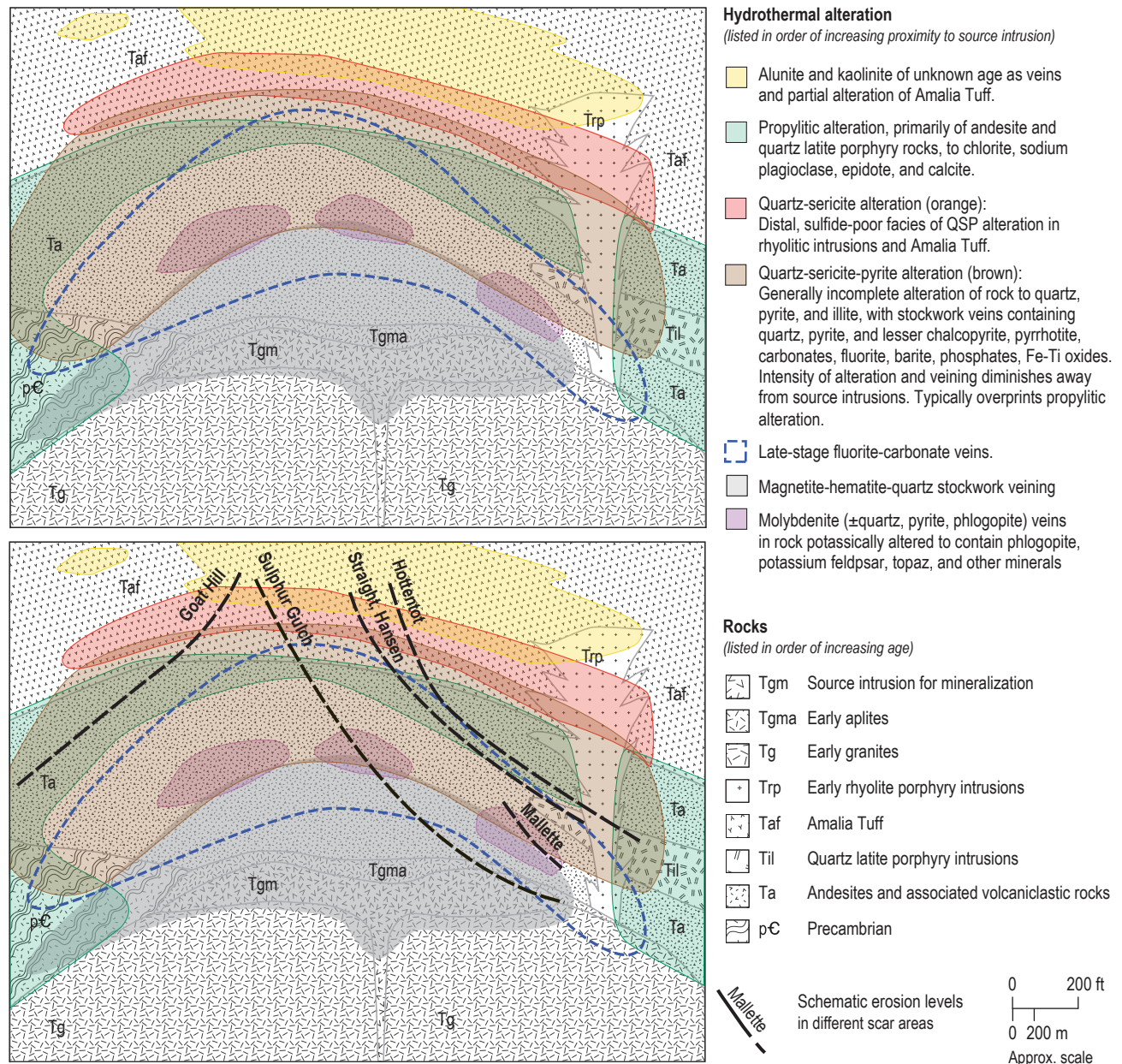
Figure 24. Cross section showing schematic spatial distributions of lithologies, alteration assemblages, and alteration scars in the Red River valley (taken from Ludington et al., 2005, which is modified from Martineau et al., 1977).
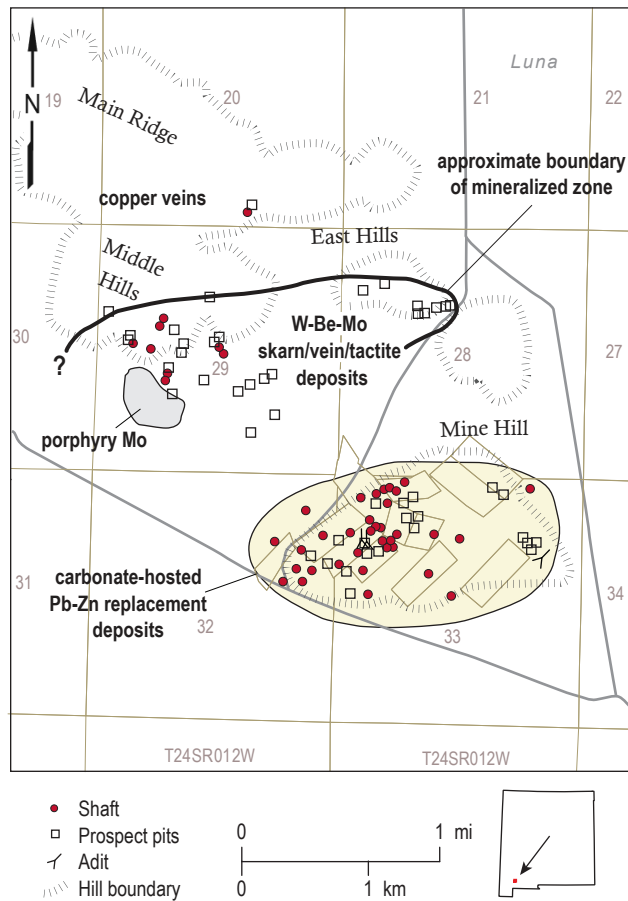
Figure 25. Map showing zoning of the mineral deposits in the Victorio district (modified from McLemore et al, 2000b). Zoning of the district consists of a porphyry-molybdenum central core grading outwards to tungsten-beryllium-molybdenum skarns and veins, to lead-zinc carbonate-hosted replacement deposits.

were typically the most productive in the past, with the most economically important deposits in the Magdalena (DIS221), Victorio, and Organ Mountains (DIS030) districts (McLemore, 2017). Cox and Singer (1986) classify these deposits as polymetallic, carbonate-hosted replacement deposits.

The host rocks are predominantly Paleozoic age, with few smaller deposits in Cretaceous carbonate rocks (i.e., Apache No. 2 district, DIS075). Many deposits are structurally controlled along fault, fracture, and contact zones. Replacement and local skarn bodies in the Magdalena district are localized along faults and fractures (Manrique and Campbell, 1987). The localization of some deposits also is stratigraphically controlled, similar to skarn deposits. Replacements and minor skarns commonly occur along the contact between Fusselman dolomite and overlying impermeable Percha Shale in some areas (e.g., Cooke's Peak; Organ Mountains). Ore

deposits at the Rickardite mine (NMDA0122) in the Organ Mountains district occurs along the crest of small anticlinal folds beneath the Percha Shale (Lueth, 1988).

The deposits vary in size and grade, ranging from a few thousands to a few hundreds of thousands of short tons and typically grading 5–30% combined lead and zinc; however, the amount of silver varies and gold is rare (McLemore and Lueth, 1996). Manganese, locally with silver replacements and epithermal veins occur peripheral to many carbonate-hosted lead-zinc replacement deposits (McLemore et al., 1996). Skarn-type mineralization in these replacement systems are poorly developed and rarely exhibits mineral zoning. Fluid-inclusion data from five deposits indicate temperatures of formation between 147–367°C and low to moderate salinities (<10 eq. wt. % NaCl) (McLemore and Lueth, 1996).

The association between carbonate-hosted lead-zinc replacement deposits and igneous activity is uncertain in many districts. In the Hillsboro district, carbonate-hosted replacement deposits (silver, lead, manganese, vanadium, molybdenum, and zinc) are found in the southern and northern parts of the district, distal to the porphyry copper deposit and along strike of the vein deposits (Fig. 21; McLemore et al., 1999b, 2000b). Tertiary-age intrusive rocks, ranging from 50–20 Ma, crop out in all districts except the Big Hatchet Mountains (DIS076). In many districts, polymetallic veins and/or disseminations of sulfides occur in the adjacent intrusive rocks.

Higher temperatures of formation and greater salinities are consistent with, but not conclusively required for the formation from magmatic fluids. Drilling in the Macho district (DIS201, Sierra County) encountered carbonate-hosted lead-zinc replacement deposits in the Fusselman dolomite 3,000 ft below the volcanic-epithermal veins (McLemore, 2012b; NMBGMR petroleum file data), suggesting that the Macho deposits may be distal volcanic-epithermal deposits. New Mexico carbonate-hosted lead-zinc replacement deposits are similar in form, mineralogy, texture, age, and temperature to the chimney, manto, and pod carbonate-hosted silver-lead-zinc (copper) deposits in Northern Mexico (Megaw et al., 1988). Geochemical, fluid inclusion, and stable-isotope data suggest that the Mexican deposits were formed by mixing of variable amounts of magmatic and meteoric fluids (Megaw et al., 1988) and a similar origin is reasonable for the New Mexico deposits. Future development of these deposits is dependent upon silver prices as well as zinc and lead production elsewhere in the world.

Carbonate-Hosted Silver (Manganese, Lead) Replacement Deposits

Carbonate-hosted silver (manganese and lead) replacement deposits occur in Southwestern New Mexico (Fig. 23) and were formed approximately 50–20 Ma. These deposits contain predominantly silver associated with manganese oxides, and include veins in carbonate rocks and replacements in carbonate rocks with little or no calc-silicate minerals. Over 20 million ounces of silver have been recovered from deposits of this type, but gold is rare (North and McLemore, 1986). Although silver and manganese are the predominant metals, lead is next in abundance (McLemore and Lueth, 1996). Manganese has been produced from the Chloride Flat, Lone Mountain, and Lake Valley districts (Farnham, 1961). Economically, the most important deposits are in the Lake Valley (Fig. 26) and Kingston districts (McLemore, 2017).

Paleozoic limestones and dolomitic limestones, typically the Fusselman dolomite and Lake Valley Formation, host most of these deposits in New Mexico. Stratigraphic relationships indicate that the Percha Shale commonly acted as an impermeable cap on mineralizing solutions in some districts, focusing fluid flow within the Fusselman dolomite (Lindgren et al., 1910; McLemore and Nutt, 2002). Jasperoids are common and likely acted similarly within these units. The deposits typically consist of native silver, silver halides, cerussite, vanadinite, wulfenite, and smithsonite, with variable amounts of argentite, acanthite, argentiferous galena, polybasite, pyrargyrite, stephanite, sphalerite, and chalcopyrite. Oxidation, either as late oxidizing hydrothermal fluids or as later supergene enrichment, has been important in concentrating

the silver in some deposits. At the Lake Valley district, the "Bridal Chamber" contained nearly pure chlorargyrite (Jicha, 1954).

The lack of geochemical data and age dates hinders our understanding of these deposits. They are distal from mid-Tertiary plutons and carbonate-hosted lead-zinc replacement deposits (Figs. 18, 22). Although several districts (e.g., Hermosa, Kingston, Tierra Blanca, Lake Valley, Georgetown, and Carpenter districts) surround the elongated, 35 Ma Emory caldera (Elston, 1994, fig. 8), stratigraphic evidence indicates that the pre-Emory caldera Sugarlump Tuff unconformably overlies jasperoids and carbonate-hosted deposits at Lake Valley, Kingston, and Hillsboro (Nutt et al., 1998; McLemore et al., 1999b, 2000b). The pre-Emory caldera Robledo Peak Formation unconformably overlies jasperoid and carbonate-hosted deposits in the Hermosa district (V.T. McLemore, unpubl. mapping). These deposits probably formed under conditions similar to the carbonate-hosted lead-zinc replacement deposits in New Mexico (i.e., low- to moderate-temperatures and salinities, probably with some mixing of magmatic and meteoric fluids). The presence of carbonate-hosted replacement deposits at Hillsboro and Lone Mountain suggests a local association with porphyry copper deposits.

The carbonate-hosted silver replacement deposits are good exploration targets for small mining companies because they tend to be high grade and small to medium size, and because limestone hosting ore are locally silicified, and they could be used as silica flux material. Metallurgical problems in recovering silver from the manganiferous ore has hampered production in the past, but new processing methods offer some hope for better recoveries in the future (Chase and Keane, 1985).
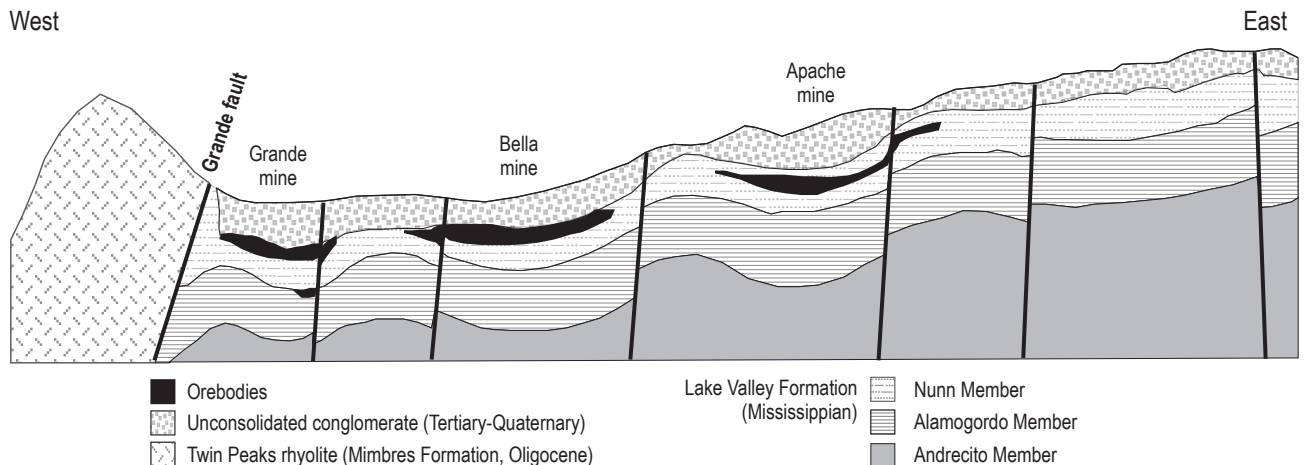

Figure 26. Schematic cross section of Grande, Bella, and Apache orebodies and the relationship to faulting in the Lake Valley district (modified from Keyes, 1908; McLemore and Nutt, 2002). The Percha Shale is eroded from this part of the district.

Great Plains Margin Deposits (Alkaline-Related)

Some of the state's largest gold deposits occur along a north-south belt roughly coinciding with the margin of the Great Plains physiographic province with the Basin and Range (Rio Grande rift) and Rocky Mountains physiographic provinces (Fig. 27). These deposits have similar characteristics that, when compared with their tectonic setting, define a class of mineral deposits referred to as Great Plains Margin (GPM) deposits by North and McLemore (1986, 1988) and McLemore (1996b, 2015a). Alternative classifications by other workers include Au-Ag-Te veins (Cox and Bagby, 1986; Bliss et al., 1992; Kelley, 1995; Kelley and Ludington, 2002; Kelley et al., 1998), alkalic-gold or alkaline-igneous related gold deposits (Fulp and Woodward, 1991; Thompson, 1991a, b; Bonham, 1988; Mutschler et al., 1985, 1991; Richards, 1995), porphyry gold deposits, gold-telluride deposits (Kelley et al., 1998), the North American Cordilleran belt of alkaline igneous rocks (Woolley, 1987; Mutschler et al., 1991) and Rocky Mountain gold province. However, not all of the

GPM deposits occur in alkaline igneous rocks and not all GPM deposits are associated with porphyritic rocks. The term Rocky Mountain gold province does not adequately encompass all of the deposits in New Mexico, some of which lie south of the Rocky Mountains in Trans-Pecos Texas and eastern Mexico, hence our use of the term GPM deposits.

Alkaline to sub-alkaline igneous rocks are found in all districts, but mineralization is locally associated with silica-saturated (monzonite) or oversaturated (quartz monzonite) rocks (Segerstrom and Ryberg, 1974; McLemore and North, 1987; McLemore and Phillips, 1991; Thompson, 1991a; McLemore and Zimmerer, 2009). Oligocene carbonatites are found only at Laughlin Peak, in the Chico Hills in Colfax County (McLemore, 2015b). Most deposits are associated with Oligocene intrusive rocks, 38–23 Ma (Fig. 28), except for the deposits in the Jicarilla Mountains and Orogrande districts, which are associated with Eocene intrusive rocks (39.45–45.6 Ma; McLemore et al., 2014b). The veins have high gold/base metal ratios and typically lower silver/gold ratios (McLemore, 1996b) than other silver/gold deposits in western New Mexico.

These deposits consist of seven associated deposit types: 1) polymetallic, epithermal to mesothermal veins, 2) breccia pipes and quartz veins, 3) porphyry copper-molybdenum-gold, 4) copper, lead-zinc, and/or gold skarns or carbonate-hosted replacement deposits, 5) iron skarns and replacement bodies, 6) placer gold and 7) thorium-REE-fluorite epithermal veins, breccias, and carbonatites (Table 2). Figure 29 illustrates these different settings, Table 4 summarizes the metals production, and Table 5 summarizes the potential resources. Placer gold deposits are described below in the Pliocene to modern deposits.

Vein deposits

Polymetallic veins are common to most GPM deposits in New Mexico and production has been locally significant (McLemore, 1996b). These veins are younger than the Laramide polymetallic veins (discussed above), and are similar to volcanic-epithermal veins (discussed below), except these veins are associated with alkaline igneous rocks. Native gold and a variety of silver minerals are found in veins in most districts along with chalcopyrite, galena, and sphalerite; tellurium may be important in some districts. Pyrite, calcite, quartz, iron and manganese oxides and clay minerals are common gangue minerals. Veins occur in both Tertiary intrusions and surrounding sedimentary rocks. Veins are typically less than 3 ft wide, have

Legend:
- Major alkaline-related gold deposits (Mutschler et al., 1991)
- Major alkaline ignrous complexes of Cenozoic age (Mutschler et al., 1991; Wooley, 1987)

Cripple Creek
Ortiz belt
Lincoln County porphyry belt
Trans-Pecos Texas-New Mexico belt

ROCKY MOUNTAINS
GREAT PLAINS
BASIN & RANGE

Approximate boundary between Rocky Mountains/Basin and Range and Great Plains
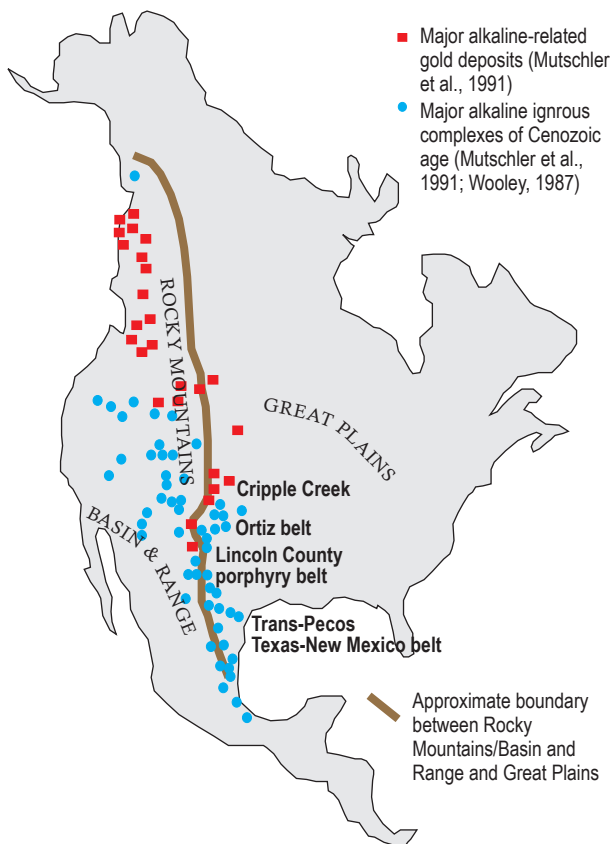
Figure 27. Great Plains Margin deposits associated with the North American Cordilleran belt of alkaline igneous rocks (Woolley, 1987; Mutschler et al., 1991; McLemore, 1996b).

Table 4. Reported and estimated base and precious metals production by district. — no reported production. * estimated, ** includes placer production. W withheld or not available. From U.S. Geological Survey (1902–1927), U.S. Bureau of Mines Mineral Yearbooks (1927–1990), Johnson (1972), McLemore (2001), and NMBMG unpublished information. District ID is from the New Mexico Mines Database (McLemore et al., 2005a, b).

District ID	County	District	Period of production	Ore (Short Tons)	Copper (Pounds)	Gold (Troy Ounces)	Silver (Troy Ounces)	Lead (Pounds)	Zinc (Pounds)	Iron (Short Tons)
DIS018	Colfax	Cimmaroncito*	1896–1940	—	W	100	1,000	—	—	
DIS019	Colfax	Elizabethtown-Baldy**	1904–1952	200,582	329,231	234,469	26,136	5,287	—	
DIS019	Colfax	Elizabethtown-Baldy**	1866–1968	—	—	471,400	—	—	—	
DIS030	Dona Ana	Organ Mountains*	1849–1961	—	4,636,000	11,500	820,000	25,000,000	1,700,000	
DIS092	Lincoln	Gallinas Mountains	1909–1955	5,367	385,418	7	23,723	1,797,838	17,344	11,540
DIS093	Lincoln	Jicarilla**	1912–1957	53,307	4,201,474	22,857	37,561	2,665	—	8,000
DIS095	Lincoln	Nogal-Bonito	1932–1955	1,626	100	1,858	2,501	7,750	—	
DIS095	Lincoln	Nogal-Bonito*	1868–1965	—		17,000	20,000			
DIS096	Lincoln	Schelerville		—	W	W	W	W	—	
DIS099	Lincoln	White Oaks**	1933–1951	2,679	450	1,432	1,044	12,200	—	
DIS099	Lincoln	White Oaks*	1850–1942	—	1,000	163,500	1,100			
DIS129	Otero	Orogrande**	1904–1966	133,819	5,695,066	15,849	45,477	157,661	—	222,948
DIS129	Otero	Orogrande*	1879–1966 (Fe until 2012)	—	5,700,000	16,500	50,000	158,000		456,765
DIS180	Santa Fe	Cerrillos	1907–1957	27,670	229,395	2,594	28,030	1,583,440	1,897,527	
DIS186	Santa Fe	New Placers	1904–1959	272,129	14,874,003	19,979	307,175	3,679,008	4,046,955	
DIS186	Santa Fe	New Placers*	1839–1968	—	17,000,000	117,000	308,000			
DIS187	Santa Fe	Old Placers	1907–1940	291	1,570	228	157	5,100	—	
DIS187	Santa Fe	Old Placers*	1828–1986	—	2,000	450,000	1,000	6,000		
	Santa Fe	Cunningham Hill	1979–1986	6,000,000		250,000				
DIS238	Taos	Red River	1907–1956	2,373	17,000	207	5,107	—	—	
DIS238	Taos	Red River*	1902-1956		17,000	365	8,051			

Table 5. Great Plains Margin deposits with reported, historic resources. Mine identification number is from the New Mexico Mines Database (McLemore et al., 2005a, b).

Mine identification	Name of deposit	Short tons of ore (million)	Au grade (ppm)	Ag grade (ppm)	Other grade (%)	Year of estimate	Reference
NMSF0116	Carache Canyon	11.8	1.9	-	-	1992	Santa Fe Gold Corporation, 8/15/11
NMSF0117	Lucas Canyon	7.6	1.39	-	0.22		Santa Fe Gold Corporation, 8/15/11
	Florencio	3	0.65	Cu			Maynard (2014)
NMLI0068	Vera Cruz	207,450 (assured)	4.5			1938	Ryberg (1991)
		435,000 (probable)	3.9				
		934,000 (possible)	3.9				
NMLI0207	Great Western	3,600,000	18.7	-	-	1992	Goff et al. (2011), McLemore et al. (2014a), NMBGMR file data
NMLI0271	Parsons	44,000	16.1	-	-	1991	Thompson (1991a, b), Goff et al. (2011), McLemore et al. (2014a)
NMLI0121	Rialto	30	-	-	0.05-0.18 Mo	1978	Hollister (1978), Goff et al. (2011), McLemore et al. (2014a)
NMLI0008	Bonito	1.7	1.6	16.1	-	1989	McLemore et al. (2014a)
Unknown	Orogrande	335,500	1.6	-	0.7 % Cu	1976	McLemore et al. (2014b)

steep dips, and occur along faults. Wall-rock alteration is typically weak propylitic to argillic (observations by the senior author; McLemore and Phillips, 1991; Phillips et al., 1991; Douglass and Campbell, 1995). Silver to gold ratios are typically low, below 5 (McLemore, 1996b; 2015a).

Gold-bearing breccia pipes and quartz veins

Many GPM polymetallic veins are associated with gold-bearing breccia deposits and quartz veins (McLemore, 1996b, 2015a). The gold-bearing breccia systems are typically exploration targets because of their potential for significant gold concentrations amenable to bulk mining and recovery techniques. Breccia deposits occur as pipes or conical bodies and vary in size up to several hundred feet in diameter. These deposits are characterized by quartz, pyrite, electrum (a naturally occurring alloy of gold and silver), and native gold with little or no additional sulfides, typically within veins, replacements, and breccia matrix. Tellurium and tungsten are present locally.

Molybdenum-bearing breccia pipes are found in some districts. The Cave Peak, Sierra Diablo, Texas, has been studied in more detail than deposits in New Mexico and are likely similar to New Mexico
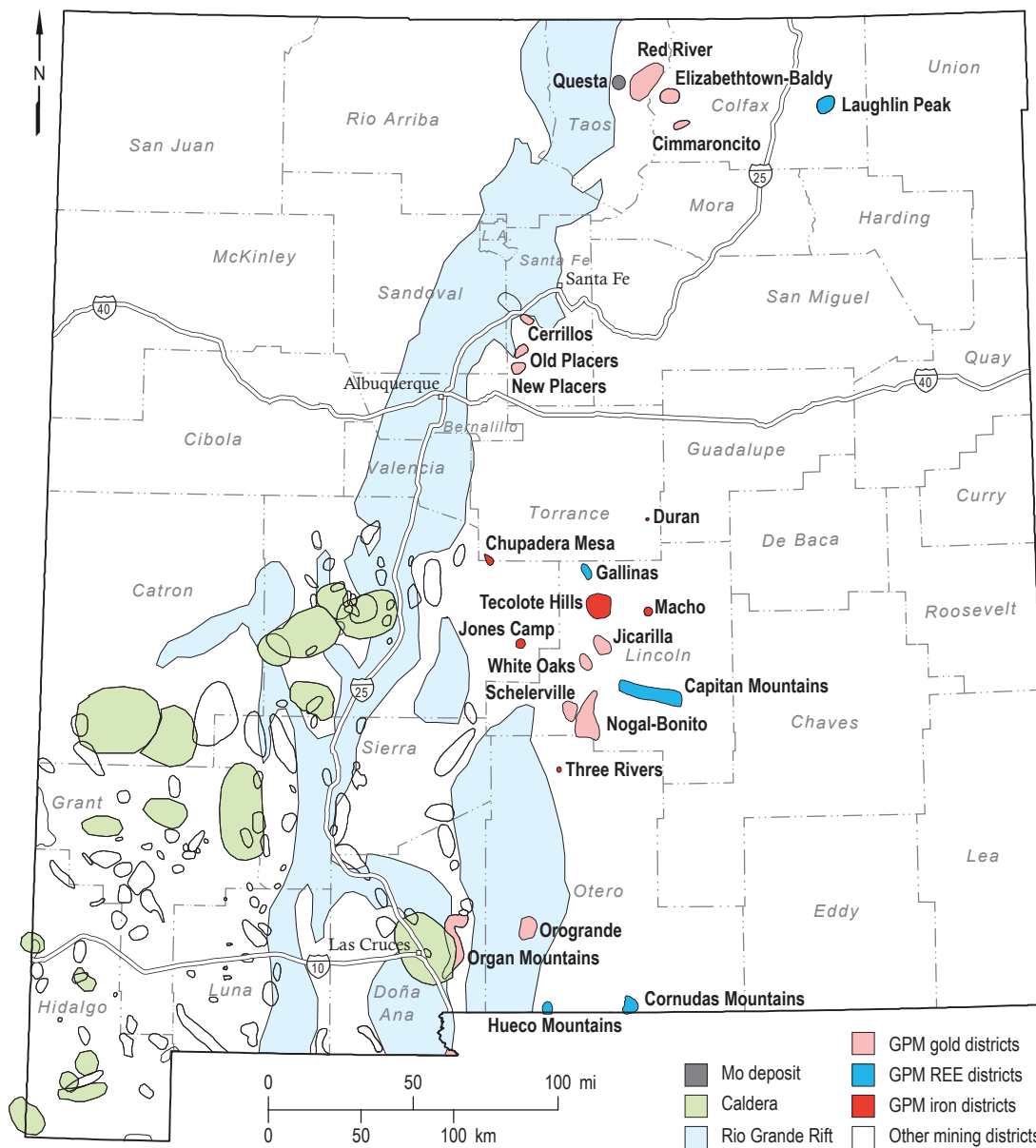
Figure 28. Great Plains Margin (GMP) deposits in New Mexico (modified from McLemore et al., 2005a, b; McLemore, 2012a). List of districts is in Table 4 and McLemore (2012a). Districts are described in McLemore (2017).McLemore.

1 Back-arc or post-collisional asthenospheric melting

rifting?

partial melting

2 Intrusion of alkaline magmas along deep-seated structures

calc-alkaline magmas

alkaline magmas

extended (rifted), thinner crust

stable craton, thicker crust

3 Magmatic-hydrothermal stage

alkaline-type porphyry Cu-Au-Mo mineralization

magmatic fluids

4 Epithermal stage

caldera formation?

circulating groundwater

boiling and epithermal deposition

residual magmatic fluids

5 Mineral alteration zoning

bedded explosion breccia

breccia pipe (Au, Cu, Hg, Sb)

stockwork breccia

ore zone

epithermal vein zone

propylitic alterationzone with disseminated pyrite

approx. 1 km

mesothermal vein zone

narrow alteration zone

skarns

carbonate-hosted Ag-Mn Pb-Zn deposits

<1–5 km depth, alkaline porphyry stock with possible Cu, Au, or Mo mineralization

Figure 29. Schematic model for formation of Great Plains Margin deposits (modified from Richards, 1995).

deposits. Three molybdenum-bearing breccia pipes at Cave Creek are associated with Sierra Diablo syenite to rhyolite to quartz monzonite intrusions (Sharp, 1979). The largest pipe is 2,500 ft in diameter and consists of up to three zones of mineralization. Molybdenum occurs as discrete concentrations of veinlets and disseminated molybdenite with variable but minor quartz, fluorite, biotite, chalcopyrite, hubnerite, cassiterite, sphalerite, marcasite, arsenopyrite, magnetite, ilmenite, rutile, and columbite (Sharp, 1979). In the Nogal district, eight molybdenum breccia pipes are associated with the monzonite Rialto

stock (Thompson, 1968). Molybdenite and other sulfides occur as thin coatings along fractures and thin quartz veins (Thompson, 1968).

Breccia deposits were emplaced in a variety of igneous and sedimentary wall rocks in New Mexico deposits. Breccia fragments are typically highly altered and vary in angularity, and size, ranging from large blocks tens of feet in diameter to clay-sized particles. Hypotheses on the origin of these breccia deposits include the following: 1) solution collapse (Maynard, 1989, 1995; Maynard et al., 1989, 1990), 2) phreatic eruptions, 3) boiling of magmas causing pressure release of volatiles forming hydrothermal brecciation, and 4) volcanic venting (Woodward and Fulp, 1991). Continued mineralization by post-brecciation hydrothermal fluids cemented the breccia fragments, along with late quartz veins. Many polymetallic veins, breccia deposits, and quartz veins have textures typical of epithermal deposits, such as multiple banding, hydrothermal brecciation, bladed calcite and/or quartz, vuggy textures, and drusy quartz. Studies at the Helen Rae mine in the Nogal district indicate fluid inclusion temperatures of 200°C, salinity of 16 eq. wt% NaCl, and $\delta^{18}O$ of 6 – 24.2‰ (Campbell et al., 1991; Douglass and Campbell, 1995); the salinity and $\delta^{18}O$ are higher than typical epithermal deposits, but the temperature is lower than most epithermal systems. Fluid inclusion and isotope studies have not been completed for most GPM deposits in New Mexico. Available data are consistent with observations of Campbell et al. (1991) that GPM deposits have low to moderate temperatures of formation and formed from high-salinity fluids (McLemore, 1996b).

Porphyry copper-molybdenum-gold deposits

Post-Laramide porphyry copper-gold, copper-molybdenum and/or gold deposits, locally with significant quantities of molybdenum, are found in some GPM deposits in New Mexico (Cerrillos, Orogrande, Nogal-Bonito, Organ Mountains; McLemore, 1996b, 2015a; McLemore et al., 2014a, b). These porphyry copper-gold, copper-molybdenum and/or gold deposits are younger, and smaller than the Laramide porphyry deposits (discussed above), but are recognized for their higher gold grade. Copper minerals and locally gold and molybdenite occur as disseminations and stockwork veinlets in, and adjacent to porphyritic intrusions that have been hydrothermally altered (Giles and Thompson, 1972; Giles, 1991; Maynard et al., 1989, 1990). Disseminated molybdenum and copper minerals occur in the Rialto stock in Lincoln County, but the low grades, low molybdenum

prices, and proximity to a wilderness area has hampered development (Thompson, 1968). Extensive alteration is irregularly distributed around most deposits with inner zones of argillic alteration and silicification, however, alteration is not as prevalent as that surrounding the Laramide porphyry copper deposits (Thompson, 1973; Wargo, 1964). At the Waterdog prospect (NMLI0276) in the Nogal-Bonito district, a porphyry copper-gold deposit is hosted by a syenite to monzonite stock that is concentrically zoned from outer propylitic to argillic to inner phyllic alteration to a core of silicified and oxidized breccia (Thompson, 1973; Fulp and Woodward, 1991). A porphyry copper-molybdenum deposit has been encountered in drill holes north of Organ in the Organ Mountains district, where the altered quartz monzonite consists of stockwork veining and averages of 0.25% copper and 0.1% molybdenum (Fig. 30; Newcomer and Giordano, 1986; Lueth and McLemore, 1998). In most GPM porphyry deposits in New Mexico, gold-to-silver ratios are typically greater than one. Bulk tonnage mining methods would be employed because of low grades and the disseminated nature of this deposit type.

Copper, lead/zinc, and gold skarns and carbonate-hosted replacements

Numerous GPM districts in southwestern New Mexico host copper, lead-zinc, and gold skarn and carbonate-hosted replacement deposits. Most are copper skarns, but they contain considerable gold concentrations, especially when compared to other copper and lead-zinc skarns (McLemore et al., 1996). The skarns typically occur in limestone adjacent to, or in the vicinity of, an intrusive contact with stocks, dikes, and/or sills. Calc-silicate minerals such as garnet, tremolite, and diopside occur with magnetite, epidote, cordierite, scapolite, and chlorite. Gold skarns are defined as carbonate-hosted deposits containing at least 1 ppm Au and exhibiting distinctive skarn mineralogy (Theodore et al., 1991). Many skarns in the GPM districts contained sufficient gold to be classified as gold skarns (Theodore et al., 1991), although most in New Mexico also contain significant copper. Skarns containing only gold have not been reported in New Mexico. Well-developed copper and local lead-zinc skarns containing gold and silver occur in Ordovician to Mississippian limestones and dolomites in the Orogrande district in Otero County (Strachan, 1976, 1991; Bloom, 1975; North, 1982; Schmidt and Craddock, 1964; Korzeb and Kness, 1994; McLemore et al., 2014b). The Cerrillos district
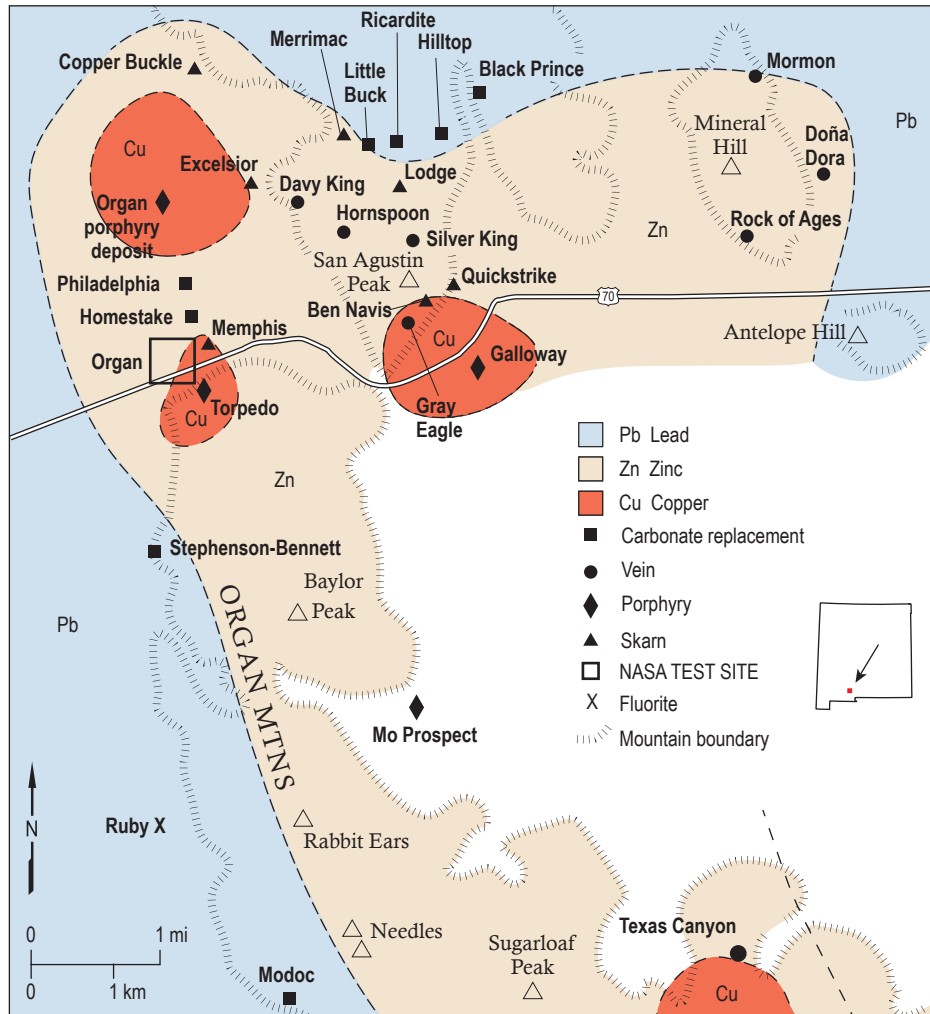
Figure 30. Metal zoning in the Organ Mountains district (Lueth and McLemore, 1998).

also has numerous copper skarns containing gold and silver in Pennsylvanian and Permian limestone (White, 1991; Giles, 1991). Skarns are found surrounding the porphyry copper deposits in the Organ district (Fig. 30).

Iron skarns and replacement bodies

Numerous iron skarns and replacement deposits occur throughout the New Mexico GPM alkaline igneous rock belt and some districts have reported iron production (Table 4). Most deposits are small and insignificant (Griswold, 1959; Kelley, 1949; McLemore, 2010b) and none are known to contain economic precious or base metal concentrations. However, selected high-grade samples from some iron contact-metasomatic and skarn deposits locally carry anomalous gold, REE and copper values. The largest iron deposit, Capitan (Fig. 28), contains

more than one million short tons grading 45.6% Fe with local trace amounts of gold (Kelley, 1949). These iron deposits consist of hematite and magnetite and occur as lenses or irregular bodies in limestone and as veins filling fractures, faults, and along bedding planes adjacent to Tertiary intrusions. Calcsilicate minerals are rare and typically occur only in the larger deposits (e.g., Jones Camp, Capitan Mountains). Fluid inclusions in garnet from the Capitan iron deposit are high-salinity, as indicated by the presence of one or more halide daughter minerals, and are similar to fluid inclusions from the REE-fluorite veins, suggesting a similar magmatic-hydrothermal origin (McLemore and Phillips, 1991; Phillips et al., 1991; Campbell et al., 1994, 1995; unpublished data). Bastnaesite with elevated REE concentrations is found in the iron skarn deposits in the Gallinas Mountains (Fig. 28; McLemore, 2010b). Recent iron production from the Orogrande

district (McLemore et al., 2014b) was sent to China and suggests that a re-evaluation of the economic potential of these iron deposits is needed.

Th-REE-fluorite (with uranium and niobium) epithermal veins, breccias, and carbonatites

Thorium-REE-fluorite epithermal veins, breccias, and carbonatites can contain potential economic concentrations of thorium, REE, niobium, fluorine, beryllium, barium, and lead and occur throughout GPM districts (Fig. 28; McLemore, 1996b, 2010b, c). Known deposits in New Mexico typically occur as tabular bodies, narrow lenses, and breccia zones along fractures, faults, and shear zones. These deposits vary from less than 3 ft to greater than 900 ft long and from less than an inch to 10 ft wide (Staatz, 1985, 1986; McLemore and Phillips, 1991; Schreiner, 1991, 1993; McLemore and Guilinger, 1993; McLemore, 2010b). The deposits are typically spotty, discontinuous, of variable grade, and contain local concentrations of REE, yttrium, thorium, uranium, niobium, tantalum, tellurium, and gold (McLemore et al., 1988a, b). The larger deposits are in the Laughlin Peak (DIS020), Capitan Mountains (DIS091), and Gallinas Mountains (DIS092) districts (McLemore, 1996b, 2010b). Total REE content ranges from 100 to 30,000 ppm in the Laughlin Peak district (Staatz, 1985). A small amount of bastnaesite was produced from the Gallinas Mountains district (Griswold, 1959; McLemore, 2010b), and a small amount of uranium was produced from the Capitan Mountains (McLemore and Phillips, 1991). A carbonatite could exist at depth in the Gallinas Mountains (Fig. 31).

Origin of Great Plains Margin systems

The origin of GPM deposits is controversial; a genetic association of GPM deposits with alkaline igneous rocks has not yet been proven, although it is noted that they coincide with a belt of alkaline igneous rocks and crustal thickening in New Mexico (Bird, 1984; Mutschler et al., 1985, 1991), which follows the tectonic boundary from Texas to Colorado between the tectonically stable Great Plains and tectonically active Rocky Mountains and Basin and Range provinces. This belt of alkaline rocks continues northward into Canada and southward into Mexico (Clark et al., 1982; Mutschler et al., 1985, 1991). Some mineral deposits in other areas along this trend (e.g. Cripple Creek, Colorado and Golden Sunlight, Montana) are geologically similar to deposits in New Mexico. The diversity

of associated igneous rocks and mineral deposit types suggest that the boundary of the Great Plains with the Rocky Mountains and Basin and Range is a region of highly fractionated and differentiated, multiple intrusive magmas, probably involving both upper mantle and lower crustal sources (Thompson, 1991a, 1992; McLemore, 1991). Hot spots could also be involved. The tectonic setting appears to be related to back-arc extension rather than to subduction (Eggler and Furlong, 1991; Thompson, 1991a).

Supporting evidence for a magmatic-hydrothermal origin include the following: 1) fluid inclusion data, age determinations, and stable isotopic evidence from the Capitan quartz veins (Phillips et al., 1991; Campbell et al., 1994, 1995) and Nogal-Bonito deposits (Douglass, 1992; Douglass and Campbell, 1994, 1995; McLemore et al., 2014a), 2) nature of stockwork molybdenum deposits at Sierra Blanca (Thompson, 1968, 1973; Giles and Thompson, 1972), 3) close spatial association of the seven types of deposits with igneous rocks (Allen and Foord, 1991; McLemore and Zimmerer, 2009), 4) presence of skarn deposits along the contacts of the igneous rocks (McLemore, 2010b; McLemore et al., 2014b), 5) similar age determinations between igneous intrusions and associated mineralization and alteration (McLemore, 1996b, 2015a), 6) geochemistry, fluid inclusion and geochemical modeling studies in the Gallinas district (Williams-Jones et al., 2000; McLemore, 2010b; Vance, 2013) and 7)
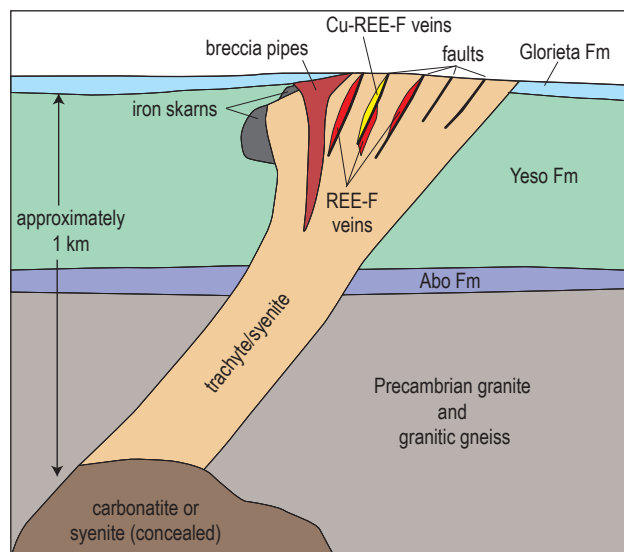

Figure 31. Schematic model of formation of the mineral deposits in the Gallinas Mountains, Lincoln County, New Mexico (McLemore, 2010b, modified in part from Staatz, 1992; Schreiner, 1993; Richards, 1995; Williams-Jones et al., 2000).

similarity of New Mexico deposits to other deposits at Cripple Creek, Colorado and elsewhere where a magmatic origin is favored (McLemore, 1991; Thompson, 1992; Maynard et al., 1989, 1990; Kelley et al., 1998; Kelley and Ludington, 2002). It is likely that the co-occurrence of gold, copper, iron, molybdenum, fluorine, tungsten, tellurium, and other elements is the result of multiple and complex magmatic fractionation and differentiation events, and tectonic sub-environments, which overlap near the Great Plains Margin, as suggested by Rice et al. (1985) for the molybdenum-gold-fluorite mineralization at Central City, Colorado. Deep-seated fracture systems or lineaments probably channeled the magmas and resulting hydrothermal fluids (Figs. 29, 31). Once magmas and fluids modified by crustal contamination have reached shallow crustal levels, local structures and wall rock compositions determined final type and distribution of the intrusive rocks and mineralization. In areas such as the Cornudas Mountains and Trans-Pecos Texas magmatic province, where relatively less mineralized alkaline igneous rocks were emplaced, gold and silver are rare and found only in small, scattered, localized occurrences (McLemore and Guilinger, 1993; McLemore, 1996b, 2010b). Future exploration along the Great Plains Margin will concentrate on the large, low-grade, bulk- tonnage breccia-pipe deposits similar to those at Ortiz in the Old Placers district (Table 4, 5), with porphyry copper-gold deposits in these districts continuing to be attractive exploration targets. Placer gold, REE veins, and copper skarn deposits also could be exploited on a small scale.

Volcanic-Epithermal Vein Deposits

Volcanic-epithermal mineral deposits are found in many districts in New Mexico (Fig. 32) in structurally complex tectonic settings that provide an excellent plumbing system necessary for circulation of hydrothermal fluids such as Steeple Rock, Mogollon, Chloride, and others (Fig. 32). Lindgren (1933) defined the term *epithermal* to include a broad range of deposits that formed by ascending waters at shallow to moderate depths (<4,500 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 (Simmons et al., 2005). White (1955, 1981) established the now-recognized

association between epithermal mineral deposits and active geothermal or hot springs systems. 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. The volcanic-epithermal vein deposits in New Mexico are restricted in this chapter to veins associated with Oligocene to Miocene volcanic fields and calderas (Cox and Singer, 1986).

Many volcanic-epithermal deposits in New Mexico occur along the margins of calderas (Fig. 32; Rytuba, 1981; Elston, 1994; McLemore, 1996a), although other structurally complex volcanic settings, such as silicic domes and andesitic stratovolcanoes, are not uncommon for these deposits. It is important to note that not all calderas are mineralized. Only a few calderas in New Mexico contain large economic epithermal mineral deposits (McLemore, 1996a), nonetheless most known epithermal deposits in New Mexico are restricted to volcanic terranes and areas immediately adjacent to volcanic fields. These volcanic-epithermal systems are confined to faults and fissures in rhyolitic ash-flow tuffs and andesites of Oligocene-Miocene age (Fig. 33; Elston, 1978; 1994; Rytuba, 1981). The mineral deposits tend to be 10–12 Ma younger than the associated volcanic activity whenever isotopic ages are available (McLemore, 1996a). The association between bimodal volcanic activity and volcanic-epithermal deposits is probably one of a favorable plumbing system in an area of abundant fluid flow, high and recurrent heat flow, favorable structural traps, and persistent, reactive geochemical environments. These deposits were formed during neutral to extensional back-arc tectonic settings.

Typical volcanic-epithermal deposits in the state occur as siliceous vein fillings (Fig. 34, 35), breccia pipes, disseminations, and replacement deposits. The characteristics of these deposits and a model for their formation were outlined by Buchanan (1981) and refined by later work (Rytuba, 1981; Henley, 1985; Henley and Brown, 1985; White and Hedenquist, 1990; McLemore, 1993, 1996a, 2008b). Common ore textures include: open-space and cavity fillings, drusy cavities, comb structures, crustifications, colloform banding, typically multi-stage brecciation (Fig. 35), replacements, lattice textures (quartz pseudomorphs after bladed
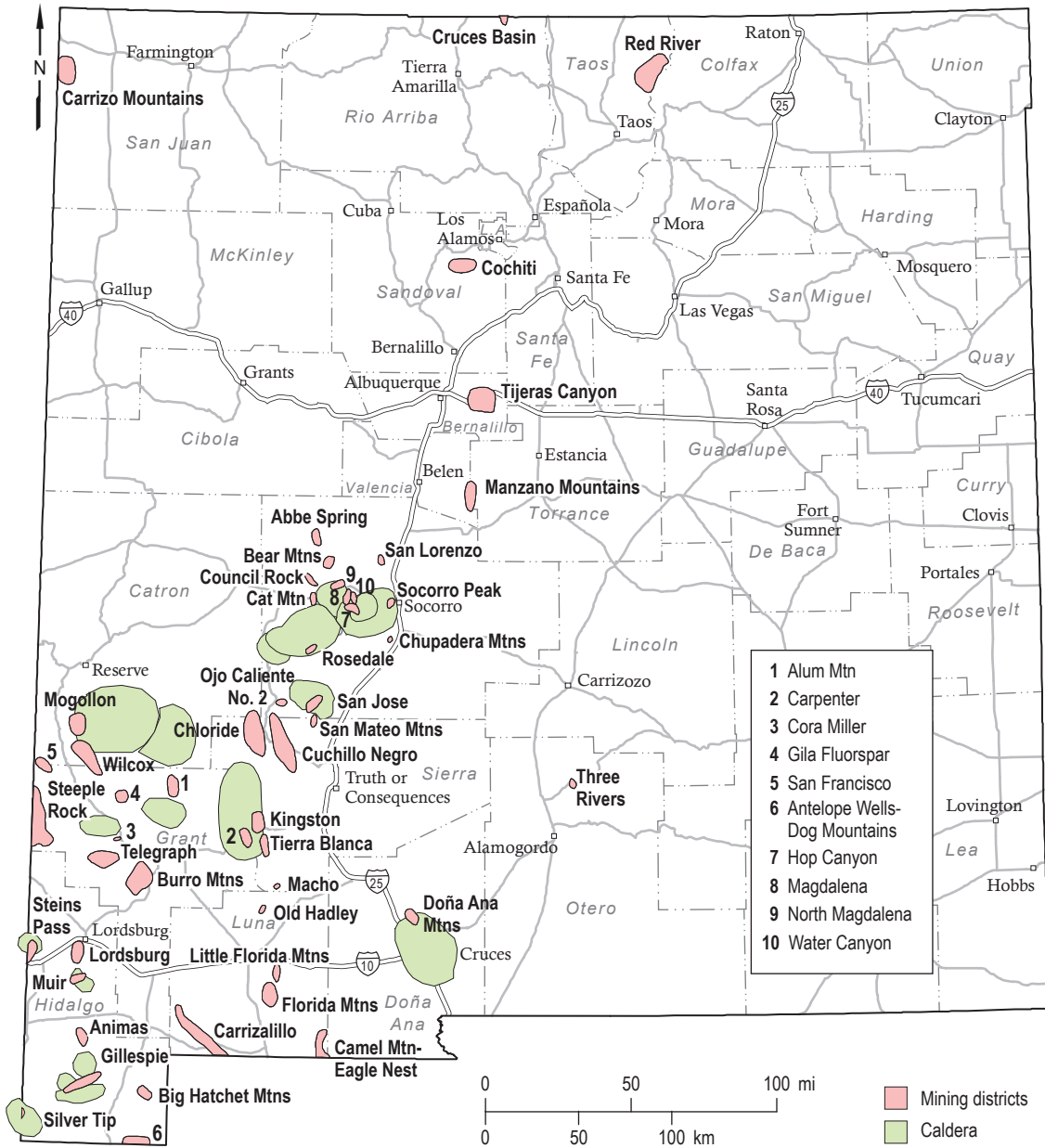
Figure 32. Volcanic-epithermal deposits in New Mexico. Volcanogenic beryllium deposits are also found in the Ojo Caliente No. 2 district.

calcite), and irregular sheeting (Buchanan, 1981; Dowling and Morrison, 1989). Ore shoots within a specific vein form at intersections of faults or at areas with deflections in strike and/or dip. The mineralogy and metal associations of these deposits are diverse, although common ore minerals include auriferous pyrite, native gold, acanthite, chalcopyrite, bornite, argentiferous galena, native silver, and sphalerite. Quartz, calcite, and pyrite are common gangue minerals, and common alteration-associated minerals include chlorite, epidote, illite/sericite, adularia, and kaolinite. Both gold and silver are usually produced from these deposits with variable amounts

of base-metal production. Other minerals sometimes produced from these deposits include fluorite, uranium, tellurium, REE, and vanadium. Most veins are less than 3 ft wide, but economic veins are as wide as 30 ft. District zoning is also diverse, and in some districts, precious metals occur in the upper levels of the epithermal system and grade into base metals at depth, illustrated by the Chloride and Steeple Rock (Fig. 36) districts (Buchanan, 1981; Harrison, 1986; McLemore, 1993, 2008b). Typical deposits are as large as a few hundred thousand short tons grading 0.2 oz/short ton Au and 6-20 oz/short ton Ag (McLemore, 1996a).

Textures, mineralogy, metal association, alteration assemblages and metal zoning vary from district to district. Hydrothermal systems undergo constant and, sometimes, abrupt physical and chemical changes, which means that geochemical equilibrium is not always achieved in these systems. This is because these systems undergo catastrophic changes resulting from 1) change from lithostatic to hydrostatic pressure (resulting in boiling), 2) changes in permeability caused by variable precipitation and dissolution of minerals, and 3) interaction of fluids derived at depth with near-surface, oxidizing, meteoric waters and host rocks of different lithologies. Consequently, fluid temperature, composition, and pressure are constantly changing. Boiling is one of the mechanisms that have been invoked to explain the precipitation of gold from mineralized fluids, however, precipitation

of metals also occurs by mixing of fluids, release of CO_2, and/or cooling. Fluid-inclusion studies have shown that most volcanic-epithermal deposits in New Mexico formed at temperatures ranging from 50–300°C and from low-salinity fluids (<10 eq. wt.% NaCl, McLemore, 1996a, 2008b).

An important advance in the knowledge of epithermal mineral deposits occurred when Hayba et al. (1985) provided a twofold classification of volcanic-hosted epithermal deposits based on mineralogy and associated alteration by defining adularia-sericite and acid-sulfate systems. In order to be consistent in terminology by defining both classes according to mineralogy, Berger and Henley (1989) refined this classification to adularia-sericite (illite) and alunite-kaolinite (±pyrophyllite). Earlier models referred to these deposits as quartz/adularia and quartz/alunite (Cox and Singer, 1986, model #25). One problem with applying this classification in the field is that some of the characteristic alteration minerals, such as alunite, diaspore, adularia, and others, are fine grained and may be difficult to identify easily (Berger and Henley, 1989). Thus, White and Hedenquist (1990) refined this classification even further to low-sulfidation and high-sulfidation deposit types. Bonham (1988) added a third type—alkaline-related, epithermal-precious metal deposits to this scheme; this added class closely resembles similar deposits found in New Mexico that are included with the GPM deposits, described above. Most of the volcanic-epithermal deposits in New Mexico are of the low-sulfidation class. Acid-sulfate alteration is present in several districts, including Alum Mountain, Steeple Rock (Fig. 36; McLemore, 1993), San Jose (Forureu, 1984), Kline Mountain in Taylor Creek (Hall, 1978; Isik et al., 1994), Macho (McLemore, 2012b), and Old

Figure 33. Summit vein in andesite in the Steeple Rock district. The vein is more than 100 ft wide at the crest of the mountain. *Photo by V.T. McLemore.*
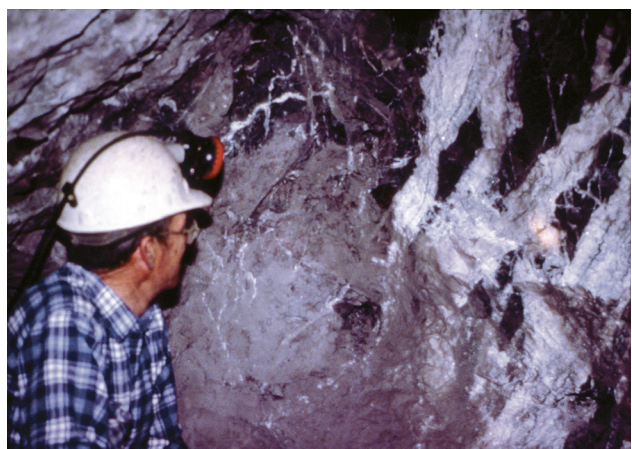

Figure 34. Brecciated quartz-gold vein in the Chllenge (Eberle) mine, Mogollon district (NMCA0167). *Photo by Virginia T. McLemore.*

Figure 35. Close-up of quartz breccia vein in the Summit mine, Steeple Rock district. The thin black veins contain gold, silver, and pyrite (NMGR0459). *Photo by Virginia T. McLemore.*
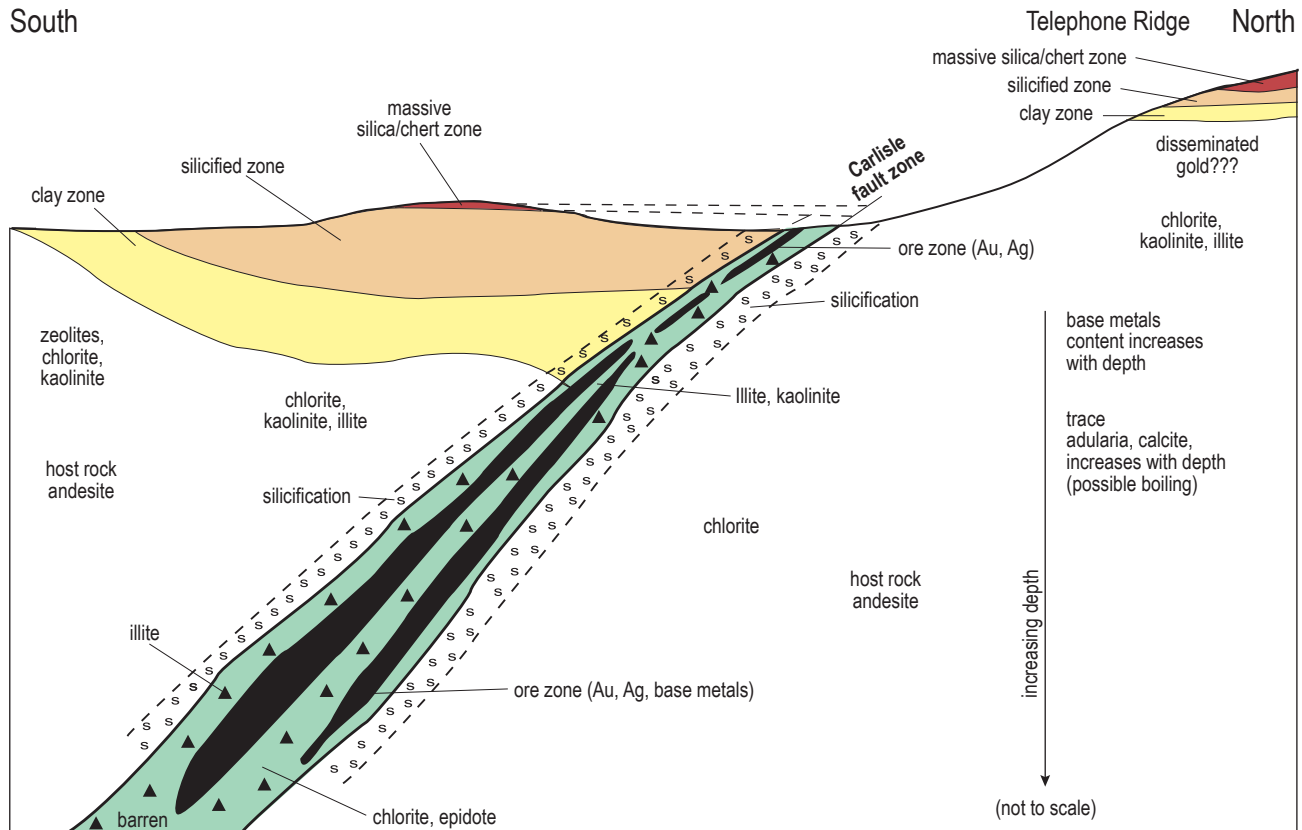
Figure 36. Schematic relationship between alteration and vein deposits along the Carlisle fault in the Steeple Rock district (McLemore, 1993).

Hadley (Hall, 1978). Although these altered areas may be indicative of high-sulfidation gold deposits, none have been discovered to date (McLemore, 1996a). These acid-sulfate altered areas could have potential for other resources, such as alunite (McLemore and Austin, 2017) and gallium.

Reserves have been reported from three districts: Steeple Rock, Chloride, and Cochiti. In 2009, production began at the Summit mine (NMGR0459) in the Steeple Rock district operated by Santa Fe Gold Corp., New Mexico's first gold-silver mine since 1993. Reserves at the Summit mine are estimated to be 531,509 short tons grading 0.129 oz /short ton gold and 8.62 oz /short ton silver (Santa Fe Gold Corporation, 8/15/11). The company also purchased a ball mill and flotation plant in Lordsburg to process the Summit ore, and the permitted Banner mill began operations in early 2010. However, the Summit mine and Banner mill temporarily closed in 2013 due to adverse economic conditions. Santa Fe Gold Corporation is filing for bankruptcy.

Volcanic-epithermal deposits in New Mexico also have potential for development of siliceous flux for Arizona copper smelters. In some districts, such as at the Mogollon district, dumps can be

reworked for gold and silver by portable heap-leaching equipment (Eveleth, 1979). Most districts in New Mexico have not been adequately explored at depth, and drilling and other exploration programs are needed to further evaluate the potential.

Volcanogenic beryllium deposits

Volcanogenic beryllium (also known as volcanic-hosted replacement, volcanic-epithermal, or Spor Mountain beryllium-fluorite-uranium) deposits are hosted by felsic volcanic rocks, especially rhyolite, and are found as volcanic-epithermal veins and/or replacements in volcanic rocks (Foley et al., 2010). Volcanogenic beryllium deposits form where hydrothermal fluids interact with volcanic rocks, especially high-silica topaz-rhyolites and granite porphyry. The beryllium-fluorite-uranium deposits at Spor Mountain in Utah are the most predominant economic, nonpegmatite beryllium deposits in the world (Lindsey, 1981; Lindsey and Shawe, 1986; Barton and Young, 2002). The formation of volcanogenic beryllium deposits is related to: 1) a high-silica, lithophile-rich magma,

2) magma mixing leading to extrusive volcanic activity, 3) permeable host rock, such as rhyolite tuffs, and 4) convecting hydrothermal fluids enriched in beryllium, iron, fluorite, and other lithophile elements.

Only one known volcanogenic beryllium deposit is found in New Mexico: the Apache Warm Springs deposit (Fig. 32; NMSO0152, also known as the Sullivan Ranch site, McLemore, 2010c, 2010d, 2012c), which lies in the Montoya Butte quadrangle on the northeastern edge of the Mogollon-Datil volcanic field in the northern Sierra Cuchillo range. Beryllium, mostly as bertrandite $(H_2Be_4Si_4O_9)$, was first noted in Red Paint Canyon in about 1961 by M. Howard Milligan (McLemore, 2010d, 2012c). Meeves (1966) described the results of field reconnaissance mapping, trenching, and drilling for beryllium by a commercial company under contract to the U.S. Bureau of Mines. Eighteen holes were drilled as part of these early exploration efforts (Fig. 37). The Beryllium Group, LLC controlled the property in 2001–2002. They drilled 14 holes, and reported a resource of 43,060 short tons. Great Western Exploration, LLC controlled the property from 2004–2007 (P and E Mining Consultants Inc., 2009). In October 2007, BE Resources Inc. acquired the property, but in September, 2011, the company placed the property on care and maintenance, and there has been no beryllium production from the property.

Rhyolite/Granite-Hosted Tin (Topaz Rhyolite) Deposits

Rhyolite-hosted tin deposits consist of discontinuous veins and veinlets in rhyolite domes and volcanic centers (Fig. 38; Cox and Singer, 1986; Christiansen et al., 1986). Tin mineralization forms from the vapor phase portion of the rhyolite magma and crystallizes within the fractured and brecciated outer parts of flow-dome complexes and are hosted by high-silica (>75% SiO_2), peraluminous rhyolites and/or pyroclastic deposits. Hematitic and argillic alteration is commonly associated with the tin deposits. Four types of tin deposits are found in and around the altered rhyolite domes and tuffs in the Taylor Creek district, Sierra and Catron Counties (Maxwell et al., 1986; Eggleston and Norman, 1986), including miarolitic cavities within rhyolite, thin veins and veinlets cutting rhyolite, disseminations in rhyolite, and placer deposits in streams and alluvial deposits adjacent to rhyolite domes and flows. The deposits are typically small in size, comprising less than several hundred thousand short tons, and low grade (<2% Sn) (Cox and Singer, 1986). Cassiterite is the predominant ore mineral.

The age of the Taylor Creek Rhyolite is about 28 Ma (Duffield et al., 1987; Duffield and Dalrymple, 1990) and consists of banded flows and tuffs that are as much as 600 ft thick that erupted from at least 20 vents. The Taylor Creek Rhyolite is a metaluminous to weakly peraluminous, high-silica, fluorine-rich
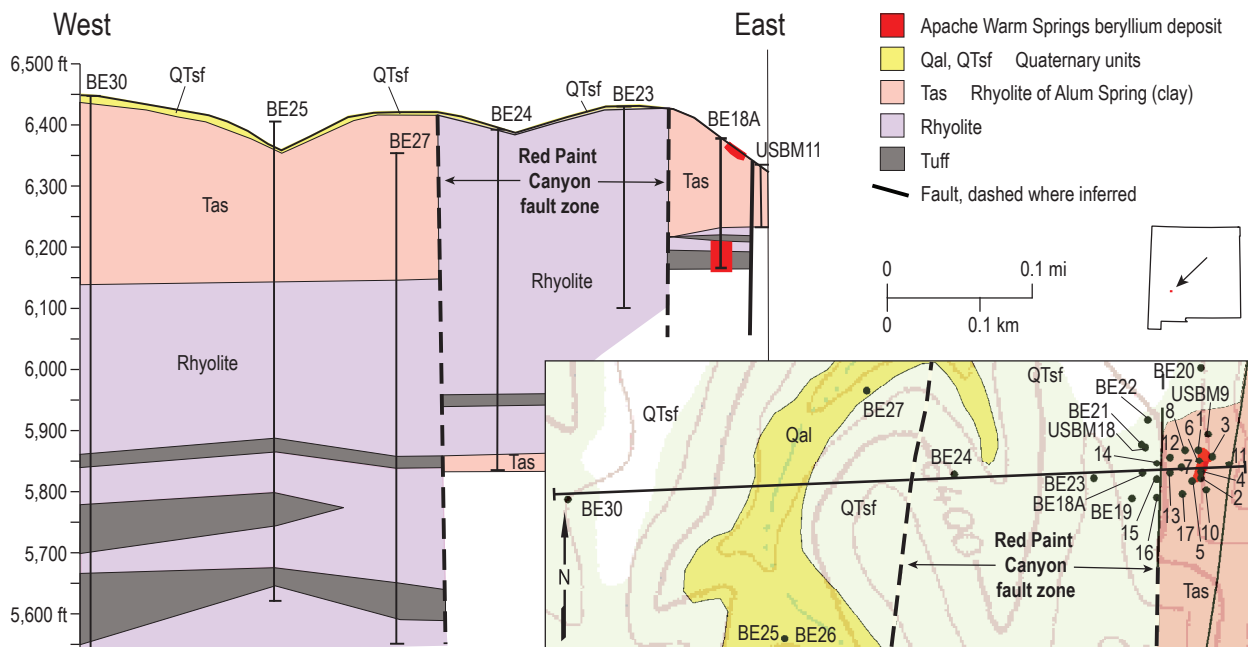

Figure 37. Detailed geologic map and cross section of the Apache Warm Springs beryllium deposit and adjacent area (N section 6, T9S, R7W; McLemore, 2010d, 2012c).

rhyolite (Duffield and du Bray, 1990) and is characterized by as much as 30% phenocrysts of sanidine (moonstone), quartz (commonly smoky), and biotite in a devitrified groundmass. Accessory minerals in the groundmass include quartz, sanidine, augite, biotite, plagioclase, and opaque minerals (Woodard, 1982; Lawrence, 1985).

The various domes of the Taylor Creek Rhyolite have similar major element compositions (Correa, 1981; Lawrence, 1985; Duffield et al., 1987), but have variable trace element concentrations, indicating that the Taylor Creek Rhyolite is a highly evolved igneous complex (Duffield and Dalrymple, 1990). Contamination of the upper part of the rhyolitic magma chamber by Proterozoic age rocks is indicated by trace element concentrations and $^{87}Sr/^{86}Sr$ ratios (Wittke et al., 1996). Geologic, geochemical, and isotopic data suggest that the Taylor Creek Rhyolite represents the upper levels of a single large magma body that erupted over a period of less than 100,000 years (Duffield and Dalrymple, 1990). Two-feldspar geothermometry, Fe-Ti-oxide geothermometry, $\delta^{18}O$,
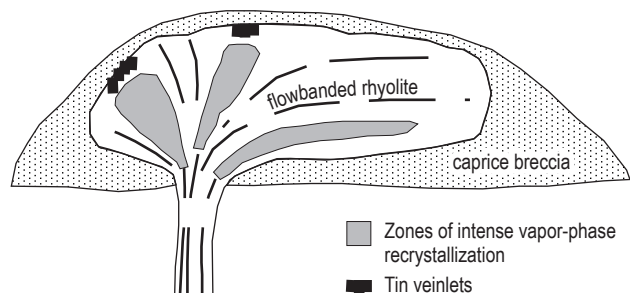

Figure 38. Schematic cross section of flow-banded Taylor Creek dome and associated rhyolite-hosted tin deposits (modified from Eggleston and Norman, 1986).

and fluid inclusion studies indicate that the rhyolite crystallized at 700–800°C at less than 2 kbar pressure (Eggleston and Norman, 1986; Duffield and du Bray, 1990). The Taylor Creek Rhyolite contained at least 6–8 ppm tin and perhaps even more tin that was lost during degassing and devitrification of the rhyolite (Duffield et al., 1987).

Carbonate-Hosted Manganese Replacement and Epithermal Manganese Deposits

Numerous replacement manganese and epithermal manganese deposits occur in carbonate, volcanic, volcaniclastic rocks and young basin fill throughout New Mexico (Farnham, 1961; McLemore et al., 1996). Manganese oxide minerals occur in veins, breccia cement, replacements, or cavity fillings in limestone and dolomite and form tabular, pod-shaped or vein deposits. Most deposits in New Mexico are typically less than a few feet thick and less than several hundred feet long, but some ore shoots were larger (Farnham, 1961; McLemore et al., 1996). Some of the larger deposits are found in the Rincon (DIS032), Hot Springs (DIS198) and Cooks Peak (DIS105) districts. Lueth et al. (2004) determined the age of manganese-calcite veins hosted by Oligocene volcanics in the Luis Lopez manganese district to be 6.3 Ma based on $^{40}Ar/^{39}Ar$ dating of cryptomelane in the ores. Younger deposits are also documented such as the Ellis deposits near Truth or Consequences that are hosted in the 400 Ka Palomas Formation and estimated to be ~225 Ka based on Rio Grande incision rates (Lueth, 2012). Most deposits in New Mexico are typically low grade (<50% Mn), small, and uneconomic.

VII. EXTENSIONAL TECTONISM MINERAL DEPOSITS

The onset of rifting (extension) and Basin and Range development in New Mexico at about 30–12 Ma marks the final stage of major tectonism in the state. Block-faulted mountain ranges produced by normal faulting shed sediments into down-dropped basins, characterized by high-heat flow. Faults provided excellent pathways for magma and hydrothermal fluids. Basaltic volcanism became more common, and hydrothermal systems developed within these basins and locally formed mineral deposits. Metallic mineral deposits that were formed during extensional tectonics in New Mexico are shown in Figure 39.

Rio Grande Rift Copper-Silver (±Uranium) Vein Deposits

North and McLemore (1986) originally classified two deposits in New Mexico as supergene-copper-uranium (silver) deposits: La Bajada and Jeter (Ladron Mountains). Similar copper-silver vein deposits have been identified in other areas (Fig. 39) and the deposit type has been renamed Rio Grande Rift (RGR) copper-silver (±uranium) vein deposits. These vein deposits were formed at low temperatures, near-surface, and along Tertiary-age faults. Copper, silver, and molybdenum occur in most deposits; whereas uranium, lead, zinc, cobalt, nickel, germanium, and minor amounts of gold are found locally (Chamberlin et al., 1982; McLemore and North, 1984; McLemore, 1999). Silver concentrations are typically low (less than 1 oz/short ton) in most deposits. Stratigraphic relationships suggest most deposits were formed during Miocene or Pliocene time, and although, hydrothermal alteration and bleaching are developed adjacent to most deposits, intense silicification, common to hydrothermal deposits, is absent. These deposits were probably formed by low-temperature mineralizing waters, possibly as a result of dewatering of rift basins and, if this origin is correct, then these deposits may be similar in origin to the Rio Grande Rift barite-fluorite-galena deposits. Deposition occurred in open-space fillings, at favorable reducing environments along the fault in the

presence of organic material, similar to formation of sandstone-uranium and sedimentary-copper deposits.

The Bent district (DIS127), Otero County (Fig. 39), was previously classified incorrectly as a sedimentary-copper deposit, and has the largest reported production of 560,000 lbs copper and 1,189 oz silver. The Virginia deposit (NMOt0008) at Bent was as much as 45 ft thick, within 10–30 ft of the surface, and contained 2.5–45% copper, 0.07–4 oz/ton silver, and 0.01–0.02 oz/ton gold (Lindgren et al., 1910; NMBMMR file data). The ore occurs as 1) lenses and veins in upper Proterozoic diorite, 2) ore stringers and veinlets in diorite and Bliss Sandstone, 3) veins and tabular, replacement deposits in the sandstone associated with glauconite, and 4) placer copper deposits in the adjacent arroyo (Bauer and Lozinsky, 1991). Chalcocite is the predominant ore mineral, although malachite, azurite, djurleite, barite, cuprite, sphalerite, molybdenite, and pyrite are also common (Schilling, 1965; Foord and Moore, 1991; V. T. McLemore, unpublished field notes, 4/14/96).

Veins at the La Bajada and Jeter mines are along faults and appear to be controlled by the distribution of organic material (Fig. 40; Haji-Vassiliou and Kerr, 1972) or carbonaceous mudstone (Collins and Nye, 1957). At the Jeter mine, the Jeter fault is a gently-dipping normal fault that places upper Santa Fe Group sedimentary rocks against Proterozoic Capirote granite. Only uranium and vanadium were produced from the Jeter mine (McLemore, 1983; Chamberlin et al., 1982). At La Bajada mine, the Oligocene Santa Fe Formation is cut by the steeply dipping north-northwest striking La Bajada fault (Fig. 40; Haji-Vassiliou and Kerr, 1972). From 1923–1966, 52 oz Ag, 5,345 lbs Cu, 27,111.04 lbs U_3O_8 and 42 lbs V_2O_5 were produced from La Bajada mine (McLemore and North, 1984; McLemore, 1999).

Several RGR copper-silver vein deposits cut Proterozoic age granite and Paleozoic-age sandstones and limestones southwest of Palomas Gap in the Caballo Mountains district (Fig. 39). Most of the reported copper and silver production (248,515 lbs copper and 25,358 oz silver) came from copper-silver veins

at the Marion (NMSI0057) and Oohoo (NMSI0065) mines. Malachite, iron oxides, azurite, calcite, and quartz are the predominant minerals. Bornite, cuprite, chalcopyrite, chalcocite, and other copper minerals occur in rich ore shoots within several veins, and the veins occur along faults, which typically strike N80°W–N80°E and are steeply dipping. Malachite occurs in veins, as disseminations in the limestone and sandstone, and as rims and coatings surrounding nodules of chalcopyrite and bornite.

The Mockingbird Gap mine (NMSO0124), in the Southern Mockingbird Gap district (Fig. 39), is the largest mine in that district and consists of a 150-ft

adit, two 50-ft shafts, and several pits. Production is unknown. The fault-controlled vein deposit occurs along and at the intersection of two faults and the unconformity between the Proterozoic granite and Bliss Sandstone. The mineralized fault strikes N15–25°W and dips 60–85°E and is intersected by a second, unmineralized fault, which strikes N0–10°E, with a vertical dip. The unconformity between the brecciated Proterozoic granite and hematite-bearing Bliss Sandstone is exposed at the portal of the adit. The sandstone strikes N5°W and dips 25°W. Ore minerals include cuprite, malachite, azurite, chrysocolla, and chalcocite in a gangue of quartz, fluorite,
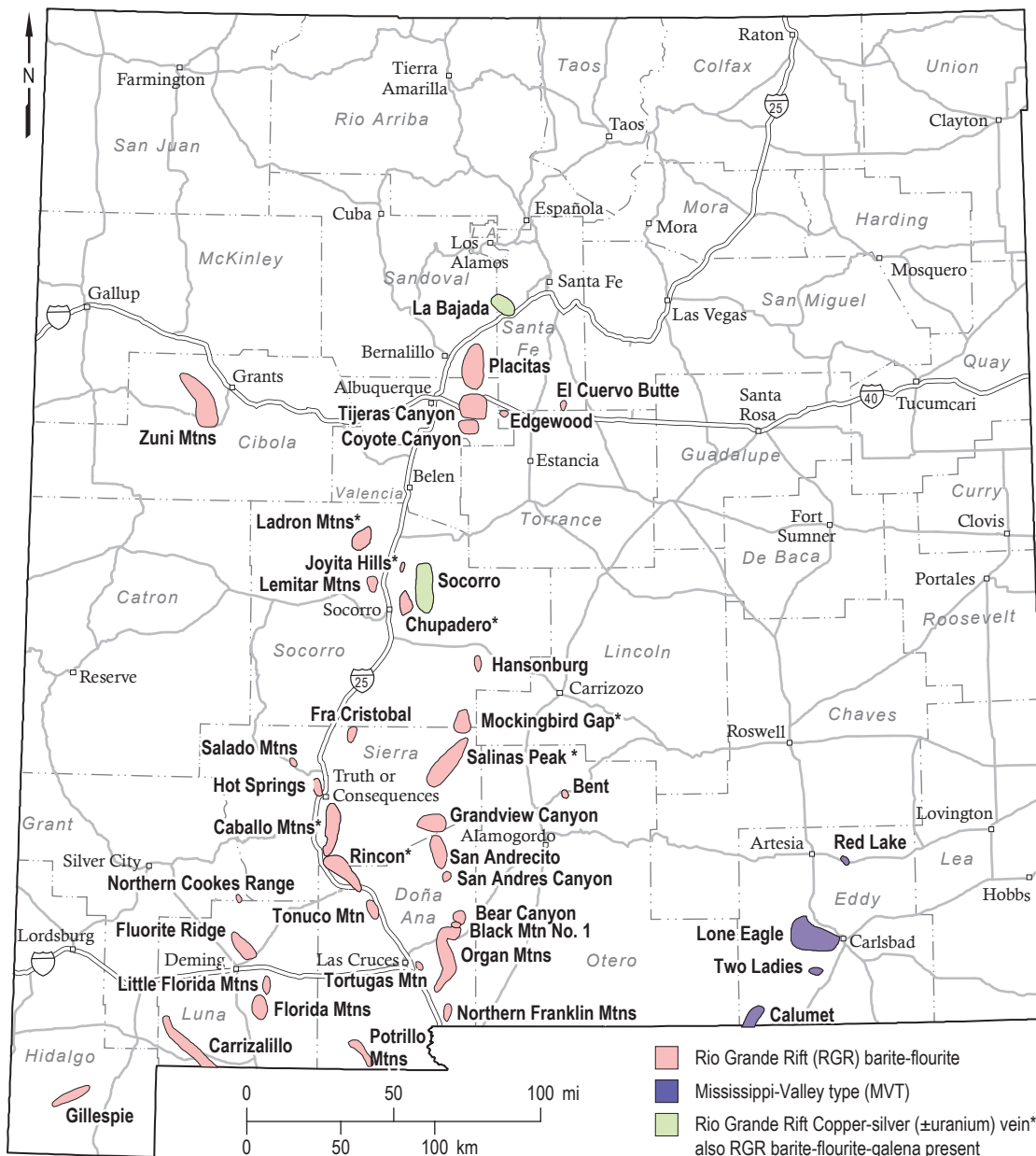

Figure 39. Metallic mineral deposits formed during extensional tectonics in New Mexico.
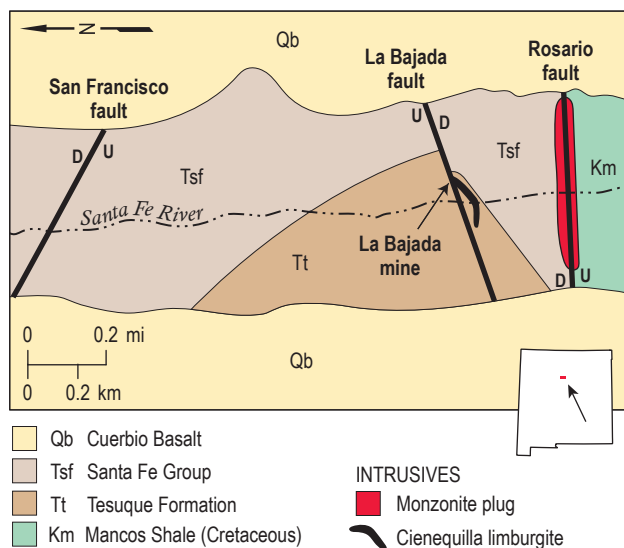
Figure 40. Schematic geologic map of La Bajada deposit (modified from McLemore, 1999).

barite, calcite, and iron and manganese oxides. Native copper has been reported (Lasky, 1932; North, 1983). The mineralized zone is 4–10 ft wide and approximately 200 ft long, and thin zones, less than one foot thick of glauconitic sandstone and shale in the Bliss Sandstone are unmineralized, in contrast to the Bliss-hosted deposits at the Virginia mine (NMOt0008) in the Bent district, Otero County.

It is unlikely that these deposits will be mined because of their small size and low grades. Silver could be recovered in secondary recovery after uranium production, but these deposits are too small and low grade to warrant uranium mining. However, this association of silver and gold with uranium and other rare metals is unusual and deserves additional study.

Mississippi Valley-Type Deposits

Mississippi Valley-type (MVT) deposits are low-temperature, lead-zinc deposits generally in carbonate rocks near the margins of marine sedimentary basins without any associated volcanic or intrusive activity. This type of deposit differs from Rio Grande Rift (RGR) barite-fluorite-galena deposits in mineralogy and association with marine basins. In southeastern New Mexico, three lead-zinc deposits are adjacent to the marine Permian Basin in Eddy County (Fig. 39) and may be oxidized MVT deposits (North and McLemore, 1986, 1988; Hill, 1993, 1996). The MVT deposits in New Mexico consist of open-space fillings in breccia zones with little or no replacement. These

deposits are small, highly oxidized, and contain only minor amounts of lead, silver, and zinc; barite and fluorite are rare to absent, and gold is extremely rare in these deposits. Geochemical and stable-isotope data suggest basin brines, possibly related to migration of oil and gas deeper within the Delaware basin during Oligocene-Miocene uplift, may have formed these MVT deposits (Hill, 1996). These deposits are similar to barite deposits at Seven Heart Gap in Culberson County, Texas, where origin by basin brines also is suggested (McAnulty, 1980). Economic potential for base and precious metals in these deposits is low (North and McLemore, 1986, 1988).

Rio Grande Rift (RGR) barite-flourite-galena Deposits

Rio Grande Rift (RGR) barite-fluorite-galena (silver, copper) deposits are found within or near the Rio Grande rift in central New Mexico (Fig. 39; McLemore and Barker, 1985; McLemore and Lueth, 1996; McLemore et al, 1998; Partey et al., 2009). The deposits were formerly called sedimentary-hydrothermal deposits (North and McLemore, 1986, 1988). These deposits are low temperature, open-space fillings with little or no replacement and are not associated with any magmatic activity (Fig. 41). Rio Grande Rift deposits are widespread and comprise predominantly of barite, fluorite, and galena, although locally they can contain significant amounts of silver, copper, and zinc. In contrast to MVT, RGR deposits in New Mexico form along continental basins along the Rio Grande rift. Vanadium and molybdenum minerals are found in some deposits, such as some in the Palomas Gap area in the Caballo Mountains. Although gold is rare in these deposits, small amounts have been recovered from a few deposits in New Mexico (e.g., Hansonburg and the Florida Mountains). Gold rarely exceeds 0.02 oz/short ton, although a few deposits may contain as much as 0.8 oz/short ton Ag.

The deposits are typically in Paleozoic age carbonate rocks as veins, breccia cements, cavity-fillings, and minor replacement bodies (i.e., Hansonburg, Salinas Peak; Smith, 1981; McLemore, 1994b; Partey et al., 2009). Locally, RGR deposits occur along faults, fractures, contact zones, shear zones, bedding planes, and solution cavities in Proterozoic, Paleozoic, and Tertiary age rocks of varying lithologies. The Gem deposit (NMSI0849) and others in the Salinas Peak and Bear Canyon districts occur along a fault contact between Paleozoic-age carbonate rocks and Proterozoic age granite and metamorphic

rocks (Smith, 1981; McLemore and Lueth, 1996; McLemore et al., 1996). The Green Crawford mines (NMDA0212, NMDA0210) in the San Andrecito-Hembrillo district consists of silicified veins along north-trending faults that cut sandstones of the Bliss Formation (Cambrian) and limestones of the El Paso and Montoya Groups (Ordovician; McLemore et al., 1996). McLemore and Austin (2017) include tables of barite and fluorite production and list of occurrences.

The age of the mineralization in some deposits is uncertain, but is limited by the age of the host rocks and mineralized faults. Previous workers have attributed these deposits to the Tertiary (Allmendinger, 1975; Ewing, 1979; Putnam et al., 1983; McLemore and Barker, 1985; North and McLemore, 1985). Age dating of hydrothermal jarosite in some of the deposits of south-central New Mexico has documented a range in age from 8 Ma (Potrillo Mountains) to as young as 400 Ka (San Diego Mountain) (Lueth and Heizler, 1997; Lueth et al., 1998, 2005). At the Copiapo deposit, age duration of over 1 million years is documented (Lueth, 1998). Some districts show evidence of multiple episodes of mineralization, specifically at Hansonburg where over three episodes are documented (Lueth et. al 2005; Lueth, 2009). Most RGR deposits occur along the margins of continental sedimentary basins and may be of a similar age as the basins. Several periods of mineralization may have occurred in other districts (North and McLemore, 1988; McLemore et al., 1996; Lueth et al., 1998, 2005).

Most RGR deposits in New Mexico are typically less than a few thousand short tons of ore. Widths range up to tens of feet and some deposits can be traced along strike for several thousand feet. The Hansonburg deposits (DIS213) are much larger, and

consist of subequal amounts of barite, fluorite, and galena. Locally, some deposits in New Mexico contain pockets or zones of high-grade barite, fluorite, or lead-silver ore that were selectively mined in the past.

These deposits are similar to Mississippi Valley-type (MVT) deposits and were formed by low-temperature basin brines that migrated along fractures, faults, and unconformities during early diagenesis or later compaction of sedimentary basins (Ohle, 1980; Sangster, 1983; McLemore and Barker, 1985). Using chlorine isotopes as a proxy for fluorine, Partey et al. (2009) indicated a potential magmatic source for some of the fluorine at Hansonburg. Stable isotope analysis of waters involved in mineralization (both fluid inclusion and calculated waters in equilibrium with various minerals) indicates they are predominantly of meteoric origin that accumulated in local sedimentary basins, possibly of varying age, and were heated by high heat-flow, magmatic activity, basinal sediment compaction, or radiogenetic heat from Proterozoic age plutons (Allmendinger, 1975; Bohlke and Irwin, 1992; McLemore et al., 1996; Lueth et al., 2005). These warm, convecting waters leached barium, sulfate, silver, and other ions from source rocks such as arkosic sediments, evaporites, Proterozoic age rocks, and mineral deposits. In central New Mexico, these basins are continental instead of marine as in the classic Mississippi Valley area. Precipitation occurred as a result of cooling of the fluids, decrease in pressure, and/or mixing of the mineralized hydrothermal fluids with subsurface brines or meteoric water.

Most of these deposits are too small to be exploited for barite, fluorite, or lead, although significant barite and fluorite production occurred in the past. If any were to be mined for barite, fluorite, or lead; silver could be recovered as a byproduct.
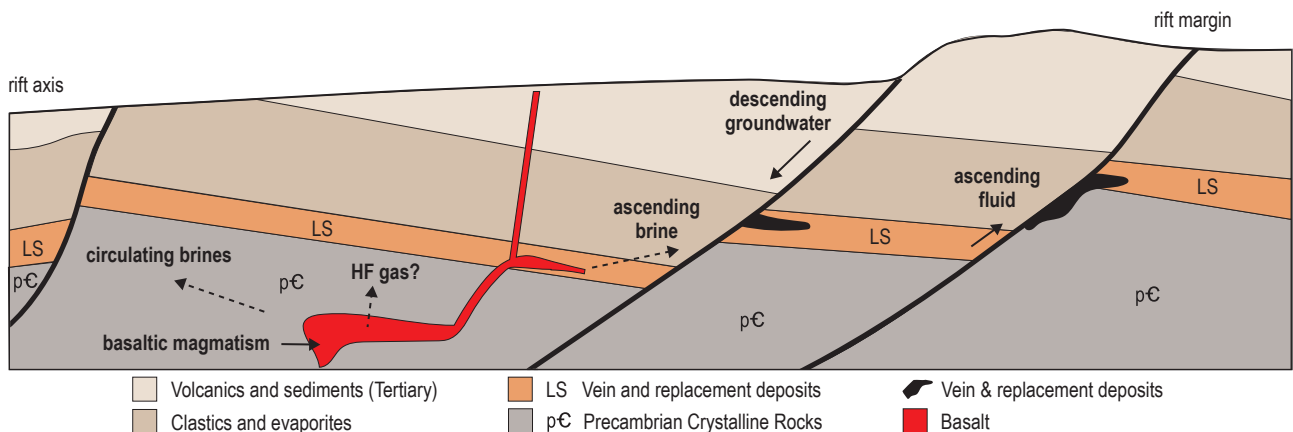

Figure 41. Schematic cross section showing formation of Rio Grande Rift deposits (McLemore et al., 1998).

VIII. PLIOCENE-RECENT MINERAL DEPOSITS

Placer deposits were formed during the Pliocene to Recent, a relatively tectonically quiet period. The only volcanism during this period was basaltic volcanism without any associated mineralization. Geothermal activity is still quite elevated, suggesting that hot spring-type mineral deposits could occur. The placer deposits are related to the formation of Basin and Range features along the Rio Grande Rift and erosion of older mineral deposits.

Placer Tungsten Deposits

Placer tungsten deposits in New Mexico are small and there has been no reported production from them in New Mexico (Fig. 42). The deposits generally occur in Late Tertiary to Holocene age alluvial fan deposits, bench or terrace gravel deposits, river-bars, and stream deposits or as residual placers formed directly on top of lode (i.e., vein, skarn) deposits. Scheelite is the predominant mineral.

Placer Tin Deposits

Placer tin deposits are found in three areas in New Mexico (Fig. 42): Taylor Creek, Cuchillo, and San Mateo Mountains districts in Sierra County; production is known only from Taylor Creek. Nodular cassiterite and wood tin forms the placer deposits, which are largely composed of boulders, coarse gravel, and minor sand. Wood tin refers to microcrystalline, concentrically banded cassiterite, which is locally intergrown with hematite. Placer tin deposits are typically small and rarely exceed 2 or 3 ft in thickness (Fries, 1940). The tin-bearing nuggets are typically black, <2 cm in diameter, and botryoidal or nodular on the surface. The nuggets exhibit three types of internal textures: colloform or layered, crystalline, and pseudomorphic (Lufkin, 1972). The chemical composition of these nuggets range from tin oxide to iron oxide (Lufkin, 1972).

Placer Gold Deposits

Placer gold deposits were an important source of gold in New Mexico prior to 1902, but placer production after 1902 has been minor (Fig. 42; Johnson, 1972). The earliest reports of placer mining were in the 1600s along the northern Rio Grande. In 1828, large placer deposits were found in the Ortiz Mountains in Santa Fe County (Old Placers district, DIS187), which began one of the earliest gold rushes in the Western United States (Jones, 1904). Known placer gold deposits were found along the southern and eastern flanks of the Ortiz Mountains; however, there could be additional placer gold deposits along the western flanks of the mountain range. Most placer deposits in New Mexico had been discovered by 1900. It is estimated that 662,000 oz of gold have been produced from placer deposits throughout New Mexico from 1828 to 1991 (Johnson, 1972; McLemore, 1994a). Only four districts have each yielded more than 100,000 oz of placer gold production: Elizabethtown-Baldy (DIS019), Hillsboro (DIS197), Old Placers (DIS187), and New Placers (DIS186).

The deposits generally occur in Late Tertiary to Holocene age alluvial fan deposits, bench or terrace gravel deposits, river-bars, and stream deposits or as residual placers formed directly on top of lode deposits typically derived from Proterozoic, Cretaceous, and Tertiary source rocks. During fluvial events, large volumes of sediment containing free gold are transported and deposited in relatively poorly-sorted alluvial and stream deposits. The gold concentrates by gravity in incised stream valleys and alluvial fans in deeply weathered highlands. Because of this natural concentration, some placers are richer in gold than the original lode deposits. Native gold and electrum occurs with quartz, magnetite, ilmenite, amphiboles, pyroxenes, pyrite, zircon, garnet, rutile, and a variety of other heavy minerals. The more productive ore zones typically occur as narrow "pay streaks" or layers of fine-grained disseminated gold, locally on top of basement rock or clay or caliche lenses within gravel

deposits. The higher gold values occur near the base of alluvial gravel deposits where the gold is trapped by natural processes such as riffles in the river bottom, fractures within the bedrock, along bedding or foliation planes, and structures that are transverse to the river flow. Gold also concentrates above cemented gravels and clay layers within gravel deposits, which constrain downward migration of gold particles. Most deposits are thin and less than 45 ft below the surface (Lindgren et al., 1910; Johnson, 1972), but thicker deposits are found in the Elizabethtown-Baldy district (up to 275 ft; Wells and Wootton, 1940) and in the Rio Grande Valley district (up to 370 ft; Jones, 1904).

Most placers in New Mexico are low grade, disseminated deposits consisting of small flakes of gold, most of which is greater than 900 fine. Small high-grade deposits are found locally. Small streaks with assays as high as 3 oz/yd^3 are reported from the Pittsburg district (DIS202), but the average grade is less than 0.03 oz/yd^3 (Harley, 1934). Early production from cemented gravel deposits in the Hillsboro district ran 0.10 oz/yd^3, but drilling and blasting was required (Heikes, 1913). Mined deposits at Old Placers typically contained 0.06 oz/yd^3 (Lindgren et al., 1910) and at New Placers 0.08 oz/yd^3 (Elston, 1967). The Picuris placer (DIS236)
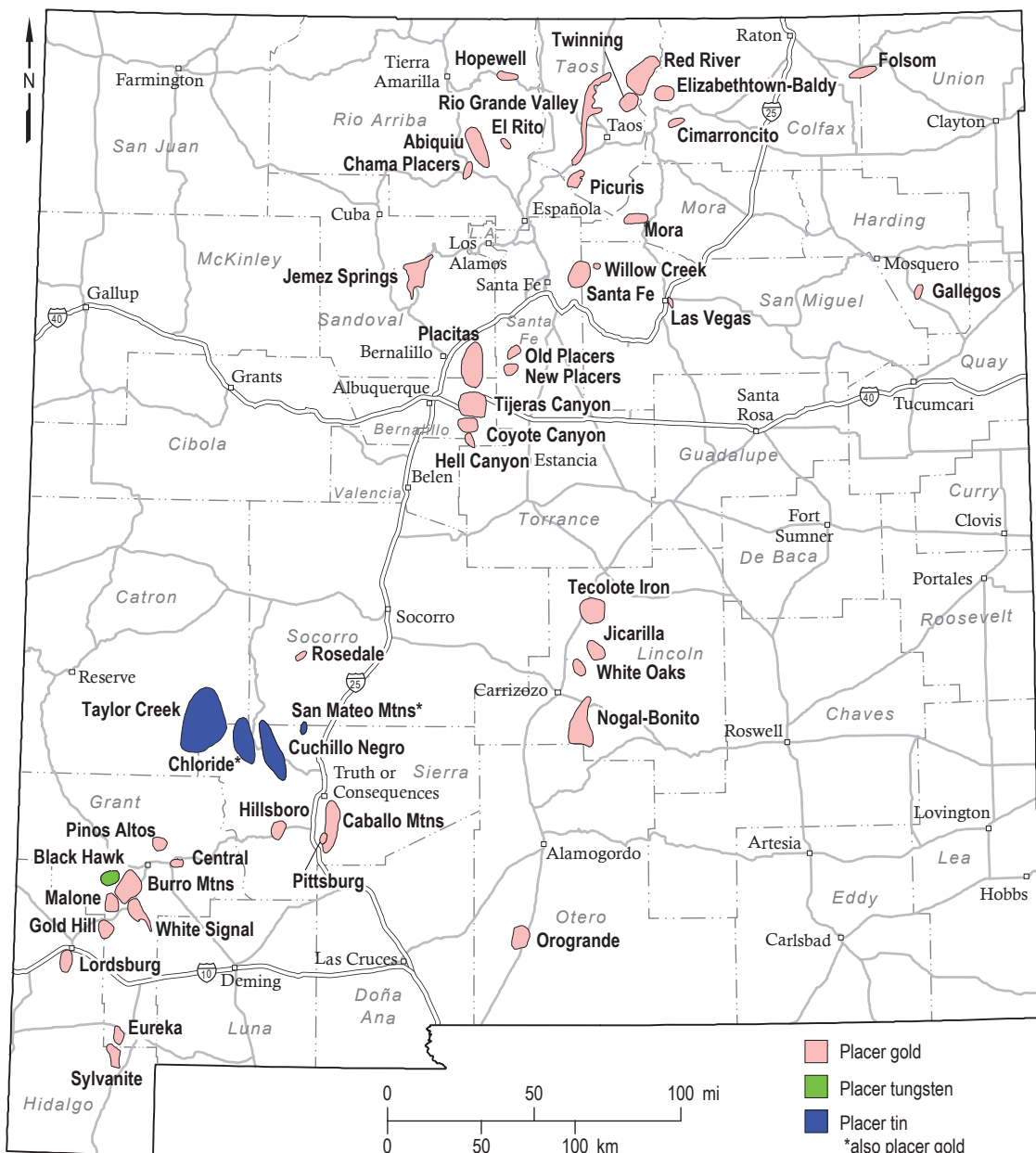

Figure 42. Placer deposits in New Mexico.

contained 1960 yd^3 of 0.003 oz/yd^3 Au (Orris and Bliss, 1985). Nuggets up to 12 oz have been found at Elizabethtown-Baldy (Jones, 1904) and up to 4 oz at Hopewell (DIS145, Wells and Wootton, 1940). However, most placers in the state contain less than 0.05 oz/yd^3. Placer gold deposits in New Mexico are similar in mode of occurrence and grades to placer gold deposits world-wide (Cox and Singer, 1986).

The economic potential of placer deposits in New Mexico is unknown and most known economic placers in the state have been worked. Many streams in New Mexico contain at least traces of gold, enough to satisfy weekend gold panners. The future economic potential will depend upon the discovery of large-volume, medium-grade deposits that can be mined by bulk-mining methods. Lack of water has hampered mining in many districts and new technology, which minimizes water usage, may stimulate activity. Current environmental and permitting restrictions have also hampered recent production in the New Placers and Jicarilla districts. Published historic reserves exist for only two districts: Jicarilla with 5.4 million yd^3 of 0.043 oz/yd^3, or approximately 230,000 oz Au in place (Segerstrom and Ryberg, 1974) and Pittsburg with 2 million yd^3 of 0.01 oz/yd^3, or approximately 20,000 oz Au in place in 1936 (Howard, 1967). Recreational mining continues intermittently in the White Oaks, Pittsburg, Hillsboro, Orogrande and Jicarilla districts to the present day. Several sand and gravel operators periodically extract minor quantities of placer gold from their quarries.

Exploration drill rig at Tres Hermanos district, 1996. *Photo by Virginia T. McLemore.*

IX. FUTURE POTENTIAL

New Mexico has a wealth of metallic mineral deposits. The most important types of deposit in the state, in terms of production, size and future mining potential, are the Laramide porphyry copper, Laramide polymetallic vein and Oligocene-Miocene volcanic-epithermal vein deposits. Placer gold deposits will continue to be developed and mined on a small scale by recreational miners.

Changing technologies and economics suggest other types of deposits, up to now unrealized, may exist in the state. The Olympic Dam deposit in Australia is an iron oxide-copper-gold ±uranium (IOCG) deposit and is one of the largest copper-uranium deposits in the world (Hitzman and Valenta, 2005). Many mineralized regions in the world are being re-examined for the potential for this class of deposit and some of the minor deposits along the Capitan, Santa Rita, and Morenci lineaments in the Chupadera Mesa area are suggestive of undiscovered IOCG deposits because they have similar structural features and metal associations (McLemore and Zimmerer, 2009). IOCG deposits are found in continental rift settings and appear to be controlled by regional lineaments. IOCG deposits contain essentially titanium-poor magnetite and hematite and most are associated with saline hydrothermal fluids, calc-alkaline to sub-alkaline to alkaline A-type igneous rocks, low sulfur contents, and enrichment in REE, copper, gold, silver, and uranium (Barton et al., 2000).

Northern Nevada contains some of the largest gold deposits in the world, known as Carlin-type gold deposits (Emsbo et al., 2006). Carlin-type deposits consist of submicron-sized gold in arsenian pyrite that is disseminated in fractured carbonaceous shale and carbonate rocks, and is associated with anomalous mercury, antimony, arsenic, and thallium. Alteration typically includes silicification, argilization, and sulfidation. Other rift areas in the world are being examined for this type of deposit, including the southern Rio Grande rift area.

Known deposits of REE occurrences in New Mexico also could become important in the future along with other critical and strategic minerals such as selenium, cadmium, and tellurium. Other metal commodities, currently not considered, could become important in the future as technology evolves. Many of these elements are typically found associated with other types of mineral deposits, especially precious and base metals deposits, and represent potential deposits in known mining areas. Future exploration programs should analyze samples for many of these strategic and critical elements for potential by-product recovery.

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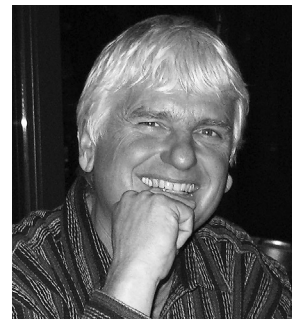
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She has written and edited two books recently published by SME (Society for Mining, Metallurgy, and Exploration, Inc.) on mining environmental issues: 1) Management Technologies for Metal Mining Influenced Water, Volume 1: Basics of Metal Mining Influenced Water and 2) Management Technologies for Metal Mining Influenced Water, Volume 6: Sampling and monitoring for the mine life cycle.

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GLOSSARY

This glossary includes terms related to economic geology, mining, and reclamation.

For a glossary of general mining and processing terms, see
http://www.coaleducation.org/glossary.htm
http://www.miningandmetallurgy.com/mining/glossary-mining-terms
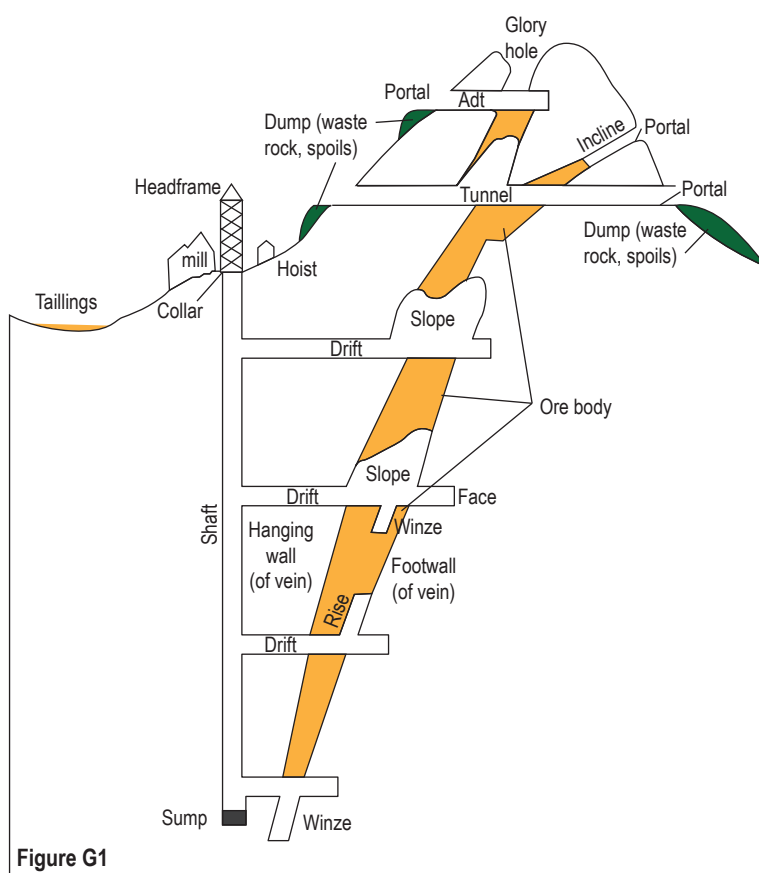
Many mine features and mine terms are shown in Figure G1 below.

Figure G1

Abandoned mine—An abandoned mine, at which exploration, development, mining, reclamation, maintenance, and inspection of facilities and equipment, and other operations ceased and with no evidence demonstrating that the miner intends to resume mining.

Adit—A horizontal or nearly horizontal passage driven from the surface for the development or dewatering of a mine (Fig. G1). If an adit is driven through the hill or mountain to the surface on the opposite side, it is called a "tunnel."

Acid mine drainage (AMD) or Acid rock drainage (ARD)—Results from oxidation of sulfide minerals exposed to weathering by mining producing sulfuric acid that further dissolves minerals in the rocks, to release metals into the water. Acid mine drainage implies that acid drainage is caused by the mining process and does not include natural drainage.

Agglutination—the clumping of particles.

Alluvium—Unconsolidated mud, sand, and gravel deposited by flowing water.

Anthracite—A hard black vitreous coal containing a high percentage of fixed carbon and a low percentage of volatile matter. Commonly referred to as hard coal.

Anthropogenic—Formed through or related to the activities of humans.

Aquifer—A body of rock or sediments capable of storing and transmitting water.

ArcGIS—A geographic information system (GIS) that allows storage, retrieval, and analysis of spatially related information in both graphical and database formats.

Background—Natural concentrations of an element in natural materials that exclude human influence. A "background measurement" represents an idealized situation and is typically more difficult to measure than a "baseline."

Beneficiation—The processing of ores for the purpose of regulating the size of a desired product, removing unwanted constituents, and improving the quality, purity, or assay grade of a desired product.

Bolson—A flat-bottomed depression surrounded by mountains, typically containing a saltpan or salt lake.

Carbonates—A family of rocks containing Ca and/or Mg carbonate, such as limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) and which excludes siderite ($FeCO_3$).

Chimney—an orebody that is irregular-shaped, chimney- or pipe-shaped shaped vertical carbonate-hosted ore deposits, generally copper, lead, zinc, silver, and/or manganese.

Compaction—Increase in soil bulk density and reflected in increased penetrometer resistance caused by loading at the surface, generally by wheel traffic.The action of moving soil particles closer together by compressing the pore space.

Contaminant—Any physical, chemical, biological, or radiological substance or matter that has an adverse effect on air, water, or soil.

Concentrating—The mechanical process, often involving flotation, by which the valuable part of an ore (the "concentrate") is separated from the "gangue", or non-economical rock minerals to be disposed of as "tailings."

Concentrator—Part of the mining plant used to separate valuable minerals from the ore. In mineral sand mining, the concentrator is often referred to as the "wet" mill because it uses a water slurry for separation, and it is often floated on pontoons in a dredge pond.

Drainage—Any water draining from a natural or man-made feature. Includes natural surface water runoff, mine drainage, and ground water that has come to the surface.

Drainage basin—The surface between topographic divides that receives precipitation. This water is conveyed down slope as surface runoff or ground water. Also known as a catchment or watershed.

Dredge mining—Frequently used in mineral sand mining to recover the ore from the mine face as a water slurry by suction. The dredge houses a powerful pump and is floated on pontoons in the dredge pond. In a suction cutter dredge, ore recovery is assisted by a revolving open basket (cutter) mounted over the suction inlet. In hard ground, the cutter can be replaced by a rotating underwater bucketwheel. This term can also be applied to a mine waste material associated with placer dredge mining.

Drill—A machine with a rotating bit used to drill holes in overburden materials. In the case of hard rock mining, these holes then are partially filled with explosives for loosening up the rock to be removed in mining

Drusy quartz—texture where a layer of closely spaced, small quartz crystals lines a surface or cavity

Environmental impact assessment—A process required under the National Environmental Protection Act for projects involving federal or state money, in which potential physical and social impacts and mitigation measures are discussed and analyzed. A provision for notifying citizens and considering their comments is integral to the process.

Erosion—The entrainment and transportation of soil through the action of wind, water, or ice.

Extraction—The process of mining and removal of coal or ore from a mine. This term often is used in relation to all processes of obtaining metals from ores, which involve breaking down ore both mechanically (crushing) and chemically (decomposition), and separating the metal from the associated gangue.

Fine tailings—Fine-grained clastic materials (silts and clays) and/or residual bitumen that consolidate very slowly.

Flotation—The method of mineral separation in which a froth, created in water by a variety of reagents, floats valuable finely crushed minerals while other minerals sink.

Fly ash—A powdery material of predominately small glass spheres that is very light and usually collected in electrostatic precipitators, bag houses, or cyclones during burning of coal in electrical power generation combustion chambers.

Galls—Small balls of clay in sedimentary walls.

Gangue—The valueless minerals in an ore; that part of an ore that is not economically desirable, but cannot be avoided when mining the deposit. It is separated from the ore during beneficiation.

Groundwater—Zone below the surface of the earth where voids are filled with water and the pressure is 9.9 MPa (1 atm). This is in contrast to surface water.

Heap-leach recovery—Industrial process that recovers metals using chemicals sprayed onto a pile of crushed ore.

Heavy mineral sands—Valuable minerals such as rutile, ilmenite, leucoxene, zircon, and monazite occurring as a sand-sized fraction, with a high specific gravity relative to that of the host sand.

Hematite—A type of iron ore with the composition formula of Fe_2O_3.

Hydrocarbons—Organic chemical compounds of hydrogen and carbon atoms that form the basis of all petroleum products.

Inactive mine—The area in which no active mining is currently taking place relative to extraction of metal ores, industrial minerals, and other minerals of economic value.

Incline—Sloped entrance to underground mine, mined from the surface usually along the dip of a vein or stratigraphic horizon (Fig. G1). Sometimes called "decline," or "declined shaft."

Jarosite—A pale yellow to gray-green potassium iron sulfate mineral [$KFe_3(OH)_6(SO_4)_2$] that forms under active acid sulfate conditions. Can be a pathfinder mineral for areas of oxidation of iron sulfides and associated acid generation.

Jasperoid—a dense, siliceous rock where silica (fine-grained quartz) has replaced carbonate minerals of limestone, dolomite, or other carbonaceous sedimentary rock

Leaching—Removal of dissolved, adsorbed, or absorbed substances from a matrix by passing liquids through the material.

Limestone—A sedimentary rock composed chiefly of calcium carbonate ($CaCO_3$). Limestone can form by either organic or inorganic means.

Lithology—The character of a rock described in terms of its structure, color, mineral composition, grain size, and arrangement of its component parts; all those visible features that in the aggregate impart individuality to the rock.

Lode—metallic deposit in veins or strat-abound in sedimentary rocks

Maars—a low-relief volcanic crater caused by a phreatomagmatic eruption (an explosion which occurs when groundwater comes into contact with hot lava or magma)

Magnetite—A magnetic iron mineral that has the formula Fe_3O_4. Can form iron ore.

Manto—an orebody that is stratabound irregular-shaped, blanket-like carbonate-hosted ore deposits, generally copper, lead, zinc, silver, and/or manganese that are usually horizontal or near horizontal in attitude.

Metallogenesis—Study of the origin of mineral deposits and their relationship of geologic time and space with other geologic processes such as tectonics.

Metallurgy—The science and technology of extracting and refining metals and the creation of materials or products from metals.

Metasomatism—The chemical alteration of a rock by hydrothermal and other fluids.

Mica—An aluminosilicate mineral in which two silica tetrahedral sheets alternate with one octahedral sheet, with entrapped potassium atoms fitting between the sheets.

Milling—The grinding or crushing of ore. The term may include the operation of removing valueless or harmful constituents from the ore and preparation for additional processing or sale to market.

Mine—An opening or excavation in the ground for the purpose of extracting minerals (Fig. G1).

Mineralogy—The study of minerals and their formation, occurrence, use, properties, composition, and classification. Also refers to the specific mineral or assemblage of minerals at a location or in a rock unit.

Mining—The process of extracting useful minerals from the Earth's crust.

Mining district—A section of country usually designated by name, having specified boundaries within which mineral deposits are found and mined, in some cases under rules and regulations prescribed by the miners therein or by a government body. There is no limit to its territorial extent, and its boundaries may be changed if vested mineral or property rights are not thereby interfered with. Can be either an informal name for a mineral area or a legally defined area encompassing all or part of a collection of mineral deposits and/or mines.

Mineral deposit—Any occurrence of a valuable commodity or mineral that is of sufficient size and grade (concentration) for potential economic development under past, present, or future favorable conditions.

Oolitic—A rock consisting of small round grains, usually of iron oxide or calcium carbonate cemented together.

Open stope (or stope)—Linear opening mined from underground to the surface along the course of a vein or mineralized zone (Fig. G1).

Ore—The naturally occurring material from which a mineral or minerals of economic value can be extracted profitably or to satisfy social or political objectives. The term is generally, but not always, used to refer to metalliferous material, and is often modified by the names of the valuable constituents.

Ore deposit (ore body)—A well-defined mineral deposit that has been tested and found to be of sufficient size, grade, and accessibility to be extracted and processed at a profit over a specific time.

Organic matter—The accumulation of disintegrated and decomposed biological residues, and other organic compounds synthesized by microorganisms, found in soil.

Overburden—Designates material of any nature, consolidated or unconsolidated, that overlies a deposit of useful and mineable materials, ores, or coal, especially those deposits that are mined from the surface by open cuts.

Oxidation—A chemical process involving reaction(s) that produce an increase in the oxidation state of elements such as iron and sulfur.

Oxidize—The chemical reaction involving the removal of electrons from an element (e.g., Fe^{2+} Fe^{3+}).

Oxidized zone—That part of the soil-geologic column from which sulfide minerals have been completely oxidized away, compared with the reduced zone. May be equivalent to the "zone of weathering".

Paleoenvironment—The ancient geologic setting (climate, geography, etc.) under which strata were deposited.

pH—A measure of the acidity (less than 7) or alkalinity (greater than 7) of a solution; a pH of 7 is considered neutral. A measure of the hydrogen ion concentration (more specifically, the negative log of the hydrogen ion activity) of a soil suspension or water.

Placer deposits—An alluvial deposit of an economically important mineral or material, usually as a mineral-gravel or sand, typically containing gold or gemstones. Also high-grade concentrations of heavy mineral sands formed as lenses on present or ancient beach berms by wave action.

Pollutant—Any substance introduced into the environment that adversely impacts the usefulness of a resource.

Porewater—Water occupying the voids in soil or sediment.

Processing—The methods employed to clean, process, and prepare coal and metallic ores for the final marketable product.

Production—The total amount of mass produced by a plant, mine, aquifer, etc.

Pozzolans—Siliceous or siliceous and aluminous materials that in themselves possess little or no cementitious value but will, in a finely divided form and in the presence of moisture, chemically react with calcium hydroxide in cement at ordinary temperatures to form compounds possessing cementitious properties. Pozzolans are used in cement and concrete.

Pyrite—An iron sulfide (FeS_2) which forms acid mine drainage upon exposure to oxidizing conditions and in the absence of $CaCO_3$. Sometimes called "fool's gold".

Quarry—Any open or surface working, usually for the extraction of sand and gravel, building stone, slate, limestone, etc.

Quartz—A very hard, inert mineral of SiO_2, commonly found in sand and sedimentary, igneous, and metamorphic rocks.

Reclamation—Restoring mined or disturbed land to the conditions that are acceptable under regulatory requirements and which return the site to a safe and useful condition (e.g., grazing, recreation, agriculture, wildlife habitat, etc.).

Refining—The purification of a crude metal product; normally the stage following smelting. For bitumen it is the fractionation into various components such as gasoline.

Refractory—A substance that is resistant to heat.

Relational database—An electronic database comprising multiple files of related information, usually stored in tables of rows (records) and columns (fields), and allowing a link to be established between separate files that have a matching field, as a column of invoice numbers, so that the two files can be queried simultaneously by the user.

Remediation—Cleanup or other methods used to remove or contain a toxic spill or hazardous materials from a site. The process of correcting, counteracting, or removing an environmental problem, often referring to the removal of potentially toxic materials from soil or water by use of bacteria (bioremediation) or plants (phytoremediation).

Remining—Returning to abandoned underground or surface mines or previously mined areas for further coal removal by surface mining and reclaiming to current reclamation standards. Also refers to the process of mining and processing of non-coal mine and mill wastes (processed or unprocessed) to extract additional metals or other commodities due to a change in extraction technology or economics that make such remining profitable.

Representative sample—A portion of material or water that is as nearly identical in content and consistency as possible to that in the larger body of material or water being sampled.

Room and pillar—Also sometimes called "board and pillar" in Europe. A form of underground mining in which typically more than half of the coal is left in the mine as pillars to support the roof. Room and pillar mines generally are not expected to subside, except where retreat mining is practiced. Also a mining method used for thick and/or flat-lying industrial, metal, and non-metal mineral deposits, such as limestone, trona, salt, etc.

Sample—A representative portion of a population.

Sands—Tailings particles of a size (generally >0.05mm) and weight that readily settle in water.

Scrubber—Equipment that entraps and removes potential pollutants with water before they are released to the atmosphere.

Sedimentation—The process of depositing entrained soil particles or geologic materials from water. In a mining context, usually resulting from erosion of disturbed land and considered a negative impact to streams and other water bodies.

Sewage—The mainly organic, solid residual materials resulting from the treatment of sewage, often used as a soil amendment.

Shaft—Vertical (or near-vertical) entrance to underground mine (Fig. G1). Climbing or powered man cage (elevator) is required to get out.

Shale—A finely laminated, hardened sediment composed of silt and clay or clay-sized particles.

Silicate ore—An ore in which the valuable metal is combined with silica rather than sulfur.

Sintering—The use of heat to fuse ores or concentrates preparatory to further processing.

Skarn—metamorphic zone developed in sedimentary rocks at the contact with igneous intrusions and containing calc-silcate minerals, such as wollastonite, diopside, forsterite, garnet

Slate—In old coal mining usage, "slate" or "draw slate" is fine-grained sedimentary rock often black (carbonaceous) and tending to split along cleavage or bedding planes, resulting in flat rocks. Usually found above and next to some coal beds. In correct geologic terminology, it is a metamorphic rock derived from shale that has been subjected to heat and/or pressure.

Slimes—The refuse material, silt or clay in size, resulting from the washing, concentration, or treatment of ground ore.

Slope—The degree to which the ground angle deviates from horizontal, expressed as a percent rise over run or as a degree angle.

Smelter—An industrial plant or process that extracts a metal from an ore at high temperature by chemical and physical processes that occur in the molten state.

Smelting—The chemical reduction of a metal from its ore by a process usually involving fusion, so that earthy and other impurities separate as lighter and more fusible slags and can readily be removed from the reduced metal. The process commonly involves addition of reagents (fluxes) that facilitate chemical reactions and the separation of metals from impurities.

Stream channel—A trough in the landscape that conveys water and sediment. Channel formed is the product of the flow. Includes ephemeral, intermittent, and perennial stream channels. Also known as gullies, washes, runs, creeks, brooks, and rivers, with the term used often depending on size of the channel or waterway.

Surface-mine (strip mine)—A procedure of mining which entails the complete removal of overburden material. May generally refer to either an area and/or contour mine.

Surface water—Water at or near the land surface, such as lakes and streams as opposed to ground water.

Swamp—A forested wetland with little peat development.

Tailings—See Fig. G1. The solid waste product (gangue and other refuse material) resulting from the milling and mineral concentration process (washing, concentration, and/or treatment) applied to crushed ore. Term usually used for sand to clay-sized refuse that is considered too low in mineral values to be treated further, as opposed to the concentrates.

Unoxidized zone—See "reduced zone".

Ventilation drift or shaft—A horizontal adit or tunnel or vertical shaft in a mine having the prime purpose of exchanging gases with the outside atmosphere.

Volcanic ash—Fine-grained uncemented material ejected during a volcanic eruption.

Vuggy textures—texture having vugs.

Waste rock—Barren or mineralized rock that has been mined, but is not of sufficient value to warrant treatment and, therefore, is removed ahead of the milling processes and disposed of on site (Fig. G1). Term usually used for wastes that are larger than sand-sized material and can be up to large boulders in size. Waste rock pile also called dump, spoil pile, or spoils.

Weathering—Process whereby earthy or rocky materials are changed in color, texture, composition, or form (with little or no transportation) by exposure to atmospheric agents.

Workings—The entire system of openings (underground as well as at the surface) in a mine (Fig. G1).

ABBREVIATIONS

Ag—silver
A-S—acid-sulfate
Au—gold
Be—beryllium
Bbls—barrels
BBO—billion bbls oil
BCF—billion cubic feet (ft^3)
BHP—Broken Hill Proprietary or bottom hole pressure if one is discussing geothermal, oil and gas wells
BHT—Bottom hole temperature (in a well)
BLM—U.S. Bureau of Land Management
Btu/lb—British thermal units per pound of fluid
CPD—Carlsbad potash district
CSDP—Continental Scientific Drilling Program
CO_2—Carbon dioxide
Cu—copper
D—Derivative waters (geothermal)
DPA—Designated Potash Area
DG—Deep geothermal waters
EMNRD—Energy, Mineral, and Natural Resources Department (New Mexico)
GCC—Grupo Cementos de Chihuahua (cement)
GPM—Great Plains Margin
HDR—hot dry rock (geothermal)
I/S—illite/smectite clays
JPSB—Jemez Pueblo-San Juan Basin type
ka—thousand years ago
KCl—potassium chloride
km—kilometers
LANL—Los Alamos National Laboratory
LBL—Lawrence Berkeley Laboratory
lbs—pounds
Li—lithium
m—meters
Ma—million years ago
Myr—Million years old
MBO—thousand bbls oil
mi—miles
MOP—muriate of potash
MORB—mid-ocean ridge basalt
MRI—Magnetic resonance imaging
MVT—Mississippi Valley-type
MWe—Megawatts (electrical)
NMBMMR—New Mexico Bureau of Mines and Mineral Resources
NMBGMR—New Mexico Bureau of Geology and Mineral Resources
NMMMD—New Mexico Mining and Mineral Division
NMIMT—New Mexico Institute of Mining and Technology

NURE—National Uranium Resource and Evaluation
OSHA—Occupational Safety and Health Administration
oz—ounces
oz/short ton—ounces per short ton
P & A'd—plugged and abandoned (well)
PGE—platinum group elements (platinum, Pt; palladium, Pl; osmium, Os; ruthenium, R; iridium, I; and rhodium, Rh)
Pb—lead
PNM—Public Service Company of New Mexico
ppb—parts per billion
ppm—parts per million
REE—rare earth elements
RGR—Rio Grande Rift
SMCRA—Surface Mine Control and Reclamation Act
Th—thorium
TCF—trillion cubic feet (ft3)
U—uranium
μm—micrometers
UNOCAL—Union Oil Company of California
USDOE—U.S. Department of Energy
USGS—U.S. Geological Survey
USBM—U.S. Bureau of Mines
VCNP—Valles Caldera National Preserve
VMS—Volcanogenic massive sulfide
WIPP—Waste Isolation Pilot Plant
Wt%—weight percent
Y—yttrium
Zn—zinc
Zr—zirconium
δ—delta value used in isotope measurements
°C—degrees centigrade

INDEX

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