CHAPTER ONE

THE PHYSICAL AND HISTORICAL FRAMEWORK

DECISION-MAKERS
FIELD CONFERENCE 2005
Taos Region

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Rio Grande gorge and Taos Mountains.

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The Geology and Landscape of the Taos Region

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With the geologist lies the special responsibility and opportunity of revealing the earth in all its beauty and power. … If geology and the geologist neglect interpretation of the earth to society, they are guilty of relinquishing what should be one of their major contributions. —David Leveson, *A Sense of the Earth*

Taos is located at the edge of radically different landscapes. The town is situated on the eastern edge of a broad, high valley known as the Taos Plateau. The Taos Plateau forms the southern part of the San Luis Basin, part of the Rio Grande rift. The basin is flanked on the east, south, and west by highlands of the southern Rocky Mountains. To the east is the Taos Range of the southern Sangre de Cristo Mountains. To the south are the Picuris Mountains, a westward prong of the Sangre de Cristo Mountains. The western highland is called the Tusas Mountains or the Brazos uplift. Geologic processes, working steadily through many millions of years, have contributed to the formation of these contrasting landscapes.

The quietude of the Taos Plateau belies the tumultuous geologic history of the region. Taos is located in one of the most dynamic and stimulating geologic settings on the planet. Buried beneath the plateau is an enormous fissure in Earth's crust (the Rio Grande rift) that is six times deeper than the Grand Canyon and thirty times larger than the Rio Grande gorge. The rift continues to be active, as indicated by the common occurrence of small to moderate earthquakes and the presence of large chambers of molten rock at depth. Evidence of past catastrophic seismic and igneous events is visible from most anywhere in the Taos area: young fault scarps where the mountains join the plateau, and a profusion of volcanoes and lava flows in the basin. Fortunately for us, neither destructive earthquakes nor volcanic eruptions have occurred in the historic past, although both will undoubtedly occur in the future.

The mountains, valleys, and volcanoes convey a tale of past landscapes that have evolved dramatically and repeatedly during the last 2 billion years, from shallow tropical seas to vast, sand-duned deserts; from enormous white sand beaches to muddy meandering rivers and lush fern forests; and from enormous mountain ranges to flat, featureless plains. These geographic features—the bold mountain escarpments, the fertile, flood-prone valleys, the deep gorge, and the dry tablelands—have greatly influenced 10,000 years of human occupation.

Landforms and Landscapes

A landform is any natural, discrete surface feature with a characteristic shape. A landscape, however, is a unique, distinct cluster of landforms. Mountain slopes, mountain valleys, and mountain peaks are landforms, whereas mountain belts are landscapes; volcanoes, calderas, craters, and lava plains are landforms, whereas volcanic fields and volcanic plateaus are landscapes.

All landforms have geological underpinnings. Most landforms are formed by a sequence of highly complex geological systems or processes, many of which are not visible or evident at the surface of the earth. Furthermore, all landforms have been modified to some extent. Some landforms in the Taos area, such as the 2.7-million-year-old Ute Mountain volcano, have maintained most of their original shapes. Other landforms have been significantly altered from their original forms by the processes of weathering and erosion. The Taos Plateau has been extensively modified by the Rio Grande and its tributary rivers to form the modern canyon system.

It is important to make a distinction between the age of a landform and the age of the materials that compose the landform. The rocks that form Wheeler Peak are nearly 1.8 billion years old, whereas the uplift of the Sangre de Cristo Mountains is about 60 million years old, and the dramatic crags of the Wheeler Peak area were sculpted by glaciers that melted only about 12,000 years ago.

GEOLOGY OF THE MOUNTAIN RANGES

The three mountain ranges that surround the Taos Plateau are the southernmost surface expression of the Rocky Mountains. In New Mexico, this area has a long history of repeated uplift, erosion, and burial. The latest uplift began approximately 70 million years ago during the Laramide orogeny and continues today. In

the Taos area the Sangre de Cristo Mountains expose three principal ages of rocks:

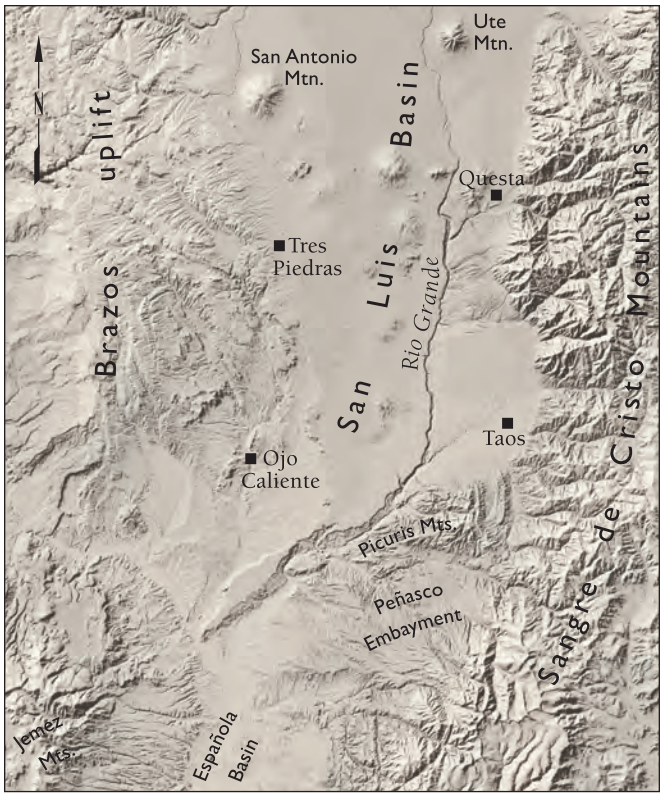
- Precambrian metamorphic rocks (1.8–1.4 billion years old)
- Pennsylvanian sedimentary rocks (about 300 million years old)
- Tertiary igneous rocks (26–18 million years old)

The Tusas Mountains contain only the Precambrian and Tertiary assemblages, whereas the Picuris Mountains are composed entirely of Precambrian rocks.

In general, Precambrian rocks are dense and strong and highly resistant to erosion. Consequently, in the Taos area, most of the highest mountain peaks and steepest slopes are composed of such rocks. They include a wide variety of rock types (granite, gneiss, quartzite, schist) and ages, including the oldest dated rock in New Mexico, near Wheeler Peak.

Even though Precambrian rocks represent more than 80 percent of the history of our planet since its formation 4.5 billion years ago, our knowledge of Precambrian geology is woefully incomplete. Precambrian rocks now exposed at the surface in the Taos area were deeply buried during much of Precambrian time, and we know little of what was happening at the surface. We do know that the crust was subjected to intense metamorphism, folding, faulting, and melting during the lengthy formation of the North American continent until about 1 billion years ago. These ancient rocks are easily seen in many places near Taos: at Taos ski valley, Ponce de Leon hot springs, Red River Pass, on top of Wheeler Peak, in the steep cliffs near Pilar, and in the hills behind the Ojo Caliente hot springs.

Precambrian rocks supply much of the mineral wealth in the Southwest, and such is the case in the Taos region. The distinctive, micaceous clay prized by Picuris Pueblo potters is derived from a Precambrian schist from the Picuris Mountains. The controversial mica mine south of Taos is located in a similar deposit. Precambrian quartzite hosts the rich copper veins at Copper Hill near Peñasco. Gold was mined from Precambrian rocks near Red River. Copper was mined at Twining (now Taos ski valley) around 1900. The schists of the Picuris Mountains contain the "fairy cross" staurolites sold in local mineral shops. The Harding pegmatite mine near Dixon is a world-famous mineral collecting locality and has produced important amounts of the rare metals lithium, beryllium,



Physiographic map of the Taos region.

tantalum, and niobium. Suggestions of gold and silver deposits have periodically piqued the interest of prospectors and speculators in the Hopewell Lake area of the Tusas Mountains.

From 1.4 billion years ago until the Mississippian Period (354 million years ago) there is no rock record to study. Where rocks are absent, geologists must determine whether sediments were not deposited, or whether sediments were deposited and later eroded. In general, an advance of the sea promotes sedimentary buildup, whereas a retreat of the sea and exposure of the landmass to the air promotes erosion. Because sediments of Cambrian to Devonian age are absent in northern New Mexico but present to the south, geologists infer that during that time the Taos area was a landmass, and southern New Mexico was ocean.

During Pennsylvanian time, 80 percent of New Mexico was submerged beneath warm, shallow, equatorial seas. Northern New Mexico probably resembled modern-day North Carolina, with a flat coastal plain, swampy forests, and high mountains to the west. Mud, silt, sand, and gravel were eroded from nearby island highlands into a large sedimentary basin known as the Taos trough. Over time, as the thousands of feet

of sediments were buried and compacted, they evolved into the sedimentary rocks that we now see east and south of Taos. These limestones, siltstones, shales, sandstones, and conglomerates are exposed over most of the southern part of the Sangre de Cristo Mountains, with excellent exposures on NM–64 along the Rio Fernando and along NM–518 south of Talpa.

A close examination of the Pennsylvanian rocks exposed near Taos reveals evidence of their original environments of deposition (rivers, deltas, shorelines, tidal flats, shallow seas), including features such as ripple marks, raindrop imprints, and crossbeds. The warm Paleozoic seas teemed with ancient life, and paleontologists have classified the fossilized remains of hundreds of marine species in the Taos area, including many varieties of clams, snails, sea lilies, corals, and brachiopods.

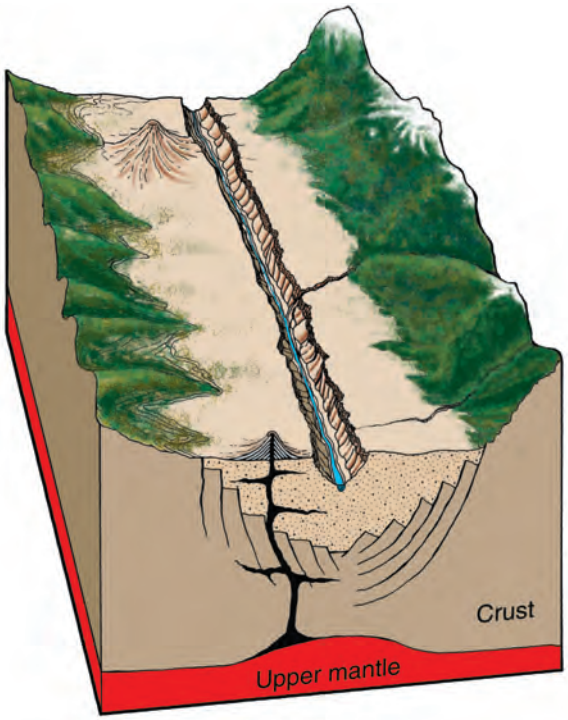
During Pennsylvanian time the region was subjected to a major mountain-building event known as the Ancestral Rocky Mountain orogeny. Today the most apparent effects of this are tilted and faulted Pennsylvanian strata. The modern Rocky Mountains mimic the chain of mountains that developed in Pennsylvanian time, because once the crust is broken it remains a zone of weakness to be exploited by later pulses of mountain-building events.

Mesozoic rocks do not exist in the Taos area, although they are exposed in the Moreno Valley near Angel Fire. The Triassic and Jurassic Periods (248–144 million years ago) were characterized by deposition of nonmarine sandstone and shale over much of northern New Mexico. Until very late in Mesozoic time, this area was alternately land and sea, as the shoreline advanced and retreated over a low-relief landscape. Great thicknesses of shale, sandstone, and limestone accumulated in these vast Cretaceous seas, and at times, much of the state was submerged. Sharks teeth are common Cretaceous fossils in New Mexico. Dinosaurs roamed the lush landscape of shorelines, river valleys, and widespread swamps for over 100 million years, until the great extinction 65 million years ago.

From Late Cretaceous time to early Tertiary time the Taos region was squeezed by forces associated with the next great mountain-building event, the Laramide orogeny. Compression of the crust resulted in major uplift and erosion and development of folds and faults. The western half of the Taos trough was uplifted and eroded, and by Tertiary time only rolling hills remained. Later, during Oligocene time, the San Luis Basin began to subside, while the Sangre de Cristo Mountains began to rise. Volcanoes erupted in the uplifted area, covering the region with lava and ash. The largest volcanic event was the explosive eruption of the Amalia Tuff from the Questa caldera about 25 million years ago, approximately coincident with the onset of the next great event, Rio Grande rifting.

The Bear Canyon pluton, visible in Red River Canyon, is one of many magma bodies that were emplaced in the Questa area following the caldera eruption. Collectively, these igneous rocks make up the "Questa magmatic system." As the magmas cooled and solidified, mineral-rich hydrothermal fluids percolated through the rock, and minerals such as molybdenite, quartz, and pyrite were precipitated in small fractures. These fracture-fillings (veins) later became the targets of prospectors and miners. Veins of the mineral molybdenite (molybdenum sulfide), an ore of the metal molybdenum, are found in unusually high concentrations in the Questa/Red River area and are now mined by Molycorp for use as lubricants and in the manufacture of stainless steel.

During the past 20 million years, the mountains have continued to rise and erode as the continental crust has continued to extend. By Pleistocene time (1.8–0.01 million years ago), the Sangre de Cristo Mountains had mostly developed their modern form.



Block diagram showing the principal geologic elements of the Rio Grande rift in the the Taos area. A deep sedimentary basin (San Luis Basin) has formed in the crust above a bulge of hot asthenosphere. The Rio Grande has eroded a deep canyon in the rift basin. Not to scale.

View northeast of the two principal elements of the Taos landscape: the Sangre de Cristo Mountains and the Taos Plateau and gorge. The gorge here contains Pleistocene landslides of the Pliocene Servilleta Basalt.

During the Pleistocene ice ages, glaciers covered the higher peaks, scouring out depressions called cirques, and dumping huge volumes of sediment-laden water into the San Luis Basin.

GEOLOGY OF THE RIO GRANDE RIFT, SAN LUIS BASIN, AND TAOS PLATEAU

Taos is situated in one of the few young continental rift valleys on Earth. The other great rift valley is the 4,000-mile-long East African rift, which, as it has torn eastern Africa apart, has created Africa's highest peaks, deepest lakes, and equally impressive landscapes. The Rio Grande rift is part of a global system of fractures in Earth's uppermost rigid layer (the lithosphere) that have formed in order to accommodate relative movements of the lithospheric plates. The lithosphere is broken into about a dozen major plates that move over an underlying layer of partially molten rocks (the asthenosphere). Although most of the activity associated with plate tectonics occurs at or near plate margins, in some cases, such as along the Rio Grande rift, activity occurs well within the continental plate.

For the last 30 million years, plate tectonic forces have slowly begun to tear the North American continent apart along the Rio Grande rift. The lithosphere has been uplifted, stretched, thinned, broken, and intruded by magma. The resulting rift valley has sliced New Mexico and half of Colorado in two for a distance of over 600 miles. Near Taos the rift basin is about 20 miles wide and approximately 16,000 feet deep. The Rio Grande flows southward through successive rift basins that are linked by geologic constrictions. The river itself did not excavate the rift; the river follows the topographically lowest path along the rift, from the San Juan Mountains in Colorado to the Gulf of Mexico.

The transition from the basin to the surrounding mountains is abrupt, and in places such as near Taos and Pilar, is marked by steep slopes and cliffs. These abrupt transitions are both physiographic and geologic boundaries; most are major fault systems that delineate the margins of the rift. The eastern fault system is known as the Sangre de Cristo fault. The southern fault (the Embudo fault) separates the San Luis and Española rift basins.

The rift basin is filled with young (less than 30 million years old) materials, principally of sediments shed

from the surrounding mountains, transported southward by the Rio Grande, and volcanic rocks of the Taos Plateau. We can see only the young basin fill at the surface, although material as old as 5 million years is exposed in the bottom of the Rio Grande gorge. The gorge is a much smaller and younger feature than the rift, and it is entirely erosional. The river began cutting down into the plateau sometime after 2.8 million years ago, which makes it younger than the Grand Canyon in Arizona. The deepest section of the gorge, at 850 feet, is located west of Questa in the Wild Rivers Recreation Area.

Visible from the rim of the gorge is a series of near-horizontal layers of basalt, known as the Servilleta Basalt. Most of the basalt was erupted as long, thin flows from topographically low volcanoes near Tres Piedras. The rift contains hundreds of such volcanoes, many of which are relatively young and retain their original conical shape. Nearly all of the isolated rounded hills that are scattered across the Taos Plateau are volcanoes that erupted from 6 to 2 million years ago.

Ute Mountain volcano rises above the basalt-capped Taos Plateau in northern Taos County. The Rio Grande excavated the Rio Grande gorge during the last 600,000 years.

The rift basin is surrounded by alluvial fans that have advanced from the mountains into the basin. An alluvial fan begins to form where a rapidly moving mountain stream flows out onto a relatively flat valley floor. As the stream suddenly loses velocity, the coarsest sedimentary material is dropped by the stream. This material forms an "apron" that radiates out from the point where the mountain stream enters the valley. Most of this clay, sand, and gravel, called the Santa Fe Group, was eroded from the mountains during the past 30 million years. Over time, as the basin subsides alluvial fans are buried under successively younger alluvium. The youngest of these alluvial fans sustain the many sand and gravel quarries in the Taos Valley.

Many thousands of feet of rock were removed from the mountains and transported into the valley as the mountains slowly pushed upward. Similarly, the Rio Grande has deposited mineral-rich sediment into the basin for millions of years. Much of the thick sedimentary material in the Santa Fe Group is porous and permeable, and therefore serves as the principal aquifer in the region. People, agriculture, and industry have tended to concentrate along the Rio Grande rift for its fertile floodplain soils and precious supply of water.

Today, as uplift of the mountains and subsidence of the basin continue, streams persist in moving weathered rock from the mountains to the basin. The uplift takes place episodically through a series of small movements, each one associated with an earthquake. Although these processes work so slowly that we see little if any change during our lifetimes, over geologic time the countless small changes translate into a never-ending cycle of magnificent landscapes that are successively reduced to sand grains and washed to the sea.

Hydrology and Water Supply in the Taos Region

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The Sangre de Cristo Mountains occupy the eastern half of the Taos region. Runoff from the steep slopes of Precambrian-age igneous rocks and Paleozoic rocks, largely limestone, supplies significant quantities of high quality water to the Taos Valley, recharges the region's aquifers, and provides most of the water used in the region. This paper provides a brief summary of water supply and water use in the Taos region.

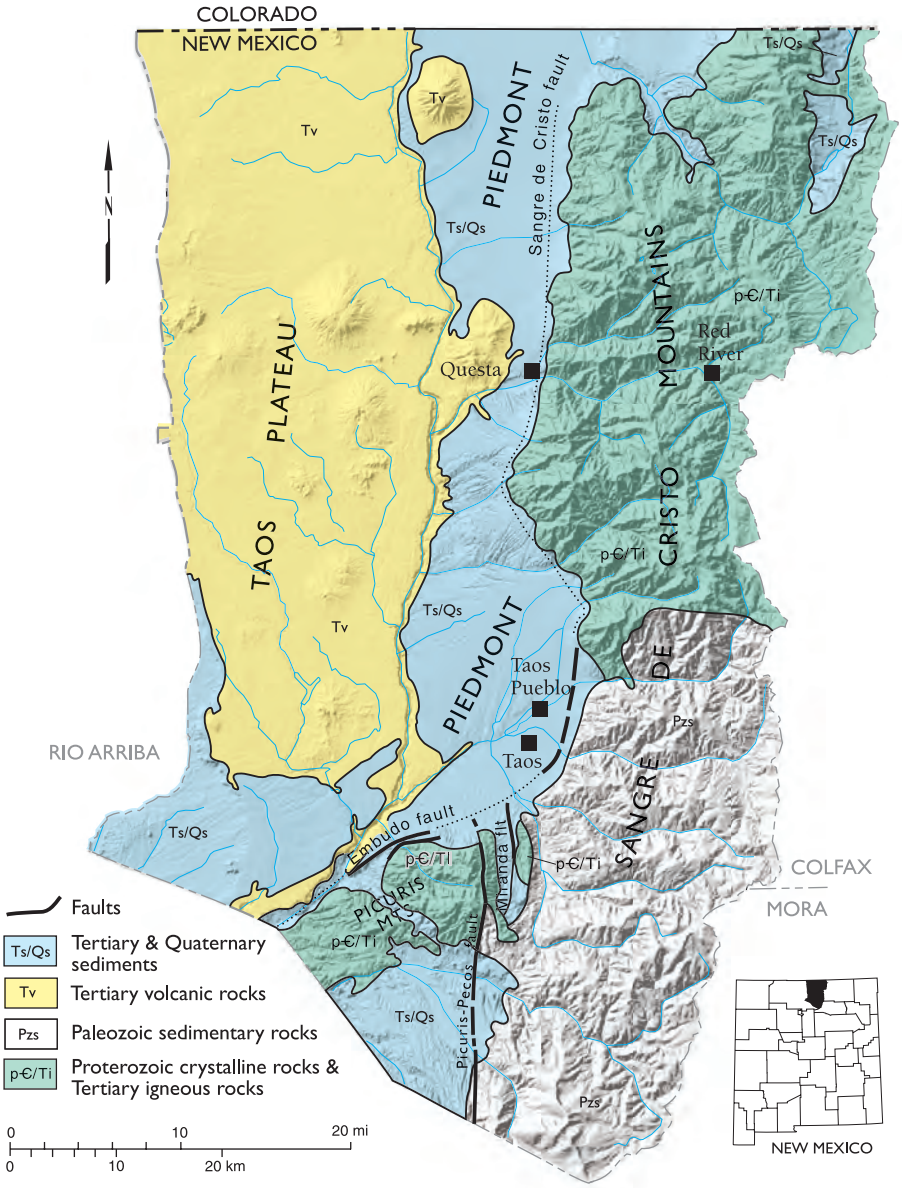
WATER SUPPLY

Water in streams and aquifers in the Taos region is important both locally and to downstream water users along the middle Rio Grande. In 2000 more than 92 percent of all water diversions in Taos County (which includes surface and ground water diverted for all uses) originated from surface water sources, and more than 97 percent of the region's domestic and public supplies originated from ground water. In short, surface water supports the region's agriculture and economy, whereas ground water provides almost all of the region's drinking water. The Taos region generates significant surface water resources through eleven perennial streams and rivers, which are important to local as well as downstream users, and stores large quantities of ground water distributed in various local and regional-scale aquifers, some of which have been developed. These two regional sources, surface water and ground water, are intricately linked, and both discharge to the region's principal hydrologic feature, the Rio Grande. The Rio Grande in Taos County is largely unavailable for use because its course is in a deep gorge through much of the region, and because most of its flow is committed downstream.

The entire Taos region is drained by the Rio Grande. The divide between the Rio Grande and Canadian River watersheds forms the county's eastern boundary. The Rio Grande brings an annual average of about 325,500 acre-feet across the state line from Colorado, but almost all of the water used in the region is supplied by the tributaries, which also contribute to the Rio Grande. The annual outflow from the region, as measured at the Embudo gage, averages 601,700 acre-feet. Thus, the Taos region contributes an average 276,200 acre-feet each year to the Rio Grande, which is more than two-thirds of New Mexico's maximum annual allocation of water under the Rio Grande compact.

As the perennial streams of the Taos region exit the high crystalline-bedrock valleys of the Sangre de Cristo Mountains and enter the lower alluvial valleys, a portion of their flow is generally lost to infiltration through the coarse sand and gravel of alluvial fans and slopes. Although this loss diminishes the stream's discharge, it in turn replenishes storage in the region's aquifers and sustains shallow water levels in the region's valleys. Mountain-front faults and low-permeability aquifer units can force shallow ground water to the surface in some localities, producing springs, seeps, and marshes and rejuvenating stream flow. The complex hydrogeologic conditions adjacent to the mountain front give rise to complicated interactions between water flow in streams and water flow in aquifers. As the region increases its reliance on ground water, withdrawals from the shallow aquifers via wells will eventually reduce stream flow by intercepting water that would otherwise maintain the streams or by drawing water directly from the stream channels.

Precipitation in the region is strongly influenced by elevation. Average annual precipitation ranges from less than 10 inches at Ojo Caliente (6,290 feet) to more than 20 inches at Red River (8,680 feet). Monthly precipitation is generally greatest in July, August, and September. Runoff in the Rio Grande tributaries, on the other hand, reaches its peak in April or May with melting of the accumulated winter snow pack. Both precipitation and stream flow conditions are highly variable from year to year, and "average" conditions are the exception rather than the rule. In general, historic stream flow fluctuates between periods of above-normal and below-normal discharge, separated by short periods of transition. The most severe dry conditions occurred between 1950 and 1964, when annual discharge for this fifteen-year period averaged only 341,000 acre-feet or 57 percent of normal. The wettest period on record occurred during the strong El Niño events of the mid-1980s, which



Generalized geologic map of Taos County.

produced a five-year average flow that was 180 percent of normal. (Given the precipitation records to date for this year, 2005 may become the wettest year on record.

WATER USE

Apart from small diversions and shallow wells in the narrow higher-elevation valleys, the region's water use takes place in the lower valleys adjacent to its perennial streams and along the east side of the Rio Grande gorge. About 99,557 acre-feet (97.9 percent of it surface water) was diverted for irrigation in the Taos region in year 2000, which in turn accounted for 92.7 percent of all the water withdrawn. Sixty-one percent (60,289 acre-feet) of the water diverted for irrigation was returned to streams. Water use for mining in year 2000 was 3,094 acre-feet, about 2,568 acre-feet of which (83 percent of the water diverted for mining) became return flow, available to other users. Overall, 60 percent of the water diverted for use in Taos County is returned to the streams and aquifers and remains available for other users.

Some 2,255 acre-feet, almost all from ground water, was withdrawn for public supply in 2000, and another 1,376 acre-feet was pumped from domestic wells. Ground water pumping for public and domestic supply roughly doubled in the fifteen years between 1985 and 2000. The largest user is the town of Taos, pumping roughly one-third of the public supply; the remainder is produced by the El Prado Water and Sanitation District and many small mutual-domestic systems. About 59 percent of the water pumped for public supply was returned to streams as treated wastewater; virtually all of the water from domestic wells is assumed to have been lost to evaporation.

WATERSHEDS

The perennial streams and rivers within the Taos region occupy large to intermediate drainage basins on the western face of the Sangre de Cristo Mountains. The principal watersheds in the region are summarized here:

Taos Valley

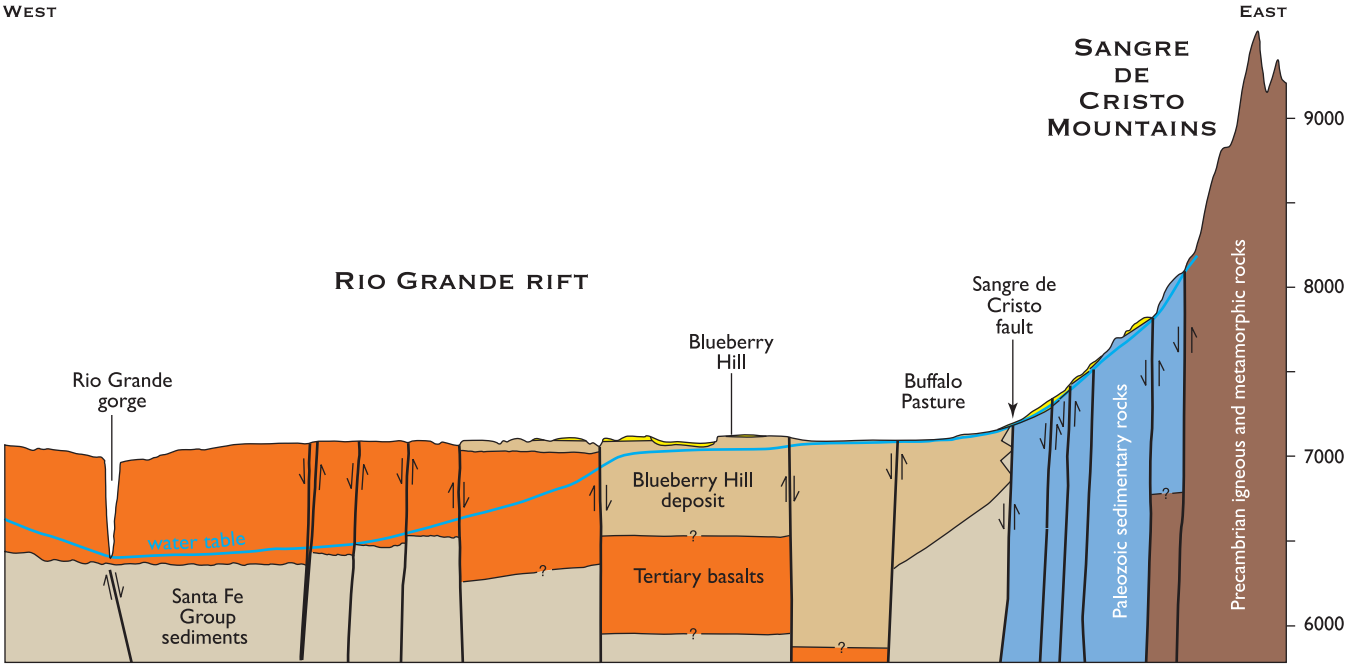
The Taos Valley includes two major drainages, Arroyo Hondo and the Rio Pueblo de Taos. The Rio Pueblo is

sustained by five major tributaries: Arroyo Seco, Rio Lucero, Rio Fernando de Taos, Rio Grande del Rancho, and Rio Chiquito. The combined drainage area of these streams is about 530 square miles. Much of the discharge in these streams is diverted for irrigation in summer, but a combination of return flow from irrigation and winter flows provides recharge to a complex aquifer system and augments flow in the Rio Grande.

The water table is at land surface in much of the eastern part of the valley, creating Taos Pueblo's Buffalo Pasture and other marsh areas and supporting innumerable small seeps and springs. These occur where the highly permeable, shallow aquifer thins, loses storage capacity, and is unable to transmit the full amount of the recharge entering the aquifer along the foot of the eastern mountains. The water table has declined in recent years, partly in response to drought and presumably also due to increased ground water pumping. The surface area of the Buffalo Pasture is said to have decreased, some springs have stopped flowing, and many shallow wells have failed.

Recharge moves westward away from the mountain front, and downward through a sequence of basalt flows and interbedded sediments close to the surface, then through sandstone, mudstone, and conglomerate beds of the Tertiary-age Santa Fe Group aquifer before discharging into the Rio Grande. The Rio Grande gorge at the western edge of the Taos Valley is 500–600 feet deep, and the 700–900-foot elevation difference between the areas of recharge and the Rio Grande, over the relatively short distance of 7–9 miles between the river and the mountain front, leads to a strong downward component of ground water flow, and probably to perched ground water and unsaturated conditions below the water table in many places. Recharge to the Taos Valley aquifer system probably averages about 37,500 acre-feet per year, a third of which is in the form of seepage from irrigation. About 15,000 acre-feet per year, or 21 cubic feet per second, discharges to the Rio Grande through seeps and springs, and flow through the channel bottom, between the mouth of Arroyo Hondo and the Taos Junction gage.

Pumping tests of wells indicate ranges in flow from a few tenths of a foot per day to 22 feet per day for the alluvium, from about 5 feet to more than 25 feet per day for the underlying Tertiary-age basalt and associated sediments, and from a few tenths of a foot to about 2 feet per day for the still deeper Tertiary-age Tesuque Formation beds in the basin fill. Well-yields vary from place to place, but pumping rates as high as



Geologic cross section showing approximate location of the water table in the Taos region. Recharge from the mountains infiltrates and moves westward toward the Rio Grande. Ground water flow is influenced by the geologic materials in the subsurface and by geologic structures, such as faults. Colors correspond to the geologic map on the inside back cover. Note that the vertical scale is exaggerated in order to show topography. Courtesy of Paul Bauer, from unpublished data.

several hundred gallons per minute have been reported for wells tapping the relatively shallow alluvium. Rates for wells in the underlying basalt and associated sediments have been as high as 120 gallons per minute and, for the still deeper beds, as high as 500 gallons per minute.

Pumping from wells affects the flows in the streams near the mountain front. Because of the strong downward flow and potential for some disconnect between shallow and deep ground water, it is likely that future wells will be deep, cased through the upper part of the aquifer, and preferentially located near the Rio Grande, in order to minimize both the effects on the streams and drawdown in the many shallow wells. Wells are commonly less than 200 feet deep in the eastern part of the valley, but must be more than 800 feet deep near the Rio Grande to penetrate below the water table. There are an estimated 1,900 private domestic wells in the Taos Valley.

The combined average yield of the Taos Valley streams is estimated at about 94,000 acre-feet per year, varying from about 80 percent of that (or 76,000 acre-feet per year) in "dry" years to 138 percent of that (or 129,000 acre-feet per year) in "wet" years. (Dry and wet years are defined by the 25th and 75th percentile, respectively, of flow in Arroyo Hondo and the Rio Pueblo de Taos.) Ditches on Taos Pueblo lands plus some fifty-five acequias on non-pueblo lands irrigate about 14,000 acres along the eastern side of the valley. Although the average annual flows of the streams that serve these ditches and acequias are theoretically sufficient to supply them, the variability from year to year, and the concentration of flows during the spring and early summer, lead to shortages during late irrigation season in most years. There is no reservoir storage on most streams.

Sunshine Valley

The Sunshine Valley is a high plain lying between the Sangre de Cristo Mountains and the Rio Grande, and between Questa and the Colorado state line. Shallow ground water pumped from alluvium, Santa Fe Group basin fill, and interbedded basalts irrigates about 600 acres (year 2000). There are no perennial streams. Recharge to the Sunshine Valley aquifer has been estimated at 20,000 acre-feet per year. If there were no ground water pumping, this amount would discharge from the aquifer system to the Rio Grande. Well yields in the Sunshine Valley are generally as high as 1,200 gallons per minute, but a 3,000-gallons-per-minute well has been reported. The high permeability of the alluvium and basalts, which accounts for the high yields, also leads to large depletion of flow in the Rio Grande as a result of pumping.

Costilla Creek Valley

Costilla Creek drains the northern Sangre de Cristo Mountains, yielding an estimated average of about 29,000 acre-feet per year. Costilla Reservoir, at almost 9,500 feet in elevation and with a nominal capacity of 16,500 acre-feet, regulates deliveries. Eighteen acequias serve about 5,500 acres of irrigation, and also deliver water to irrigators in Colorado and the Sunshine Valley. Ground water use is limited to domestic and livestock supplies, and about 100 acres of irrigation.

Red River Valley

The Red River watershed yields an estimated average of about 50,400 acre-feet per year. The thin, narrow body of alluvium in the bottom of the valley and fractured bedrock close to the river are sufficiently permeable to support relatively high yield wells, but their production is, in effect, diversion from the river. About 3,100 acres are under irrigation from the Red River and its tributary Cabresto Creek. The Molycorp operations above Questa represent the only other large diversion. The town of Red River diverted about 87 acre-feet of surface water in 2000 and pumped about 487 acre-feet of ground water for public supply.

This summary is based on published reports, but water rights in the Taos Valley are in the process of adjudication, and much new work, confidential as of this writing, has been done to refine the inventory of irrigated acreage, the understanding of the flows in streams and the ground water system, and the expected pattern of future water use.

Suggested Reading

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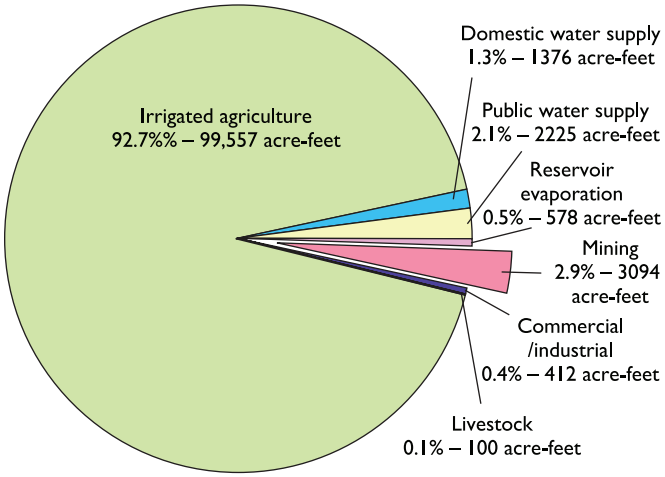
A History of Agricultural Water Development in the Taos Valley

Peggy Johnson, *New Mexico Bureau of Geology and Mineral Resources*

The agricultural tradition in the Taos Valley began hundreds of years ago with Pueblo culture, expanded with Spanish settlement, and continues today as an important economic foundation for rural communities in the valley. Irrigated agriculture is sustained in Taos, and throughout much of the Rio Grande valley, by stream flow originating in the Sangre de Cristo and Picuris Mountains east and south of the Taos Valley. The ancient and historic settlement patterns that created the present-day population centers surrounding Taos Pueblo, Taos, El Prado, Ranchos de Taos, Ranchitos, Cañón, and Arroyo Hondo among others, were determined by the abundance of fertile land and irrigation waters surrounding the valley's major streams.

Although irrigation in the Taos Valley is typically associated with the Spanish acequia culture, the practice of irrigated agriculture was initiated by Pueblo farmers long before Spanish settlement. When the Spanish first arrived in the Taos Valley in 1540, they were notably impressed by the stature of Taos Pueblo. Narratives of the Coronado expeditions noted that all pueblos, including Taos, grew maize, beans, and squash, and observed that the Rio del Pueblo (Rio Pueblo de Taos) that divided the village flowed swift and deep. When Spanish settlers returned to the Rio Grande in 1598, Juan de Oñate admiringly described Pueblo agriculture to the Spanish king and viceroy, noting that the Pueblo Indians were skilled farmers. Some fields were irrigated, and others relied on summer rains. The region later proved particularly well adapted for irrigated wheat production, and bumper crops grown with a dependable water supply made the region New Mexico's breadbasket when shortages threatened elsewhere. Today 92 percent of Taos County's water requirements (107,342 acre-feet) are supplied by surface water, most of which is used for irrigated agriculture.

The issues of population growth, water demand, and over-allocation that dominate today's headlines and planning agendas first emerged with Spanish colonization on land surrounding Taos Pueblo. During the turbulent years before the Pueblo Revolt of 1680, early Spanish occupants settled along the rivers north and west of the pueblo to take advantage of the fertile lands and abundant water for irrigation. Post-revolt resettlement in the Taos Valley renewed requests for agricultural and grazing lands situated along the valley's major streams, resulting in land grants throughout the valley by the Spanish government. One of the earliest references to a specific acequia in the Taos area (September 1715) cites the Acequia de los Lovatos, the eastern boundary of the Gijosa Grant, which originates in the Rio Pueblo and is still in use today. Modern records document approximately eighty acequias and ditches operating in the Taos Valley, most of which date from Spanish development in the eighteenth and nineteenth centuries.



Distribution of water use in Taos County today.

Early settlers and provincial officials knew that no community could exist without an assured water supply. As early as 1795, accelerating population growth caused increased competition between Hispanos and Pueblo Indians for water, and the early New Mexican water administrators (*cabildos or ayuntamientos*) developed various methods to adjust land policy with water availability in a semiarid environment. Hence began the practice of water administration that still embroils the region today.

From the earliest Spanish chronicles of water resources to the recent state engineer assessments in the late twentieth century, observers have noted, quantified, and apportioned the prodigious but highly

Drainage basins and streams in Taos County.

variable flows in the major streams of the Taos Valley, which include the Rio Hondo, Rio Lucero, Rio Pueblo de Taos, Rio Fernando, and Rio Grande del Rancho. The Red River, which occupies a major watershed north of Arroyo Hondo, drains the area developed by the Molycorp molybdenum mine and provides water for irrigation and domestic use for the community of Questa. These six streams and their watersheds provide much of the water that sustains the Rio Grande on its course through New Mexico.

RIO PUEBLO DE TAOS AND RIO FERNANDO

The Rio Pueblo drains an area of 67 square miles in the Sangre de Cristo Mountains and produces an average annual discharge of approximately 22,000 acre-feet. Waters from the Rio Pueblo have been used by residents of Taos Pueblo for untold years before Spanish settlement, but the earliest written descriptions of the valley were made by Franciscan friars during visits to New Mexican missions. These early reports always noted the "fair-sized rivers" and the fields of wheat and corn cultivated by Taos Indians and irrigated from the Rios Lucero and Pueblo. The earliest Spanish settlement along the Rio Pueblo began downstream of Taos Pueblo with authorization of the Gijosa Grant on September 20, 1715. A population explosion during the 1790s caused increased competition for land and water between settlers and the pueblo and among the settlers themselves. A census in 1796 confirmed a Pueblo Indian population of 510 at Taos and 199 at Picuris, approximately one-half of the area's total population. The Hispano population had grown from 330 to 779 since the last census in 1790, a 135 percent increase in six years. The census indicated about ten families at each of the villages within the Gijosa Grant along the Rio Pueblo now known as Upper and Lower Ranchitos.

Despite being the smallest of the principal tributaries feeding the Rio Pueblo de Taos, the Rio Fernando irrigates many acres of crops and pasture. Dependent on springs and snowmelt, the Rio Fernando drains 70

square miles below Palo Flechado Pass in the Sangre de Cristo Mountains, with a mean annual discharge of 4,140 acre-feet. Authorized Hispano settlement began in 1796 with the Don Fernando de Taos Grant, which encompassed lands adjacent to Taos Pueblo and bisected by the Rio Fernando. With sixty families taking residence in the first year, followed by a number of new arrivals a year later, the Fernando Grant quickly became the largest Hispano community in the valley. In the fall of 1797, after only two planting seasons, a request was made by the new residents for rights to the surplus waters (*sobrantes*) from the Rio Pueblo and Rio Lucero, suggesting that the Rio Fernando had already proved inadequate for the settlers' needs. A *sobrante* right meant that the newcomers at Don Fernando could use any water remaining after Pueblo farmers had satisfied their requirements. For many years Hispano farmers managed to maintain good relations with the pueblo, and irrigators found ways to share the stream's water without resorting to lawsuits. In 1871, however, litigation changed the settlers' sobrante right into an absolute share, thus initiating an era of repeated controversies over apportionment between the pueblo and downstream users. The Abeyta adjudication represents the current apportionment suit.

An unusual water management case, possibly the first with environmental implications, occurred on the Rio Fernando in the spring of 1877. Several landowners who depended on the Rio Fernando for irrigation water complained that a certain Juan Sánchez had been systematically cutting down large numbers of cottonwood trees near the river's headwaters, thus eliminating the cooling shade that protected the stream. Exposure to the blazing sun, they claimed, would cause water shortages from evaporation. The presiding judge ruled in favor of the plaintiffs, finding that excessive timber cutting in the bosque would lead, little by little, to diminution of the water necessary for agriculture in the valley. Thereafter, anyone convicted of such destruction would be regarded as a transgressor, subject to all the rigors of the law. Although nineteenth century New Mexicans appeared generally unaware of environmental issues, this case demonstrates an intuitive understanding of the basic concepts of a hydrologic cycle and water balance applied by present-day hydrologists.

RIO GRANDE DEL RANCHO

The Rio Grande del Rancho, with tributaries the Rio Chiquito, the Rito de la Olla, and Arroyo Miranda, drains the south side of the Fernando Mountains and the north side of the Picuris Mountains. This fairly large watershed (150 square miles) is mostly coincident with the Rio Grande del Rancho Land Grant authorized in 1795 and includes the towns of Talpa and Llano Quemado. Diversion of stream flow below Talpa through nineteen acequias and ditches currently provides irrigation for more than 3,380 acres. A stream gage located on the Rio Grande del Rancho near Talpa has operated since 1953, recording a mean annual discharge of 15,340 acre-feet.

The oldest Spanish grant in Taos Valley, authorized on June 15, 1715, to Captain Cristóbal de la Serna, allocated a tract of agricultural and grazing land west of the Rio de las Trampas (Rio Grande del Rancho) near present Ranchos de Taos. The Serna Grant was later sold to Diego “El Coyote” Romero, developed successfully, and passed to his heirs. One of the earliest conflicts concerning water and land allocation occurred along the Rio Grande del Rancho when Ranchos residents protested upstream settlement by outsiders on the proposed Rio Grande del Rancho Grant early in 1795. Additional irrigation above their fields, they said, would inevitably diminish their share of the river's flow and endanger the livelihood of present landowners (and added that decreased harvests meant a corresponding decline in tithes and first fruits necessary for maintenance of the church). In an effort to thwart upstream settlement, the protestors petitioned the governor, asking that they themselves receive possession of the grant lands. The request was approved on February 4, 1795, thus consolidating control of the river's headwaters into the hands of the Ranchos residents.

THE RIO LUCERO AND ARROYO SECO

Arroyo Seco and the Rio Lucero begin in adjoining canyons south of the Rio Hondo and run southwest from sources high in the Sangre de Cristo Mountains to meet the Rio Pueblo near Los Cordovas and Upper Ranchitos. Settlement between the Lucero and the Hondo began before the Pueblo Revolt of 1680 and continued through the eighteenth century in a bewildering series of overlapping grants, including Antonio Martínez in 1716, Pedro Vigil de Santillanes in 1742, and Antonio Martín in 1745. Actual colonization at Arroyo Seco and Desmontes was delayed until the early nineteenth century, when the land between Arroyo Seco and Arroyo Hondo came under the control of Mariano Sanches, an aggressive land developer, who began a vigorous campaign to colonize the brush-covered flats. In a plan involving exchange of

The Embudo Gage and Stream Flow Measurement in Taos County

Embudo gage today.

Modern efforts to measure discharge from the region's streams rely on a series of stream gages or measurement stations installed and administered by the U.S. Geological Survey (USGS) and the New Mexico Office of the State Engineer and Interstate Stream Commission. The oldest such station in the United States, active since 1890, is located on the main stem of the Rio Grande at Embudo station. In March of 1888, responding to a sudden interest in western irrigation, Congress passed a joint resolution authorizing the Secretary of the Interior to examine potential irrigated lands, locate possible sites for water storage, and determine the capacity of various streams. Responsibility for the project fell to John Wesley Powell, then serving as director of the U.S. Geological Survey. Recognizing a shortage of personnel trained in water measurement, Powell ordered the establishment of a school for hydrographers on a western river. The Rio Grande near Embudo station was selected because of its location in an arid region on a major stream unlikely to freeze in winter. For five months between December 1888 and April 1889, eight recent graduates from prestigious eastern engineering schools worked under Frederick Haynes Newell to learn a technique of water measurement known as stream gaging. The class made regular measurements of water temperature, depth, and velocity in the Rio Grande at Embudo station from a makeshift raft, thus providing the first such measurements recorded in the United States.

Historically, thirty-five such stations have operated between the New Mexico–Colorado state line and Embudo, although only twenty-one are currently active. These gages measure stream discharge (in units of cubic feet per second or cfs) on an hourly basis. Real-time data reflecting current conditions are recorded at 15 to 60 minute intervals, stored on site, and then transmitted to USGS offices every four hours. Recording and transmission times may be more frequent during critical events. Data from real-time sites are relayed via satellite, telephone, or radio and are available for viewing within three minutes of arrival. Online data for Embudo station can be found at **http://nwis.waterdata.usgs.gov/nwis/nwisman/?site_no=08279500&agency_cd=USGS**.

These geologists measuring flow on the Arkansas River in Colorado ca. 1890 are using procedures developed at Embudo.

What began at the Embudo gage in 1889 developed into a program encompassing approximately 1.5 million sites in all fifty states, the District of Columbia, and Puerto Rico. This network of stream gage stations provides a critical dataset that allows monitoring during critical flood events, supports a statistical assessment of the amount of water available for diversion and use, and facilitates water management and administrative decisions.

land for services, the entrepreneur offered potential farm sites to workmen (*trabajantes*) enlisted to clear (*desmontar*) the plain's thick growth of sage, piñón, and juniper. Named by the brush cutters, Desmontes grew up as a scattered settlement on the high, dry plains north and west of the Arroyo Seco. Not surprisingly, Arroyo Seco provided only a bare minimum of water for irrigation, causing the trabajantes to cooperate in the construction of two major canals that divert waters from other streams. Each one represents a formidable project; both are still in use. The Acequia Madre del Rio Lucero del Arroyo Seco diverts water from the Rio Lucero and runs it for more than a mile across the dry plain to Arroyo Seco Creek, where it follows the channel downstream for later diversion or crosses the creek for distribution through a network of smaller ditches totaling several miles in length. The main canal, La Acequia de la Cuchilla, represents an even greater task. Diverting water from the Rio Hondo above present Valdez, the Cuchilla climbs up the south wall of Hondo Canyon for more than two miles before reaching the plain at the top, where it divides into several laterals that water fields at Desmontes. The ditch, which seems to run uphill, is still regarded

The Rio Hondo in the Wheeler Peak area.

with awe by professional engineers. However, Arroyo Seco's claims to water from two other rivers caused recurrent disputes with Arroyo Hondo, Taos Pueblo, and Fernando de Taos.

RIO HONDO

From its source among the high peaks of the Sangre de Cristo Mountains, the Rio Hondo rushes westward past the villages of Valdez and Arroyo Hondo before joining the Rio Grande 14 miles northwest of Taos. With an average annual discharge of more than 25,000 acre-feet, the river irrigates 3,700 acres through fifteen acequias. Official colonization in the Hondo Valley began in 1815 with authorization of the Arroyo Hondo Grant. Settlers along the Rio Hondo lived in harmony with their southern neighbors on the plain until the founding of San Antonio (today's Valdez) in 1823. While certifying Arroyo Hondo Grant papers in 1823, Alcalde Juan Antonio Lovato added language to the grant records in order to resolve the water dispute with Arroyo Seco. Lovato made the right of Arroyo Hondo village superior to that of San Antonio, and put both ahead of Arroyo Seco and Desmontes. Desperate for irrigation water, residents of the southern plain persuaded Arroyo Hondo to allow them a substantial part of the flow from their stream, a practice that became a matter of local custom. After New Mexico became a territory, citizens turned to the newly established court system to resolve water disputes. On May 19, 1852, Arroyo Hondo again brought suit in probate court against the inhabitants of Desmontes to determine rights of the two communities to water from the Rio Hondo. The presiding judge ruled that Arroyo Hondo had first priority, but allowed Desmontes one-third of the river's flow, even in time of scarcity. According to local residents this apportionment is still observed by the mayordomos of the acequias involved, with Arroyo Hondo's two-thirds divided between its own users and those of Valdez and Cañoncito.

Suggested Reading

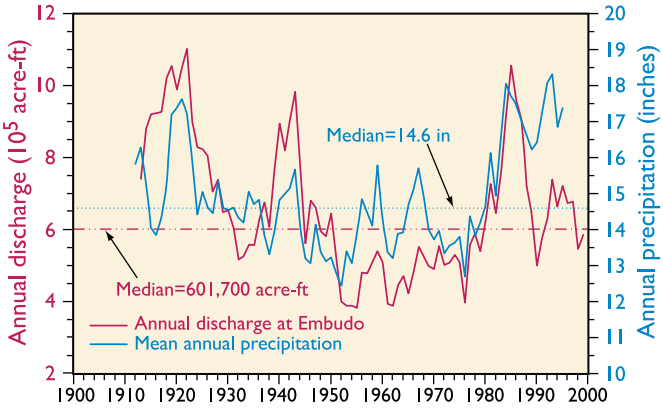
Historic notes regarding Pueblo and Spanish agriculture and water development and early New Mexican water administration are taken from the two works of Baxter listed below. Information on water availability in the region's major streams is from the two Johnson references listed.

Baxter, John O., 1990, Spanish irrigation in Taos Valley. New Mexico State Engineer Office, Santa Fe, NM, 126 pp.

Baxter, John O., 1997, Dividing New Mexico's waters, 1700-1912. University of New Mexico Press, Albuquerque, NM, 135 pp.

Johnson, Peggy, 1998, Surface-water assessment, Taos County, New Mexico. New Mexico Bureau of Geology & Mineral Resources Open-File Report 440.

Johnson, Peggy, 1999, Availability and variability of surface-water resources in Taos County, New Mexico - an assessment for regional planning. New Mexico Geology, vol. 21, no. 1, February 1999.



Five year moving average of annual discharge for the Rio Grande at Embudo, compared to mean annual precipitation for Cerro, Red River, and Taos.

Taos County's Mineral Heritage—A Unique Page in New Mexico's Mining History

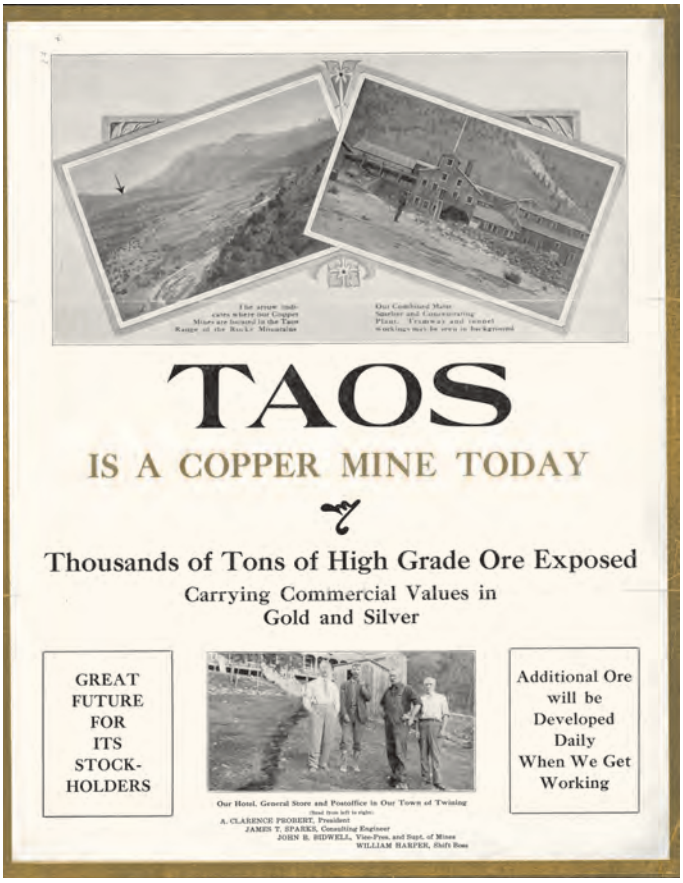
Robert W. Eveleth, *New Mexico Bureau of Geology and Mineral Resources*

Mighty mountains, sparkling streams, valleys fair to look upon, set like precious stones in a region which combines the lovely and the lofty, the bold and the beautiful, the placid and the picturesque—this is the new El Dorado of Red River, Taos county, northern New Mexico…. –Anon 1897

The mineral riches and grandeur of Taos County that moved this unknown scribe to wax so eloquently have weighed heavily on the human imagination since prehistoric times, beginning in earnest soon after the arrival of the Spanish in 1540. However, various factors limited the development of its resources on a large scale well into the twentieth century. Remoteness and elevation were major adversities, then and now. The infrastructure usually associated with heavy industry, such as main and branch line railroads and factories, was totally lacking or long in coming. Moreover, the high country, one of the county's many endearing attractions, has always been difficult to access.

Native Americans took advantage of the mineral substances indigenous to the area for uses that they deemed necessary to their everyday lives: clay and mica for the manufacture of pottery, the various silica minerals for fashioning tools, knives, and weaponry, and certain colorful minerals for use in personal adornment and pigmentation. Historically speaking, gold placers, particularly at Arroyo Hondo, as well as other mines and prospects in the "Embuda" and Picuris areas, were said to have been worked by the Spanish long before the Pueblo Revolt in 1680. American miners often encountered evidence of their Spanish predecessors. Garnet "mines" were reported in the Picuris area around 1627 by Father Salmeron, and the ex-governor of Picuris Pueblo escaped the rather serious charge of witchcraft by disclosing the location of four veins of silver in Picuris Canyon in 1713. Prospectors during the Mexican period (1821–1848) worked the placers near what would become Amizette during the 1820s and 30s.

Taos County's many contributions to mineral discoveries and developments elsewhere in the Old West are also of significance. Many of the legendary pioneer trailblazers such as Kit Carson, Lucien Maxwell, and others were involved with mining and prospecting in Taos County and environs. Taos miner J. P. L. Leese arrived in California in 1833 or 34 with a considerable quantity of gold dust—gold that likely originated from the Arroyo Hondo placers, the small product of which had long been traded in Taos commerce and became part of the first gold shipment out of California.



The Taos Mining Company (a successor to the Fraser Mountain Copper Company) was without doubt the most elaborate and costly attempt to develop the elusive metal deposits in the Red River district before 1920. The mill and smelter at the base of Frazer Mountain are pictured along with company officials Clarence Probert, James Sparks, John Bidwell, and William Harper. [Author's collection.]

The Denver & Rio Grande Western Railroad pushed its narrow-gage tracks south from Antonito along the western flanks of the Rio Grande through such garden spots as No Agua, Tres Piedras, and Embudo, thereby forever bypassing the more populous Taos. Thus Tres Piedras (shown here in this ca. 1910 view) and Embudo were Taos county's sole railroad shipping points. Had the railroad survived beyond 1941, it doubtless would have thrived on the No Agua perlite traffic. The long abandoned Tres Piedras water tank still stands today.

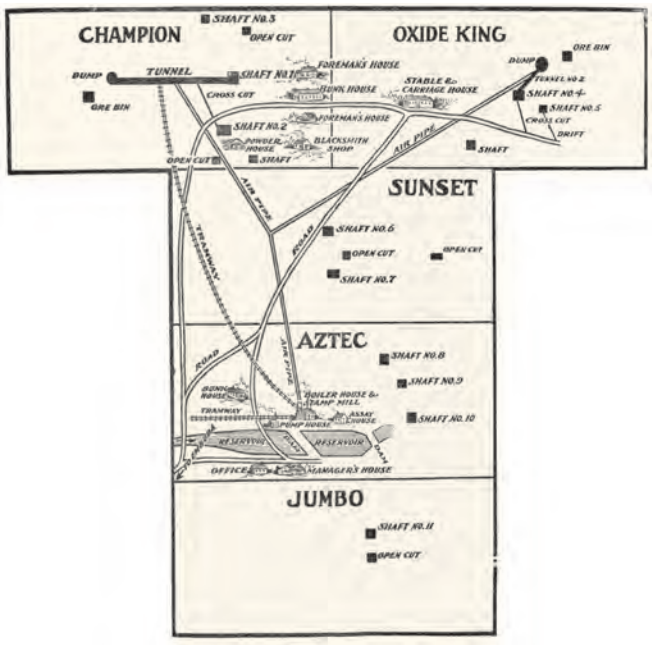
The instrument that opened the floodgates to the vast American West, including New Mexico west of the Rio Grande, was the 1848 Treaty of Guadalupe Hidalgo, which transferred ownership of much of Arizona and New Mexico from Mexico to the U.S. The new American proprietors immediately assumed the responsibility of dealing with the Apaches, Comanches, and others; they spent the next half-century engaging in military action to pacify the region. The American military provided some of the earliest accounts of rich mines and mineral resources. The early American press obligingly waxed eloquently on the existence of rich mines in the Taos area and elsewhere in the new territory and fired the imaginations of American prospectors. But the greatest influx of prospectors came with the close of the American Civil War.

MT. BALDY TO THE TAOS RANGE

Fort Union, near present day Watrous in Mora County, was the principal supply depot for the military infrastructure in New Mexico Territory and was of paramount importance in protecting travelers and the pioneer merchants along the Santa Fe Trail. All representatives of Old West society ventured to this outpost, including Native Americans who regularly traded with the prospectors stationed there. In 1866 a Ute stopped by with some high-grade copper specimens to barter for supplies and was directed to William Kroenig and others of the prospecting fraternity. Recognizing the potential value, the group either traded or paid the Indian for the specimens and, as part of the deal, were escorted to the locality near the top of Mount Baldy (near Elizabethtown) where they located the famous "Mystic Copper Mine." Additional prospecting soon revealed the presence of placer gold on Ponil Creek, and the rush was on. Elizabethtown was soon established; from there the miners fanned out to the west toward Taos and scrutinized the major drainages and peaks in search of more treasure. The few prospectors in the Taos area were doing much the same in reverse by tracing the placers eastward to their sources. Many promising discoveries followed, and miners were soon working the ground at Arroyo Hondo and Red River. During the next two decades localities such as Black Copper, Keystone, Anchor, Midnight, LaBelle, Gold Hill, Twining, and Amizette experienced the touch of the pick, shovel, pan, and sluice.

The arrival of the railroads in the 1880s brought immediate attention and development to New Mexico's vast coal resources: Magdalena's lead, silver,

The Independence mine on Bitter Creek, Red River, ca. 1905.



Sketch map of surface improvements at the Champion Copper Company property on Copper Hill, Picuris district, from the 1917 annual report. Most of the improvements should have been postponed pending the development of economically minable ore.

and zinc deposits, and southwestern New Mexico's base and precious metal districts. For a time Taos County was left far behind in the developmental scheme of things. The Denver & Rio Grande Western Railroad constructed its right of way down the west bank of the Rio Grande (thereby avoiding a very costly bridge across the gorge but forever bypassing Taos) through such thriving burgs as No Agua, Tres Piedras, and Embudo, on its way to a terminus in the Española Valley, the only real population center along the line. The inevitable talk of a branch line railroad was revisited as each little mining camp experienced its fleeting moment in the sun. The railroads wisely assumed a "wait and see" stance, with the result that Tres Piedras, Taos Junction, and Embudo were, through September 1941, the only real railroad shipping points Taos County ever had.

LATE NINETEENTH / EARLY TWENTIETH CENTURY MINING VENTURES

Despite nearly a century of prospecting, exploration, and sometimes extraordinary developmental effort, few if any mines and prospects in Taos County could be considered successful before 1920. Small zones of high-grade precious metal-bearing ores were occasionally encountered, which only further served to encourage the miners to pursue the inconsistent and elusive deposits so typically hosted by the Precambrian and Tertiary rocks in the Taos County area. Notably rich but woefully small pockets of gold ore were discovered in such mines as the Memphis and Independence (both on Bitter Creek). These discoveries too often resulted in premature, ill-advised investments in elaborate milling and, at least in one case, smelting facilities at properties such as the Caribel Group on Pioneer Creek, the Buffalo–New Mexico property on Placer Creek, the Champion Copper Company on Copper Hill, the Fraser (sic) Mountain Copper Company mine at Twining, and many others.

Arthur Montgomery and crew sorting beryl ore at the Harding pegmatite mine, Taos County, New Mexico, ca. 1952. The Harding was at times the nation's leading producer of beryl and the rare-earth minerals columbite-tantalite and microlite.

Even with the extravagant efforts of the Fraser Mountain Copper Company (and its successor, the Taos Mining Company) and others, the mineral production record for Taos County before 1923 was approximately $100,000—a mere trifle of the amount invested. The small production of gold dust won by the pioneer miners went largely unrecorded, but regardless of all the hype, hope, and eternal optimism expressed by such camps as Amizette, LaBelle, Black Copper, and others, officially credited production is at or near zero. Events in the twentieth century would quickly change all that, and Taos County would finally enter the ranks of world-class mineral producers.

ALL THAT GLITTERS IS NOT GOLD (SOME OF IT IS MICA)

Taos County is unique among New Mexico's mineral producers for commodities such as beryl, columbite-tantalite, microlite, and one of the world's largest deposits of optical calcite at the Harding mine; mica (sericite) at the U.S. Hill (Tojo) mine; and molybdenum at Questa. Add to that the No Agua perlite, and the value of Taos County's mineral production *since* 1923 (exclusive of sand, gravel, and crushed stone products) approaches a half *billion* dollars.

The Harding pegmatite, located as early as 1900, went largely unappreciated until a miner from the Black Hills recognized in 1919 the true identity of the mineralogical suite. The lithium-bearing minerals were found to be of value in the manufacture of glass (and Edison's alkaline storage batteries), and a new industry was born. The Embudo Milling Company erected a grinding plant at Embudo station on the Denver & Rio Grande Western Railroad and shipped over 10,000 tons of lithium-bearing concentrates before suddenly ceasing operations in 1930—due, it is said, to the contamination by some "troublesome" tantalum mineral. The mine ultimately proved to be a veritable treasure trove of rare and unusual minerals (including that very same troublesome columbite-tantalite and microlite, beryl and optical-quality calcite. The Harding pegmatite yielded the lion's share of the nation's tantalum supply—over 20,000 pounds of microlite and columbite-tantalite concentrates during World War II—and at times was the nation's leading producer of beryl. The nearby Iceberg calcite deposit, the second largest ever discovered in the world, produced well over 1,000 pounds of optical-quality material, much of it sold to Bausch & Lomb Optical Company. The U.S. Bureau of Standards, upon examination of the crystals and rhombs, declared them "to be the finest in quality and the largest in size ever known." The mine is now a priceless mineralogical and geological "laboratory" administered by the University of New Mexico, a gift of the late Arthur Montgomery.

The yellowish outcroppings near Questa, originally thought to be sulfur, turned out to be ferrimolybdite and were an indication of a subsurface molybdenum sulfide deposit. The Molybdenum Corporation of America acquired the property from its early owners in 1920 and has since produced molybdenum sulfide more or less continuously. The mine has gone through three distinct phases beginning with traditional underground methods focusing on the narrow, high-grade veins, then evolving into open-pit mining in 1965, and finally back to large-scale underground mining of lower-grade material in 1983. Milling at Questa has similarly gone through many technological changes and improvements since the early days. Questa is truly a world-class deposit, having produced about a quarter billion pounds of molybdenum sulfide to date.

The value of perlite went unrecognized until the late 1940s. Within a few short years of initial testing and research, perlite was found to be invaluable for a whole host of end uses including lightweight aggregates, abrasives, potting soil additive, filtering media, insulation, absorbents, and many others. The No Agua perlite deposit a few miles north of Tres Piedras, currently recognized as the world's largest, gave Taos County its second so-called "world-class" deposit. F. E. Schundler built the first mill in the district and began production in 1951. Johns Manville took over the property in 1959, and since then several other companies and/or successors have been active in the district.

Mica, unlike perlite, has a long history of exploitation in New Mexico but was of little economic importance until recently. One of the largest recently mined deposits of mica (sericite) in the United Stated is at the U.S. Hill mine (aka Tojo) in southeastern Taos County, once owned and operated by the cleverly named "Mineral Industrial Commodities of America, Inc." (M. I. C. A.) and most recently by Oglebay Norton. The ore is mined by standard mechanical stripping techniques, screened, and then trucked to the company's grinding and flotation mill on the Rio Grande near Velarde. Reserves are sufficient for decades of operations, but the future of the mine is in doubt due to very strong resistance of the local populace over environmental and cultural concerns (the local pueblos use the mica in their pottery).

MINING LAWS, THE ENVIRONMENT, AND THE FUTURE

Attitudes and opinions of society have changed radically. Well into the middle of the twentieth century Americans often perceived their local mining activity with a sense of pride. Despite the tradeoffs, such as mine dumps and sometimes malodorous mills, they were keenly aware of the economic benefits. This is the two-edged sword of our mining legacy: The benign side is represented by the vast amounts of wealth and useful materials won from the earth. The negative side is represented by the non-essential byproducts derived from those commodities: tailings dams, slag piles, and other wastes left over from past operations.

What has changed most, however, is the world's population, and that has spawned a staggering demand for the mineral feedstocks of civilization. The mining industry has responded by conducting operations on a much larger and more efficient scale. Where the pick, shovel, sluice, pan, and single-horsepower haulage once prevailed, miners of today take advantage of motorized trucks capable of hauling a hundred times more tonnage in a single load than our pioneer miners handled in an entire week. A similar revolution has taken place in the explosives end of the business: Black powder and hand steel have given way to multi-gang hydraulically operated percussion drills capable of drilling hundreds of feet of blast hole in a single 8-hour shift, which, when loaded with modern-day explosives, break hundreds of thousands of tons in a single blast. The downside of this modernization and efficiency is that piles of non-ore-bearing rock and other waste streams have grown enormously. The magnitude of environmental problems has soared, and we have all become more cognizant of the fragility of our environment.

Our increasing population is rarely perceived as part of the underlying problem; instead our ire is usually focused on the laws that permit the development of mineral deposits in the first place. The days are gone forever when an individual or a company could develop and mine a mineral deposit on and within lands of the United States, whether under the purview of the American Mining Law, the Minerals Leasing Act, or the Saleable Minerals Act, without full environmental compliance. Anyone desiring to participate in such activity today is subject to superior laws and regulations (such as the Clean Air and Water Acts, National Environmental Protection Act, and dozens of others) administered at the federal, state, and local level.

Today, environmental, cultural, and a host of other considerations are carefully weighed against the need to extract resources. If the former are deemed more critical or socially valuable than the latter, a mine such as that at U.S. Hill could quickly become part of history or never make it through the permitting process. These issues will challenge us as we become more, not less, dependant upon a reliable stream of mineral commodities. Balancing our need for them against the desire for a pristine environment and the preservation of our cultural heritage will doubtless be among the more vexing issues of the future, because the earth is not only our home but also our sole source of those resources.

Special thanks to Homer Milford and Spencer Wilson, both of whom have long shared and exchanged historic data and photographs with the author; and to Meghan Jackson for ferreting out information on the "Indian Paint" mines and the local pueblos micaceous pottery.

The History and Operating Practices of Molycorp's Questa Mine

Anne Wagner, *Molycorp, Inc.*

Molycorp's Questa molybdenum mine has been in operation since 1918. For more than eighty years the mine has been a strong source of economic vitality in northern New Mexico. Producing hundreds of millions of tons of molybdenum since its inception, the Questa mine continues to operate, providing a valuable natural resource to the world market while fully committed to operating in a safe and environmentally responsible manner. This paper provides a brief history of Molycorp's operations and insight on the mine's present and future operations.

Molycorp's earliest workforce, ca. 1920.

A HISTORY OF OPERATIONS

In 1914 two local prospectors staked multiple claims in an area of the Sangre de Cristo mountain range called Sulphur Gulch. During their exploration they discovered an unknown dark, metallic material. The common belief at the time was that it was graphite, and it was rumored to have been used for a myriad of functions from lubricating wagon axles to shoe polish. In 1917 a sample of the ore was sent out to be assayed for gold and silver. The report included a mention of molybdenum and its rising value resulting from an increase in usage during World War I. Early in the summer of 1918 the R & S Molybdenum Mining Company began underground mining of the high-grade molybdenum veins in Sulphur Gulch. On June 1, 1920, the Molybdenum Corporation of America was formed and acquired the R & S Molybdenum Mining Company (which later became Molycorp).

By August of 1923 Molycorp had built its own on-site processing mill, which could produce 1 ton of molybdenum concentrate daily from 25 tons of ore. All molybdenum production during this period was from high-grade molybdenite (molybdenum sulfide), with grades running as high as 35 percent molybdenum. This mill was one of the first flotation mills in North America. The mill was rebuilt several times and operated continuously until 1956, when the underground mining operations ceased. In 1963 this mill was dismantled to make way for the current mill.

From 1957 to 1960 exploration by drifting, cross-cutting, and core drilling methods was conducted under the Defense Minerals Exploration Act. After completion of the contract, Molycorp continued exploration, and in early 1963 core drilling from the surface and underground was accelerated to determine whether or not an open-pit mine was economically feasible. By 1964 sufficient reserves had been blocked out to justify the development of an open-pit mine and the construction of a mill that could handle 10,000 tons per day. Pre-production stripping was started in September 1964, and the first ore from the pit was delivered to the mill in January 1966.

Production from the pit continued until August 1982. During this period the mill capacity increased to 18,000 tons per day, and the stripping rate increased to 120,000 tons. At this time the mine employed approximately five hundred workers. Also at this time, additional exploration drilling in the area of the existing open pit delineated several other orebodies. The largest of the orebodies contained approximately 125 million tons of ore averaging 0.3 percent molybdenum sulfide.

Molycorp was acquired by Union Oil Company of California in August of 1977. In November 1978 development of the existing underground mine began,

with two vertical shafts bottoming out at approximately 1,300 feet deep, and a mile-long decline was driven from the existing mill area to the haulage level. The mill flotation area was modernized to accommodate the higher-grade of underground ore. In 1982 mining from the open pit ceased, and in August 1983 the new underground mine began operating. Employment at this time reached approximately nine hundred workers.

In 1986 an extremely "soft" market caused the first shutdown of the mine in recent history. The mine was restarted in 1989 and continued to operate until January 1992, when the mine was shut down again due to low prices. The mine restarted in 1995, and most of that year was devoted to mine dewatering and repair. Production began in late 1996, and over the next several years approximately 30 million pounds of molybdenum concentrate were produced. Development of the current orebody began in 1998. Production from this orebody began in October 2000. This orebody and three adjacent ones collectively have sufficient ore reserves for production to continue for several decades.

MINE OPERATIONS

The mine has operated by several methods over the past eight decades. Initially, the mine was a small, underground working, with donkey-hauled ore cars delivering ore broken up by workers to the surface. In the early 1960s Molycorp decided it was more technically feasible to mine the orebody via an open pit.

Molycorp's underground workforce in 2003 standing in lift, ready for transportation into the underground

Molycorp's molybdenum mill and conveyor system with product in sling bags packaged for sale.

For twenty years, miners at Molycorp blasted pit rock to access ore. Because open-pit operations generate much more non-ore-containing rock, the company developed a system of disposal through the construction of nine rock piles located throughout the site, common practice throughout the industry. Molycorp disposed of several hundred million tons of rock into these piles. Currently Molycorp is working to ensure the long-term stability of these piles, including the mitigation work on the Goathill North pile that is underway.

In the late 1970s Molycorp determined that the orebody was too deep to mine by an open pit. In 1982, after several years of development at a cost in the hundreds of millions of dollars, the current underground operation was opened. The mine is now an underground gravity block cave mine, designed to produce 18,000 tons of ore per day.

Blocking caving is a bulk mining method. It takes a relatively weak and fractured orebody and collapses it under its own weight. The ore is then drawn down into a series of excavation areas for sizing and transportation by mechanical belt to the surface for further refinement and milling.

During the milling process, the molybdenum ore is physically separated from the rest of the rock. Through the use of a flotation system, the molybdenum is literally "floated" to the top of the tank, and

Molycorp tailings facility interim revegetation. As a routine practice Molycorp caps the inactive tailings areas with soil and seeds with native species.

the remaining material is carried by pipeline nine miles to the tailings facility west of the village of Questa.

OPERATING PRACTICES

Since the mine began in 1918, accepted operational practices have changed. These changes have led Molycorp to adopt and incorporate best management practices throughout its site. Always closely connected with the village of Questa, Molycorp is continuing to work with the village and other stakeholders to promote successful economic opportunities in the community.

Molycorp is using its resources to promote economic development opportunities in two key ways. The first is a comprehensive program to use local contractors whenever possible, and if it is not possible, outside contractors are encouraged to use local suppliers or subcontractors when possible. The second is a program that supports the use of local suppliers and vendors of materials as much as possible. In addition, Molycorp is collaborating with many of the stakeholders who have an interest in economic and social sustainability of the village of Questa.

Environmental practices have also changed over the years as regulations and expectations have changed. Today, Molycorp is devoting significant efforts to environmental investigations, best management practices, mitigation, etc. as the company continues to mine.

Current best management practices along the Red River include collecting poor quality, shallow ground water and treating it to improve the water quality of the Red River. Ongoing voluntary investigations include annual monitoring and reporting on the aquatic biology of the Red River.

On the mine site Molycorp is collaborating with the state of New Mexico, the village of Questa, and other stakeholders to understand the extent of the instability of the Goathill North rock pile and to determine the best approach for long-term stabilization of the rock pile in an expedient manner. Work on the mitigation project began in July 2004 and is expected to be completed in mid-2005.

Another significant effort on the rock piles is an extensive test plot program that was established in late 2003. The purpose of the test plot program is to further refine an appropriate reclamation approach that Molycorp will implement upon closure of the mine. This undertaking exemplifies the uniting of on-site studies, off-site research, and state-of-the-art technology. Twenty-three research test plots were constructed over 20 acres. The test plots consist of areas of various slopes including level areas, and slopes with gradients of 2:1 and 3:1. Various cover depths (zero, one, and three feet) were placed on the plots to evaluate the effectiveness of the cover for reclamation, and more than 26,000 seedlings were planted by hand along with seeding of grass and other plants. It is anticipated that this research will redefine high-elevation reclamation in the western U.S.

THE FUTURE

Although Molycorp anticipates continuing operations into the future, planning for closure is also important. A reclamation plan is required by the New Mexico Mining Act, but Molycorp believes planning for closure goes beyond reclamation. Current best practice in the industry means thinking and planning ten or even twenty years ahead of developments when it comes to closure. Molycorp is now working to shift the community away from its dependency on mining through supporting other economic development opportunities. Molycorp has also committed to continue operating the mine even when prices for molybdenum drop, moving employees from mining to reclamation and remediation projects until prices return to economic levels. Molycorp is committed to mining responsibly, protecting the environment, working safely, and partnering with local communities to develop additional economic opportunities so the communities remain viable into the future.

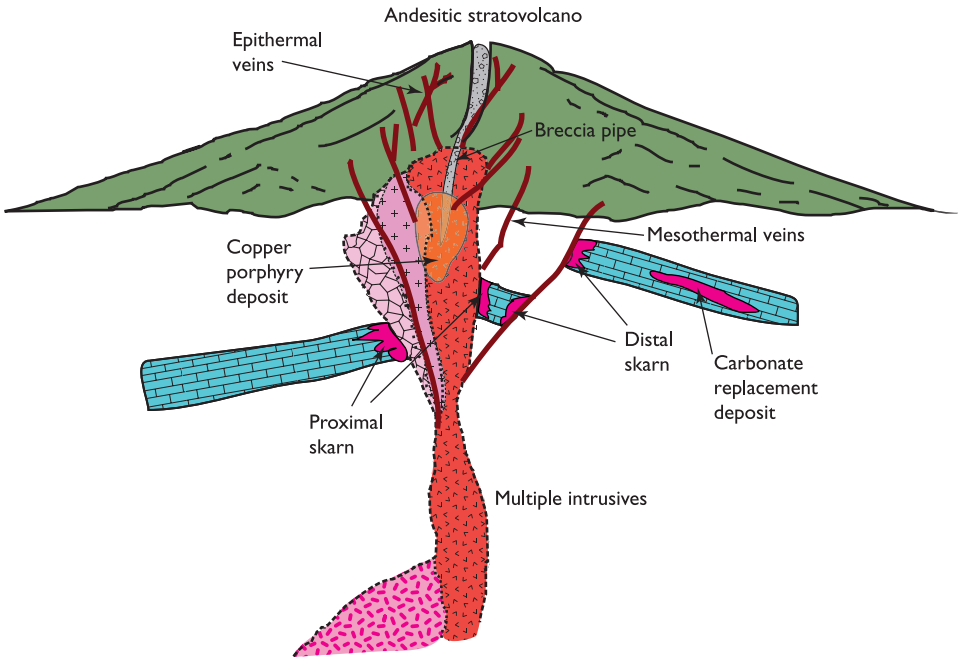
Metal Deposits in New Mexico—How and Where They Occur

Robert M. North, *Phelps Dodge Chino Mines Company*
Virginia T. McLemore, *New Mexico Bureau of Geology and Mineral Resources*

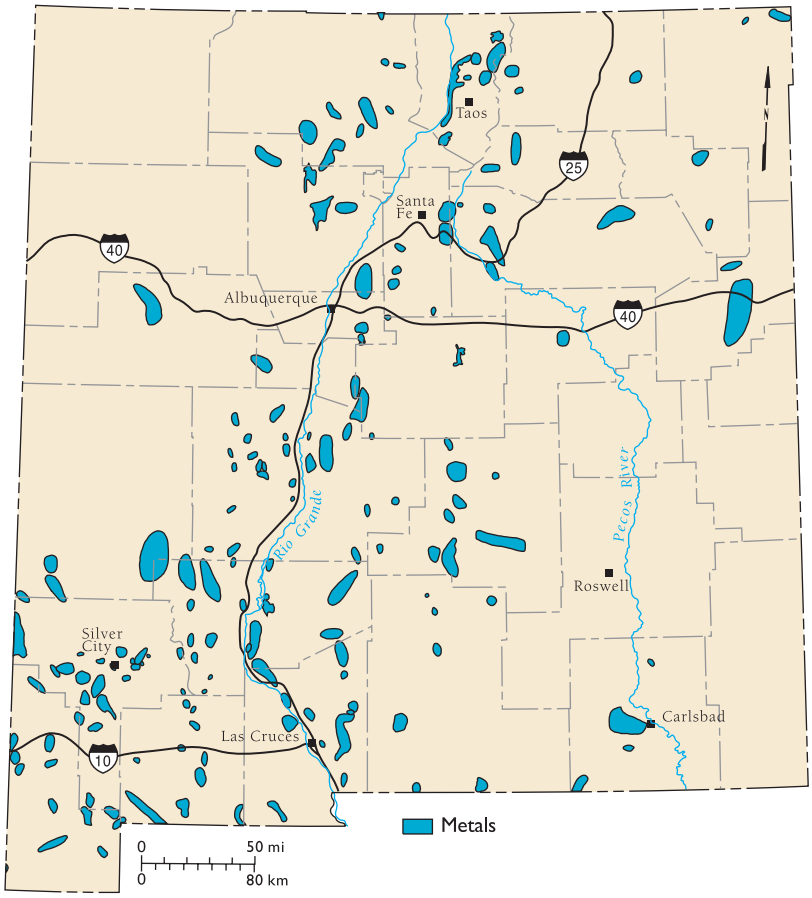
New Mexico is at the eastern edge of one of the world's great metal-bearing provinces. Copper is particularly important, with large and (in come cases) world-class deposits in Arizona, New Mexico, Utah, and Sonora, Mexico. Nevada and (to a lesser extent) the entire Southwest are well endowed with gold and silver. Some of the largest molybdenum deposits in the world are found in Colorado and New Mexico. This is the nature of metal deposits; they are relatively common in certain geologic settings and almost unknown in others. Prospectors have known this intuitively for many years, and it was the prospector who found most of the important deposits in southwestern North America.

The metals found in New Mexico deposits are often the results of the interaction of hydrothermal (hot water) solutions with a host rock. In some cases further enrichment takes place when cooler, meteoric water (rain and snow melt) interacts with low-grade mineralization to concentrate the metal through a process called *supergene* ("from above") *enrichment*. Many of the deposits discovered so far in New Mexico are the result of water-rock interactions. These same types of reactions can create environmental concerns later on when the deposits are developed.

The important fact is that metals occur in distinct minerals, and to recover the metals, minerals must be concentrated through processing. As higher-grade deposits are depleted, lower-grade deposits will supply the metals that society needs. This is especially important in New Mexico, where low-grade stockpiles and tailings of earlier mining operations exist and could be processed in the future for their metal content. This becomes increasingly significant as technological advances facilitate the economic recovery of metals from lower-grade ores.



Simplified porphyry copper system. Mineralization typically occurs in and around porphyritic diorite, granodiorite, monzonite, and quartz/monzonite plutons, which are surrounded by concentric zones of hydrothermal alteration. The porphyritic igneous intrusion is locally surrounded by copper and lead/zinc bearing skarns.



Metal mining districts in New Mexico. Most of these districts are not presently active.

COPPER DEPOSITS

Copper has historically been the most important metal produced in New Mexico. Copper is prized as the second-best conductor of heat and electricity (after silver) and has many uses, especially in the generation and transmission of electricity. Copper occurs in a number of specific geological environments in New Mexico. Most important of these are the porphyry-copper and associated contact metamorphic (or *skarn*) deposits mined in the southwestern part of the state (the Chino mine near Silver City). Sedimentary red-bed type copper deposits are fairly common in New Mexico but have produced only small amounts of copper. Copper is also a byproduct of the mining of zinc and lead vein and volcanogenic massive-sulfide deposits.

Porphyry Copper Deposits

Porphyry copper deposits are the most important metal deposits both in New Mexico and worldwide. These deposits occur in porphyritic igneous rocks and adjacent host rocks of small igneous intrusions at shallow depths within 1.2 miles (2 km) of the surface in the earth's crust. The term porphyritic refers to a specific texture of igneous rocks characterized by large crystals "floating" in a finer-grained matrix, each representing a different episode of cooling. Not all porphyritic igneous rocks host economic mineral deposits, although porphyritic textures are commonly associated with metal deposits. The molten rock or magma intrudes cool host rocks. As the magma cools, it solidifies from the contact toward the center of the intrusion. Volatiles in the magma, primarily steam and carbon dioxide gas, build up within the magma until the pressure fractures the solidified porphyry and host rocks above the magma chamber. Hydrothermal solutions are released through these fractures and react with the host rocks, altering them in a characteristic manner. Copper minerals are deposited as a part of this interaction. Typically these deposits are very large, some in excess of a billion tons of mineralized rock. Copper grade varies from about 0.10 percent copper to over 1 percent copper with 2–5 percent pyrite. The important deposits in New Mexico at Chino and Tyrone were relatively low-grade ore after this initial mineralization and were upgraded through this process of *supergene* enrichment. The porphyry copper deposits in New Mexico are 55–58 million years old.

Supergene enrichment occurs when rocks with high pyrite content come into contact with water in an oxidizing environment. When this happens, water, oxygen, and pyrite react to form sulfuric acid. This acid naturally leaches copper from the mineral chalcopyrite, putting copper into an acidic solution. Copper stays in solution as long as the solution is acidic and oxidized. However, when the acidic solution is neutralized, or conditions becoming reducing, the copper comes out of solution. Typically in natural systems, conditions become reducing just beneath the water table. When this happens, the copper in solution easily combines with sulfur. The sulfur available in pyrite and the copper in solution combine and replace pyrite with the copper mineral chalcocite. This process preserves copper through chemical dissolution and sub-

sequent enrichment. Otherwise the metal is eventually lost through the erosion of copper-bearing rock by mechanical means. Without this process, deposits such as Tyrone would never have been economic, and the deposits at Chino would be much smaller.

Skarn Deposits

Deposits of copper and other metals can form when hot magma comes into contact with relatively cool, reactive rocks such as limestone, resulting in the distinctive rock termed skarn. The term skarn refers to rocks with diverse origins but similar mineralogy. Commonly these rocks have significant calcium-bearing varieties of garnet and pyroxene, sometimes with significant quantities of magnetite. Although such deposits form in a number of geological environments, they are most common in the southwestern U.S.

Polymetallic Vein Deposits

Polymetallic vein deposits formed as a result of tectonic and igneous activity in the Southwest between 75 and 50 million years ago and are found in a number of districts. These veins exhibit different textures and mineralogy but are similar in form and age. The most important deposits of this type in New Mexico are in the Hillsboro, Pinos Altos, Bayard, and Lordsburg districts. Vein deposits occur where hot, metal-bearing solutions that are formed near an igneous intrusion are channeled through fractures, typically fault zones. These hot-water solutions can deposit metallic minerals when the physical or chemical conditions of the solution change, or through an interaction between the wall rock and solution. For example, something as simple as cooling the solution can cause precipitation of metallic minerals. Boiling the solution is a common mechanism for precipitation of metals. Host rocks can be sedimentary, intrusive igneous, or associated volcanic rocks. Veins were typically worked for both base and precious metals and locally contain uranium, tungsten, tellurium, and beryllium. Mineralogies and metal associations are diverse, even within a district.

The ores from veins of this type have potential for use as quartz-rich smelter flux, which can be an important component of the smelting process. Nearly two million tons of mineralized siliceous flux has been shipped from veins in the Lordsburg district to smelters in New Mexico, Arizona, and Texas, for example. Past production indicates that these vein deposits are small in size relative to porphyry copper deposits.

Typical porphyritic texture, in a quartz monzonite porphyry from the Orogrande district in Otero County, New Mexico. The large white crystals (phenocrysts) are feldspar.

Sedimentary Copper Deposits

Copper is deposited in sedimentary rocks either as part of the sedimentary process or during the process of diagenesis, the compaction and solidification of sediments into rock. The mineralized bodies typically occur as lenses or blankets of disseminated and/or fracture coatings. The copper minerals are predominantly chalcopyrite, chalcocite, malachite, and azurite with local uranium minerals, galena, sphalerite, and barite. Ore minerals in these sedimentary copper deposits are typically associated with organic debris and other carbonaceous material. Sedimentary copper deposits are the world's second most important source of copper after porphyry deposits; however, no large copper-producing deposits of this type are found in New Mexico. The most important sedimentary copper deposits in New Mexico were mined in the Nacimiento district near Cuba and the Pastura district near Santa Rosa.

MOLYBDENUM DEPOSITS

Molybdenum in New Mexico has been produced as a byproduct of copper and uranium mining and is cur-

rently produced from primary molybdenum deposits at Questa. Molybdenum is used in steel alloys, and molybdenite, the most common molybdenum mineral, is used as a lubricant.

Porphyry Molybdenum Deposits

Porphyry molybdenum deposits are large, low-grade deposits containing tiny, disseminated veins of molybdenum sulfides and are associated with porphyritic intrusions. They occur in three areas in New Mexico: near Questa, in the Nogal district (Lincoln County), and in the Victorio Mountains (Luna County). The largest deposits are at Questa in Taos County. The deposits consist of thin veinlets, fracture coatings, and disseminations of molybdenite (molybdenum sulfide) in granitic host rock. The deposits are similar in form to the porphyry copper deposits described above but are probably younger, 35–25 million years old.

GOLD AND SILVER DEPOSITS

Gold and silver have been produced in New Mexico mostly as a byproduct of copper mining, but some deposit types were mined primarily for their precious metals. Gold is used as a monetary standard, in jewelry, and in specialized electronic applications. This takes advantage of the fact that gold is malleable, a good conductor of electricity, and resistant to corrosion. Silver is the best conductor of electricity and heat, allowing for specialized applications, as well. Most silver is used in photography, but it is also used in jewelry and electrical components.

Volcanic-Epithermal Deposits

Gold and silver occur in deposits classed as epithermal, a term for deposits formed high in the earth's crust at relatively low temperature (less than 300° C). Epithermal mineral deposits in New Mexico (and elsewhere in the world) are found in structurally complex geologic settings that provide an excellent plumbing system for circulation of hydrothermal fluids. Geologists studying deposits of this type established the now-recognized association between epithermal mineral deposits and active geothermal (or hot spring) systems. However, there are many small hot spring systems with no gold or base metals associated with them. The Mogollon district in Catron County is the most productive example of this type of deposit; other productive examples are the Steeple Rock, Socorro Peak, Chloride, (near Winston), and Cochiti (Sandoval County) districts.

Carbonate-Hosted Silver (manganese, lead) Replacement Deposits

Carbonate-hosted silver (±manganese, lead) replacement deposits formed in southwestern New Mexico approximately 50–20 million years ago. The deposits contain predominantly silver and manganese oxides, in veins and as replacements in carbonate rocks. More than 20 million ounces of silver have been recovered from deposits of this type, but gold is rare. Although silver and manganese are the predominant metals, lead is next in abundance. Manganese has been produced from the Chloride Flat, Lone Mountain, and Lake Valley districts. Economically, the most important silver deposits are in the Lake Valley and Kingston districts.

Great Plains Margin Deposits

Some of the state's largest gold deposits are found along a north-south belt roughly coinciding with the margin between the Great Plains physiographic province and the Basin and Range (Rio Grande rift) and Southern Rocky Mountain provinces. These deposits have similar characteristics that, when considered with their tectonic setting, define a class of mineral deposits referred to as Great Plains margin deposits by workers in New Mexico. Most deposits are associated with igneous intrusive rocks that are 38–23 million years old. The veins have high gold/base metal ratios and typically low silver/gold ratios in contrast with high silver/gold deposits in western New Mexico. The most important deposits of this type are found at Elizabethtown–Baldy, Old Placers, White Oaks, and Orogrande districts.

Placer Gold Deposits

Placer gold deposits were an important source of gold in New Mexico before 1902, but placer production since 1902 has been minor. The earliest reports of placer mining were in the 1600s along the northern Rio Grande. In 1828 large placer deposits were found in the Ortiz Mountains in Santa Fe County (Old Placers district), which began one of the earliest gold rushes in the western United States. Most placer deposits in New Mexico had been discovered by 1900. It is estimated that 662,000 ounces of gold have

COMMODITY	YEARS OF PRODUCTION	ESTIMATED QUANTITY OF PRODUCTION	ESTIMATED CUMULATIVE VALUE ($)	QUANTITY IN 2002	VALUE IN 2002 ($)	RANKING IN U.S. IN 2002
Copper	1804–pres.	>10.2 million tons	>13.5 billion	277,094 tons	419 million	3
Uranium	1948–2001	>347 million pounds	>4.7 billion	264,057 pounds	2.6 million	—
Gold	1848–2002	>3.2 million troy ounces	>394 million	32,337 troy ounces	9.5 million	—
Zinc	1903–1991	>1.51 million tons	>338 million	—	—	—
Silver	1848–1998	>117 million troy ounces	>252 million	433,596 troy ounces	2.4 million	—
Molybdenum	1931–pres.	>146 million pounds	>214 million	7,339,117 pounds	24 million	5
Lead	1883–1992	>367,000 tons	>56.8 million	—	—	—
Iron	1883–1962	8.2 million long tons	17.3 million	—	—	—
Manganese	1883–1963	>1.9 million tons	5 million	—	—	—
Tungsten	1907–1956	1.1 million pounds	250,000	—	—	—
Total	**—**	**—**	**20 billion**	**—**	**475.5 million**	**—**

Estimated total production of major metal resources in New Mexico. Figures are subject to change as more data are obtained (these are conservative estimates). Tons = short tons, unless otherwise stated.

been produced from placer deposits throughout New Mexico between 1828 and 1991. Only four districts have each yielded more than 100,000 ounces of placer gold: Elizabethtown–Baldy, Hillsboro, Old Placers, and New Placers.

LEAD AND ZINC DEPOSITS

Lead and zinc commonly occur together and have been produced in several districts in New Mexico. Zinc has been the more important of the two; approximately 1.5 million tons worth more than $338 million have been produced. Zinc's most important use is in galvanizing of steel; it is also important in the manufacture of brass and other alloys. Lead is used primarily in lead-acid batteries.

Volcanogenic Massive-Sulfide Deposits

Volcanogenic massive-sulfide deposits are polymetallic, stratabound deposits formed contemporaneously with submarine volcanism by hot saline brines. Modern analogies to this type of mineralization include the "black smoker" deposits at ocean rifts. Volcanogenic massive-sulfide deposits contain varying amounts of base and precious metals and are associated with rocks formed between 1,650 and 1,600 million years ago, or perhaps earlier. Four districts in New Mexico contain known deposits of this type: Willow Creek, Santa Fe, Rociada, and La Virgen. Only the Willow Creek district near Pecos has yielded any significant production. Many of the volcanogenic massive-sulfide deposits and suspected deposits are found within or near wilderness areas and probably will not be developed in the foreseeable future.

Carbonate-Hosted Lead/Zinc Replacement Deposits

Carbonate-hosted lead/zinc replacement deposits are found in southwestern New Mexico and formed approximately 50–20 million years ago. The deposits include replacements and minor veins in carbonate rocks. They are typically lead/zinc dominant, with byproduct copper, silver, and gold. The near-surface oxidized zones were typically the most productive in the past. Economically, the most important deposits are in the Magdalena, Victorio (west of Deming), and Organ Mountains districts.

Polymetallic Vein Deposits

Polymetallic vein deposits with important lead and zinc production are found in a number of districts, particularly near Bayard. These veins exhibit different textures and mineralogy but are similar in form and age. The Bayard deposits are the only important lead-zinc producers of this type in New Mexico.

Industrial Minerals in New Mexico—Different from Metals, but Crucial and Complex

Peter Harben, *Las Cruces, New Mexico*

Industrial minerals have been called the third world of the extractive industry. They seem to trail the invariably glamorous metals and the politically charged energy products. Metals have defined industrial ages, and energy has framed government policy. They are obvious in everyday life as steel automobiles and aluminum beverage cans, not to mention utility bills and gasoline prices. What remains in the extractive industry are the more than fifty diverse nonmetallic and non-fuel materials that tend to vanish into common products. Few people at a dinner party think of a bottle of wine as a melted and shaped blend of silica sand, feldspar, limestone, and soda ash encapsulating a liquid based on a fertilized crop and clarified with bentonite, diatomite, and/or perlite; secured by a plastic "cork" filled with calcium carbonate and talc; and identified by a label of cellulose containing kaolin, calcium carbonate, and titanium dioxide.

Despite such a low profile, industrial minerals are essential for our modern society and contribute significantly to New Mexico's economy. New Mexico ranks first in the country in the production of potash, perlite, and zeolites; second in humate; third in copper and pumice/pumicite; and fifth in molybdenum. Our state is also a significant producer of construction sand and gravel and crushed stone (10 million tons per year valued at some $64 million), gypsum, and dimension stone.

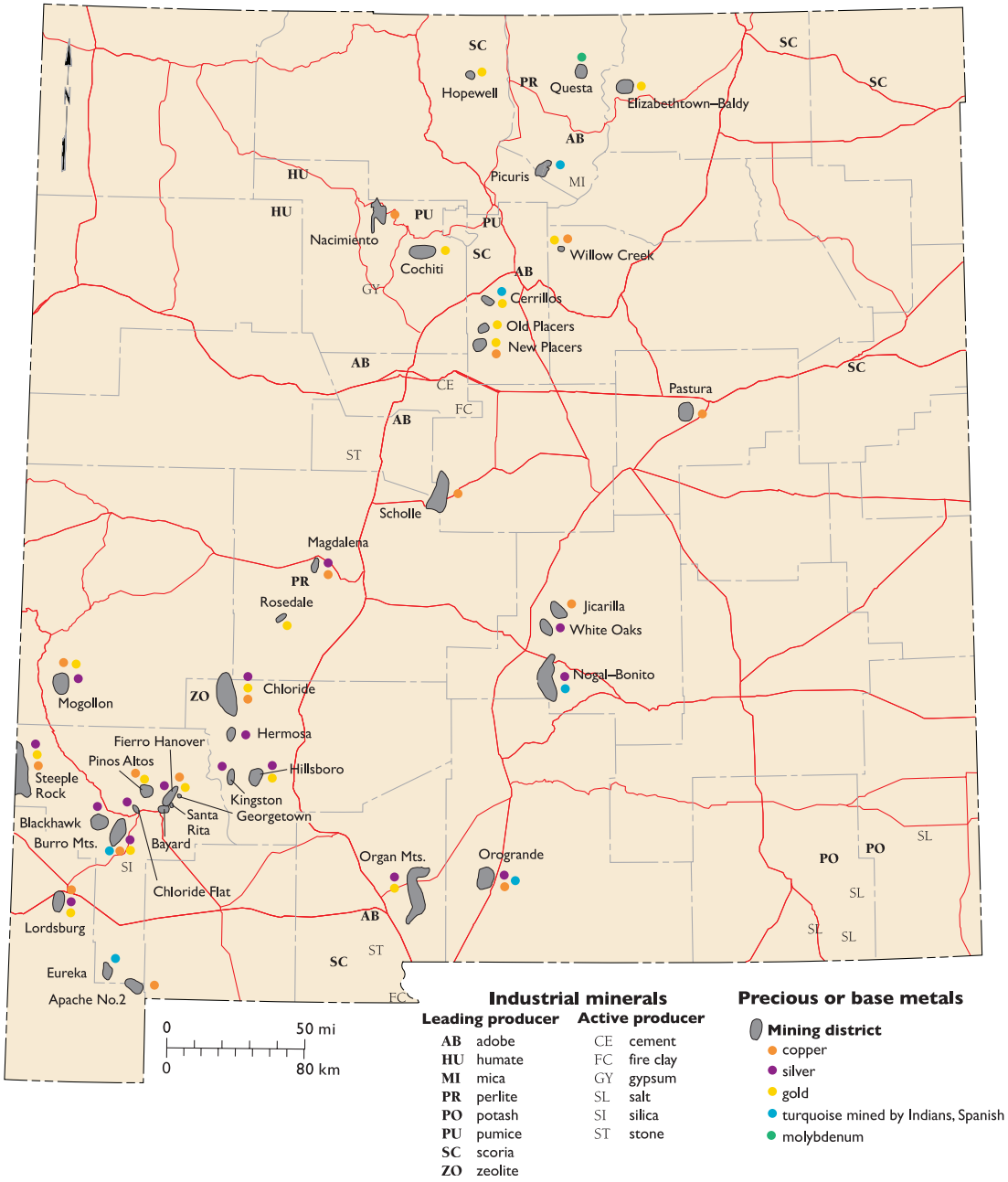
Today the total value of non-fuel mineral production in the state of New Mexico is almost $600 million, of which industrial minerals constitute approximately two-thirds. These industrial minerals have a positive effect on society. Potash from Carlsbad is a key ingredient in fertilizer, and salt helps to de-ice roads; travertine from Belen provides unique architectural features; zeolites in Sierra County promote animal hygiene and environmental cleanliness; perlite from Socorro and Tres Piedras contributes to ceiling tiles and horticultural soils; and pumice from the Jemez Mountains and the Mogollon-Datil volcanic field puts the stone in stone-washed jeans. Local limestone from around the state helps remove pollutants from the environment, and construction aggregates from New Mexican limestone, granite, sandstone, and volcanic rocks support the construction boom and improve the state's expanding infrastructure.

This important sector of the economy may represent a viable development path for the future and help to offset declining metal production. What is needed is a clear understanding of the differences between industrial minerals and metals; horror stories abound about metal producers who wandered into non-metals using a metal-mining mentality and were doomed to failure.

LOW PRICES—LOW PROFILE

One prime reason for this lackluster appreciation of the industrial minerals business is the relatively low selling price, with most in the $10–$100 per ton category, though industrial diamonds, iodine, and some rare earths sell for more than $10,000 per ton. What makes industrial minerals interesting is the large number of tons produced and sold. An average price of $5–6 per ton for aggregates in the United States is unimpressive until it is multiplied by the annual production rate of 2.5 billion tons generating sales of more than $14 billion. To put metals in perspective: The value of all non-fuel minerals and metals sold in the United States is approximately $38 billion, of which

The U.S. Hill mica mine in Taos County.



Industrial minerals in New Mexico. Metals are also shown.

$30 billion is for industrial minerals (half of which are aggregates) and $8 billion is for metals. The value of cement sold in the United States is about equal to the *combined* value of copper, gold, and iron ore. Nevertheless, the relatively low price per ton dictates whether or not a mineral can be mined commercially and how far it can be shipped. Consequently, distance to market is more important for the average industrial mineral than for a metal.

LOCATION, LOCATION, AND LOCATION

To borrow a realtors' phrase, three of the most important characteristics of most industrial mineral deposits are location, location, and location. Specifically, certain industrial minerals like silica sand and limestone for glass or ceramics are relatively common and inexpensive and, therefore, restricted to servicing local markets; no local glass or ceramics plant means no market. Less common minerals like perlite or potash

$1–10/METRIC TONS	
aggregates	
anhydrite	
gypsum	
salt	
sand & gravel	
$10–100/METRIC TONS	
aplite	magnesite
aragonite	nepheline syenite
bentonite	olivine
calcium carbonate	phosphates
cement	pumice
celestite	propylite
dolomite	salt
feldspar	salt cake
ilmenite	zeolites
kaolin	
$100–1,000/METRIC TONS	
alumina	magnesite
anatase	mica
andalusite	monazite
attapulgite	nepheline syenite
barite	nitrates
bauxite	perlite
bentonite	petalite
borax	rare earth oxides
calcium carbonate	rutile
chromite	silica
diatomite	sillimanite
flint clay	spodumene
fluorspar	sulfur
garnet	talc
graphite	vermiculite
iron oxide	wollastonite
kaolin	xenotime
kyanite	zircon
$1,000–10,000/METRIC TONS	
antimony oxide	graphite
asbestos	rare earth oxides
bastnaesite	rutile
bromine	synthetic zeolites
OVER $10,000/METRIC TONS	
diamonds	
iodine	
rare earth oxides	

Industrial minerals by price.

can serve regional and even international markets because the higher prices can absorb the cost of transportation, and competition may be more distant or less intense. Still rarer products like borates have limited sources of supply and can service international markets. This need for proximity to the market is of particular relevance to New Mexico, where market demand is limited by a relatively modest regional population and manufacturing base. For the most part, mineral use in North America is concentrated in the traditional markets of the Northeast and Midwest and (more recently) the fast-growing southern states. Manufacturing in the West tends to be restricted and concentrated and serves a relatively large area, thus limiting viable mineral supply points. At the same time, many manufacturing plants are moving offshore. For example, ceramics plants are moving from the United States to Mexico and Asia.

The geographic spread of industrial minerals is being extended through the increased use of elaborate processing techniques to develop value-added grades. Kaolin, for example, may be ground and air floated to produce a low-cost filler used locally for rubber; water washed for use nationally as a fine, white filler in paper; or floated, delaminated, calcined, and magnetically separated to produce a bright "engineered material" for use in lightweight coated grades of paper all over the world. In contrast, perlite is shipped unprocessed in its compact form and later expanded to a much larger volume close to the point of consumption.

SPECIFICATIONS, SOPHISTICATION, AND SERVICE

One key difference of industrial minerals is that they are prized for a combination of several physical and chemical properties, whereas metals are generally valued for a specific element that is extracted from the ore. Specifications for industrial minerals, therefore, may require a combination of physical characteristics such as whiteness, particle shape, size and size distribution, viscosity, oil absorption, as well as chemical purity and strict maximums on impurities such as iron or heavy metals. Each end use requires a different set of specifications; in fact, industrial minerals are often described by the end-use grade—for example, drilling-mud-grade barite, coating-grade kaolin, and refractory-grade bauxite. The importance of the mineral's end use is illustrated by the fact that titanium minerals are included in the industrial minerals category because 95 percent of the consumption is as an oxide for pigment rather than as a metal for jet fighters or bicycles. Other metallics overlap into the industrial minerals camp because of their nonmetallic uses—refractory, chemical, and abrasive-grade bauxite; refractory, chemical, and pigment-grade chromite; beryllium as beryllium oxide; etc.

In contrast, metal specifications are relatively simple, and there is no "fingerprint." Copper from New

Fresh cut at the No Agua perlite mine in Taos County, owned and operated by Harborlite Corporation. Note the stratified layers of volcanic ash that are characteristic of the deposit.

Mexico works as well as copper from Zambia or Chile, and 14-carat gold from a family heirloom sells for the same price as freshly poured bullion from Witwatersrand, South Africa. Place value is relatively unimportant in metals. Therefore, these undifferentiated metals command little or no consumer loyalty and are sold at published prices. In contrast, many industrial minerals need to be characterized by a multitude of chemical and physical characteristics and often require an exhaustive evaluation process in order to qualify for use by a particular consumer or plant, which may be optimized for material from a single mine. This requirement tends to generate loyalty to the supplier, and this loyalty may be cemented further as the supplier works with the consumer to improve quality or delivery methods, reduce transportation costs, develop new grades, etc.

In some cases, specifications can only be met by blending minerals from various sources. For example, graphite houses may blend graphite from China, Brazil, and Canada, and a large paper plant may work with a blend of kaolin and ground calcium carbonate. Suppliers of industrial minerals tend to encourage customer loyalty through good service, consistent quality and delivery, and even joint technical research. This makes market penetration for a newcomer difficult, because a lower price is not always a means to wrest away a market share. To make matters still more complex, the selling price of industrial minerals is reached through negotiation between supplier and consumer, based on the quantity purchased and the terms of the contract, rather than (say) the fixed market price of gold set daily in London.

If an industrial mineral fails to meet the industry specifications on a consistent basis, then it is unlikely to be sold regardless of price. In contrast, metals such as gold or copper can be mined and refined with the sure knowledge that they can be sold at a price approaching a level dictated by a terminal market and published in the press or on the internet. In the case of products like iron ore, the buyer can financially penalize the seller for higher levels of impurities such as phosphorus or arsenic. This rarely happens with industrial minerals; the product is simply rejected.

This increased sophistication has been encouraged by the advent of fast, automated methods of manufacture demanding raw materials with a high degree of uniformity. This in turn has placed heavy responsibilities on the suppliers of raw materials and has reduced still further the concept of "price is king" as it is in the metal markets. Today in the industrial minerals arena it is price plus quality, consistency, and service that makes for a complex and demanding business.

WITHOUT A MARKET, A DEPOSIT IS MERELY A GEOLOGIC CURIOSITY

Metals and nonmetals share some common ground—both require geologic exploration, mining, materials handling, and processing designed to produce commercially viable materials. Even here there are exceptions, as many large industrial mineral deposits are obvious surface outcrops or may be discovered incidentally during the process of drilling for oil, gas, or

The Harding pegmatite mine in Taos County during its productive years.

Split-face travertine at New Mexico Travertine in Belen.

water. Consequently, high-profile regional exploration programs for common industrial minerals are rather rare. More commonly, the many known industrial mineral deposits are continually evaluated based on location, transportation, quality, processibility, and market demands.

Industrial minerals are market driven, a fact encapsulated in the saying that "without a market, a deposit is merely a geologic curiosity." This means that a detailed market study is required to test the economics of a given project. However, most modern mining companies employ a crew of managers, accountants, lawyers, investor relation gurus, engineers of all stripes, plus the odd geologist and even botanist, yet very few feel the need to engage in-house market research help. At the same time, companies continue to build mines and plants on the fly, and exploration geologists still scour the far corners of the world for industrial mineral deposits without the slightest notion of whether anything found can be sold at a profit or even sold at all. The concept that industrial minerals demand strong market analysis in order to become viable and valuable is lost in the rush to drill, raise capital, engineer, construct, debug, and produce a product on schedule.

There are important differences between the economic behavior of industrial minerals and metals based on their different end-use pattern, which in turn dictates the method of marketing required. In general, industrial minerals tend to be used more in the non-durable consumer-goods sector of the economy, whereas metals are more in the durables and engineering sectors such as transportation. These differences in end-use markets are reflected in variations in demand behavior. Capital cycles that affect metals tend to be more extreme than consumption cycles for industrial minerals, which tend to lag behind. As consumer demand for industrial minerals advances, it generates pressures for the creation of new production capacity. The markets for industrial minerals are regarded as "steady" whereas metal markets tend to be more volatile (however, when copper prices climb above $1.00 per pound, industrial minerals become "boring" rather than "steady"). Some mining companies find that the steadiness of industrial minerals—cat litter is still necessary during a recession, but a new washing machine can be delayed—is a good counterpoint to the volatility of metals.