Energy and Mineral Resources of New Mexico

Industrial Minerals and Rocks

Virginia T. McLemore and George S. Austin

VOLUME E

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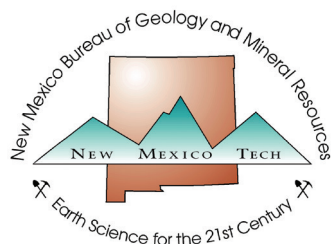
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and Maureen Wilks

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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
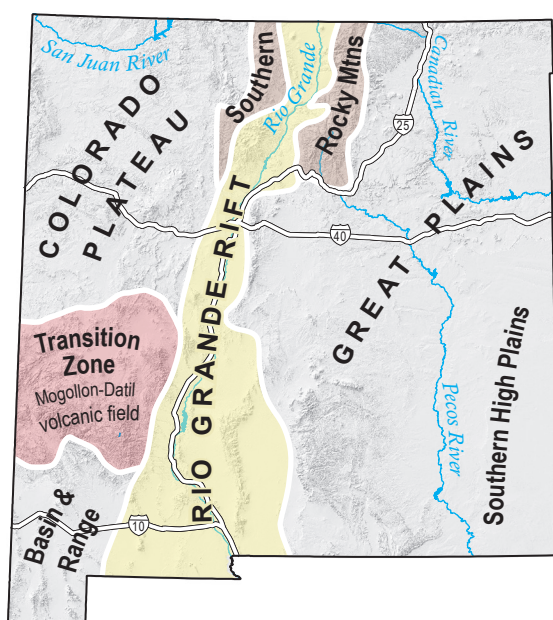
Figure 2. Physiographic provinces of New Mexico.

Geologic unit

Q	Quaternary sediments	
QT	Quaternary - Tertiary sediments	
Qv	Quaternary rhyolites, tuffs	
QTb	Quaternary - Tertiary basalts, andesites	
T	Tertiary sediments	
Tv	Tertiary volcanics	

TKi	Tertiary-Cretaceous intrusives	
K	Cretaceous sediments	
JŦ	Jurassic-Triassic	
P	Permian	
IP	Pennsylvanian	
Pz	Paleozoic undifferentiated	
pϾ	Precambrian	
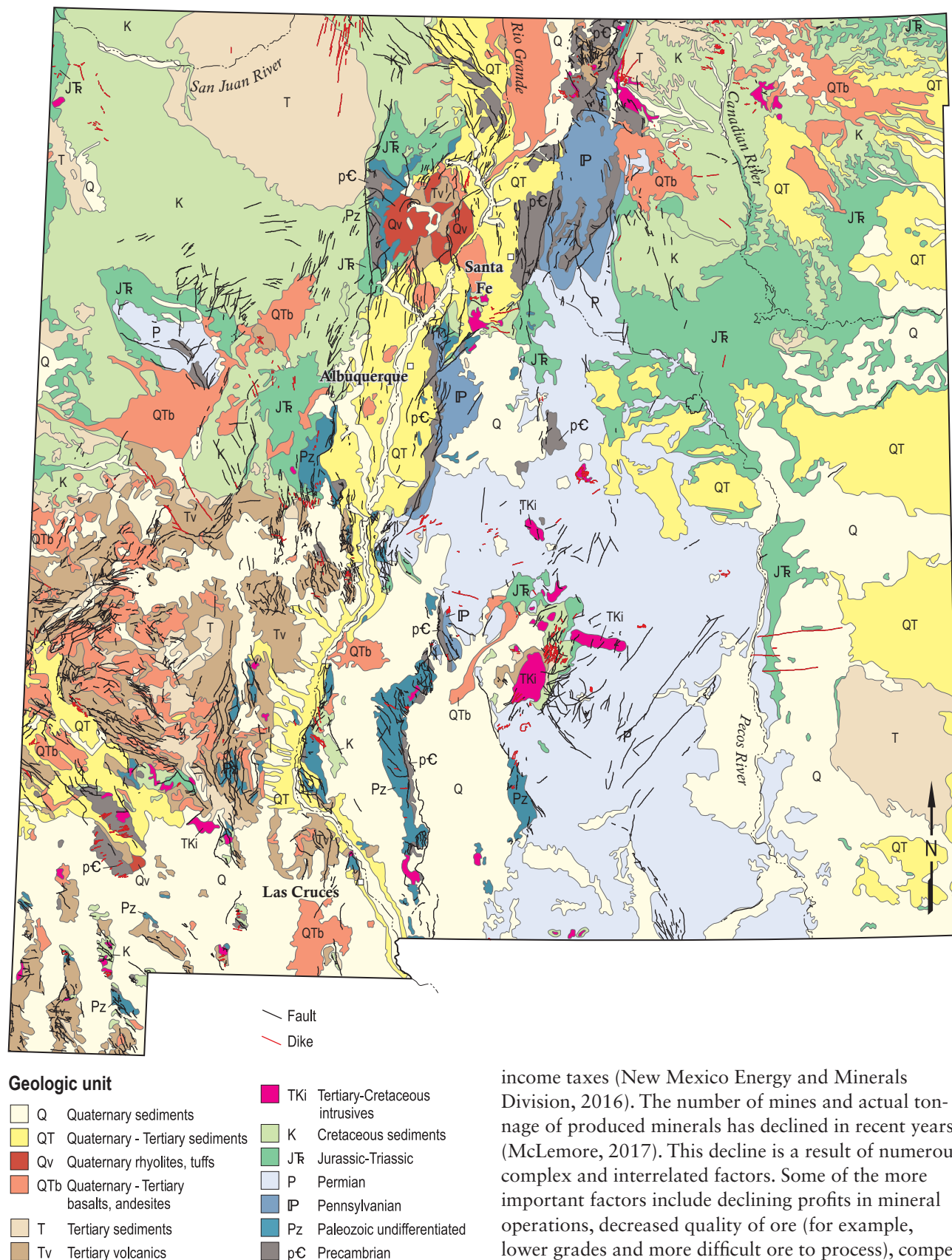
Figure 3. Simplified geologic map of New Mexico.

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 ft³ 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 ft³	—	$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		0.01
		Pleistocene	Bandelier Tuff	2.8
	Tertiary	Pliocene	Late Tertiary 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	65.5
			Laramide orogeny	
Mesozoic	Cretaceous	Upper	Kirtland Formation, Fruitland Formation, Pictured Cliffs Sandstone, Mesaverde Group, Mancos Shale, Dakota Sandstone	
		Lower		145.5
	Jurassic	Upper / Middle / Lower	Morrison Formation, Bluff Sandstone, Summerville Formation, Todilto Formation, Entrada Sandstone	199.6
	Triassic	Upper / Middle / Lower	Chinle Group, Santa Rosa Formation, Moenkopi Formation	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			1,600
	Early		Proterozoic rock of the Sangre de Cristo Mtns., Oldest rock in New Mexico	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
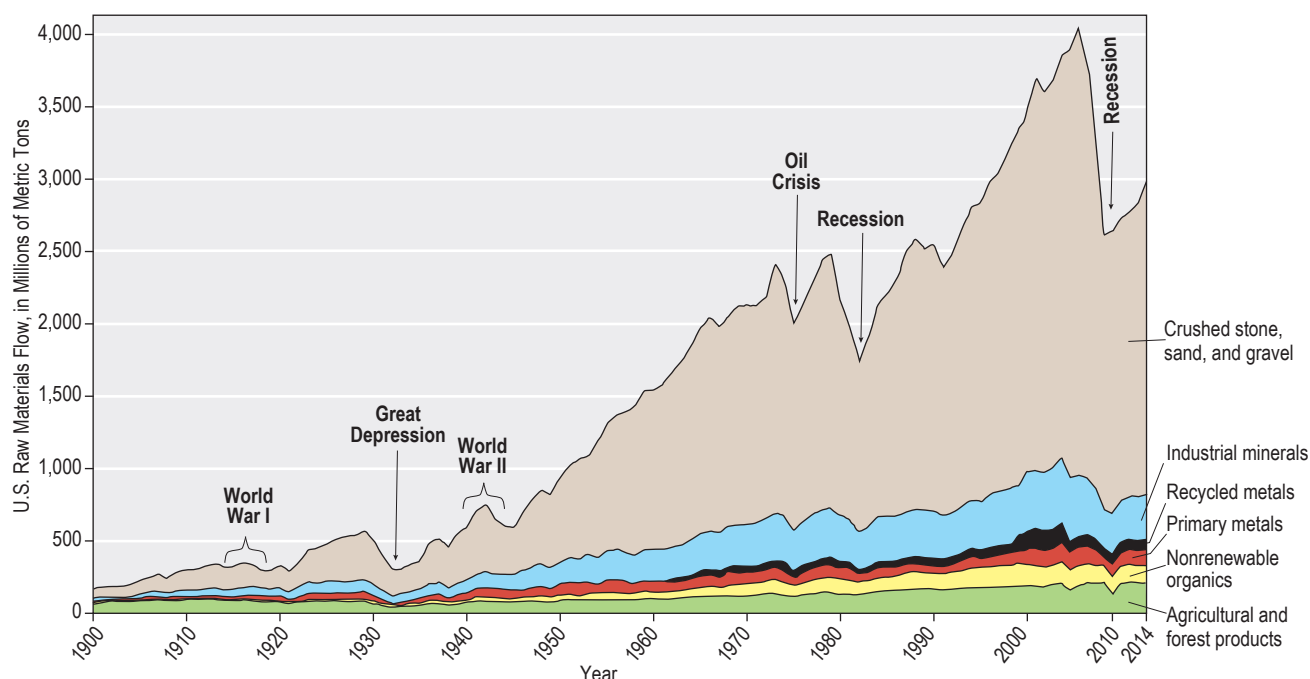
Figure 5. United States flow of raw materials by weight from 1900–2014. The use of raw materials increased dramatically during the last 100 years (modified from Wagner, 2002).

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

Industrial minerals and rocks are any rock or mineral, or other naturally occurring substance of economic value, excluding most metals, fuels, and gemstones. Industrial minerals and rocks are used in the manufacture of many products, from ceramics to plastics and refractories to paper. Production of industrial minerals has been and remains important to the rural economy of New Mexico. In 2017, some 240 mines were registered in New Mexico. This total includes 25 industrial mineral operations and approximately 115 aggregate operations. New Mexico leads domestic production of potash, perlite, zeolite, and travertine. Other production includes aggregate, humate, pumice, gypsum, salt, common and fire clay, scoria, limestone, fly ash, cement, magnetite, silica, and decorative stone. New Mexico has potential for additional production of industrial minerals. At least one company is exploring for garnet. Cretaceous beach placer black sandstones in the San Juan Basin have drawn interest for titanium, iron, rare earth elements (REE), and zircon. Other REE deposits are being explored. Recent exploration has occurred for beryllium in the San Mateo Mountains, Iron Mountain, and Victorio districts. Aggregate continues to be produced throughout New Mexico as construction activities increase, including highway construction and repair.

Belen travertine facility, 1989 (NMVA0014). *Photo by Virginia T. McLemore.*

I. INTRODUCTION

Industrial minerals and rocks are literally the building blocks of our way of life. They are an exceptionally diverse and vital group of raw materials that underpin almost all aspects of human activity, infrastructure, and standard of living. Industrial minerals and rocks are used in the manufacture of many products, from ceramics to plastics and refractories to paper. Although industrial minerals permeate every aspect of daily life, their presence and their role are typically invisible. A widely used definition of industrial minerals and rocks is "any rock, mineral, or other naturally occurring substance of economic value, exclusive of metal ores, mineral fuels, and gemstones: one of the non-metallics" (Bates, 1975). This definition includes the important construction materials sector as well as specialized industrial minerals, but complex interactions between consumer industries produce a number of apparent anomalies to this definition. Some metals are included as industrial minerals because their use is industrial rather than as a metal. Waste products of several bulk industrial processes also are included, because they are important industrial raw materials in their own right. Pulverized fuel ash from power stations may not be a natural raw material, but it is an important pozzolan used in the cement and construction industry. Sulfur is now predominantly extracted as a by-product of cleaning natural gas, one of the world's major energy fuels.

Production of industrial minerals has been and remains important to the rural economy of New Mexico. Industrial minerals constitute more than 40% of the more than $2.5 billion generated by mineral production in New Mexico in 2015 (Table 1; New Mexico Energy, Minerals, and Natural Resources Department, 2015). In 2015, some 240 mines were registered in New Mexico. This total includes 25 industrial mineral operations and approximately 115 aggregate operations. New Mexico leads domestic production in potash, perlite, zeolite, and travertine. Other production includes aggregate, humate, pumice, gypsum, salt, common and fire clay, scoria, limestone, fly ash, cement, magnetite, silica, and decorative stone. Additional production statistics are in Harben et al. (2008).

Table 1. Production of industrial minerals, aggregates and potash from New Mexico from 2000–2015 (from New Mexico Mining and Minerals Division, 2000–2016). Other industrial minerals include gypsum, perlite, salt, limestone, dimension stone, silica flux, clay, humate, scoria, pumice, mica, and zeolites.

Year	Other industrial minerals		Aggregates		Potash		Total mineral production (including coal)
	short tons	dollars	short tons	dollars	short tons	dollars	dollars
2000	2,925,926	$162,402,617	13,752,251	$66,810,485	1,377,801	$215,737,596	$1,377,411,947
2001	2,561,004	$166,705,643	12,353,090	$61,115,960	985,574	$191,732,005	$1,236,641,553
2002	2,393,754	$174,603,868	15,441,510	$73,499,682	1,014,529	$188,611,426	$1,255,111,627
2003	2,274,999	$153,198,856	14,838,772	$77,848,579	1,064,485	$202,166,863	$1,235,443,804
2004	2,379,183	$168,557,974	34,547,746	$103,810,297	1,069,285	$237,619,345	$1,556,919,881
2005	2,466,281	$200,871,063	20,014,987	$128,730,636	988,782	$282,710,833	$1,859,392,448
2006	2,285,585	$261,668,905	19,317,521	$140,022,212	825,540	$237,603,468	$2,169,731,560
2007	2,110,308	$192,398,110	15,864,974	$140,214,362	922,628	$273,946,696	$2,200,256,141
2008	2,108,801	$157,840,649	16,740,148	$102,273,471	1,076,759	$612,745,114	$2,359,634,440
2009	156,111	$124,402,302	13,537,659	$110,879,335	602,231	$491,276,710	$1,756,799,711
2010	2,343,734	$110,718,970	10,752,950	$81,697,488	812,756	$512,426,376	$1,780,236,662
2011	1,472,746	$107,097,166	9,813,528	$68,432,817	781,282	$636,047,697	$2,214,706,950
2012	1,491,760	$108,975,769	8,543,379	$76,945,909	1,548,047	$953,477,008	$2,801,634,159
2013	1,248,312	$91,113,849	9,393,307	$81,505,531	2,188,874	$914,659,051	$2,010,776,277
2014	1,199,137	$77,800,389	11,339,585	$93,439,942	2,130,352	$1,093,208,523	$3,105,241,950
2015	1,411,731	$87,305,356	8,169,753	$62,625,896	1,433,245	$659,505,518	$2,522,092,050
Total 2000–2015	**30,829,372**	**$2,345,661,486**	**234,421,160**	**$1,469,852,602**	**18,822,170**	**$7,703,474,229**	**$31,442,031,160**

Many industrial minerals are low-value commodities and depend upon locally available transporation networks (highways, railroads) in order to ship the respective commodity at low cost. Thus, some industrial minerals could be produced in the future as new highways or railroads are built in New Mexico. Other industrial minerals in New Mexico could see declining production because better and more efficient transporation networks are built elsewhere, which allows for cheaper transportation costs (Barker, 1996; Kogel et al., 2006). For example, many of the perlite mines in New Mexico have closed, because it is cheaper to transport perlite to the east coast of the United States (where the manufacturing plants are located) from Greece by ocean transport ships, then it is to ship New Mexico perlite by highway or railroad.

The purpose of this volume is to summarize the industrial mineral deposits found in New Mexico. 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. (2002) can be obtained by request using the mine id number. The deposit types used in this report are generally the same used for the metallic minerals as described by McLemore and Lueth (2017). The districts are shown in McLemore (2017) with the same district ID number.

Data used in this report have been compiled from a literature review, field examinations, and unpublished data by the authors. For a summary of industrial minerals and rocks in New Mexico, see USGS (1965). For less comprehensive information on the industrial minerals and rocks of the state, Austin (1982), Austin et al. (1996), Clark (1996), Harben et al. (2008), and McLemore (2017) are useful.

For information on mineral occurrences, the reader is urged to consult Northrop (1996) and the many publications of the New Mexico Bureau of Geology and Minerals Resources (NMBGMR). For detailed information on the uses and world-wide deposits, the reader should examine Kogel et al. (2006) and the U.S. Geological Survey (USGS) commodity reports (http://minerals.usgs.gov/minerals/pubs/commodity/, accessed 10/20/14). Information on active mines is from the New Mexico Mining and Minerals Division (http://www.emnrd.state.nm.us/MMD/gismapminedata.html, accessed 10/20/14) and their annual reports (New Mexico Mining and Minerals Division, 1999-2015). Mining districts are shown in McLemore (2017). This chapter includes information from all of these sources. 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.

The presentation of information in this chapter uses the sequence established in Kogel et al. (2006) with four exceptions. First, whereas Kogel et al. (2006) uses a three-fold sequence: 1) introduction and overview, 2) commodities, and 3) markets and uses, this report uses only a two-fold sequence of 1) introduction and 2) commodities and uses. As such, the sections on adobe and earthen construction and soil amendments are grouped alphabetically with the commodities. Second, the natural abrasives that are found in New Mexico are considered individually rather than as a group. Third, iodine, phosphate rock and tripoli (microcrystalline silica), are three commodities described in Kogel et al. (2006) that are not found in New Mexico, and are not included here. Finally, alunite and tellurium are included because of their potential importance as critical and strategic commodities. Helium and carbon dioxide are discussed by Broadhead (2017).

II. COMMODITIES AND USES

Adobe and Earthen Construction

Adobe has been used as a building material for centuries. Adobe soil used by present and past New Mexican producers is principally from stream deposits, particularly Holocene (Recent) terrace deposits and older, loosely compacted geologic formations, such as the Santa Fe Group (Quaternary-Paleogene) located in the Rio Grande valley. Most producers use a sandy loam (50% clay and silt) associated with or derived from the Santa Fe Group. Some producers use a mixture of materials from the screened fines of aggregate operations in the river valleys combined with varying amounts of sand to produce the proper mix. The general public also uses these materials but probably with lesser specifications. Most adobe soils contain too much lime or alkali salts for manufacture of bricks (Talmage and Wootton, 1937). Figure 1 shows the locations of selected past and present commercial adobe producers in New Mexico.

X-ray diffraction analyses of whole-rock samples show the major constituents of New Mexican adobe soils are quartz and feldspar, with lesser amounts (in order of abundance) of calcite, clay minerals, and gypsum. The quartz, feldspar, most of the clay minerals, and some calcite are derived from the mechanical/chemical breakdown of older rocks units. Some clay minerals, much of the calcite, and all the gypsum are precipitated from evaporating water.

Clay-size particles are the most compositionally variable in commercial adobe soils. However, the clay mineral groups in this size fraction consist of approximately equal parts of expandable clay minerals (smectite and mixed-layer illite/smectite [I/S]), non-expandable clay minerals (kaolinite, illite, and chlorite), with minor quartz, calcite, and feldspar (Austin, 1990; Smith and Austin, 1996). The smectite is universally calcium-rich and, I/S is disorganized, randomly interstratified smectite and illite. Expandable clay minerals tend to be more sticky than non-expandable varieties and thus are more effective in binding silt and sand particles together. Expandable clay minerals also form colloidal suspensions with water and therefore moisture, whether as rainfall or groundwater, has the greatest effect on

adobe soils with the largest proportion of smectite and I/S. Soils in the arid New Mexican climate are typically alkaline. Groundwater near the Rio Grande valley is generally hard to extremely hard, containing total dissolved solids (TDS) ranging from approximately 100 to several thousand parts per million (Anderholm, 1987). Soluble salts, notably calcium carbonate and calcium sulfate, precipitate as this water evaporates.

For past and present adobe producers in New Mexico, expandable clay minerals are a problem. Cracking of drying adobe brick is probably due to the somewhat large proportion of smectite and I/S in adobe soil; soils with higher clay content but lower smectite and I/S content, will have less tendency to crack. Soils with high clay content shrink or crack when sun dried (Talmage and Wootton, 1937). Sandy soils typically do not have enough clay bonding material to prevent crumbling (Talmage and Wootton, 1937). Cracking is extreme on windy days when the shrinking clay structure is changing rapidly. Drying slowly over many calm days allows multiple layers of finely crystalline calcite (and some gypsum) to form on a clay-size scale, strengthening the bricks and preventing cracks. The resulting adobe wall can resist torrential late-summer rains for long periods if the adobe bricks do not contain too much clay material and are properly cured.

Adobe walls in New Mexico are remarkably durable in this arid climate. With proper care, adobe walls will last hundreds of years. Great care is taken to keep the wall interiors dry. Walls in the Native American pueblos are recovered with a natural plaster on a yearly basis as part of community service by the inhabitants. The natural plaster has approximately the same mineral and chemical composition as the walls themselves, but is slightly finer grained. It is expected to wash off slowly during the year and to be replaced during the next replastering event. The slow weathering of the plaster is apparently due to calcite and gypsum precipitation from the mixing water that forms a caliche-like bond between grains as the mud slowly dries. Caliche is gravel, soil, or alluvium that has been cemented typically with calcium carbonate or gypsum forming variously indurated layers on or near the surface in an arid climate.
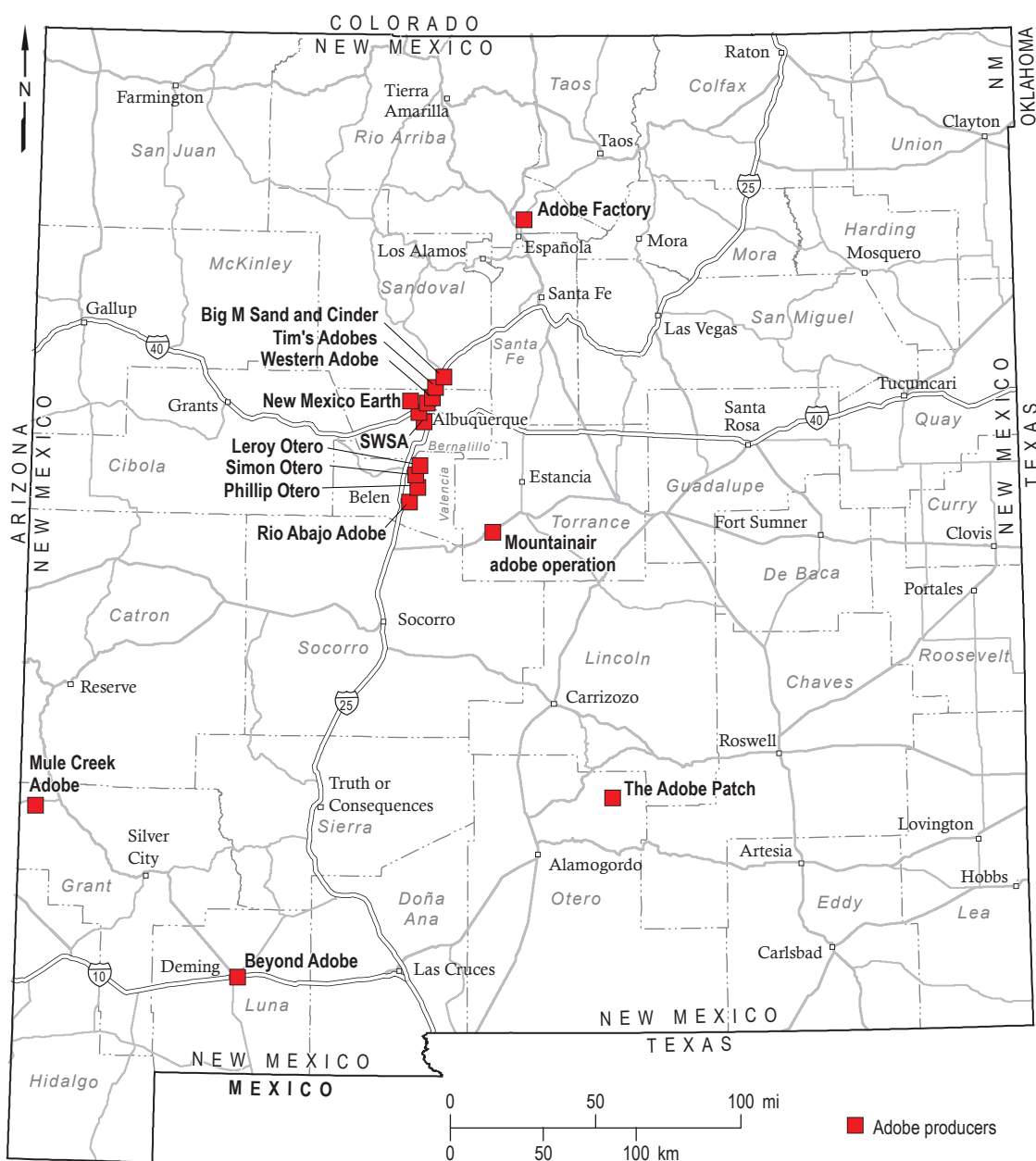
Figure 1. Selected past and present commercial adobe producers in New Mexico.

Commercial soils contain an average of approximately 90% insoluble and 10% soluble material; the latter is dominantly calcite and some gypsum (Austin, 1990). The soluble material ranges from 36 wt% to essentially 0 wt%. Adobe soils with the smallest amount of soluble material are also the highest in sand and larger-size particles.

New Mexican adobe producers claim that their soil mix is usually one-half sand and one-half clay or fines (silt and clay), but actually commercial adobe soils range from 85–99 wt% nonclay-size particles (Smith and Austin, 1996). The average grain-size composition is typically 67 wt% sand-and-larger,

27 wt% silt, and 6 wt% clay. The wide variation of particle sizes, particularly in the sand-and-larger- and silt-size grains, affects the penetration of paint or stabilizer sprayed or painted on walls. Adobe walls with high clay- and/or silt-size content would need the largest amount of stabilizer. An abundance of clay-size particles in adobe soils causes excessive cracks as blocks dry in an adobe yard. To combat this, producers add straw and/or additional sand to the mud mixture.

Large-scale commercial adobe producers (Figs. 2, 3) use adobe soils with less clay-size material than do small-scale commercial and non-commercial

adobe producers. Some of the former are as low as 1 wt% clay, whereas many of the latter are between 8–15 wt% (Smith and Austin, 1996). In part, this is because large-scale commercial adobe producers use stabilizers that not only protect blocks from rain damage, but aid in consolidation of the drying soil mix. Adobe walls keep buildings cool in the summer and warm in the winter. Thick massive walls of a typical adobe are well-known sound deadeners making these homes remarkably quiet. Windows in older adobe building are normally small, adding further to the quietness. Newer solar adobe homes take advantage of the many sunny days in arid climates with large windows but use well-insulated glass to retain much of the sound deadening characteristics of adobe dwellings.

The identification of radon gas as a health hazard in homes and the low-strength materials used in adobe homes when they are in seismically-active areas have caused owners to wonder about the safety of their adobe structures. Radon enters buildings through cracks, particularly when the homes are

Figure 2. Lifting the ladder mold at a medium-size adobe yard. *Photo by George S. Austin.*

Figure 3. An adobe-laying machine at a large-scale adobe yard. *Photo by George S. Austin.*

closed and have a negative air pressure, as is commonly true during the heating months in winter, and radon accumulates in low spots in the homes. Although adobe buildings have not been shown to have significantly more radon than other types of construction, good ventilation and positive interior air pressure are the easiest ways to prevent a buildup of radon (Smith and Austin, 1996).

Seismic activity is very destructive in many parts of the world that use low-strength masonry walls and designing the slab to resist cracking both during normal life of the structure and possible earthquakes is prudent in seismic areas. Recent work in California suggests that a combination of proper slab construction, reinforcing walls with rebar, the use of wire mesh used both inside and outside the building beneath the plaster and stucco, interconnected bond beams and roof beams at the top of walls, and buttresses can all serve to reduce hazards relating to earthquakes (Tibbets, 1986). Other physical properties that make adobe construction appealing are that homes so constructed are water resistant, flame retardant, unaffected by termites, and energy efficient.

Traditional (untreated) adobe bricks

Typically called untreated or sun-dried adobe brick, traditional adobe is made with soil composed of sand with some larger particles, and of silt and clay. Straw is locally added for strength and to prevent excessive cracking during drying. The moistened soil mixture commonly is packed into a brick-like mold, released, and allowed to dry and cure for several weeks before use.

Stabilized adobe bricks

Fully stabilized adobe brick is defined by the New Mexico Building Code as water-resistant adobe made of soil with certain admixtures that limit the brick's seven-day water absorption to less than 4 wt%. A fully stabilized adobe brick usually is made with 6–12 wt% of asphalt emulsion (California Research Corporation, 1963; Scheuch and Busch, 1988).

Exterior walls constructed with stabilized mud mortar and brick require no additional protection and can be left exposed without stucco. The production of fully stabilized adobe brick is low because most walls are stuccoed with water-resistant plaster, and the additional waterproofing agent adds extra cost.

Semi-stabilized adobe brick was developed by major adobe producers in New Mexico and is classified as a water-resistant brick because of the addition

of 3–5 wt% of a stabilizer or water-proofing agent (California Research Corporation, 1963; Scheuch and Busch, 1988). The stabilizer protects the brick from rainstorm damage during the curing process.

Asphalt emulsion is the primary stabilizer because of the ease of use and the low cost, but 5–10 wt% Portland cement produces the same result. Semi-stabilized adobe is made the same way as traditional adobe, except the stabilizer is mixed into the adobe soil prior to packing it into a form.

Pressed-earth blocks

Pressed-earth blocks presently make up a small portion of earth bricks used in New Mexico (Smith and Austin, 1996). The Cinva-Ram hand-operated compressed earth block press (http://www.cinvaram.org/, accessed 10/20/14) was developed by a Chilean engineer in the 1950s and has been used in New Mexico, but most pressed-earth blocks in New Mexico are made by gasoline- or diesel-powered machines (Fig. 4). Several have been designed and used in the past in New Mexico to press the adobe soil mixture into a form, minimizing the amount of time required between forming the block and placing it into the wall. Portland cement or asphalt emulsion has been used to partly or fully stabilize pressed-earth blocks. Most producers are small-volume and/or part-time, or non-commercial.

Rammed-earth walls

Rammed-earth homes commonly have much thicker walls than most other earthen dwellings, up to several feet thick. Wooden or metal concrete-type forms are put in place on stone or concrete footings and 5–7-inch-thick layers of moistened soil are put between the walls of the forms. Hand or hydraulic tampers are used to pound the soil into the shape of the form, compacting and reducing the volume of the mixture by 25–30% (McHenry, 1984; Middleton, 1987).

Once the layers of tamped soil reach the desired height, the forms are removed and the wall is allowed to dry (Fig. 5). Portland cement is the common stabilizer used. Producers say rammed-earth walls continue to harden, or cure, during the first year after construction. New Mexico's rammed earth producers together commonly produce between three and five rammed-earth homes each year.

Tradition and economic factors

Today, most builders purchase the adobe bricks from commercial yards located throughout New Mexico (Smith and Austin, 1996; Austin and Goolsby, 1996). The adobe-block operation is a labor-intensive but fuel-efficient seasonal industry with the production of blocks usually limited by the number of frost-free days. The principal standard-size adobe brick produced and used in New Mexico measures 4 x 10 x 14 inches (Smith and Austin, 1996).

Tradition is the most important factor in determining markets for adobe materials. In areas that have a strong tradition of mud construction, adobe is appealing, even preferred. In other areas where the population is not familiar with adobe, or worse, considers it beneath them to live in such buildings, new adobe buildings will not be built and any old buildings will disappear. An example of the first area is Santa Fe, New Mexico. The Santa Fe style of construction is adobe pueblo and territorial style (Smith and Austin, 1996). Adobe buildings are preferred by many wealthy landowners, and even contractors who use other types of construction mimic the adobe styles. Adobe can be made on

Figure 4. Pressed-earth adobe machine. *Photo by George S. Austin.*

Figure 5. Rammed earth walls topped by concrete bond beams. *Photo by George S. Austin.*

the construction site, but in recent years it is more likely to be made in adobe yards and transported to building sites. Although transport to distant construction sites is uncommon, some producers ship adobe several hundred miles. The problem is not normally in the availability of the raw material. Acceptable, if not superior, adobe can be made with most native raw materials, if a qualified adobe maker is involved. However, in many places, builders and contractors have neither the training nor talent for adobe construction.

Rammed-earth construction methods require that the walls are made at the building site. Consequently, the normal method of construction is to use local materials or materials that have not been transported far.

Aggregate

Aggregate is defined as: a) a mass or body of rock particles, mineral grains, or a mixture of both; or b) any of several hard, inert materials, such as sand, gravel, slag, or crushed stone, used for mixing with a cementing material to form concrete, mortar, or plaster; or used alone, as in railroad ballast or graded fill (Jackson, 1997). As it is used in this report, aggregate is for construction purposes and there are three types: 1) construction sand and gravel, 2) crushed stone, and 3) lightweight aggregate (Austin and Barker, 1990). Aggregate also can be used for decorative purposes and is discussed in other sections below by specific commodity type. The American Society for Testing and Materials (2011) provides brief descriptions of some of the more common rock types that comprise mineral aggregates as they occur in nature.

Aggregates are some of the most abundant natural resources and are a major basic raw material used by construction, agriculture, and industries employing complex chemical and metallurgical processes. The largest demand for aggregates in New Mexico is for highway construction (Sullivan, 2006) and then for building construction. Since aggregate is a high-bulk, low-unit-value commodity, transportation of these materials can be more expensive than the actual material and most aggregate pits are found close to highways and near the larger towns and cities (Fig. 6). In New Mexico, sand and gravel from the Rio Grande valley supplies much of New Mexico's need for aggregate. Crushed stone is produced principally along the eastern and western borders and to supply specialized needs. Recent production of total aggregates in New Mexico is in Table 1. A detailed description of the aggregate resources in New Mexico is beyond this report and is described in more detail by Carter (1965a); Barker et

al. (2001), Langer (1988, 2006a, b), and reports of the New Mexico Department of Transportation (formerly State Highway Department).

Construction sand and gravel

Construction sand and gravel is a basic building material for buildings, highways, and other construction. Sand and gravel deposits of New Mexico are so widespread and abundant (Fig. 6) that most of the geologic units in New Mexico contain potential sources of sand and gravel. Production is in Table 2. Principal deposits consist of alluvial sand and gravel of Pleistocene to recent age that comprise the beds of the Rio Grande and adjacent terraces and plains. They extend from north of Bernalillo in Sandoval County southward to the Texas and Mexico borders. Such deposits are particularly widespread in Doña Ana, Luna, and Sierra Counties in south-central New Mexico. Similar large deposits are found along the Rio Grande in Taos County to the north and on the drainage of the Pecos River in Chaves, Eddy, and Lea Counties to the southeast. Smaller deposits of the same type and pocket-like lenses filling old channels, known as bolson deposits, are found in the upper reaches of the Pecos River, along the Canadian River, and their tributaries in the northeastern part of New Mexico (Harben et al., 2008). Eastern New Mexico is dominated by lesser quality caliche.

Reports of the USGS and NMBGMR show that nearly every county in New Mexico has produced sand and gravel at one time or another (Harben, et al., 2008).

Table 2. Production of commercial sand and gravel in New Mexico from 2000–2009 (from Bolen, 2000–2014).

Year	Quantity (metric tons)	Value (dollar)	Unit value (dollar)	Total active operations
2000	13,400,000	66,800,000	4.97	107
2001	10,600,000	54,500,000	5.17	113
2002	12,800,000	62,600,000	4.87	107
2003	13,300,000	63,300,000	4.89	114
2004	13,600,000	89,500,000	6.56	111
2005	16,000,000	112,000,000	7.01	107
2006	18,400,000	157,000,000	8.51	106
2007	18,300,000	157,000,000	8.55	119
2008	14,600,000	126,000,000	8.69	110
2009	14,700,000	118,000,000	7.99	121
2010	11,600,000	84,400,000	7.30	119
2011	9,410,000	74,600,000	7.92	110
2012	10,200,000	83,200,000	8.19	112
2013	8,370,000	71,800,000	8.58	–
Total 2000–2013	**185,280,000**	**1,320,700,000**	**–**	**–**
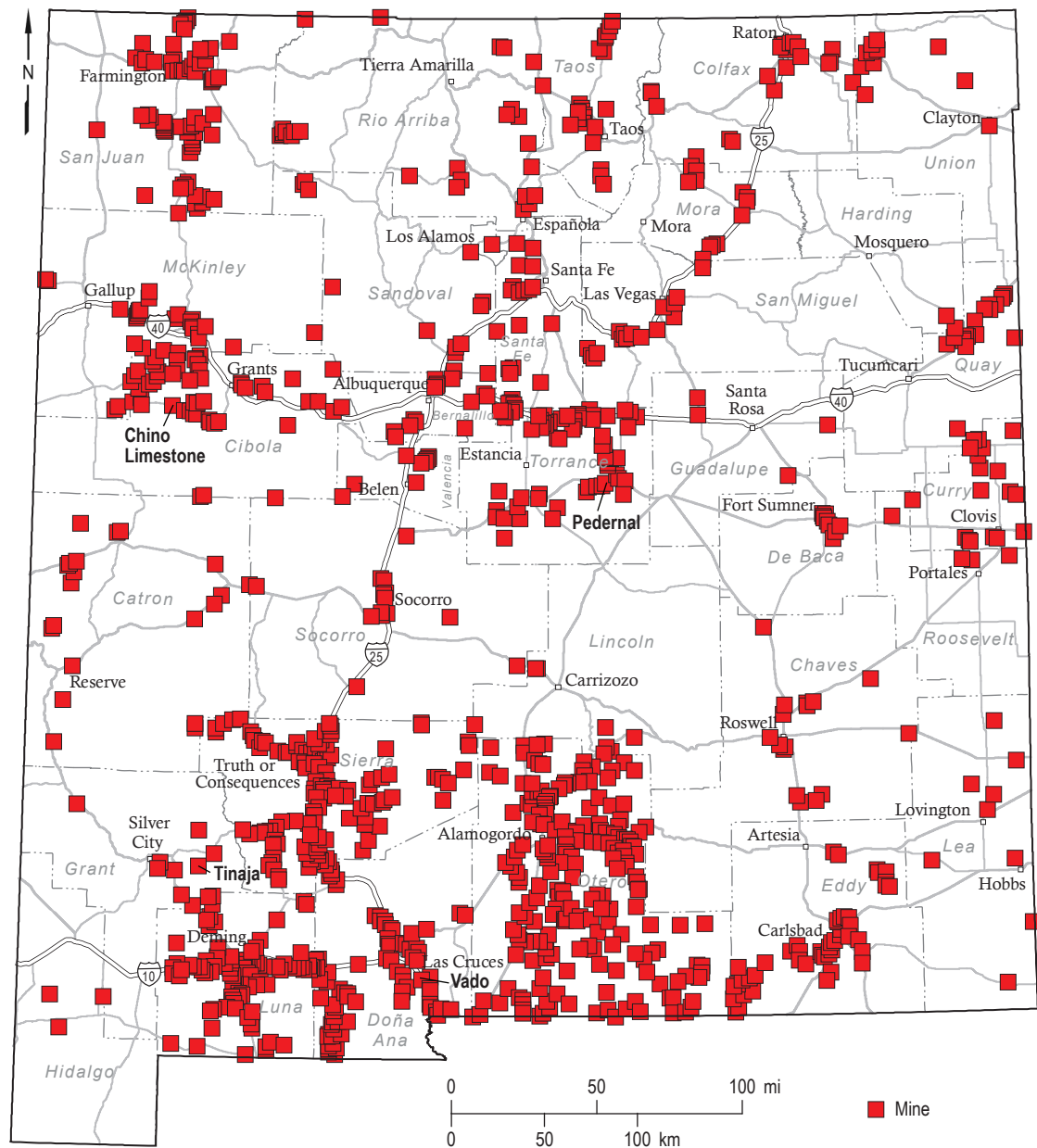
Figure 6. Selected aggregate (sand and gravel including caliche) mines in New Mexico (data from the New Mexico Mines Database).

However, the major aggregate activity is concentrated near the major centers of population and industrial expansion and along highways (Fig. 6).

Crushed stone

Most crushed stone is used as construction aggregate, commonly in the form of asphalt or concrete. In many cases it is required for use in asphaltic concrete, because the angular surfaces provide the needed intergranular strength. Crushed stone also is used in road metal, railroad ballast, riprap, filter beds, roofing granules, and as decorative material in gardens, patios, and landscaping.

Crushed and broken stone are obtained from a variety of igneous and sedimentary rocks in New Mexico, but the largest volume is produced from limestone (Table 3). Desirable qualities for use as crushed and broken stone include strength, durability, and ease of quarrying and processing. The rock should crush to firm, roughly equidimensional granules, with minimal amounts of dust and powder. Bonding quality is important in rock to be used as aggregate. Limestone ordinarily makes ideal concrete aggregate. Basalt and limestone generally adhere to bitumen better than granite or sandstone, although any of these rocks may serve as aggregate. Rock

Table 3. Production of crushed stone in New Mexico from 2000–2012 (from USGS, 2000–2009; Tepordei, 2000–2004; Willett, 2005–2012). w=withheld proprietary information.

Type	Limestone	Scoria (Volcanic cinder)	Sandstone, quartzite	Total (includes other crushed stone production)	Number of active operations
2000 metric tons	2,200,000	w	w	3,690,000	42
2000 value	$9,320,000	w	w	$22,400,000	
2001 metric tons	2,240,000	314,000	w	4,230,000	34
2001 value	$9,690,000	$3,640,000	w	$26,100,000	
2002 metric tons	2,340,000	280,000	w	3,680,000	37
2002 value	$10,500,000	3,080,000	w	$23,300,000	
2003 metric tons	2,310,000	168,000	w	3,730,000	31
2003 value	$12,400,000	1,290,000	w	$26,000,000	
2004 metric tons	2,120,000	196,000	w	3,430,000	24
2004 value	$11,500,000	1,520,000	w	$24,400,000	
2005 metric tons	2,250,000	338,000	w	3,750,000	28
2005 value	$13,800,000	$2,620,000	w	$25,400,000	
2006 metric tons	1,960,000	255,000	w	4,830,000	39
2006 value	$12,000,000	$2,290,000	w	$32,900,000	
2007 metric tons	2,880,000	164,000	164,000	7,590,000	40
2007 value	$21,100,000	$1,940,000	1,940,000	$56,700,000	
2008 metric tons	3,750,000	334,000	287,000	7,020,000	49
2008 value	$19,400,000	$3,280,000	$2,450,000	43,400,000	
2009 metric tons	3,690,000	290,000	208,000	6,128,000	48
2009 value	$21,200,000	$2,640,000	$1,630,000	$65,670,000	
2010 metric tons	2,780,000	226,000	w	5,280,000	48
2010 value	$21,700,000	$1,520,000	w	$34,400,000	
2011 metric tons	3,510,000	265,000	178,000	5,180,000	46
2011 value	$24,400,000	$1,590,000	$1,260,000	$36,600,000	
2012 metric tons	2,770,000	242,000	w	5,560,000	52
2012 value	$18,400,000	$1,710,000	w	$39,500,000	
2013 metric tons	2,440,000	176,000	240,000	5,040,000	–
2013 value	$21,100,000	$1,610,000	$1,420,000	$46,400,000	
2014 metric tons	2,120,000	240,000	214,000	4,720,000	–
2014 value	$17,200,000	2,290,000	$2,250,000	$42,000,000	

that is to be used as railroad ballast, should be hard, durable, and crush to sharp-edged particles (Langer, 2006b). Recycled asphalt concrete and regular concrete are used as well (Table 4).

Where sand and gravel is not available, particularly on the eastern plains, caliche is the only source of larger size material and is crushed for use as in the base course in highway construction. Many counties maintain their own caliche pits supplying base course material.

Other sources of crushed rock are available throughout New Mexico. Railroad ballast from Proterozoic quartzite and granite was produced in Torrance County at the Pedernal quarry (NMTO0215). Large-diameter crushed rock is produced from an andesite at the Vado quarry (NMDA0009) in Doña Ana County south of Las Cruces for use in rock walls. Diorite has been quarried and crushed from Railroad Mountain, northeast of Roswell for decorative use (Lovelace, 1972). Limestone

is quarried at the Tinaja pit (NMCI0119) in the Zuni uplift of Cibola County in west central New Mexico for use in concrete. Crushed limestone is produced at the Chino Limestone quarry (NMGR0154) for use in copper production (Harben et al., 2008). Scoria (volcanic cinder) is discussed separately below.

Lightweight aggregate

Lightweight aggregates are those minerals, natural rock materials, products, and by-products of manufacturing processes used as bulk fillers in lightweight structural concrete, concrete masonry units, precast concrete structural products, road-surfacing materials, plaster aggregates, and insulating fill. Other uses include architectural wall covers, suspended ceilings, lightweight structural fill, soil conditioners, and other agricultural uses (Mason, 1994; Bush et al., 2006).

Table 4. Recycled asphalt concrete and Portland cement concrete used by producers in New Mexico (from Tepordei, 2000 – 2004; Willett, 2005 – 2012). w=withheld proprietary information.

Year	Recycled Asphalt Concrete			Recycled Portland Cement Concrete		
	Quantity (metric tons)	Value (dollar)	Unit value (dollar)	Quantity (metric tons)	Value (dollar)	Unit value (dollar)
2000	w	w	w	w	w	1.58
2001	5,000	17,000	3.40	10,000	37,000	3.70
2002	w	w	w	w	w	w
2003	0	0	0	0	0	0
2004	0	0	0	0	0	0
2005	1,000	8,000	8.00	0	0	0
2006	4,000	13,000	3.25	1,000	2,000	2.00
2007	222,000	1,960,000	8.83	87,000	607,000	6.98
2008	195,000	1,410,000	7.25	171,000	1,840,000	10.74
2009	47,000	262,000	5.57	1,000	2,000	1.10
2010	78,000	473,000	6.10	5,000	38,000	7.71
2011	78,000	578,000	7.39	2,000	13,000	7.71
2012	236,000	1,360,000	5.77	2,000	12,000	6.64
Total 2000–2012	**861,000**	**6,064,000**	**–**	**269,000**	**2,514,000**	**–**

Most lightweight aggregates are natural raw materials, but also include waste or synthetic products (Mason, 1994). Lightweight aggregate materials are generally classified into four groups: 1) natural lightweight aggregate materials (prepared by crushing and sizing natural rock materials such as pumice, pumicite, scoria or volcanic cinder, tuff, and breccia), 2) manufactured structural lightweight aggregates (prepared by processing shale, clay, or slate in rotary kilns or on traveling grate sintering machines), 3) by-product lightweight aggregates (prepared by crushing and sizing foamed and granulated slag, organic cinders, and coke breeze), and 4) manufactured insulating ultra-lightweight aggregates (prepared by processing ground vermiculite and perlite; Mason, 1994). Only tuff of group 1 will be discussed here. Pumice, pumicite, and scoria (volcanic cinder) are discussed separately in this chapter below. Members of the second and third groups are not produced in New Mexico. Of the members of the fourth group, only perlite, discussed separately in this chapter, is mined in New Mexico and is discussed below.

Tuff or tuffaceous rocks are products usually of explosive volcanism, differing in chemical composition but characterized by lighter weight caused by the collapse of pumice vesicles as the ejecta lithify. Although, there is no production of New Mexico tuffs presently, some older buildings at Los Alamos were constructed of local tuff blocks that were quarried with chain saws. Soft initially, they hardened with desiccation and time.

Alunite and Alum

Alunite and alum are potential sources of aluminum and have been mined in several places in the world for their aluminum content (Hall, 1978; Hall and Bauer, 1983). Most of the aluminum used in the United States comes from foreign sources, primarily from bauxite deposits (Bray, 2013). Alunite can be calcined to form alum, which is used in a range of industrial processes, including food preservation, purification of drinking water, flame retardant, and taxidermy, among others. Calcination is the thermal treatment of ores in the absence of oxygen to decompose the material, bring about a phase change, or remove voatiles. During World War I, alunite was used as a source of potassium fertilizer. In the 1960s, the Soviet Union produced alunite for its aluminum content; potassium sulfate and sulfuric acid were recovered as by-products (Hall and Bauer, 1983). Alunite is one end member of a series of sulfates that occur in several geologic environments, all of which require base leaching of the host rock by acidic fluids. Minerals of the alunite group have the general composition $AB_3(SO_3)_2 \bullet (OH)_6$ where A is typically K^+, Na^+, Pb^{++}, NH^{4+}, or Ag^+ and B is typically Al^{+3} or Fe^{+3} (Brophy et al.,1962). The more common alunite species are listed in Table 5. Solid solution between the species is common.

Alunite and/or alum are found in several areas in New Mexico (Table 6). Alunite typically occurs with a variety of minerals including quartz, kaolinite, pyrophyllite, alunogen, and iron oxides. Pure alunite deposits are not found in New Mexico. However, local zones contain as much as 30% alunite in the Alum Mountain and Steeple Rock districts (Hall, 1978; McLemore, 1993). Age determinations of alunite

Table 5. The more common alunite minerals (Brophy et al., 1962; Altaner et al., 1988).

Mineral species	Chemical formula
Alunite	$KAl_3(SO_4)_2(OH)_6$
Natroalunite	$NaAl_3(SO_4)_2(OH)_6$
Ammonioalunite	$NH_4Al_3(SO_4)_2(OH)_6$
Jarosite	$KFe_3(SO_4)_2(OH)_6$
Natrojarosite	$NaFe_3(SO_4)_2(OH)_6$
Ammoniojarosite	$NH_4Fe_3(SO_4)_2(OH)_6$
Argentojarosite	$AgFe_3(SO_4)_2(OH)_6$
Plumbojarosite	$PbFe_6(SO_4)_4(OH)_{12}$
Potash Alum	$KAl(SO_4)_2 \cdot 12H_2O$

Table 6. Alunite and/or alum occurrences in New Mexico. See McLemore (2017) for location of districts.

District or mine ID	Name	County	References
DIS237	Questa district	Taos	Jones (1915), Campbell and Lueth (2008)
DIS238	Red River district	Taos	Jones (1915), Campbell and Lueth (2008)
none	Near Wagon Mound	Mora	Jones, 1915)
NMLU0363, DIS109	Rattlesnake Canyon, Old Hadley district	Luna	McLemore et al. (1996c)
DIS201	Macho district	Sierra	McLemore (2012b)
DIS042	Alum Mountain	Grant	Hall (1978), Ratté et al. (1979)
DIS066	Steeple Rock district	Grant	McLemore (1993)
DIS226	San Jose district	Socorro	McLemore (2012c, d)
DIS194	San Mateo Mountain district	Socorro	McLemore (2012c, d)
DIS204	Taylor Creek district	Catron, Sierra	Harrison (1992)
NMGR0029	Chino mine	Grant	Cook (1993)
DIS095	Bluefront Canyon, Nogal-Bonito district	Lincoln	Segerstrom et al. (1979), Goodell et al. (1998), McLemore et al. (2014)
NMSO0152, DIS230	Apache Warm Springs, Ojo Caliente No. 2 district	Socorro	McLemore (2010d)

suggest two periods of formation: alunite associated with volcanic-epithermal veins is between 28 and 33 Ma (McLemore, 1996b; McLemore et al., 1996c) and alunite associated with supergene alteration of porphyry copper deposits around 46.5, 39.5, 25.4, 16–19, and 8.4 Ma (Cook, 1993; McLemore, 1996b; S. S. Cook, personal communication, 1994).This suggests at least five supergene events.

Asbestos

Asbestos is the generic name given to six fibrous silicate minerals that have been widely used in commercial products. As an industry term rather than a mineralogical term, it is applied to mineral particles that possess high tensile strengths, large length-to-width ratios, flexibility, and resistance to chemical and thermal degradation. The Occupational Safety and Health Administration (OSHA) defines asbestos fiber as any particle that is 5 microns or longer, with a length-to-width ratio of 3:1 or longer. Asbestos also exhibits high electric resistance, and many forms can easily be woven in fireproof textiles. Asbestos minerals can be found in bundles of fibers, which can be separated from the host matrix. The fibers have high tensile strength. The aspect ratios range from 20 to 100. The fibers are flexible and

can be spun (Virta, 2002). The term asbestos is typically used to identify commercial deposits of chrysotile, grunerite (commercially known as amosite or cummingtonite), and riebeckite (commercially known as crocidolite). Anthophyllite and tremolite asbestos have no significant industrial applications. Asbestos is used in flame and fire retardant materials and has not been mined in the United States since 2002 because of the carcinogenic risk to humans.

The six types of asbestos that have been recognized in commercial use are: actinolite asbestos, amosite, anthophyllite asbestos, chrysotile, crocidolite, and tremolite asbestos (Table 7). Chrysotile is the asbestiform variety of serpentine; the other five are amphiboles. Chrysotile historically has been the most commonly used form of asbestos, followed by crocidolite, amosite, and then anthophyllite asbestos. Relatively small amounts of tremolite asbestos and actinolite asbestos have been produced and used (Virta, 2006). Nonfibrous ricolite (a form of serpentine) has been produced from the Ricolite district (DIS063) in Grant County (Fig. 7) for carving, decorative, and dimension stone (Talmage and Wootton, 1937; Benjovsky, 1946). Fibrous ricolite also is found in the Ricolite district.

Small amounts of actinolite, anthophyllite, chrysotile, and tremolite have been reported in New Mexico, but only actinolite, chrysotile, and tremolite asbestos have been recognized (Northrop, 1996). In New Mexico, asbestos minerals are found in small amounts in limestones adjacent to Laramide copper and lead-zinc skarn deposits, Laramide (polymetallic) vein deposits, molybdenum-tungsten-beryllium contact metasomatic deposits, and porphyry copper deposits (see McLemore and Lueth, 2017). Asbestos minerals are found in serpentinized ultramafic and mafic rocks in some Proterozoic terranes in New Mexico and can be associated with talc deposits. Actinolite asbestos has been reported in the Organ Mountains district, Doña Ana County (DIS030), Petaca district, Rio Arriba County (DIS148), and the El Porvenir district, San Miguel County (DIS161)(Fig. 7). A subvariety of actinolite asbestos composed of felt-like

Table 7. Asbestos minerals (after Virta, 2006).

Mineral species	Chemical formula
Serpentine mineral	
Chrysotile	$Mg_3Si_2O_5(OH)_4$
Amphibole minerals	
Grunerite (amosite)	$(Fe, Mg)_7Si_8O_{22}(OH)_2$
Riebeckite (crocidolite or blue asbestos)	$Na_2(Fe^{+2}_3Fe^{+3}_2)Si_8O_{22}(OH)_2$
Anthophyllite	$Mg_2Mg_5(Si_8O_{22})(OH)_2$
Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$
Actinolite	$Ca_2(Mg, Fe^{+2})_5Si_8O_{22}(OH)_2$

aggregates called mountain leather has been identified in Grant and Hidalgo Counties. Sierra and Taos Counties are reported to have possible occurrences of actinolite asbestos. Chrysotile asbestos has been reported as irregular veinlets between the Buck and Hilltop mines (NMDA0083) in the Organ Mountains district (Fig. 7). Occurrences were also reported in the Fierro-Hanover (DIS054), Georgetown (DIS056), and Ricolite (DIS063) districts, Grant County (Fig. 7). A tremolite asbestos deposit in the Gallinas Canyon of the Elk Mountain mining district (DIS162), San Miguel County (Fig. 7), was going to be commercially developed in the 1950s. However, no record of further development was noted (Northrop, 1996). The amount

of asbestos is so small in these areas that it is unlikely that asbestos minerals would be found in any alluvial deposits adjacent to these areas (Harris, 2004).

Asbestos minerals can pose a health risk, specifically asbestosis, lung cancer, and mesothelioma (Tweedale and McCulloch, 2004; Dodson and Hammer, 2006). Asbestos minerals are found in minor amounts in various geologic terranes throughout New Mexico (Fig. 7), but the amount of asbestos is so small in these areas that it is unlikely that any health risk exists for residents and visitors. Other amphibole minerals are known to occur as fibers or asbestoform habit (winchite, riechterite, and fluoro-edenite), but these minerals are not specifically listed
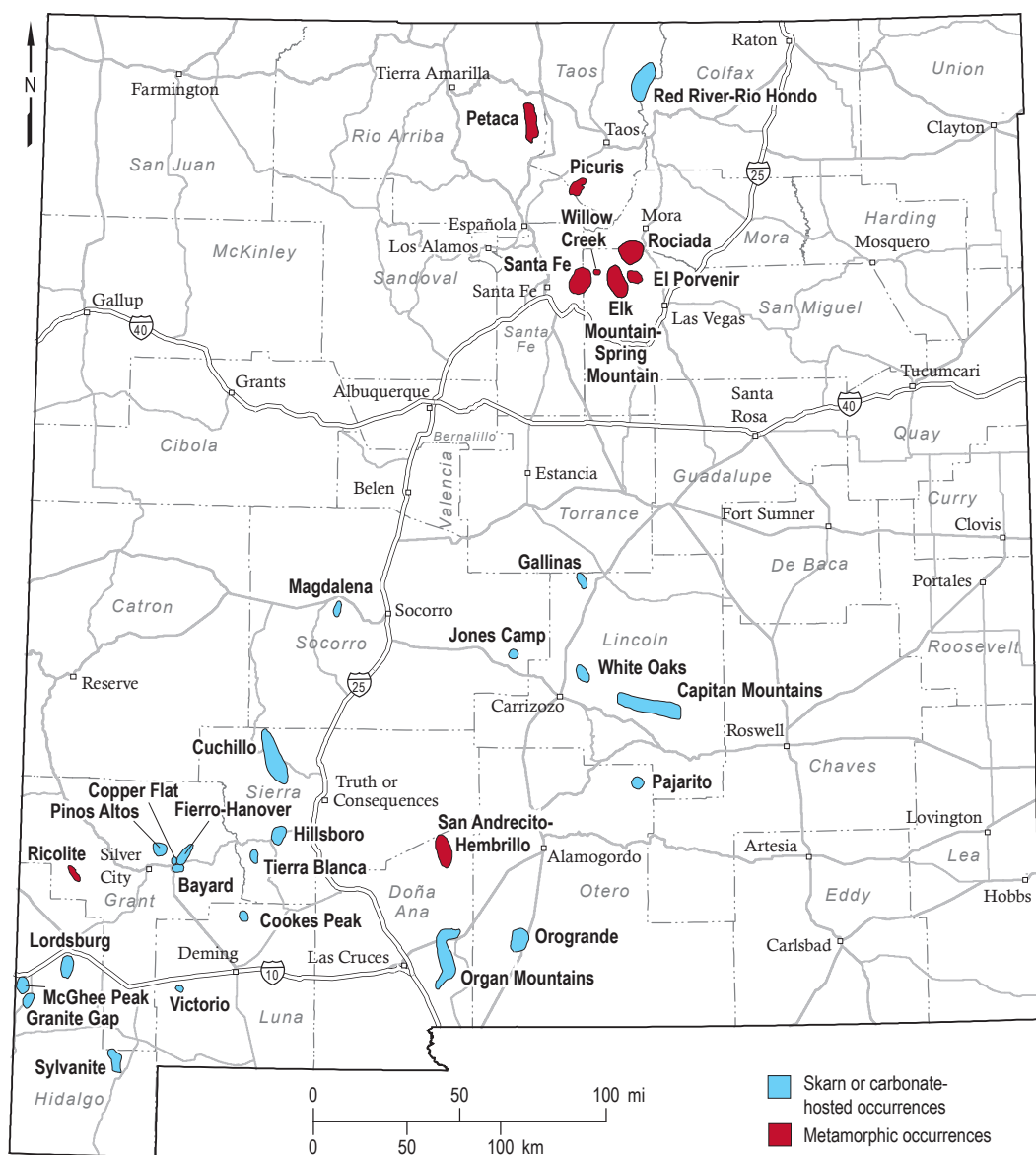
Figure 7. Asbestos minerals found in mining districts in New Mexico. List of occurrences can be found at http://geoinfo.nmt.edu/staff/mclemore/documents/asbestos_nm.pdf. None of these areas contain enough asbestos to be economic or pose a health risk to humans.

in the asbestos regulations (Skinner et al., 1988; Van Gosen, 2007). However, workers and others that could be exposed to dust in those areas that could contain asbestos minerals should have the dust examined for potential asbestos minerals and, if present, follow appropriate protection recommendations.

In summary, New Mexico has only a small amount of asbestos occurrences (Fig. 7). None are large enough to be developed or to be considered an environmental hazard.

Barium Minerals

Barite ($BaSO_4$) is a heavy, nonmetallic material containing 65.7% barium oxide (BaO) and 34.3% sulfur trioxide (SO_3) and crystallizes in flat crystals having lateral dimensions several times their thickness. The mineral is translucent to opaque with a vitreous luster, commonly colorless to white (Fig. 8), but sometimes in light shades of red, yellow, or blue. It is the heaviest nonmetallic mineral, with a specific gravity of 4.5 and is used in drilling muds, as a filler and extender in many manufactured materials, and in heavy cements.

Commercial production of barite in New Mexico began in 1918 (Table 8), but it has been insignificant compared with national barite production and consumption. Barite was produced from the Hansonburg district (DIS213) for many years and concentrated at a mill in San Antonio. Barite from the Smallwood-Baca mine (also known

as Elaine mine; NMSO0338) near Socorro was sold as a weighting agent for drilling muds in the Farmington area (Williams, 1965). Other areas have produced barite (Table 8).

Barite in New Mexico occurs in veins or veinlets and as wall rock replacement in igneous, sedimentary, and metamorphic rocks, but chiefly in limestone. It is commonly associated with quartz or some other form of silica, fluorite, and metallic sulfides or carbonates. Some sandstones or breccias are cemented with barite. The miscellaneous occurrences include

Figure 8. White to cream barite blades at the Palm Park mine (NMDA0202) in the Rincon district, Doña Ana County. *Photo by Virginia T. McLemore.*

Table 8. Barite production from New Mexico.

	District or mine ID	District (mine)	Barite production (short tons)	Cumulative estimated value (dollar)	Period of production	References
Doña Ana County	DIS024 NMDA0019	Bear Canyon (Stevens)	50	<500	1932	Dunham (1935), Williams et al. (1964), McLemore (1994)
	DIS030 NMDA0051	Organ Mountains (Devil's Canyon, Tennessee, Golden Lily, Ruby)	600	15,000–75,000	1933, mid 1900s	Talmage and Wootton (1937), Rothrock et al. (1946), Williams (1966), Williams et al. (1964), McAnulty (1978), McLemore (1994)
	NMDA0056	Rincon (Palm Park, Horseshoe)	10,250	<100,000	unknown	Williams et al. (1964), Filsinger (1988)
	NMDA0077	Tonuco Mountain	200	77,200–386,000	1919–1935	Rothrock et al. (1946), Clippinger (1949), Williams et al. (1966), McAnulty (1978)
	NMDA0152	Organ Mountains (Devil's Canyon, Tennessee, Golden Lily, Ruby)	600	15,000–75,000	1933, mid 1900s	Ladoo (1923), Rothrock et al. (1946), McAnulty (1978)
	DIS032 NMDA0202	Rincon (Palm Park, Horseshoe)	10,250	<100,000	unknown	Williams et al. (1964), Filsinger (1988)
	DIS035	Tonuco Mountain	200	77,200–386,000	1919–1935	Rothrock et al. (1946), Clippinger (1949), Williams et al. (1966), McAnulty (1978)
	DIS036	Tortugas Mountain	100	200,000–1,000,000	1919–1943	Ladoo (1923), Rothrock et al. (1946), McAnulty (1978)
Socorro	DIS213	Hasonburg	37,500	<50,000	1951–1960	—
	DIS211	Chupadero (Smallwood-Baca)	unknown	unknown	1965	Williams (1965)
		Total	**~60,000**		**1880–1978**	

barite as a gangue constituent in sulfide ore bodies. Barite is frequently found in fluorite deposits, and vein-type fluorite mineralization will commonly include barite. No sedimentary exhalative or residual-type barite ore bodies are known to occur in New Mexico (Clark and Orris, 1991). More than 80 deposits and occurrences are found in New Mexico (Williams et al., 1964; Williams, 1965; McLemore and Barker, 1985; McLemore, 2000). Major barite mining districts in New Mexico are listed by counties in Table 9 and shown in Figure 9.

Bauxite

Bauxite is a rock and is the primary raw material used to produce aluminum metal. In addition bauxite is used in a number of significant nonmetallurgical applications, including abrasives, cements, chemicals, and refractories. Bauxite used in producing end products for these and other specialty applications must meet more stringent compositional and physical requirements than the crude ore commonly employed for general aluminum production (Hill and Sehnke, 2006).
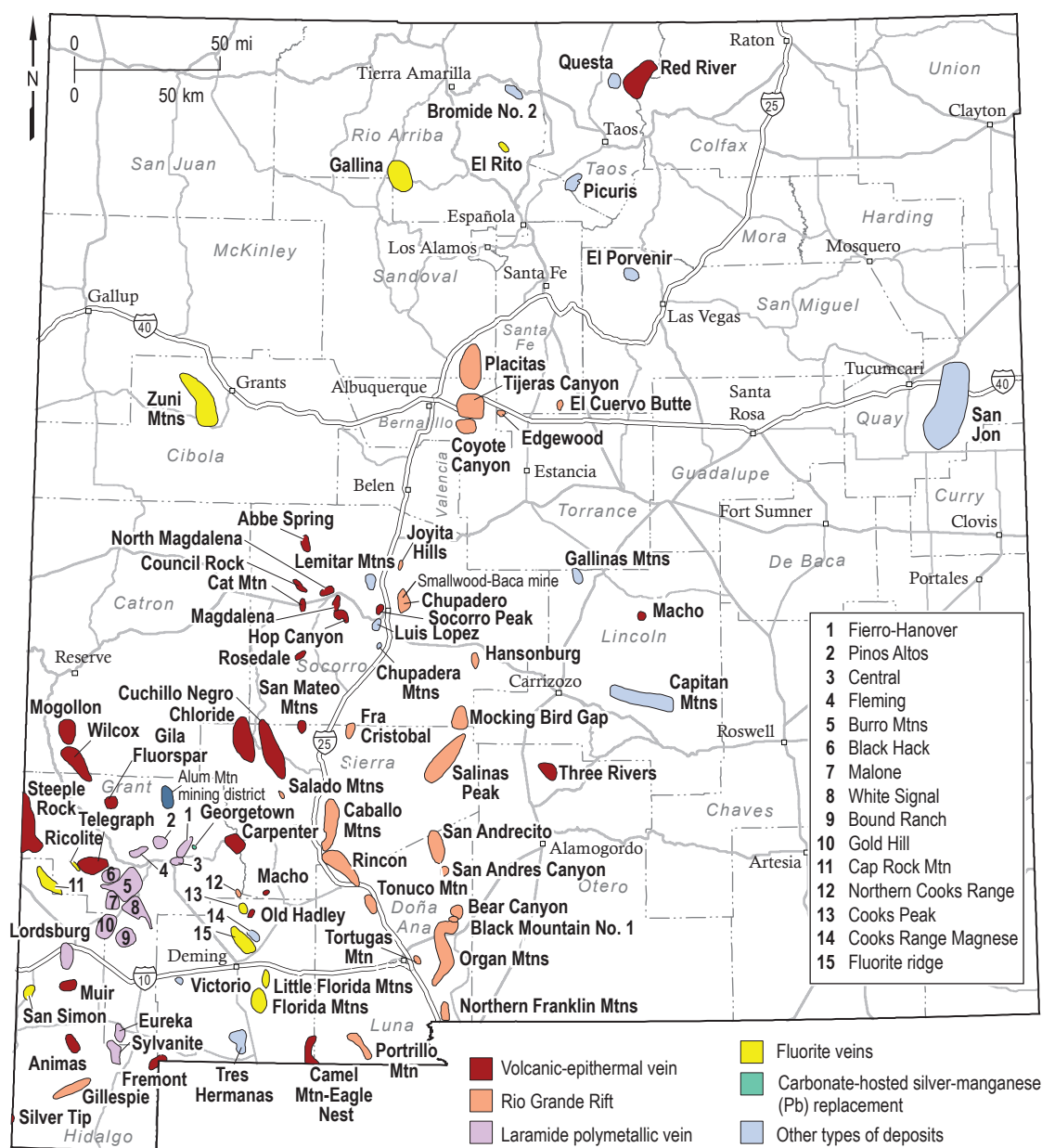
Figure 9. Mining districts containing barite and fluorite in New Mexico. Description of deposit types in McLemore and Leuth (2017).

Table 9. Mining districts containing barite (Ba) and fluorite (F) in New Mexico (Williams, 1965; Williams et al., 1964; Clippinger, 1949; McLemore and Barker, 1985; and McLemore, 2000; 2005). Description of deposit types in McLemore and Leuth (2017).

District ID	District	County	Type of deposit	Commodity
DIS002	Coyote Canyon	Bernalillo	RGR	Ba, F
DIS004	Tijeras Canyon	Bernalillo	RGR	Ba, F
DIS007	Mogollon	Catron	volcanic-epithermal vein	Ba, F
DIS010	Wilcox	Catron, Grant	volcanic-epithermal vein, fluorite veins	F
DIS017	Zuni Mountains	Cibola	fluorite veins	Ba, F
DIS024	Bear Canyon	Doña Ana	RGR	Ba, F
DIS025	Black Mountain No. 1	Doña Ana	RGR	Ba, F
DIS029	Northern Franklin Mountains	Doña Ana	RGR	Ba, F
DIS030	Organ Mountains	Doña Ana	RGR, fluorite veins	Ba, F
DIS031	Potrillo Mountains	Doña Ana	RGR	Ba, F
DIS032	Rincon	Doña Ana, Sierra	RGR	Ba, F
DIS033	San Andrecito	Doña Ana	RGR	Ba, F
DIS034	San Andres Canyon	Doña Ana	RGR	Ba, F
DIS035	Tonuco Mountain	Doña Ana	RGR, fluorite veins	Ba, F
DIS036	Tortugas Mountain	Doña Ana	RGR	Ba, F
DIS043	Central	Grant	Laramide polymetallic vein	Ba
DIS044	Black Hawk	Grant	Laramide polymetallic vein	Ba, F
DIS045	Bound Ranch	Grant	Laramide polymetallic vein, fluorite veins	Ba, F
DIS046	Burro Mountains	Grant	Laramide polymetallic vein, fluorite veins, volcanic-epithermal vein	F
DIS048	Cap Rock Mountain	Grant	fluorite veins	F
DIS049	Carpenter	Grant	volcanic-epithermal vein	Ba, F
DIS053	Eureka	Grant, Hidalgo	Laramide polymetallic vein	Ba, F
DIS054	Fierro-Hanover	Grant	Laramide polymetallic vein	F
DIS055	Fleming	Grant	Laramide polymetallic vein, fluorite veins	F
DIS056	Georgetown	Grant	carbonate-hosted silver-manganese (Pb) replacement	Ba, F
DIS057	Gila Fluorspar	Grant	volcanic-epithermal vein, fluorite veins	Ba, F
DIS058	Gold Hill	Grant, Hidalgo	Laramide polymetallic veins	Ba, F
DIS060	Malone	Grant	Laramide polymetallic vein, fluorite veins	F
DIS061	Northern Cooks Range	Grant	RGR, fluorite veins	F
DIS062	Pinos Altos	Grant	Laramide polymetalic veins	Ba
DIS063	Ricolite	Grant	fluorite veins	F
DIS066	Steeple Rock	Grant	volcanic-epithermal vein, fluorite veins	Ba, F
DIS067	Telegraph	Grant	volcanic-epithermal vein, fluorite veins	Ba, F
DIS068	White Signal	Grant	Laramide polymetallic vein	Ba, F
DIS078	Fremont	Hidalgo, Luna	volcanic-epithermal vein	Ba, F
DIS079	Gillespie	Hidalgo	RGR, volcanic-epithermal vein	F
DIS080	San Simon	Hidalgo	fluorite veins	F
DIS082	Lordsburg	Hidalgo	Laramide polymetallic veins, fluorite veins	Ba, F
DIS084	Muir	Hidalgo	volcanic-epithermal vein, fluorite veins	F
DIS086	Animas	Hidalgo	volcanic-epithermal vein	F
DIS087	Silver Tip	Hidalgo	volcanic-epithermal vein	Ba, F
DIS088	Sylvanite	Hidalgo	Laramide polymetallic vein	Ba, F
DIS091	Capitan Mountains	Lincoln	Great Plains margin-REE-Th- U veins	F
DIS092	Gallinas Mountains	Lincoln	Great Plains margin-REE-Th- U veins	F
DIS102	Camel Mountain-Eagle Nest	Doña Ana, Luna	volcanic-epithermal vein	F
DIS104	Cookes Range Manganese	Luna	epithermal manganese	F
DIS105	Cookes Peak	Luna	fluorite veins	Ba, F
DIS106	Florida Mountains	Luna	fluorite veins	Ba, F
DIS107	Fluorite Ridge	Luna	fluorite veins	Ba, F
DIS108	Little Florida Mountains	Luna	fluorite veins	Ba
DIS109	Old Hadley	Luna	volcanic-epithermal vein	Ba
DIS113	Tres Hermanas	Luna	pollymetallic vein	F

Table 9. Continued.

Table 9. Continued.

District ID	District	County	Type of deposit	Commodity
DIS114	Victorio	Luna	Mo-W-Be contact-metasomatic deposits	F
DIS132	Three Rivers	Otero	volcanic-epithermal vein	Ba
DIS136	San Jon	Quay	sedimentary-copper	Ba
DIS139	Bromide No. 2	Rio Arriba	REE-Th-U veins	Ba, F
DIS143	El Rito	Rio Arriba	fluorite veins	F
DIS144	Gallina	Rio Arriba, Sandoval	fluorite veins ?	F
DIS161	El Porvenir	San Miguel	Vein and replacement deposits in Proterozoic rocks	F
DIS178	Placitas	Bernalillo, Sandoval	RGR	Ba, F
DIS182	El Cuervo Butte	Santa Fe	RGR	Ba
DIS190	Caballo Mountains	Sierra	RGR, fluorite veins	Ba, F
DIS191	Chloride	Sierra, Catron	volcanic-epithermal vein	Ba, F
DIS192	Cuchillo Negro	Sierra, Socorro	volcanic-epithermal vein	F
DIS193	Fra Cristobal	Sierra	RGR	Ba, F
DIS194	San Mateo Mountains	Sierra	volcanic-epithermal vein	F
DIS201	Macho	Sierra	volcanic-epithermal vein	Ba
DIS203	Salinas Peak	Sierra	RGR	Ba, F
DIS206	Abbe Spring	Socorro	volcanic-epithermal vein	Ba
DIS209	Cat Mountain	Socorro	volcanic-epithermal vein	Ba, F
DIS210	Chupadera Mountains	Socorro	carbonatite	Ba, F
DIS211	Chupadero	Socorro	RGR	Ba, F
DIS212	Council Rock	Socorro	volcanic-epithermal vein	Ba, F
DIS213	Hansonburg	Socorro	RGR	Ba, F
DIS215	Hop Canyon	Socorro	volcanic-epithermal vein	Ba
DIS217	Joyita Hills	Socorro	RGR	Ba, F
DIS218	Ladron Mountains	Socorro	RGR	Ba, F
DIS219	Lemitar Mountains	Socorro	carbonatite, RGR	Ba, F
DIS220	Luis Lopez	Socorro	epithermal manganese	Ba
DIS221	Magdalena	Socorro	volcanic-epithermal vein	Ba, F
DIS222	Mockingbird Gap	Socorro, Sierra	RGR	Ba, F
DIS223	North Magdalena	Socorro	volcanic-epithermal vein	Ba
DIS225	Rosedale	Socorro	volcanic-epithermal vein	F
DIS229	Socorro Peak	Socorro	volcanic-epithermal vein	Ba, F
DIS236	Picuris	Taos	Vein and replacement deposits in Proterozoic rocks	Ba
DIS237	Questa	Taos	porphyry molybdenum (tungsten)	F
DIS238	Red River	Taos	volcanic-epithermal vein	F
DIS242	Edgewood	Torrance	RGR	Ba, F
DIS254	Salado Mountains	Sierra	RGR	F

Bauxite is a naturally occurring, heterogeneous weathering product composed primarily of one or more aluminum hydroxide minerals, plus various mixtures of silica (SiO_2), iron oxide (Fe_2O_3), titanium oxide (TiO_2), aluminosilicate (clay, etc.), and other impurities in minor or trace amounts. The principal aluminum hydroxide minerals found in varying proportions within bauxite are gibbsite, $Al(OH)_3$, and the polymorphs boehmite and diaspore, both $AlO(OH)$.

Although in 1894 a bauxite occurrence was reported in the Alum Mountain district (DIS042, Grant County), further work 10 years later indicated that the material had "no free aluminum oxide, but show that the residual rock is essentially the silicate of aluminum, having approximately the composition of kaolin" (Northrop, 1996). Although, the Alum Mountain district (DIS042) has potential for aluminum, it is in the form of alunite (see above), alum, and alunogen; chemical analyses range from 18–32% alumina (Ratté et al., 1979). There appears to be little likelihood that a large deposit of bauxite ore will be found in New Mexico.

Beryllium Minerals

Beryllium has been an essential material in the manufacture of products for the aerospace and defense, automotive, energy, medical, and electronics industries for decades. It is a unique material that exhibits

physical and mechanical properties unmatched by any other metal. Beryllium possesses high heat-absorbing capability and has dimensional stability over a wide range of temperatures (Sabey, 2006). It is a strategic and critical material for many industries and poses no special health risk in the solid mineral form. The beryllium industry produces three primary forms, in order of production importance: 1) beryllium-containing alloys (e.g., copper-beryllium, nickel-beryllium), 2) beryllium metals, and 3) beryllium ceramics (beryllium oxide [BeO]).

The low productivity of domestic pegmatites and the small size of pegmatitic beryllium deposits in general have caused more attention to be given to nonpegmatitic veins and other deposits since 1946. New Mexico was among the top three beryl-producing states for many years with most production from the Harding mine (NMTA0015, Picuris district, DIS236), Taos County. The Harding mine yielded more beryl ore than any other North American pegmatite mine. In addition, the skarn deposit at Iron Mountain (Cuchillo Negro district, DIS192), Sierra and Socorro Counties, was one of the first American nonpegmatitic deposits to be explored for beryllium. These nonpegmatitic deposits were particularly attractive, because some are large and the grade is commonly in the tenths percent range, higher than that of pegmatitic deposits (Griffitts, 1965).

Although there are more than 50 beryllium minerals, only bertrandite ($Be_4Si_2O_7(OH)_2$), beryl ($Be_4Al_2Si_6O_{18}$), and phenakite (Be_2SiO_4) are commercially important. Granite pegmatites are the world's principal source of beryllium as beryl (Sabey, 2006), but bertrandite is now the principal domestic beryllium ore mineral. In the U.S., nonpegmatite sources comprise approximately 65% of the known reserves (Jaskula, 2011). Other beryllium minerals found in New Mexico are helvite ($Mn_4Be_3Si_3O_{12}S$) found at Iron Mountain, chrysoberyl (Be_2AlO_4) in northern Taos County, and gadolinite ($Be_2Y_2FeSi_2O_{10}$) reported to occur in eastern Rio Arriba County (Griffitts, 1965).

McLemore (2010a) divides New Mexican beryllium occurrences (Fig. 10) into 1) Proterozoic pegmatite deposits; 2) porphyry molybdenum (±tungsten, beryllium) deposits; 3) beryllium in alkaline igneous rocks; 4) beryllium in carbonate-hosted replacement and skarn deposits; 5) granite/rhyolites (topaz rhyolites) and tin skarns deposits; and 6) volcanogenic beryllium deposits. Beryllium also is found in some vein deposits. Beryllium production is in Table 10.

Table 10. Beryllium production from Proterozoic pegmatites in New Mexico (Meeves et al., 1966). Additional production in 1963–1969 is withheld. Additional production from Iron Mountain (Cuchillo Negro district, DIS192), Santa Fe (DIS189), and Mora districts (DIS126) is unknown.

County	Year	Beryl (pounds)
Rio Arriba	1951–1963	12,748
San Miguel	1951–1963	49,015
Taos	1951–1963	1,678,054
Harding, Taos	1950–1959	18,546
TOTAL	**1950–1963**	**1,758,363**

Pegmatite deposits

Pegmatites are coarse-grained granitic dikes, lenses, pods, or veins and represent the last and most hydrous phase of crystallizing magmas. Nearly all of the pegmatites in New Mexico and adjacent areas are Proterozoic in age and intruded metamorphic and granitic rocks; mid-Tertiary pegmatites are found in the Organ Mountains and Black Range (McLemore, 2010a). The pegmatites vary in size, but can be more than 300 ft long and more than 30 ft 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. Several commodities in addition to beryllium minerals have been produced from complex pegmatites in the past; including mica, lithium, uranium, thorium, rare earth elements (REEs), feldspar, niobium, tantalum, tungsten, and gemstones. Typically beryllium minerals are scattered discontinuously throughout the pegmatite, thereby hampering recovery. Although beryl has been produced from some of the pegmatites, most pegmatites in New Mexico and adjacent states will not constitute an economic resource today because of low grade, small size, and the expensive hand-sorting techniques required in order to recover any of the commodities, especially beryl (McLemore, 2010a).

For many years the Harding pegmatite was a significant producer of beryl in the United States. The pegmatite at the Harding mine occurs as a nearly horizontal dike that dips very gently southward. The mineralized part averages 50–55 ft in thickness and contains beryl, lithium, and tantalum-columbium minerals for several hundred ft along strike and down dip. Beryl occurs in several places in the dike, but is concentrated mostly in the wall zones, which are 0.5–5 ft thick. Exceptionally large masses of nearly pure-white or very pale-pink beryl were found just below the hanging wall of the dike. Much beryl, which had escaped notice from earlier mining of
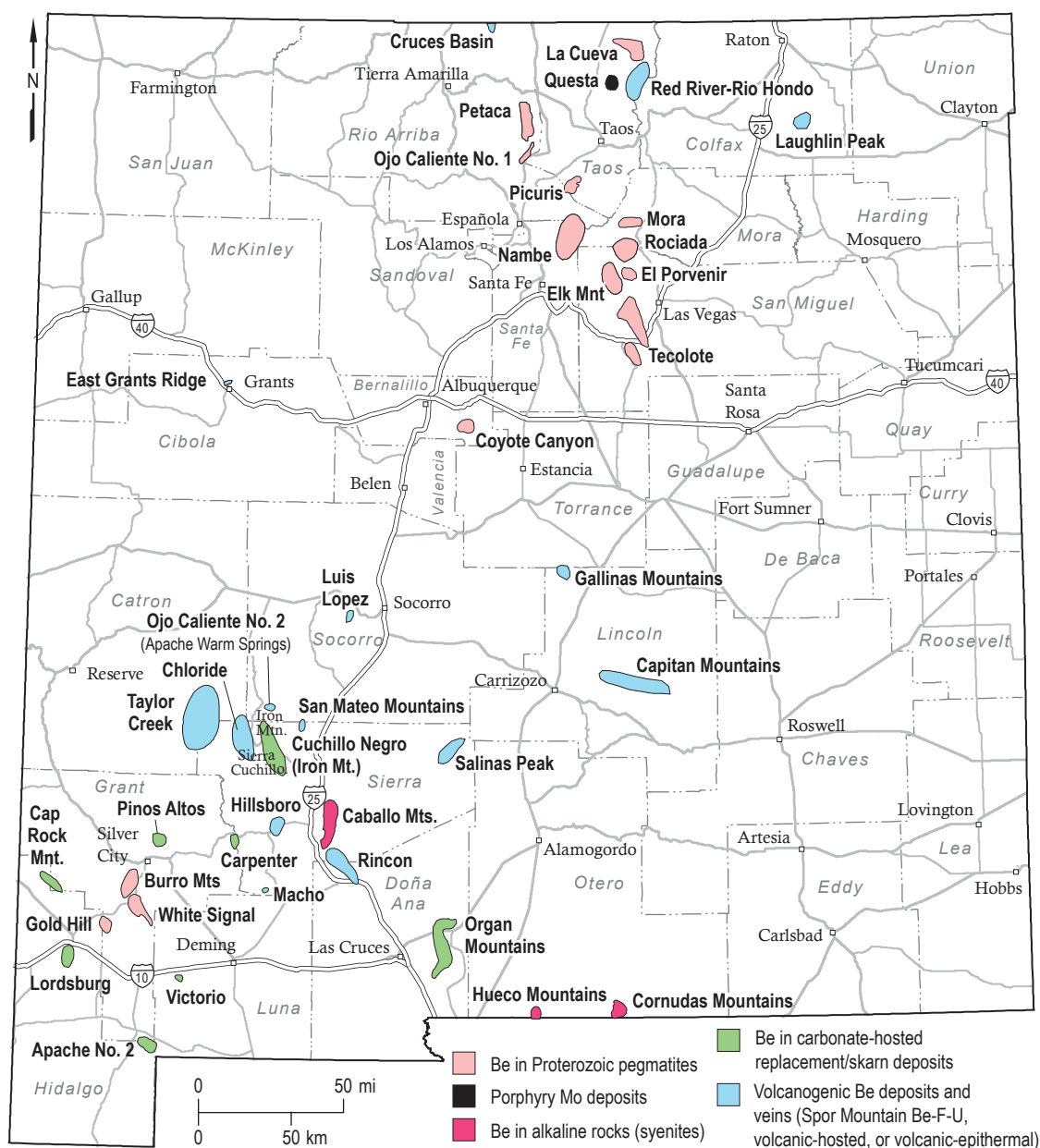
Figure 10. Mining districts in New Mexico that contain beryllium (McLemore, 2010a).

lithium and tantalum minerals, was recovered from the dumps (Griffitts, 1965).

In addition to the Harding pegmatite, McLemore (2010a) described the beryllium-bearing pegmatites in the Gold Hill (DIS058), White Signal (DIS068), Burro Mountains (DIS046), Ojo Caliente No. 1 (DIS147), Petaca (DIS148), Nambé (DIS185) districts, and the Tertiary pegmatites at Rabb Canyon (NMGR0176) in the Black Range. Smaller occurrences are present in the Rociada (DIS164), El Porvenir (DIS161), Elk Mountain (DIS162), Tecolote (DIS166), La Cueva (DIS232), Mora (DIS126), and Coyote Canyon (DIS002) districts.

Porphyry molybdenum (±tungsten, beryllium) deposits

Porphyry molybdenum (±tungsten, beryllium) deposits are large, low-grade deposits that contain disseminated and stockwork veinlets of molybdenum sulfides with minor to trace tungsten and beryllium and are associated with porphyritic intrusions. Four styles of porphyry molybdenum deposits are found and mineralized breccia deposits are common. Porphyry molybdenum deposits containing beryllium occur in three areas in New Mexico: Questa (DIS237, Taos County), Rialto stock (NMLI0121, Nogal-Bonito

district, DIS095, Lincoln County), and Victorio district (DIS114); the largest molybdenum deposits are at Questa. The deposits consist of thin veinlets, fracture coatings, and disseminations in granitic host rock and ore minerals include beryl and helvite. Beryllium concentrations are uneconomic in New Mexico porphyry molybdenum deposits, except perhaps for the Victorio district (McLemore, 2010a).

Alkaline igneous rocks containing beryllium deposits

Some alkaline igneous rocks, typically syenite or alkali-granite, have higher concentrations of beryllium than other types of igneous rocks. Peralkaline rocks are particularly enriched in beryllium, but known beryllium deposits in these rocks in New Mexico are low grade and typically uneconomic. In these deposits, beryllium minerals are found disseminated within the igneous rock (McLemore, 2010a).

The Cornudas Mountains (DIS128) in southern Otero County, New Mexico and northern Huspeth County, Texas are part of the Trans-Pecos alkaline belt. The Cornudas Mountains have been examined for potential deposits of uranium, beryllium, REE, niobium, gold, and silver, but there has been no production except for test shipments. The Cornudas Mountains consist of sills, plugs, and laccoliths that intrude relatively flat-lying limestones. The Wind Mountain laccolith (NMOt0013) is one of the largest intrusions and is mineralogically, texturally, and chemically zoned. Past exploration for beryllium in the Cornudas Mountains was inconclusive. A few samples assayed as much as 0.2% BeO. Beryllium occurs in other minerals within dikes, sills, and laccoliths; however, no beryllium minerals have been identified. The abundant rare mineralogies at Wind Mountain suggest the area has potential for undiscovered deposits of REE, niobium, beryllium, and zirconium. The igneous rocks probably have no potential because of the low concentrations; however, areas surrounding the intrusions could have potential for beryllium, REE, niobium, and other elements (McLemore, 2010a).

Other alkaline igneous rocks containing beryllium deposits described by McLemore (2010a) include the Caballo Mountains (DIS190, Sierra County), Hueco Mountains (DIS255, Otero County), Laughlin Peak (DIS020, Colfax County), and the Gallinas Mountains (DIS092, Lincoln County) districts. Although the beryllium concentration is anomalous in these areas, no beryllium has been produced.

Carbonate-hosted replacement and skarn deposits

Carbonate-hosted replacement and skarn (tungsten-molybdenum-beryllium and fluorite-beryllium) deposits are found as small veins and replacement lenses within the limestones and dolostones adjacent to or in the vicinity of granitic or rhyolitic intrusions; high silica and topaz rhyolites are particularly favorable. Ore minerals in the tungsten-molybdenum-beryllium deposits, such as those in the Victorio district (DIS114), Luna County, and at Iron Mountain include helvite (McLemore, 2010a).

Beryllium and tungsten skarn and vein deposits were discovered in the Victorio district in the early 1900s. Based on field mapping and examination of drill core, three types of deposits have been found in the Victorio Mountains: 1) carbonate-hosted lead-zinc replacement, 2) tungsten-molybdenum-beryllium skarn/vein, and 3) porphyry molybdenum deposits. At the surface, the tungsten-molybdenum-beryllium skarn/vein deposits occur as small veins and replacement lenses within the Ordovician limestones and dolostones in the vicinity of rhyolite intrusions. Samples assayed by Warner et al. (1959) ranged from 0.002–0.3% beryllium and 0.01–0.04% tungsten. In drill core, nearly all of the sedimentary rocks are mineralized to some extent. Based on optical examination, ore minerals include helvite and beryl in gangue (McLemore, 2010a). McLemore (2010a) also described the similar deposits at Iron Mountain and beryllium ores in the Carpenter district (DIS049), Grant and Sierra Counties.

Granite/rhyolites (topaz rhyolites) and tin skarn deposits

Topaz rhyolites are compositionally distinct, less-common high-silica rhyolites that are metaluminous to slightly peraluminous and are enriched in fluorite, beryllium, lithium, rubidium, cesium, gallium, yttrium, niobium, uranium, thorium, and tantalum with flat REE patterns with large europium anomalies, and high iron/magnesium ratios. They are genetically related to deposits of beryllium, molybdenum, iron, uranium, and tin. Topaz rhyolites erupted contemporaneously with a variety of other igneous rocks, but most typically they form bimodal associations with basalt or basaltic andesite and are unrelated to large collapse calderas. Topaz rhyolites appear to be evolved from partial melts of Proterozoic lower crust in an extensional tectonic setting, which is consistent with the

formation of rhyolites in the Sierra Cuchillo and San Mateo Mountains (McLemore, 2010a).

Beryllium minerals are found in tin skarn deposits associated with granites and rhyolites, but rarely in economic concentrations. Rhyolite-hosted tin deposits consist of discontinuous veins and veinlets in rhyolite domes and volcanic centers. The tin deposits occur in the fractured and brecciated outer parts of flow-dome complexes and are hosted by high-silica (>75%), peraluminous rhyolites and/or pyroclastic deposits. Hematitic and argillic alteration is commonly associated with these tin deposits. The deposits are typically small and low grade, but can contain high amounts of beryllium, among other elements (McLemore, 2010a).

McLemore (2010a) discusses beryllium potential in the Taylor Creek (DIS204, Catron, Sierra, and Socorro Counties), East Grants Ridge (DIS013, Cibola County), Capitan Mountains (DIS091, Lincoln County), and Salinas Peak (DIS203, Sierra County) districts. All have anomalous concentrations of beryllium, but all are sub-economic.

Volcanogenic beryllium deposits

Volcanogenic beryllium deposits, formerly known as Spor Mountain beryllium-fluorite-uranium deposits. are hosted by felsic volcanic rocks, especially rhyolite, in several areas of New Mexico and are found as volcanic-epithermal veins and/or replacements in volcanic rocks (McLemore and Lueth, 2017). Volcanogenic beryllium deposits form where hydrothermal fluids interact with volcanic rocks, especially high-silica topaz-rhyolites and granite porphyry. 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.

The Apache Warm Springs deposit (NMSO0152, Ojo Caliente No. 2 district, DIS230) lies on the northeastern edge of the Mogollon-Datil volcanic field in the northern Sierra Cuchillo range in Socorro County (McLemore, 2010d; 2012a). It is characterized by intense acid-sulfate alteration that produces the multiple shades of white, red, yellow, orange, purple, green, brown, and black. The alteration at the Apache Warm Springs beryllium deposit can be differentiated into two zones on the basis of mineralogy, texture, and inferred temperatures as a clay zone and silicified zone. Boundaries between the zones are typically gradational and are distinguished by

quartz content and texture. Bertrandite is found in small quartz veins and stringers, along fractures with clay minerals, and disseminated with the rhyolite and rhyolite ash-flow tuff (Fig. 11; McLemore, 2010d).

Vein deposits

The Cap Rock Mountain district (DIS048, Grant and Hidalgo Counties) is north-northwest of Lordsburg (Fig. 10) and was discovered in 1917. Beryllium is associated with epithermal manganese and fluorite veins in disconnected, lenticular shoots as well as carbonate-hosted deposits. A sample from veins in rhyolite contained 0.05% Be (McLemore, 2010a).

Boron and Borates

Boron does not occur alone in nature. Except for a few rare minerals, it is always combined with oxygen. Borates are therefore defined as minerals containing boric oxide or boron-oxygen molecules. These can generally be expressed on the basis of B_2O_3 in combination with a major cation.

Borates today are used mainly as chemical raw materials in combination with other commodities to produce products used by consumers. Fiberglass and glass fibers, glass and ceramics, soaps and detergents, fertilizers and herbicides, and wood preservatives are the major segments of today's market, although more than 25% of the world's borates are used in numerous other consumer products (Carpenter and Kistler, 2006).

Figure 11. Apache Warm Springs beryllium deposit as determined from trenching and drilling, looking northeast (N section 6, T9S, R7W; McLemore, 2010d, NMSO0152). *Photo by Virginia T. McLemore.*

Of the 14 commercially important borate minerals, only borax ($Na_2B_4O_7 \cdot 10H_2O$), datolite ($CaBSiO_4(OH)$), and dumortierite ($Al_7BO_3(SiO_4)_3O_3$) have been reported in New Mexico (Northrop, 1996). Borax, at approximately 4%, was reported in near Alkali Flat, west of the White Sands district (DIS134, Otero County). Borax is found in Lake Lucero in the White Sands district (Alto and Fulton, 1969). Northrop (1996) also reports dubious borax in beds near Farmington in San Juan County and equally dubious datolite at the head of the Gila River in Grant County. Dumortierite is found south of the Tres Hermanas district (DIS113, Luna County), where the mineral is found in narrow quartz veins more than 1,000 ft long and used as a semi-precious stone as well as ornamental stone (Carter, 1965b). Dumortierite also is found in the Petaca district (DIS148). None of these deposits are economic.

Boron can be found in saline brines in New Mexico. A well in sec. 26, T25S, R26E contained 1,300 mg/l B (Kunkler, 1972). Several NURE (National Uranium Resource Evaluation) water samples near a playa lake in the northern Estancia Basin (DIS243), Torrance County, contain anomalously high boron (as much as 5,013 ppb, McLemore, 2010a). The Estancia Basin is a closed basin bounded on the east by the Pedernal Hills and on the west by the Sandia and Manzano Mountains. The water samples also contain anomalously high concentrations of uranium (as much as 344.7 ppb), stronium (as much as 6,091 ppb), magnesium (as much as 1,320 ppm), and lithium (as much as 624 ppb).

Bromine

The major source of bromine, used in flame retardants, drilling fluids, pesticides and water treatment, are subsurface brines, although bromine also is found in sylvite and carnallite in the Carlsbad potash district (DIS038). Brines associated with evaporative deposits can have concentrations as high as 5,000 ppm Br (Williams-Stroud, 1991b). Brine deposits in the Rustler Formation, Dewey Lake redbeds, and Bell Canyon Formation (Artesia Group) in the Permian basin, southeast New Mexico contain 26–78 ppm Br (Bartsch-Winkler and Donatich, 1995). Carnallite, halite and sylvite in the Salado Formation also contain as much as 105 ppm Br in the Carlsbad potash district (Lindberg, 1946; Adams, 1969). Any processing of brines for fresh water could also recover bromine.

Chromite

Chromite is the major ore of chromium and it has useful properties for the refractory and foundry industries. Although there are secondary lateritic and placer deposits, primary deposits that contain chromite are generated by deep mafic magmas. The only chromite reported in New Mexico is found in meteorites in Harding and Union Counties (Northrop, 1959).

Clay

The term *clay* is somewhat ambiguous unless specifically defined, because it is used in three ways: 1) as a diverse group of fine-grained minerals, 2) as a rock term, and 3) as a particle-size term. *Clay minerals* are hydrous aluminum phyllosilicates, typically with variable amounts of iron, magnesium, alkali elements, and other elements. Clay minerals are fundamentally built of tetrahedral and octahedral sheets. As it is used in this report, clay is a fine-grained, natural, earthy, argillaceous material; the particle size of clay minerals is very fine and is generally considered to be approximately 2 µm or less; and the minerals are hydrous silicates composed mainly of silica, alumina, and water. Several of these minerals also contain appreciable quantities of magnesium, iron, alkalis, and alkaline earths. Although, many definitions state that clay is plastic when wet, not all clays have this property (Harvey and Murray, 2006).

Clay materials have been used for building construction in New Mexico for many centuries; Native Americans were making crudely shaped adobe blocks prior to the arrival of the first Spanish settlers. Adobe was the most common building material for many years and is still used in new construction, particularly in north-central New Mexico (see above). The extensive use of sun-dried adobe prevented the expansion of New Mexico's brick and tile industry at the same rate as in other states. The valuable clays that can be sold at distant markets have not been mined on a large scale in New Mexico.

Clay materials produced commercially or consumed locally today are miscellaneous clays used in the manufacture of brick and Portland cement, loam and soil used for adobe, fire clay used in low- and moderate-heat-duty refractory products, and pottery clay. Minor quantities of miscellaneous clays are occasionally produced for use in drilling mud. Bentonite has been produced in New Mexico, but

the only bentonite plant operating in 2014 is near Belen and it processes Ca-bentonite mined in Arizona. Virtually all the meerschaum (sepiolite) mined in the U.S. came from two districts in Grant County (Alum Mountain and Piños Altos) prior to World War I, although there has been no recent production.

The suitability of clays in New Mexico for various uses depends on physical properties that are controlled by the mineral and chemical composition of the clay. The common clay minerals in New Mexico include kaolinite, calcium montmorillonite, illite, halloysite, sepiolite (or meerschaum), chlorite, and mixed-layer illite-smectite (I/S) clay minerals. All clays contain nonclay mineral impurities. Quartz, cristobalite, tridymite, feldspar, titanium minerals, carbonate minerals, and mica are common in many clays, and gypsum and organic matter are abundant in others. The value of clays for most uses varies directly with the purity of the clay mineral present; however, for some products nonclay minerals or organic matter having certain properties are important. Physical properties of clays, one or more of which make them suitable for different uses, include plasticity, bonding strength, color, vitrification range, deformation with drying and firing, resistance to high temperatures, gelation, wall-building properties, viscosity of
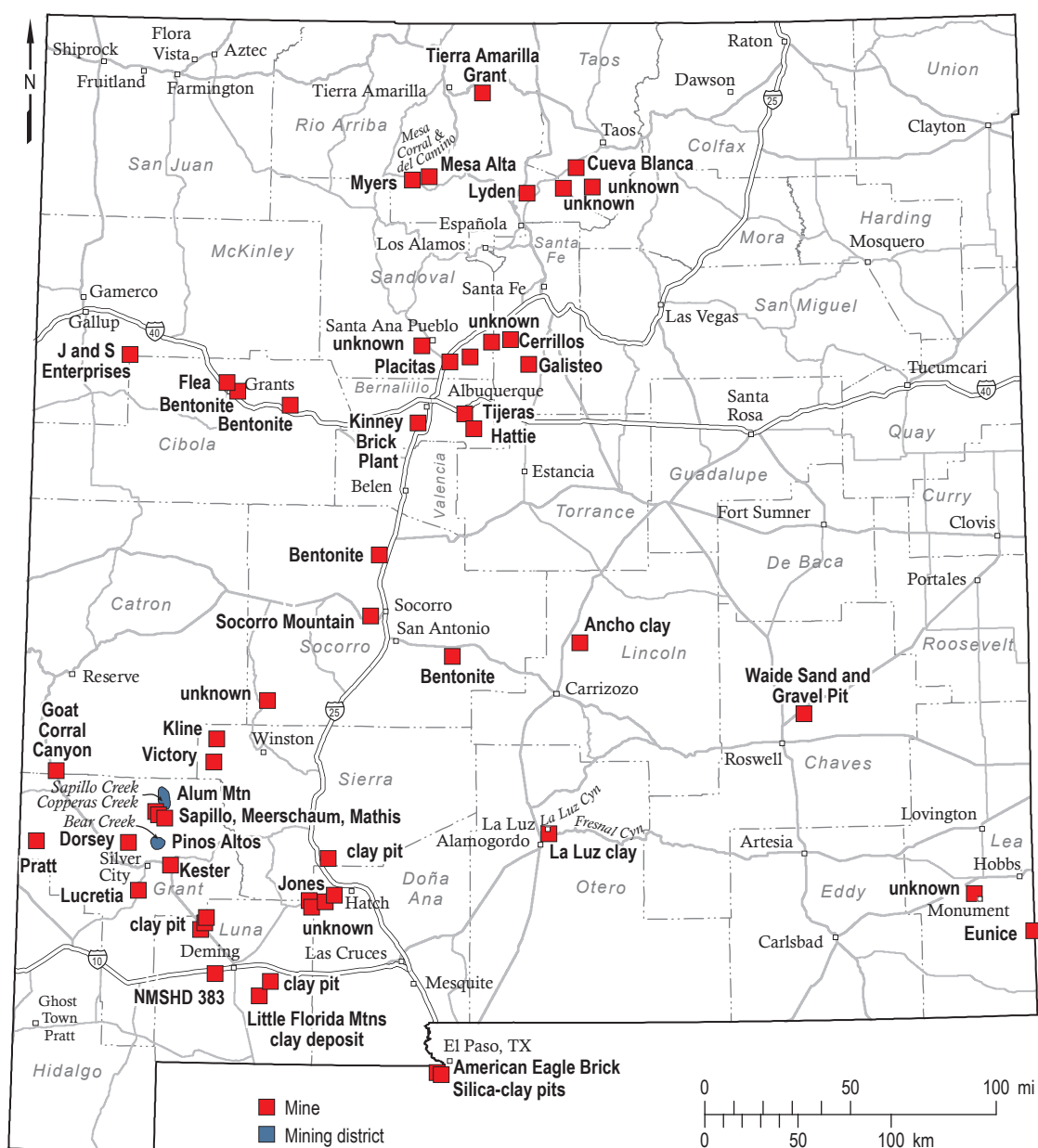
Figure 12. Major clay deposits in New Mexico.

slurries, swelling capacity, ion exchange capacity, and absorbent properties (Patterson and Holmes, 1965). Figure 12 shows the locations of major clay deposits in New Mexico.

Ball clays

Ball clays are kaolinitic sedimentary clays that are an important component in most ceramic materials because they confer strength and elasticity. Most ball clays impart a light cream to white fired color in an oxidizing atmosphere. Ball clays have varying proportions of kaolinite, illitic mica, or sericite, and fine quartz, with small amounts of organic matter and other minerals such as smectite. They are commercially valued because they increase the workability and strength of ceramic bodies (McCuistion and Wilson, 2006). No ball clays have been identified in New Mexico.

Bentonite

Bentonite is a clay material that has altered from volcanic ash or tuff and it is composed chiefly of montmorillonite. One kind of bentonite known as Wyoming- or sodium-type has very high-swelling capacity, extremely fine particle size, and other properties that make it valuable for use in well-drilling mud; as a bonding material for foundry sands and in palletizing fine-grained iron ores, where high dry strengths are required; and as a relatively impervious lining for reservoirs, irrigation ditches, and stock tanks. A second kind of bentonite called calcium bentonite, southern-type, or non-swelling is mineralogically similar to the Wyoming-type but has different physical properties. Non-swelling bentonites are ordinarily not as efficient in drilling muds as the Wyoming-type but they are more suitable for bonding materials requiring high-green strength (the ability to withstand damage), for catalysts in refining petroleum, bleaching clays, for cat litter, as a desiccant, and other purposes. The United Desiccants plant (NMVA0022) near Belen, now closed, used Ca-bentonite from Arizona to produce desiccant clays.

A deposit with properties similar to the Arizona clay has been identified in New Mexico (NMSA0136), but the bed, while fairly widespread is only about 1.5 ft thick and is located on Santa Ana Pueblo land (Austin, 1994). Bentonite was mined near Socorro and Hatch for drilling muds. Bentonite occurs in most counties in New Mexico, but has been mined only on a small scale at a few localities and none are mined at present.

Common clays and shales

Common clays and shales used in making brick, pottery, and tile and for other purposes have been mined at a number of places in New Mexico (Fig. 12). Production is in Table 11. Clay minerals present consist of all of the clay mineral groups, but chlorite is rare. Quartz is abundant and clay minerals make up less than 50% of these materials. Current production from clay deposits is mostly for bricks. Note the decreased production in 2008–2009 due to the economic recession (Table 11).

Plants using these materials have operated at various times since 1900 at most centers of population, including Albuquerque, Santa Fe, Gallup, Aztec, Farmington, Flora Vista, Fruitland, Shiprock, La Luz, Las Vegas, Socorro, San Antonio, Silver City, and others (Jones, 1915; Talmage and Wootton, 1937). The state penitentiary in Santa Fe produced bricks for sidewalks from a local clay (Jones, 1915). Most of the plants supplied local markets and closed after such demands were satisfied. The only brick plants in operation in 2017 are those of the Kinney Brick Co. (NMBE0028, Albuquerque) and the American Eagle Brick Company (NMDA0030, Sunland Park, just west of El Paso, Texas). The pit of the Kinney Brick plant, in production since 1928, is in the Pine Shadow Member of the Wild Cow Formation, Madera Group of Upper Pennsylvanian age. The American Eagle Brick pit, in production since 1979, consists of marine shales and siltstone of Lower Cretaceous age. Miscellaneous clays of Pennsylvanian age also are used in making Portland cement at the Tijeras cement plant (NMBE0012) located east of Albuquerque.

Table 11. Production of common clay from New Mexico from 2000–2009, in metric tons (from USGS, 2000–2013).

Year	Quantity	Value
2000	34,000	$256,000
2001	34,000	$256,000
2002	33,000	$175,000
2003	36,000	$209,000
2004	34,000	$177,000
2005	36,000	$221,000
2006	35,000	$228,000
2007	28,000	$269,000
2008	14,000	$120,000
2009	10,000	$90,000
2010	13,000	$160,000
2011	8,000	$70,000
2012	8,000	$48,000

Clays and shales for miscellaneous uses have been mined from several types of rocks, including altered volcanic rock and sedimentary formations. The Percha Shale west of Silver City was mined to mix with clays from Copperas Creek to obtain colored brick. Clays and shales were mined east of Mesquite, Doña Ana County, to supply brick plants in El Paso, Texas. Clays and shales in the Mancos Shale and Mesaverde Group of Cretaceous age were mined for brick at a number of places in northwestern New Mexico, including the former brick plant at Gallup (NMMK0428) and Las Vegas. Similar materials mined in the old Carthage coal field were used in the plant at Socorro, and clays and shale have been used for brick on a small scale in northeastern New Mexico. Red gypsiferous and highly plastic clays of probable Tertiary age were dug near Monument, Lea County, and used for drilling mud in the Hobbs oil field, and small tonnages of organic shales in the Blanco pit, Chaves County, are also used in drilling mud. Alluvial clays were formerly used for low-quality brick at Albuquerque and Socorro (Patterson and Holmes, 1965).

Plastic clays have been used on a small scale in making pottery, primarily Indian wares and art pottery objects. La Luz Clay Products Pottery Plant (NMOt0369, Otero County) was founded in La Luz, New Mexico about 1929 by Rowland Hazard III and produced a range of fired clay products from about 1930 through 1950 (McLemore, 2014a). The clay was mined from several clay pits along La Luz Canyon, near the junction with the Fresnal Canyon (Eidenbach, 2013). Some material was from a gray to black shale interbedded with limestone in the Magdalena Group, probably the Holder Formation (Pray, 1961; Koning et al., 2007). This material, when ground and mixed with water, produced a high plastic, easily worked clay with little drying and firing shrinkage. The black color of the unfired clay was a result of organic material and burned off upon firing to a light buff color (Talmage and Wooton, 1937). Numerous additional clay pits produced red, pink, and reddish-brown material along the bank of La Luz Creek near the plant (Eidenbach, 2013). One type of clay had 10–12% iron oxide and a yellow clay also had high amount of iron (Furman, 2009). Some of the existing clay pits are approximately 4–8 ft deep. The pottery characteristics were dependent on the length of firing time (Furman, 2009).

Plastic clays suitable for Indian wares are dug locally near Gamerco, McKinley County, and near Española, Rio Arriba County. A deposit of plastic pottery clay, which probably is kaolin altered from

volcanic rock, in secs. 2 and 11, T23N, R2E, northwest of Santa Fe, formerly supplied local ceramic needs (Patterson and Holmes, 1965).

Fuller's earth

Fuller's earth is a general term for industrially versatile smectite or palygorskite-sepiolite clays (hormites) with high surface area and strong sorptive, binding, gelling, thickening, or decolorizing ability. Fuller's earth has been in common use from perhaps biblical or at least medieval times, when such clays and earths were used for fulling, or cleaning raw wool to remove greasy lanolin and dirt before the wool was spun, dyed, and woven. Fuller's earths are composed of various combinations of absorptive clay minerals, often with varying amounts of impurities such as silica (at times in the form of fossil diatoms), kaolinite, illite, zeolites, clay-size micas, and carbonate minerals. Although fuller's earth is a widely used commercial term, it has often been inconsistently applied to a variety of smectites, hormites, bentonites, zeolites, impure diatomites, and other such clay occurrences. No economic deposits of fuller's earth have been identified in New Mexico. Although some clay material has been designated as absorbent, they have been used to absorb water and not oils.

Kaolin

Kaolin clays are a group of clays having related mineralogy and chemical composition. These clays are classified according to uses, as: 1) kaolin or china clays, 2) ball clays, 3) halloysites, and 4) fire clays. Kaolins are used in adhesives, medicines, cosmetics, fillers, chemicals, and many other purposes. No halloysite deposit has been exploited in New Mexico (Patterson and Holmes, 1965). The kaolin in New Mexico occurs under various geologic conditions and has been used principally in making tile and refractory brick. Deposits, part of which are composed of chiefly kaolin and part montmorillonite and nonclay mineral impurities, have altered from volcanic rock along Copperas Creek (Alum Mountain district, DIS042, Grant County). Kaolin is found at the Torpedo (NMDA0156) and Memphis (NMDA0311) mines in the Organ Mountains district and on Mesa Alta (NMRA0369), near Coyote, where it was used for making porcelain ware.

Large deposits consisting of a mixture of highly crystalline kaolinite and cristobalite occur in hydrothermally altered tuffs and other volcanic rocks along the continental divide about 14 mi west of Winston,

Sierra County at the Kline deposit (NMSI0881). Portions of this deposit consist of rather uniform light colored clay, but much of it contains appreciable vein quartz or other forms of silica and only partially altered volcanic rock. A few short tons of clay from this deposit were used experimentally in making ceramic tile, and the deposit was explored in some detail, including evaluations for use as paper coater. However, the presence of considerable amounts of cristobalite and tridymite make these deposits unsuitable for this use at this time (Isik et al., 1994).

Palygorskite and sepiolite (hormites)

Meerschaum or sepiolite, $Mg_8(Si_{12}O_{30})$ $(OH)_4(OH_2)_4$ • NH_2O, is a tough clay material and so lightweight that dry meerschaum (German word for sea foam) will float on water. Meerschaum can be carved and shaped and has been used for nearly 200 years in making pipes and other articles for smokers, and small quantities have been used for a number of other uses, including an absorbent for nitroglycerine.

Meerschaum was discovered along Sapillo Creek in the Alum Mountain district in 1875. An estimated 2 million pounds of meerschaum was shipped from the Meerschaum mine (NMGR0223) and from the Dorsey mine (NMGR0665) along Bear Creek in the Piños Altos district (DIS062) (Sterrett, 1908; Bush, 1915; Petar, 1934; Ratté et al., 1979). Production of meerschaum ceased shortly before World War I, but resumed in 1943 when approximately 1,000 lbs was shipped for experimental purposes in an attempt to find improved materials for insulators in radios (Patterson and Holmes, 1965). X-ray diffraction analysis indicates that the New Mexico meerschaum also contains palygorskite, $Mg_5(Si_8O_{20})(OH)_2(OH_2)_4$ • $4H_2O$ (Christ et al., 1969).

Refractory clays

Refractory or fire clays, commonly associated with coal beds, occur in sedimentary formations of Cretaceous age in several counties. The largest production of these clays has been in the Gallup region, McKinley County, where thick beds of plastic, moderately thick beds of semiplastic, and thin seams of flint clay occur in the Mesaverde Group. These deposits were worked as early as 1898. The highest production was in 1907 when 27,000 short tons of fire-clay mortar, raw fire clay, and fire brick were shipped (Patterson and Holmes, 1965). Some of this production went to Arizona for copper smelting.

Clay production in the Gallup coal field has been negligible in recent years, because the best grade clays are thin and can only be mined by underground methods.

Small-scale production of fire clay from strata of Cretaceous and Paleocene age has been reported at a number of localities, and a few undeveloped deposits occur at scattered localities. Clays and shales in the Dakota Sandstone have been used for refractories at Ancho (NMLI0075, Lincoln County) (Van Sant, unpublished report; Austin, 1993), and Las Vegas, San Miguel County (Van Sant, unpublished report). Shales and clays in the Vermejo and Raton Formations were used many years ago in making coke ovens at Dawson, Colfax County, and are, therefore, probably at least low-grade refractory clays. Some of the clay in the Mesaverde Group mined for brick in the Carthage coal field (DIS208, Socorro County) (Talmage and Wootton, 1937), was suitable for low-heat-duty fire brick (Van Sant, unpublished report). Clay near Pratt, Hidalgo County has produced fire clay for use in copper smelting has been mined for many years.

Refractory clay consisiting of mostly kaolin clay occurs in sedimentary beds at the top of the Morrison Formation of Jurassic age and in the basal part of the overlying Dakota Sandstone of Cretaceous age at many places in northwestern New Mexico. The best exposures of this clay are on Mesa Corral and Mesa del Camino, near the highest part of north-facing Mesa Alta, Rio Arriba County. At this locality bedded kaolin on an old erosion surface at the top of the Morrison Formation has been partly reworked and both kaolin clay chips and kaolin cement are present in the overlying Dakota Sandstone. A sample of this clay tested as a refractory clay, and a sample of the sandstone cemented with kaolin from the overlying Dakota Sandstone is also a refractory material (Patterson and Holmes, 1965).

Diamonds

Diamond is an extraordinary mineral with extreme hardness and inherent beauty that is sought for personal adornment and industrial use (i.e., abrasives, grinding, drill bits). Because the genesis of this unique mineral requires extreme temperature and pressure, natural diamond is rare, so rare that some diamonds are the most valuable commodity on earth, based on weight (Hausel, 2006).

Northrop (1996) identified a number of reports of diamonds in New Mexico, but none that were confirmed by qualified authorities. All were either from newspaper accounts or unsubstantiated identifications. The crystals known as Pecos diamonds are actually quartz or dolomite crystals (Albright and Lueth, 2003).

Diatomite

The term diatomite is applied both geologically and commercially to the nearly pure sedimentary accumulation of diatoms. Diatoms (class Bacillariophyta) are a type of silica-based algae and are unicellar organisms, colonies, or filaments found in marine, freshwater, and brackish streams, lakes, and oceans. When diatoms die, their siliceous skeletons sink to the bottom of the lake or sea and form a chalky, siliceous mud that becomes diatomite or diatomaceous earth, a soft, fine-grained sedimentary deposit. Commercial diatomite deposits in the United States are found in marine sedimentary rocks that accumulated near the continental margins, lacustrine lakes or marshes, and modern lakes, marshes, and bogs (Dolley and Moyle, 2003). The sediments are fine-grained, highly siliceous, and consist primarily of amorphous opaline silica with only minor amounts of organic residue, secondary minerals, and co-deposited non-diatomaceous or crystalline clastic debris. In the geological sense, the name diatomite implies sedimentary accumulations that have reached appreciable thickness, and consequently, when thick enough, such accumulations may have possible commercial potential. Although the term diatomite is popularly and inappropriately applied to any sediment in which there is an abundance of diatom frustules, alternative terminology is more correctly employed to describe less pure diatomaceous sediments (for example, clay-bearing diatomite or diatom-bearing clay; Shenk, 1991; Breese and Bodycomb, 2006).

The unique physical properties of diatomite are derived from the size, shape, and structure of individual diatom skeletons and the packing characteristics of the skeletons. Diatoms range in diameter from 10 μm to more than 500 μm and generally have a spiny structure with intricately pitted surfaces. Diatoms are very porous, light weight, chemically inert, do not conduct heat, do not burn, are abrasive, have low density, and are composed of silica. Thus, diatomite or diatomaceous earth is used as a 1) filter to make syrups, drinks (including alcoholic beverages), medicines, solvents, and chemicals, 2) additive in cement and other compounds, 3) absorbent for industrial spills and pet litter, 4) filler in paint, paper, ceramics, and detergents, 5) high-temperature insulation (fire doors, sound insulation), 6) whitener in paint,

7) mild abrasive, 8) measuring optical image quality, and 9) various pharmaceutical and biomedical uses (Crangle, 2011). Very pure diatomite is used 1) in animal feed, 2) for use as a wormer in livestock, 3) for protecting grain and seeds from insects, and 4) as insecticides. Diatomite was once used in manufacturing dynamite.

Diatomite has been mined only on a small scale in New Mexico (Patterson, 1965). The deposits that were worked in the 1950s are in the Jemez Mountains at the Rhodes mine (NMRA0361), Rio Arriba County. Production statistics are unavailable, but the total was probably not more than a few thousand short tons. The diatomite occurs in the Tesuque Formation of the Santa Fe Group and it is calcareous and contains fine-grained mineral impurities. The bed is approximately 10 ft thick, but the total thickness of diatomaceous rock is appreciably greater. Diatomite deposits in the area occur under thin overburden, and they pass laterally beneath a cap rock of basalt for what may be a considerable distance. Presumably the resources of diatomite in this vicinity are large (Patterson, 1965).

In addition to the deposits in Rio Arriba County, diatomite deposits occur at the Buckhorn zeolite deposit (NMGR0618), Grant County (discussed below under zeolites; McLemore, 2008) and diatom-bearing beds occur at two localities in Roosevelt County (Blackwater Draw, NMRO0005 and Anderson Lake, NMRO0006). Numerous other areas in the central and western parts of New Mexico contain sedimentary rocks that accumulated in lakes and are favorable for the occurrence of diatomite (Northrop, 1959).

Diatomite is found associated with maars at Monticello Point (NMSI1743, Sierra County) at the mouth of Alamosa Canyon, along the shores of Elephant Butte Lake (Fig. 13) where a Texas company examined the deposits for commercial development (McLemore et al., 2012). The Monticello Point diatomite is white to pale orange to tan, is finely laminated, and consists of clay, calcite, amorphous silica, quartz, and silt (Fig. 14). The base of the maar is not exposed and the diatomite deposit is overlain by piedmont deposits of the Pliocene-Pleistocene Palomas Formation. The presence of fine-grained marl in the deposit indicates a moderately saline (3–10%), high pH, alkaline, shallow water lake. This area has not been adequately explored.

Feldspar

Feldspar is the general name for a group of aluminum silicate minerals that contain varying amounts of potassium, sodium, or calcium and constitute nearly 60% of igneous rocks. The principal potassium
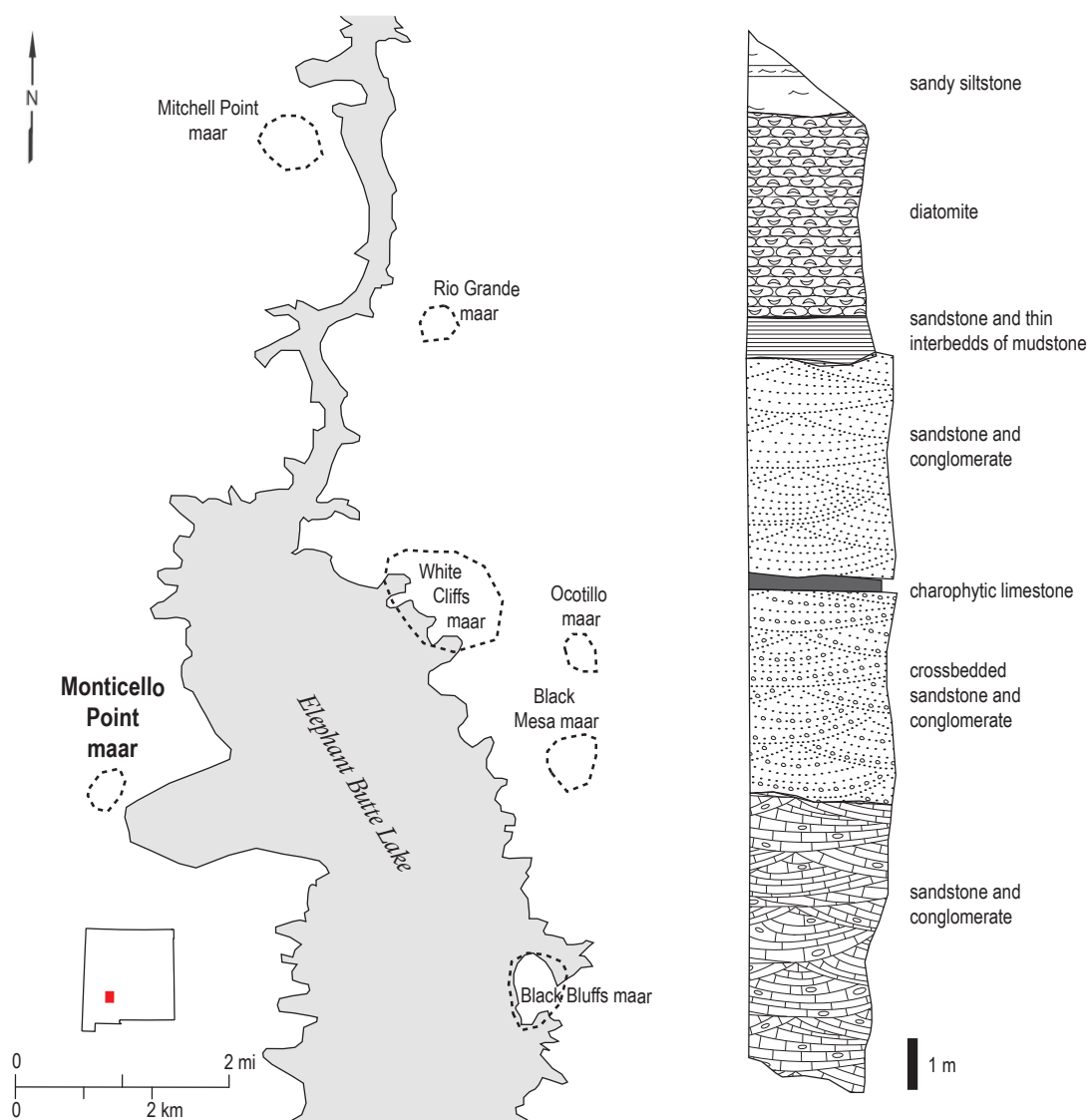
Figure 13. Location and measured stratigraphic column of the Monticello Point diatomite deposit, Sierra County (McLemore et al., 2012).

feldspars are orthoclase and microcline, which have the same chemical composition ($KAlSi_3O_8$) but different crystal forms. The sodium-calcium feldspars, called plagioclase, form a complete series of minerals that range from pure $NaAlSi_3O_8$ (albite) to pure $CaAlSi_2O_8$ (anorthite). Most orthoclase and microcline contain 10–25% $NaAlSi_3O_8$ and plagioclase generally contains 5–15% $KAlSi_3O_8$. Intergrowths of orthoclase or microcline with albite are called perthite, a common pegmatite mineral. Cleavelandite, a platy form of albite, is common in many pegmatites in New Mexico. Feldspars are used in glass and ceramic manufacturing, among other uses, including fillers, extenders, and as a flux.

The potassium feldspars and the more soda-rich varieties of plagioclase are the types generally mined. Until recently much of the feldspar produced was

Figure 14. View looking north of the Monticello Point diatomite (NMSI1743). *Photo by Virginia T. McLemore.*

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perthite, which is commonly concentrated as very large crystals in certain zones in pegmatite bodies. Today finer-grained pegmatite is mined in bulk and a mixture of potassium and sodium feldspars is recovered by milling and flotation (Lesure, 1965).

Production of feldspar from New Mexico is not always reported, although some has been produced from pegmatites and stockpiled during the course of mining for other pegmatite minerals. Substantial resources of high-grade potassium feldspar are available in New Mexico, especially in pegmatites in the Petaca district (DIS148, Rio Arriba County) (Jahns, 1946). Potential sources of feldspar are found in the Capitan Mountains (DIS091), where portions of the Capitan granite are low in iron (less than 1% Fe_2O_3) and could be suitable for glass and ceramics (Allen and McLemore, 1991; Korzeb and Kness, 1992).

Fluorspar

Fluorspar is the commercial name for fluorite, calcium fluoride (CaF_2). The name, derived from the Latin word *to flow*, refers to its low melting point and its early use in metallurgy as a flux. It is the principal industrial source of the element fluorine, used to manufacture hydrofluoric acid, which is critical in the manufacture of many materials. Until recently, there has been no domestic production of fluorspar in the United States for several decades, with the exception of fluorosilicic acid, which was recovered from phosphoric acid plants processing phosphate rock. China, one of the world's leaders in fluorspar production, has limited exports and many countries are looking at their own deposits to meet their demands. The USGS reports the opening of a fluorspar mine in western Kentucky in 2011 (Miller, 2011).

Fluorite occurs in a wide variety of geological environments, indicting deposition under an extended range of physical and chemical conditions (Fulton and Miller, 2006). From an economic standpoint, the most important modes of occurrence of fluorite are:

- Fissure veins in igneous, metamorphic, and sedimentary rocks

- Stratiform replacement deposits in carbonate rocks

- Replacements in carbonate rocks along contacts with acid-igneous intrusives

- Stockworks and fillings in shattered zones

- Deposits associated with carbonatite and alkalic rock complexes

- Residual concentrations resulting from the weathering of primary deposits

- Occurrences as recoverable gangue in base metal deposits

Fluorite production from New Mexico is in Table 12. Mills were at Deming and Los Lunas. Most of the known fluorspar deposits in New Mexico are in fissure veins, jasperoid bodies, and bedding-replacement stratiform, also known as mantos; a few minor occurrences are in breccia pipes and brecciated shear zones and stockworks; many are found with barite deposits (Fig. 9, Table 9). Fissure veins, both void-filling and replacement, are found in silicic intrusive and intermediate to silicic extrusive igneous rocks, and in carbonate and detrital sedimentary rocks. Fissure vein deposits in Proterozoic granites in the Caballo Mountains, Cookes Range, Burro Mountains, and Zuni Mountains are, or have been, the most important type of deposit both quantitatively and productively in New Mexico. Jasperoid deposits, both concordant and discordant, are widespread and numerous in both sedimentary and igneous host rocks and probably constitute the most important type in terms of future production. Small, concordant bedding-replacement deposits in limestones in the southern Caballo Mountains have yielded minor production (Table 12; McAnulty, 1978).

Vein deposits have been the principal source of fluorspar in New Mexico in the past for several reasons: 1) they are numerous and widespread in a variety of host rocks, particularly in Proterozoic granites in the Caballo Mountains, Cookes Range, Burro Mountains, and Zuni Mountains; 2) many veins contain void-filling deposits from which a marketable product can be produced with little or no beneficiation by selective mining; 3) such relatively high-grade deposits lend themselves to small-scale mining for a small amount of capital; and 4) there were no beneficiation plants within economic hauling distances of deposits to process low-grade ores (McAnulty, 1978). Considerable tonnages of fluorspar remain in New Mexico should economic conditions warrant future development of production facilities.

Garnet

Garnets are a group of complex silicate minerals with similar crystalline structures and diverse chemical compositions common to skarns and igneous rocks. The general chemical formula is $A_3B_2(SiO_4)_3$, where A can be calcium, magnesium, ferrous iron,

Table 12. Fluorite production from New Mexico.

District ID	District	Fluorite production (short tons)	Cumulative estimated value ($)	Period of production	References
	Bernalillo County				
DIS002	Coyote Canyon	200	2,000–10,000		McAnulty (1978)
DIS004	Tijeras Canyon	400	4,000–20,000		—
	Catron County				
DIS010	Wilcox	10,603	100,000–500,000	1880s, 1926–1953	Williams (1966), McAnulty (1978)
	Cibola County				
DIS017	Zuni Mountains	182,244	1,700,000–8,400,000	1918–1953	McAnulty (1978)
	Doña Ana County				
DIS030	Bishops Cap area (Organ Mountains district)	150	1,500–7,500	1944, 1969–1972	Williams (1966), McAnulty (1978), Seager (1981)
DIS100	Black Mountain	1,100	11,000–55,000	?	Dunham (1935), McAnulty (1978), Smith (1981), McLemore (1994b)
DIS030	Organ Mountains (White Spar, Tennessee, Golden Lily, Ruby)	1,500	15,000–75,000	1933, mid 1900s	Talmage and Wootton (1937), Rothrock et al. (1946), Williams (1966), Williams et al. (1964), McAnulty (1978), McLemore (1994b)
DIS032	Rincon (Palm Park, Horseshoe)	—	<100,000		Williams et al. (1964), Filsinger (1988)
DIS035	Tonuco Mountain	7,720	77,200–386,000	1919–1935	Rothrock et al. (1946), Clippinger (1949), Williams et al. (1966), McAnulty (1978)
DIS036	Tortugas Mountain	20,751	200,000–1,000,000	1919–1943	Rothrock et al. (1946), McAnulty (1978)
	Grant County				
DIS044	Black Hawk	615	6,000–31,000	?	Richter and Lawrence (1983)
DIS045	Bound Ranch	3,230	30,000–162,000	?	Gillerman (1964), Williams (1966), Richter and Lawrence (1983)
DIS046	Burro Mountains	172,539	1,700,000–8,600,000	1880–1954	Richter and Lawrence (1983)
DIS054	Fierro-Hanover	110	1,000–5,000		McAnulty (1978)
DIS055	Fleming	232	2,000–10,000		Williams (1966)
DIS057	Gila Fluorspar	47,586	470,000–2,350,000	1880–1953	McAnulty (1978)
DIS058	Gold Hill	3,240	30,000–150,000	1952–1953	McAnulty (1978)
DIS060	Malone	408	4,000–20,000	?	Gillerman (1964), Williams (1966)
DIS061	Northern Cooks Range	63,531	630,000–3,150,000	1948–1953	McAnulty (1978)
DIS063	Ricolite	15,289	150,000–750,000	?	McAnulty (1978)
DIS066	Steeple Rock	11,000	110,000–500,000	?	McLemore (1993)
DIS067	Telegraph	16,603	160,000–800,000	1911–1945	Williams (1966)
DIS068	White Signal	3,644	30,000–150,000	1932–1952	Williams (1966), McAnulty (1978)
	Hidalgo County				
DIS084	Muir	9,175	90,000–400,000	1940s, 1952–1953	Rothrock et al. (1946), McAnulty (1978)
DIS082	Lordsburg	3,527	30,000–150,000	?	Lasky (1938), Rothrock et al. (1946); Richter and Lawrence (1985)
DIS079	Gillespie (Red Hill)	1,500	15,000–75,000	?	Zeller and Alper (1965), Williams (1966), McAnulty (1978)
	Lincoln County				
DIS092	Gallinas Mountains	2,400	24,000–120,000		McAnulty (1978)
	Luna County				
DIS105	Cookes Peak	452	4,000–20,000	1918–1954	Rothrock et al. (1946), Griswold (1961), Williams (1966)
DIS106	Florida Mountains	200	2,000–10,000	?	Griswold (1961), McAnulty (1978)
DIS107	Fluorite Ridge	93,827	930,000–4,650,000	1909–1954	Rothrock et al. (1946), Griswold (1961)
DIS108	Little Florida Mountains	13,428	130,000–650,000	?	Lasky (1947), Griswold (1961), Williams et al. (1964)
	Rio Arriba County				
DIS144	Gallina	19	<1,000		—
	Sierra County				
DIS190	Caballo Mountains	33,000	330,000–1,650,000	1918–1954	McAnulty (1978)
DIS192	Cuchillo Negro	500	5,000–25,000		McAnulty (1978)
	Socorro County				
DIS213	Hasonburg	—	<50,000		—
DIS218	Ladron Mountains	50	<2,500		—
	TOTAL	**720,773**		**1880–1978**	—

or manganese and B can be aluminum, chromium, ferric iron, or rarely, titanium. Angular fractures, high hardness, and an ability to be recycled characterize industrial garnet. The complex mineralogy of garnet determines its utility for a variety of uses. In the past garnet was mostly of interest as a gemstone. However, today garnet also is used as an abrasive in hydroblasting applications, sand blasting media, petroleum hydrofracting, and for granular filter media in sewage.

Six species of garnets are reported from New Mexico (Lueth, 1994; Northrop, 1996). Almandine garnets, $Fe^{+2}_2Al_2(SiO_4)_3$, are typically found in metamorphic mica schists and gneisses and pegmatites in the Petaca district (DIS148) in northern New Mexico. Yellow to black spessartine garnets $Mn^{+2}_2Al_2(SiO_4)_3$, are found in igneous rocks in the East Grants Ridge district (DIS013) and pegmatites in the Petaca district. Pyrope, $Mg_3Al_2(SiO_4)_3$, a magnesium aluminum silicate ranging in color from deep ruby-red to nearly black, is the most popular gemstone garnet and is associated with mafic to ultramafic igneous rocks. Blood-red pyrope from the Red Lake volcanic field-Buell Park area along the Arizona-New Mexico border about 10 mi north of Fort Defiance has long been admired. This pyrope along with peridot is found loose in ant hills and in the alluvium and gravels on the Navajo Reservation of McKinley County. Here the pyrope has weathered out of the surrounding volcanic kimberlite tuffs (Carter, 1965b; Lueth, 1994). Grossular garnets, $Ca_3Al_2(SiO_4)_3$, are found in skarns and contact replacement deposits in southern New Mexico. Andradite, $Ca_3Fe^{+2}_2(SiO_4)_3$, also is found in skarns and contact replacement deposits in southern New Mexico with grossular garnets. Bright green uvarovite, $Ca_3Cr_2(SiO_4)_3$, is rare and found only in small grains in South Canyon, Doña Ana County (Lueth, 1994). Economic garnet deposits should contain a minimum of 2 million short tons of ore containing greater than 20% garnet (Evans and Moyle, 2006).

Garnet deposits must be large enough to sustain production for 10–20 years, contain the right type and size of garnet for the end-user, be easily and inexpensively processed, and be close to markets and/or transportation routes. Although garnet has not been produced in New Mexico in recent years, at least one company was reported to be exploring for garnet in 2007–2017. Garnet exploration has mainly centered in three areas (Fig. 15): San Pedro mine (NMSF0159, Santa Fe County), Fierro-Hanover district (DIS054, Grant County), and Orogrande (DIS129) district (Harben et al., 2008). Andradite and grossular garnets are found in skarn deposits in all three areas, and large reserves of garnet remain in the waste rock piles after recovery of metals in these areas. Iron skarns tend to be more favorable.

The San Pedro mine, which reportedly has 7–8 million short tons of 85% garnet reserves (Lueth, 1996), was acquired by Royalstar Resources Ltd. in the early 1990s, but dropped the project in 1993. Local opposition to the project forced delays that eventually led, along with other problems, to failure to acquire a Santa Fe County mining permit (Harben et al., 2008). In 1996, San Pedro Mining Corp. received a state permit to mine and process garnet from the mine, but still needed to obtain a permit from Santa Fe County. Garnet is concentrated along or near the marble contacts (Lee and Atkinson, 1985).

Large reserves of garnet crop out on claims just west of Orogrande, in the Jarilla Mountains, Otero County (Lueth, 1996; McLemore et al., 2014b). These deposits were drilled and sampled in the late 1990s to early 2000s, but no significant development occurred. The deposits are currently being evaluated once again for future development.

Garnet is a major constituent of waste rock piles remaining after recovery of metals in tailings piles at Fierro-Hanover (Cetin et al., 1996). Approximately 149,000 short tons of 20–36% garnet are estimated to occur in tailings piles at Hanover (Cetin et al., 1996).

Other areas include Iron Mountain in the Cuchillo Negro (DIS192) and Magdalena (DIS221) districts. Development of the garnet resources in New Mexico is dependent upon detailed studies of garnet geochemistry, texture, density, angularity, hardness and resistance to abrasion (Evans and Moyle, 2006).

Gilsonite

Gilsonite is a naturally occurring solid hydrocarbon of the asphaltite group of hydrocarbon bitumens. It has a dull, black, coal-like appearance on weathered surfaces and a shiny, black, obsidian-like appearance on a fresh, conchoidal to hackly fracture surface (Tripp and White, 2006). Gilsonite occurs in disseminated blebs and in dikes (veins), sills, and fracture fillings, often in association with oil shale or bituminous deposits (tar sands). Gilsonite is used in more than 160 products, including printing inks and paints, oil well drilling muds and cements, asphalt modifiers, foundry sand additives, and a wide variety of chemical products.
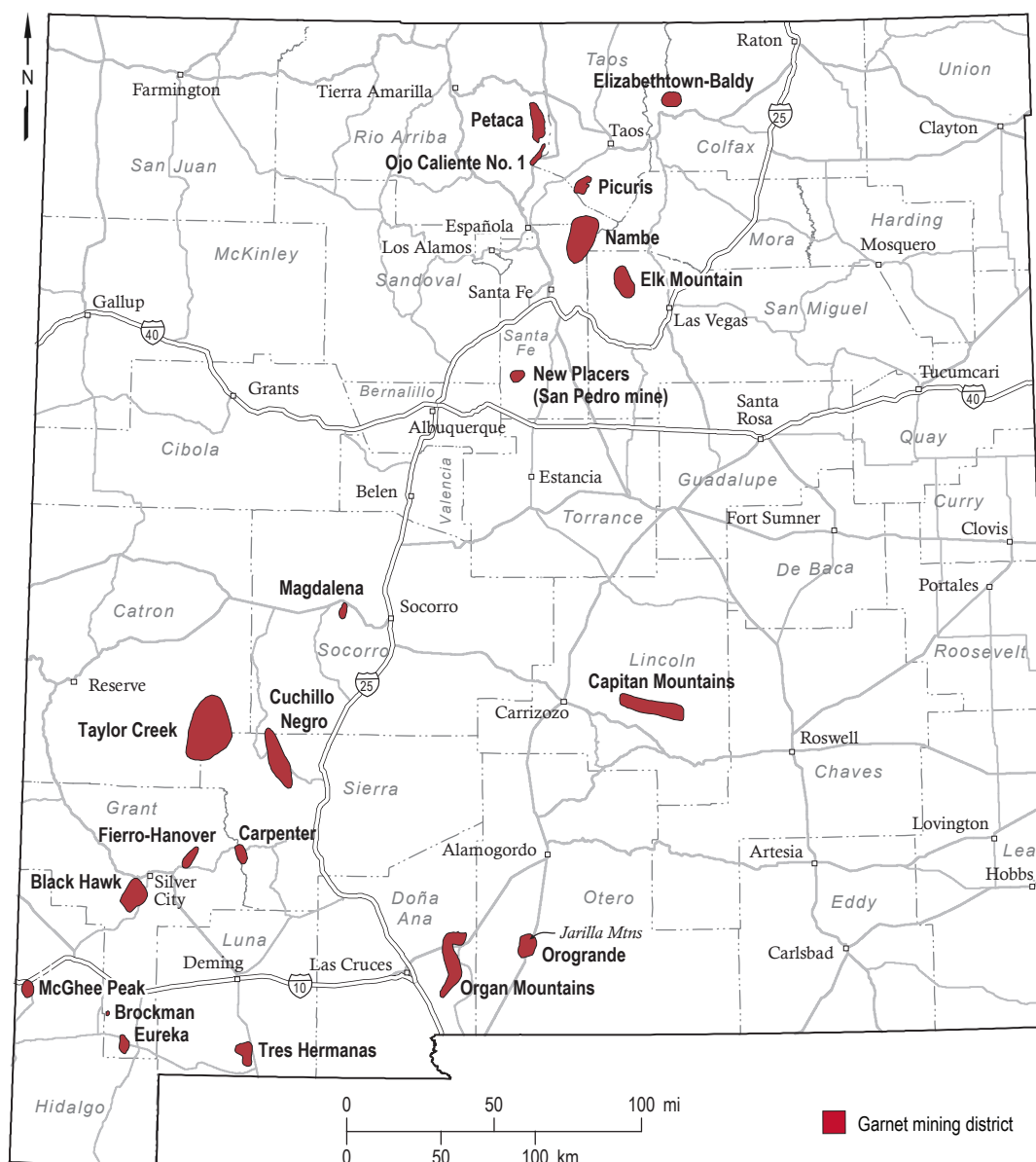
Figure 15. Mining districts with garnet deposits in New Mexico.

Northrop (1959) reports that gilsonite has been found in excavations at Chaco Canyon (San Juan County). Veins of it have been reported in sandstone southwest of Aztec. It is usually used for ornaments, inlays, and buttons.

Glauconite

Glauconite is a group of dioctahedral, potassium, iron-rich, compositionally heterogeneous, phyllosilicate (clay) minerals. In sufficient amounts, glauconite imparts an olive green to greenish black color to sediment. Glauconite-rich sediment is informally referred to as greensand, green earth, greensand marl, clay marl, sand marl, lime sand marl, or simply marl, as it is known in New Jersey. The term greensand as a rock name for glauconite-bearing sediment is more appropriate than greensand marl or marl, terms that have been perpetuated in the literature (Dooley, 2006).

Because of its potash and phosphate content, greensand was mined and marketed as a natural fertilizer and soil conditioner for more than 100 years. The advent of manufactured fertilizers with adjustable nutrient ratios led to a decline in the use of greensand in agriculture. The material has since been used in water purification and softening. Unfortunately, despite large reserves and worldwide distribution, glauconite has not been used to any

significant commercial extent because no major application has been found for a substance with its chemical composition and properties.

Glauconitic greensands are unconsolidated sandy, silty, or clayey sediments of marine origin found in formations ranging in age from Proterozoic to Recent. Although greensands are generally moderately sorted because of the presence of fine matrix, the glauconite fraction of these sediments is usually well sorted because glauconite pellets are remarkably uniform in size when autochthonous, although reworked glauconitic sediments can be poorly sorted. In the geologic strata, the contacts with overlying and underlying sediments are either gradational or unconformable. Primary sedimentary structures are generally lacking, but cross bedding, massive bedding, and bioturbation have been reported. The clay (phyllosilicate) fraction in the greensand matrix consists of mainly illite/smectite, illite, micas, ferric illite, kaolinite, and chlorite.

Most greensand deposits contain, in addition to glauconite, minerals such as quartz, mica, pyrite, some heavy minerals, and calcium carbonate in the form of shell or cement derived from marine organisms. Iron oxides, phosphatic nodules, fecal pellets, and foraminifera are locally common, and skeletal remains of marine vertebrates are occasionally found (Dooley, 2006).

In New Mexico, malachite-green glauconite in disseminated grains is abundant and widespread in the sandstone and sandy shale of the Bliss Formation (Upper Cambrian to Lower Ordovician in age) in southern New Mexico, particularly in Grant and Sierra Counties (Lewis, 1962; Northrop, 1996).

Doña Ana County has glauconite in the South Canyon, Organ Mountains district (DIS030) and in the Franklin and San Andres Mountains. In Grant County, glauconite is present in the Fierro-Hanover (DIS054), and Chloride Flat (DIS050) districts (Lewis, 1962). It is abundant in the Bliss Formation near San Lorenzo and reported from the Mimbres Mountains. In Hidalgo County, glauconite is present in the Hatchet Mountains. In Luna County, glauconite is found in the Cookes Peak (DIS105), Fluorite Ridge (DIS107) and Florida Mountains (DIS106) district. In Sierra County, glauconite is present in the Caballo Mountains (DIS190) and Tierra Blanca (DIS205) districts. In the Tierra Blanca district, it is present at the Pierce (NMSI0959) iron deposit. The San Andres Mountains also contains glauconite. Future economic potential of these deposits is low.

Graphite

Elemental carbon also takes the form of diamonds and fullerenes (carbon spheres or buckyballs). In this report, only natural graphite will be considered. Graphite was confused with other minerals, especially galena and molybdenite and two common names that are still used for graphite are plumbago, meaning lead-silver, and black lead. The latter implies that graphite is either composed of lead or contains a large percentage of it. The United States has long relied on imports for its graphite supply because of the lack of suitable domestic graphite reserves. Mexico has supplied the United States with most of its amorphous graphite requirements (Taylor, 2006). Graphite is used in refractories, batteries, steelmaking, brake linings, foundry facings and lubricants.

Natural graphite can be divided into three classes: disseminated flake, crystalline vein (fibrous or columnar), and amorphous. Flake graphite is a lamellar form found in metamorphic rocks, such as marble, gneiss, and schist. Each flake is separate, having crystallized as such in the rock. Crystalline vein graphite (also called lump or high crystalline graphite) is found in well-defined veins or pocket accumulations along intrusive contacts of pegmatites with limestones. The graphite in these deposits is of two types, fibrous and columnar.

Amorphous graphite commonly is found as minute, micro-crystalline particles fairly uniformly distributed in weakly metamorphosed rocks, such as slates, or in beds consisting almost entirely of graphite (Sutphin, 1991). The latter usually are metamorphosed coal seams with as much as 80–85% graphitic carbon, whereas the former are altered carbonaceous sediments, commonly ranging from 25–60% carbon. The graphite content of amorphous graphite deposits depends upon the amount of carbon present in the original sediments; there is no evidence of enrichment by intrusive rocks. Certain amorphous graphite deposits undoubtedly were formed by contact metamorphism, while others are probably the result of dynamic (regional) metamorphism (Taylor, 2006).

In the Canadian River Canyon southwest of Raton, there is a large body of amorphous graphite, occurring in pockets or irregular masses adjacent to diabase sills, which metamorphosed the adjacent coal (Graphite mine, NMCO0077, Colfax County). Standard Graphite Co. mined 250 short tons of graphite in 1889 and tested the deposit for use in paint (Lee, 1924).

In New Mexico, graphite also is reportedly found at the Ross mine (NMBE0041) in the eastern Tijeras Canyon district (DIS004, Bernalillo County), near Whitcomb's Springs (Jones, 1915; Northrop, 1996). It was mistaken for coal.

The Red River district (DIS238, Taos County) was reported to have graphite. Schilling (1956) stated that the graphite is intimately mixed with molybdenite at places. Other reports indicate graphite occurs in graphite schist over a large area near Cabresto Lake in the Sangre de Cristo Mountains and in sandstone of the Taos Range. Graphite is reported in muscovite-albite gneiss at the Pinabete (NMTA0555) and Esperanza (NMTA0518) mines, near Cerro (Northrop, 1996).

In Grant County, an occurrence was described in the Burro Mountains district (DIS046). In the vicinity of Santa Fe, graphite was reported in 1893 (Northrop, 1996). In Sierra County, graphite is reported at Iron Mountain (Cuchillo Negro district, DIS192).

Gypsum and Anhydrite

Gypsum (hydrous calcium sulfate, $CaSO_4 \cdot 2H_2O$) and anhydrite (anhydrous calcium sulfate, $CaSO_4$) are closely related industrial minerals of value that are used in the manufacture of construction materials (i.e., wallboard) and other products, as soil additives in agriculture, and as potential sources of industrial chemicals. Consumption is tied largely to the level of building construction. Anhydrite is used to a lesser extent than gypsum as a cement retarder and for agricultural purposes. It is preferred over gypsum for the manufacture of ammonium sulfate and sulfuric acid in Europe because of its higher sulfur content, but current processes are not competitive in the United States with readily available supplies of elemental sulfur. Gypsum and anhydrite are widely distributed rock-forming minerals, and important commercial deposits consist largely of beds of relatively high purity, which were deposited from solution during the evaporation of sea water. Similar deposits were formed through evaporation of highly saline inland lakes.

The use of gypsum in New Mexico has had a long history, but it was not until 1960 that a sizable modern industry based on the manufacture of gypsum products was established. The Tijeras cement plant (NMBE0012), then operated by Ideal Cement Co., was opened in 1959 and used a small amount of gypsum as a retarder in cement. The cement plant is now owned by Grupos Cementos de Chihuahua and the gypsum comes from the White Mesa mine (Fig. 16; NMSA0170) of Eagle Materials, Inc.

Eagle Materials operates the White Mesa mine near Cuba and two wallboard plants (Albuquerque and Bernalillo). The annual gypsum wallboard capacity at the Albuquerque plant is 425 million square feet and at the Bernalillo plant 550 million square feet. The mine has estimated reserves of more than 45 million short tons in the Todilto Formation that should last more than 50 years (Eagle Materials, 2013). The mine and wallboard plants were temporarily closed in 2009 until the

Figure 16. Sizing equipment at the White Mesa gypsum mine (NMSA0170), Sandoval County. *Photo by Virginia T. McLemore.*
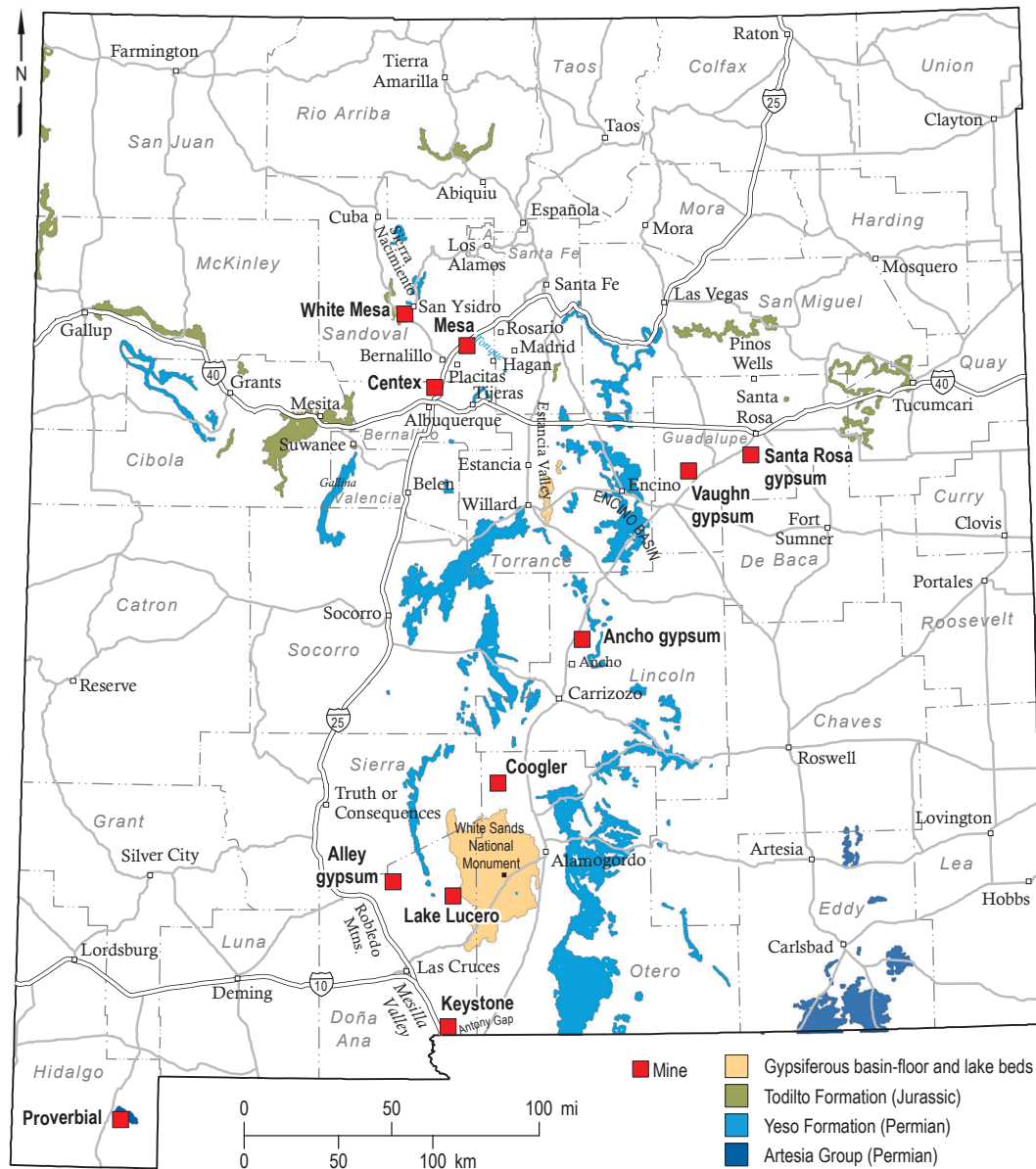
Figure 17. Major gypsum and anhydrite in New Mexico.

construction industry improves. The Albuquerque plant is currently operating in 2017. Other smaller gypsum mines are operated in Sandoval and Doña Ana County.

Deposits of rock gypsum, gypsite, and buried anhydrite are widely distributed throughout a large part of New Mexico in rocks ranging in age from Pennsylvanian to Pleistocene (Weber and Kottlowski, 1959), with local gypsum dune sands of recent age, notably at White Sands National Monument (Fig. 17). Large areas in New Mexico are, however, lacking in significant outcrops of gypsum beds (Fig17).

Pennsylvanian gypsum

The Panther Seep Formation (Kottlowski et al., 1956) of Pennsylvanian age contains two zones of gypsum in the southern San Andres and northern Franklin Mountains, Doña Ana County. Outcrops extend from San Andres Canyon southward to Bear Creek in the San

Andres Mountains and in the western foothills of the Franklin Mountains southwest of Anthony Gap. A similar gypsum unit in the northern Hueco Mountains was reported by Hardie (1958). The upper zone ranges in thickness from 30–100 ft in the San Andres Mountains and 10–35 ft in the Franklin Mountains. Gypsum from the Franklin Mountains locality was utilized by the now defunct El Paso Cement Co. (NMDA0039).

Permian gypsum and anhydrite

At the western edge of Otero (Horse) Mesa, south of New Mexico Highway 33, Otero County, a 25 ft bed of gypsum lies between red-beds typical of the Abo Formation and underlying limestones of the

Hueco Limestone in an intertonguing zone between these two Permian units. A laterally correlative gypsum bed was noted to the south (sec. 1, T25S, E10E) by Darton (1928). Kottlowski has assigned the gypsum to the Hueco Formation (Weber and Kottlowski, 1959).

Permian gypsum beds, that can be 200–300 ft thick, are exposed beneath thrust sheets in the Big Hatchet Mountains of southeastern Hidalgo County. A number of thin- to thick-anhydrite beds were cut by the Humble State BA 1 well southwest of the Hatchet Mountains. These beds were correlated with the Epitaph Dolomite (Weber and Kottlowski, 1959).

The Yeso Formation of Permian age is highly gypsiferous in most areas, as indicated by the name (Yeso, Spanish word for gypsum). A major part of New Mexico's total reserves of gypsum are within the Yeso Formation, whose wide distribution in central New Mexico (Valencia, Torrance, Socorro, Lincoln, Sierra, Doña Ana, and Otero Counties) makes it the most widely available source of gypsum (Fig. 17). Gypsum makes up 12% of the 700-ft-thick type section of the Yeso northeast of Socorro and 40% of the 1,500-ft-thick section in the San Andres Mountains. The Cañas Gypsum Member ranges from 49–115 ft in thickness from Mesa del Yeso southeastward to the northern Sacramento Mountains, and from 49–170 ft on Chupadera Mesa. The Torres Member also contains numerous gypsum beds. Gypsum that is locally suitable for agricultural purposes is found in the Yeso Formation. A 25 ft bed of gypsum in the Yeso Formation in the east-central Caballo Mountains has been mined for agricultural use in the Mesilla Valley (Weber, 1965a). Despite its wide distribution, however, gypsum in the Yeso Formation is in many places unfavorable for mining because of a thick capping of resistant beds that restrict the width of outcrop; local interbeds of siltstone, sandstone, limestone, and dolomite; and solution collapse, landslides, and tectonic deformation.

Prominent beds of gypsum in the Permian San Andres Limestone are exposed at a number of places in central New Mexico. Significant localities include southeastern Valencia County east of Mesa del Oro, north-central Socorro County northeast of Socorro, northeastern Socorro, and southwestern Torrance Counties on Chupadera Mesa, southwestern Guadalupe County in the region around Vaughn, and western Lincoln County near Ancho and Carrizozo (Fig 17). Gypsum beds 20 ft or more in thickness are fairly widespread, but exposures are poor in some of the more extensive tracts, such as those on Chupadera

Mesa and near Vaughn. Solution collapse has seriously affected the distribution and continuity of the beds at a number of localities, and is particularly evident in the vicinity of Ancho and Carrizozo (Weber, 1965a). Gypsum at Ancho was mined in the early 1900s for cement plaster (Lindgren et al., 1910).

Gypsum and anhydrite are prominent components of the Grayburg, Seven Rivers, and Tansill Formations of the Artesia Group of Permian age. Outcrops extend southward along the Pecos River Valley and its tributaries from the vicinity of Santa Rosa, Guadalupe County, to Carlsbad, Eddy County. Accessible outcrops of gypsum in the Seven Rivers and Tansill Formations are located west of Carlsbad, and along the east side of the Pecos Valley from Carlsbad northward to central DeBaca County. Economic possibilities of these beds are limited locally by their thinness, lateral gradation into dolomitic limestones and redbeds, and abrupt pinch outs (Weber, 1965a).

The Upper Permian Castile and Rustler Formations in Eddy County contain large amounts of gypsum and anhydrite. In the Castile, laminated calcite-gypsum beds are characteristic in many outcrops, such as those in the Yeso Hills near the southern edge of Eddy County. As reported by Adams (1944), gypsum extends to depths of 500 ft, below which anhydrite appears. According to Hayes (1964), massive, fine-grained white gypsum is the most abundantly exposed component of the Castile southeast of the Guadalupe Mountains. Beds as much as a few hundred feet thick lie at or near the surface. Gypsum beds within the Rustler Formation are generally poorly exposed in the Frontier Hills southwest of Carlsbad, and east of the Pecos River from near Carlsbad southward to the State line (Weber, 1965a).

Jurassic gypsum and anhydrite

The gypsum member of the Todilto Formation of Late Jurassic age contains some of the most important reserves of commercial-grade gypsum in New Mexico. In contrast to the previously described marine deposits, the Todilto Formation is a product of deposition in an inland lake basin. Massive gypsum beds of the upper member are present only in the central part of the basin, whereas limestones and calcareous shales of the lower member predominate elsewhere. Outcrops are limited to northwestern and north-central New Mexico, extending southward along the eastern margin of the San Juan Basin, west of the Sierra Nacimiento, from near Abiquiu, Rio

Arriba County, to San Ysidro, Sandoval County; along the Rio San Jose near Mesita and Suwanee, Valencia County; in the Tijeras Basin north of Tijeras, Bernalillo County; east and northeast of Placitas, Sandoval County; and in eastern Sandoval and western Santa Fe Counties from Rosario siding to west of Madrid and from Arroyo Tonque to southeast of Hagan. Thicknesses of the gypsum beds generally range from 49–100 ft. Well cuttings show that anhydrite prevails at depth, although hydration to gypsum appears to be complete in outcrops. Recent mining operations are centered on White Mesa at San Ysidro by Eagle Materials Inc. for their American Gypsum Co. division. Minor past production has come from near Gallina for local use as plaster, from White Mesa for agricultural purposes, from Mesita for use as plaster and as a rock dust in coal mines, and from Suwanee for agricultural purposes. Undeveloped reserves are very large (Weber, 1965a).

Cretaceous gypsum

Uppermost beds of the Lower Cretaceous rocks in southeastern Hidalgo County contain at least two beds of gypsum aggregating up to 60 ft in thickness (Zeller, 1965). Outcrops were noted in the foothills south of the Big Hatchet Mountains.

Tertiary gypsum

Gypsum beds of Tertiary age are known to occur in the southern Robledo Mountains along Apache Canyon, northwest of Las Cruces (Weber and Kottlowski, 1959). Beds from 1–10 ft thick are within redbeds in the basal part of the Tertiary volcanic sequence. The nearness of these beds to the highly productive agricultural lands of the Mesilla Valley offers some advantages.

Quaternary Gypsum

Crystalline to massive gypsum beds of Quaternary and possibly late Tertiary age are exposed locally in the Tularosa Basin in Doña Ana and Otero Counties. Outcrops have been noted around the edges of playa Lake Lucero and Alkali Flat, west of the White Sands, and eastward as far as Alamogordo (Weber and Kottlowski, 1959). These beds are, at least in part, products of deposition in saline lakes; locally, however, there are beds formed by consolidation and recrystallization of gypsum dune sands, and others that represent

gypsiferous caliches. Alley Gypsum Mining Company of Las Cruces operated a gypsum mine (NMDA0323) from Quaternary piedmont deposits for agricultural purposes east of Hatch in northern Doña Ana County.

Although these indurated deposits contain large reserves of gypsum of potential commercial value, they are overshadowed in this area by extensive gypsum dune sands of higher purity (up to 99% gypsum). The best known of the dune tracts lies within White Sands National Monument where dune formation and migration are currently active. Large tracts of similar character also lie outside the monument boundaries to the north. Kottlowski has tabulated the areas covered by relatively pure gypsum sands 10–50 ft thick (Weber and Kottlowski, 1959). Older, stabilized gypsum dunes south of the White Sands contain more quartz southeastward toward the Jarilla Mountains. Despite the vastness of the reserves of high-purity sands in this area, sufficient for several hundred years at the current rate of national consumption, their exploitation will be inhibited by their location within the White Sands Missile Range.

Less extensive gypsum dune sands of lower purity border the eastern margins of three saline playa basins in Torrance County (Weber and Kottlowski, 1959). The largest of these is in the southeastern part of the Estancia Valley where stabilized dunes, generally 50 ft or less in thickness, contain variable proportions of sand made up of selenite cleavage flakes with intermixed clay and silt. The western edge of the dune tract is east of Willard. Similar, though much less extensive, gypsum dune sands occur along the eastern border of the modern playa in the Encino Basin, south of Encino. An irregular tract of stabilized gypsum dunes several miles long and roughly half a mile wide borders the eastern side of modern playas in the Pinos Wells Basin, east-northeast of the village of Pinos Wells.

Summary

New Mexico is clearly endowed with vast resources of gypsum and anhydrite; reserves of gypsum at the surface could readily supply the total demands of the United States for hundreds of years. Existing gypsum products manufacturing facilities are sufficient to supply current requirements for construction materials within New

Mexico and the surrounding market areas served by these plants. Future growth will be closely related to the level of construction in the region, plus modest increases in local agricultural usage (Weber, 1965a).

Iron, Iron Oxide and Magnetite

The earliest use of iron oxides in New Mexico was by Native Americans as pigments and glazes. Iron ore has also been mined in New Mexico as flux for smelters and blast furnaces in Pueblo, Colorado and El Paso, Texas. Estimated iron production from New Mexico is in Table 13. Iron ore as magnetite is shipped from the magnetite tailings at the Cobre mine (NMGR0033), Grant County and is used by cement plants to increase the strength of their cement. The Capitan Iron mine (NMLI0046) in the Capitan Mountains, Lincoln County has produced magnetite-hematite from contact-metasomatic deposits for the cement plant in the past (Fig. 18). In 2012, Gulf Coast Mining Group, LLC recovered iron ore from the waste rock piles at the Iron Duke (NMOt0038), Cinco de Mayo (NMOt0026), Virginia (NMOt0093), and Barbara (NMOt0076) mines in the Orogrande district. Approximately 198,000 short tons of iron ore were produced (McLemore et al., 2014b). Iron deposits are described by McLemore and Lueth (2017).

Kyanite, Andalusite, Sillimanite, and Mullite

Kyanite, sillimanite, and andalusite are polymorphs of Al_2SiO_5 and used primarily in refractory and ceramic products. Mullite is a very rare mineral named for its discovery site on the Scottish Isle of Mull. Mullite is seldom found in nature but can be artificially produced by heating any number of aluminum silicate minerals in certain proportions to the correct temperature.

New Mexico occurrences of the sillimanite group of minerals of possible economic interest are restricted to metamorphic complexes of Proterozoic age. Kyanite and sillimanite are restricted to meta-quartzite. These minerals are typically disseminated in the metaquartzite (Bingler, 1965b), but in some areas, notably the Picuris Range, Taos County and the Petaca district (DIS148), Rio Arriba County, they form veins, pods, and lenses several feet thick (Corey, 1960). Systematic exploration for sillimanite group minerals is hampered by the meager knowledge available regarding the distribution and composition of rock units within the Proterozoic.

Approximately 1,500 short tons of kyanite ore were produced from the Big Rock mine (NMRA0177), Petaca district in 1928 by P.S. Hoyt (Corey, 1960; Bingler, 1965b; McLemore, 2011a).

Table 13. Iron ore production in New Mexico 1880–2012 (Kelley, 1949; Harrer, 1965; Smith, 1991; McLemore, 2014). Recent production from the Cobre mine, Fierro-Hanover district is unknown and not in this table.

District ID	District	Years of production	Iron production (long tons)	Estimated value (dollar)
Grant County				
DIS054	Fierro-Hanover	1888–1962	5,500,000	11,000,000
DIS050	Chloride Flat	1900–1962	2,700,000	5,000,000
DIS065	Santa Rita	1943–1944	55,491	100,000
DIS051	Copper Flat	1931–1937	12,200	24,000
Otero County				
DIS129	Orogrande	1913–2012	456,765	1,000,000
DIS130	Pajarito	1952	50	100
DIS132	Three Rivers	1943	87	160
Lincoln County				
DIS099	White Oaks	1913–1942	20,008	40,000
DIS166	Tecolote	1915–1937	14,743	24,000
DIS092	Gallinas Mountains	1942–1943	10,304	20,000
DIS093	Jicarilla	1918–1943	7,749	15,000
DIS091	Capitan Mountains	1975–1991	200,000–250,000	500,000
Socorro County				
DIS216	Jones	1916	500	1,000
DIS213	Hansonburg (Iron Horse)	1942–1943	5,469	10,000
Santa Fe County				
DIS183	Glorieta (Kennedy)	prior to 1910	3,500	4,000
TOTAL		**1880–2012**	**8,786,866**	**17,738,260**

Figure 18. Iron skarn surrounding white limestone xenolith at the Capitan Iron mine (NMLI0046) in the Capitan Mountains, Lincoln County. *Photo by Virginia T. McLemore.*

The origin of these quartz-kyanite pods has been attributed to weathering (i.e., paleosol), hydrothermal Al-Si alteration (Barker, 1958), metamorphic differentiation of siltstone (Corey, 1960), or metasomatism along shear zones (Gresens, 1971, 1972, 1976, Gresens and Stensrud, 1974a, b). Geochemical, oxygen isotopic, and metamorphic petrographic evidence presented by Simmons (1999) and Simmons and Larson (2001) support a hydrothermal alteration that was subsequently sheared and metamorphosed. The kyanite has relatively light delta O^{18} values (10.5 per mil), which are consistent with hydrothermal alteration (Simmons and Larson, 2001; Simmons et al., 2011). The presence of kyanite, staurolite, papagonite, and albite indicate peak temperature-pressure conditions of nearly 600°C and 6 kbars, which is supported by oxygen-isotope thermometry on kyanite of 530–590°C (Simmons and Larson, 2001). Corey (1960) estimated the total kyanite resources as 277,620 short tons grading 26–46% kyanite. However, the Big Rock and nearby kyanite deposits do not have any kyanite resource potential in today's economic market, because remaining kyanite resources are low in grade and tonnage (McLemore, 2011a).

Lime

Lime, or calcium oxide (CaO), is one of the most versatile chemicals, and its manufacture and use is fundamental to society. A number of pre-1680 Pueblo sites in New Mexico show archeological evidence of the use of lime plaster, as well as gypsum plaster (Use of Lime in Colonial New Mexico: Documentary Evidence for El Paso Lime Kilns, http://newmexicohistory.org/places/use-of-lime-in-colonial-new-mexico-documentary-evidence-for-el-paso-lime-ki, accessed 1/29/16) and a number of Pueblo kilns are found in New Mexico. Lime is a manufactured chemical product resulting from the calcination of limestone in its various forms. Its major mineral ingredient—calcium carbonate ($CaCO_3$)—is dissociated by the application of thermal energy, producing CaO and CO_2. When water is added, it is commonly known as hydrated lime, or slaked lime ($Ca(OH)_2$). Almost 40 different lime products are available, a fact that contributes to confusion and misunderstanding over the use of the term lime. Frequently, the word is used erroneously to denote almost any kind of calcareous material, including finely ground limestone and/or dolomite (Krukowski, 2006).

Although New Mexico has abundant deposits of limestone, no lime is produced in New Mexico at the present time. Spanish lime kilns are found throughout central New Mexico indicating the production during the Spanish and Mexican eras. Most of the more recent use of lime was for smelting at the copper mines near Silver City in southwestern New Mexico (Kottlowski, 1965a). Any lime used in New Mexico is now imported (John Pfeil, New Mexico Energy, Minerals and Natural Resources Department, written communication, August 2, 2011).

Limestone and Dolomite

Limestone and dolomite are sedimentary rocks composed mainly of calcium and magnesium carbonates, respectively. Limestones crop out or are near the surface in about 25% of New Mexico (Fig. 19); they range in age from thin dolomitic limestone lenses in the Cambrian part of the Bliss Sandstone to Cenozoic travertine, calcareous tufa, and caliche. Some of the high-calcium limestones of Mississippian, Pennsylvanian, Permian, and Early Cretaceous ages exceed 100 ft in thickness, and locally 1,000 ft. Their purity ranges from almost pure calcite to calcareous tufa and caliche, which in places contain as much as 40% insoluble residues, Kottlowski, 1965a; Kottlowski and Armstrong, (1996). Limestone is used in Portland cement, as an aggregate in concrete and asphalt, and in many other products. Limestone is a major crushed stone, as described above.

Cement commonly refers to hydraulic cement, especially Portland cement. Hydraulic cements are those that have the property of hardening under water and are the chief binding agents for concrete and masonry. Portland cement is made by heating limestone and other materials (iron oxide, silica and alumina as sandstone or shale, and gypsum; Harben et al., 2008) to 1,450°C in a kiln. Only one cement plant is found in New Mexico, the Tijeras plant (NMBE0012) near Albuquerque operated by GCC Rio Grande, Inc. (a subsidiary of Grupo Cementos de Chihuahua SA de CV or GCC). The Tijeras plant was built in 1958 by Ideal Basic Industries and the first cement was ground in 1959. GCC acquired the Tijeras plant in 1994 and produces seven different types of cement with a total estimated capacity of 800,000 metric tons annually. GCC also has two plants in the Juarez area supplying cement to the El Paso market. The older Juarez plant is capable of producing approximately 500,000 metric tons annually. A newer Samalayuca, Mexico plant is rated at 1.2 million metric tons.

Concrete is made by mixing water, aggregate (crushed stone, rock, and sand), and cement (the binder). Concrete cannot be made without cement. There are numerous ready-mix concrete companies in New Mexico.

High-calcium limestone

High-calcium limestone refers to limestone with at least 90% calcium carbonate, typically greater than 95%. High-calcium limestone has been collected from Holocene travertine of the Mesa del Oro and Ladron Mountains areas; the Tertiary algal limestone of Apache Valley in the southwest part of the Caballo Mountains; Lower Cretaceous limestone of southwestern New Mexico; Upper and Lower Permian limestone of the Guadalupe, Sacramento, Robledo, Florida, and Oscura Mountains; Pennsylvanian limestone of the Sandia, Sangre de Cristo, Sacramento, Ladron, Magdalena, Oscura, Franklin, and Hueco Mountains, Cerros de Amado, and near Luna; and Mississippian limestone of the Sacramento, Tres Hermanas, and Peloncillo Mountains. Selective quarrying may yield high-calcium limestone from the Todilto Limestone of Jurassic age southeast of Grants, from local deposits of Cenozoic travertine and caliche throughout New Mexico, and from the El Paso Limestone of Ordovician age in southwestern and south-central New Mexico.

Most of the high-calcium limestones in New Mexico are of Paleozoic age and mainly of late Paleozoic (Mississippian through Permian) age. Most of the dolomites, in contrast, are of early Paleozoic (Ordovician and Silurian) age, although some of the Permian units are made up of dolomite and dolomitic limestone. Locally, limestone of the Todilto is high in calcium. The Lower Cretaceous beds of southwestern New Mexico include high-calcium limestone but limestone from Upper Cretaceous beds (throughout central and northern New Mexico) contains at least 10% impurities. Cenozoic caliche and travertine are impure except for local high-purity lenses such as the algal limestone in the Tertiary Palm Park Formation (Kelley and Silver, 1952), a high-calcium limestone in the Caballo Mountains.

Some of the high-calcium limestones of Mississip-pian, Pennsylvanian, Permian and Early Cretaceous age exceed 100 ft, and locally even 1,000 ft in thickness. Reef limestone of the Guadalupe Mountains in southeastern New Mexico ranges from dolomite to high-calcium limestone. Locally the reef complex is 1,400–2,000 ft thick and is several miles wide.

Limestone

Northwestern New Mexico—In northwestern New Mexico, limestone occurs in the Mississippian and Pennsylvanian Systems, in the Permian Yeso Formation and San Andres Limestone, in the Jurassic Todilto Limestone and Upper Cretaceous sequence, and as travertine and calcareous tufa of Cenozoic age (Fig. 19). Carbonate rocks in the Yeso Formation of this

area are mostly dolomitic and silty. Limestone in the San Andres Limestone of the Zuni Mountains and Lucero Mesa areas is chiefly cherty, arenaceous, or dolomitic. Limestone beds of Late Cretaceous age are within sequences of dark marine shale, such as the Mancos Shale; they are highly argillaceous.

Along Arroyo Colorado Valley within the Laguna Indian Reservation of northwestern Valencia County, limestone in the Todilto Formation is 15–60 ft thick

and caps extensive benches. Locally, the main part of the limestone contains as much as 94% $CaCO_3$. Northwest of Gallup, the limestone is 5–13 ft thick but contains about 12% silica.

Lucero Mesa and the nearby mesas of northwestern Socorro County and adjoining parts of Valencia County are isolated, but contain thick limestone beds in the San Andres Limestone and within the Pennsylvanian System. Much of the limestone is

Figure 19. Limestone, caliche, and dolomite in New Mexico.

impure but some of the Pennsylvanian limestone is high in calcium. Travertine and calcareous tufa spring deposits are extensive along the fault zones bordering some of these mesas; these Cenozoic limy rocks are being quarried as decorative "marble." Their purity varies greatly; most of the travertine contains 15% impurities.

Mississippian and Pennsylvanian limestone units, some high in calcium, crop out on the west edge of the Ladron Mountains (Preface Fig.1). To the west is an extensive plain underlain by Cenozoic travertine; analyses of some of the purer lenses indicate 99% $CaCO_3$. These deposits are relatively inaccessible and are reached by ranch roads 17–25 mi from I-25 at Bernardo.

North-Central New Mexico—Limestone from the Mississippian and Pennsylvanian Systems, from the Yeso Formation, and from the San Andres Limestone in the Nacimiento Mountains area is mostly arenaceous and cherty. Limestone from the Todilto Formation is impure and only 1–10 ft thick near the Nacimiento Mountains and to the north. In central Rio Arriba County, the limestone beds in the Mancos Shale reach a maximum thickness of only 3 ft and are highly argillaceous.

Pennsylvanian rocks cover large areas of the Sangre de Cristo Mountains and are underlain in many areas by Mississippian beds; both sequences contain numerous limestone beds that range widely in purity. Quarries have been operated in these limestone beds near Santa Fe, Las Vegas, and Taos. The Todilto Limestone crops out in local areas near Lamy, Santa Fe County, and caps a bench along the steep slopes of the Canadian Escarpment extending eastward to and beyond the Canadian River Canyon. Limestone in the formation is impure and only 3–15 ft thick in this area, but it is the only limestone available in most of central and eastern San Miguel County. Highly argillaceous, dark limestone occurs within Upper Cretaceous shale units near Galisteo, Cerrillos, and Madrid, as well as north and east of Las Vegas. This Upper Cretaceous limestone contains about 85% $CaCO_3$, and is too impure for high-calcium uses.

The thick limestone units in the Pennsylvanian System form extensive dip slopes in the east parts of the Sandia and Manzano Mountains. Much of the Pennsylvanian limestone is arenaceous or cherty, but some contains more than 95% $CaCO_3$. Limestone in the Yeso Formation, San Andres Limestone, and

Todilto Limestone in this area is thin and impure. Madera Limestone is mined at Tijeras (Fig. 19) for cement with additional materials obtained locally throughout New Mexico (Harben et al., 2008). Mississippian limestone units in the northeast part of the Sandia Mountains are as much as 85 ft thick and include some high-calcium limestone.

Northeastern New Mexico—The northeast-trending belt of Upper Cretaceous outcrops in northeastern New Mexico contains relatively thick limestone units only in the Fort Hays Limestone Member of Niobrara Formation of eastern Colfax County and northwesternmost Union County, and the Greenhorn Limestone of northwesternmost Union County. Greenhorn limestone beds southwest of Union County are too thin and too impure to be of much use except as a low-grade crushed stone. Similarly impure limestone of the Greenhorn crops out in a small block 22 mi southeast of Tucumcari. These limestone units range from 14–60 ft in thickness, and consist of beds (85% $CaCO_3$) averaging 18 inches thick separated by limy shale beds of similar thickness.

Eastern New Mexico—Caliche is used in eastern New Mexico as road metal. The caliche caps high surfaces cut on gravel of the Pliocene Ogallala Formation and underlies much of the High Plains area. However, the caliche varies greatly in thickness and in most places is impure. An average sample contains about 35% quartz sand and silt.

Central New Mexico—Limestone in central New Mexico occurs within the Mississippian, Pennsylvanian, Permian rocks and Cretaceous Mancos Shale. Cenozoic travertine and caliche are relatively sparse except near the Ladron Mountains. Mississippian limestone, mostly cherty, crops out in the Lemitar, Magdalena, and San Andres Mountains and Coyote Hills. Thick limestone units mark the Pennsylvanian sections of the region. Limestone units in the Yeso Formation are thin and impure.

The San Andres Limestone crops out over large areas on Chupadera Mesa, Socorro County, Mesa Jumanes, Torrance County, the western flank of the High Plains west of the Pecos River, eastern dip slopes of Sierra Bianca and the Sacramento Mountains, western cuestas of San Andres Mountains, the high ridges east of Socorro, the Phillips Hills, and on Carrizozo dome. Many of the limestone beds include variable amounts of dolomite, and some are cherty

and arenaceous. In general in this region, where the San Andres Limestone is 500 or more ft thick, it consists of a lower limestone and an upper dolomite.

Limy beds in the Mancos Shale are thin lenticular impure black limestone intercalated with black shale, but they have been used locally for crushed rock. They contain about 75% $CaCO_3$ and more than 15% combined silica and alumina.

The north end of the Manzano Mountains has interbedded Middle Pennsylvanian limestones and shaly, clastic strata. Where clastic strata has been removed, as near the Tijeras cement plant, high-calcium limestones are covered by thin overburden. Near Abo Pass between the Manzano Mountains to the north and Los Piños Mountains to the south, Pennsylvanian limestone beds have been prospected for cement use. Some of the limestone beds are high in calcium. Nearby are outcrops of shale, and gypsum is available from the Yeso Formation a few miles to the east.

High-calcium limestone beds of Pennsylvanian and early Permian age crop out over large areas in the Oscura Mountains and Cerros de Amado east of Socorro. Some of the noncherty beds contain 96–98% $CaCO_3$, are thick, almost horizontal, and cap extensive mesas where they could be quarried without removal of thick overburden.

Southwestern New Mexico—Limestone occurs within the Cambrian and Ordovician Bliss Sandstone, Ordovician El Paso Limestone, Ordovician Montoya and Silurian Fusselman Dolomites, and Devonian, Mississippian, Pennsylvanian, Permian, and Cretaceous strata. Pre-Pennsylvanian sedimentary rocks thicken southward to about 4,000 ft near El Paso, TX, and to 3,600 ft in the southwesternmost corner of New Mexico. Most of the limestone in the pre-Mississippian sequence, however, contains magnesium and grades into dolomite.

The Lake Valley Limestone of Mississippian age exceeds 100 ft in thickness in the Cookes Peak, Lake Valley, southern Black Range, Silver City, and Santa Rita areas. The thicker, partly correlative Escabrosa Limestone is 500–1,000 ft thick in the Tres Hermanas, Peloncillo, Big Hatchet, and Animas Mountains and Klondike Hills. Selected samples of the purer beds contain at least 98% $CaCO_3$.

Pennsylvanian rocks are 780–2,400 ft thick in the region and, except locally, are mainly limestone. Many of the mountain ranges are capped by Pennsylvanian limestone that forms extensive outcrops in the Fra Cristobal, Mud Springs, Caballo, Big Hatchet, and Peloncillo Mountains, Sierra Cuchillo,

Black Range, and Silver City/Santa Rita areas. Much of the limestone is cherty but beds of high-calcium limestone are numerous.

The Hueco Limestone of Early Permian age crops out in the Florida and Tres Hermanas Mountains. The Pennsylvanian Horquilla limestone and the Pennsylvanian and Permian Earp Formation occur in the Big Hatchet, Animas, and Peloncillo Mountains. Some limestone in the Horquilla and Hueco contains 95–98% $CaCO_3$. In the parts of southwestern New Mexico where the Permian Yeso Formation and San Andres Limestone crop out, the limestone appears to be dolomitic or impure.

Lenticular, black, argillaceous limestone occurs in the Mancos Shale of the Caballo and Fra Cristobal Mountains area and in the Colorado Shale near Cooks Peak, and in the Silver City-Santa Rita area. The Lower Cretaceous sequence that occurs in southern Doña Ana, southern Luna, southern Grant, and southern and central Hidalgo Counties includes thick fossiliferous limestone units, many of which are high in calcium.

Impure caliche caps many of the extensive surfaces of this semiarid region; samples analyzed contain at least 29% insoluble residues. High-calcium algal limestone occurs in the Tertiary rocks of the southwestern Caballo Mountains area but it is far from transportation facilities.

South-central New Mexico—The Sacramento and Guadalupe Mountains are largely underlain by limestone. West of the Sacramento Mountains crest, most of the limestone outcrops are of pre-Permian rocks; to the east, the outcropping limestone units are of Permian age, other than the caliche capping Llano Estacado. Pre-Mississippian formations thicken southward along the San Andres-Organ-Franklin chain of ranges to about 3,500 ft in the northern Franklin Mountains near the New Mexico-Texas State line. None of these pre-Mississippian units contains high-calcium limestone in this part of New Mexico. The Lake Valley limestone of Mississippian age is 60–410 ft thick in the San Andres and Sacramento Mountains, and its crinoidal beds contain 98% $CaCO_3$ in many areas. Near Alamogordo, the Tierra Blanca Member of the Lake Valley limestone has been quarried as marble, and used as building stone (McLemore, 2014b). Pennsylvanian rocks vary greatly in thickness and lithology throughout south-central New Mexico, but most areas contain much limestone, and high-calcium beds occur in parts of the sequence in the San Andres, Sacramento, Robledo, Organ, and northern Franklin Mountains.

Lower Permian rocks include much limestone. Some are high in calcium in the Robledo, Doña Ana, San Andres, Sacramento, Franklin, and Hueco Mountains. The Yeso Formation is dominantly limestone in the south part of the Sacramento Mountains and on Otero Mesa. High-calcium limestone is present in the San Andres Limestone of the San Andres and Sacramento Mountains, although eastward, in the Guadalupe Mountains area, the entire formation is dolomitic or dolomite.

Upper Permian rocks of the Guadalupe Mountain and Pecos Valley area include many carbonate-rock beds but they are chiefly thin, impure, and dolomitic. Reef limestone of the Guadalupe Mountains ranges from dolomite to high-calcium limestone. It is exposed along the southeast front of the Guadalupe Mountains from near Carlsbad to south of the New Mexico-Texas State line.

Lower Cretaceous limestone beds crop out in the Potrillo Mountains and on Cerro de Muleros (El Cristo Rey) in southern Doña Ana County. Some of this limestone is high in calcium but there is much interbedded and intermixed clay and quartz sand. Limestone beds in the East Potrillo Mountains have been quarried for building stone, and those bordering Cerro de Muleros were used, along with Cretaceous shale, at former cement plant in El Paso, TX.

Southeastern New Mexico—Caliche caps many of the older gravel surfaces of the Pecos Valley and elsewhere. Caliche is especially thick (up to 40 ft) as the caprock of the Llano Estacado, the High Plains east of the Pecos River. Local lenses may be of high-calcium limestone but most of this caprock contains 19–40% impurities and is used mainly for road metal throughout the plains area.

Dolomite

In addition to limestone, there are large deposits of high-purity, magnesium-rich dolomite in the south-central part of New Mexico, in the region from the Sacramento Mountains west to Deming, and from the north tip of the San Andres Mountains south to Mexico. The dolomite is mainly of early Paleozoic age and occurs in the El Paso (Ordovician) Limestone and Montoya (Ordovician) and Fusselman (Silurian) Dolomites in the Sacramento, San Andres, Organ, Robledo, Caballo, Mud Spring, Florida, Victorio, Big Hatchet, Peloncillo, and Franklin Mountains; at Bishop Cap, Sierra Cuchillo, Black Range, Cooks Peak, and Snake and Klondike Hills; near Lake Valley; on the west side of the Mimbres River valley;

and near Silver City. Dolomites are used to make magnesia, which has important medicinal applications, and in the chemical industry in the manufacture of magnesium salts, used to lower acidic levels of soil. Magnesium also is used in batteries.

The El Paso Limestone is predominantly limestone, but in many areas thick beds and irregular masses have been dolomitized, and in some localities, such as the San Andres Mountains, most of the beds of the formation are dolomitic limestone or dolomite. The Montoya Dolomite in most places is almost entirely dolomite. Most of the high-purity dolomite of the Montoya occurs near the base of the formation (the Upham Member), although the lower part of the Montoya is highly arenaceous. Except where removed by post-Ordovician erosion, the Upham Member is 40–120 ft thick.

The Fusselman Dolomite is almost entirely pure dolomite except in localities where chert forms appreciable parts of some beds. The Fusselman thickens southward from a knife edge in the central part of the San Andres Mountains to nearly 1,000 ft in the Florida and southern Franklin Mountains. Millions of tons of high-purity Fusselman Dolomite are available in the Sacramento, Robledo, San Andres, and Florida Mountains. American Magnesium LLC is examining the high-magnesium dolomites in the Florida Mountains for potential economic development of magnesium for use in batteries.

Much of the upper part of the San Andres Limestone in the large area east of the crest of the Sacramento Mountains is dolomite and most of the formation in the Guadalupe Mountains is dolomite. Interbeds of dolomitic limestone are numerous, and many of the dolomite beds are siliceous. There are thick persistent beds of high-purity dolomite in the San Andres Formation on the west side of the Guadalupe Mountains.

Lithium

Lithium has become an important commodity because it is now used in lithium batteries to power a variety of electronic devices. Other uses include cosmetics, drilling gels, building materials, ceramics and glass, and manufacture of lubricants and greases. The chief lithium minerals obtained from pegmatites in the United States was spodumene (a lithium aluminum silicate that is the main source of lithium), lepidolite (a lithium mica that is used in glass and ceramics), and amblygonite (a lithium aluminum phosphate). More than 13,000 short tons

of lepidolite ore and several hundred short tons of spodumene ore have been produced from pegmatites in New Mexico since 1920. Most of this production, which represents nearly 10% of the total U.S. production between 1920 and 1950, came from the Harding mine (NMTA0015, Taos County). A small amount came from the Pidlite mine (NMSM0117, San Miguel County). No production of lithium minerals in New Mexico has been recorded since 1950. In the second half of the 20th century, there was a dramatic shift of sources away from pegmatite minerals towards lithium carbonate extracted from brines, chiefly in Chile.

The Harding mine was discovered in 1910, but mining did not start until 1920 for lepidolite. Operations ceased in 1930 after the production of more than 12,000 short tons of lepidolite ore averaging 3.5% Li_2O (Schilling, 1960). Beginning in 1942 some beryl and spodumene were recovered by hand sorting. Drilling in 1943 and 1945 outlined a large deposit of microlite and spodumene (Soulé, 1946; Berliner, 1949). Lithium minerals have been produced mainly by open pit methods.

The Harding pegmatite is a tabular body that dips gently to the southwest, is more than 300 ft wide, extends 3,000 ft down dip, and averages 50–55 ft thick. It is complexly zoned and contains a quartz-microcline-muscovite-albite-beryl wall zone; a zone of massive quartz below the hanging-wall zone which grades downward into a thick zone of quartz and spodumene that contains some beryl; and a core of coarse-grained spodumene, microcline, and quartz with varying quantities of albite, muscovite, lepidolite, and tantalum minerals. Although the pegmatite may have been symmetrically zoned, many of the original lithologic units in the lower half have been obscured by the formation of albite and mica replacement units (Jahns, 1951).

Several lithium-bearing pegmatite dikes in Precambrian gneiss and schist are exposed in an area at least 2 mi long on the east slope of the Sangre de Cristo Range near the headwaters of Sparks and Maestas Creeks in Mora and San Miguel Counties (Jahns, 1953). One of the largest of these bodies was mined by the Hayden Mining Co. at the Pidlite mine in 1946–1947. The pegmatite is a discoidal lens that contains a border zone of albite-quartz-muscovite-perthite pegmatites with accessory apatite, beryl, fluorite, spessartite, and tourmaline; a wall zone of coarse-grained perthite-quartz-albite-muscovite pegmatite; an intermediate zone of quartz-perthite; and a core of massive quartz. Cleavelandite, muscovite, and lepidolite occur in replacement bodies.

Several NURE water samples near a playa lake in the northern Estancia Basin, Torrance County, contain anomalously high lithium (as much as 624 ppb Li, McLemore, 2010e). The Estancia Basin is a closed basin bounded on the east by the Pedernal Hills and on the west by the Sandia and Manzano Mountains.

Lithium also is found in ancient closed basins in the form of high-lithium clays, hectorite, and bentonite (Asher-Bolinder, 1991a, b). In New Mexico, lithium-rich tuffs in the Popotosa Formation contain lithium values as high as 3,800 ppm Li (Brenner-Tourtelot and Machette, 1979: Asher-Bolinder, 1982, 1991a). No lithium has been produced from these deposits. Lithium can occur in surface and subsurface brines (Asher-Bolinder, 1991b).

Magnesium Minerals and Compounds (excluding Dolomite and Olivine)

Although magnesium is found in more than 60 minerals, only a few are of commercial importance. In addition to magnesium minerals, seawater and well and lake brines are also important sources of magnesium. One of the more important magnesium minerals is magnesite ($MgCO_3$); this carbonate mineral represents the world's largest source of magnesia. Other commercially important magnesium-bearing minerals are dolomite, brucite, olivine, talc, and serpentine (Kramer, 2006). Olivine and talc are discussed in separate sections of this volume. Magnesium is used as a metal, alloy, in electronics, refractory material in steel and copper kilns and furnaces, and other uses, including crankcases in aircrafts, frames in automobiles, electronics, medicines, and batteries.

Magnesite and brucite occur in New Mexico (Kottlowski, 1965b) in potential commercial deposits in the Organ and San Andres Mountains in east-central Doña Ana County and near Red Rock in southwestern Grant County. Scattered crystals of magnesite, small masses, and layers up to 2.5 cm thick occur amid the Permian potash-bearing beds of southeastern New Mexico in Eddy, Lea, and Chaves Counties. Some of the contact-metamorphosed deposits of the Fierro-Hanover mining district in east-central Grant County contain dense magnesite associated with magnetite and serpentine.

The magnesite near Red Rock is in small scattered deposits (Magnesite, NMGR0425 and Ash Creek Magnesite, NMGR0420) along the west side of Ash Creek and the largest exposure is about 60 ft wide by 75 ft long, containing horizontally bedded

magnesite, fine-grained quartz, and lenses of finely crystalline dolomite (Hewitt, 1959; McLemore et al., 1996c). The dolomite and fine-grained quartz were originally bedded sedimentary rocks that have been veined by quartz and then veined and replaced by magnesite. The magnesite deposit is small and impure. It is on the New Mexico Department of Game and Fish Redrock Wildlife Refuge and withdrawn from mineral development.

In the Organ Mountains, scattered xenoliths of brucite-serpentine marble and of magnesite are found on the southeast and south sides of the range in quartz monzonite (NMDA0052). Some of the xenoliths are more than 1,000 ft long and 500 ft wide, where the magnesite and brucite have selectively replaced beds in the lower Paleozoic sequence, including parts of the El Paso Limestone, Montoya Dolomite, and Fusselman Dolomite (Dunham, 1935). Prospect pits are in lenses of magnesite that range from 1–5 ft thick. Some production was reported.

North of Organ in the southwestern San Andres Mountains (NMSI1773), a few beds of impure magnesite are found within contact-metamorphosed Montoya and Fusselman dolomites near the contact with the quartz monzonite. These dolomite and magnesite lenses are poorly exposed in a few prospect pits. These deposits along with the magnesite of the southern Organ Mountains are within White Sands Missile Range and are not open to commercial exploitation.

Thick dolomite units are intruded by many large bodies of igneous rocks in southwestern New Mexico and the difficulty of distinguishing magnesite from common dolomite or limestone marble allows for the possibility of large magnesite-brucite bodies to occur in southwestern New Mexico. Detailed mineralogical studies while prospecting for metal deposits are recommended.

Saline brines in southeastern New Mexico can contain magnesium; one well in Roosevelt County contained as much as 18,000 ppm Mg (Theis and Hale, 1942; Kunkler, 1972). Magnesium is found in waste water from recovery of potash (Nylander and Jensen, 1964). Several NURE water samples near a playa lake in the northern Estancia Basin, Torrance County, contain anomalously high magnesium (as much as 1,320 ppb Mg, McLemore, 2010a).

Manganese

Manganese is found in several types of deposits in New Mexico (McLemore and Lueth, 2017): carbonate-hosted Ag-Mn (Pb) replacement, carbonate-hosted manganese, and volcanic-epithermal vein deposits. From 1883–1963, more than 1.9 million long tons of manganese were produced from deposits in New Mexico (Table 14; Fig. 20). Deming was a government buying and storage facility. In recent years, manganese was recovered from the Deming

Table 14. Manganese production from New Mexico 1883–1963 (from Farnham, 1961; Dorr, 1965).

District ID	County	District	Ore production (long tons)	Grade % Mn	Concentrate production (long tons)	Grade % Mn	Estimated value ($)
DIS010	Catron	Wilcox	87	21	—	—	100
DIS032	Doña Ana	Rincon	1,529	27–40	—	—	2,000
DIS050	Grant	Chloride Flat	1,634,000	11,7–16	—	—	3,200,000
DIS048	Grant	Caprock	1,148	21–36	3,339	33–35	2,000
DIS074	Hidalgo	Antelope Wells- Dog Mountains	5.6	37.9	—	—	<100
DIS108	Luna	Little Florida Mountains	19,526	19–21	21,393	30–45	80,000
DIS106	Luna	Florida Mountains	1,421	22-30	—	—	2,000
DIS104	Luna	Cooke's Peak manganese	—	—	450	33–46	1,000
DIS170	Sandoval	Cuba manganese	—	—	2,302	40	4,000
DIS272	Santa Fe	Santa Fe manganese	100	?	?	?	200
DIS200	Sierra	Lake Valley	4,224	3	57,800	25	122,000
DIS199	Sierra	Hot Springs	198	18	16,877	19	32,000
DIS199	Sierra	Kingston	2,520	34–39	1,651	35–40	6,000
DIS204	Sierra	Taylor Creek	87	21	—	—	200
DIS220	Socorro	Luis Lopez	15,000	28	118,000	35–48	266,000
TOTAL			**1,900,000**	**<35**	**176,515**	**>35**	**5,000,000**
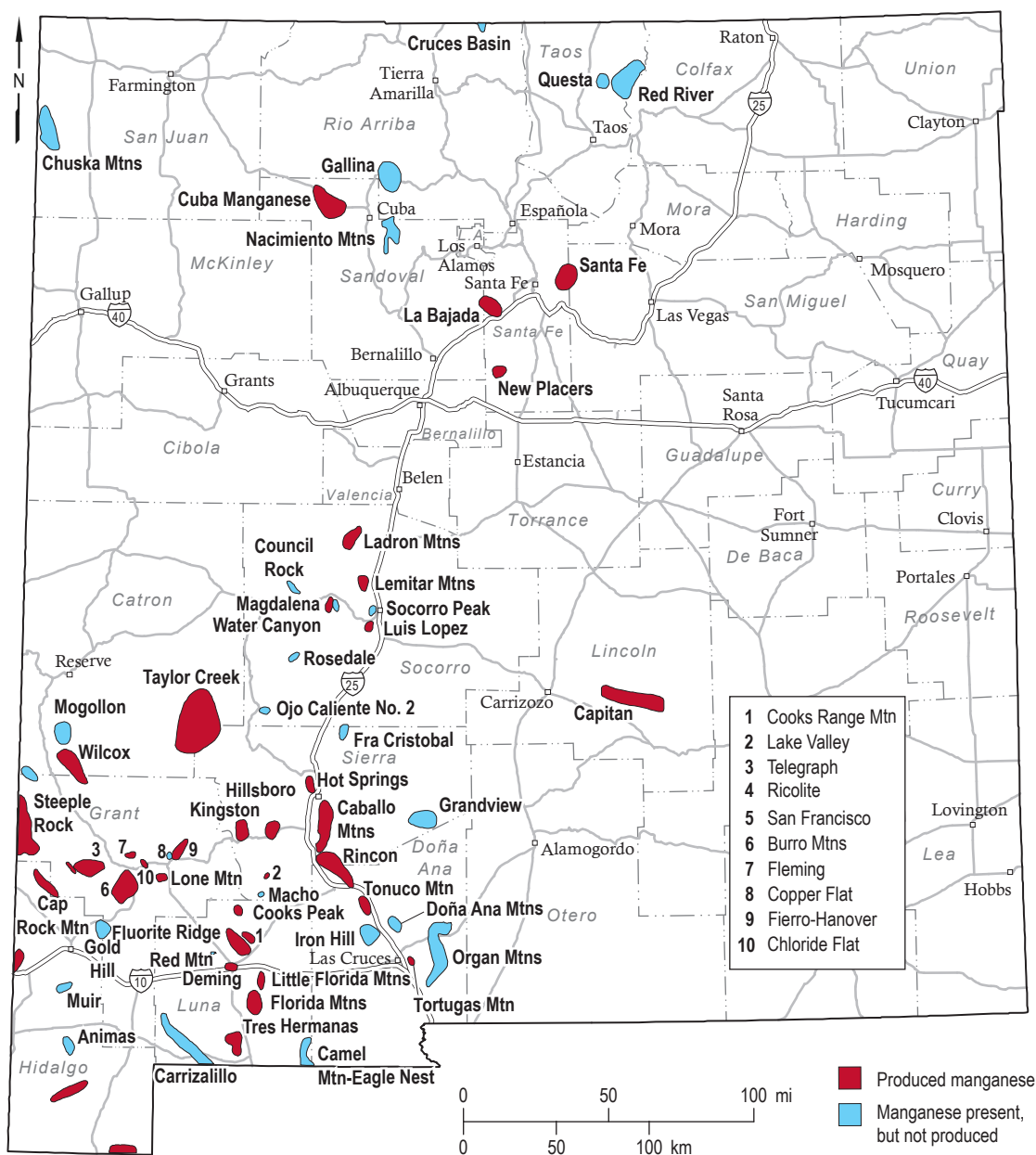
Figure 20. Mining districts with manganese deposits in New Mexico.

stockpiles and sold to El Paso brick manufacturers for a coloring agent. Manganese is used to prevent rust and oxidation of steel, in aluminum alloys, and as an additive in unleaded gasoline. It is also used in coins, alkaline batteries, and pigments in paints, ceramics, and glass.

Carbonate-hosted silver (manganese, lead) replacement deposits occur in southwestern New Mexico and were formed approximately 20–50 Ma. These deposits contain predominantly silver and manganese oxides and include veins in carbonate rocks and replacements in carbonate rocks with little or no calc-silicate minerals. 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 (DIS191), Lone Mountain (DIS059), and Lake Valley (DIS200) districts (Farnham, 1961).

Numerous replacement manganese and epithermal manganese deposits occur in carbonate, volcanic and volcaniclastic rocks throughout New Mexico (Farnham, 1961; McLemore et al., 1996c). Significant production has come from the Luis Lopez district. Manganese oxide minerals occur in veins, breccia cement, replacements, or cavity fillings in limestone and dolomite and form tabular or 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., 1996c). Most deposits in New Mexico are typically low grade (<50% Mn), small, and uneconomic in today's market.

Mica

The most common commercial micas are: muscovite, a potassium-based mica, usually colorless to pale green, phlogopite, a magnesium-based mica that is yellow to dark brown, vermiculite, a hydrated biotite found as bronze-yellow flakes, and lepidolite, a lithium-based mica with a purplish hue. Other micas with less commercial value include zinnwaldite, a lithium/iron-based mica that is gray to brown; biotite, a magnesium/iron-based black mica; and roscoelite, vanadium/potassium/magnesium mica that can be green or brown (Schlanz and Tanner, 2006).

Muscovite mica enjoys the most diverse market applications, followed by phlogopite and vermiculite. Muscovite and phlogopite possess unique characteristics and are highly valued because of their physical, chemical, electrical, thermal, and mechanical properties. Color plays a key role in identifying markets for these two micas: muscovite is lighter and used in more color-sensitive applications.

Phlogopite, however, will typically give superior aspect ratios after grinding, adding to its value as a reinforcement additive.

Commercially, mica is marketed in several forms:

- *Sheet mica* refers to books of mica mined from pegmatite or loosely consolidated clay deposits. The books can be readily split into thin sheets with specific thicknesses ranging from 0.003–0.10 mm. The quality of sheet mica is graded according to 10 quality classifications. Flawed books (excess inclusions, cracks, etc.) are termed scrap mica and can be used in ground products.

- *Built-up mica* was developed in the late 1800s because of the scarcity and cost of sheet mica, and served as a ready substitute for electrical parts. Formed by layering pieces of mica splittings and binding them with inorganic or organic binders, the constituted sheets are pressed under high temperature.

- *Reconstituted mica* is mica paper matted from thin delaminated flakes of scrap mica. The mat is usually impregnated with an organic binder and dried at 110°C. Feedstock for reconstituted mica is typically trimmings from sheet mica operations.

- *Flake mica* is finer mica recovered from scrap or trimmings produced during the processing of sheet mica, or can be beneficiated mica recovered from feldspar, clay, and sand operations.

Table 15. Mining districts in New Mexico containing major mica deposits.

District ID	County	District	Type of deposit	Comments
DIS017	Cibola	Zuni Mountains	mica schist	Scrap mica produced 1961–1962
DIS046	Grant	Burro Mountains	pegmatite	No production
DIS058	Grant	Gold Hill	pegmatite	No production
DIS068	Grant	White Signal	pegmatite	No production
DIS125	Mora	Coyote Creek	pegmatite	Some production
DIS126	Mora	Mora	pegmatite	
DIS147	Rio Arriba	Ojo Caliente No. 1	pegmatite	Sheet and scrap mica produced
DIS148	Rio Arriba	Petaca	pegmatite	Sheet and scrap mica produced
DIS161	San Miguel	El Porvenir	pegmatite	Small production
DIS162	San Miguel	Elk Mountain	pegmatite	Some production
DIS164	San Miguel, Mora	Rociada	pegmatite	Some production
DIS166	San Miguel	Tecolote	pegmatite	Some production
DIS167	San Miguel	Willow Creek	pegmatite	Production unknown
DIS185	Rio Arriba, Santa Fe	Nambe	pegmatite	Some production
DIS189	Santa Fe	Santa Fe	pegmatite	Some production
DIS232	Taos	La Cueva	pegmatite	No production
DIS234	Taos	M.I.C.A.	mica schist	Mica produced 1959–2005
DIS236	Taos	Picuris	pegmatite	No production
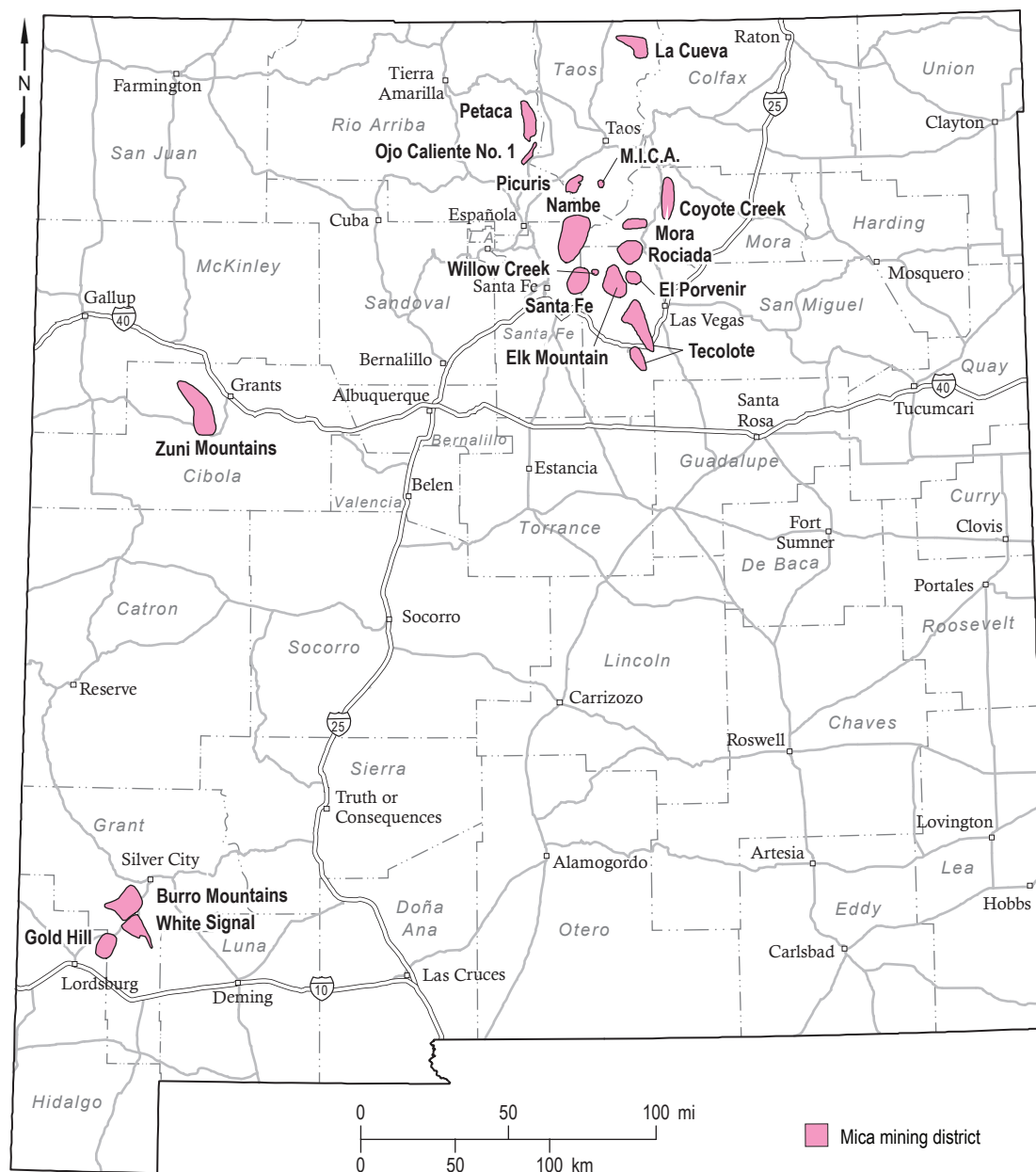
Figure 21. Mining districts in New Mexico containing major mica deposits.

- *Ground mica* is produced by wet or dry grinding and sizing of scrap or flake mica. It is by far the largest use of mica, both quantitatively and by application.

- *Synthetic mica* is produced by crystal growth in slowly cooled melts of various chemical oxides. Cooling periods at controlled viscosities dictate the size of the crystals; extended cooling times result in larger crystals.

Mica mining began in New Mexico as early as the 18th century when mica from the Petaca district (DIS148, Rio Arriba County) (Fig. 21; Table 15),

Figure 22. Wall of the quarry at the M.I.C.A. mine (NMTA0008) showing mica schist in the Proterozoic Rio Pueblo Schist of the Vadito Group. *Photo by Virginia T. McLemore.*

was used in windows in Santa Fe (Just, 1937; Northrop, 1959; 1996). Interest in the mica deposits was renewed in 1870 when mining began to supply mica for stove windows. Cribbensville, New Mexico, which was the center of mica mining, was named after the maker of a popular brand of stove that used mica for windows (Just, 1937; Lesure, 1965).

Mica most commonly comes from pegmatites (Table 15). Pegmatites are reported throughout rocks of Proterozoic age in New Mexico, but the principal deposits are in Rio Arriba, Taos, San Miguel, and Mora counties and are described in detail by Jahns (1946, 1951, 1953) and summarized by Lesure (1965). Table 15 lists mining districts with deposits in New Mexico that have produced, or have the potential to produce mica. There are many more pegmatite occurrences in New Mexico that are not listed that have lesser amounts of mica.

Mica was mined in 1959–2005 at the U.S. Hill mine (M.I.C.A., NMTA0008) in the Proterozoic Rio Pueblo Schist of the Vadito Group northeast of Peñasco in Taos County (Fig. 22). The schist consists of 70–85% muscovite. After processing, the mica ranged in size from 1–100 µm and was used for paints and conductor plates (Austin et al., 1990a; Nelson, 1996). In 2005 the mine was closed, the land reclaimed, and control of the property given to the Picuris Indian Pueblo.

Nepheline Syenite

Nepheline syenite is a light-colored, medium- to coarse-grained holocrystalline, silica-deficient feldspathic plutonic igneous rock largely made up of nepheline, sodium feldspar (albite), alkali feldspar (orthoclase, microcline), but no quartz. Nepheline syenites are essentially syenites that are undersaturated in silica. Crystallizing from magma undersaturated in silica results in the formation of nepheline instead of albite feldspar (Harben, 2002; McLemore, 2006). Trace minerals include sodalite, augite, aegirine, biotite, hornblende, sphene, zircon, iron oxides (magnetite), apatite, garnet, muscovite, corundum, and other minerals rich in alkalis or rare earths elements (REE). Nepheline syenites high in alumina (>23%), low in silica (<60%), low in iron (<2% Fe_2O_3) and high in alkalis ($Na_2O + K_2O$ >15%) can be used in the manufacture of glass and ceramics, which account for the bulk of its commercial use.

Wind Mountain (NMOt0013) is one of several alkaline plutons that form the Cornudas Mountains in the northern Cenozoic Trans-Pecos alkaline magmatic province (Fig. 23). Wind Mountain is one of the largest exposed nepheline syenite intrusions in this belt (McLemore et al., 1996a, b). There has been no production except for test shipments of nepheline syenite for use as sandblasting material in 1995.

Table 16. Chemical composition of nepheline syenite from Cornudas Mountains, New Mexico. [1]Modified from McLemore and Guilinger (1993) and McLemore et al. (1996a, b), unaltered surface and drill core samples (n=5). [2]Average from Barker et al. (1977, n=4) and Schreiner (1994, n=2). *Total iron as Fe_2O_3. Additional chemical analyses of economic nepheline syenite deposits in the world are in McLemore (2006). TNSP[2] shown in Figure 23.

% Oxide	Average Wind Mountain (TNSP[2])[1]	Range of Wind Mountain (TNSP[2]) Samples[1]	Deer Mountain[2]	Processed Wind Mountain TNSP[2] Pit 1	Processed Wind Mountain TNSP[2] Pit 2
SiO_2	59.84	56.3–63.3	57.3	64.70	63.80
TiO_2	0.12	0.03–0.14	0.48	<0.01	<0.01
Al_2O_3	18.84	17.6–20.8	19.6	20.50	20.90
Fe_2O_3*	4.90	1.54–6.48	6.85	0.52	0.40
MgO	0.73	0.07–1.80	0.44	<0.05	<0.05
CaO	1.23	0.68–1.40	1.52	0.23	0.20
K_2O	5.35	4.80–6.32	5.46	6.74	6.73
Na_2O	7.82	7.20–8.80	7.03	7.62	8.23
MnO	0.27	0.14–0.35	0.38	—	—
P_2O_5	0.11	<0.05–0.11	0.13	<0.05	<0.05
LOI	2.24	1.02–2.91	2.62	—	—
TOTAL	**101.45**	**—**	**101.81**	**100.31**	**100.26**

Table 17. Chemical composition of raw and processed North Cape nepheline syenite, Stjernoya, Norway used in glass manufacture (modified from Guillet, 1994).

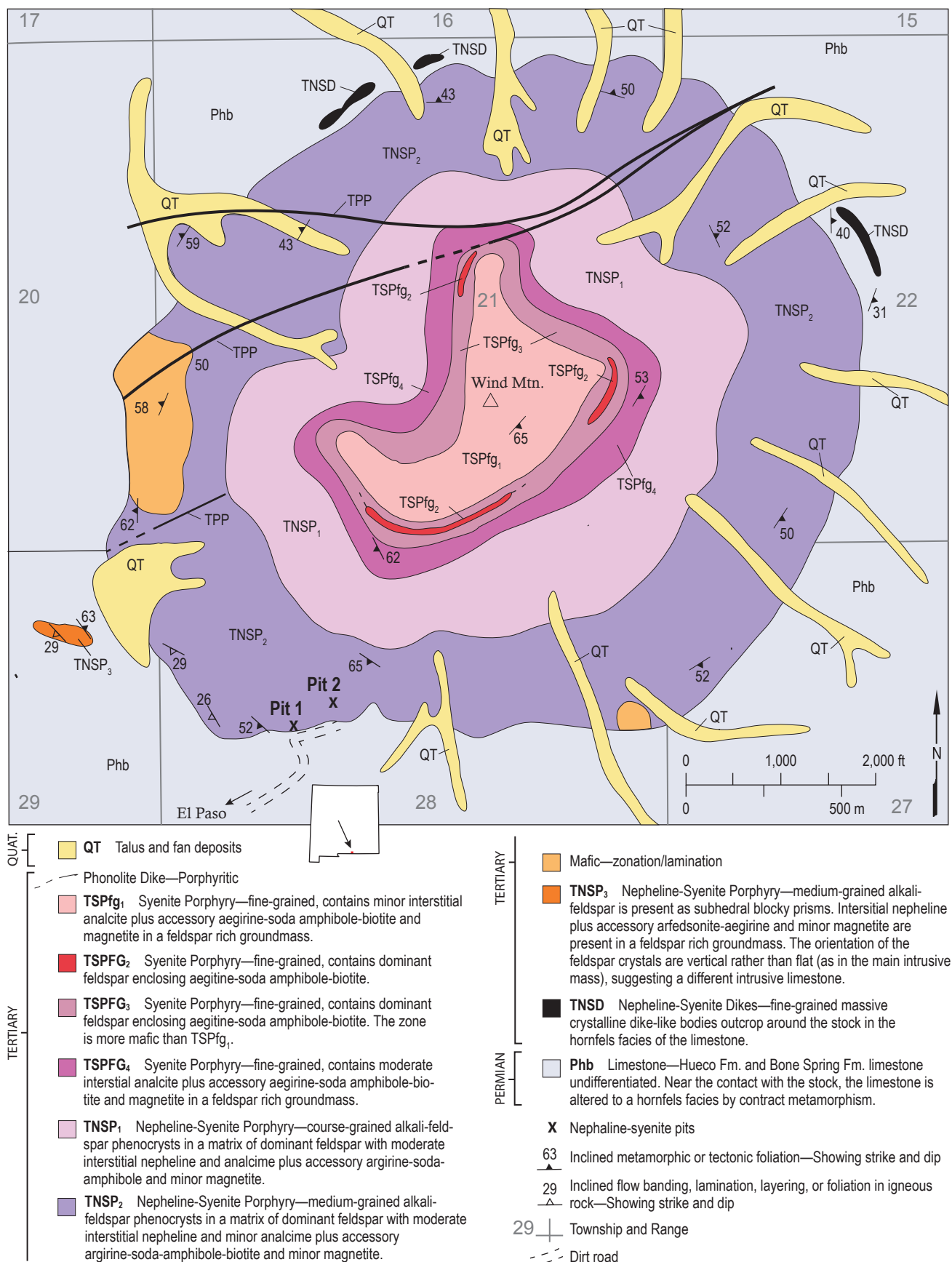| % Oxide	Stjernoya, Norway (pyroxene)	Stjernoya, Norway (biotite)	Glass grade after processing	Ceramic grade after processing
SiO_2	52.73	52.37	57.0	57.0
TiO_2	0.51	1.14		
Al_2O_3	23.71		23.8	23.8
Fe_2O_3	1.90		0.10	0.12
FeO	1.89	1.10		
MgO	0.24	3.11		
CaO	2.54	8.30	1.3	1.1
K_2O	8.08	6.87		
Na_2O	7.78	0.61	7.9	7.8
MnO	0.06	0.25	9.0	9.1
P_2O_5	0.01	0.05		
CO_2	0.77	1.88		
LOI	0.26	0.26		
TOTAL			**99.1**	**98.92**

Figure 23. Geologic map of Wind Mountain, southern Otero County in T26S, R14E (McLemore et al., 1996a, b; P. Graseah, field mapping, July 1992).

The Wind Mountain laccolith consists of six mineralogical and textural zones (listed in the legend of Fig. 23; McLemore et al., 1996a, b; McLemore and Guilinger, 1996). The laccolith is typically gray to cream colored and weathers to darker colors. Accessory minerals form dark-colored aggregates dispersed throughout the rock. Chemical variations among the individual map units within the laccolith cannot be readily discerned by utilizing major element analyses (McLemore et al., 1993, 1996a, b). However, the syenites contain more barium and strontium than the nepheline syenites (McLemore et al., 1996a, b). These chemical analyses of the Wind Mountain laccolith suggest that the zonation appears to be controlled by crystal fractionation, volatile separation, and cooling history, not different pulses of magma (McLemore et al., 1996b). Differential cooling of the magma resulted in the textural variations at Wind Mountain.

The outer zone of the Wind Mountain nepheline syenite ($TNSP_2$ in Fig. 23) was being developed for use as a constituent in glass, ceramics, and flatware and for use as an abrasive by Addwest Minerals Inc. between 1991 and 1995, but closed due to poor market conditions. The nepheline syenite contains high iron (Tables 16, 17) compared to other commercial sources of nepheline syenite. However, when the Wind Mountain nepheline syenite is crushed and passed through a specialized rare-earth magnet, the resulting product is similar in composition to Grade B product specified by Unimin Canada, Ltd., and has been certified by Coors, Inc., as being suitable for amber-colored glass and ceramics. Physical and chemical test results of Wind Mountain nepheline syenite meet or exceed standards for use as roofing granules, dimension stone, aggregate, and abrasives (McLemore and Guilinger, 1996).

Mining at Wind Mountain was planned to be underground using room and pillar methods. Processing would involve crushing, grinding, magnetic separation, and screening. At full production, Wind Mountain was expected to process 3,000 short ton per day or 700,000 short tons per year. Reserves total 200 million short tons for a mine life of more than 100 years (Industrial Minerals, 1995).

Additional mineral resource potential for nepheline syenite elsewhere in the Cornudas Mountains is limited. The nepheline syenite of nearby Deer and San Antonio Mountains may have potential for glass or ceramic use. The other laccoliths, dikes, plugs, and sills are not suitable for glass or ceramic use because of high iron contents and heterogeneous composition. Other areas in New Mexico have limited to no potential for nepheline syenite because of large concentrations of iron.

Nitrogen and Nitrates

Nitrogen, as anhydrous ammonia (NH_3), is obtained by fractional distillation through the Haber-Brosch process from natural gas (Harben and Theune, 2006). This is the predominate process used today; however, natural nitrates, saltpeter and guano also are mined for fertilizers. The nitrate minerals and guano are discussed together because of their common close relationship in nature and because their principal use is as a fertilizer. The nitrate minerals of importance are niter or saltpeter (KNO_3) and soda niter ($NaNO_3$). In addition to use as a fertilizer, nitrates are used in the manufacture of chemicals and gunpowder. Prior to the discovery of large reserves of potassium chloride and sulfate in Permian beds of southeastern New Mexico, there was an interest in saltpeter in the United States as a possible source of potassium for fertilizer (Hayes, 1965).

Guano is a natural accumulation of manure, usually mixed with variable amounts of animal remains and inorganic matter. Marine bird guano makes up the largest deposits in the world, but bat guano forms smaller deposits in caves throughout much of the world, including New Mexico. Nitrate salts occur as surficial precipitates derived from waters that have percolated over or through guano deposits or organic-rich soils. Because niter and soda niter are very soluble in water, they form naturally only in very arid regions.

In New Mexico small accumulations of nitrate salts were found at numerous localities, mostly in southern New Mexico (Mansfield and Boardman, 1932; Hayes, 1965; Northrop, 1996). Soda niter from the extreme southern edge of New Mexico adjacent to the Mexican border apparently was once mined in small quantities (Mansfield and Boardman, 1932) and approximately 125 short tons of niter was reported to have been mined between 1899 and 1902 from a small deposit in a lava tunnel in the Jornada del Muerto flow east of the Rio Grande in Socorro County. Guano for fertilizer was reportedly mined from the Jornada cave in the 1980s (http://www.nature.org/ourinitiatives/regions/northamerica/unitedstates/newmexico/explore/jornada-bat-caves-in-new-mexico.xml). Talmage and Wootton (1937) expressed the opinion that no

reported nitrate occurrence in New Mexico offered commercial promise; there is no reason at present to contradict that opinion.

Bat guano is present in numerous caves in New Mexico but most of the deposits are too small to be of commercial consequence for other than limited local markets. Before it was made a national park, an estimated 100,000 short tons of guano was removed from Carlsbad Cavern (NMED0046). Commercial guano was mined from New Cave, now a part of Carlsbad Caverns National Park (Hayes, 1965). Other areas from which some guano has been mined include a cave in the Caballo Mountains (Kelley and Silver, 1952), lava tunnels in the Jornada del Muerto (Mansfield and Boardman, 1932), and places in the Tres Hermanas Mountains (Talmage and Wootton, 1937).

Olivine

Olivine $(MgFe)_2SiO_4$ is a solid solution series between magnesium-rich forsterite and iron-rich fayalite that occurs in basic igneous and metamorphic rocks. Olivine is a common mineral in the low-silica rocks making up the oceanic crust. It is particularly common in pre-Ordovician to Tertiary basalts and other mafic igneous rocks and is the essential mineral of peridotite. Rock containing more than 90% forsterite is known as dunite. Deposits commonly contain 92% olivine, 5% pyroxene, and 1% spinel, chromite, and magnetite, along with 2% secondary minerals. Olivine also occurs in basic igneous rocks such as olivine gabbro, basalt, and diabase (dolerite). Commercial deposits of olivine, however, are generally restricted to dunite bodies of the alpine type that intruded from the upper mantle into the upper lithosphere along deep faults in partly crystallized form (Harben and Smith, 2006). Olivine is a gemstone and is a source of magnesium, which is also used in batteries (see above).

New Mexico contains no reported dunites but olivine commonly is found in mafic igneous rocks such as basalts, olivine basalts, lavas, and basic dikes. These occur in Bernalillo, Catron, Chaves, Cibola, Colfax, Doña Ana, Grant, Lincoln, Luna, Mora, Rio Arriba, Sandoval, San Juan, Sierra, Socorro, Taos, and Union Counties. Olivine also occurs in sandstones and/or conglomerates in Guadalupe, Sierra, and Taos Counties (Northrop, 1996).

Olivine has been found in and around Buell Park, east of Fort Defiance, in the Red Lake volcanic field, Navajo Indian Reservation. Olivine also comes from the Zuni Reservation and the Fort Wingate

areas, but most of the material came from the Buell Park region, along the New Mexico–Arizona line. For many years this general area seems to have been about the only source of olivine gems—usually referred to as peridots. Peridot is a transparent to translucent green gem variety of olivine. It is the well-crystallized semiprecious gem variety found in dark volcanic rocks. It is especially abundant in many ant hills, and may constitute up to 60% of the material. One-to two-carat stones are not uncommon (Northrop, 1996).

In Doña Ana County pale green nodular masses of peridot occur in the basalt flows of the Kilbourne Hole near Afton. The nodules found around this extinct volcano average about 5 cm in diameter and, although badly shattered, have yielded small but handsome gems. A faceted peridot of 3.4 carats from the flow was reported in 1949 (Carter, 1965b).

Perlite

The term *perlite* was originally applied to natural siliceous glasses of volcanic origin characterized by abundant concentric fractures and commonly having a pearly luster (Weber, 1965a). The industrial term has been extended to include any volcanic glass that will expand appreciably by vesiculation under appropriate heat treatment, thus embracing some obsidians, pitchstones, vitrophyres, and the resultant expanded products. True perlites, in the original sense, are sometimes distinguished from nonperlitic varieties in the trade by the textural term onionskin perlite. Perlite is used in lightweight plasters and mortars, insulation and ceiling tiles. New Mexico leads the nation in domestic perlite production.

Perlite and related natural glasses are products of volcanic processes. Their distribution is accordingly limited to volcanic fields where they are associated with ordinary lava flows, volcanic breccias, and tuffs, particularly those of rhyolitic composition. Modes of occurrence of commercial perlites include lava flows and extrusive domes, plugs, pyroclastic breccias, welded tuffs, and shallow intrusive dikes and sills. Because the glassy state is relatively unstable, they tend to devitrify by crystallization with increasing age. They also are readily altered to clays, zeolites, and other minerals by geothermal, hot spring, and hydrothermal alteration processes. As a consequence, commercial deposits are Tertiary or younger in age. The water

content, which is essential to the expansion process, commonly lies in the range of 3–5%, but may be as low as 1.5% in expansible obsidians and as high as 10% in expansible pitchstones.

Perlite deposits of developed or potential commercial value are widely distributed in western New Mexico (Fig. 24; Table 18) and are closely related to volcanic fields of rhyolitic composition at or near eruptive centers. Available analyses indicate that volcanic glasses of perlitic type are prevailingly rhyolites of high silica content. All known deposits are Tertiary or early Quaternary in age.

North-Central New Mexico

The principal developed resources of perlite in northern New Mexico are at No Agua Peaks and east of No Agua Peaks in northwestern Taos County (Fig. 24). No Agua volcanic area is made up of a cluster of four hills of rhyolite whose structural relationships suggest extrusion as a volcanic dome or composite dome. Several varieties of glassy and lithoidal rhyolite are present. Pale gray to buff, flow-banded, pumiceous perlite (nonperlitic) forms large masses of commercial grade that are easily mined by open-pit methods.
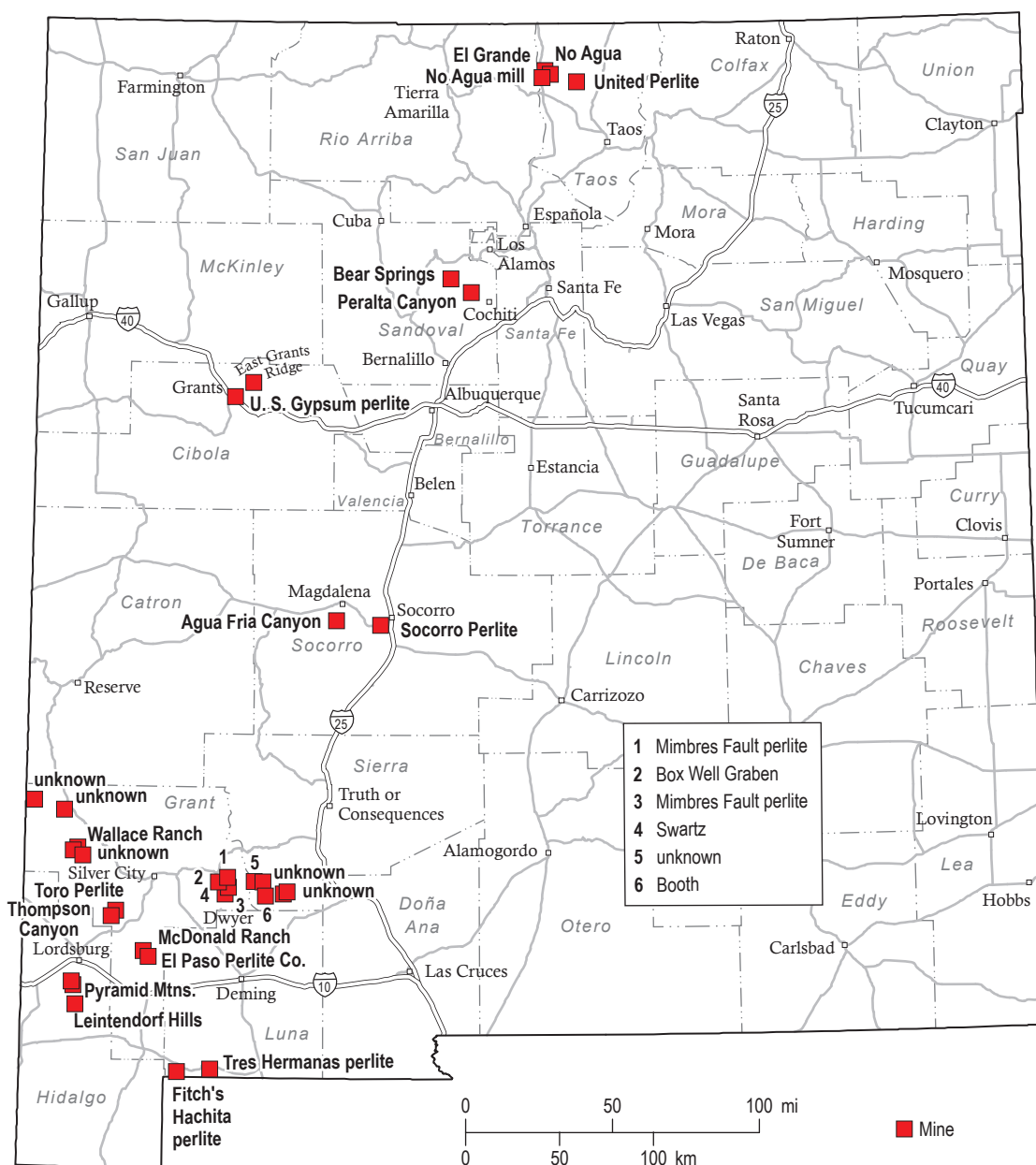

Figure 24. Perlite occurrences and mines in New Mexico.

Table 18. Perlite mines and prospects (Weber, 1965b; NMBGMR files; Mine id from New Mexico Mines Database).

Mine ID	County	Mine name	Latitude	Longitude	Year of initial production	Year of last production	Comments on production
NMCI0166	Cibola	U.S. Gypsum perlite	35.216779	107.736345	1953	1990	production continued until the early 1990s, few 100,000 tons
NMCI0167	Cibola	U.S. Gypsum perlite mill	35.148111	107.845333	1953	1990	production continued until the early 1990s, few 100,000 tons
NMGR0633	Grant	Box Well Graben	32.75287	107.902925			none
NMGR0634	Grant	El Paso Perlite Co.	32.383415	108.3202166	1953		approximately 3000 short tons
NMGR0631	Grant	McDonald Ranch	32.395129	108.333111	1950		3000 tons
NMGR0635	Grant	Mimbres Fault Perlite	32.77056	107.8633			none
NMGR0636	Grant	Mimbres Fault Perlite	32.72667	107.8633			none
NMGR0630	Grant	Swartz	32.691389	107.870271			none
NMGR0321	Grant	Thompson Canyon	32.569444	108.5347222			none
NMGR0413	Grant	Toro Perlite	32.585769	108.5189303			none
NMGR0637	Grant	unknown	32.86333	108.7088			none
NMGR0638	Grant	unknown	33.13639	109.0013			none
NMGR0639	Grant	unknown	33.09056	108.8183			none
NMGR0325	Grant	Wallace Ranch	32.891054	108.74926	1958	1960	200 tons
NMGR0632	Grant	Wallace Ranch	32.900631	108.743031	1958	1960	200 tons
NMHI0090	Hidalgo	Leintendorf Hills Perlite	32.136389	108.7363889	1950	1953	Selectively mined in 1950–53
NMHI0328	Hidalgo	Leitendorf Hills	32.241849	108.7559623			none
NMHI0100	Hidalgo	Pyramid Mountains	32.231357	108.7514502	1950	1954	
NMHI0095	Hidalgo	unknown	32.239291	108.7531548	1950	1950	small
NMLU0162	Luna	Fitch's Hachita perlite	31.8139	108.1395			test holes
NMLU0179	Luna	Tres Hermanas perlite	31.82247	107.949949			none
NMSA0315	Sandoval	Bear Springs	35.735011	106.538361			none
NMSA0321	Sandoval	Cochiti	35.756541	106.46265			none
NMSA0314	Sandoval	Peralta Canyon	35.6692	106.4219			none
NMSI1737	Sierra	Booth	32.6894	107.618106			none
NMSI0482	Sierra	unknown	32.681389	107.5183333			none
NMSI1738	Sierra	unknown	32.679352	107.5261405			none
NMSI1739	Sierra	unknown	32.687388	107.6418525			none
NMSI1740	Sierra	unknown	32.7431	107.6917			none
NMSI1741	Sierra	unknown	32.7439	107.6633			none
NMSI1742	Sierra	unknown	32.7375	107.6756			none
NMSO0541	Socorro	Agua Fria Canyon	34.042424	107.2273281			none
NMSO0146	Socorro	Socorro Perlite	34.024195	106.94277	1949	present	
NMSO0235	Socorro	Stendel	34.106146	107.206587			none
NMTA0010	Taos	El Grande	36.742174	105.968359	1958	present	plant in Colorado
NMTA0539	Taos	Johns-Manville	36.758572	105.949703	1952	1981	operated by Johns Manville then Celite, now Harborlite
NMTA0011	Taos	No Agua	36.74832	105.9558898		present	
NMTA0513	Taos	No Agua	36.74265	105.956203	1951	present	
NMTA0515	Taos	No Agua	36.746896	105.936326	1981	present	
NMTA0514	Taos	No Agua mill	36.733804	105.9686244	1951	present	150,000 tons per year
NMTA0540	Taos	United Perlite	36.709599	105.754815	1959		

The Imerys Corp. No Agua operation (NMTA0011, NMTA0513, formerly Harborlite) consists of a series of high-silica rhyolite flows that are more geologically complex than the adjacent Dicaperl single flow to the west (Ennis, 2011). Production comes from the South and West Hills. The perlite is both granular and pumiceous, although some denser material similar to true perlite is at the core of the hills.

In general, a lateral progression from denser perlite, to granular to pumiceous exists from South Hill southward. Some fine-grained, gray-to-clear obsidian is present in the classical and granular perlite, but the pumiceous perlite contains virtually none (Harben et al., 2008).

El Grande mine of Dicaperl (NMTA0010) is located on the southwestern side of No Agua Mountain, 1.5 mile south of the Imerys Corp.

operation and operates sporadically during the year. The El Grande mine is in a single flow altered to granular perlite with considerable obsidian on the southwest flank of the four No Agua Peaks (Harben et al., 2008).

A separate deposit, previously mined by Silbrico (NMTA0540), is about 10 mi east-southeast of No Agua Peaks. It is exposed in a group of hills that are similar in character and origin, but more friable with considerably more wastage than those of the No Agua deposits.

Commercial grade perlite occurs among the varied assemblage of volcanic glasses in the Jemez Mountains in Sandoval County (Fig. 24). Among the more accessible localities of record are those on the southern slopes of the range in Cochiti and Peralta Canyons, west of Santa Fe, and at Bear Springs, farther west. Pale gray to black ribs and dike-like masses of vitreous to pitchy volcanic glass are interlaced with rhyolitic breccias in Bland Canyon below the old mining camp of Bland (NMSA0321). Both perlitic and nonperlitic varieties are present.

Small segments of a mass of perlite in Peralta Canyon (NMSA0314) consist of pale gray perlitic to pumiceous perlite of commercial grade. Large parts of the body, however, contain interleaved flow bands of lithoidal rhyolite and perlite.

Highly vitreous green to gray perlite in the vicinity of Bear Springs (NMSA0315) contains brecciated zones cemented with glass and lithoidal rhyolite and numerous zones that are altered. Exploitation of the Bear Springs perlite has been handicapped by the prevalence of impurities and relatively remote location.

Only one deposit of commercial importance is recorded for northwestern New Mexico; it is located in East Grants Ridge (NMCI0166) about 8 mi northeast of Grants, Cibola County (Fig. 24). Although the area is at the southwestern edge of the Mount Taylor volcanic field, the volcanic sequence was erupted from local vents rather than from the main center of Mount Taylor. Pumiceous tuff, felsitic rhyolite, obsidian, and perlite in East Grants Ridge are pierced by a basaltic neck and overlain by basaltic flows that form the cap rock of the ridge. Flow-banded, pumiceous, gray perlite in the peripheral zone is similar to commercial perlites at No Agua and Socorro and was exploited by open-pit methods by U.S. Gypsum Co. The ore was transported by truck to the mill in Grants, where it was crushed, packaged, and shipped by railroad to various markets.

Central New Mexico

Occurrences of perlite and related volcanic glasses are common minor constituents of near-vent rhyolite assemblages in the Socorro, Chupadera, Magdalena, and San Mateo Mountains of Socorro County (Fig. 24). Deposits near Socorro and Magdalena have attracted attention as sources of commercial perlite, but only the Socorro deposit has been productive. The distribution and character of Cenozoic volcanic rocks in Socorro County were discussed by Weber (1963, 1965b).

The Socorro deposit of granular perlite with no obsidian is a high-potassium, high-silica rhyolite at the southeastern edge of the Socorro Mountains. The mine is currently producing 150,000 short tons of raw ore per year and is adjacent to the plant (Fig. 25), occupying 69–89 acres southwest of Socorro (Harben et al., 2008). Prominently flow-banded, pumiceous, pale gray to buff-gray glass makes up a body having the form of a volcanic dome with exposed dimensions of about 2,000 by 2,600 ft and an exposed vertical extent of more than 400 ft. Vitric breccias and tuffs composed largely of the pumiceous perlite overlap the north and south margins, whereas east and west margins are formed by high-angle normal faults. Large reserves of economical minable perlite still remain.

Perlite, vitrophyre, and vitric breccia are relatively widespread in the belt of rhyolitic eruptives that extends southward and southwestward from Magdalena Peak, about 1.8 mi south of Magdalena (Fig. 24). At the Stendel deposit, south of Magdalena (NMSO0235), a tabular body of porphyritic gray perlite of rhyolitic composition with a thickness of approximately 200 ft and a mapped linear extent of more than a mile, is interbedded with a sequence of rhyolite flows, tuffs, and thin vitrophyres. Zones of

Figure 25. Socorro perlite quarry, looking west (NMSO0146). *Photo Virginia T. McLemore.*

abundant spherulites and of montmorillonitic and zeolitic alteration impair the commercial possibilities of the deposit (Weber, 1957).

Southwestern New Mexico

A number of occurrences are scattered across extensive volcanic tracts in Sierra, Catron, Grant, Luna, and Hidalgo Counties (Fig. 24). Sporadic attempts have been made to develop several of the deposits commercially, mining operations have been short lived, and only small amounts of perlite have been marketed. The remote location and high costs of transportation have largely discouraged development in much of this region.

Perlite and related volcanic glasses are associated with several rhyolitic vent complexes in northwestern Grant County (NMGR0637, NMGR0638, NMGR0639). Local masses of perlite, interlayered with flow-banded, spherulitic rhyolite, cap a series of small peaks along the Arizona-New Mexico State line west of Silver City (Fig. 24). A correlative sequence that includes conformable tabular bodies of perlite makes up the main mass of the Mule Mountains a few miles east of Mule Creek. Other areas of outcrop have been noted in the Mogollon Mountains along the canyons of Iron Creek and the West Fork of the Gila River, east of Mogollon (Weber, 1965b).

An area of upper rhyolite containing appreciable amounts of perlite is shown by Elston (1960) in a northwesterly trending belt about 1 mi wide and 8 mi long west and southwest of Cliff. At the southeast border is the Wallace Ranch deposit (NMGR0632, NMGR0325). Scharkan (1992) describes that deposit as a gray, banded, granular perlite breccia, 15–1,300 ft thick, under black true perlite.

Perlitic phases are a minor constituent of rhyolitic flows and associated pyroclastics in several areas west of Lake Valley, western Sierra County (NMSI0482, NMSI1737, NMSI1738, NMSI1739, NMSI1740, NMSI1741, NMSI1742). The largest deposit, as described by Jicha (1954), is a sill about 40 ft thick, with overburden of 100–200 ft, and an aerial extent of 2,000–2,400 acres (NMSI1737). This area may include outcrops noted by Weber (1965b) of an irregular flow sheet of gray to bluish-gray perlitic glass overlain by flow-banded felsitic rhyolite and underlain by rhyolitic tuffs and breccias. The upper part of the perlite is at least locally contaminated by spherulitic and lithoidal bands. The remaining perlite occurrences in the Dwyer and Lake Valley

quadrangles are of doubtful commercial value and have been described by Elston (1957). Modes of occurrence here include bases of flows, margins of intrusive bodies, dikes, breccias, and lenses in tuff.

Perlite deposits on the McDonald ranch and vicinity crop out continuously for 6 mi along Burro Cienega (NMGR0631, NMGR0634; Scharkan, 1992) (Fig. 24). The main body has a tabular form up to 100 ft in thickness. It is black glass, with clear feldspar or altered white phenocrysts, and is ~6–250 ft thick including lenses (Weber, 1965b; Austin and Barker, 1998). Spherulitic and lithoidal rhyolite bands and layers are intercalated with the perlite at several levels.

A separate deposit to the northwest (NMGR0321, NMGR0413) in Thompson Canyon has been described by Ballmann (1960) as the Brock perlite and includes the Toro deposit. The character of the deposit suggests a highly fractured and faulted perlite dome. Many of the joints in the perlite are filled with quartz veins.

Massive brownish-red to dark-green perlitic pitchstone forms bold outcrops up to 500 ft high in the Leitendorf Hills, southwest of Lordsburg (NMHI0090, NMHI0328) (Fig. 24). The deposit crops out for nearly 1.8 mi in length, a few hundred feet in width, and has an exposed area of about 6 acres. The form is suggestive of a volcanic dome, but emplacement may have been by laccolithic intrusion. Irregular lenses and seams of devitrified glass and alteration products are prevalent.

Perlitic pitchstone, similar in physical properties to that near Lordsburg, is poorly exposed in low hills north of Hermanas Station, Luna County (NMLU0179). Widespread devitrification of the glass and the prevalence of bands of lithoidal rhyolite are unfavorable for commercial development of this deposit. Other larger perlitic bodies may, however, occur locally in the belt of rhyolite pyroclastics that extends for more than 20 mi to the northwest (NMLU0162). The prevalence of agate-filled spherulites (thunder eggs) in this area suggests the former abundance of volcanic glass that has been altered and devitrified.

Resource potential

As may be inferred from the foregoing discussion, New Mexico is amply supplied with potential reserves of commercial-grade perlite for a number of years of production at current rates. Total resources are extensive and many deposits remain undeveloped because existing economic factors preclude their profitable exploitation.

Potash

Potash is the common industrial term for potassium in various chemical combinations with sodium, calcium, magnesium, chloride, and sulfate, forming soluble minerals. Potassium is the third most widely used fertilizer nutrient after nitrogen and phosphorus (Jasinki et al., 1999), and this use accounts for more than 90% of total potash consumption supplied as potassium-bearing minerals, ores, and processed products. The mineralogy of potash is summarized in Table 19; additional potash mineralogy is described by Orris et al. (2014). The most common form is potash (or sylvite), potassium chloride or KCl, or muriate of potash (MOP), with a minimum analysis of 60% K_2O and differentiated by grain size as granular, coarse, standard, and soluble. Most fertilizer-grade MOP is colored pink to red due to iron oxide content and contains 60–60.5% K_2O with 2.0–3.0% NaCl and other impurities; refined grades (62.0% K_2O and higher with a maximum of 1.0% NaCl) are white. The mineral langbeinite, or sulfate of potash magnesia (SOPM) or KMS, is used as a specialty fertilizer and an animal feed additive. Theoretically, this natural source of SOPM contains 22% K_2O and 18% MgO and is produced commercially in New Mexico (Harben et al., 2008).

The Carlsbad potash district is the largest potash producing area in the U.S., and New Mexico is ranked number one in national potash production. Intreped Mining LLC and Mosaic Co. operate mines in the district (Fig. 26). Mining is mostly by

underground methods at depths of 800–1,500 ft. The estimated potash reserves in the district amount to more than 553 million short tons. In New Mexico, potash is found in bedded salt deposits (Williams-Stroud, 1991a) and the important natural, commercial, soluble potassium salts are sylvite (KCl) and langbeinite (K_2SO_4-2MgSO$_4$). Sylvinite, a mixture of sylvite and halite, is the typical ore mined in the Carlsbad potash district (CPD) in southeastern New Mexico. The Potash Enclave, also designated the Designated Potash Area (DPA) (formerly the Known Potash Leasing Area or KPLA; 2012 Secretarial Order for Co-Development of Oil & Gas and Potash Resources in Southeast New Mexico, http://www.blm.gov/nm/st/en/prog/energy/2012_secretarial_order.html, accessed 1/29/16), consists of that part of the district where federal and state lands require competitive bidding for mineral leases, under the U.S. Bureau of Land Management (BLM) oversight. The DPA (Fig. 26) was first established in 1939 to withdraw oil and gas leasing from the area and was modified in 2012. Recent production of potash in New Mexico is in Table 1.

Table 19. Common potash minerals found in southeastern New Mexico (Barker and Gundiler, 2008). The potassium in potash minerals and fertilizer is reported as potassium oxide (K_2O) in order to compare fairly diverse mineralogy and composition. Sylvite and langbeinite are produced from sylvinite and langbeinite ore, locally associated with carnallite, kainite and leonite. Polyhalite is currently considered a waste mineral in the Designated Potash Area (DPA) and underlies approximately 27,000 square miles in New Mexico and Texas. However, it is the primary source for Intercontinental Potash Corp.'s Ochoa mine southeast of the DPA.

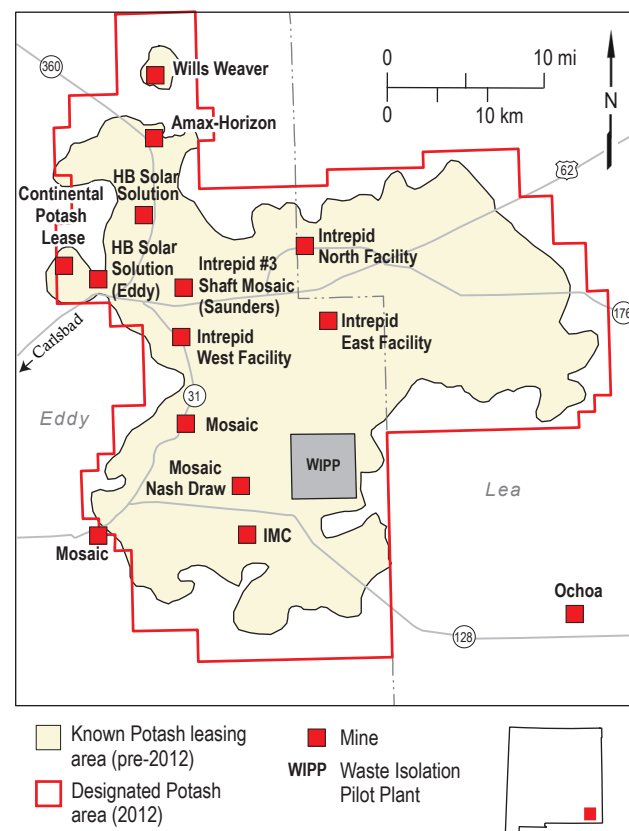| Compound or mineral	Chemical formula	Potassium oxide %
Potassium oxide	K_2O	100
Sylvite	KCl	63.17
Sylvinite	KCl + NaCl	10-35
Langbeinite	$K_2SO_4 \cdot 2MgSO_4$	22.7
Carnallite	$KCl \cdot MgCL_2 \cdot 6H_2O$	16.95
Kainite	$KCl \cdot MgSO_4 \cdot 3H_2O$	18.92
Leonite	$K_4SO_4 \cdot MgSO_4 \cdot 4H_2O$	25.69
Polyhalite	$K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$	15.62

Figure 26. Potash facilities in Eddy and Lea Counties, southeastern New Mexico, showing the general outline of the Designated Potash Area (DPA) (after Barker and Austin, 1999). WIPP=Waste Isolation Pilot Plant.

When Cargill Crop Nutrition merged with IMC Global in October 2004, Mosaic Co. was born and is now the world's largest potash and phosphate producer. The total reserves at Mosaic include an estimated total of 101 million tons of potash ore in three mining beds at thickness ranging from 4.5 ft to more than 11 ft. These ore reserves are estimated to yield 5 million short tons of concentrate from sylvinite with an average grade of 60% K_2O and 18 million short tons of langbeinite concentrate with an average grade of approximately 22% K_2O. These reserves are expected to last 15–23 years.

Intrepid Mining NM LLC announced on March 1, 2004 it completed the acquisition of all of the assets of Mississippi Potash, Inc. and Eddy Potash, Inc. Since 2004, Intrepid Mining NM LLC has spent approximately $231 million in upgrading the underground mines and processing facilities. Intrepid employs approximately 650 people at 3 facilities in New Mexico. The West Facility (NMED0028), which consists of a potash mine and refinery was originally built in 1929 by U.S. Potash and has an annual production capacity of approximately 538,000 short tons of red potash. The East Facility (NMED0026), which has an annual production capacity of approximately 560,000 short tons of white potash, consists of a potash mine, refinery, and compaction plant. The North Facility (NMED0032) consists of a granular compaction plant and storage facilities. Two types of ore are processed. Flotation is used to produce red potash and hot leach crystallization is used to produce the higher purity white potash.

Potash is being produced by solution mining at the HB Solar Solution mine (NMED0033). Saline brines are injected into the old underground workings (formerly the Eddy mine) and potash-rich solutions are extracted. The HB Solar Solution mine has 5 million short tons of proven and probable reserves and an estimated mine life of 28 years.

Potash-bearing evaporites occur in Ochoan (Upper Permian) marine rocks in the Delaware Basin portion of the Permian Basin of west Texas and southeast New Mexico (Fig. 27). The Ochoan is divided into four formations, of which the second oldest, the Salado Formation, contains minable potash. The Salado, up to a maximum of 2,100 ft thick, is an evaporite sequence dominated by 650–1,300 ft of halite and muddy halite in the DPA. It hosts 12 ore-bearing zones; 11 in the middle or McNutt Member, and one in the upper member. The McNutt Member of the Salado Formation dips about 1 degree to the east within the district and is about 400 ft thick (Fig. 28).

Potash ore zones are 3–10 ft thick (Fig. 29) and are laterally consistent except where interrupted by barren halite, collapse features, and igneous dikes. Commercial deposits were created in some localities by magnesium-undersaturated fluids moving through the zones, but in other areas late fluids dissolved ore, producing barren halite (salt horses). The McNutt Member is absent in the subsurface just west of the present mines. A typical mixed ore from the Salado in the district contains 60% halite and 30% sylvite (usually together as sylvinite), with 5% langbeinite, 2% polyhalite, and 2% insolubles.

In a recent development, Intercontinental Potash Corp. (IPC) has announced their intention to open an underground mine a few miles southeast of the DPA (Ochoa, NMLE0017), consisting of polyhalite from the Tamarisk Member of the Rustler Formation (Fig. 30). Polyhalite (Table 19) is a low sodium and chloride mineral that is of particularly high value for some agricultural crops sensitive to those ions. IPC's holdings are in eight townships and the depth of polyhalite bed to be mined is from 1,200 ft on the west side to 2,200 ft on the east side of the properties.
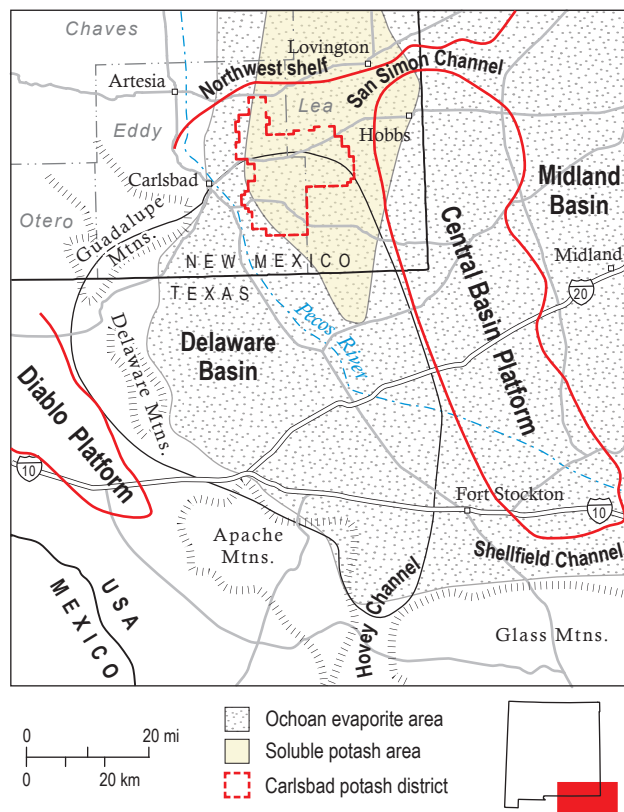

Figure 27. Location of the Carlsbad Potash district in southwestern New Mexico and its relation to the regional subsurface geology (after Barker and Austin, 1999 and Chemrox Technologies and Gustavson Associates LLC, 2009).
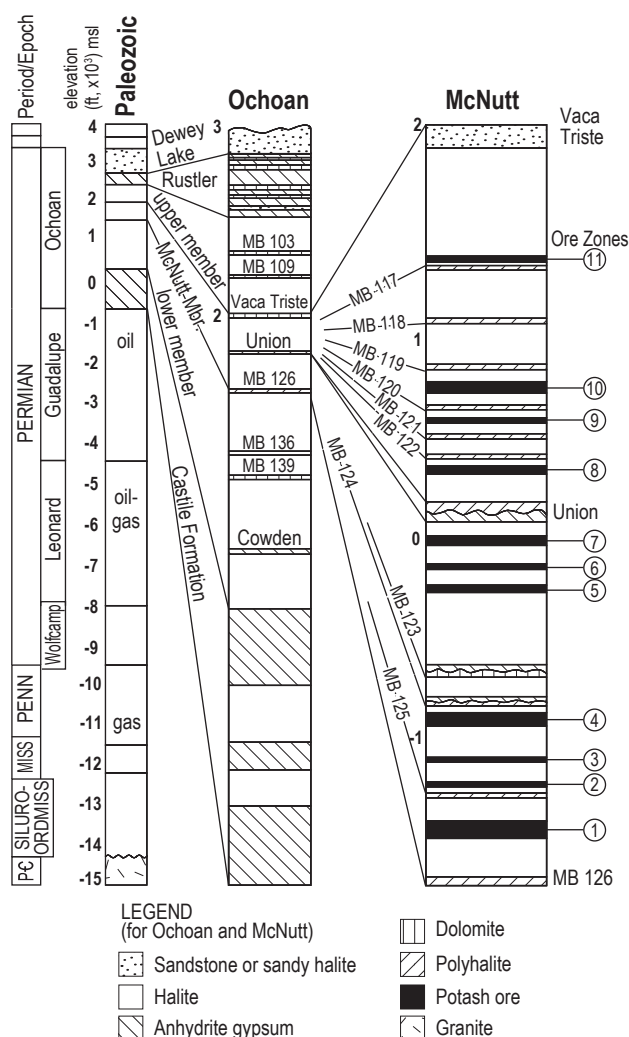
Figure 28. Regional stratigraphic column with expanded sections of the Ochoan evaporite and McNutt Member of the Salado (after Griswold, 1982 and Barker and Austin, 1999). Numbers 1–11 are ore zones. MB = marker bed.

Figure 29. Underground operations at Mosaic potash mine, Carlsbad. *Photo by Virginia T. McLemore.*

With an average minable thickness of 7 ft, ICP's Ochoa Project is calculated to contain 399,600 short tons of ore. A minimum minable thickness of 6 ft (1.8 m) and an 85% polyhalite grade is assumed (Chemrox Technologies and Gustavson Associates, LLC, 2009).

Pozzolans and Supplementary Cementitious Materials

Pozzolans by definition are 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 (Jackson, 1997). Pozzolans are used in cement and concrete.

Pozzolans fall into two categories, either natural or artificial, depending on their provenance. Natural pozzolans are either raw or calcined natural materials, such as volcanic ash, opaline chert, tuff, some shale, and some diatomaceous earth that have pozzolanic properties. The amount of amorphous or unstructured material often determines the reactivity of the natural pozzolans.

There are three categories of natural pozzolans: 1) volcanic ash, called tuff when indurated, in which the amorphous constituent is a glass produced by rapid cooling of magma; 2) those derived from rocks or earth in which the silica is mainly opal, and diatomaceous earth; and 3) some clays and shales. Volcanic glass has a disordered structure because of the relatively quick cooling time and tends to have a porous texture created by escaping gases. Hydrothermally altered volcanic glass can become zeolitic, and when finely ground, zeolitic tuffs become reactive with lime.

For a more complete discussion of natural and artificial pozzolans, the reader is referred to Hoffman (2006). The only pozzolan produced and marketed in New Mexico is fly ash, an artificial pozzolan.

Fly ash is a by-product of burning finely ground coal either for industrial application or production of electricity. Fly ash has pozzolanic properties making it saleable as a mineral additive to concrete. During the coal combustion process to produce electricity, the non-combustible material in coal becomes molten and can remain in the combustion chamber as slag, or drops to the bottom of the combustion chamber as bottom ash, or the lighter particulate matter is carried out of the chamber in the flue gasses, as fly ash. This molten material moves upward with the flue gas,

Geologic units of the Ochoan project **Units of the Rustler Formation**

System Series	Formation	Member
TRIASSIC	Santa Rosa	
	Dewey Lake	
PERMIAN (Ochoan)	Rustler	Forty-niner
		Magenta Dolomite
		Tamarisk
		Culebra Dolomite
		Los Medanos
	Salado	
	Castile	

Legend:
- Anhydrite
- Micisteria
- Barditaite
- Halite
- Dolomite

Note: Units on the right labeled
A- are dominant by anhydrite
H- are halite dominante
M- are mudstone or clay

Units of the Rustler Formation (right column, top to bottom): Dewey Lake Formation; Forty-niner Member (A-5, M-5, H-4, A-4); Magenta Dolomite Member; Tamarisk Member (A-3, M-3, H-3, A-2); Culebra Dolomite Member; Los Medanos Member (M-2, H-2, A-1, M-1, H-1), Dumal Member; Salado Formation.

Figure 30. Stratigraphy at the Ochoa polyhalite project (NMLE0017) area (after Chemrox Technologies and Gustavson Associates LLC, 2009).

cooling rapidly with the air movement giving 60% of the particles a spherical shape. Electrostatic precipitators (ESPs) or mechanical precipitators such as bag houses or cyclones, capture the fly ash from the flue gas. ESPs have a 99+% efficiency in capturing fly ash and are the most common anti-pollution devices used by generating stations. The ratio of bottom to fly ash is dependent on the burner and boiler types with fly ash percentage varying from 65–85%. Fly ash consists mainly of SiO_2, Al_2O_3 and Fe_2O_3. The chemical makeup of the fly ash is dependent on the type of coal and the amount of unburned carbon (loss on ignition, LOI) remaining in the fly ash is dependent on the combustion process. The type of flue gas desulfurization method can affect the characteristics of the fly ash. Placement of a dry scrubber system in line before the fly ash is captured coats the fly ash with the desulfurization byproducts ($CaO + CaSO_4$) and cannot be used as a pozzolan.

Three major coal-fired generating stations in New Mexico produce fly ash that is marketed by Salt Rivers Materials Group (SRMG), Scottsdale, Arizona. Characteristics that make fly ash saleable are its pozzolanic properties that can offset the amount of

cement required for concrete. Other characteristics fly ash imparts to concrete are increased durability, lower heat of hydration, ease of pour, lower permeability, and strength and durability over time. Fly ash from all three generating stations is Class F fly ash that has a minimum of 70% $SiO_2 + Al_2O_3 + Fe_2O_3$ composition (American Society for Testing Materials, 2003). Not all the fly ash captured meets the specifications as a pozzolan. Size is an important factor and the coarser material (>44 µm) is not suitable as a pozzolanic material. To meet ASTM C618 (American Society for Testing Materials, 2003) specifications, no more than 34% of the fly ash can be retained on a 45 µm (325-mesh) sieve. To ensure the consistency of the fly ash. SRMG has classifiers at the Four Corners, and San Juan generating stations to control the size characteristics of their product. They also do continual testing of the fly ash coming from the different generating units to ensure consistency in the percent LOI, fineness, and color. Of the 2–3 million short tons of fly ash produced at New Mexico generating stations, approximately 10–30% is used as a pozzolan (Dale Diulus, SRMG, 2011, personal communication).

The unused fly ash from the San Juan power plant is returned to the adjacent coal mine for use in stabilization and reclamation; the Four Corners fly ash goes to ponds and landfills (Dale Diulus, SRMG, 2011 personal communication). Over half of the fly ash sold from both San Juan and Four Corners is trucked to a rail load out facility near Gallup. At the Gallup facility, SMRG has the capability to mix material from both power plants and retest to meet ASTM C618 standards. The remaining fly ash from these plants near Farmington is trucked to the job site or silos near population centers. SRMG has storage facilities in California, Arizona, New Mexico, and Colorado (Salt River Materials Group, 2011). Escalante fly ash can be shipped by rail as this power plant is along a spur to the main line of Burlington Northern-Santa Fe railroad, or trucked via I-40.

Primary use of New Mexico fly ash is in concrete and road construction. Departments of Transportation in New Mexico, Arizona, Colorado, Wyoming, and Utah require 20% minimum Class F fly ash when using aggregates that are reactive or potentially reactive to prevent alkali-silica reaction (Dockter and Jagiella, 2005). Alkali-silica reaction (ASR) is a common problem in the Southwest because of the predominance of reactive material in aggregate, such as opal, chalcedony, or siliceous shales. ASR occurs when silicate minerals react with alkali metal ions (Na_2O and K_2O) in Portland cement paste to form a gel. With moisture, the gel swells, causing expansion and cracking of the concrete around individual aggregate.

SRMG also markets the hollow, glassy sphere portion of the fly ash called cenospheres from the Four Corners generating station. Cenospheres are lightweight, have a high compressive strength, and high melting point. These glassy spheres have many uses as fillers in paint, plastics, and industrial putty, as well as acoustical insulation. The Four Corners plant produces 5–10,000 short tons of cenospheres annually, on a wet basis (Dale Diulus, SMRG, 2011, personal communication).

Pumice, Pumicite, and Scoria (Volcanic Cinder)

Pumice and pumicite

Pumice and pumicite are pyroclastic materials produced by the rapid expansion of dissolved gases in a viscous siliceous magma generally ranging from rhyolite to dacite composition. Pumiceous materials are inert to most chemicals and are composed primarily of SiO_2. Pumicite originates when dissolved gases in the viscous magma produce a froth or a large quantity of bubbles in a short period of time followed by rapid rupture of the vesicles. If fewer bubbles develop in the magma, and the glass vesicle walls are allowed to solidify rapidly enough to prevent collapse, then pumice will form. Vesicles can range in size from less than 0.01 mm to over 20 mm.

The principal pumiceous deposits in New Mexico are used in the construction industry and occur within the volcanic units related to the resurgent Valles caldera in the Jemez Mountains in north-central New Mexico (Fig. 31, Table 20). Minable units include: 1) the 0.17 Ma El Cajete Pumice of the Valles Rhyolite and 2) the 1.45 Ma Guaje Pumice Bed, within the Otowi Member of the Bandelier Tuff in Santa Fe, Sandoval, Rio Arriba, and Los Alamos counties (Hoffer, 1994). The Las Conchas/El Cajete mine (NMSA0313) produced both locatable and saleable pumice (Fig. 32). Three other mines produced from the Guaje Pumice Bed: the Guaje Canyon (NMSF0163), Rocky Mountain (NMRA0362), and U.S. Forest Service mines (NMSA0320). The Guaje Pumice Bed is exposed in several road cuts east of Los Alamos (Fig. 33) and there are many abandoned pumice mines on the east flank of the Jemez Mountains (Fig. 34).

Pumiceous lapilli tuffs in East Grants Ridge, northeast of Grants, were formerly a source of high-quality abrasive pumice. The tuff consists of lapilli and blocks of pumice, rhyolite, and exotic rock fragments in a matrix of white ash (Kerr and Wilcox, 1963; McLemore, 2013b). Pumice was produced from East Grants Ridge from 1939 until 1952, when U.S. Gypsum Co. purchased the property from Pumice Corporation of America (Barker et al., 1996). U.S. Gypsum Co. abandoned the pumice operations to open the perlite quarry. Pumice production amounted to 59,563 short tons from 1947–1952, worth $1,008,281 (McLemore, 2013a); additional unrecorded production occurred during World War II from 1941–1943 and again in 1953–1967. A pumice mill was built below the mine, where gravity separation techniques were employed to separate the pumice from the rhyolite, exotic rock fragments, and ash (Weber, 1965b). Although pumice resources remain on East Grants Ridge, most lie underneath the basalt flow, which would be difficult and expensive to extract. Similar pumiceous tuffs in adjacent areas have been described by Hunt (1938).
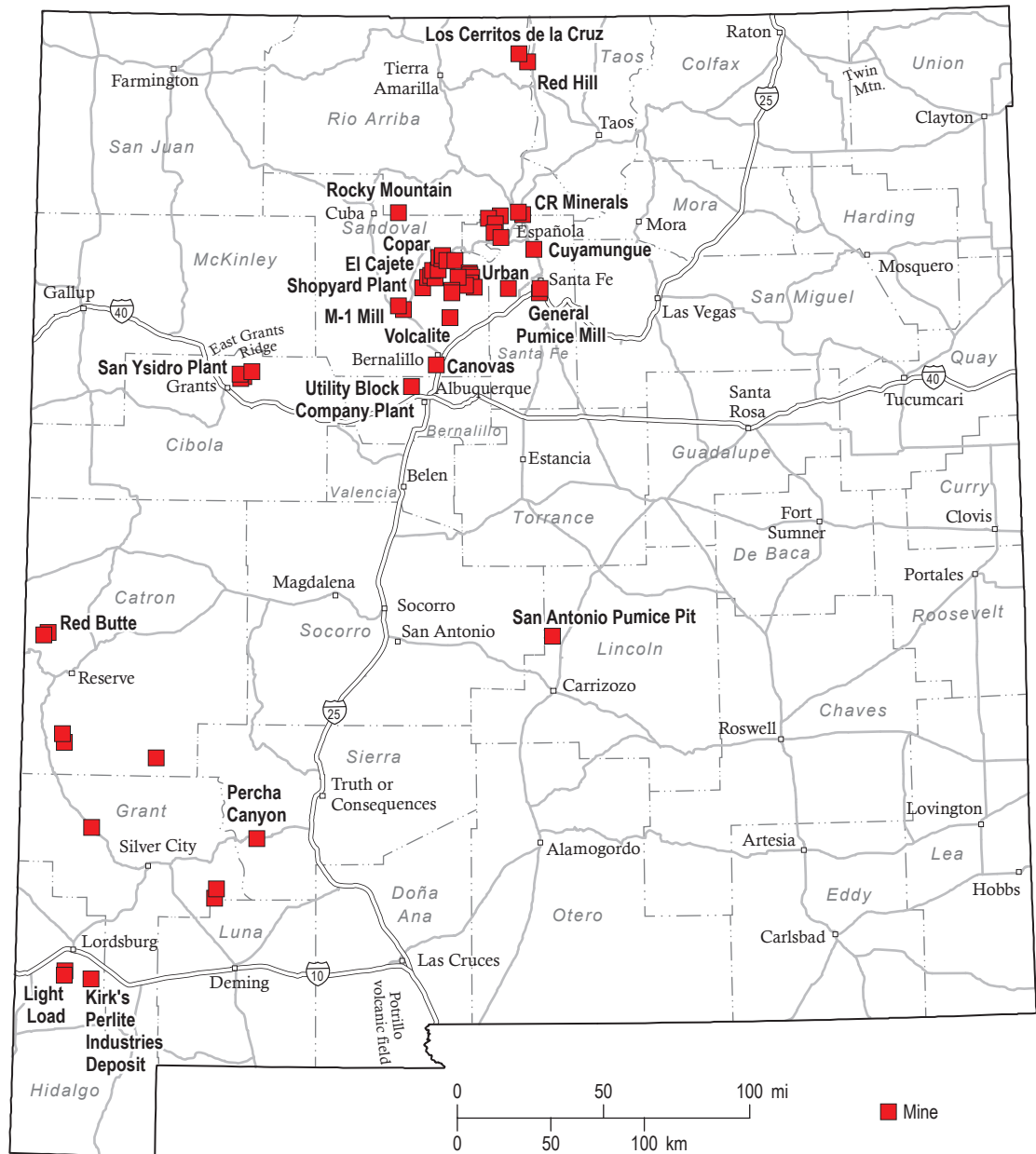
Figure 31. Index map showing the major pumiceous deposits and occurrences in New Mexico (modified from Hoffer, 1994).

Table 20. Pumice and pumicite occurrences from mines in New Mexico (from Hoffer, 1994; New Mexico Mines Database). Datum is NAD27.

Mine ID	Mine name	County	Latitude	Longitude	Comments on production
NMBE0029	Utility Block Company Plant	Bernalillo	35.1669972	106.736247	active
NMCA0037	Red Butte	Catron	33.9167923	108.911039	
NMCA0180	Red Butte	Catron	33.9191667	108.898333	
NMCA0238	unknown	Catron	33.4079091	108.799611	
NMCA0237	unknown	Catron	33.308946	108.243931	
NMCA0236	unknown	Catron	33.3804798	108.796945	
NMCI0175	pumice	Cibola	35.207458	107.752169	1946–1952
NMCI0172	pumice	Cibola	35.206494	107.764298	1946–1952
NMCI0271	pumice	Cibola	35.2116524	107.764352	
NMCI0170	pumice	Cibola	35.207618	107.769226	1946–1952
NMCI0171	pumice	Cibola	35.203793	107.765293	1946–1952
NMCI0174	pumice	Cibola	35.2189382	107.77163	
NMCI0173	pumice mill	Cibola	35.204456	107.767823	1946–1952

Table 20. Continued.

Mine ID	Mine name	County	Latitude	Longitude	Comments on production
NMCI0270	unknown	Cibolia	35.2332812	107.716386	
NMGR0501	unknown	Grant	32.626058	107.88006	
NMGR0502	unknown	Grant	32.669149	107.879307	
NMGR0331	unknown	Grant	32.9623586	108.619686	
NMHI0086	Kirk's Perlite Industries Deposit	Hidalgo	32.2044444	108.600278	1950
NMHI0330	Light Load	Hidalgo	32.22517	108.75136	1950
NMHI0095	unknown	Hidalgo	32.2392906	108.753155	1950
NMRA0364	Copar	Rio Arriba	35.9623028	106.218408	
NMRA0363	CR Minerals	Rio Arriba	36.0188583	106.091968	active
NMRA0365	Espanola Plant	Rio Arriba	36.0097668	106.063984	
NMRA0366	General Pumice	Rio Arriba	36.0085375	106.2013999	closed
NMRA0371	Los Cerritos De La Cruz	Rio Arriba	36.8188929	106.069018	
NMRA0150	Red Hill	Rio Arriba	36.7758	106.0158	active
NMRA0296	Rocky Mountain	Rio Arriba	36.0225	106.816667	active
NMRA0362	Rocky Mountain	Rio Arriba	36.003144	106.191131	active
NMSA0316	Caldwell	Sandoval	35.7926126	106.510496	closed
NMSA0296	Canovas	Sandoval	35.2826706	106.570574	occurrence
NMSA0317	Cochiti Pumice Pit No. 1	Sandoval	35.656313	106.360624	closed
NMSA0318	Copar South Pit	Sandoval	35.7634659	106.579951	closed
NMSA0319	El Cajete	Sandoval	35.8173733	106.571289	active
NMSA0349	Esquire	Sandoval	35.750689	106.608392	
NMSA0331	Gazebo	Sandoval	35.8126792	106.562203	
NMSA0313	Las Conchas/El Cajete	Sandoval	35.8171743	106.543947	active
NMSA0344	M-1 Mill	Sandoval	35.5561362	106.792888	
NMSA0342	pumice	Sandoval	35.71535	106.6244	
NMSA0327	pumice	Sandoval	35.7161767	106.630935	
NMSA0337	pumice	Sandoval	35.6389968	106.486993	
NMSA0339	pumice	Sandoval	35.712343	106.387192	
NMSA0340	pumice	Sandoval	35.7099884	106.385846	
NMSA0338	pumice	Sandoval	35.66945	106.4102	
NMSA0332	Pumice Group	Sandoval	35.6361115	106.48858	
NMSA0333	Pumice Group	Sandoval	35.6472826	106.487988	
NMSA0336	Pumice Group	Sandoval	35.6389968	106.488591	
NMSA0335	Pumice Group	Sandoval	35.7185658	106.389701	
NMSA0334	Pumice Group	Sandoval	35.7089209	106.38309	
NMSA0345	San Ysidro Plant	Sandoval	35.5460917	106.780608	
NMSA0341	Santa Barbara	Sandoval	35.7072126	106.39123	
NMSA0347	Santa Clara Canyon	Sandoval	35.9929878	106.257382	occurrence
NMSA0326	Shopyard Plant	Sandoval	35.6616816	106.662463	
NMSA0329	U.S. Forest Service	Sandoval	35.7193413	106.604361	
NMSA0320	U.S. Forest Service	Sandoval	35.7250204	106.61888	closed
NMSA0348	unknown	Sandoval	35.7059453	106.451976	occurrence
NMSA0346	Urban	Sandoval	35.6741053	106.378742	
NMSA0328	Utility Block	Sandoval	35.7088586	106.6151	
NMSA0330	Valle Grande	Sandoval	35.796947	106.462873	
NMSA0343	Volcalite	Sandoval	35.4987004	106.5007262	
NMSF0038	Cerrito Pelado	Santa Fe	35.6540253	106.145356	active
NMSF0160	CR Minerals Santa Fe Mill	Santa Fe	35.6468192	105.957703	closed
NMSF0161	Cuyamungue	Santa Fe	35.8485595	105.984463	closed
NMSF0162	General Pumice Mill	Santa Fe	35.6595228	105.955435	closed
NMSF0163	Guaje Canyon	Santa Fe	35.9187475	106.221793	closed
NMSF0166	Whitte Eagle	Santa Fe	35.9104186	106.203003	occurrence
NMSI1772	Percha Canyon	Sierra	32.9175507	107.644739	occurrence
NMSI0389	unknown	Sierra			Exact location unknown
NMSO0578	San Antonio Pumice Pit	Socorro			occurrence
NMVA0015	unknown	Valencia			Exact location unknown

Figure 32. Guaje Pumice Bed exposed in a now abandoned mine in the Jemez district. *Photo by George S. Austin.*

Figure 33. El Cajete Pumice Bed exposed in a road cut on the eastern flank of the Jemez Mountains (NMSA0313). *Photo by George S. Austin.*

Elsewhere in New Mexico, there has been little development of commercial deposits. Scattered lenses of water-laid lump pumice and pumicite are poorly exposed in low bluffs adjoining the Rio Grande from east-northeast of San Antonio southward to beyond Fort Craig, Socorro County. Bedded pumiceous tuff northwest of Magdalena, Socorro County, has apparently yielded small test lots of rather impure pumice. A deposit south of Lordsburg was a source of small amounts of pumice aggregate mined in the 1950s (Weber, 1965b).

Scoria (volcanic cinder)

Scoria is a cellular, dark-colored volcanic rock of basic composition (commonly basalt or basaltic andesite). In industrial usage, scoria is also known as volcanic cinders. In addition to compositional differences, scoria differs from pumice in its darker color, higher density, coarser vesicles, more crystalline texture, and generally higher strength. Uses include natural lightweight concrete aggregate, road surfacing aggregate, and railroad ballast. As a constituent of lightweight concrete, scoria characteristically provides less weight reduction accompanied by higher

strength than pumice. Cinder for these purposes must meet the same specifications as any other aggregate material, including abrasion resistance, immersion disintegration, and aggregate degradation. Cinders that qualify have a higher density than those used for lightweight concrete. The friable, fragmental nature of cinder deposits results in much lower production costs than from nonvesicular rock that must be crushed (Presley, 2006).

By heating scoria in the laboratory for variable amounts of time, the vent-centered color pattern of a scoria cone can be duplicated. The typical pattern observed is dark-reddish-brown scoria in the vent zone, where maximum heat exposure occurs, brownish to dark-gray scoria at intermediate distances from the vent, and very dark gray to black scoria in perimeter zones, where volcanic ejecta are well insulated from the vent. As the demand for dark-reddish-brown scoria for landscaping aggregate expands, the value of being able to predict color variation in a particular deposit becomes more important (Osburn, 1982).

Scoria deposits, found throughout New Mexico, are mostly associated with cinder cones of Quaternary age (Osburn, 1980, 1982). Resources are exceedingly large; production is in Table 3. Noteworthy variations in form occur in many of New Mexico's scoria cones. Strong winds during the eruption produce reduced deposition on the windward side of the cone; the resultant lopsided form is common in the cones of the Potrillo volcanic field in the Aden district (DIS023) south-central New Mexico. Twin Mountain in the Folsom district (DIS248) northeast New Mexico erupted from a

Figure 34. El Cajete Pumice exposed in one of the many abandoned mines on the east flank of the Jemez Mountains. *Photo by George S. Austin.*

fissure vent to form an elongate cone. Both sorting and grain size of the tephra reflect the sedimentary nature of the deposit. All volcanic ejecta emanate from a point source, the vent. Tephra in the vent are the largest and most poorly sorted in the deposit. Agglutinating also occurs in the vent area. In contrast, at the perimeter of the cone, scoria from each eruptive pulse is well sorted and graded. The average grain size is small, with the exception of an occasional block or bomb (Osburn, 1982).

The large number of scoria or cinder cones in New Mexico and the relative ease of scoria mining make scoria an attractive source of lightweight aggregate. The majority of New Mexico's scoria output is used to make concrete to produce strong, lightweight cinder blocks.

Pyrophyllite

Pyrophyllite is a hydrous aluminum silicate ($Al_2O_3 \cdot 4SiO_2 \cdot H_2O$) that rarely exists in large enough concentrations to be economic and is normally associated with accessory minerals such as quartz, kaolin, diaspore, corundum, andalusite, boehmite, sericite, chlorite, and alunite. Pyrophyllite ores also can include iron-containing impurities such as pyrite, hematite, and limonite; therefore, different mineral samples that are classified as pyrophyllite can contain various combinations of accessory minerals and have different chemical compositions.

Pyrophyllite ores have been used for many years in a range of applications. The quality requirements, however, have recently become much stricter as a result of competition from other minerals. Consumption is also decreasing for a number of reasons, including advances in paper-manufacturing techniques, in which pyrophyllite is used as a filler; decreases in the number of dustings with insecticides because of improvements in agrochemicals; and the trend toward the use of longer-lasting bricks in the refractory industry (Hida and Kitagawa, 2006).

Northrop (1996) reports minor New Mexico occurrences of pyrophyllite in a zone extending from the Merrimac mine (NMDA0081) to the Black Prince mine (NMDA0072) in the Organ district, Doña Ana County; in Todilto Park, McKinley County; in the Petaca district (DIS148), Rio Arriba County; and in the Harding mine (NMTA0015), Picuris district (DIS236) of Taos County. Pyrophyllite also is found associated with alunite in the acid sulfate areas in New Mexico described

above and in McLemore and Lueth (2017), especially Steeple Rock (DIS066) and San Jose (DIS226). Pyrophyllite may also occur in or near some of the kyanite deposits in the Petaca district in the Tusas Mountains. None of these deposits are economic.

Rare Earth Elements (REE)

Rare earth elements (REE) include the 15 lanthanide elements (atomic numbers 57–71), yttrium (Y, atomic number 39), and scandium (Sc, atomic number 21) and are commonly divided into two chemical groups, the light REE (lanthanum through europium) and the heavy REE (gadolinium through lutetium and yttrium). REE are lithophile elements (or elements enriched in the crust) that have similar physical and chemical properties and, therefore, occur together in nature. However, REE are not always concentrated in easily mined economic deposits and only a few deposits in the world account for current production (Committee on Critical Mineral Impacts of the U.S. Economy, 2008; Hedrick, 2009). Thorium (Th), uranium (U), niobium (Nb) and other elements are typically found with REE; most deposits are radioactive because of their thorium and uranium content. REE have many highly specialized applications in industry, especially in electronic devices, and for many applications there are no other known substitutes (McLemore, 2011b, 2015).

Table 21. REE production from New Mexico deposits.

District ID	Name	Production	Reference
DIS092	Gallinas Mountains	146,000 lbs of bastnaesite concentrate from fluorite production from veins	Griswold (1959), Adams (1965), McLemore (2010a)
DIS148	Petaca district	112 lbs of samarskite, few hundred lbs of monazite, 12,000 lbs of Ta-Nb-REE ore from pegmatites	Bingler (1968), Jahns (1946)
DIS162	Elk Mtn-Spring Mtn	500 lbs of Ta-U-REE concentrate from pegmatites	Jahns (1946), Holmquist (1946)
DIS164	Rociada	Several thousand tons of REE-Ta ore from pegmatites	Sheffer and Goldsmith (1969), Jahns (1953)
DIS166	Tecolote	$10,000 worth of beryl, tantalite-columbite and monazite from pegmatites	Redmund (1961)
DIS058	Gold Hill	Unknown production in 1950s from pegmatites	Gillerman (1964)

Table 22. Mining districts in New Mexico containing REE. GPM=Great Plains Margin deposits (see McLemore and Lueth (2016) for a description of the types of deposits). See Mclemore (2017) for descriptions.

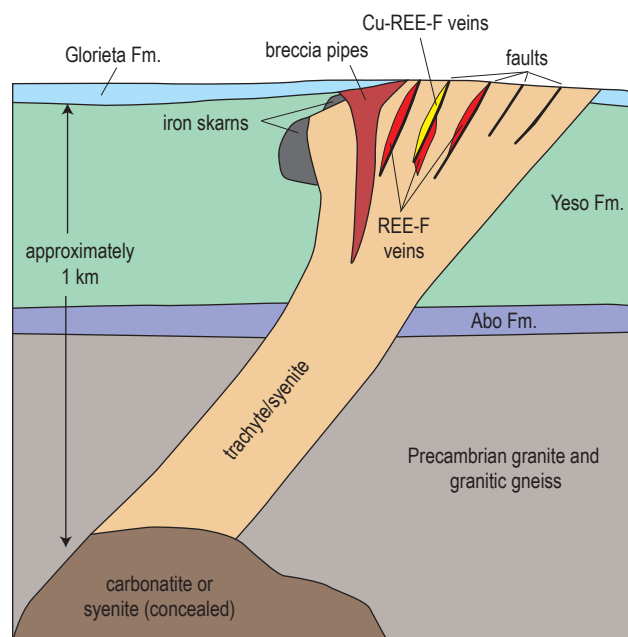| District	Age of REE deposits	Type of REE deposit
Bernalillo County		
Monte Largo	Cambrian-Ordovician	Carbonatite
Herrera Ranch	Cretaceous	Beach placer sandstone
Tijeras Canyon	Proterozoic	Pegmatite
Cibola County		
Zuni Mtns (Copper Hill, Coopperton, Montezuma, New Cornwall)	Proterozoic	REE-Th-U veins in alkaline rocks
Colfax County		
Laughlin Peak (Chico Hills) Taos	32.3–22 Ma	GPM (REE-U-Th veins), carbonatite
Cimarron	Cretaceous	Beach placer sandstone
Doña Ana County		
Organ (Mineral Hill, Bishops Cap, Organ, Gold Camp, Modoc, South Canyon, Texas)	34.5 Ma	REE-Th-U veins in alkaline rocks
Grant County		
Black Hawk (Bullard Peak)	Proterozoic	REE-Th-U veins in alkaline rocks
Bound Ranch (Langford Hills, Separ)	Proterozoic	polymetallic vein
Burro Mtns (Tyrone)	Proterozoic	REE-Th-U veins in alkaline rocks
Gold Hill (Camp Bobcat)	Proterozoic	pegmatite
Telegraph (Red Rock, Anderson, Ash Creek, Wild Horse Mesa, Clarks Peak)	Cambrian-Ordovician	Disseminated Y-Zr deposits in alkaline rocks
White Signal (Cow Spring)	Proterozoic, Cambrian-Ordovician	Pegmatites, REE-Th-U veins in alkaline rocks
Hidalgo County		
Granite Gap (San Simon)	33.2 Ma	Carbonate-hosted Pb-Zn, skarn
Lordsburg (Animas)	Laramide	Bastnaesite
Lincoln County		
Capitan Mtns	34.0 Ma	GPM (REE-U-Th veins)
Gallinas (Red Cloud)	30.7 Ma	GPM (REE-U-Th veins)
Jicarilla (Ancho)	38.2 Ma	GPM (REE-Th-U veins in alkaline rocks)
Tecolote Hills	Tertiary	GPM (REE-Th-U veins in alkaline rocks)
Luna County		
Florida Mtns	Cambrian-Ordovician	Disseminated Y-Zr deposits in alkaline rocks
McKinley County		
Gallup (Torriva anticline)	Cretaceous	Beach placer sandstone
Miguel Creek Dome	Cretaceous	Beach placer sandstone
Standing Rock	Cretaceous	Beach placer sandstone
Farr Ranch	Cretaceous	Beach placer sandstone
Otero County		
Cornudas Mtns (Wind Mtn)	36.3 Ma	GPM (REE-U-Th veins, disseminated Y-Zr deposits in alkaline rocks)
Hueco Mtns	34.5–34.7 Ma	GPM (disseminated Y-Zr deposits in alkaline rocks)
Otero County		
Pajarito	1230–1140 Ma	Disseminated Y-Zr deposits in alkaline rocks
Three Rivers (Apache No. 1, White Mtn)	~45.3 Ma	REE anomalies in ground water
Rio Arriba County		
Bromide No. 2	1750 Ma	Precambrian veins/replacement
Hopewell (Headstone)	~1467 Ma	Precambrian veins/replacement
Ojo Caliente	Proterozoic	Pegmatite
Petaca	Proterozoic	Pegmatite
Sandoval County		
B.P.Hovey Ranch	Cretaceous	Beach placer sandstone
Herrera Ranch	Cretaceous	Beach placer sandstone
San Juan County		
Sanostee	Cretaceous	Beach placer sandstone
Farmington (Hogback)	Cretaceous	Beach placer sandstone
Toadlena	Cretaceous	Beach placer sandstone
San Miguel County		
Elk Mtn-Spring Mtn	Proterozoic	Pegmatite, disseminated Y-Zr deposits in alkaline rocks
El Porvenir	Proterozoic	Pegmatite
Rociada	<1720 Ma,	Pegmatite
Tecolote (Villanueva, Mineral Hill, Rio de la Vaca)	Proterozoic	Pegmatite
Santa Fe County		
Nambe (Aspen Ranch)	Proterozoic	Pegmatites
Sierra County		
Caballo Mtns (Palomas Gap, Red Hills)	Cambrian-Ordovician	REE-Th-U veins in alkaline rocks
Cuchillo (Cuchillo Negro, Chise, Iron Mtn, Limestone)	48.8 Ma	Beach placer sandstone
Salinas Peak (Good Fortune Creek, Bearden Canyon, Bear Den)	Tertiary	RGR
Taylor Creek	Tertiary	Tin-bearing rhyolites
Socorro County		
Chupadera Mtns (Coyote Hill)	Cambrian-Ordovician	Carbonatite, REE-Th-U veins in alkaline rocks
Lemitar Mtns	449 Ma	Carbonatite, REE-Th-U veins in alkaline rocks
Ojo Caliente No. 2	Tertiary	Be veins in rhyolite
Taos County		
La Cueva (Costilla Creek)	Proterozoic	Pegmatite, REE-Th-U veins
Picuris (Copper Hill, Harding)	Proterozoic	Pegmatite
Torrance County		
Lobo Hill	518 Ma	Carbonatite, REE-Th-U veins in alkaline rocks
Pedernal Hills	REE are 469 Ma	REE-Th-U veins in alkaline rocks

Types of REE deposits in New Mexico

In New Mexico, REE have been produced from a few deposits. Production form REE deposits in New Mexico is in Table 21 and REE deposits found in New Mexico are listed in Table 22, shown in Figure 35, and briefly described below and in McLemore and Lueth (2017).

Alkaline igneous rocks

Many alkaline igneous rocks, typically of syenite or granite composition, have higher concentrations of REE then other types of igneous rocks. Alkaline rocks are defined as rocks with higher concentrations of alkalis (sodium and potassium) than can be accommodated only in feldspars, with the excess alkalis found in alkali-bearing minerals, such as feldspathoids, pyroxenes, and amphiboles (Shand, 1951; LeMaitre, 1989, 2002). Some disseminated REE deposits have been found in alkaline rocks, but known REE deposits in these rocks are low grade (Castor and Hedrick, 2006). In these deposits, REE, zirconium, beryllium, niobium, tantalum, and other elements are found disseminated in the igneous rock.

Carbonatites

Carbonatites are carbonate-rich rocks containing more than 50% magmatic carbonate minerals, less than 20% SiO_2, are of apparent magmatic derivation

Figure 35. REE deposits in New Mexico (McLemore, 2011b, 2015).

Figure 36. Schematic sketch showing the inferred relationship of thorium-REE veins to alkaline rocks and carbonatites in the Gallinas Mountains (from McLemore, 2010b).

Figure 37. Bastnaesite from the Red Cloud mine, Gallinas Mountains. Crystal is approximately 1 cm long (NMLI0040). *Photo by Virginia T. McLemore.*

(LeMaitre, 1998, 2002), and typically found in zoned complexes consisting of alkaline igneous and/or carbonatite stocks, ring dikes, and cone sheets (Fig. 36). Carbonatites typically contain disseminated REE, uranium, thorium, niobium, tantalum, zirconium, hafnium, iron, titanium, vanadium, copper, apatite, magnetite, vermiculite, and barite (Singer, 2000). The Mountain Pass carbonatite in California is the largest economic carbonatite in North America, where as much as 15% bastnaesite ($(Ce, La)(CO_3)F$) was produced from 1954–2002 and starting again in 2012 to 2016. There has been no REE production from any of the New Mexico carbonatites.

REE-thorium-uranium hydrothermal veins

REE-thorium-uranium vein and breccia deposits (McLemore, 2010b) consist of various thorium and REE minerals found in hydrothermal veins and are commonly associated with alkaline igneous rocks and carbonatites. Thorium-REE vein and breccia deposits are typically found as tabular bodies, narrow lenses, and breccia zones along faults, fractures and shear zones. They are 1–1,000 ft long, as much as 10 ft wide, and can be discontinuous, with varying grades and mineralogies. Thorium-REE veins are typically associated with carbonatites and alkaline rocks (Fig. 36). REE-veins in the Gallinas Mountains are being evaluated for their REE potential, where bastnaesite (Fig. 37) is the predominant mineral of interest.

This class includes the REE-thorium-uranium-bearing episyenites found in the Caballo, Burro, Zuni, and Nacimiento Mountains, Pedernal Hills, Lobo Hill, and Fra Cristobal Mountains districts in New Mexico (Fig. 35; McLemore, 1986; McLemore et al., 1988a, b; 2012; McLemore and Lueth, 2017). The alkaline episyenites are metasomatic spotty, discontinuous tabular bodies, narrow lenses, and occur in breccia zones along faults, fractures, and shear zones. They are found in nonfoliated, nonmetamorphosed igneous rocks, cross-cut Proterozoic foliations and are enriched in REE, uranium, thorium, niobium, and other elements. Select samples of episyenites from the Red Hills area in the Caballo Mountains districts contain as much as 20,000 ppm thorium, 1,600 ppm uranium, 500 ppm niobium, 5,000 ppm yttrium, 600 ppm beryllium, 7,500 ppm gallium, and 200 ppm lanthanum.

Pegmatite

Pegmatites are coarse-grained igneous rocks, lenses, or veins with granitic composition, contain essential quartz and feldspar, and represent the last and most hydrous phase of crystallizing magmas. Complex

pegmatites include mineralogical and/or textural zones. Pegmatites can contain a variety of economic minerals, including, mica, quartz, feldspar, lithium, REE, cesium, tantalum, niobium, rubidium, yttrium, scandium, uranium, thorium, tin, boron, beryllium, zirconium, hafnium, and others. A number of pegmatites in New Mexico have yielded REE production in the past (Table 21), but in general pegmatites are poor mining targets, because the REE minerals are generally scattered throughout the pegmatite and are difficult to selectively mine and process.

Placer

Placer deposits form by mechanical concentration of heavy minerals in a sedimentary environment, such as a river or beach. Many beach-placer sandstone deposits contain high concentrations of thorium, REE, zirconium, titanium, uranium, niobium, tantalum, and iron. In New Mexico, Cretaceous, beach-placer sandstone deposits contain concentrations of heavy minerals sorted by wave action on beaches or in long-shore bars in a marginal-marine environment

(Fig. 38; Houston and Murphy, 1970, 1977; McLemore, 2010c; McLemore and Robison, 2016). 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, and allanite, among others. 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. 39). 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 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 because of increased demand and short supplies, the dollar value per ton of ore may rise, enhancing deposit economics.
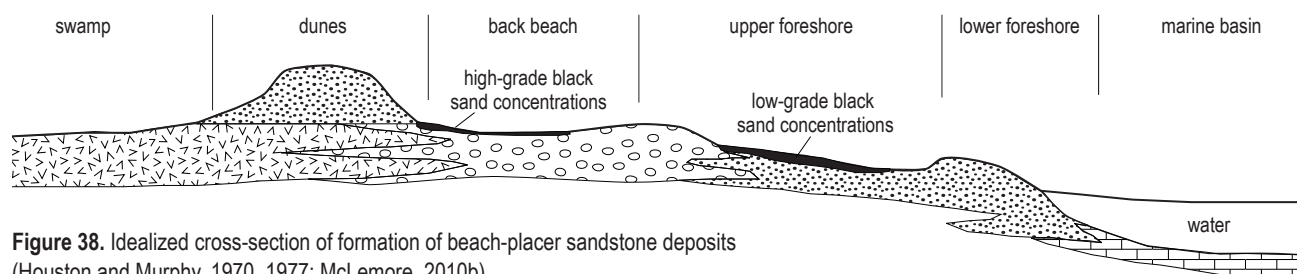
Figure 38. Idealized cross-section of formation of beach-placer sandstone deposits (Houston and Murphy, 1970, 1977; McLemore, 2010b).

Figure 39. Dark-brown beach- placer sandstone capping ridge at Sanostee, San Juan County (SJ0088). *Photo by Virginia T. McLemore.*

Other REE-bearing deposits

Minor amounts of REE can be found in uranium, thorium, and phosphate deposits and REE could be recovered as a by-product (Jackson and Christiansen, 1993). Fluvial and alluvial placer deposits can carry anomalous amounts of REE. Fluorite veins can carry high concentrations of REE.

Salt

Salt or halite (NaCl) is present in many marine bedded salt deposits of Late Permian age in eastern and southeastern New Mexico (Table 23, Fig. 40; Raup, 1991a). These units include the Yeso and San Andres Formations, the Artesia Group (Guadalupian series; including the Grayburg, Queen, Seven Rivers, Yates, and Tansill Formations), and the Castile, Salado, and Rustler Formations (Ochoan series) (Alto and Fulton, 1969; Pierce and Rich, 1962; Jones et al., 1973; Jones, 1974a, b). The most abundant, thickest, and purest salt is in the Guadalupian and Ochoan series sedimentary units in the Permian Basin (Fig. 40; Pierce and Rich, 1962; Jones et al., 1973; Jones, 1974a, b). However, salt is found in other units and surface localities (Table 23, Fig. 40). The Waste Isolation Pilot Plant (WIPP) site stores transuranic radioactive waste in the bedded salt in the Permian Basin. Salt also is reported in the Tularosa Basin; the Standard of Texas No. 1 Heard well contains 900 ft of salt (Griswold, 1959; King and Harder, 1985). Salt
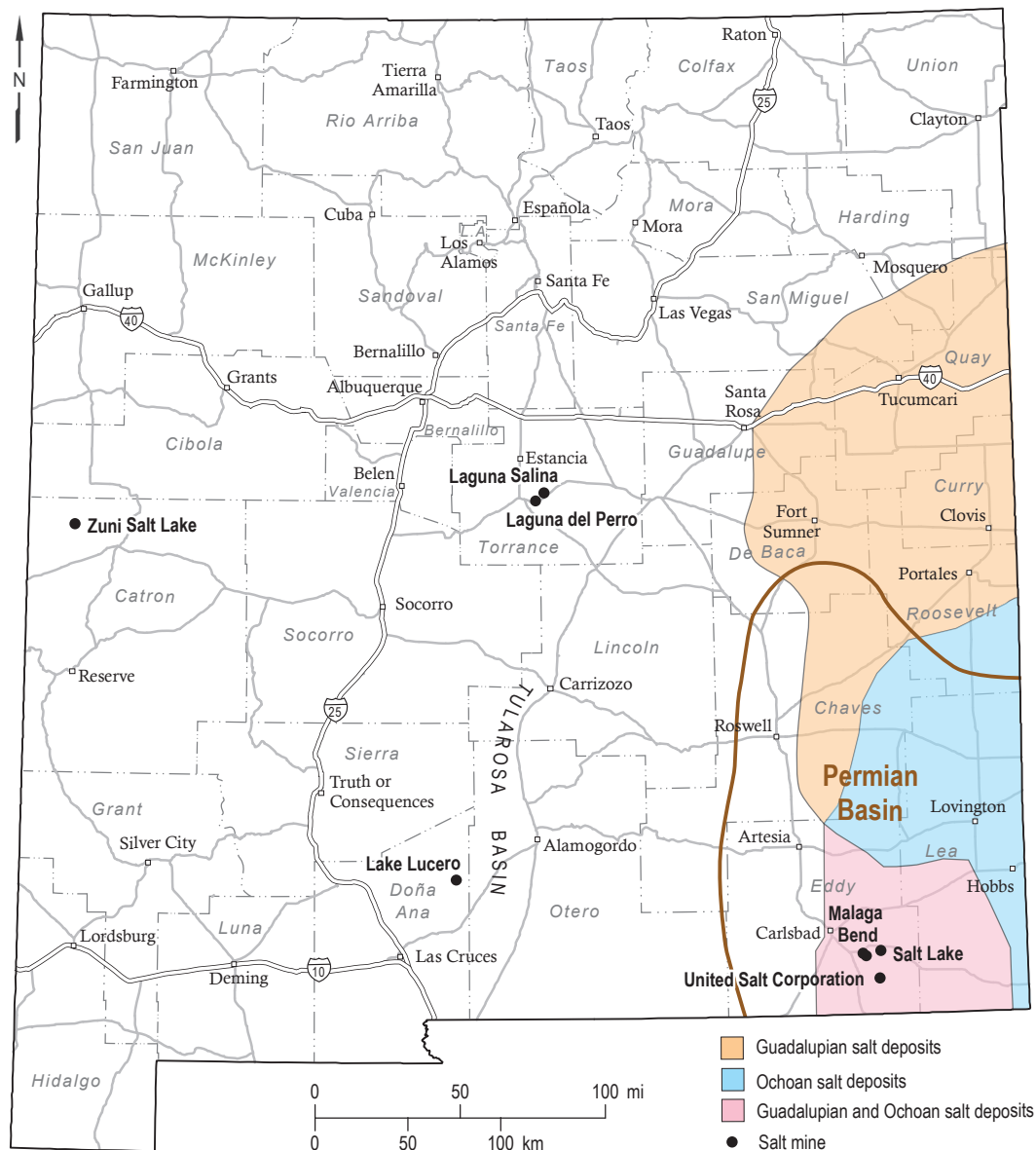
Figure 40. Distribution of major salt deposits and mines in New Mexico. Distribution of salt deposits is from Jones (1974a).

Table 23. Important surface occurrences of salt (NaCl). Datum is NAD27.

Mine ID	Mine Name	County	Latitude	Longitude	Year of production	Comments	Development
NMED0043	Salt Lake	Eddy	32.316861	103.936582	1981	as brine	solar lake
NMED0065	United Salt Corporation	Eddy	32.290738	104.023616	present		quarry
NMED0042	Malaga Bend	Eddy	32.1791715	103.9452302	1963–present		drill holes
NMED0044	New Mexico Salt	Eddy	32.305101	104.041066		brine from potash tailings, 30,000 tons per year	surface, mill
NMTO0220	Laguna del Perro	Torrance	34.588383	105.967273	1915	salt produced during Spanish times	shallow pits
NMTO0219	Laguna Salina	Torrance	34.631275	105.917569	prehistory, 1915–1930s	salt produced during Spanish times, salt in 1915–1930s	shallow pits
NMDA0006	Lake Lucero	Dona Ana	32.69167	106.445833		small halite, borax production	shaft
NMCA0185	Zuni Salt Lake	Catron	34.4495762	108.7677948	1540		

domes, a major source of salt in the United States, are not known to occur in New Mexico (Raup, 1991b).

Two companies are currently in operation in Eddy County: New Mexico Salt and Minerals and United Salt Corporation. Underground deposits of halite and sylvite are mined for the potash, and the salt is discharged during potash processing as a brine to tailing ponds and left to evaporate (solar evaporation). Over the years, many feet of salt have accumulated. United Salt Corp. acquired the Carlsbad solar evaporation salt plant in 1962 (T22S, R30E; http://www.unitedsalt.com/site/html/about.htm). The salt is harvested from a 2,600 acre salt lake near the Mosaic potash mine (T23S, R30E) after the sun has evaporated the water from the brine. The salt is then carefully washed three times before it is packaged into a variety of solar salt products. Originally, the salt at Carlsbad was sold as deicing salt for roads. Today, the salt is used in water conditioning, agricultural feed products, chemical feed stocks, for swimming pool chlorine generation and numerous other industrial applications. United Salt Corporation also operates the Salt Lake mine. In the same general area, New Mexico Salt and Minerals has a surface mine and harvests salt in T23S, R28E. Salt has also been recovered from subsurface brines.

Silica

Four types of silica categories are generally covered under silica: industrial sand and gravel, quartz crystals, special silica stone products, and tripoli. Industrial silica sand is used for glass manufacture, foundries, abrasives, and other industrial specialty uses, including proppant or hydrofracturing (frac sand) for extracting oil and gas. Specifications on the sand depend upon the final uses; most silica sand should be free of other minerals, especially heavy minerals. Zdunczyk (2001) summarizes the uses and specifications of industrial

silica sand. Electronic-grade quartz crystals, including cultured quartz crystals, are single-crystal silica with properties that make it uniquely suited for accurate filters, frequency controls, and timers used in electronic circuits. Silica stone products are quartz-rich materials used for abrasive tools, such as deburring media, grinding pebbles, grindstones, hones, oilstones, stone files, tube-mill liners, and whetstones. These products are manufactured from novaculite, quartzite, and other microcrystalline quartz rock. Tripoli, broadly-defined, includes extremely-fine-grained crystalline silica in various stages of aggregation. Grain sizes usually range from 1–10 micrometers (µm), but particles as small as 0.1–0.2 µm are common. Commercial tripoli contains 98–99% silica and minor amounts of alumina (as clay) and iron oxide. Tripoli has unique applications as an abrasive because of its hardness and its grain structure, which lacks distinct edges and corners. It is a mild abrasive, which makes it suitable for use in toothpaste and tooth-polishing compounds, industrial soaps, and metal- and jewelry-polishing compounds. Only industrial sand and sandstone have been produced in limited quantities in New Mexico and are discussed below. Some quartz crystals from pegmatites may have been produced in the past. Most quartzites in New Mexico contain impurities and are unsuited for special silica stone products. Novaculite and tripoli are not known to occur in New Mexico.

Industrial sand and gravel, often called silica, silica sand, and quartz sand, includes quartz-rich sands and gravels with high SiO_2 content. Some examples of uses for industrial sand and gravel are in abrasives, filtration, foundry, glassmaking, hydraulic fracturing (frac), and silicon metal applications. The specifications for each use differ, but silica resources for most uses are abundant. It has been estimated that 5.3 million metric tons of frac sand was used by the petroleum industry in the Permian Basin (Benson and Wilson, 2015) and future demands could result in an increased demand for additional frac sand.

The Zuni Sandstone, a white quartz sandstone, is a possible source of industrial sand (Elston, 1961) and is considered to be equivalent to parts of the Entrada, Todilto, Summerville, Bluff, and Morrison beds. The Chuska Sandstone, consisting of pale gray to pale yellow, cross-bedded, massive sandstone 1,000 ft thick, has been mentioned as a possible source of glass sand and could be suitable for hydro-fracting, but characterization is needed.

Silica sand that meets American Petroleum Institute (API) Standards is used as a frac sand to extract oil and gas wells (Benson and Wilson, 2015). To meet API Standards, tests are conducted for roundness, sphericity, crush resistance, acid solubility and size range. In northeastern Arizona, Preferred Sands is mining frac sand from the Bidahochi Formation near Sanders, Arizona, where 130 million short tons of reserves are estimated (Benson and Wilson, 2015). The Bidahochi Formation in New Mexico extends from the Hopi Buttes area in Arizona eastward to the Zuni Mountains south of Gallup, New Mexico (Love, 1989). Although few studies have been performed on this unit, the eolian facies could have potential for frac sand and other high silica sand uses. In New Mexico, portions of the Bidahochi and Mojado formations, Wingate, Navajo, Entrada, Glorieta, Zuni, Chuska and Bliss sandstones, and modern sand dunes could have potential for frac sand, but more mineralogical work is required to assess the economic potential of all New Mexico sandstones.

Silica was mined from the Glorieta Sandstone in the San Pedro Mountains at the Oro Quay (NMSF 0053, San Pedro) mine for potential glass and ceramic use (Elston, 1967). The Glorieta Sandstone was explored elsewhere in the eastern end of the San Pedro Mountains by the New Mexico Quartz Manufacturing Co., Inc. The Glorieta is a pure, poorly cemented quartz sand that may be suitable for glass manufacture or other industrial purposes. Elsewhere in New Mexico it is cemented by calcium carbonate or iron oxide. Silica sand has been produced from the Mojado Formation (Cretaceous) from the Brockman mine (NMHI0163), Hidalgo County from the early 1900s until 2000 for use as flux in the nearby copper smelters. El Paso Brick Co. also produces silica sand from quarries in Doña Ana County. Once the smelters closed in 2000, the silica mines closed. Wind-blown dune sands have been used for roofing sand from deposits along the Jemez River near Santa Ana Pueblo in Sandoval County (Elston, 1961).

Soda Ash

Soda ash is the common name for sodium carbonate (Na_2CO_3), an alkali compound that is one of the largest inorganic chemicals needed for the manufacture of all domestic inorganic and organic chemicals. It also is an important industrial compound used to manufacture glass, chemicals, soaps and detergents, pulp and paper, and many other familiar consumer products. A primary source of soda ash is trona ($Na_2CO_3 \bullet NaHCO_3 \bullet 2H_2O$) and dawsonite ($NaA1(OH)_2CO_3$).

Sodium carbonate resources commonly occur as precipitates in shallow, nonmarine alkaline lakes and marshes and usually coexist with various chloride and sulfate salts (Dyni, 1991). For this reason, it is not uncommon to find different sodium-carbonate-bearing minerals within the same deposit. Because sodium carbonate generally was deposited in shallow bodies of water, many of the deposits were subjected to vast seasonal changes in area and mineral concentration, and were susceptible to destruction by mechanical and chemical erosion caused by the relative softness and solubility of the minerals. Therefore large economic sodium carbonate deposits are relatively rare and are typically geologically young, ranging from the Eocene to Pleistocene epochs. Pre-Tertiary deposits are virtually absent from the geologic record (Santini et al., 2006).

In New Mexico, minor, uneconomic occurrences of trona are found in lava tubes in El Malpais National Monument, Cibola County, at Point of Rocks in Colfax County, and at Ojo de Tao, in the Valle de San Miguel, north of Cerro de Alesna in McKinley County (Northrop, 1996). Thermonatrite ($Na_2CO_3 \bullet H_2O$) has been identified at Point of Rocks in Colfax County and in Westwater Canyon in the Grants district in McKinley County (Northrop, 1996).

Sodium Sulfate Resources

Sodium sulfate is a common constituent of many mineral waters and seawater. Because sodium is usually the dominant cation, some make an anionic distinction, referring to lakes containing predominantly sulfate as bitter lakes and those containing predominantly carbonate as alkali or soda lakes. Sodium sulfate in its natural form is found in two principal minerals, mirabilite ($Na_2SO_4 \bullet 10 H_2O$) and thenardite (Na_2SO_4). Mirabilite is commonly called Glauber's

salt. Thenardite is the anhydrous variety. Sodium sulfate is found in varying degrees of purity, from theoretically pure efflorescent crystals of mirabilite to combinations and admixtures of other salts and impurities. It is a common constituent of some brines; from this source, much is extracted commercially (Austin and Humphrey, 2006).

In New Mexico, sodium sulfate was recovered from brines produced in southern Eddy County from gypsum strata of the Castile Formation (T24S to T26S, R25E to R27E). The operation began in 1951 and closed in 1957 (Lesure, 1965).

Soil Amendments (including Humate)

Soil amendments are defined as any natural or synthetic soil-conditioning materials that are worked into the soil or applied on the surface to enhance plant growth. This term commonly refers to added materials other than those used primarily as fertilizers. Soil amendments mainly modify physical characteristics and microbial action, or change the pH of a soil, or both, rather than directly supplying nutrients to plants. They give soil the needed physical properties to allow plant growth, fight erosion, or retain water. Although some soil amendments do provide nutrients in addition to altering the physical, biological, or chemical characteristics of soil, this is not their primary purpose. A more complete discussion of soil amendments is given in Hoffman and Austin (2006) and Hoffman (2009).

Both inorganic and organic materials are used as soil amendments. Several inorganic soil amendments have been used since the early 20th century: limestone, lime, and similar calcium-rich carbonates and oxides for acid soils, and calcium sulfate (gypsum) and native or uncombined sulfur for alkaline soils. The use of these amendments (limestone, lime, gypsum, and sulfur) or their equivalents has been studied and documented in many basic soils studies. In some cases, such as perlite, vermiculite, and zeolites, the soil amendment application is only a minor end use of these particular minerals or rocks, and other sections in this chapter provide more detailed information.

Peat is the principal natural organic soil amendment, however manure, both as a fertilizer and soil conditioner, is used universally. In less-developed countries, manure is the primary soil fertilizer/conditioner. An organic-rich material designated as humate or leonardite has been marketed as a soil amendment for many years and is addressed here. Other materials (such as synthetic products) are not discussed here.

Soils amenable to treatment with amendments are separated into five general categories: acid, saline, alkaline (pH >7.0), saline-alkali, and calcareous (soil containing sufficient free calcite ($CaCO_3$) and other carbonates to effervesce visibly or audibly when treated with cold 0.1 M hydrochloric acid (HCl). Optimum plant growth occurs for a great majority of crops and plants at a soil pH of 6–7 (neutral).

Organic soil amendments are widely thought to contain humic acids that are beneficial to plants. Humic material is not a pure substance, and much confusion exists in the scientific and business communities about its terminology. Humic acids are defined as base-soluble humic, fulvic, and ulvic acids and their salts, formed during partial or complete decay of organic matter. Humic acids raise the acidity of alkali soil, thus increasing the availability of several elements to plants. They also stimulate the growth of microorganisms that process plant nutrients.

Humate, when used as a lithologic term, includes oxidized coals and lignites, organic-rich mudstones and claystones, and the concentrations of humic substances often found in sandstones. Humate is commonly associated with both weathered coal and lignite, particularly in southwestern United States. The humic acid content of lignite decreases rapidly as coal rank increases and oxidation decreases. Organic-rich mudstones primarily within the coal-bearing sequences generally have a lower humic acid content than either the oxidized lignites or coals.

Humates are tested for the humic acid content that in part determines the product's end use. Studies by Verploegh and Brandvold (1990) showed that leach solutions of 0.1 M NaOH and leach times of 1 hour are sufficient to determine the humic acid content. Reporting on humic and fulvic acids on an ash-free basis eliminates metals inherent in the humate structure and contaminants such as sodium and chloride. This is especially true for fulvic acids.

Humates are not beneficial for every type of soil, particularly soils already rich in clay. The humic and fulvic acids in humates are organic colloids, which are similar in behavior to clay minerals. They increase water retention and the cation exchange capacity of the soil. Humate also lowers the pH of alkaline soil, thus increasing plant nutrient availability and stimulating growth of microorganisms (Hoffman et al., 1995). Humates are also used in drilling mud for increased circulation. Humates are most beneficial on sandy soils lacking in clay material.

Humates, claystones, and some sandstone that have concentrations of humic substances, such as the Jurassic Jackpile Sandstone found in the Grants uranium

Table 24. Humate mines, mills, and exploration projects in New Mexico.

Mine ID	Mine name	County	Company
NMMK0713	Black Spring	McKinley	Menefee Mining Corporation, Dallas, TX
NMMK0714	Brie	McKinley	Miocene, LLC, Denver, CO
NMSA0312	Clod Buster	Sandoval	Farm Guard Products (closed)
NMSA0352	Cuba mill	Sandoval	Horizon Ag Products, L.P., Louisville, CO
NMMK0715	Double Tree	McKinley	Miocene, LLC, Denver, CO
NMSA0353	Eagle Mesa	Sandoval	Ramsco Operations, Inc., Katy, TX
NMMK0716	Escondido Ranch	McKinley	Bruce Reid Enterprises (Mesa Verde Resources), Placitas, NM
NMSA0354	H2 Screen facility	Sandoval	Horizon Ag Products, L.P., Louisville, CO
NMSA0355	Horizon-Ag Products Cuba Facility	Sandoval	Horizon Ag Products, L.P., Louisville, CO
NMMK0717	Jaramillo	McKinley	Anasazi Stone, LLC
NMSA0357	Menefee mill	Sandoval	Menefee Mining Corporation, Dallas, TX
NMSA0356	Mesa Verde mill	Sandoval	Bruce Reid Enterprises (Mesa Verde Resources), Placitas, NM
NMMK0718	Morningstar	McKinley	Morningstar Minerals, Farmington, NM
NMSJ0409	Morningstar mill	San Juan	Morningstar Minerals, Farmington, NM
NMMK0400	Pueblo Alto	McKinley	Bruce Reid Enterprises (Mesa Verde Resources), Placitas, NM
NMSA0358	San Luis (closed and reclaimed)	Sandoval	Horizon Ag Products, L.P., Modesto CA
NMMK0720	Section 2	McKinley	Miocene, LLC, Denver CO
NMMK0721	Section 3 and 9	McKinley	Miocene, LLC, Denver CO
NMMK0719	Section 12	McKinley	Miocene, LLC, Denver, CO
NMMK0722	Star Lake Menefee	McKinley	Menefee Mining Corporation, Dallas TX
NMMK0524	Star Lake Mesa Verde	McKinley	Bruce Reid Enterprises (Mesa Verde Resources), Placitas, NM
NMMK0525	U-Mate	McKinley	U-Mate International, Inc., Scottsdale, AZ

district (McLemore and Chenoweth, 2017). In New Mexico, oxidized coals and organic rich mudstones and claystones of the Upper Cretaceous Fruitland and Menefeee formations are mined for their humic content. A number of small producers have operated in northwestern New Mexico (Shomaker and Hiss, 1974; Hoffman and Austin, 2006) and active producers are listed in Table 24.

Stone

Stone is defined as a general term for rock that is used in construction, either crushed for use as aggregate or cut into shaped blocks as dimension stone or memorials (Jackson, 1997). In this publication, stone will be further defined as consisting of crushed stone for aggregate, dimension stone, and decorative stone. Because stone is so common in New Mexico, greater emphasis will be placed on how it is used in other sections. Crushed stone used as aggregate was discussed earlier. Decorative stone and dimension stone produced in New Mexico will be examined here.

Decorative stone

Decorative stone, including ornamental stone, is more broadly defined here as any stone used primarily for its color, texture, and general appearance. It is not used primarily for its strength or durability, such as construction stone, or in specific sizes, such as dimension stone. The decorative stone industry uses a wide range of stone classes. Decorative stone usually serves some structural purpose, but is not load-bearing to any great extent. Weak or costly stones serve in decorative, not structural applications (Austin et al., 2006).

Rough stone is used as it is found in nature with very limited processing such as minor hand shaping, edge fitting, and size or quality sorting (L. Perath, 1992, written communication). This stone is often marketed locally in relatively small tonnages and includes fieldstone and flagstone. The primary end uses of rough stone are landscaping, edging, paving, or large individual landscape stone or interior accents.

Fieldstone is picked up or pried out of the ground (gleaned) without extensive quarrying and includes garden or large landscaping boulders

(Austin et al., 1990b). Boulders and cobbles may be split or roughly trimmed for use in rubble walls and veneers, both interior and exterior. Popular fieldstone rock types include sandstone, basalt, limestone, gneiss, schist, quartzite, and granite, but many others are suitable.

Much fieldstone is collected by individuals or small companies because the industry is labor intensive and markets are small. It may be sold locally in small quantities from the back of vehicles (Austin et al., 1990b). Fieldstone includes many sizes and shapes with the only common denominator that it must be set by hand and be durable (W.R. Power, 1992, written communication). In New Mexico, it is used for many similar uses including walls, wall facings, foundations, and, in some cases, complete buildings. Fieldstone includes moss-covered sandstone, cobbles and boulders of basalt, limestone, gneiss, schist and granite.

The most productive fieldstone operations in northern New Mexico are near Las Vegas, Ribera, San Miguel, and Tecolote where extensive deposits of Triassic and Permian flagstone and moss-covered sandstone occur. Stone yards and landscapers in northern New Mexico have stockpiles of fieldstone, garden or landscaping rock that have been obtained locally. Fieldstone production in New Mexico is difficult to estimate, but is relatively large in value and tonnage.

Moss rock is fieldstone partially covered by algae, mosses, lichens, and fungi that give the rock an aged and variegated patina (Austin et al., 1990b). The plants are supported by moisture and nutrients in the stone. Moss rock is used for landscaping, walls, and fireplaces. Although almost any durable rock can be a moss rock, most are slabby or rounded sandstone and limestone. Moss rock, a popular sandstone, is found throughout the flagstone areas where it occurs as loose fieldstone on surface outcrops. Moss rock is also collected near Cuba, New Mexico.

Flagstone or flagging consist of thin irregular slabs used for paving, walkways, and wall veneers. Suitable stone breaks very easily in one direction producing flags. Any fissile stone can be used, but sandstone (bedding planes) and slate (cleavage surfaces) are best. Sandstone flags can be split to a thickness of 1 in or less. Flagstone slabs 1–3 in thick are used for walkways in high-traffic areas and must be resistant to abrasion. If used in walkways, these thin slabs must be set on a very firm base. Thicker flags of sandstone or granite may be used in walls or set on edge as curbing.

Although flagstone can be produced in New Mexico from sedimentary rocks like sandstones, limestone and dolostones, most sandstone used by the building industry is quarried near Las Vegas, Ribera, San Miguel, Anton Chico, and El Rito. The flagstone along with dimension stone are of Permian and Triassic ages. It easily splits into smooth flagging of 1–2-in-thick slabs and blocks of various sizes in colors varying from white to brown to red. The Anton Chico quarries are noted for their white-to-buff sandstone. The Abiquiu-El Rito quarries produce flagging that is primarily buff to brown. Flagstones of various reds are widely produced in the Ribera, San Miguel, Las Vegas, Tecolote, and Abo Pass areas.

Aggregate used as decorative stone

Uncrushed stone or natural aggregate is lightly processed, usually by washing or screening, yielding products suitable for decorative use. Fragments can be either rounded or angular and must be durable. Many types can be used for rock lawns or area covers in virtually unlimited colors. Typically, local materials are used, which limits choice but lowers cost. The aggregate is placed on UV-resistant black, impermeable or semipermeable polyethylene (4 mil) covering a prepared surface treated with herbicides. A wide variety of sizes are used. Some special categories of uncrushed stone are described below.

River rock is the water-rounded pebbles, cobbles, and boulders, commonly used as an area cover. White to gray is typically specified, but other colors are available. River rock most commonly is granite or gneiss, but any durable rock may be used. White to buff vein quartz is a popular river rock for landscaping in some areas.

Scoria (volcanic cinder) is a lightweight, vesicular equivalent of basalt or other basic volcanic rocks. It is used primarily for desert landscaping in the southwestern U.S. and is less common elsewhere. Scoria or volcanic cinder is discussed in pumice, pumicite, and scoria (volcanic cinder) above. Recent production is in Table 3. Scoria is sold as either red to brown or black to gray varieties, but both are otherwise similar. Reddish hues are more popular, and hence, more valuable than other hues (Osburn, 1980). South-central New Mexico south of Las Cruces contains a number of cinder cones that supply the building and landscaping industries (Osburn, 1980). The area produces coarse-to-fine sized cinders in red, black, brown-and-black, and charcoal-to-russet colors. Scoria is a

less dense, vesicular equivalent of basalt and is used mainly in cinder blocks and for landscaping. Other uses are as dimension stone.

Basalt, a fine-grained, hard, tough, dense and durable rock, is produced from volcanic terrains principally in northeast New Mexico and near the Rio Grande in the center of New Mexico. Tertiary and Quaternary basaltic rocks are exposed for hundreds of square miles near Grants, Albuquerque, Santa Fe, Española, and Taos where large quantities of basaltic stone have been produced. Large volumes of basalt and scoria are in volcanic terrains east and west of the Sangre de Cristo Mountains. Major outcrops are at Caja del Rio, Black Mesa, West Mesa and the Taos Plateau. Basalt is well suited for use as aggregate, dimension stone, railroad ballast and riprap. Some basalt has been used as an aggregate in concrete. Lava rock in used barbecues and anti-skid material on icy highways. The majority of basalt is on federal land, so permits for removal must be obtained.

Fused argillaceous rock was formed by natural fires of lignite in New Mexico and forms a fused, interbedded claystone and sandstone locally called red dog or clinker. This material is used in the same manner as volcanic cinder, most commonly as road-building material in coal mines (Hoffman, 1996).

Rubble consists of large rough stone or blocks produced in quarrying, often as waste, used for retaining walls, seawalls, bridgework, and landscaping. Only landscaping rubble is considered decorative stone because it is used primarily because of color, texture, or general appearance. In New Mexico, large boulders of pegmatite are used as landscaping pieces (Austin et al., 1990b). Property walls composed of rubble are relatively common, particularly in southern New Mexico near the Vado stone quarry south of Las Cruces. Smaller rubble is popular as wall facing in homes and commercial buildings.

The primary purpose is aesthetic, it replaces brick or other veneer, but ease of installation, weather resistance, lightweight, and ability to bond well with mortar are also important. Rubble may be set in random patterns from about 0.05–4 m^2 of exposed rock. Low-density rock, such as pumice, has several advantages. Shipping costs are lower, setting is easier for stonemasons, and few to no anchors are required to tie stone veneer to the walls (Power, 1983).

Exposed aggregate is one of the most common methods to use crushed stone. Exposed aggregate is small pebbles and rocks embedded in concrete to form elegant designs on building faces, driveways, or patios. The aggregate is mixed in with concrete or it is set into the surface. Stith (1970) found the most

desirable properties to be color, hardness, soundness, absorption, shape, size distribution, and impurities. Many colors and shapes are possible making exposed aggregate compatible with almost any architectural scheme. Color should be uniform and permanent because it is the main criterion used by architects. Observation of weathered and fractured outcrops of the proposed aggregate can be very useful in determining how the stone will react (Cutcliffe and Dunn, 1967). Spalling and other forms of physical deterioration should be noted. The color should vary only slightly, if at all, between weathered and fresh outcrops. Variations in color, based upon exposure to sunlight or weather, should be noted to minimize color differences across the sides of a structure (Cutcliffe and Dunn, 1967). Color segregation of stone by quarry procedures, blasting, stockpiling, blending, batching, or due to weathering or lithology should be avoided (Cutcliffe and Dunn, 1967). Uniform color locally is obtained by hand sorting methods.

The ability to cast exposed aggregate in complex shapes and with background coloring (dash) of cement gives the architect great freedom. Aggregate, mixed with white or gray cement in a 2:1 ratio, can be precast into panels, or cast in place in walls and floors or walkways, with the aggregate dispersed or concentrated in the facing layer (Stith, 1970). The aggregate is exposed by subjecting the surface of the aggregate/cement mixture to sand blasting, bush hammering, wire brushing, or acid washing (Cutcliffe and Dunn, 1967) and it is finally sealed.

Terrazzo was produced by the Romans more than 1,500 years ago, and terrazzo floors provide quality, at low original and maintenance cost, and very long life. Terrazzo, a mixture of sized, crushed stone, and cement, offers variety in color and design. This mixture is poured into a prepared floor area and after hardening, ground smooth, sealed, and often polished (Reed, 1978). The stone aggregate has low porosity and low absorption. The portion of the terrazzo that needs protection is the Portland cement matrix, which is porous and absorbs stains. The primary application of terrazzo is in high traffic, public areas, and buildings. Relatively soft stone, usually limestone, dolostone, or marble is preferred, but granite is also used. Quality control is paramount during quarrying, so that color can be matched through repeated batching, and during processing, so quality, color continuity, and freedom from impurities are assured. Most terrazzo in New Mexico is used in large government and commercial buildings in larger cities.

Dimension stone

Dimension stone consists of blocks, slabs, or sheets of stone which are either sawed or chipped to specific dimensions for structural, ornamental, or monumental uses. In the past, dimension stone was used extensively as building blocks to support the full weight of the structure. More recently, however, supporting structures have been mainly of steel or reinforced concrete, and stone is used chiefly as a decorative veneer. Some dimension stone is used in constructing ashlar masonry walls (finely dressed or cut masonry, including individual squared stones or walls made of such stones), and also for decorative purposes as ornamental stone, including panels for interior and exterior walls, window sills, mantels, and tops for furniture and lavatories. There is also a continuing demand for dimension stone for use as monuments in cemeteries (Lindvall, 1965).

Dimension stone can be developed from a variety of rock types including sandstone, limestone, marble, travertine, quartzite, granite, basalt, and related igneous rocks. The type of rock is commonly not as important as is the color, durability, texture, and freedom from flaws. Deposits of rock should be large enough to develop a sizable quarry, and overburden should not be excessive.

In 2017, only commercial marble (travertine) was produced as dimension stone. New Mexico Travertine (NMT) of Belen, New Mexico (NMVA0014), produces travertine from quarries on Mesa Aparejo. These quarries were operated intermittently prior to NMT operations along with several others along the Comanche thrust between the Sierra Ladrones and New Mexico Highway 6.

Commercial marble is any crystalline rocks composed predominantly of calcite, dolomite, or serpentine that is capable of taking a polish (Meade and Austin, 2006). Marble is probably the oldest term used for dimension stone. In ancient Rome, the root word for marble, marmore, was used for all hard stones that could be polished. The same practice is followed in Italy today where the term marble is used for all hard stone that will take a polish, including granite.

Travertine is widespread in New Mexico (Kottlowski, 1965a; Barker et al., 1996). Other large occurrences near the NMT quarries are west of Sierra Ladrones and at Mesa del Oro. About 50 discrete deposits are reported in the literature (Barker, 1986, 1988) with many additional unreported occurrences in the extensive limestone terrains of southeastern New Mexico. Most deposits are associated with the extensional Rio Grande rift or on the Jemez volcanic zone that intersects it.

Past production of dimension stone

Most parts of New Mexico contain deposits of marketable stone, and small quantities of stone have been produced from many of these deposits. Quarries from which stone for highway construction has been obtained are widespread and varied, due to the transient nature of most of these operations.

Dimension stone was produced at the Gallinas mine, northeast of Las Vegas in San Miguel County, which marketed monumental and ornamental granite in northeastern New Mexico. Also near Las Vegas, the Mavalo mine produced flagstone. The Alamora Marble Quarry (NMOt0003) in Marble Canyon, about 3 miles east of Alamogordo in Otero County, first opened in 1899 and operated through the 1920s or later, and produced marble from a 27-ft thick bed for a variety of uses (McLemore, 2014b). The marble was shipped to 17 different states as Golden Vein. The quarries are in the Tierra Blanca Member of the Lake Valley Limestone that was metamorphosed by mid-Tertiary diorite sills and small stocks. Crinoid stems and other fossils are preserved in the marble. Total production is estimated as 300,000 cu ft, valued at $600,000 (Talmage and Wootton, 1937), or approximately 3,700 short tons. Most of the marble was drilled and blasted. A photograph of the quarry is in Talmage and Wootton (1937, pl. 11a). A cream-colored sandstone (Glorieta Sandstone) was quarried near Lamy in Santa Fe County in north-central New Mexico and has been used in the construction of some public buildings in Santa Fe. Dark-red, gray, and brown sandstones from quarries west of Las Vegas have been used in buildings at New Mexico Highlands University. Other quarries in various parts of New Mexico have produced small quantities of stone for local use.

Strontium Minerals

Strontium is the 15th most abundant element in the earth's crust, averaging 0.034% in igneous rocks. Only two minerals, however, celestite, or celestine ($SrSO_4$), and strontianite ($SrCO_3$) contain strontium in sufficient quantities to make recovery practical, and these minerals are found predominantly in sedimentary rocks. Of the two, celestite is more common in economic deposits. It is similar in structure to barite. Strontianite is more desirable of the two common minerals because strontium is used most commonly in the carbonate form and contains more strontium, but few deposits have been discovered that are suitable for economic development.

Nearly all celestite is converted to strontium carbonate, which is used as is or converted into other strontium compounds, including strontium chloride, chromate, nitrate, oxalate, oxide, and peroxide. The largest end use for strontium is in faceplate glass for cathode-ray tubes (CRTs) such as is used in televisions and computer monitors. Probably the oldest use for strontium is in pyrotechnics such as fireworks, signal flares, and tracer ammunition, because strontium compounds burn with a brilliant crimson flame; strontium nitrate and peroxide are the most common strontium compounds used in pyrotechnics. These and other strontium compounds are used in lesser quantities in ceramics and glass, permanent ferrite magnets, paint, and toothpaste for temperature-sensitive teeth (Ober, 2006).

Northrop (1996) reports a number of minor occurrences of celestite in New Mexico. In the Rio Puerco Valley west of Albuquerque in Bernalillo County, a concretion yielded radiating prismatic crystals of celestite. Additional specimens were later collected from concretions in Upper Cretaceous strata in the Rio Puerco Valley. Lechuguilla cave in Eddy County has cave crusts of celestite. In Harding County near Bueyeros, celestite was found in the basal part of the Morrison Formation. Celestite was also reported in the Gallinas Mountains district in Lincoln County, in the San Andres Mountains in Sierra County, and in the Sierra Oscura region of Socorro County. Northrop (1996) also cites occurrences of strontianite at two localities in Bernalillo County: the Tijeras Canyon district has occurrences of strontianite as radiating fibrous masses in the vicinity of Hell Canyon, west-southwest of the village of Tijeras.

Several NURE water samples near a playa lake in the northern Estancia Basin, Torrance County, contain anomalously high strontium (as much as 6,091 ppb, McLemore, 2010a).

Sulfur

Sulfur is widespread in nature and occurs both in the free state and in combination with other elements. In the United States in 2017, elemental sulfur was recovered, in descending order of tonnage, at petroleum refineries, natural-gas-processing plants, and metal smelters. Sulfur by-product production is a result of regulations limiting sulfur emissions in the atmosphere and has closed all primary sulfur operations in the U.S. Most sulfur consumed was in the form of sulfuric acid. Agricultural chemicals, primarily fertilizers, account for over half of identified sulfur

demand, followed in decreasing order by petroleum refining and metal mining. Other uses, such as in pesticides and other chemicals, are widespread because a multitude of industrial products require sulfur in one form or another during some stage of their manufacture (Apodaca, 2011).

New Mexico has produced sulfur, mostly as a by-product of natural gas plants, although there are geological occurrences of sulfur in New Mexico (Fig. 41). Another deposit, locally called Sulfur Springs, north of Jemez Springs, was reported to contain 60% sulfur. It was mined in 1902–1904 from underground workings extending over a roughly circular area more than 590 ft in diameter. Kelly (1962) states that from 1902–1904 a small quantity was produced in Sandoval County from surficial deposits associated with hot springs, i.e. fumarolic sulfur deposits (Long, 1991). Since 1953 in New Mexico, sulfur has been produced from natural gas (Broderick, 1965).

Sulfur occurs around some of the vents and fumaroles associated with hot springs in the Jemez Sulfur district in Sandoval County. One deposit, north of Jemez Springs, extends about 400 ft along the west bank of the Jemez River and is 60–74 ft wide. It consists of residual material derived from Carboniferous limestone leached by acidulated water and permeated by sulfurous vapors, which deposited sulfur irregularly in crevices and pores in the upper few feet of the rock. The deposit is a thin layer measuring only 2–3 ft thick. Samples of the material contained from 15–39% free sulfur and from 6–8.5% of sulfur combined as sulfate (Broderick, 1965).

Native sulfur is reported also to occur north of Lone Mountain or Red Peak near White Oaks in Lincoln County, near Artesia in Eddy County, in McKinley County in the Church Rock-Crownpoint subdistrict (Grants distric district (DIS117), in Otero County near the Texas border, in an extinct volcanic cone north of Tres Piedras in Rio Arriba County, in La Bajada district (DIS184) in Santa Fe County, in the Hansonburg district (DIS213) of Socorro County, and southwest of Clines Corners in Torrance County (Northrop, 1996). These deposits are not significant potential sources of commercial sulfur.

Sulfuric acid production in New Mexico started in 1955, but molten sulfur from Texas was used as a raw material. Gypsum and anhydrite are abundant in New Mexico, but sulfur has not been recovered from these deposits and it's unlikely to happen in the near future. Future production of sulfur from oil and gas fields in the San Juan basin of northwestern
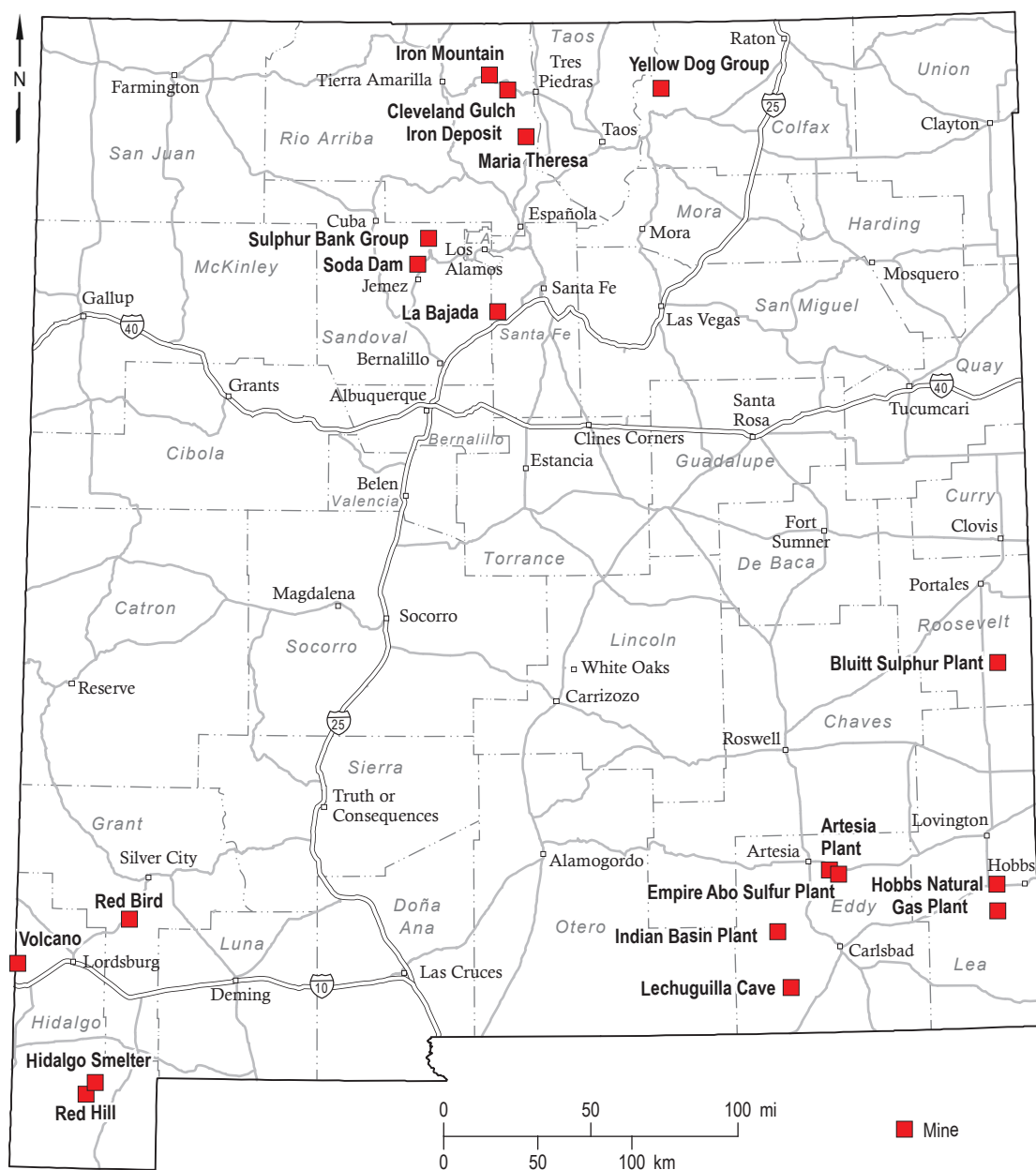
Figure 41. Sulfur occurrences in New Mexico.

New Mexico and the Delaware basin of southeastern New Mexico constitutes a potentially large sulfur resource in New Mexico.

The sulfide ores of various metalliferous deposits in New Mexico are also potential sources of sulfur. Most of the known reserve is in the Central district (DIS043) in Grant County, the Pecos mine (NMSM0137) in San Miguel County, and the Magdalena district (DIS221) in Socorro County (Broderick, 1965). Sulfur has not been produced commercially from these deposits, but sulfuric acid was produced at the copper smelters for many years.

Talc

The term talc refers both to the pure mineral (3MgO • 4SiO$_2$ • H$_2$O) and a wide variety of soft, talc-containing rocks that are mined and utilized for a variety of applications. Talc occurs fairly widely in a range of purities. The commercially exploited ores contain 20–99% of the pure mineral, and, although the trend is toward more upgrading and higher purity, many applications require the properties of the minerals that occur with talc.

The terms talc, steatite, and soapstone are widely used and misused in discussions of talc, its origin, and geology. Today there are two widely accepted uses of

steatite. In geology, steatite refers to a relatively pure, massive talc ore. In ceramics, steatite refers to a composition containing 80% talc and some fluxes, which is fired and used for electrical insulation, referred to here as synthetic steatite. Soapstone generally refers to a lower-purity talcose ore of mafic or ultramafic origin, which can be sawed or carved.

Talc occurs in metamorphosed sedimentary rocks, chiefly dolomite, in metamorphosed volcanic rocks, and in the ultramafic and mafic rocks (rocks rich in ferromagnesium minerals and low in silica) like, serpentinite, dunite, gabbro, and peridotite. The deposits, restricted to areas of folding, faulting, and metamorphism, may be surrounded by country rocks of other types that are altered to talcose rock. Most of the deposits of talc appear to have been formed by selective replacement owing to the action of dilute hot solutions from diabasic or granitic intrusive masses (Kottlowski, 1965c).

Ricolite, banded talc serpentinite, as well as some of the mottled and massive varieties of this talcose rock, has been quarried in small amounts from the Ash Creek area, Ricolite district in southwestern Grant County (NMGR0427). The rocks in the Ricolite district were regionally metamorphosed to the greenschist or amphibolite facies, but in Ash Creek, adjacent to the Redrock Granite, they also exhibit younger contact metamorphism (McLemore et al., 1996c). Small pods of hornfels and skarn formed where the Redrock Granite intruded the serpentine-carbonate rocks. Veins of serpentine and carbonate are common within and adjacent to the intrusive contact between the Redrock Granite and the metamorphic rocks. Metamorphic foliation is well to poorly developed and variable in orientation. The carbonate rocks, which are older than the Redrock Granite, may correlate with the Castner Marble in the Franklin Mountains in west Texas, which is 1,260 ±20 Ma.

The ricolite consists of alternating bands of talc and of serpentine with flakes of chlorite, fracture fillings of calcite and quartz, and cross-fiber veins of the asbestiform serpentine, chrysotile. Locally talc predominates over serpentine, the talc-rich variety being light cream and in bands up to several feet in thickness.

Talc has been mined in the Hembrillo Canyon area, San Andrecito district (DIS033) of the central San Andres Mountains in both Sierra and Doña Ana Counties (Kottlowski, 1965c). The deposits are associated with Proterozoic argillite, phyllite, diabase, calcite, dolomite, and silica-carbonate rock. These rocks are overlain unconformably by the Cambrian-Ordovician Bliss Sandstone. The talc is in steeply dipping lenticular masses 200–295 ft long and as much as 20 ft wide. The ore varies widely from white pure talc to dark-gray and green talcose argillite.

The Hembrillo mine on the south wall of the canyon (NMSI1117) was opened in two lenses of talc about 35 ft wide and 295 ft long to a depth of 40–70 ft and yielded 10,000 short tons of ore. The Red Rock mine (NMSI0533) on the north side of Hembrillo Canyon also explored two lenses of talc but only the lower ore body was mined (Kottlowski, 1965c; Fitzsimmons and Kelley, 1980). Both mines closed in 1945 when the land was designated as part of the White Sands Proving Ground (now White Sands Missile Range).

Similar metamorphic rocks (argillite and diabase) make up part of the Proterozoic units along the east edge of the San Andres Mountains for a distance of 15 mi from Sulphur Canyon on the north to Mayberry Canyon on the south; this is a rugged area that is no longer accessible owing to its location in White Sands Missile Range (Kottlowski, 1965c).

Tellurium

Tellurium (Te) is one of the least abundant elements in the crust and tends to form minerals associated with copper, lead, zinc and iron sulfide deposits. Today, most tellurium production comes from the anode slimes and other wastes generated in metal refining. Most of the current tellurium produced in the world is used as an alloying agent in iron and steel, as catalysts, and in the chemical industry. However, future demand and production could increase because tellurium is increasingly used in solar panels and some electronic devices (McLemore, 2016b).

In New Mexico, tellurium is found in gold-silver-tellurium alkaline-related veins, volcanic-epithermal vein deposits, skarns, polymetallic veins, vein and replacement deposits in Proterozoic rocks, and porphyry copper (±molybdenum, gold) deposits (Fig. 42; McLemore, 2013a, 2016b). Several areas in New Mexico have potential for tellurium deposits and some tellurium production has occurred.

The Lone Pine deposit (NMCI0023) is in the Wilcox district (DIS010) in the Mogollon Mountains, where 5 short tons of tellurium was produced from gold-tellurium epithermal veins. Some of the first tellurium minerals found in New Mexico were reported from this deposit, including native
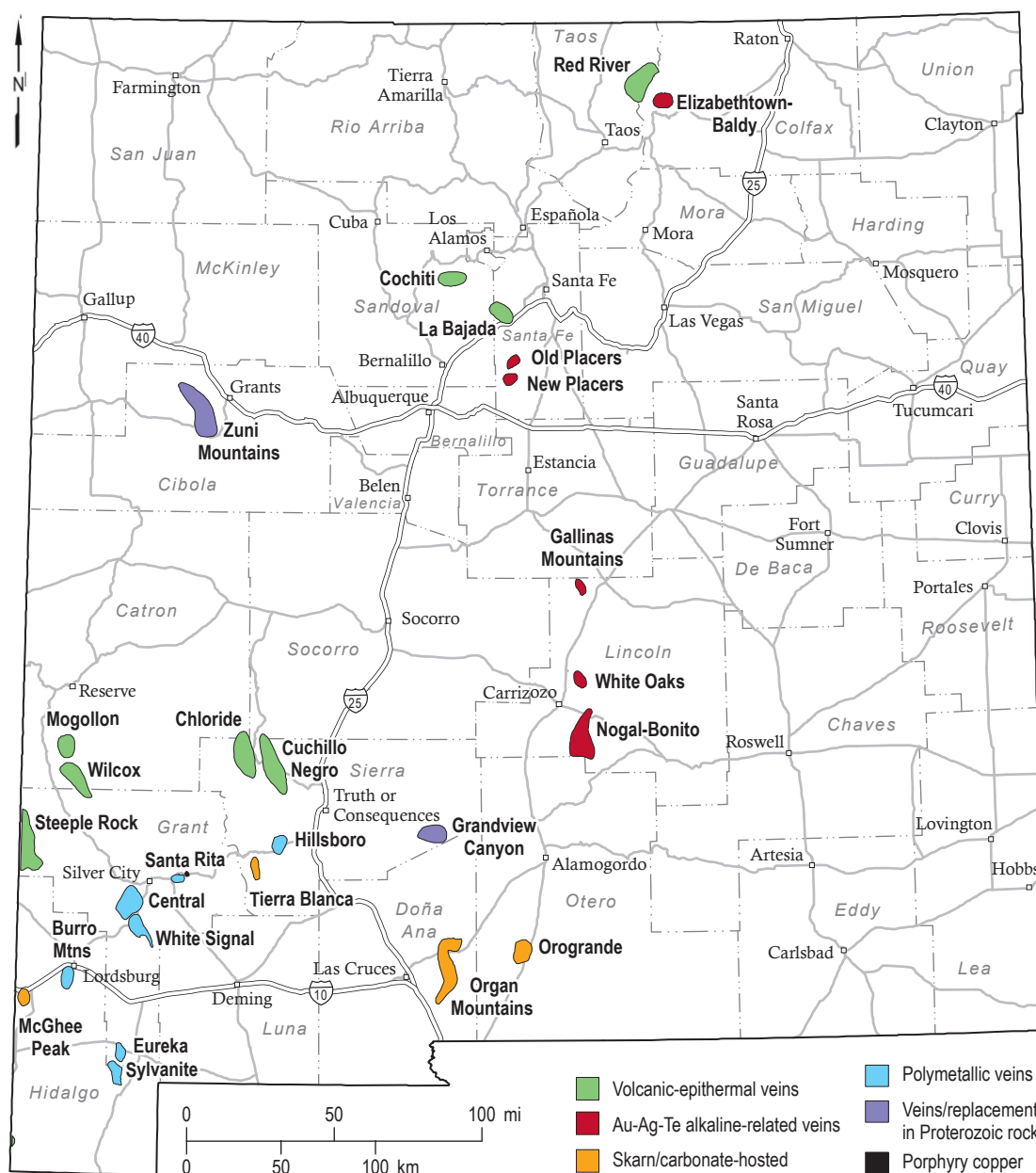
Figure 42. Mining districts in New Mexico with tellurium minerals or chemical assays >20 ppm (McLemore, 2016).

tellurium (Ballmer, 1932; Gillerman, 1964; Ratté et al., 1979; Lueth et al., 1996; McLemore, 2016b). Primary mineralization occurs as fracture fillings in veinlets in silicified flow banded rhyolite at most of the prospects in the region (Fig. 43). Disseminated mineralization is also present. At the Lone Pine mine primary mineralization occurs in a large zone of silicified flow banded rhyolite and silicified andesite. Primary mineralization consists of pyrite, fluorite, native tellurium, molybdenite and gold-tellurides. A vertical zonation is apparent with pyrite stratigraphically lowest, grading into a pyrite-tellurium assemblage, followed by a fluorite-rich zone at the highest

elevations. Tellurium mineralization is strongest at the pyrite-fluorite transition zone. Samples assayed as much as 3,500 ppm tellurium (Ratté et al., 1979) to 5,000 ppm tellurium (McLemore, 2016b).

In the Organ Mountains district (DIS030), where metal production from the district amounts to $2.7 million worth of copper, lead, zinc, silver, and gold (McLemore et al., 1996c), six types of deposits are distributed in five mineral zones; a core of copper-molybdenum porphyry deposit is surrounded by zinc-lead, lead-zinc, gold-silver, and outer fluorite-barite zones (Lueth and McLemore, 1998; Lueth, 1998) and are associated with the Organ batholith.
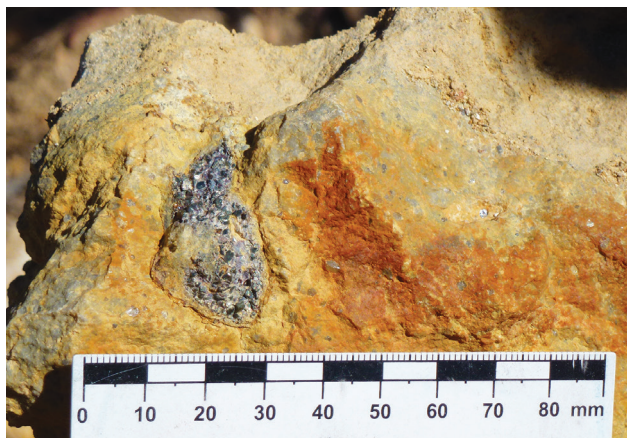
Figure 43. Tetradymite along fractures at the Lone Pine mine (NMCI0023) in the Wilcox district in the Mogollon Mountains. *Photo by Virginia T. McLemore.*

The Sugarloaf Peak quartz monzonite, one of three major phases of the Organ batholith, is 34.4 ±0.3 Ma (McLemore et al., 1996c). Samples collected from selected mines in the district range from <0.1–160 ppm tellurium (McLemore et al., 1996c, table 23). Tellurium minerals are found at several mines in the district. Most of the district is on the White Sands Missile Range and is withdrawn from mineral entry.

In the Sylvanite district (DIS088), in the Little Hatchet Mountains where Laramide skarn, Laramide vein, and gold placer deposits are found, mineral production is estimated at approximately $315,000, including 2,500 oz gold and 35,000 oz silver (McLemore et al., 1996c; McLemore and Elston, 2000). In 1908, placer gold and tetradymite (Bi_2Te_2S) were found at the Wake-Up-Charlie mine (NMHI0158). Native gold and tetradymite also were found in veins at Gold Hill (NMHI0143) and Green (NMHI0145) mines (Lasky, 1947). Tellurobismuthite (Bi_2Te_3) was found at the Buckhorn mine (NMHI0295). Additional sampling is required to determine the potential for tellurium and gold in this district.

The Tierra Blanca or Bromide No. 1 district (DIS205) lies south of the Kingston district (DIS199) in the Black Range of western Sierra County. Tierra Blanca is Spanish for white earth, named after the white capped hills and mountains formed by rhyolitic rocks. Gold, silver, and lead were produced from carbonate-hosted silver-manganese replacement deposits. Volcanic epithermal vein and sedimentary-iron deposits also are found in the district. Tellurium minerals are found at the Lookout (NMSI0971) and other mines.

The resource potential for tellurium deposits in New Mexico depends upon the economic potential for gold-silver veins or porphyry copper deposits.

Tellurium is found in trace amounts in the porphyry copper deposits, but detailed mineral chemistry is required to determine what minerals contain tellurium.

There have not been specific geologic models developed on how tellurium deposits form or how to explore for them, and detailed studies are required to develop these models. Detailed mapping, mineralogical, and geochemical analyses are required in all of the New Mexico deposits, especially those in the Wilcox, Organ Mountains, and Sylvanite districts and porphyry copper deposits to fully understand the formation and future resource potential of tellurium. All porphyry copper and gold deposits in New Mexico, including placer gold deposits, should be analyzed for tellurium.

Titanium

Titanium occurs in the earth's crust in two predominant commercial minerals, ilmenite and rutile. Ilmenite ($FeTiO_3$) is a common accessory mineral in many igneous and metamorphic rocks and forms a solid solution with hematite above 600°C. Below 600°C, ilmenite commonly occurs with hematite. Rutile (TiO_2) is a common accessory mineral in many igneous rocks and some metamorphic rocks.

The principal application for titanium minerals is as a feedstock for the manufacture of titanium dioxide (TiO_2) pigment, which accounts for more than 90% of global titanium mineral consumption. As the most widely used white pigment, TiO_2 is employed mainly for its opacifying properties in a wide variety of consumer goods such as paint, paper, and plastics. The titanium feedstock industry as a whole, all the way down to the exploitation of titanium mineral deposits, is therefore predominantly driven by trends in the TiO_2 pigment industry and the specific technical requirements of TiO_2 pigment manufacturing processes.

In New Mexico, titanium occurrences have been reported from pegmatites, iron ores, river sands, and Upper Cretaceous heavy-mineral beach sandstones along with beryllium and REE (Fig. 10, 39; McLemore and Robison, 2016). Titaniferous heavy-mineral beach sandstone lenses in the San Juan Basin contain the only known titanium resources of possible economic interest in New Mexico (Fig. 39, see REE deposits above), although river sands derived from the beach sandstone deposits have not been adequately examined for their titanium potential. The beach sandstone deposits are similar in mode of occurrence and mineralogy to deposits of Late

Cretaceous age reported from Montana, Wyoming, Utah, and Colorado (McLemore and Robison, 2016). Bingler (1963) described the mineralogy and stratigraphy of the largest known deposit, at Sanostee, San Juan County. According to Dow and Batty (1961), New Mexico deposits contain an estimated 4,751,200 short tons of titaniferous sandstone with an average titanium content of about 13%. Reliable estimates of tonnage are hampered, however, 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, 1965a). Drilling occurred at the Apache Mesa deposit (formerly Anomaly No. 1–2) on the Jicarilla Indian Reservation and future reports will describe the titanium resources (McLemore and Robison, 2016).

Vermiculite

Vermiculite is the mineralogical name generally applied to the group of minerals commonly formed by the alteration of biotite and iron-bearing phlogopite. Vermiculite possesses a number of important properties that include high aspect ratio, particles in a range of sizes from less than 50 μm to more than 1 cm, a high ion-exchange capacity, directional intumescence, and an active crystal surface with catalytic properties (Hindman, 2006).

Within the internal structure of vermiculite lie water molecules that, when rapidly heated to high temperature, transform into steam, causing the vermiculite particles to increase in volume. This process of thermal exfoliation produces a lightweight product that finds use in various construction products and in agricultural, horticultural, and other industrial applications.

Commercial-grade deposits of vermiculite are unknown in New Mexico, although mineralogical occurrences are not uncommon (Weber, 1965b). Northrop (1996) cites occurrences in Grant, Mora, Rio Arriba, and San Miguel Counties. Southwest Vermiculite Co., Inc. has a vermiculite plant in Albuquerque and has 1–9 employees, but their vermiculite is imported from outside New Mexico. The vermiculite is used for fire proofing.

Wollastonite

Wollastonite is a calcium metasilicate with the chemical formula $CaSiO_3$. It is the only naturally occurring, nonmetallic, white mineral that is acicular (radiating mass of needle-like crystals) in crystal habit. This crystal habit and the mineral's chemistry are the main reasons for wollastonite's rise in commercial use, which began in the 1970s. As a nontoxic partial substitute for short-fiber asbestos, wollastonite became sought after in many polymer systems where mechanical strength and heat stability are needed. The end uses range from friction brake materials to fire-resistant asbestos board to ceramic tile to industrial coatings. Exterior automotive parts and under-the-hood applications have benefited from the use of high-aspect-ratio grades of wollastonite.

Wollastonite is formed by both metamorphic and magmatic processes that usually involve carbonate and intrusive igneous rock (Orris, 1991). Two types of deposits are known—skarn deposits (thermal metamorphic and metasomatic) and carbonatites (magmatic). Wollastonite-rich skarn deposits are formed by the thermal metamorphism of siliceous limestone during regional deformation or as a result of local intrusive igneous activity. The mineral can also form through metasomatism of limestone by siliceous hydrothermal solutions along contacts with igneous intrusions or along fractures and faults.

Wollastonite is found in metamorphosed limestone in the Organ Mountains district. Wollastonite is present at depths of greater than 2,300 ft in the cuttings of a deep well in Hidalgo County (Budding and Broadhead, 1977).

Zeolites

Zeolites are aluminosilicates, composed of a three-dimensional crystal lattice with loosely bound cations, able to hydrate and dehydrate without altering their crystal structure (Holmes, 1994). Major uses of zeolites include pet litter, animal feed, soil amendments, wastewater treatment and filtration. Zeolites have fixed pore sizes and active sites in the crystal lattice. Approximately 48 natural zeolites and 100 synthetic zeolites exist (Eyde and Holmes, 2006). Zeolite minerals occur in rocks of diverse lithology, age, and depositional environments. Sedimentary zeolites are found in open, hydrologic systems, in tephra sequences in nonmarine and shallow marine basins in volcanic terrains (Sheppard, 1991a). Zeolites also are found in closed-basins, saline, alkaline-lake deposits, where zeolites are commonly the product of diagenetic reaction between volcanic glass and saline, alkaline pore solutions (Sheppard, 1991b). Deposit characteristics differ due to varying depositional

and diagenetic conditions during zeolitization. Clinoptilolite, the main commercial natural zeolite, is found in geologically young volcanic ash altered by alkaline groundwater in the western U.S.

The Stone House deposit (NMSI0915, Cuchillo Negro or St. Cloud Mining Company) is currently being mined by St. Cloud Mining Co. (White et al., 1996). Two other occurrences discussed here were mined in the past (Buckhorn, NMGR0618) or show potential (Foster Canyon, NMDA0001). All three were discussed by Bowie et al. (1987). Many other zeolite occurrences are present in New Mexico, principally in southwestern New Mexico (Fig. 44).

Cuchillo Negro clinoptilolite deposits (Stone House mine)

The Tertiary tuff of Little Mineral Creek and overlying tuffaceous sedimentary rocks (Harrison, 1986) have been variably altered to zeolite, specifically the mineral clinoptilolite, most likely by alkaline/saline meteoric and/or low-temperature hydrothermal fluids in an open hydrologic system (Sheppard, 1991a). The zeolitic units include the clinoptilolitic tuff and conglomerate unit of Maxwell and Heyl (1976). The deposit was first termed the Cuchillo Negro clinoptilolite deposit by Bowie et al. (1987) before
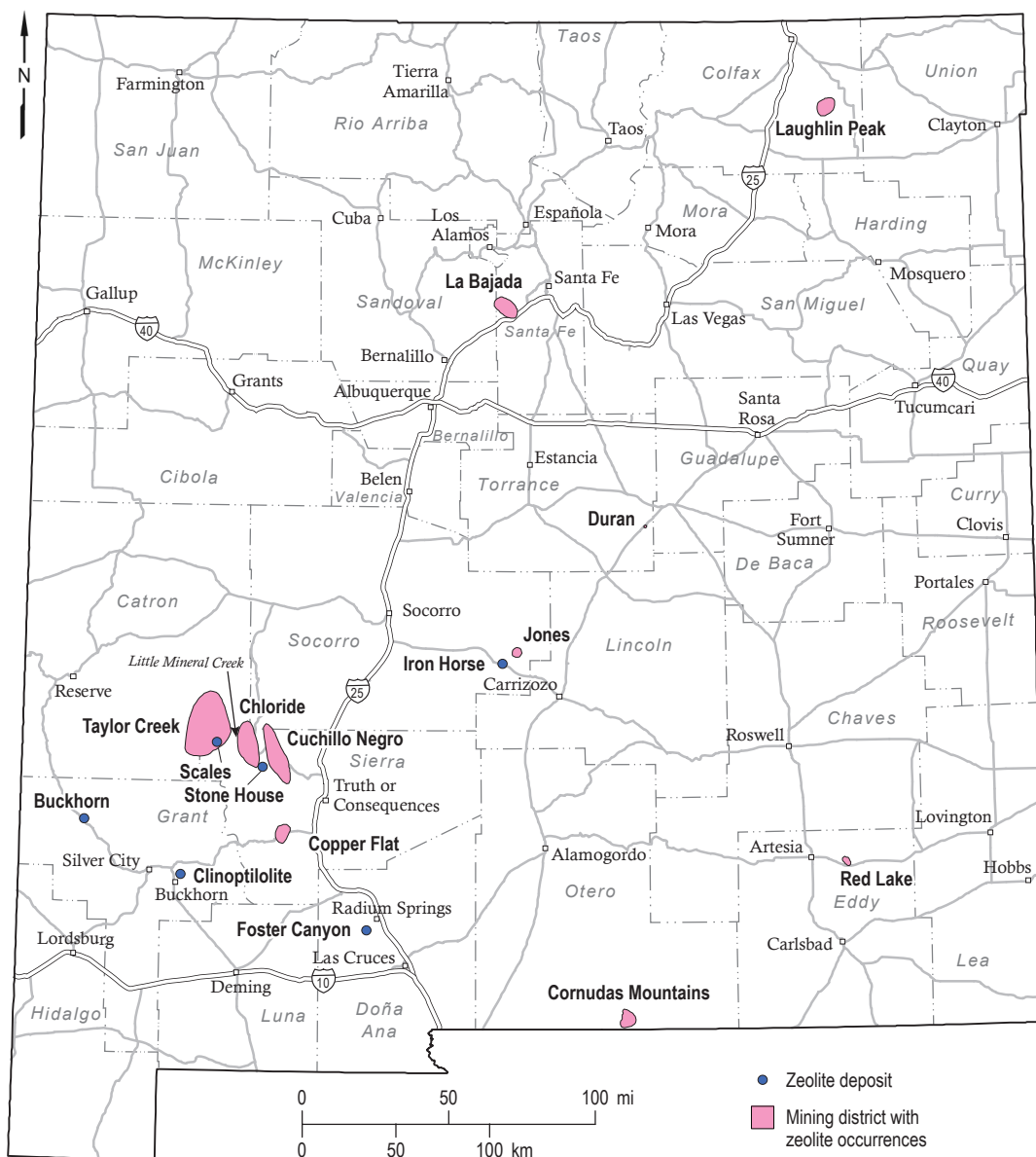
Figure 44. Zeolite deposits in New Mexico.

mining commenced; after mining it became the Stone House deposit. It is exposed in the southern end of the Winston graben and at numerous localities in the adjacent Black Range and Sierra Cuchillo. The clinoptilolite deposit is currently mined about 4 mi south of Winston.

Most of the rocks in the Sierra Cuchillo area represent an intermediate to felsic volcanic and volcaniclastic sequence within a complex volcano-sedimentary section that is at least 2,200 ft thick (Harrison, 1986). The period of volcanism represented by this volcanic sedimentary stratigraphy concluded with deposition of the tuff of Little Mineral Creek. Overlying this unit is a sequence of immature tuffaceous volcaniclastic rocks that are compositionally similar to the tuff of Little Mineral Creek. Capping these rocks is a thick sequence of unconsolidated conglomerates of the Santa Fe Formation. The contact between the tuffaceous clastic unit and the conglomerates of the Santa Fe Formation is conformable and gradational.

Host rocks for commercial-grade clinoptilolite alteration include the tuff of Little Mineral Creek, a lithic-rich rhyolitic ash flow crystal tuff that is about 590 ft thick, and a tuffaceous sedimentary sequence from 50–200 ft thick that overlies the tuff of Little Mineral Creek (Fig. 45, 46). The tuffaceous sediments consist of immature tuffaceous arenite interbedded with tuffaceous conglomerates with clast compositions similar to the lithic fragments of the underlying tuff of Little Mineral Creek. These rock units are exposed in the mine vicinity along a strike length of about 5 km. However, field studies indicate that potentially commercial clinoptilolite alteration occurs along nearly 2.5 mi of strike length of these variably zeolitized volcano-sedimentary rocks. North of the zone of strong clinoptilolite development, the tuffaceous volcaniclastic rocks are relatively unaltered or only incipiently altered. South of this zone host rocks are strongly altered to clinoptilolite.

Zeolite does not appear to have been preferentially developed along bedding planes within tuff or tuff-clastic units in the mine area. The availability of fine-grained volcaniclastic and tuff horizons for zeolitization apparently favored replacement of groundmass and the smaller phenocrysts. The occurrence of quartz as micrometer-scale overgrowths on quartz phenocrysts suggests that silica was mobile during zeolitization; apparently at least some of this silica precipitated as quartz, with amorphous silica as a possible but as yet undocumented coproduct. Replacement of groundmass and phenocrysts varies from approximately 85 vol% replacement to essentially complete zeolitization.

Buckhorn clinoptilolite occurrence

The Buckhorn clinoptilolite in New Mexico originated in a late Cenozoic network of closed-hydrologic, lacustrine basins (Sheppard, 1991b; McLemore, 2008) extending from southeast Arizona into southwest New Mexico (Scarborough and Peirce, 1978). At the Buckhorn deposit, two clinoptilolite-rich tuffs are interbedded with lacustrine mudstone in the upper part of the Gila Conglomerate. The lower zeolite tuff contains up to 90% clinoptilolite. The upper zeolite tuff contains over 60% clinoptilolite. The tuffs at both deposits were zeolitized by reaction of vitric tuff with ponded, saline, alkaline-lake waters (Bowie et al., 1987).

Figure 45. St. Cloud Mining Co. zeolite mill (NMSI0888). *Photo by Virginia T. McLemore.*

Figure 46. Stone House clinoptilolite mine, Sierra County (18.3 million tons of reserves) (NMSI0915). *Photo by Virginia T. McLemore.*

The Buckhorn clinoptilolite deposit is in the Mangas Trench, a northwest-southeast-trending structural low, bounded by normal faults on the east and west. Clinoptilolite has been mined at Buckhorn from one of two zeolitic air-fall tuffs. These tuffs are exposed on the west side of Duck Green Valley W, south of Buckhorn, Grant County. Some potentially zeolitized tuffs crop out in the central and eastern portions of Duck Green Valley.

The zeolitized air-fall tuffs of the Buckhorn deposit are interbedded with the Pliocene-Pleistocene Cactus Flat beds of the upper part of the Gila Conglomerate (Heindl, 1958). Diatomite beds are found in the center of the lake, not far from the zeolitic beds (McLemore, 2008). The two clinoptilolite-rich tuffs at the Buckhorn deposit are traceable for approximately 0.8 mi along strike. The tuffs are separated by about 20 ft of green and brown mudstone containing abundant smectite, zeolites, quartz, and calcite, and minor to trace illite, plagioclase, and secondary gypsum (Sheppard and Mumpton, 1984).

The yellowish-white, massive, lower zeolite tuff is 3–4 ft thick and contains up to 70–90% clinoptilolite. A lower layer in this tuff is 6 inches thick and contains about 48% clinoptilolite and about 48% chabazite (Eyde, 1982). The lower tuff also contains a clinoptilolite-heulandite intermediate phase, heulandite, analcine, magadiite chert, quartz, calcite, illite/smectite, plagioclase, fluorite, hornblende, and biotite (Sheppard and Mumpton, 1984). The upper zeolite tuff is massive, yellowish- to grayish-white, and is 1 ft

thick. It contains over 60% clinoptilolite and a trace of erionite (Bowie et al., 1987).

Fluorite in a zeolitic tuff occurs east of Buckhorn. The fluorite is very small (<1 micron) and makes up 20–30% of the tuff. It occurs as pellets and ooids embedded in a matrix consisting predominantly of micrometer-size mordenite and smectite (Sheppard and Mumpton, 1984). The pellets and ooids probably are products of primary precipitation of fluorite and magadiite. They formed where dilute, calcium-bearing water from springs or streams mixed with fluorine-rich, saline, alkaline-lake water. The pellets are possibly biogenic and often form the cores of ooids. Both pellets and ooids were transported and reworked into the tuff prior to zeolitization (Sheppard and Mumpton, 1984).

Clinoptilolite deposit at Foster Canyon

The Foster Canyon clinoptilolite deposit is north-west of Las Cruces, near Radium Springs, Doña Ana County. Several zeolitically altered air-fall tuffs are exposed in the Foster Canyon collapse area of the Tertiary Cedar Hills and Selden Hills volcanic-vent zone (Seager and Clemons, 1975).

In the Cedar Hills and Selden Hills vent zone, the Tertiary section includes the Eocene Palm Park Formation, the Oligocene Bell Top Formation, and the Miocene to Pliocene(?) Rincon Valley Formation (Seager and Clemons, 1975). The Palm Park Formation is unconformably overlain by the Bell Top Formation. The Bell Top in the vent zone can be subdivided into four units: 1) lower tuffs and breccia, 2) ash-flow tuff, 3) upper air-fall and epiclastic deposits, and 4) flow-banded rhyolite domes and flows (Seager and Clemons, 1975). Porous to dense crystal-vitric ash-flow tuff and muddy to sandy conglomerate interfinger with tuffaceous sedimentary members.

In Foster Canyon, up to 780 ft of white to tan, rhyolitic air-fall tuff, breccia, and interbedded epiclastic pebbly sandstone were deposited as moat-fill after vent-clearing, explosive eruptions. Clemons (1976) refers to these deposits as the upper tuffaceous sedimentary member. The lower parts of the member contain clasts of Paleozoic limestone, Palm Park Formation, ash-flow tuff, and vesicular andesite. Ash, crossbedded epiclastic sediment, and pumiceous, vitrophyre tuffs dominate the upper parts (Seager and Clemons, 1975). Basaltic andesite either formed dikes and plugs intruding the member or formed interbedded flows.

The upper tuffaceous sedimentary member is extensively zeolitized and locally opalized (Bowie et al., 1987). Several siliceous or fused-tuff structures are conspicuous at the surface as resistant, sinuous, cross-cutting ridges with up to one meter of relief above the surrounding surface. The tuffs were probably silici-fied as silica-rich hydrothermal solutions moved up along fractures. The relative abundances of smectite and clinoptilolite are inversely proportional to their distance from the fused-tuff ridges. Clinoptilolite is more concentrated at the ridges and smectite is more concentrated away from them. This relationship supports a hydrothermal origin for at least some of the zeolite. Other zeolite may be post hydrothermal. Clinoptilolite and chabazite were detected.

The tuffs contain up to 60% zeolite, and average 40–50% clinoptilolite. Reserves are tentatively esti-mated at 200,000–300,000 short tons of 50% clinopti-lolite. Exact reserve calculations are difficult to make because of the irregular gradation between zeolitized and nonzeolitized tuff and the intermixing of siliceous, fused-tuff zones with zeolitic tuff (Bowie et al., 1987).

In addition to zeolites, opal and smectite, the tuffs contain lithic fragments ranging in composi-tion from basalt to rhyolite, varying amounts of unaltered volcanic glass, and minor quartz, calcite, biotite, kaolinite, sanidine, K-feldspar, and albite. The zeolitic tuff is generally massive and structure-less. Local cross-bedding is present probably due to the tuffs having been reworked by fluvial processes. Clinoptilolite occurs as subhedral to euhedral, coffin-shaped laths that are commonly intergrown and chaotically arranged.

Other zeolite occurrences

The lower portion of the Turkey Springs Tuff in the central San Mateo Mountains has been altered to zeolites in zones as thick as 200 ft (Ferguson, 1990). Clinoptilolite (20–30%) is found as aggregates in mudstone and altered tuff in the Brushy Basin Member of the Morrison Formation in the Chama River area (Ridgley et al., 1988).

Zirconium and Hafnium

Zirconium and hafnium are corrosion-resistant ele-ments mostly found in zircon ($ZrSiO_4$) and locally as trace elements in ilmenite ($FeTiO_3$), typically in a zirconium:hafnium ratio of 50:1. Zirconium with trace amounts of hafnium also are found in bad-deleyite (ZrO_2), eudialyte ($Na_4(Ca,Ce)_2(Fe,Mn,Y)$

$ZrSi_8O_{22}(OH,Cl)_2$), and gittinsite ($CaZrSi_2O_7$). Zircon is a common accessory, rock-forming mineral in most igneous rocks, especially granites, syenites, pegmatites, and rhyolites. In most areas zircon is only a trace mineral and generally not of economic importance. Although there has been no zirconium or hafnium production from New Mexico, four types of potential deposits in New Mexico contain high concentrations of zirconium and hafnium; dissemi-nated yttrium-zirconium deposits in alkaline rocks, Great Plains Margin alkaline-related igneous rocks, carbonatites, and Cretaceous beach placer sandstones (Fig. 47). In New Mexico, Cretaceous beach placer sandstone deposits are found in the San Juan basin (Fig. 38) and contain anomalous amounts of zircon. Currently none of the New Mexico deposits are economic today.

Disseminated yttrium-zirconium deposits in alkaline rocks

Many alkaline igneous rocks, typically of syenite or granite composition, have higher concentra-tions of zirconium than other types of igneous rocks. Disseminated yttrium-zirconium deposits in Proterozoic alkaline rocks are found at Pajarito (NMOt0095), in the northeastern part of the Mescalero Apache Indian Reservation, south of Ruidoso in Otero County (Fig. 47; Sherer, 1990; McLemore, 1990, 1991). A joint leasing-operating agreement was reached between Molycorp, Inc. and the Mescalero Apache Tribe and a recoverable 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, this deposit has never been mined. Eudialyte, the major ore mineral at Pajarito Mountain, is disseminated throughout the syenite, quartz syenite, and alkali granite (Kelley, 1968; Moore et al., 1988; Sherer, 1990).

Great Plains Margin alkaline-related igneous rocks

Other areas in New Mexico contain Tertiary alka-line rocks and could have potential for zirconium and hafnium as a by-product of other commodities (McLemore, 1996a). The Cornudas Mountains are in southern Otero County, New Mexico, and north-ern Huspeth County, Texas, part of the Trans-Pecos alkaline belt and have been examined for potential deposits of uranium, beryllium, zirconium, REE, niobium, gold, and silver (McLemore and Guilinger, 1993; Schreiner, 1994; Nutt et al., 1997).

Carbonatites

Carbonatites are carbonate-rich rocks containing more than 50% magmatic carbonate minerals, less than 20% SiO_2, are of apparent magmatic derivation (LeMaitre, 1989, 2002), and typically found in zoned complexes consisting of alkaline igneous and/or carbonatite stocks, ring dikes, and cone sheets (Fig. 36 in REE section). Carbonatites typically contain REE, uranium, thorium, niobium, tantalum, zirconium, hafnium, iron, titanium, vanadium, copper, apatite, magnetite, vermiculite, and barite (Singer, 2000). In New Mexico, Cambrian-Ordovician carbonatites occur as dikes and associated veins and stockworks in four areas (Fig. 35): Lemitar and Chupadera Mountains, Lobo Hill, and the Monte Largo area in the Sandia Mountains. A fifth carbonatite locality in New Mexico is the Oligocene carbonatite dikes at Laughlin Peak in the Chico Hills, Colfax County (see Great Plains Margin deposit type) and carbonatites could be in the subsurface in the Gallinas Mountains as suggested by alteration, geochemistry, and previous drilling, but no samples have
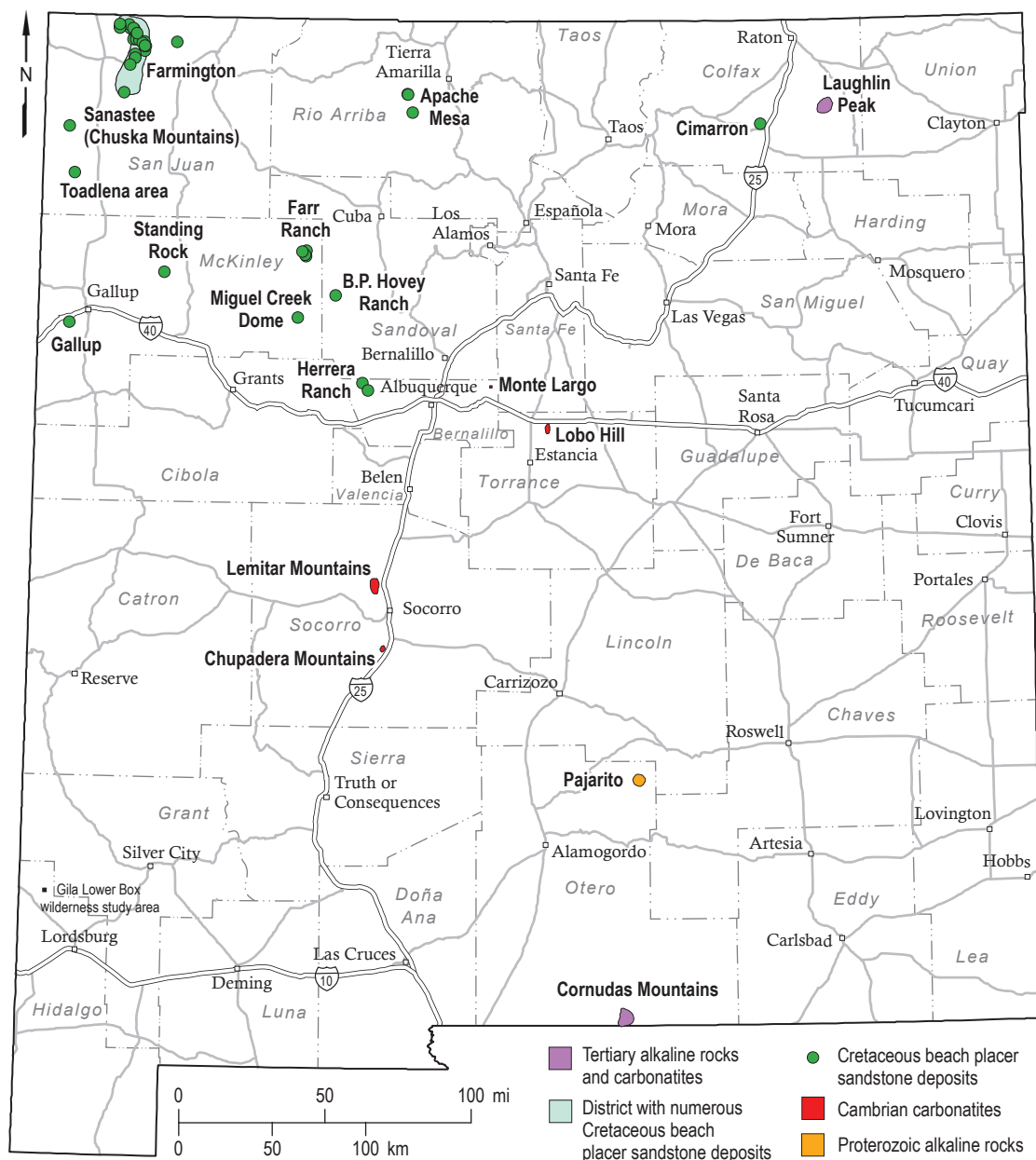
Figure 47. Mining districts in New Mexico with anomalous zircon and hafnium.

been obtained for precise determination of the lithology (McLemore, 2010c). The dikes are typically 3–4 ft wide and up to 1,500 ft long. There has been no production from any carbonatites in New Mexico.

Beach-placer sandstone deposits

Heavy mineral, beach-placer sandstone deposits 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. 38; McLemore, 2010c; McLemore and Robison, 2016; see REE section and McLemore and Lueth, 2017). Beach-placer sandstone deposits in the San Juan Basin in New Mexico with appreciable heavy minerals 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, 2010b; McLemore and Robison, 2016). Many beach-placer sandstone deposits contain high concentrations of thorium, REE, zirconium, hafnium, titanium, uranium, niobium, tantalum, chromium and iron (McLemore, 2010b). Most of the deposits in the San Juan Basin contain zircon, which could be recovered as a by-product.

Other Industrial Minerals in New Mexico

Asphalt, bitumens, and other hydrocarbon-bearing rocks are found in New Mexico and used in asphalt concrete and emulsion for road construction and other uses, including lacquers, paint, marker inks, and alkaline batteries (Foster, 1965). The Santa Rosa Sandstone at Santa Rosa Lake contains as much as 9.1% bitumen, mainly as asphalt. A quarry (NMGU0006) produced nearly 150,000 short tons of material. Reserves were estimated at more than 100 million short tons. However, the deposits are along and near Santa Rosa Lake and have not been mined for many years. Asphalt and oil-saturated sandstone is in the Gallup Sandstone northeast of Gallup (Foster, 1965), but has not been developed.

Optical calcite or Iceland spar (transparent calcite crystals) is found near the Harding pegmatite, near Dixon, New Mexico (Johnson, 1940; Schilling, 1960). Approximately 850 lbs of optical grade calcite was mined before and during World War II from a pipe-like body in Proterozoic schist and quartzite. Optical grade calcite was used in Norton bombsights by U.S. Army Air Forces in World War II for the purpose of precision bombing.

A thin ash-flow tuff is found in the Gila Conglomerate north of the Gila Lower Box wilderness study area that was used for sand casting by a local silversmith (Richter et al., 1988). No other information is known.
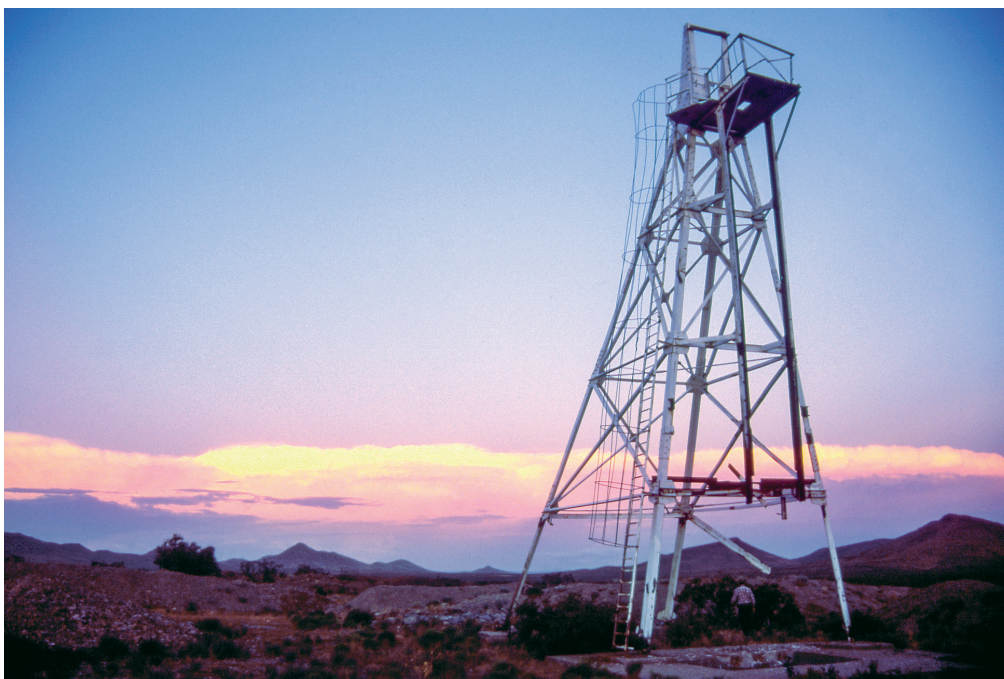
Headframe at Fluorite Ridge district in Luna County, 1995. *Photo by Virginia T. McLemore.*

III. CONCLUSIONS

Production of industrial minerals has been and remains important to the rural economy of New Mexico. New Mexico leads domestic production of potash, perlite, zeolite, and travertine. It is 2nd in humate, 4th in pumice, 11th in salt, and 13th in gypsum. Other production includes clay, scoria, limestone, fly ash, cement, magnetite, silica, and decorative stone. At least one company is exploring for garnet. Development of the low-grade nepheline syenite at Wind Mountain in the Cornudas Mountains (Otero County) is on hold. Cretaceous black sandstone in the San Juan Basin has drawn interest for titanium, iron, REE, and zircon.

REE deposits are being explored. Recent exploration has occurred for beryllium in the San Mateo Mountains, Iron Mountain, and Victorio districts. Aggregate continues to be produced throughout New Mexico as construction activities, including highway construction and upgrading, increase.

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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
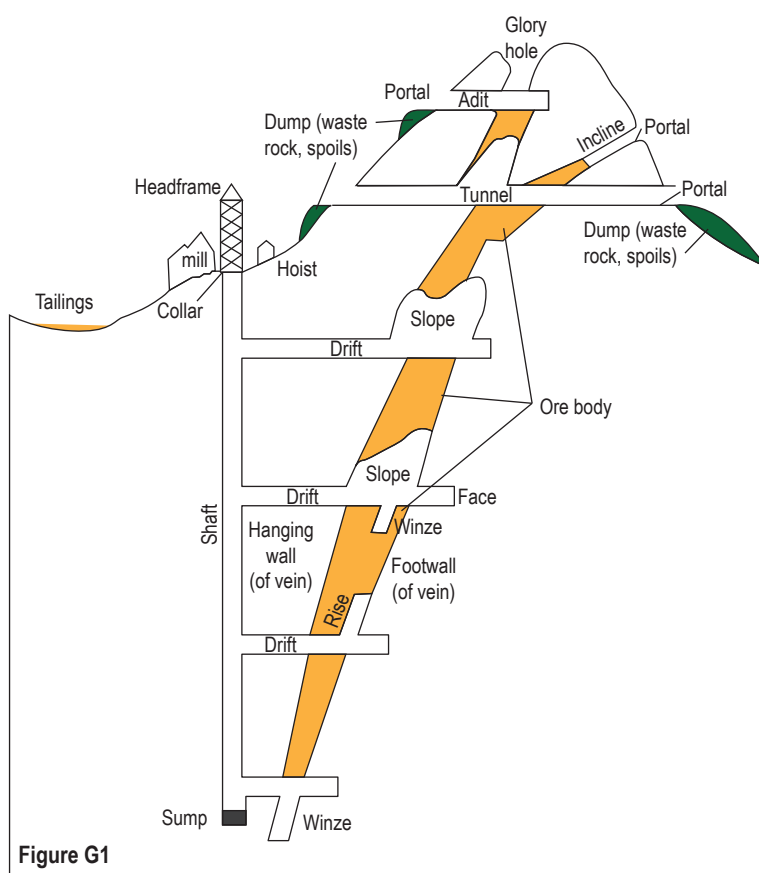
Many mine features and mine terms are shown in Figure G1 below.

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 (ft^3)
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 per cent
Y—yttrium
Zn—zinc
Zr—zirconium
δ—delta value used in isotope measurements
°C—degrees centigrade

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