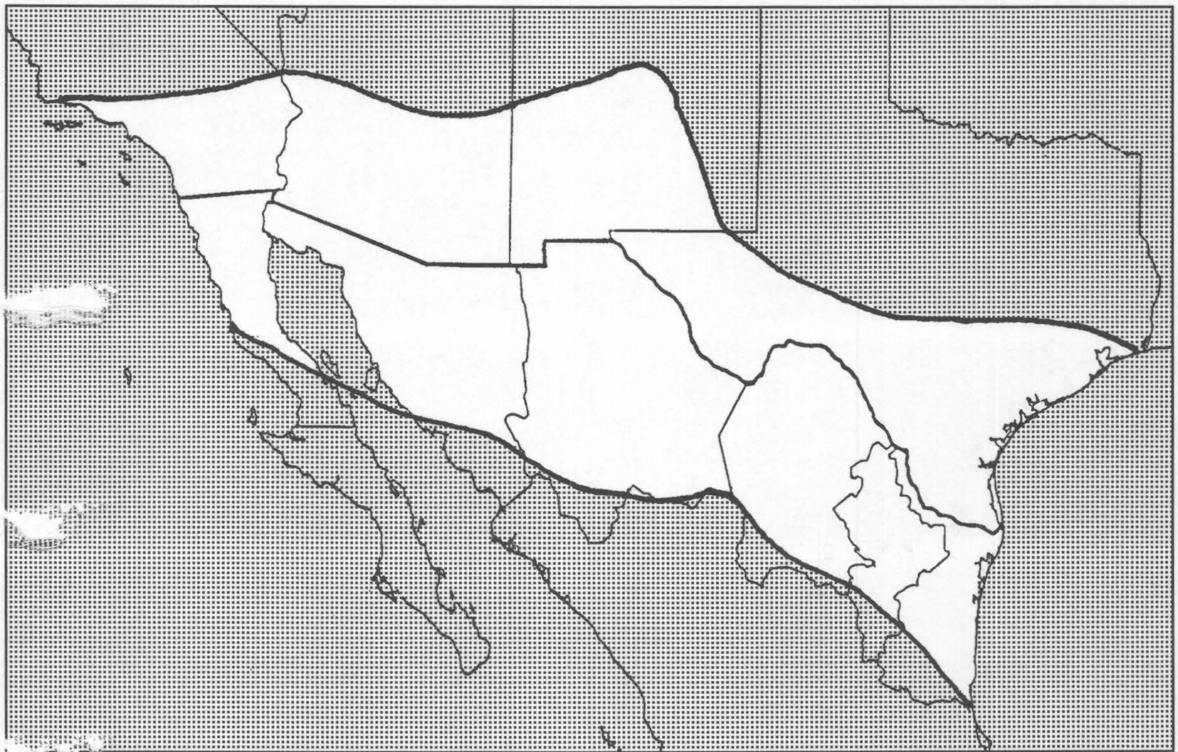
Nonfuel Mineral Resources in the United States-Mexico Border Region—

A Progress Report on Information Available from the Center for Inter-American Mineral Resource Investigations (CIMRI)

U.S. GEOLOGICAL SURVEY CIRCULAR 1098



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GEOLOGIC TIME CHART

Terms and boundary ages used by the U.S. Geological Survey in this report

EON	ERA	PERIOD		EPOCH	AGE ESTIMATES OF BOUNDARIES IN MILLION YEARS (Ma)
Phanerozoic	Cenozoic	Quaternary		Holocene	0.010
				Pleistocene	1.6
		Tertiary	Neogene Subperiod	Pliocene	5
				Miocene	24
			Paleogene Subperiod	Oligocene	38
				Eocene	55
				Paleocene	66
	Mesozoic	Cretaceous		Late	96
				Early	138
		Jurassic		Late Middle Early	205
		Triassic		Late Middle Early	~240
	Paleozoic	Permian		Late Early	290
		Carboniferous Periods	Pennsylvanian	Late Middle Early	~330
			Mississippian	Late Early	360
		Devonian		Late Middle Early	410
		Silurian		Late Middle Early	435
		Ordovician		Late Middle Early	500
		Cambrian		Late Middle Early	[1]~570
Proterozoic	Late Proterozoic				900
	Middle Proterozoic				1600
	Early Proterozoic				2500
Archean	Late Archean				3000
	Middle Archean				3400
	Early Archean				
		(3800?)			
pre-Archean[2]					

[1]Rocks older than 570 Ma also called Precambrian, a time term without specific rank.
[2]Informal time term without specific rank.

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ABSTRACT

The exploitation of minerals has played a significant role in population growth and development of the U.S.-Mexico border region. Recent proposed changes in regulations related to mining in the United States and changes in mining and investment regulations in Mexico have led to increased mineral exploration and development in Mexico, especially in the border region. As a preliminary step in the study of the mineral industry of this area, the Center for Inter-American Mineral Resource Investigations (CIMRI) of the U.S. Geological Survey has compiled mine and occurrence data for nonfuel minerals in the border region. Analysis of this information indicates that a wide variety of metallic and industrial mineral commodities are present which can be used in agriculture, infrastructure, environmental improvement, and other industries. Therefore, mining will continue to play a significant role in the economy of this region.

INTRODUCTION

Increasing mineral trade and the prospect of a free trade agreement with Mexico (North American Free Trade Agreement) raise many mineral-resource issues specific to the U.S.-Mexico border area. A free trade agreement, along with current and anticipated favorable changes in the Mexican mining and investment codes and increasing regulation in the United States, could lead to a revival of the transborder mining industry that existed in the late 19th century (Martino and others, 1992). Urban, agricultural, and industrial growth along the border will likely accelerate under a free trade agreement, resulting in increased demand for development and improvement of the infrastructure and for goods which require minerals that can be supplied from either side of the border. Pressure is already mounting to clean up industrial contamination along the border, an effort that would create a strong local demand for minerals useful for the treatment of effluent and the storage of hazardous wastes.

Many borderlands geologists know that the mineral resources of the border area are able to support a substantial minerals industry that could meet the demands of an expanding economy and population. This report is for policymakers, corporate managers, borderlands specialists, and the general public, who may have scant knowledge of borderlands mineral resources and of the mineral-related policy issues. Information regarding resource limitations, such as water supply, prior land-use decisions, or lack of infrastructure, that may affect economic development of the border area is widely dispersed or unavailable. The Center for Inter-American Mineral Resource Investigations (CIMRI), which is part of the U.S. Geological Survey, is involved in a multiyear study to investigate the geologic, economic, and environmental aspects of the minerals industry in the U.S.-Mexico border region.

This report begins with a brief overview of the history of the border region as it relates to mineral-resource development. Sections on land status, infrastructure, geologic setting, and data sources lead to the summary of currently available mineral-resource data for the border region. Maps of mineral-commodity occurrences are included. The primary archive of data on mineral occurrences, prospects, and deposits utilized for this project is the Mineral Resources Data System (MRDS) of the U.S. Geological Survey, which is described below in "Data Sources and Collection."

For this report, the border region is defined to include parts of southern California, Arizona, New Mexico, and Texas on the U.S. side and the northern parts of Baja, Sonora, Chihuahua, Coahuila, Nuevo León, and Tamauli-

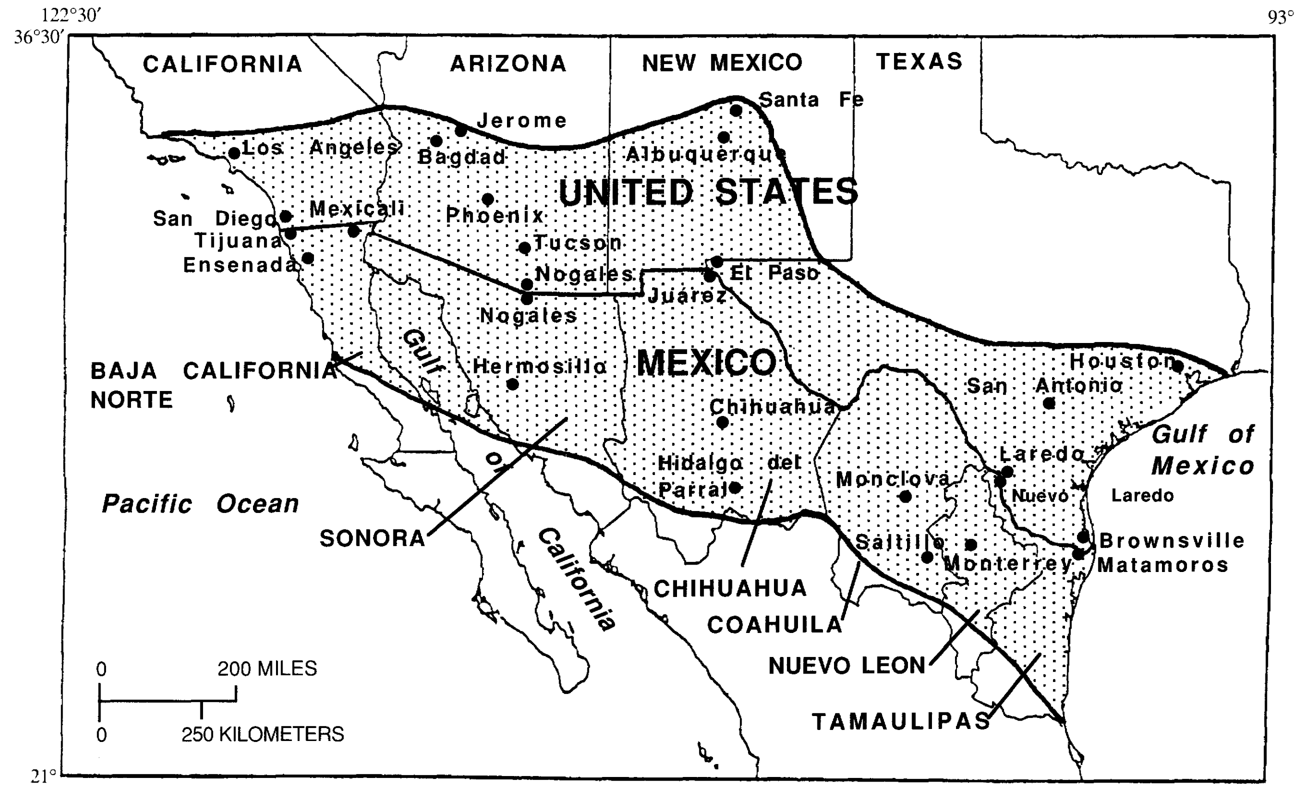

Figure 1. Area defined as the U.S.-Mexico border region for this report. Area shaded.

pas on the Mexican side of the border (fig. 1). The boundaries of the CIMRI study area were selected to include the major population centers away from the actual border and do not conform to existing political boundaries. Major population centers play important roles in the transport, processing, marketing, and demand for mineral commodities.

MINING HISTORY OF THE BORDER REGION

From pre-Columbian through modern time, the border region has played a vital role in the settlement and development of western North America. The resources of the border region were first utilized by North American indigenous peoples, who mined a wide variety of materials (Forrester, 1969; Gerald, 1984). Turquoise, jet (gem material made of dense coal), opal, copper, and silver were mined for decorative uses. Coal was utilized as a fuel. Obsidian and other igneous rocks were mined to produce projectile points, mortars and pestles, grinding stones, stone axes, and a variety of other tools. Clay, asbestos, and other materials were used to make pottery. Salt was mined for use as a preservative and flavoring, and sodium sulfate for use as a purgative. Extraction of these mineral products established some of the early flows of resource materials from the border region to other parts of North America.

The Spanish Crown granted the right to mine in the New World in 1504; from the 16th century to the early 19th century, the Spanish explored for and then exploited the silver and gold resources of the border region (table 1). Mining was done under a variety of laws and regulations that affected claim sizes, mining rights, royalties, taxes, ownership, and the level of exploration and development. Exploration and mining in the study area were also affected by repeated conflicts between settlers and miners and native peoples until the late 19th century. Near the present U.S.-Mexico border, mines were operated only sporadically due to the threat of violence.

Early discoveries during the Spanish Colonial period include silver districts in Chihuahua such as Parral (discovered about 1544), Batopilas (1632), and Santa Eulalia (1652) (Alvarez-Ruiz, 1983). These districts have produced for centuries and are responsible for the border region becoming one of the world's largest silver-producing areas. Many other mineral discoveries were made during the early Spanish Colonial period, including gold in the San Juan Bautista district, Sonora, in 1657 and silver along the Sonora-Arizona border in 1736 (Officer, 1991). In the north, salt was being produced in the Estancia Valley of New Mexico by the year 1650 to supply the silver-mining operations at Parral in Chihuahua (Bachman, 1965).

The 19th century saw continuous expansion of mining in the border region and the identification of other metal resources still produced today. In 1803, the United States acquired rights to much of the land west of the Mississippi through the Louisiana Purchase, and its citizens began to rapidly spread westward. In 1810, Mexico revolted against Spanish Colonial rule. By the end of the revolution in 1821, much of the mining industry in the new country of Mexico was in shambles, and foreign investment was restricted.

Continuing conflicts during the next 40 years, including the secession of Texas in 1836, the U.S.-Mexican war (1845–48), and the Mexican Revolution against France (1862–67), hampered efforts to rebuild the Mexican mining industry. At the end of its war with Mexico, the United States acquired most of the territory that is now New Mexico, Arizona, and California through the Treaty of Guadeloupe Hidalgo and the Gadsden Purchase. The end of the U.S.-Mexico war also led to the establishment in 1851 of a "Free Zone" (no tariffs on most imports) at Matamoros, Mexico. In the next 30 years, the "Free Zone" was expanded across Mexico, until it was a zone approximately 20 kilometers (12 miles) wide spanning the entire U.S.-Mexico border region (Engineering and Mining Journal, 1905). When Porfirio Diaz became president and dictator of Mexico in 1877, American and Canadian firms were encouraged to operate freely in that country (Griggs, 1907). Hundreds of mines opened up during this time, and the border-region industries grew as industrialization spread over the continent (Heylmun, 1988). Housing, roads, aqueducts, and railroad lines all required natural resources, many of which were produced in the border region. As the population of northern Mexico and the southwestern United States grew, so did the demand for raw materials and transportation of those materials. This situation lasted until the turn of the century, when social inequities and unrest led to widespread strikes, the end of the "Free Zone," restrictions on foreign investments, and, eventually, the third Mexican Revolution (1910–17).

Following the revolution, Mexico entered a period of nationalism where foreign control of mining and other industries was restricted and the flow of minerals across and within the border region was diminished. In 1926, Mexico prohibited any new foreign ownership of mines. This was followed by nationalization of certain mineral commodities and reservation of large tracts of land. In 1937, Mexico nationalized the railroads and, 1 year later, the oil industry.

Significant mineral discoveries continued to be made during the first half of the 20th century. Potash was discovered at Carlsbad, New Mexico (1925), and celestite in Coahuila (prior to 1942). Iron was discovered at La Perla, Chihuahua (1937). Minor amounts of iron, tungsten, nickel, and cobalt were extracted from the border region and sent to Allied Forces during World War II. After World War II, mining in the border region boomed as large low-grade copper, molybdenum, and gold resources, as well as other deposits, were more fully exploited.

In the second half of the 20th century, there has been a diversification of uses and exploitation methods for natural resources within the border region. As late as the 1950's, commodities such as celestite and fluorite (at Pico Etéro, Coahuila, in 1952) became significant products of the region. Today natural resources flow across the border, and large amounts flow in and out of the border region. The Mexican government is reversing many of the nationalistic policies of the earlier part of the century. Revision of the mining regulations in 1990 allows foreign control of mining projects for 12 years, and investment policies have been liberalized in the last few years. These changes have large numbers of international mining firms, including Canadian and American companies, investing in mineral exploration and development in Mexico, especially in the border region. Historically, the role of minerals and other resources in the region has been significant. In the coming century, as international commerce becomes greater, resources in the border region should continue to play an important role in socioeconomic development.

LAND STATUS AND INFRASTRUCTURE

In natural-resource development, one of the more important issues is land status. Availability of land for mineral exploration and development influences costs associated with exploitation. In the United States, the Bureau of Land Management in the U.S. Department of the Interior is responsible for the survey of Federal lands and maintains public land records and records of mining claims. In the United States, national park, Wilderness, and Department of Defense lands are mostly excluded from mineral exploration and production, whereas most lands managed by the Forest Service (part of the U.S. Department of Agriculture) and the Bureau of Land Management are open to mineral exploration and development under Federal regulation. Exploration for and development of some commodities on Federal lands can be done only under Federal lease; leasing of mineral rights is under the aegis of the Bureau of Land Management. Indian- and State-owned lands have diverse regulations governing mining, but exploration is severely restricted on most Indian lands. With the exception of Texas, which contains State-owned and privately owned land almost exclusively, the U.S. portion of the borderlands study area consists largely of Federal and Indian lands (fig. 2). Taxes, royalties, and other fees are often partially determined by the land status and commodity.

In Mexico, land status and the system controlling mineral exploration and development provide a significant contrast. In Mexico, just as in the United States, national parks and military training grounds are excluded from mineral exploration. However, the land-governing system set up through the Federal and State governments delegates control to individual municipios. Municipios, like counties

Table 1. Historical events related to mining in the U.S.-Mexico border region.

[Data from Alvarez-Ruiz (1983), Bachman (1965), Diaz-Unzueta (1986), Forrester (1969), Lacy (1987), Martino and others (1992), Officer (1991), Ordóñez Cortés (1986–90), Pearson (1974), and Ruiz and others (1986)]

16th Century	17th Century	17th Century—Continued	18th Century	18th Century—Continued
1504—Spanish Crown grants right to mine in New World	1600—Smelter at Parral, Chihuahua, begins to process silver ores	1666—Discovery of Cusihuiriachic silver and gold deposit, Chihuahua	1702—Discovery of Terrazas copper deposit, Chihuahua	1749—Discovery of Palmarejo lead deposit, Chihuahua
1536 to 1550—Viceroy Mendoza Codes (include mining laws)	1628—Discovery of Guazapares silver and gold district, Chihuahua	1670—First use of pumps to dewater a mine at Parral, Chihuahua	1719—Discovery of lead, zinc, and silver replacement deposits at Aldama, Chihuahua	1750(?)—Discovery of Ajo copper district and Arivaca (?) district, Arizona
1544(?)—Discovery of silver and lead at Parral, Chihuahua	1630—Discovery of Urique polymetallic vein district, Chihuahua	1674—Silver and lead discovered at Naica, Chihuahua	1725—Silver discovered in "Planchas de Plata" district, Sonora	1760—Jesuit missionaries discover and exploit gold and silver at Cananea, Sonora
1548—Vein mining of copper begins at Cerro Panuco, Coahuila	1632—Discovery of Batopilas silver district, Chihuahua	1675—Minting of first gold money in Mexico; previously all coinage was silver	1728—Spanish forbid production of mercury in New World to protect their monopoly; mercury was used to refine gold	1772—Discovery of Dolores gold and silver veins, Chihuahua-Sonora border area
1565—Discovery of gold at Santa Barbara, Chihuahua	1649—Discovery of La Calera lead and silver skarn and General Trias silver and gold veins, Chihuahua		1729—Discovery of Poreachi lead deposit, Coahuila, and Ocampo silver and gold deposit, Chihuahua	1774—Petition sent to King Carlos II asking for lower taxes, Mexican currency, national mining, and education system
1575—Saltillo, Coahuila, founded; agriculture and mineral exploration center	1650(?)—Salt mining, Estancia Valley, New Mexico		1732—Discovery of zinc veins, Uruachic district, Chihuahua	1783—Regal Code of Charles III—Reales Ordenanzas de la Minería de Nueva-España
1584—Regal Code of Philip II (includes mining regulations)	1652 —Discovery of Santa Eulalia silver district, Chihuahua; undocumented reports indicate discovery in 1591		1734—Discovery of gold and copper in Chinipas area, Sonora and Chihuahua	1799—Discovery of La Cienega gold placers, Sonora
1596—First smelter founded in Monterrey, Nuevo León	1657—Discovery of gold in San Juan Bautista district, Sonora		1736—Discovery of Arizonac (Arissona) silver deposit near Nogales along the present Arizona-Sonora border	
	1658—Discovery of San Francisco del Oro silver and fluorite district, Chihuahua		1740—Discovery of graphite in Sonora and gold and silver veins at La Colorada, Sonora	
			1748—Discovery of gold at Maguarichic, Chihuahua	

Table 1. Historical events related to mining in the U.S.-Mexico border region—Continued.

19th Century	19th Century—Continued	20th Century	20th Century—Continued
1801—Discovery of Janos copper district, New Mexico-Chihuahua border	1860—Cananea copper pipes begin production, Sonora	1905—U.S. and Mexico begin joint smelter production at Torreon, Coahuila, and Chihuahua, Chihuahua	1937—Discovery of La Perla iron deposit, Chihuahua
1804—Discovery of Santa Rita copper deposit, New Mexico	1862 to 1867—Mexican Revolution against France	1905—Diaz abolishes "Free Zone," enacts tariffs on mineral imports to Mexico	1937—Nationalization of Mexican railroads
1810 to 1821—Mexican Revolution against Spanish rule	1864—Arizona Territory Mining Code	1908—Strikes in Mexican border region cripple mining industry	1938—Nationalization of Mexican oil industry
1811—Namiquipa silver veins discovered, Chihuahua	1868—Copper discovered at Barranca del Cobre, Chihuahua	1910 to 1917—Mexican Revolution; foreigners lose effective control of mines	1942 or 1943—First production of celestite (a source of strontium) in Mexico
1823—Discovery of El Pilar de Moris gold deposit, Chihuahua, and law allowing foreigners to own mines in Mexico	1870—First gold production from Baja California Norte at Real de Castillo	1911 to 1917—First open pit porphyry copper mines developed at Ray, Arizona, Santa Rita, New Mexico, and Ajo, Arizona	1950—Discovery of silver and lead at La Encantada, Coahuila
1836—Texas declares independence from Mexico	1870—Discovery of gypsum(?) at Salinar de Jaco, Chihuahua	1912—Frasch mining of sulfur begins at Bryan Mound salt dome, Gulf Coast, Texas	1952—Discovery of fluorite at Pico Etéro, Coahuila
1845 to 1848—U.S.-Mexican war, U.S. acquisition of most of California-Arizona-New Mexico area	1873—First edition of the periodical *El Minero Mexicano*	1924—El Azufre sulfur mine begins production, Baja California	1961—Foreign interests in Mexican mines limited to 49 percent
1851—Mexico establishes "Free Zone" (few or no tariffs zone) at Matamoros; later extended across entire U.S.-Mexico border area	1877—Production of copper starts at Bisbee, Arizona	1925—Discovery of Carlsbad potash deposit, New Mexico	1964—Discovery of Hércules iron deposit, Coahuila
1853—Gadsden Purchase	1890—Morenci copper mine begins production in Arizona	1926—Mexico prohibits new foreign-owned mines; Ley de Industrias Mineras	
1855?—First production of graphite in Sonora	1893—Production of zinc at Lampazos, Sonora	1934—Mexico nationalizes mining of specified commodities and reserves lands; Ley Minera	

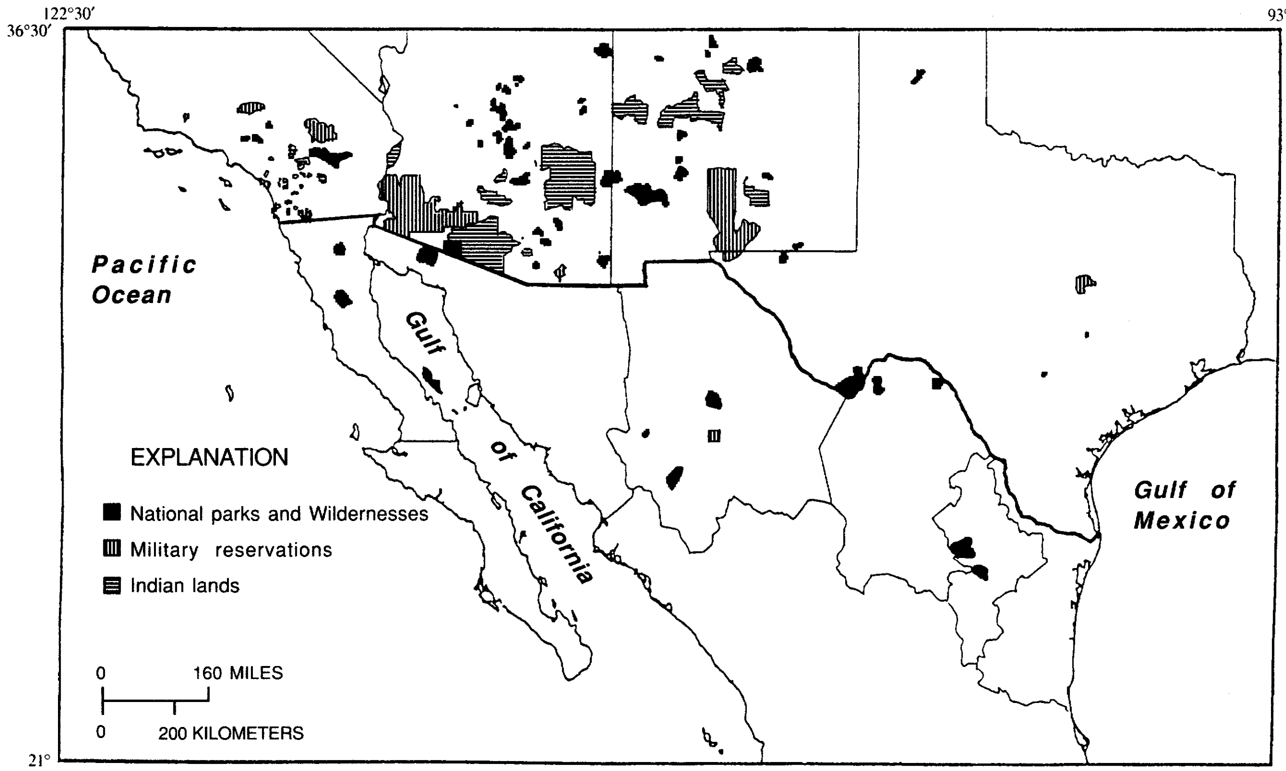

Figure 2. Distribution of lands known to be closed to mineral exploration and (or) development in and adjacent to the U.S.-Mexico border region. Data from Paul G. Schruben (U.S. Geological Survey, unpub. data, 1993).

in the United States, have a governmental seat where mining documents are filed with the Agencia de Minería. Municipio land is open to mineral exploration on a case-by-case basis, and agreements between the municipio government and individual companies are used to allocate mining lands. Most of the ranch land in the Mexico portion of the border region is privately held; the desert lands are typically government controlled. Taxes are paid to the State and Federal governments for all mining claims.

Figure 2 shows various types of land excluded from mineral exploration in the border region. More exact information on land status should be obtained from the U.S. Bureau of Land Management (address in table 2) or Mexican municipio offices.

Infrastructure plays a significant role in the ability of the borderlands to process and export mineral products. Infrastructure for the purposes of this report includes power sources and transportation routes. Power sources and facilities in the Western United States are shown on a map prepared by the U.S. Department of Energy (1992). Much like the U.S. railroad system, that in Mexico was constructed largely in the late 19th century and earliest 20th century. Although as much as 80 percent of the capital for this infrastructure development came from the United States (Martino and others, 1992), the railroads were nationalized in 1937. Figure 3 shows major standard-gauge railroad routes within and near the study area. Cross-border connections exist at various locations (fig. 3). The density of railroad lines in the southwestern part of the study area is low, and there is no rail service in Baja California Norte. Scheduling problems, lack of railcars, and other bottlenecks have led to truck rather than rail transport of ore in many Mexican mining operations (Martino and others, 1992). Recent decentralization of Mexican railroad operations has improved the speed and efficiency of the rail transport system; however, service to the rural areas has been diminished.

Over 65,000 kilometers (40,000 miles) of paved roads exist in Mexico (Martino and others, 1992), but most of them are in or near Mexico City; the density of paved roads in the border region is low (fig. 4). Nevertheless, trucking is the major transport mode in northern Mexico, operating largely on dirt roads. In Mexico, the mining industry relies heavily on truck transport. Paved roads link the United States and Mexico at 10 border cities, and the daily international truck commerce is valued in millions of dollars.

GEOLOGIC SETTING

The U.S.-Mexico border region extends 1,800 kilometers (1,100 miles) and, for purposes of this discussion, can be divided into six geologic provinces (fig. 5) from east to

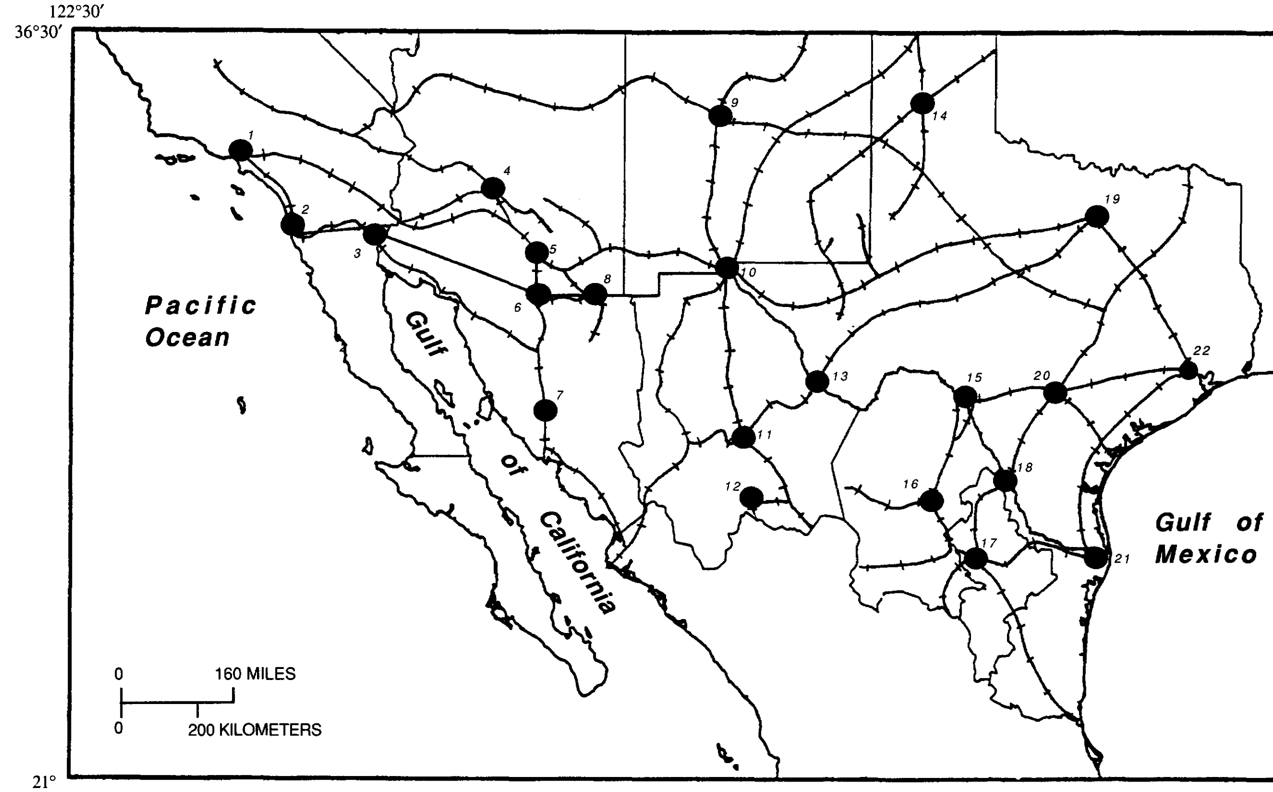

Figure 3. Major standard-gauge railroad routes in and adjacent to the U.S.-Mexico border region. Modified from México Secretaría de Comunicaciones y Transportes (1990) and U.S. Geological Survey (1970). State names shown in figure 1. Selected cities indicated by numbers: 1, Los Angeles; 2, San Diego-Tijuana; 3, Mexicali; 4, Phoenix; 5, Tucson; 6, Nogales; 7, Hermosillo; 8, Douglas; 9, Albuquerque; 10, El Paso-Juárez; 11, Chihuahua; 12, Hidalgo del Parral; 13, Presidio-Ojinaga; 14, Amarillo; 15, Del Rio–Villa Acuña and Eagle Pass–Piedras Negras; 16, Monclova; 17, Monterrey; 18, Laredo-Nuevo Laredo; 19, Dallas-Ft. Worth; 20, San Antonio; 21, Brownsville-Matamoros; and 22, Houston.

west: (1) the Gulf of Mexico Coastal Plain, (2) Paleozoic and Mesozoic platform rocks, (3) an area of terrestrial volcanism, (4) an area of structural extension, (5) a transitional area between platform rocks and the area of extension, and (6) an accreted terrane. These provinces and their associated mineral commodities are briefly described below.

The Gulf of Mexico Coastal Plain is the easternmost geologic province and is composed of the Tertiary to Holocene sedimentary rocks of Texas, Tamaulipas, and Nuevo Léon shown on the simplified geologic map in figure 5*A* and geologic province map in 5*B*. These rocks are relatively undeformed and overlie Paleozoic basement. Significant mineral deposits in the Gulf of Mexico Coastal Plain include sulfur, evaporites, and clays.

To the west of the Gulf of Mexico Coastal Plain are platform rocks of Paleozoic and Mesozoic age in western Texas, New Mexico, southern Tamaulipas, Nuevo León, and Coahuila. These dominantly carbonate rocks overlie Precambrian basement. Paleozoic and Mesozoic sedimentary rocks are also in the Colorado Plateau area of northwestern New Mexico and northeastern Arizona. Silver is the most important metal mined in the area of Paleozoic and Mesozoic rocks, although lead-zinc-silver replacement deposits and small copper deposits have also been mined. This province is also a major source of celestite (which yields strontium), fluorite, and potash. Other industrial minerals produced from Paleozoic and Mesozoic platform rocks include barite, sulfur, and sodium sulfate.

In the central part of the study area, a third geologic province is formed by the largely terrestrial volcanic rocks of west-central New Mexico, east-central Arizona, western Chihuahua, and eastern Sonora. Major mineral products of this area include silver and some gold, copper, pumice, and perlite.

The fourth province is a zone of extension. This province, the Basin and Range, is composed largely of Tertiary volcanic rocks and intervening basin fill and extends from southeastern California southeast through most of Sonora and east-southeast through Arizona and New Mexico to westernmost Texas and eastern Chihuahua. The Basin and Range province is possibly the richest in mineral wealth. World-class porphyry copper and gold deposits are found in this environment. Other mineral products include barite, borates, clays, diatomite, evaporites, fluorite, lead, zinc, and zeolites.

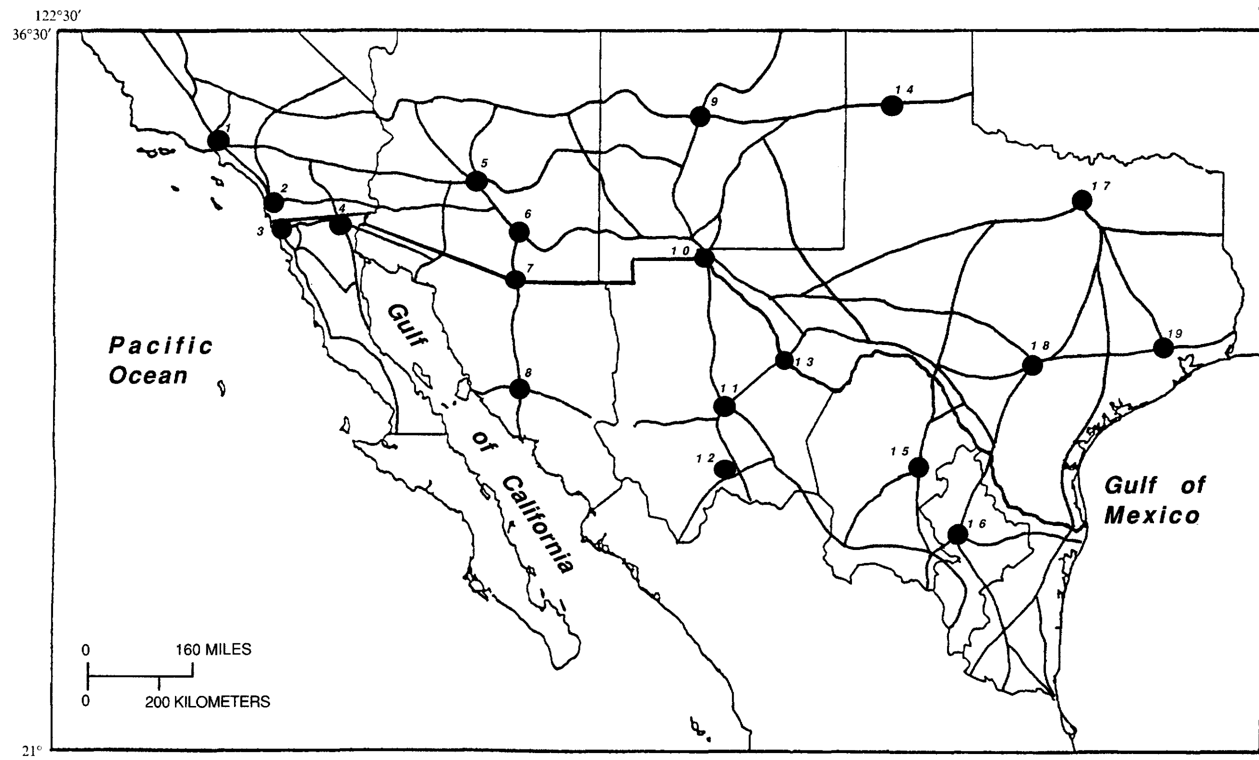

Figure 4. Selected primary paved highways and roads in and adjacent to the U.S.-Mexico border region. Modified from México Secretaría de Comunicaciones y Transportes (1990) and Rand McNally (1989). State names shown in figure 1. Selected cities indicated by numbers: 1, Los Angeles; 2, San Diego; 3, Tijuana; 4, Mexicali; 5, Phoenix; 6, Tucson; 7, Nogales; 8, Hermosillo; 9, Albuquerque; 10, El Paso-Juárez; 11, Chihuahua; 12, Hidalgo del Parral; 13, Presidio-Ojinaga; 14, Amarillo; 15, Monclova; 16, Monterrey; 17, Dallas-Ft. Worth; 18, San Antonio; and 19, Houston.

In Arizona, a southeast-trending transition zone occurs between the Basin and Range province to the southwest and platform rocks to the northeast. This area is the fifth geologic province and contains the most extensive exposures of Precambrian rocks in the border study region. These very old rocks are known for the massive sulfide deposits near Jerome and Bagdad.

The sixth province is the far western part of the study area; it consists of accreted terranes and includes Mesozoic plutonic, sedimentary, and metamorphic rocks with Tertiary to Holocene basin fill. Gold is the dominant mineral product.

Figure 6 shows the distribution of Tertiary and Quaternary volcanic rocks and Paleozoic through Tertiary intrusive rocks. Magmatically the compositions vary widely from alkalic in the east to calc-alkalic and alkalic-metaluminous in the west (Clark and others, 1982); thus, the mineral commodities associated with these rocks vary widely. The deposits in the border region formed during as many as five distinctive magmatic-tectonic pulses. In the Jurassic, shearing and mafic magmatism gave rise to minor metallic ore deposits. During the Cretaceous, gold-silver veins, copper and tungsten skarns, and numerous pegmatites formed in the batholithic regions of the far western border region.

The Late Cretaceous and early Tertiary was a time of extensive volcanic and plutonic activity (known as the Laramide orogeny). World-class copper-molybdenum porphyry, silver-gold, and lead-zinc-silver deposits formed in and around the area during this period. From 80 million to 40 million years ago, the center of magmatism transgressed from west to east and caused multiple periods of magmatism and mineralization to affect the same area. These multiple events led to extensive mineralization of the border region. As the magmatism moved eastward, hydrothermal ore deposits formed progressively to the east.

During the middle Tertiary 36 million to 20 million years ago, volcanoes and felsic magmatism generated numerous gold-silver, lead-zinc-silver, and fluorite deposits. The environments of mineralization ranged from continental volcanic and magmatic environments to fault-block basins; these areas extend from Arizona and New Mexico southward through most of western Mexico. Late Tertiary to Holocene igneous activity is associated with hot-spring gold, red-bed copper, volcanic sulfur, borate, and zeolite deposits. Magmatic rocks of late Tertiary age are concentrated near the Gulf of California.

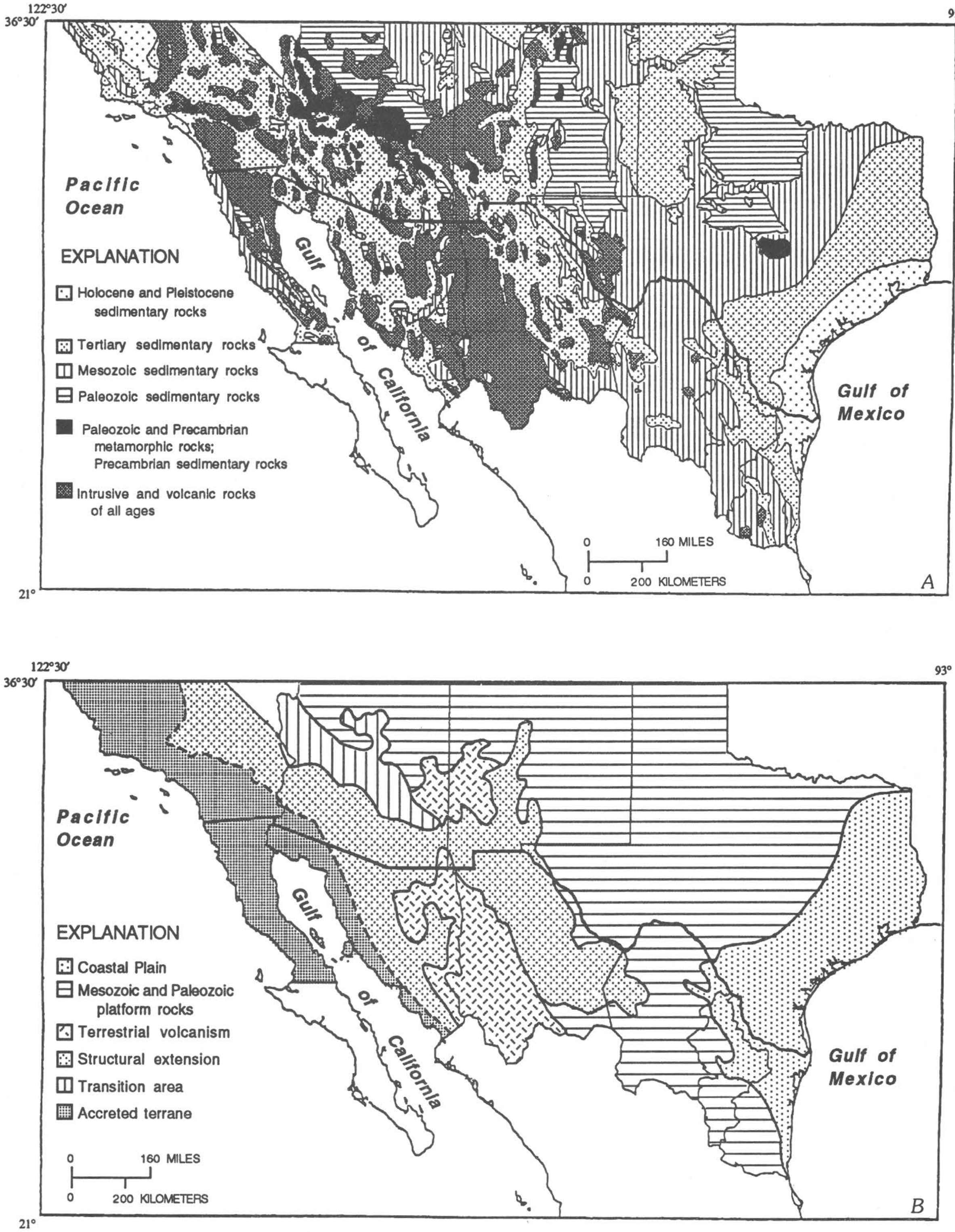

Figure 5. Simplified geology (*A*) and geologic provinces (*B*) in and adjacent to the U.S.-Mexico border region. Modified from U.S. Geological Survey (1970) and Ortega-Gutiérrez and others (1992). Geologic province boundaries dashed where uncertain.

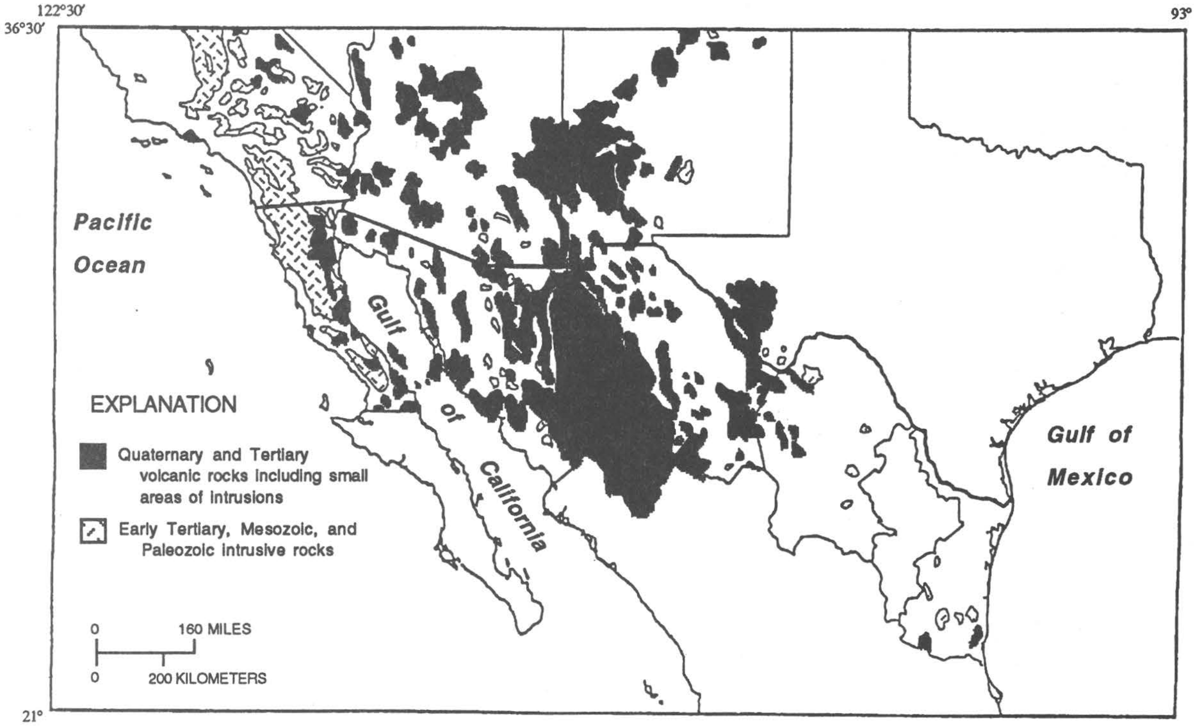

Figure 6. Generalized distribution of volcanic and plutonic rocks in and adjacent to the U.S.-Mexico border region. Modified from U.S. Geological Survey (1970) and Ortega-Gutiérrez and others (1992).

DATA SOURCES AND COLLECTION

An initial step of the CIMRI border-region project is an inventory of known mines, prospects, and occurrences, which are referred to collectively as deposits. Data for each site include name, location, commodity, deposit type, and geology. CIMRI archives these data in the U.S. Geological Survey's Mineral Resources Data System (MRDS), a publicly available computerized data base of mine and occurrence information for nonfuel minerals. MRDS contained approximately 5,400 records for deposits within the study area prior to CIMRI's project, and many of these have been updated. Most of the existing records were for metal mines and occurrences in Arizona, California, and New Mexico. CIMRI has added approximately 4,000 additional records for the border-region study area; most of these records are for Mexico or for industrial mineral sites throughout the border region. Data collection is not yet complete, and this circular is a progress report; efforts are continuing to collect data on metallic and industrial mineral deposits of southeastern California, industrial mineral deposits of northwestern Mexico and southwestern Texas, and sand and gravel deposits of Arizona. The reader should be aware that the completeness of the information for mines and occurrences varies with the area and the available literature. Also, in much of Coahuila and Chihuahua, all mineralization within 2 kilometers (1.2 miles) of a mine is considered to be a single mine or occurrence.

The total number of border-region records in the MRDS as of May 1993 was just under 9,300 for sites distributed as shown in figure 7. Figure 8 is a plot of all sites in the approximate area of study for which the MRDS contains records. In general, the density of data is much higher in the United States, although incomplete data sets for southern California and southwestern Texas are noticeable. A more detailed discussion of mineral-site data collection can be found in Center for Inter-American Mineral Resource Investigations (1993). MRDS data for the study area are available from Mineral Information Offices of the U.S. Geological Survey in digital form or as listings, tables, and plots; write to one of the five addresses shown in table 2. Table 2 lists additional sources of mineral-resource information.

In addition to mineral-resource information, CIMRI is interested in the role of minerals relative to border-region issues such as trade, infrastructure development, agriculture support, and environmental problems. To help understand these relations, CIMRI is also compiling information on power generation capabilities, infrastructure, mineral exports and imports of the border area, mineral-processing plants, environmental cleanup sites, and other topics.

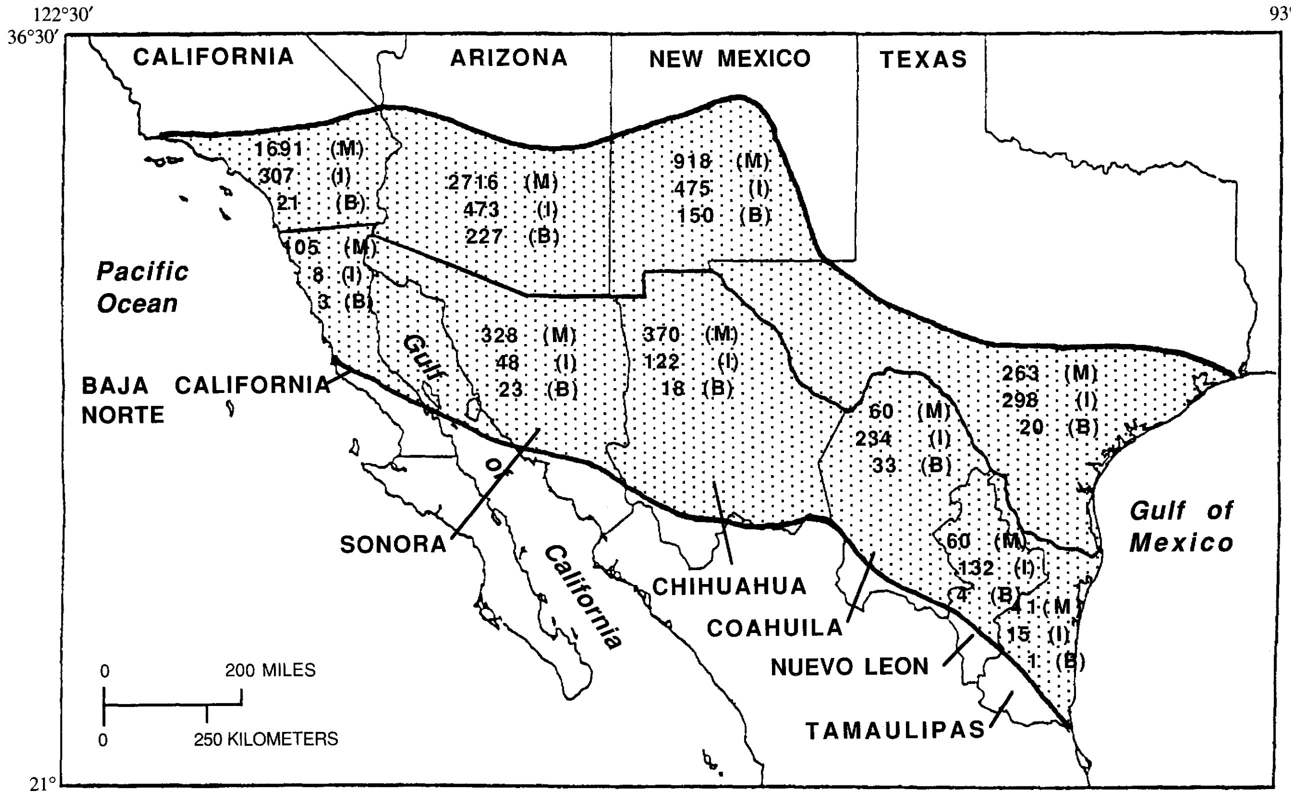

Figure 7. U.S.-Mexico border region showing the number of Mineral Resources Data System records for sites containing metallic minerals only (M), industrial mineral commodities only (I), and both metallic and industrial mineral commodities (B).

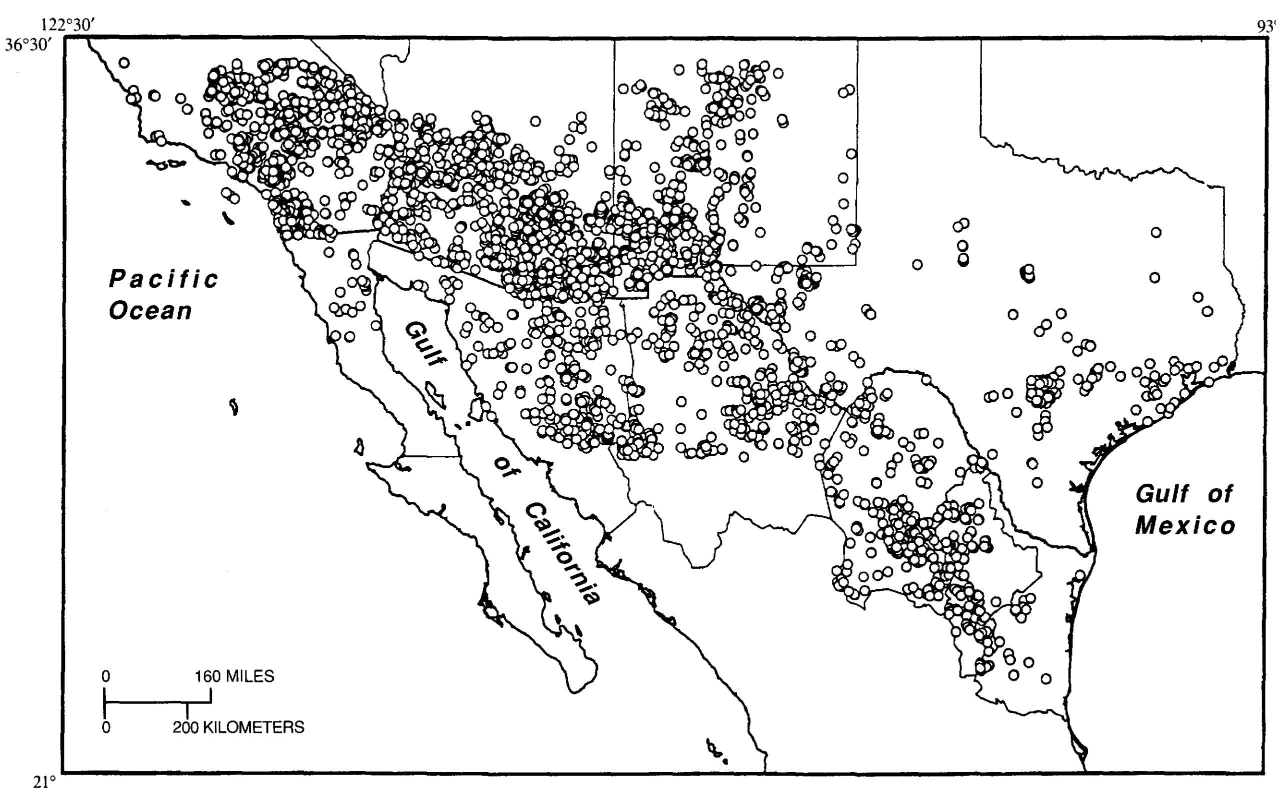

Figure 8. Distribution of all mines, prospects, and occurrences of metallic and industrial mineral commodities in and adjacent to the U.S.-Mexico border region for which the Mineral Resources Data System included records as of May 1993.

Table 2. Some general sources of information on mineral resources of the U.S.-Mexico border region.

PUBLICATIONS

Mexico	**United States**
The mineral economy of Mexico (Martino and others, 1992)	Mineral and water resources of Arizona (U.S. Geological Survey and others, 1969)
Economic geology, Mexico (Salas, 1991)	Arizona industrial minerals (Phillips, 1987)
Plano nacional de la República Mexicana (México Secretaría de la Defensa Nacional, 1980)	Mineral resources of California (U.S. Geological Survey and others, 1966)
Mexican mines (Ordóñez Cortés, 1986–90)	Mineral and water resources of New Mexico (U.S. Geological Survey and others, 1965)
Preliminary deposit-type map of northwestern Mexico (Leonard, 1989)	Mines and mills in New Mexico (Hatton and others, 1990)
	Industrial rocks and minerals of the Southwest (Austin, 1982)
	Annotated bibliography of mineral deposits in Trans-Pecos Texas (Price and others, 1983)

ORGANIZATIONS

Mexico	**U.S. Federal** [All part of the U.S. Department of the Interior]	**U.S. State**
Comisión de Fomento Minero Av. Puente de Tecamachalco No. 25 Col. Lomas de Chapultepec C.P. 11000 México, D.F.	Center for Inter-American Mineral Resource Investigations U.S. Geological Survey 210 E. 7th Street Tucson, AZ 85705	Arizona Geological Survey 845 N. Park Avenue Tucson, AZ 85719
Consejo de Recursos Minerales Boulevard Felipe Angeles S/N KM 93–5 Col. Venta Prieta C.P. 42080 Pachuca, Hidalgo	Minerals Information Offices	Arizona Department of Mines and Mineral Resources 1502 West Washington Phoenix, AZ 85007
Instituto de Geología Universidad Nacional Autónoma de México Estación Regional de Noroeste Apart. Postal 1039 8300 Hermosillo, Sonora	U.S. Geological Survey 340 North 6th Avenue Tucson, AZ 85705	California Division of Mines and Geology 801 K Street, MS12–30 Sacramento, CA 95814–3531
	U.S. Geological Survey U.S. Department of the Interior MS 2647–MIB, Room 2647 1849 C Street NW. Washington, DC 20240	New Mexico Bureau of Mines and Mineral Resources Campus Station Socorro, NM 87801
	U.S. Geological Survey Mackay School of Mines Scrugham Engineering Mines Building University of Nevada-Reno Reno, NV 89557–0047	Texas Bureau of Economic Geology Balcones Research Center University Station, Box X Austin, TX 78713–7508
	U.S. Geological Survey Room 133 W. 904 Riverside Ave. Spokane, WA 99201	
	U.S. Geological Survey Federal Center MS 936 Bldg. 20, Rm. B1324 Denver, CO 80225	
	U.S. Bureau of Land Management 18th & C Streets NW. Washington, DC 20240	
	U.S. Bureau of Mines 810 7th Street NW. Washington, DC 20241	

Table 3. Mineral commodities produced within the U.S.-Mexico border region.

[Data from the Mineral Resources Data System]

METALS		INDUSTRIAL MINERALS AND MATERIALS	
Major	**Minor**	**Major**	**Minor**
Copper	Iron	Aggregate (crushed stone and gravel)	Building stone
Gold	Mercury	Barite	Diatomite
Lead	Molybdenum	Bentonite	Feldspar
Silver	Rhenium	Borates	Kaolin
Zinc	Tungsten	Celestite	Magnesia-magnesite
		Clays	Mica
		Fluorite	Nitrogen-nitrates
		Graphite (amorphous)	Perlite
		Gypsum	Phosphates
		Halite	Wollastonite
		Limestone (for use in cement)	
		Potash	
		Pumice	
		Sand and gravel	
		Sodium sulfate (natural)	
		Sulfur	
		Zeolites	

MINERAL-RESOURCE DISTRIBUTION

One of the goals of this study is to identify which resources occur within the study area and which need to be imported to supply border-region industries. In addition, minerals that might be exported from the region will be identified. The variety and number of occurrences of metallic and nonmetallic resources in the border region are extensive. These resources include precious and base metals and materials used in agriculture, infrastructure development, environmental improvement, and production of chemicals. Commodities produced in the study area are listed in table 3. Fuel materials (coal, uranium, oil, and gas) are prevalent in the border region but are not addressed in this study. Metals for producing steel, aluminum, and nonferrous alloys occur in minor amounts and are not available in the quantity necessary to support an extensive industry in the border region. Ferrous metals occur in a number of deposits and have supported an integrated steel plant at Monclova, Coahuila, in the recent past, but increased reserves would be needed to revitalize this plant (Martino and others, 1992). A major integrated steel plant continues to operate in Monterrey, Nuevo León, but is dependent on imported ores.

The distribution of major mines, prospects, and occurrences of gold and silver in the border region is shown in figure 9. The sites shown in this figure represent both placer and lode deposits where gold and (or) silver were listed as major commodities. The distribution of precious metals in the study area indicates that the western part of the area is more gold rich and that the southeastern part of the area is silver dominated. There are no reported major gold occurrences in Nuevo León, Tamaulipas, or Coahuila, although a few small occurrences have been reported. Precious metals, gold and silver, were the dominant commodities of interest in the border region until the mid-19th century, when lead, zinc, and copper deposits began to produce and eventually dominated metal production. In the 1970's and 1980's, gold again became the focus of mineral exploration on the U.S. side of the border and continues to be the main commodity of exploration interest throughout the study area. The change in regulations concerning exploration and mining in Mexico in 1990 has created an explosion of activity by foreign investors in precious-metal exploration in Mexico. Current opinion of the potential for undiscovered deposits in northern Mexico and the large gap between early exploitation and modern exploration indicate that the border region will continue to be a source of considerable precious-metal wealth in the foreseeable future.

With the discovery of base-metal deposits (lead, zinc, and copper) in the mid-1800's, the resource focus changed to the development of lead and zinc industries. The distribution of known mines, prospects, and occurrences where copper or lead and zinc are the main commodities is shown in figure 10. Lead and zinc deposits appear to be more abundant in the eastern part of the border region, particularly in Chihuahua, Coahuila, and Tamaulipas. These base metals have played a key role in mineral-resource development in the border region. By World War I, the border region had become a significant copper producer and, in fact, there was a copper boom spurred by the technology to recover copper from large tonnages of low-grade copper material. Mexico's copper production grew to be the 11th

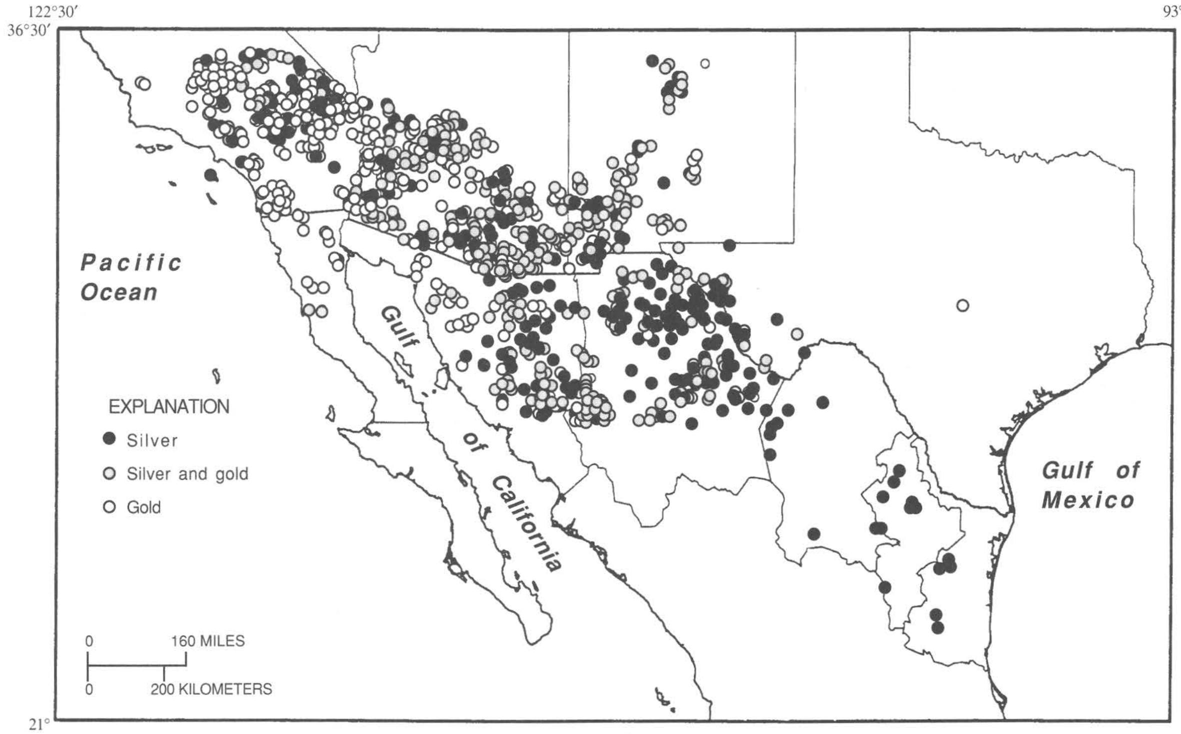

Figure 9. Distribution of major gold and silver mines, prospects, and occurrences in and adjacent to the U.S.-Mexico border region. Data from the Mineral Resources Data System.

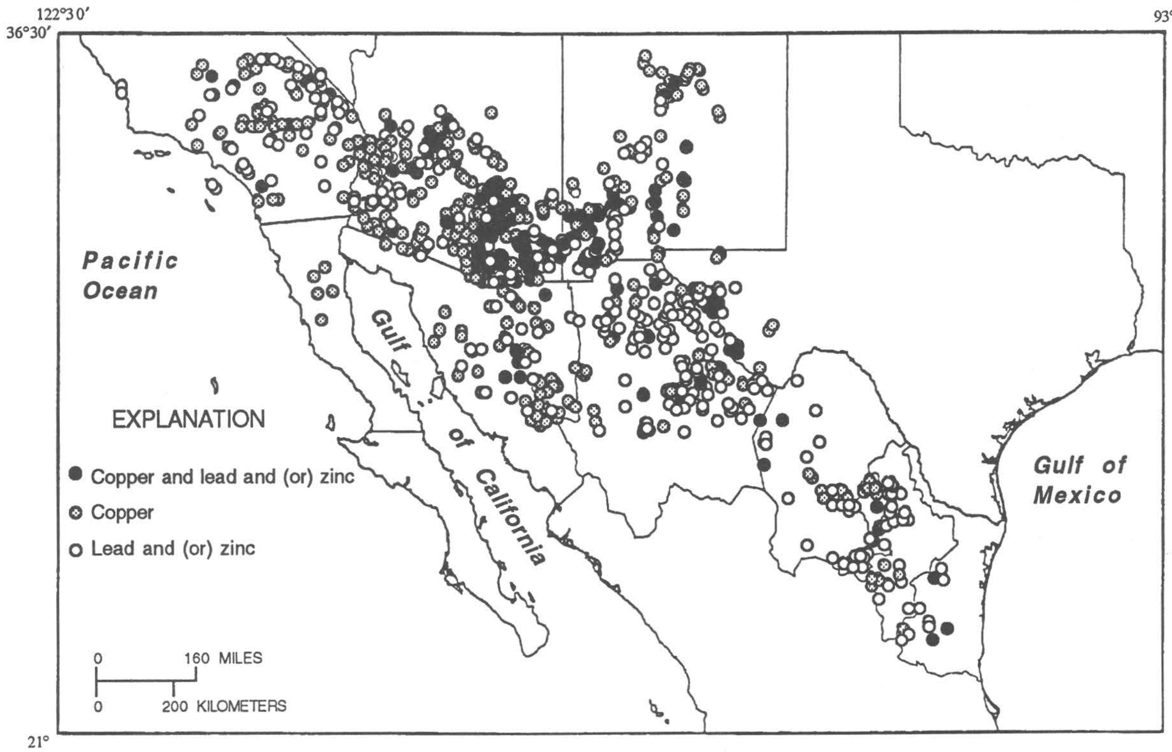

Figure 10. Distribution of major lead and (or) zinc and copper mines, prospects, and occurrences in and adjacent to the U.S.-Mexico border region. Data from the Mineral Resources Data System.

Table 4. Significant industrial mineral commodities used in agriculture, infrastructure, and environmental improvements in the U.S.-Mexico border region.

[Industrial mineral commodities produced in the border region are listed in table 3. Some commodities used in the border region are produced there, and some are brought in. Data from the Mineral Resources Data System]

	Limestone	Gypsum	Light-weight aggregate	Sand, gravel, stone	Zeolites	Diatomite	Clays	Potash, halite	Sulfur	Borates	Phosphates	Nitrates
AGRICULTURE												
Fertilizers or conditioners	X	X	X				X	X	X	X	X	X
Feeds					X			X				
Chemicals or insecticides	X		X		X		X			X		
INFRASTRUCTURE												
Cement	X	X	X	X			X					
Roads				X								
Bridges and overpasses	X			X			X					
Railroads				X								
Power	X									X		
ENVIRONMENTAL IMPROVEMENTS												
Acid lakes	X											
Acid mine drainage	X				X	X						
Spill cleanup					X		X	X	X			
Hazardous material transport			X		X		X					
Noise abatement		X	X									
Energy efficiency		X	X			X				X		
Waste treatment or containment	X	X	X	X	X	X	X			X		

largest in the world by 1992, with nearly all the copper coming from the border region, and copper production in the United States made it the 2d largest producer in the world (Thompson, 1993). Most of the U.S. copper also comes from the border region. The U.S.-Mexico border region is one of the richest copper provinces in the world.

Many of the same mineral materials used in agriculture are also used for infrastructure development and environmental improvement (table 4). For example, limestone, gypsum, light-weight aggregate, and boron (from borates) all have applications in these three areas. Many other materials are used in two areas. Most of the materials are used in agriculture. Figure 11 shows the distribution of known mines, prospects, and occurrences of limestone (including marble and dolomite), light-weight aggregate (including perlite, pumice, vermiculite, and other volcanic materials), sand and gravel, and stone used as aggregate or building stone. The absence of data points for these materials in Baja California Norte and Sonora in the figure is probably a function of incomplete data collection and not a result of the geology. The gap in known occurrences of these commodities in southern Arizona coincides with an Indian reservation adjacent to military lands. These materials, although used mainly in infrastructure development, have other uses as shown in table 4.

Zeolite, gypsum, and diatomite distribution in the border region is shown in figure 12. Their applications cross several areas of use, but they are generally important to environmental cleanup because of their absorbent properties. Lack of known occurrences of these commodities outside of Arizona, Nuevo León, and Coahuila is a reflection of incomplete data.

The border region is a leading producer of strontium from celestite and fluorine from fluorite, and the distribution of these commodities is shown in figure 13. Included on this figure is the distribution of barite, which is used in drilling mud. Again, the apparent lack of barite, fluorite, and celestite deposits in California, Baja California Norte, western Sonora, and western Coahuila is probably a function of the incomplete data.

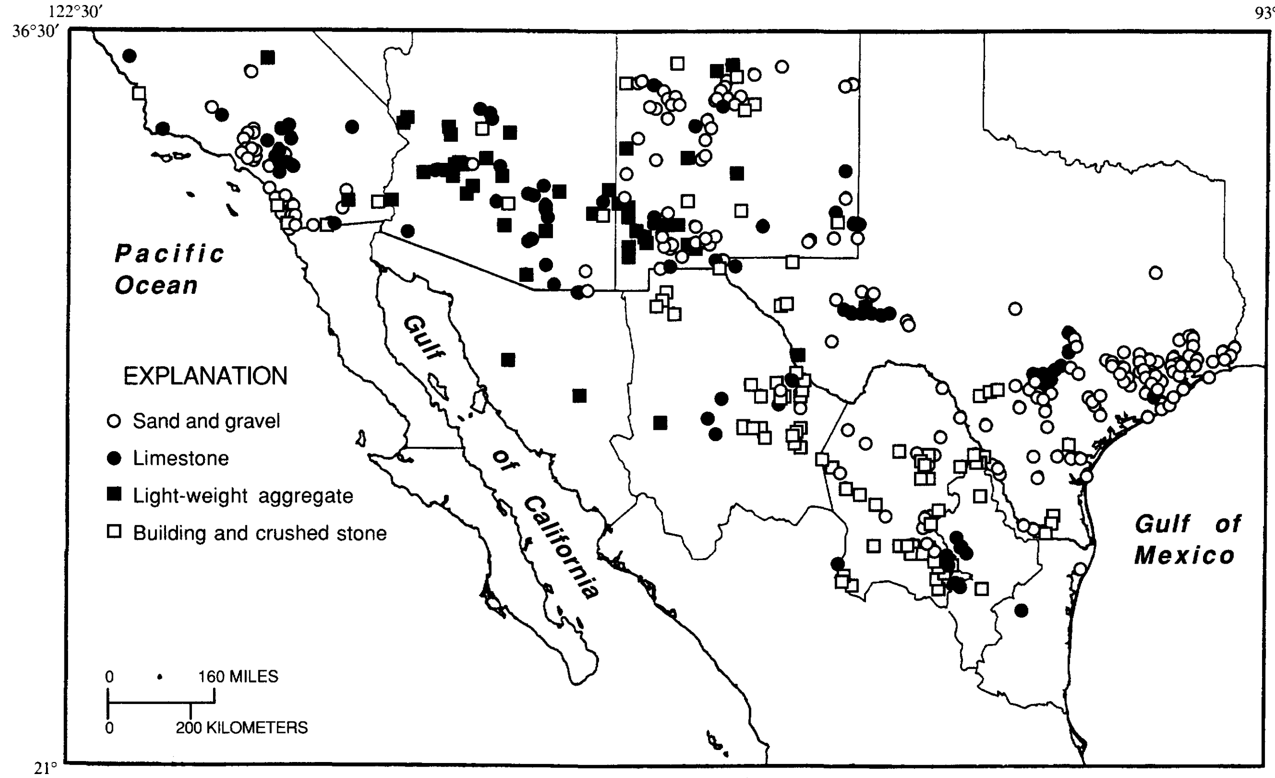

Figure 11. Distribution of mines, prospects, and occurrences of construction materials in and adjacent to the U.S.-Mexico border region, including sand and gravel, limestone, light-weight aggregate (pumice, perlite, vermiculite), and stone for aggregate or building stone. Data from the Mineral Resources Data System.

Figure 14 shows the distribution of four disparate groups of industrial minerals: all clays, evaporite minerals (potash and (or) halite), sodium sulfate and sodium carbonate, and sulfur. Again, there are large gaps in the plot of occurrences in northern Mexico that are probably due to incomplete data.

Other materials and metals occur in the border region. Readers interested in the distribution of commodities not included in this publication should contact the U.S. Geological Survey offices listed in table 2.

DISCUSSION

Initial compilation of nonfuel mineral-resource data has thus far identified approximately 9,300 known deposits and occurrences in the U.S.-Mexico border region of precious metals, base metals, and mineral commodities used in infrastructure, agriculture, and environmental improvement. Preliminary assessment of the geological terranes implies that further exploration in northern Mexico could augment the known deposits of many industrial minerals, including zeolites and clays. The low density of existing road and railroad infrastructure in parts of northern Mexico could impede future resource development, especially the development of low-value industrial minerals and bulk construction materials such as aggregate and sand and gravel.

Investment capital for exploration and mining will probably accelerate its flow to Mexico. The reasons for this include the decreasing land area in the southwestern United States open to mineral exploration and exploitation, increasingly restrictive U.S. regulations, the extensive amount of land open to mining in Mexico, and favorable Mexican investment and mining regulations. Expansion of mining activities in Mexico will probably mean increasing flows of many minerals and materials from Mexico to the United States and Canada. However, known deposits of materials for environmental cleanup efforts are limited in northern Mexico, and, in the short term, these materials may be expected to flow southward. Iron and aluminum alloys will also have to be imported into the border region.

In the future, with increased exploration and financial investment, the border region is likely to experience significant growth. As this growth occurs, the demand for minerals for industry, infrastructure, housing, agriculture, environmental cleanup, and other uses will also increase. The ability of the border region to supply many basic minerals to industries within its boundaries and outside of its boundaries contributes to the prospect of a bright economic future.

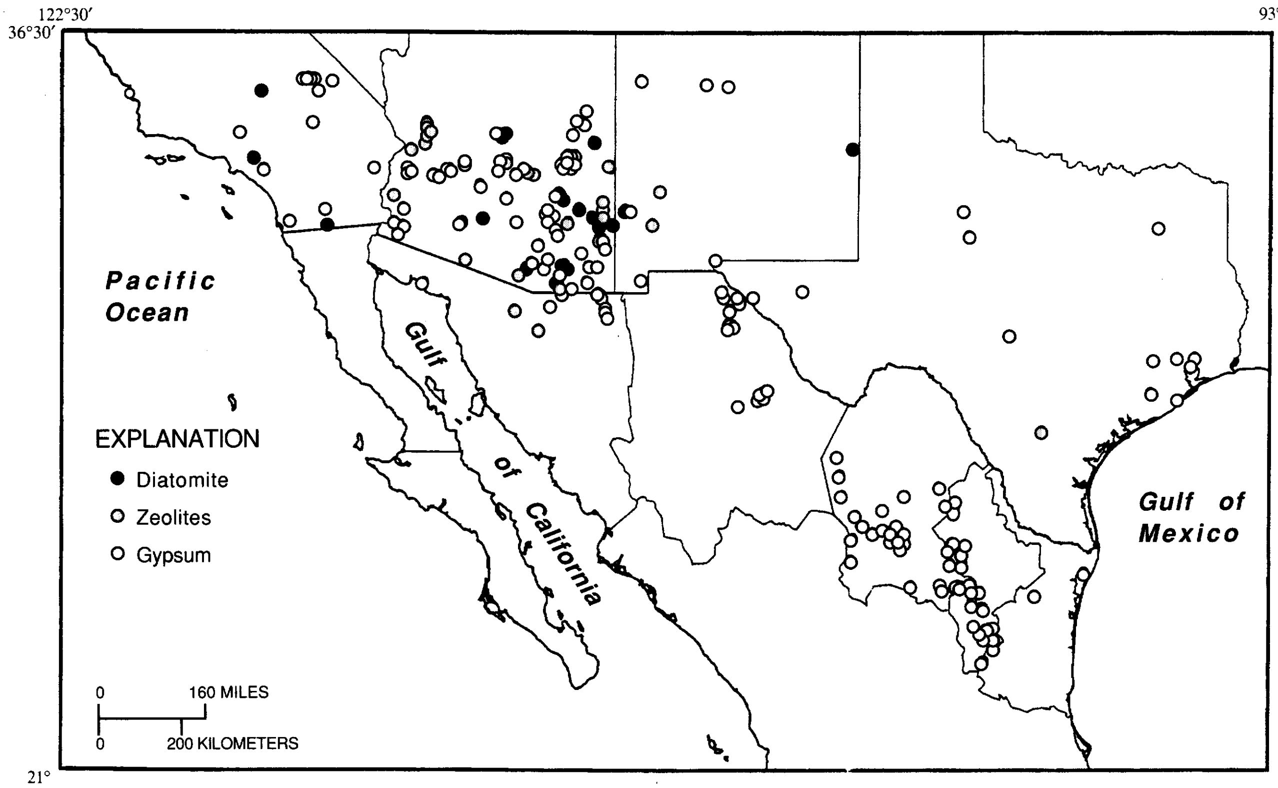

Figure 12. Distribution of mines, prospects, and occurrences of gypsum, zeolites, and diatomite in and adjacent to the U.S.-Mexico border region. Data from the Mineral Resources Data System.

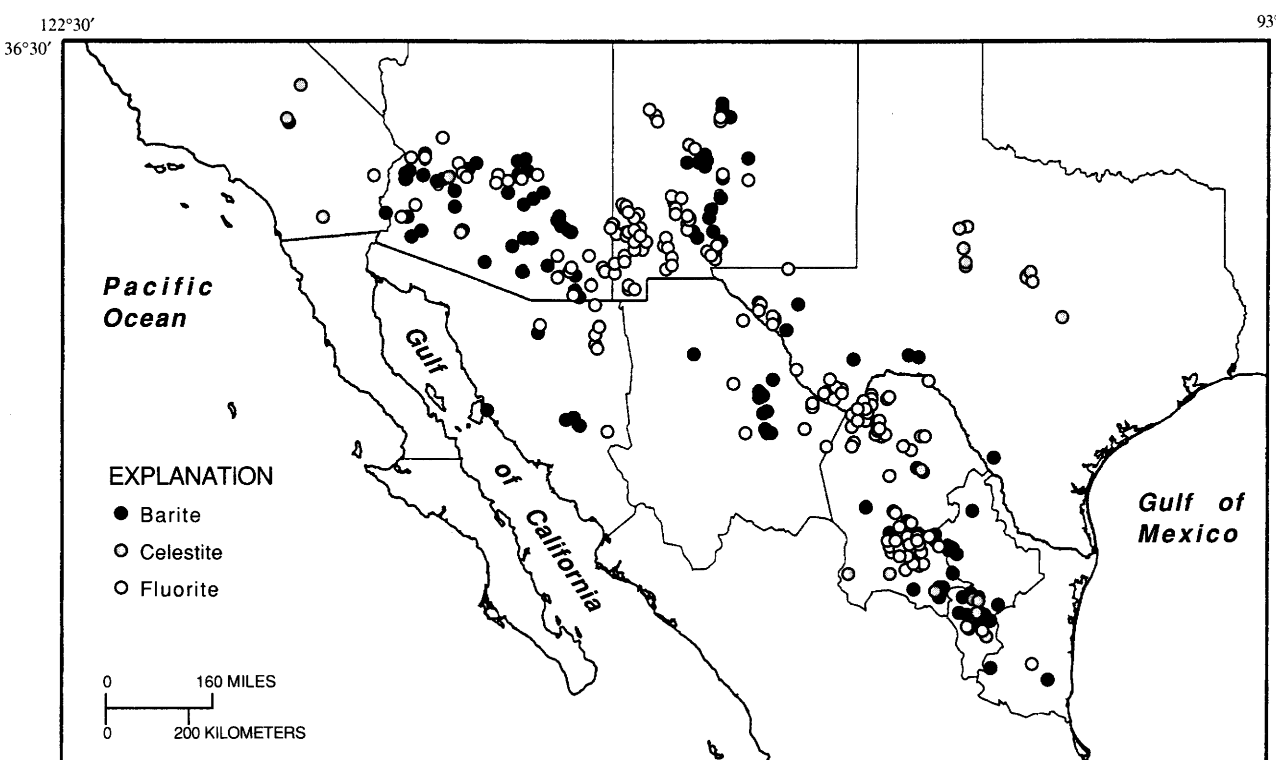

Figure 13. Distribution of mines, prospects, and occurrences of barite, fluorite, and celestite (a source of strontium) in and adjacent to the U.S.-Mexico border region. Data from the Mineral Resources Data System.

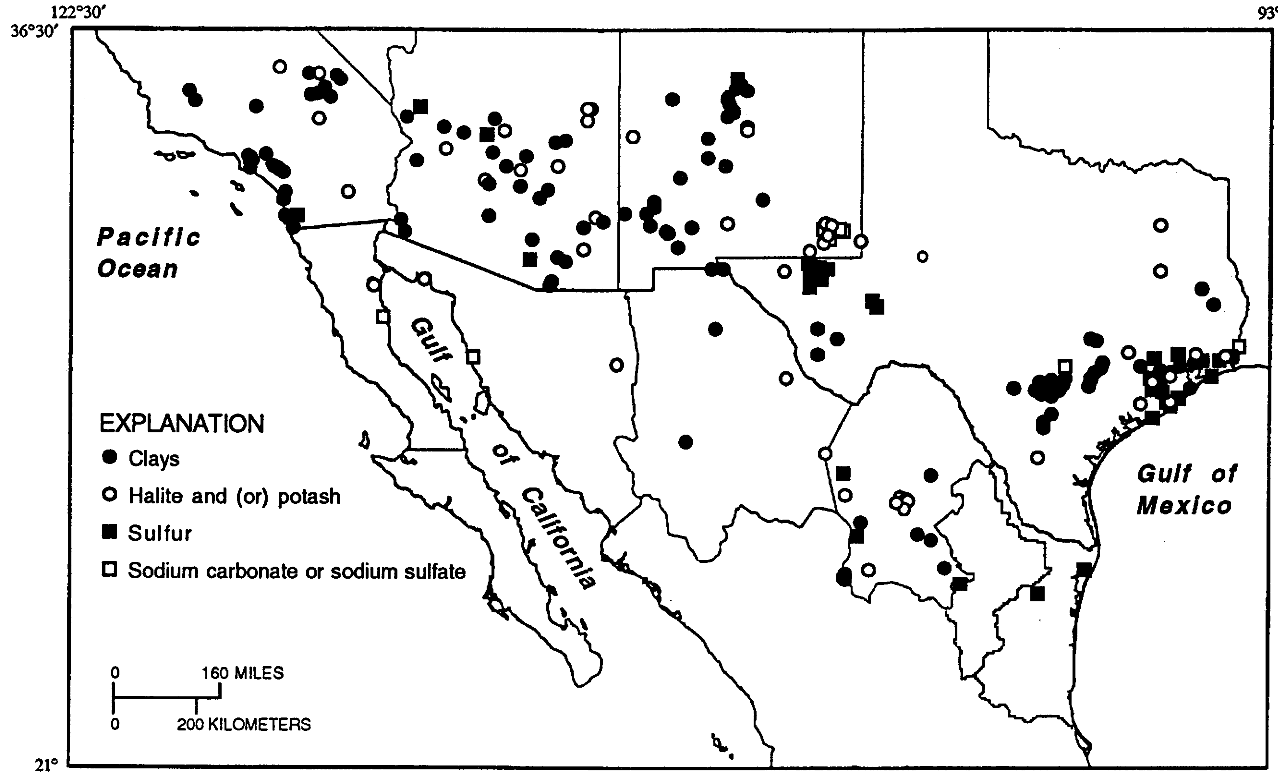

Figure 14. Distribution of mines, prospects, and occurrences of clays, evaporite (halite or potash), sodium carbonate or sodium sulfate, and sulfur in and adjacent to the U.S.-Mexico border region. Data from the Mineral Resources Data System.

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Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations, as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7.5- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7.5-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases for quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Map Distribution, Box 25286, Bldg. 810, Federal Center, Denver, CO 80225. (See latest Price and Availability List.)

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