INTRODUCTION

Gypsum (CaSO₄•2H₂O) is a versatile mineral with hundreds of uses. The predominant use of gypsum since ancient times has been as a construction material. According to Schroeder (1970), gypsum was used as a mortar in the Egyptian pyramids in 3000 BC, and Pressler (1985) indicated that the burning or calcining of gypsum was described by the early Greeks. Gypsum mortar was used in Egypt during construction of the Pyramid of Cheops in the 18th Dynasty (1580–1350 BC). Hydraulic gypsum mortar was used in medieval times in castles and fortresses in what today is Germany. Remnants of walls constructed with hydraulic gypsum mortar have existed for centuries in the Hartz Mountain region of Germany (Wilder 1918).

The development of gypsum plasters is difficult to trace; by the late 1800s, however, a commercial process had been developed to slow the setting time, thereby allowing widespread use of finishing plaster. Prefabricated wallboard panels were developed in 1918 (Adams 1991) but were not widely used until the great construction boom after World War II. Before that time, plastered walls were more common in residential and commercial construction.

Worldwide, the predominant use of gypsum is in the manufacture of construction plasters and portland cement (anhydrite, most commonly used in the manufacture of portland cement, is often sold as a mixture of impure gypsum and anhydrite). The predominant use of gypsum in North America, however, is in various types of wallboard panels. In 2003, about 90% of the total gypsum produced in the United States was used in wallboard and construction plasters.

Gypsum has been used in agriculture as a soil amendment since the middle of the eighteenth century. The earliest accounts of gypsum’s agricultural applications were published in Switzerland in 1768. George Washington and Benjamin Franklin were proponents of the use of gypsum in agriculture in the United States in the late 1700s. Benjamin Franklin promoted the use of gypsum by applying ground gypsum, commonly known as “land plaster,” to a field of clover in a pattern forming the phrase “Land Plaster Used Here” (Wilder 1918). The clover grew thicker and greener in the areas where gypsum was applied.

Specialized methods of calcination of gypsum and formulation with additives allow for manufacturing of more than 400 products. Uses vary from simple ground gypsum in agriculture to specialized plaster products in art and statuary; medical applications; intricate cast architectural detail; and fast-setting, high-strength construction products. There is no recognized commodity value of a ton of raw gypsum. Although mining costs are relatively low, the energy-intensive postmining processing and ultimate end use add significant value to the products made from the gypsum. Freight costs are a significant factor in marketability of a gypsum deposit.

Synthetic gypsum, derived primarily from environmental controls on coal-fired power plants by a process known as flue gas desulfurization (FGD), has become a significant raw material resource used in the manufacture of gypsum wallboard products. Demand for synthetic gypsum has steadily grown since the 1980s, and in 2003 about 26% of the total gypsum used for manufacturing wallboard in the United States was synthetic. Originally thought of as a waste product from the environmental controls on coal-fired power plants requiring disposal in landfills, technological improvements allowed synthetic gypsum to become a marketable coproduct. Many of the wallboard plants in the United States built since the late 1990s use only synthetic gypsum as a raw material.

Gypsum deposits are distributed throughout much of the world, and gypsum is produced in more than 90 countries (USGS 2004). The value of a deposit of gypsum depends on geological, mining, engineering, and other factors in order to be used economically.

The utility and value of a gypsum deposit can change over time as technological innovations in mining and manufacturing occur and new products are developed. Factors that must be considered when evaluating a gypsum resource for potential development, mining, manufacturing, and marketing include the following:

- Proximity to market area—because gypsum has a low unit value, an ideal deposit of gypsum would be located within the heart of a growing metropolitan area
- Transportation—shipment of raw and finished materials by truck, train, ship, or barge; import of paper used in wallboard manufacturing; transportation of finished products to job sites, distributors, and retail outlets; potential for backhauls of raw materials or finished products
- Fuel and utilities—wallboard manufacturing is highly energy intensive and requires an infrastructure of electrical service and a source of fuel for calcination and drying of wallboard panels
- Water—the availability of process water is essential for the manufacturing of wallboard products but not for plasters, portland cement rock, or agricultural gypsum
Table 1. World gypsum production, 2002–2003

<table>
<thead>
<tr>
<th>Country</th>
<th>Production, kt</th>
<th>2002</th>
<th>2003*</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>15,700</td>
<td>16,000</td>
<td></td>
</tr>
<tr>
<td>Iran</td>
<td>11,500</td>
<td>11,500</td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>8,850</td>
<td>9,000</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>7,500</td>
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</tr>
<tr>
<td>China</td>
<td>6,850</td>
<td>6,900</td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>6,600</td>
<td>6,800</td>
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<tr>
<td>Thailand</td>
<td>6,330</td>
<td>6,500</td>
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<tr>
<td>Japan</td>
<td>5,900</td>
<td>5,700</td>
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<tr>
<td>Australia</td>
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<td>France</td>
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<tr>
<td>India</td>
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<tr>
<td>Egypt</td>
<td>2,000</td>
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<td></td>
</tr>
<tr>
<td>Brazil</td>
<td>1,510</td>
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</tr>
<tr>
<td>United Kingdom</td>
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<td>1,500</td>
<td></td>
</tr>
<tr>
<td>Italy</td>
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<tr>
<td>Uruguay</td>
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<td>1,100</td>
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<tr>
<td>Poland</td>
<td>1,100</td>
<td>1,100</td>
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</tr>
<tr>
<td>Austria</td>
<td>1,000</td>
<td>1,000</td>
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<tr>
<td>Other countries</td>
<td>12,500</td>
<td>12,500</td>
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<tr>
<td><strong>World production (rounded)</strong></td>
<td><strong>101,000</strong></td>
<td><strong>102,000</strong></td>
<td></td>
</tr>
</tbody>
</table>

Source: Olson 2004.
* Estimated.

Table 2. Sources of gypsum imported to the United States in 2003

<table>
<thead>
<tr>
<th>Country</th>
<th>Total Imports</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>5,700,000</td>
<td>68.7</td>
</tr>
<tr>
<td>Mexico</td>
<td>1,820,000</td>
<td>21.9</td>
</tr>
<tr>
<td>Spain</td>
<td>710,000</td>
<td>8.6</td>
</tr>
<tr>
<td>Dominican Republic</td>
<td>67,900</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Total imports</strong></td>
<td><strong>8,300,000</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>


PRODUCTION AND TRADE

The United States is both the largest producer of gypsum (Table 1) and the largest consumer of products manufactured from gypsum in the world. Canada and Mexico are significant producers, and the majority of their production is exported to the United States. Thailand and Spain are also significant exporters of gypsum. Almost two thirds (63%) of the total world production of gypsum in 2003 came from seven countries: United States (15.7%), Iran (11.3%), Canada (8.8%), Spain (7.4%), China (6.8%), Mexico (6.7%), and Thailand (6.4%).

United States


The total amount of gypsum consumed in the United States in 2003 was 33 Mt. Mining of natural gypsum amounted to 16 Mt. Approximately 28.8% of the total gypsum demand, 9.5 Mt, was supplied by synthetic gypsum. Imports of foreign gypsum totaled 8.3 Mt, with Canada supplying almost 69% (Table 2). Manufacturing of gypsum wallboard and plaster products accounted for about 90% of the total amount of gypsum consumed in 2003. About 2.62 Mt were used in portland cement production. Agricultural applications accounted for about 1.0 Mt.

Iran

Iran is the second largest producer of gypsum products in the world, exceeded only by the United States (USGS 2004). In 2002, Iran produced about 11.5 Mt of gypsum and exported about $5.7 million worth (Hobbs 2002). Approximately 60% of the total annual production is estimated to be in the manufacture of construction plaster. Portland cement production in Iran during 2002 was about 30 Mt, and it is estimated that 1.5 Mt of gypsum was consumed in the manufacturing of portland cement, based on a usage of about 5% gypsum by weight.

Canada

The world’s third largest producer of gypsum is Canada. There are 11 wallboard manufacturing plants in Canada, but a significant proportion of gypsum is exported to plants along the east coast of the United States. Canadian gypsum imported into the United States during 2003 was about 5.7 Mt, representing about 17% of the total consumption. Gypsum is produced in the provinces of Newfoundland, Nova Scotia, Ontario, Manitoba, and British Columbia.

The majority of Canada’s production comes from Nova Scotia; National Gypsum Canada Ltd. operates the world’s largest gypsum quarry at Milford Station, near Halifax. Fundy Gypsum Company and Little Narrows Gypsum, subsidiaries of U.S. Gypsum (USG), operate two large quarrying operations in Nova Scotia for export to the United States and external portland cement rock customers. There is only one active underground gypsum mining operation in Canada, located at Hagersville, Ontario, and operated by Canadian Gypsum Company Ltd., a subsidiary of USG.

Spain

Spain has abundant resources of gypsum located predominantly in the eastern half of the country and the Balearic Islands of Mallorca, Ibiza, and Menorca. Abundant gypsum resources occur along the Mediterranean coast between Gibraltar and eastward to the French border. Iberyeso is the largest producer in the country.

The Triassic-age gypsum deposits are significant in terms of reserves, quality, and marketability (Regueiro and Barros 1995). In most cases, Triassic-age gypsum deposits have a high purity of 93% to 96%. Tertiary-age gypsum deposits are significant in terms of the economic potential, continuity, thickness, and quality. Eocene deposits are relatively rare, but Oligocene-age deposits are extensive, have a high purity, favorable geophysical locations, and ease of exploitation. Abundant Miocene–Pliocene-age gypsum deposits occur in the Alicante Area, between Almeria and Alicante. The gypsum has a high quality (about 94% purity) and is interbedded with marl. Studies by the Spanish government identified 77 large deposits with purities ranging from 70% to 96% and resources of more than 20 billion t.

China

The annual production of gypsum for all uses in China is about 11 to 12 Mt, primarily from the provinces of Shandong, Hubei, Jiangsu, Hunan, Shanxi, Sichuan, and Gansu. O’Driscoll (1994) reported 54 state-operated mines and approximately 100 privately
operated mines in 16 provinces. The major gypsum mining operations in China include Pingyi and Tai’an in Shandong Province and Yingcheng in Hubei Province. About 65% of China’s gypsum resources occur in Shandong Province. Gypsum deposits in Hubei and Hunan provinces provide high-purity gypsum to the growing market for industrial gypsum products in the cities of Guangzhou and Shanghai. The gypsum resources in China are widely distributed and immense, with reserves estimated to be in the billions of metric tons. The reported reserves vary from 57 to 100 billion t. In the mid-1990s, gypsum reserves of 114 billion t were identified in Hubei Province alone.

The gypsum deposits in China are highly variable in the areal extent, in thickness, and in quality. The gypsum occurs as thin seams of fiber gypsum (satin spar), flake gypsum (selenite), and rock gypsum. Depth of the deposits varies from very shallow to about 600 m. Gypsum-bearing sequences from a few centimeters to more than 100 m in thickness occur throughout the country.

The mining and processing of gypsum in China are labor intensive. Underground mining is generally accomplished by manual methods such as sorting ore from waste, loading ore cars with gypsum, and tramming the cars to incline or shaft stations. Waste rock is hand-stacked to provide roof support. The gypsum is sorted at the surface into stockpiles of different grades depending on purity and end use. Snow gypsum is the term used often for white rock gypsum, and fiber gypsum is the term used for very pure satin spar gypsum.

Snow and fiber gypsiums are used for the manufacture of ceramic plasters (sanitary and dinnerware), dental and orthopedic plasters, art plasters, chalk, glass-reinforced gypsum ceiling panels, and decorative architectural details such as cornices. Some land plaster is produced for the brewery and tofu industries.

**Mexico**

Gypsum is mined in the following states in Mexico: Nuevo Leon, Coahuila, Colima, Chihuahua, Sonora, Puebla, Oaxaca, Jalisco, and Baja California del Sur. A significant amount of gypsum in Mexico is used internally in the manufacture of portland cement. Mexico is a significant exporter of gypsum to the Pacific coast of the United States and periodically to Pacific Rim countries such as Japan. Exports to the United States in 2003 were about 1.8 Mt.

The majority of gypsum exports are produced from two quarries operations in Baja California del Sur. COMSA, on San Marcos Island in the Sea of Cortez, and CAOPAS, just north of the town of Santa Rosalia, provide the majority of gypsum to wallboard plants on the Pacific coast of the United States.

Numerous small gypsum plaster calcining facilities, known as yeseras, are distributed throughout Mexico. Yeseras manufacture construction plasters for local markets and vary in size from crude beehive kilns to relatively modern calcining operations.

Gypsum wallboard is currently manufactured at only three sites in Mexico. One plant is located in Puebla, about 120 km southeast of Mexico City, and two are near Monterrey, Nuevo Leon State, in northern Mexico.

**GEOLOGY**

The most common sulfate minerals are gypsum and anhydrite, which are formed from diverse origins. Gypsum (CaSO4•2H2O) is primarily formed as a chemically precipitated sedimentary rock in basin or sabkha environments, but it may also form as the result of solutional, karst, hydrothermal, and volcanogenic processes. Table 3 shows the chemical composition of gypsum and anhydrite. Anhydrite (CaSO4) is the anhydrous form of the calcium sulfate family of minerals. Anhydrite may form as a primary mineral in a sabkha depositional environment or deep-basin environments. The terms gypsum and anhydrite are commonly used interchangeably for the minerals and rocks that are composed primarily of these minerals.

Gypsum and anhydrite may be deposited simultaneously in a sedimentary environment and are easily converted from one to another under varying conditions of heat, pressure, and the presence of water. The occurrence and relationship of anhydrite and gypsum in a deposit is complex. Mineralogical, textural, cross-cutting relationships and microscopic examination may be necessary to determine the ultimate origin of anhydrite in a deposit. Some deposits exhibit multiple episodes of conversion from gypsum to anhydrite and vice versa.

**Mineralogy**

Gypsum forms monoclinic crystals with a perfect (010) cleavage and distinct cleavages along (100) and (101). It is distinguishable from anhydrite by its lower Mohs hardness (2.0 versus 3.5) and specific gravity (2.24 versus 2.97 g/cm³). Pure gypsum is colorless, but may be tinted yellow, red, and brown because of the presence of impurities. Twinning is common along (100), forming “swallowtail twins.” Gypsum is relatively soluble in fresh water (about 0.2 g/100 g H2O) and is easily dissolved or eroded in conditions of high humidity or rainfall.

Anhydrite forms orthorhombic crystals with perfect cleavages along (100) and (010) and a good cleavage along (001). Forming “swallowtail twins.” Gypsum is relatively soluble in fresh water (about 0.2 g/100 g H2O) and is easily dissolved or eroded in conditions of high humidity or rainfall.

**Lithology**

Commercial deposits of gypsum may be almost pure or contain variable amounts of syndepositional impurities such as limestone, dolomite, clay, anhydrite, and soluble salts of potassium, sodium, and magnesium. Primary gypsum deposits consist of rock gypsum and alabaster. Selenite, satin spar, and gypsite are secondary varieties of gypsum. Anhydrite may occur as either primary or secondary minerals in a deposit, depending on its geological history.

Petrographically, most rock gypsum has a medium to coarse crystalline texture. Some deposits contain coarse crystalline gypseous poikiloblasts. Gypsum in the Upper Miocene Boleo Formation in Baja California del Sur, Mexico, contains euhedral selenite crystals up to about 25 cm in width. The Mississippiian Windsor Group in Nova Scotia, Canada, contains abundant scattered poikiloblasts.

Petrographically, anhydrite has a massive or granular texture. Scattered gypseous crystals commonly occur in the anhydrite groundmass and increase near the gypsum–anhydrite contact. Complex hydroxyl salts of sodium, potassium, and magnesium sulfate commonly occur in conjunction with anhydrite and are concentrated in the gypsum near the contact.

**Alabaster**

Alabaster is a compact, fine-crystalline, translucent variety of primary gypsum that has been used by artists to produce statuary for thousands of years. Typically found in a variety of colors depending
on the type and amount of impurities present, alabaster generally occurs as zones within larger gypsum deposits.

**Selenite**

Large, clear, euhedral crystals of gypsum are known as selenite. Bladed selenite crystals commonly form in fluid-filled cavities. Selenite may also form along fault zones. Cleavage fragments may be mistaken for muscovite mica. Poikilitic masses of selenite crystals, commonly known as "gypsum roses," are formed by the crystallization of gypsum from interstitial pore fluid in unconsolidated sand.

Possibly the largest selenite crystals in the world are located in Chihuahua State, Mexico. The Cave of Swords (La Cueva de las Espadas) has been well known since 1910 for the large-bladed selenite crystals. In 2000, however, a cavity containing enormous selenite crystals was discovered in the Naica underground silver and lead mine operated by Industriales Peñoles, SA de CV. The cavity was encountered at a depth of about 300 m and has dimensions of about 9 m by 18 m. The temperature in the cavity is up to 65°C with 100% humidity. Selenite crystals with a diameter of 1.2 m and up to 15 m in length occur in the cavity.

The Lechuguilla Cave complex, located near Carlsbad Caverns, New Mexico, contains large selenite speleothems. The caves are believed to have been formed at the groundwater table by the reaction of groundwater with sulfur dioxide rising from deeper natural gas deposits, producing sulfuric acid. The sulfuric acid dissolved the limestone forming very large openings and extensive speleothems.

**Satin Spar**

Satin spar is a fibrous variety of needle-shaped gypsum crystals filling fractures or along bedding planes. The needle-shaped gypsum crystals form with the C-axis oriented at a steep angle or perpendicular to the vein walls in fractured rocks undergoing deformation. The orientation and steepness of the crystals define the direction and amount of strain, such as dilation or shearing. It is important to recognize that satin spar is not an asbestiform mineral. The stresses may be caused by regional tectonism or induced in the rock by the hydration of anhydrite to gypsum. During hydration anhydrite undergoes a volumetric increase of 26% and may induce stresses of 2 to 69 MPa.

Satin spar is mined in China for use in the manufacture of gypsum plasters. Concordant, horizontally oriented veins of gypsum up to 0.5 m thick are interbedded with shale. The satin spar is mined and sorted by hand to produce an extremely pure product.

**Gypsumite**

Gypsumite is an earthy, pulverulent variety of gypsum that forms a surficial deposit in shallow saline lakes, playas, and salt pans in arid environments. The calcium and sulfur required to form gypsum are derived from the erosion and weathering of rocks and transported in surface and groundwater to closed basins. Gypsum precipitates at the surface by capillary movement and evaporation of groundwater. Since gypsum is less soluble than halite a crust of gypsum forms over the soft beds of halite. Gypsumite is often contaminated by windblown sand or silt and clay from periodic flooding of the playas.

**Rock Gypsum**

The most common variety of the mineral is known as rock gypsum. Rock gypsum commonly consists of aggregates of gypsum crystals interbedded or mixed with mudstone, shale, siltstone, limestone, or dolomite. Gypsum rock and anhydrite may be nodular, massive, laminated, or bedded. The primary sedimentary structures in gypsum and anhydrite deposits are associated with the depositional model and the proximity to terrigenous detritus. The Fish Creek Gypsum in California contains trace amounts of biotite mica. The Permian Castile formation, deposited in the Delaware Basin of Texas and New Mexico, contains well-laminated anhydrite with varves of organic matter and calcite that have correlated over a distance of more than 100 km (Blatt, Middleton, and Murray 1980). The evaporites were deposited in a standing, deep body of water. Alternatively, in a sabkha environment, gypsum and anhydrite form by the nucleation and growth of crystal masses from pore fluids within soft, unconsolidated tidal-flat sediments, consisting of terrigenous or carbonate mud. Nodular masses grow and displace the surrounding host sediments, forming a "chickenwire" texture. Gypsum may be precipitated within more rigid host sediments of clay or sand and form large poikilitic crystals that encase the host sediment. The Mississippian Macrady Formation in southwestern Virginia contains gypsiferous mudstone with poikilitic gypsum crystal faces up to 50 cm exposed in underground mine workings.

**Anhydrite**

Anhydrite may form as a primary mineral in a sabkha depositional environment and deep basin, subaqueous deposits such as the Castile formation in the Delaware Basin. Gypsum may begin to dehydrate under the lithostatic loading below a depth of burial of about 600 m and transform into anhydrite. Subsequent uplift or erosion of overlying rocks decreases the lithostatic load, allows the percolation of groundwater through fractures and along bedding plans, and rehydrates the anhydrite to gypsum. Some deposits, such as the Devonian Wapsipinicon Formation in southeastern Iowa, exhibit evidence of several cycles of dehydration and rehydration. The gypsum-anhydrite contact is subhorizontal and the anhydrite cuts across enterolithic folds in gypsum as the result of an earlier phase of hydration.

**Impurities**

Most gypsum is white to grayish white, although type and amount of impurities in any given deposit determines the color of the rock. The impurities may be intimately mixed with the gypsum because of primary sedimentary processes previously described, or be present as the result of the secondary effects of solution, weathering, and erosion.

The most common impurities in gypsum are carbonates, clay, anhydrite, and soluble salts. With certain limitations, carbonate and clay impurities may not be detrimental in the manufacture of gypsum wallboard, plasters, and agricultural gypsum. Portland cement rock is less sensitive to the presence of anhydrite or soluble salts. The minimum gypsum purity (percentage content of gypsum) for wallboard and other quality-control parameters are established by organizations such as the American Society for Testing and Materials (ASTM) and Underwriters Laboratories (UL).

Impurities may have little or no effect on the quality of products manufactured from gypsum. Certain types of impurities, such as soluble evaporite minerals or montmorillonite clays, may expand on hydration in humid environments.

**Carbonate**

Limestone, composed primarily of calcium carbonate, has relatively little effect on the manufacturing of wallboard, the predominant gypsum product. The most significant effect is to increase the weight of the wallboard, which affects the level of installation effort and freight costs. Dolomite is a detrimental impurity in industrial gypsum plaster used for the manufacture of ceramics, such as dishes, and sanitary ware, such as sinks and toilets. Dolomite has a higher specific gravity.
than gypsum. Particles of dolomite in ceramic grade plaster sink to the bottom as the slurry is poured into molds. The dolomite particles form projections at the mold–cast interface; these projections leave surface pits in the product being cast.

**Clay**

Clay is the second most abundant impurity in gypsum deposits. Clay impurities may be present as a result of both primary and secondary depositional processes. Primary impurities of clay occur as laminae, thin interbeds, internodular matrices, and intraclasts within the gypsum. Nucleation and growth of gypsum or anhydrite nodules from interstitial fluids in soft terrigenous or carbonate mud forms an internodular matrix, leading to the chickenwire description of its texture. Postdepositional solutional and erosional processes commonly result in the presence of clay, sand, and organic impurities in fractures.

The type of clay mineral, particularly members of the smectite group, may have deleterious effects on the quality of wallboard products. Smectite group clays have an affinity for absorbing multiple molecules of water or other liquids and, thus, increase in volume. This characteristic is useful in the manufacture of cat litter or oil absorbent, but may be deleterious in the manufacture of gypsum wallboard. Soluble salts, primarily sulfates, and chlorides of potassium, magnesium, and sodium adsorb onto clay crystals.

If wallboard containing a high percentage of smectite clays or soluble salts is installed in a humid environment, hydration of these mineral species results in an increase in volume and may cause a quality defect known as “humidified split.” Humidified split occurs when soluble salts migrate to the gypsum core–paper interface and absorb multiple molecules of water from the atmosphere, forming complex salts and blisters on the surface of the wallboard. Alternatively, the volumetric expansion of the smectite clays may also produce humidified split.

Improper control of the calcining temperature of gypsum during the manufacturing process may result in an inaccurate determination of gypsum purity. Calcining at a temperature that is too high may begin to thermally dehydrate the clay, giving a false purity determination.

**Anhydrite**

Anhydrite is a common impurity in deposits of gypsum and may occur as a primary depositional mineral or the product of dehydration of deeply buried gypsum. Anhydrite can be found as a massive rock or as a mixture of gypsum and anhydrite in partially hydrated deposits. Soluble salts, such as sodium, magnesium and potassium chlorides, and sulfates are commonly concentrated in a halo in gypsum adjacent to the anhydrite contact. The soluble salts are leached from the anhydrite during hydration and precipitated in tensional features, such as fractures, many of which form during the volumetric expansion during hydration.

Anhydrite may be viewed either as a contaminant in a gypsum deposit or as a marketable coproduct. As a contaminant, the anhydrite is harder and denser than gypsum and contains higher levels of soluble salts. Anhydrite increases the weight of the finished wallboard products and is abrasive to grinding and processing equipment. As a coproduct, quarry-run anhydrite or a blend of gypsum and anhydrite may be used as a portland cement rock. Portland cement manufacturers use a variety of products from gypsum, anhydrite, or an anhydrite–gypsum blend, depending on the manufacturing process. The primary function of gypsum or anhydrite in portland cement is to control the setting time of the finished product. The SO3 content of the portland cement rock is the most important quality parameter.

**Soluble Salts**

Gypsum deposits commonly contain soluble evaporite minerals, such as halite (NaCl); sylvite, (KCl); mirabilite (Na2SO4•10H2O); and epsomite (MgSO4•7H2O). Soluble evaporite minerals may form during (1) evaporation of seawater in restricted basins; (2) late-stage diagenetic processes in sabkha environments; (3) gypsification of anhydrite; or (4) leaching from interbedded clay. During the evaporation of seawater in a restricted depositional basin, excess sulfate ions not consumed in the formation of gypsum or anhydrite may combine with either magnesium or sodium to form epsomite and mirabilite, respectively. Sodium and potassium may combine with chloride ions to form halite and sylvite, respectively.

In a sabkha environment, gypsum and anhydrite are formed by diagenetic processes within tidal-flat sediments. The pore-water chemistry changes as dolomitization of carbonate sediments occurs. Soluble evaporite mineral components can be released from fluid inclusions within carbonate crystals, or be included in a disordered crystal lattice. Mud-rich sabkhas contain clay crystals into which soluble salts may be adsorbed. During the conversion of anhydrite to gypsum, soluble salts are released and form an enriched halo in the gypsum near the anhydrite–gypsum contact. The volumetric expansion during the conversion provides fractures for the transport of saline fluids.

Soluble evaporite minerals are rarely directly observable in outcrops in humid environments or drill core because they are highly soluble in fresh water. In arid environments, gypsum outcrops may have an efflorescent crust of magnesium sulfate formed by the wicking of water by capillary action at the rock’s surface and rapid evaporation. Very fine, acicular crystals of epsomite form on the floor and roof in some underground gypsum mines by the evaporation of humid air.

Calcium sulfate hemihydrate reacts with water to form gypsum–water slurry in the manufacturing of wallboard. Soluble evaporite mineral components in the slurry migrate to the gypsum–paper interface by capillary action. The installation of wallboard containing a high soluble-salt content in a humid environment may result in the formation of complex salts of sodium, potassium, and magnesium sulfate with up to 15 molecules of water in their crystal structures. The volumetric increase associated with the absorption of more than two molecules of water may result in the failure of the gypsum core–paper bond and the formation of blisters, known as “humidified split.”

**Other Impurities**

Yellow to red discoloration results from mud staining and the presence of iron oxides. Dark purple to black discoloration may be caused by the presence of manganese oxide, carbonaceous limestone, mafic rock fragments, or detrital minerals. The presence of copper or certain types of algae may stain gypsum a greenish color. In some deposits trace amounts of celestite (SrSO4) may be present, and siliceous nodules are found in some deposits.

**Bassanite**

Bassanite is an unusual type of an impurity in a few gypsum deposits, notably in the Miocene Fish Creek Gypsum in California. Bassanite is a naturally occurring form of calcium sulfate hemihydrate that forms from the interaction of hydrothermal fluids with gypsum. Although white, bassanite has a distinct earthy texture that differentiates it from gypsum. Bassanite will not rehydrate to form gypsum in the presence of water. Hill (1979) reported the unusual occurrence of bassanite in three small caves in southwest Texas. Although originally precipitated on the walls and ceiling as gypsum, high cave
Young's modulus, Permeability, Unconfined compressive strength, Point load strength, Young's modulus, Permeability, Specific gravity, Dry density, Porosity, millidarcy, $2.1 \times 10^{-9} \text{m/sec}$, 2.1, 28.22, 2.09, 1.98, 2.19, 2.2, 2.9, 27.5, 97.5, 11.7, 25.8, 4.6, 2.9, 4.8, 5.1, 2.44, 6.2, 0.3, na, na

### Chemical Properties

Gypsum and anhydrite are able to undergo repeated dehydration and hydration, depending on the depth of burial and availability of water. Gypsum will begin to thermally decompose into the metastable species, calcium sulfate hemihydrate (CaSO$_4$•½H$_2$O), in heated air above 70°C and at 1 atm of pressure. Differential thermal analysis curves show two endothermic peaks between 100° and 200°C (Deer, Howie, and Zussman 1966). The first peak represents the loss of ½ molecules of water during the formation of calcium sulfate hemihydrate. Further heating totally dehydrates gypsum forming deadburned (anhydrous) anhydrite (CaSO$_4$), which is used as a filler in plastics and as a moisture absorbent. The second decomposition peak occurs when the remaining one-half molecule of water is removed. Calcining processes for the manufacture of gypsum wallboard and plasters involve heating gypsum to about 155°C for 1 to 3 hr, during which time calcium sulfate hemihydrate forms.

Heating gypsum liberates water vapor, which helps hinder the spread of fire. Specialized types of wallboard are formulated and manufactured for use as a firestop between multifamily housing, in the lining of elevator shafts, and in the walls and ceilings between living spaces and garages.

Gypsum’s solubility in fresh water is approximately 150 times greater than that of limestone. This chemical characteristic provides a source of calcium and sulfur when gypsum is used in agricultural applications. The ionic exchange capability of calcium for sodium, potassium, and hydration, depending on the depth of burial and availability of water. Gypsum will begin to thermally decompose into the metastable species, calcium sulfate hemihydrate (CaSO$_4$•½H$_2$O), in heated air above 70°C and at 1 atm of pressure. Differential thermal analysis curves show two endothermic peaks between 100° and 200°C (Deer, Howie, and Zussman 1966). The first peak represents the loss of ½ molecules of water during the formation of calcium sulfate hemihydrate. Further heating totally dehydrates gypsum forming deadburned (anhydrous) anhydrite (CaSO$_4$), which is used as a filler in plastics and as a moisture absorbent. The second decomposition peak occurs when the remaining one-half molecule of water is removed. Calcining processes for the manufacture of gypsum wallboard and plasters involve heating gypsum to about 155°C for 1 to 3 hr, during which time calcium sulfate hemihydrate forms.

### Physical Properties

The softness of gypsum is its most prominent physical feature. It is distinguished by its softness (Mohs hardness of 2) and three distinct cleavage planes. Anhydrite is distinguishable from gypsum because of its higher specific gravity and greater hardness. When scratched with a piece of copper, gypsum will be gouged, but anhydrite will abrade the copper (a copper residue will be visible on the scratched surface).-)

### ORIGIN AND MODES OF OCCURRENCE

Evaporites are deposits of minerals that formed from the evaporation of seawater or brine. The types and amounts of minerals formed depend on (1) the composition of the source water, (2) the relative solubilities of the dissolved mineral constituents, (3) the climatic conditions and extent of evaporation, and (4) the depth and extent of the depositional basin. Brine may have formed from evaporative concentration of seawater or might have been reconstituted by the dissolution of preexisting rocks (primarily evaporite rocks) by rainwater or groundwater and its subsequent recrystallization in closed basins in an arid climate. Seawater is concentrated by several mechanisms, described here.

The primary depositional environments for evaporites are considered to be either sabkha or subaqueous, with variations related to proximity of terrigenous material and the depth of the basin and seawater. Sabkha evaporites include continental deposits in playa lakes and the more extensive tidal flat deposits. Subaqueous evaporites are formed in either shallow- or deep-water basins. All modern evaporite depositional environments, however, including sabkha deposits, are believed to be of shallow-water origin (Pettijohn 1975). In either case, gypsum and anhydrite are formed from the concentration of dissolved mineral constituents in saline water. Kendall (1981a, 1981b) provides a good overview of each of the depositional facies. Other useful resources for determining depositional environments for gypsum are works by Dean and Schreiber (1978), Kendall (1978), and Raup (1991). There is considerable discussion in geological literature about whether the original mineral deposited is gypsum or anhydrite. Gypsum is metastable, converts to anhydrite at a depth of more than about 600 m, and is readily soluble in groundwater. Two additional environments are salt-dome cap rock and volcanogenic.

### Brine Concentration and Evaporite Precipitation

Seawater contains about 3.5% by weight of dissolved solids (Pettijohn 1975). Approximately 78% of the dissolved solids consist of sodium chloride, and calcium sulfate accounts for about 3.6%. If a 1,000-m column of seawater of normal salinity were to evaporate, only 75 cm of gypsum and approximately 13.7 m of halite would be precipitated (Blatt, Middleton, and Murray 1980).

Gypsum will begin to precipitate in an evaporating basin of seawater when the volume has been reduced by evaporation by about 66% and if replenishment and dilution by fresher water do not occur. Halite does not precipitate until approximately 90% of the brine has been evaporated. A natural horizontal and vertical zonation of mineral deposition develops. Calcium carbonate will be precipitated first, followed by gypsum and anhydrite, halite, magnesium sulfate, and potassium salts. Normal seawater is undersaturated with respect to both gypsum and halite. The presence or absence of halite in a thick deposit of gypsum is an indicator of the degree of brine concentration, because considerably more evaporation and brine concentration are required to precipitate halite than gypsum.

Gypsum also forms from diagenetic processes during the dolomitization of carbonate sediments in tidal flat environments. As seawater evaporates to the point at which gypsum begins to
precipitate, the ratio of the activity constants for magnesium ($\alpha_{Mg}^{2+} = 1.32 \times 10^{-2}$) and calcium ($\alpha_{Ca}^{2+} = 2.34 \times 10^{-5}$) increases above the normal ratio in seawater of 5.6 (Blatt, Middleton, and Murray 1980). The molar ratio of Mg$^{2+}$/Ca$^{2+}$ also increases from about 5.2 to more than 20. Concentration of seawater by evaporation produces more dense brine that can sink downward through the pores of underlying calcareous sediments. An ion exchange reaction occurs with one magnesium ion replacing one calcium ion. Because the brine has already reached a concentration where gypsum precipitates, the additional calcium released during dolomitization is available to react with any excess sulfate in the brine to form additional gypsum. The chemical reactions that liberate calcium ions and form gypsum from saline brines are as follows:

$$2CaCO_3 + Mg^{2+} = CaMg(CO_3)_2 + Cu^{2+}$$

$$Ca^{2+} + SO_4^{-2} + 2H_2O = CaSO_4 \cdot 2H_2O$$

**Sabkha Evaporites**

**Sabkha** is an Arabic term referring to a coastal tidal flat. Numerous geological studies in the 1960 and 1970s examined the formation of gypsum and anhydrite minerals along the Trucial Coast region of the Persian Gulf (e.g., Kinsman 1966, 1969; Butler 1970). These deposits are characterized by a distinctive suite of sediments, including lagoidal limestone, intertidal algal mat limestone and nodular gypsum, and anhydrite-bearing, fine-grained terrigenous or calcareous sediments.

Gypsum and anhydrite form by precipitation of supersaturated brine in the pore space of the tidal-flat sediments. Nodular gypsum and anhydrite are the most common forms, but large poikilitic selenite crystals may also form. Many of the commercially developed gypsum deposits in North America are probably of sabkha origin.

If the tidal-flat sediments are calcareous, dolomitization occurs during the diagenetic reactions that form gypsum and anhydrite. If terrigenous clastic sediments are present, they are generally chemically unaffected but undergo soft-sediment deformation as the gypsum and anhydrite crystals and nodular masses form. The sabkha environment does not require the presence of a basin for deposition of evaporite minerals, and thick chloride mineral accumulation would not be expected (Schroeder 1970). Depending on the surface water chemistry, laminated gypsum and argillaceous limestone may be deposited in lagoons or ponds on the sabkha surface. The primary difference between carbonate-evaporite and mud-rich sabkhas is the amount of terrigenous sediment deposited on the sabkha surface.

Crystals of gypsum and anhydrite form in several modes in the sabkha environment. The most common mode is the nucleation and displacive growth of crystalline masses in the soft tidal-flat sediments. Soft carbonate or terrigenous clay or silt sediments are pushed aside as nodular masses of gypsum or anhydrite grow. Eventually, the nodules coalesce and the internodular matrix forms a fabric that looks like chickenwire. Laminated or bedded gypsum may be precipitated in shallow, hypersaline ponds, lagoons, or salt pans on the sabkha surface. If the ponds are periodically flooded by fresher water from surface runoff or precipitation, the sediments formed may be argillaceous, micritic limestone.

**Carbonate-Evaporite Sabkha**

The carbonate-evaporite sabkha environment consists almost entirely of dolomite and gypsum–anhydrite. The most seaward portion of a carbonate-evaporite sabkha environment consists of inner-shell dolomitic mudstone and pellet wackestone. The dolomitic rock either is massive or has faint, wispy laminae of darker colored, organic-rich clay (subtidal algal mat). Proceeding landward are coarser-grained carbonates such as oolitic or pellet packstone and grainstone that occur in the intertidal zone. The uppermost sediments (supratidal) include dolomitic mudstone and pellet packstone. Algal mat deposits are present as wispy, black, organic-rich clay. Gypsum intervals up to about 6 m thick are common.

Ancient examples of carbonate-evaporite sabkha gypsum deposits include the Wapspinicon Formation (Devonian) in southeastern Iowa and the St. Louis Formation (Mississippian) in southwestern Indiana (Jorgensen and Carr 1972).

**Mud-Rich Sabkha**

In the mud-rich sabkha, most of the tidal-flat sediments consist of clay, silt, and some sand deposited by sheetflood flow from the mouths of wadi channels near the landward margin of the wadi plain (Handford and Fredericks 1980). Marine floodwaters such as storm surges rework the terrigenous sediments to form an extensive, low-slope, tidal-flat surface. Mud-rich sabkha sediments may occur along with carbonate-evaporite sabkha sediments, either interfingered with or prograding across the calcareous tidal-flat surface.

The Mississippian Macrady Formation of southwestern Virginia and the Jurassic Arapien Shale in south-central Utah are ancient examples of mud-rich sabkha environments. Modern-day examples include the coastal mud flats at the mouth of the Colorado River delta at the northern end of the Gulf of California and along the Trucial Coast of the Persian Gulf.

**Subaqueous Evaporites**

Although most of the commercial gypsum deposits in North America are believed to be of sabkha origin, many thick, widespread, ancient evaporite deposits were deposited by subaqueous processes within enclosed or hypersaline basins. And even though there are several modern-day analogues of sabkha environments, there are no modern-day equivalent depositional environments of subaqueous evaporites.

Three general models of subaqueous evaporites have been developed based on conditions of the depth of the basin and the depth of water: (1) the deep water, deep basin model; (2) the shallow basin, shallow water model; and (3) the deep basin, shallow water model. Each model has one common factor: the presence of a seaward, subaqueous barrier (sill) that restricts the complete circulation of seawater in and out of the basin. High evaporation rates concentrate the trapped seawater and form brine, which is saturated or nearly saturated with respect to gypsum and halite. Crystal precipitation occurs at the air–water interface, and the crystals settle through the water column as a pelagic rain. Variations in the water chemistry from influx of seawater by storm surges, temperature, or evaporation rate form laminations in the rock column. Laminae of sulfate, carbonate, and organic matter 1 to 10 mm thick occur over large areas of the basin. Thin laminations have uniform thicknesses over short distances, and individual laminations have been stratigraphically correlated in wells over distances up to about 100 km.

Ancient subaqueous evaporite deposits include the Castle Formation (Permian) in the United States and the Zechstein Group (Permian) in Europe. The Castle Formation underlies almost 81,000 km$^2$ of western Texas, parts of New Mexico, and northern Mexico. The Zechstein Group underlies at least 250,000 km$^2$ of northern Europe, including Germany, Poland, and much of the North Sea.

**Continental Evaporites**

Continental evaporites are similar in origin to mud-rich sabkhas. Mineralization occurs at the surface of playa lakes or within the interstitial pore spaces of soft, terrigenous sediments. Gypsum,
halite, and complex salts of magnesium, potassium, and bromine are deposited in closed basins (no external drainage) in arid environments. Weathering and erosion of rocks in the surrounding higher terrain provide the mineral constituents for the formation of minerals in the playa. Coarser detritus is deposited in alluvial fans at the margins of the playa and surface runoff and groundwater transport the dissolved mineral constituents toward the center of the playa. Mineralization occurs at the surface and within the playa sediments by evaporative pumping and vertical movement by capillary action at the playa surface. Gypsum, with a lower solubility than halite, is deposited within the sediments and also as an efflorescent gypsum crust around the distal margin of the playa. Post-depositional inmation of the playa surface by storm-water runoff and wind erodes and reworks the exposed crusts and underlying soft sediments.

Economic deposits of continental evaporites occur in many parts of the world. The only deposit in the United States commercially used for manufacturing wallboard, however, is the Muddy Creek Formation (Miocene) near Las Vegas, Nevada. The deposit covers about 13 km² and is up to about 30 m thick (Papke 1987). Enormous deposits of playa gypsum ( gypsum) occur in Australia, Lake Macleod, located near the northwestern coast, covers 2,072 km² and has a gypsum crust about 2 m thick. Lake McDonnell in South Australia covers about 90 km² and has a gypsum crust about 5 m thick; the deposit occupies a former lagoon that was cut off from the sea in post-Pleistocene times. Periodic landward surges of storm water and high tides overflow the barrier and replenish the lagoon with seawater.

Salt-Dome Cap Rock
Gypsum commonly occurs in the near-surface portions of salt domes in the Gulf Coast basin of the United States. Thick layers of the Jurassic-age Louann Salt occur at a depth of about 9 km. Most salt domes are roughly circular in plan view and vary in diameter from 1 km to more than 10 km. Some near-surface domes have a surface expression of elevated topographic relief of about 20 m above the surrounding terrain. Salt domes are diapiric masses of rock salt (halite) that rise upward along fractures or faults by differential lithostatic loading and plastic flow. Salt domes occur in about 100 sedimentary basins worldwide. The Zechstein Salt in northern Europe contains numerous salt domes.

Salt domes contain 5% to 10% water-insoluble material. About 99% of the insoluble impurities in the Louann Salt are anhydrite and a trace amount of calcite (Walker 1974). As a salt dome rises through near-surface, water-bearing sediments, the halite dissolves and a residue, primarily anhydrite, accumulates in the upper portion of the dome. Increased upward vertical pressure occurs during the salt dome’s rise and compacts the insoluble residue to form a massive anhydrite rock. As the salt dome rises near the ground surface, groundwater percolation rehydrates the anhydrite to form gypsum.

Salt-dome cap rock forms only minor economic deposits of gypsum in the United States. The gypsum generally contains high levels of soluble salt impurities that are detrimental to the manufacture of wallboard products. Some cap-rock deposits, however, have been developed for portland cement gypsum resources.

Volcanogenic Gypsum
Gypsum sometimes occurs in volcanogenic massive sulfide deposits (VMSDs). Only relatively small economic VMSD gypsum deposits, however, have been developed. The Falkland deposit in southern British Columbia, Canada, is an example. Although relatively small and rarer than any other type of deposits previously discussed, VMSDs warrant a brief description. They are associated with extensional tectonic settings and submarine depressions such as backarc, mid-ocean spreading centers, and intracontinental rift zones (Ohimoto 1996).

Seawater percolates into the thin crustal rocks and is heated by deep convective circulation in the vicinity of a heat source such as plutonic or upper-mantle rocks. Sulfate mineralization generally occurs during the later stages of hydrothermal activity. In the Kuroko (black ore) metallogenic model, sulfide minerals are deposited by the interaction of hydrothermal fluid (at approximately 350°C) emanating from sea-floor vents with cold seawater. The vents are known as “black smokers” because of the smoke-like appearance of the plume of instantaneously precipitated sulfide minerals. The precipitated minerals accumulate in mound-shaped deposits around the black-smoker vents.

Sulfate mineralization can also occur as a chemical precipitate around the sea-floor vents and as an alteration product of the country rocks. Precipitation of anhydrite is associated with the “black ore” mineral suite (sphalerite + galena + pyrite + barite + anhydrite) that occurs from the interaction of the hot hydrothermal fluids and cold seawater.

Anhydrite and gypsum can also precipitate in the porosity of lower temperature (<150°C) country rocks. Downward percolation of seawater through fractures in lower-temperature country rocks may precipitate disseminated sulfate (SO₄)²⁻ minerals. In the later stages of hydrothermal activity, gypsum and anhydrite may be reduced by Fe²⁺-bearing minerals and organic matter forming hydrogen sulfide (H₂S) that, in turn, leaches additional metals from the country rock.

DISTRIBUTION OF DEPOSITS
Gypsum occurs throughout the world—found to date on every continent except Antarctica (Table 5). More than 90 countries produce gypsum worldwide, and global gypsum resources are enormous. Some known occurrences contain as much gypsum as the total world annual demand. For example, Libya contains more than 80,000 Mt of Jurassic-age gypsum with an estimated purity of 80% underlying an area 65 km long, up to 25 km wide, and locally up to 400 m thick. Latvia contains gypsum resources estimated at 1,000 Mt at a depth of less than 50 m and 14,000 Mt at a depth of greater than 50 m (USBM 1993).

The first gypsum mining in North America occurred in Nova Scotia in 1779. Gypsum was first mined in the United States from Silurian deposits near Syracuse, New York, in 1808. Several gypsum-producing districts have operated continuously since the 1800s. Gypsum was found in the early 1800s during exploration for salt brines in the Mississippian Maccrady Formation in southwestern Virginia. The Plastero, Virginia, operations of the United States Gypsum Company were worked continuously from as early as 1835. Jurassic-age gypsum has been mined in northwestern Iowa since 1872. The Mississippian-age Michigan Formation has produced gypsum in northeastern Michigan since 1862.

Since the publication of the 6th edition of Industrial Minerals and Rocks, some of the oldest gypsum-producing regions of the United States have ceased operations. Notably, the Silurian deposits of western New York and northern Ohio and the Mississippian deposits in Virginia ceased operations after more than 170 years. In most cases, the deposits were not depleted; rather the older, high-cost wallboard manufacturing plants were closed and the manufacturing capacity was replaced by new plants on navigable rivers using synthetic gypsum from coal-fired power plants.

Considerable gypsum resources occur in the western part of the United States, Canada, and Mexico. These areas are generally
remote, vary in size from small to very extensive, have complex property ownership issues, and may not be workable year-round because of severe weather conditions. Very often the main factor that would make these deposits valuable is an inexpensive method of transportation of the raw materials or the finished products. Other factors are proximity to market area, work force, utilities, and other parts of infrastructure. Several small operations in the western United States produce portland cement or agricultural gypsum.

**United States**

Gypsum is currently mined in Arkansas, California, Colorado, Indiana, Iowa, Kansas, Michigan, Nevada, New Mexico, Oklahoma, Texas, Utah, and Wyoming. Outcrops of gypsum in the Arapien Shale in Utah and the Chugwater Formation in Wyoming cover hundreds of square kilometers.

In 2003, the top producing states were, in descending order, Oklahoma, Texas, Nevada, Iowa, California, Indiana, and Michigan; they accounted for 73% of the domestic output (USGS 2004).

Calcium sulfate minerals are found within geological strata ranging from the Ordovician through the Holocene. The largest production comes from Mississippian rocks in Atlantic Canada (Nova Scotia, Newfoundland, and New Brunswick), Michigan, Indiana, and, until recently, Virginia. Permian-age rocks are the second largest producer in Texas, Oklahoma, Kansas, Colorado, Wyoming, Nevada, and Arizona. Gypsum is produced from Tertiary-age rocks in California, Jamaica, and Arizona. Gypsum is produced from Jurassic-age rocks in Iowa, Colorado, Utah, and Wyoming.

Texas, Oklahoma, New Mexico, and Kansas contain inedible resources of gypsum, and other chemically precipitated minerals such as salt and potash. The evaporite minerals were deposited in the enormous Permian Basin, which underlies portions of the four states. Two subbasins in west Texas and southeast New Mexico—the western Delaware Basin and the eastern Midland Basin—are separated by the Central Basin Platform. Where extensive hydration of anhydrite has occurred, the resulting purity is high (>92% purity). Most of the high-quality, value-added products derived from gypsum are manufactured from Permian-age gypsum. The highest purity and whitest gypsum occurs in the Blaine Formation at Medicine Lodge, Kansas, and Southard, Oklahoma, and in the Easly Creek Formation at Blue Rapids, Kansas.

**Oklahoma**

The primary area of production of high-value-added gypsum products in Oklahoma is in the northwestern part of the state at Southard, Blaine County. In the Anadarko Basin in northwestern Oklahoma, economic gypsum deposits occur within the Shimer, Nescatunga, and Medicine Lodge members of the Blaine Formation in the middle portion of the Beckham evaporite unit. The stratigraphic relationships of the gypsum beds in the Blaine Formation are well exposed in Salt Creek Canyon, just north of Roman Nose State Park, in Blaine County. The Blaine Formation is also a major source of gypsum in southwestern Oklahoma, whereas the Permian-age Cloud Chief Formation contains significant resources in west-central Oklahoma.

The evaporite beds in the Blaine Formation are generally 3 to 9 m thick, and gypsum in the Cloud Chief Formation is up to 30 m thick. Gypsum within the Blaine Formation has a purity of 95% to 99%. Interbeds of shale 0.7 to 9 m thick separate the gypsum intervals. The gypsum beds are typically underlain by thin dolomite beds. Anhydrite thickness increases in the downdip direction, toward the west, under increasing overburden thickness.

**Texas**

Gypsum is produced in west-central Texas from the Eskota Member of the Peacok Formation (Permian). Outcrops of gypsum occur along a low topographic escarpment with numerous incised lateral drainages. Hydration and erosion or solution occurs in the downdip direction, and in lateral drainage courses formed along structural lineaments such as fractures. Several beds of gypsum up to about 6 m thick are interbedded with shale. Overburden consists
of sandy shale. The thickness of the overburden is a significant control on the hydration pattern of the gypsum.

The Castile Formation is an extensive occurrence of gypsum in the Delaware Basin of west Texas and southeastern New Mexico. It is a 440-m section of varved anhydrite and carbonate laminations (laminae 1 to 10 mm thick). Some of the laminae have been traced horizontally for more than 110 km (Anderson et al. 1972). Halite (NaCl) and sylvite (KCl) deposits of the Salado and Rustler formations overlie the Castile Formation.

**Nevada**

Two companies produce gypsum and anhydrite from the Late Triassic to Jurassic-age Nightingale Sequence of the Auld Lang Syne Group in northern Nevada. The evaporites occur as complexly folded and faulted sequences encased in metasedimentary rocks. A quarriable portion of the deposit is a geologically recent hydration rim extending to a depth of about 40 m. Three wallboard companies operate in the Las Vegas area of southern Nevada. One operation produces gypsite from Miocene-age playa deposits of the Muddy Creek Formation near the plant. The other two companies shifted from using gypsum from nearby quarries to using gypsum imported from northwestern Arizona, almost 160 km away. Papke (1987) published a comprehensive review of Nevada’s gypsum resources.

**Iowa**

The largest concentration of gypsum mining and wallboard manufacturing operations in the United States is in northwestern Iowa. The evaporites occur as complexly folded and faulted sequences encased in metasedimentary rocks. A quarriable portion of the deposit is a geologically recent hydration rim extending to a depth of about 40 m. Three wallboard companies operate in the Las Vegas area of southern Nevada. One operation produces gypsite from Miocene-age playa deposits of the Muddy Creek Formation near the plant. The other two companies shifted from using gypsum from nearby quarries to using gypsum imported from northwestern Arizona, almost 160 km away. Papke (1987) published a comprehensive review of Nevada’s gypsum resources.

**California**

The only domestic source of gypsum used for manufacturing wallboard in California is located in Imperial County, the southernmost county of the state. The gypsum occurs in the Miocene-age Fish Creek Gypsum Member of the Split Mountain Group. This deposit, located on the flank of the Fish Creek Mountains, has the largest gypsum production in the United States. The gypsum interval is up to 50 m thick and was deposited on an unconformable surface consisting of granite, fanglomerate deposits derived from the underlying and nearby granitic rocks, arkose, and sandstone. The characteristics and stratigraphic relationships of the gypsum are very similar to the enormous occurrence of gypsum in the Miocene Boleo Formation midway down the Baja Peninsula. The gypsum is unusual in that it has very few impurities; the deposit is devoid of calcium carbonate. The gypsum does, however, contain zones that have been discolored by manganese and iron oxides and zones of bassanite. The bassanite and discolored zones are believed to be related to hydrothermal alteration. The deposit is on the western edge of the Salton Trough, a rift zone with a thin crust and both extensional and right lateral ground movements.

Holocene-age deposits of gypsite at the southern end of the Central Valley have been used as a soil conditioner for many years. These deposits produce gypsite with a purity of 45% to 75% gypsum. Although the purity is too low for use in portland cement or plaster products, the gypsite is useful in treating the alkaline soils of the great agricultural districts of the San Joaquin and Central valleys. A comprehensive review of the gypsum deposits and resources of California was published by ver Planck (1952).

**Indiana**

Two companies operate underground gypsum mines in southwestern Indiana. An interval of gypsum 4 to 5 m thick in the Mississippian-age St. Louis Formation occurs at a depth of 100 to 250 m. The variation in depth is caused by the deeply incised surface topography developed in the overlying Pennsylvanian clastic strata. These deposits are good examples of the carbonate-sabkha depositional environment described by Jorgensen and Carr (1972). The St. Louis Formation is about 45 m thick and contains at least 10 discrete carbonate-sabkha depositional cycles. Only the uppermost two cycles, however, contain economic quantities of gypsum. The depositional cycles represent the transgressions and regressions of a very shallow sea over a broad tidal flat in a coastal sabkha environment.

The beds dip westward into the Illinois Basin about 6.6 m/km. The updip edge of the gypsum is exposed to subsurface groundwater activity and is actively undergoing solution. Groundwater percolating through the overlying strata and downdip from the Mitchell Karst Plain has formed an extensive cavity system of hydrogen-sulfide-bearing, water-filled fractures and caves. One of the mines has been flooded twice during its almost 50 years of operation. The first flood occurred when a development entry encountered the cavity system during blasting. The second occurred when groundwater continued to dissolve gypsum and worked around the engineered bulkhead constructed after the first flood. Careful evaluation of diamond core drilling information, mine planning, and ongoing underground examination assist in keeping active mining areas away from potential solution zones.

**Michigan**

Gypsum is produced in the eastern part of the Michigan Basin near the western shore of Lake Huron. Since the publication of the 6th edition of *Industrial Minerals and Rocks*, the underground mining operations in the Grand Rapids area have ceased. The deposits here are in the Michigan Formation of Mississippian age, and consist
of multiple units of gypsum from 1.5 to 13 m thick, separated by beds of shale varying from a fraction of a meter to 15 m thick. Overburden is glacial till ranging in thickness from 13 to 25 m. Three companies operate in the Alabaster–National City area: USG, National Gypsum Company, and Michigan Gypsum. These companies supply gypsum to wallboard plants in Detroit, Michigan, and Waukegan, Illinois, and cement plants in situated on or near Lake Michigan, Lake Huron, and Lake Erie.

**Colorado**

Extensive resources of Permian-age gypsum up to about 27 m thick occur near the town of Gypsum in Eagle County, west-central Colorado. One quarrying and wallboard manufacturing operation is located in the area. Gypsum also occurs in the Great Plains near the town of La Junta in southeastern Colorado.

**Kansas**

Gypsum occurs in Lower Permian rocks in central Kansas. The Georgia–Pacific operation extracts gypsum from Easy Creek Shale Formation in the upper part of the Council Grove Group. The National Gypsum Company quarries gypsum from the Medicine Lodge Member of the Blaine Formation in south–central Kansas, which corresponds to the lowermost gypsum strata that occur in the USG operations in northwestern Oklahoma.

**New Mexico**

Although considerable Permian calcium sulfate occurs in the Permian Basin deposits in southeastern New Mexico, none is currently being mined. There are, however, three operating quarries in the north-central part of the state that are producing gypsum from the Todilto Formation of Jurassic age.

**Utah**

Gypsum has been produced for many years from the Jurassic-age Arapien Shale in south–central Utah. Several stratigraphic intervals of gypsum are interbedded with shale and mudstone and have been complexly folded into a series of anticlinal and synclinal folds. The Arapien Shale outcrops in the foothills along the western slope of the southern extent of the Wasatch Mountains. The gypsum is more resistant to erosion than the elastic rocks and occurs as ridges. The Arapien Shale is also exposed on the western flank of the San Rafael Swell in southeastern Utah. The San Rafael Swell is an asymmetric structural dome and several beds of gypsum are exposed over more than 100 km².

**Wyoming**

Two companies produce gypsum in northwestern Wyoming. Large resources of gypsum are located southeast of Greybull in north–central Wyoming. A gypsum interval up to 22 m thick occurs near the top of the Chugwater Formation (Triassic). The gypsum is interbedded with shale.

**Canada**

The majority of gypsum produced in Canada comes from Nova Scotia. Several companies produce gypsum and various blends of gypsum and anhydrite from the Mississippian-age Windsor Group. The majority of the material produced is exported to gypsum wallboard and portland cement customers along the Atlantic and Gulf coast regions. Several companies operate large quarries in Nova Scotia. The National Gypsum Canada Ltd. quarry at Milford, near Halifax, is the largest gypsum quarry in the world. Adams (1991) published a comprehensive review of gypsum deposits and occurrences in Nova Scotia. Gypsum is also produced in other provinces, including Newfoundland, New Brunswick, Ontario, Manitoba, Alberta, and British Columbia.

**Atlantic Canada**

The major deposits of gypsum in Nova Scotia occur in the Mississippian Windsor Group, consisting of up to 760 m of interbedded marine evaporites and nonmarine sediments that were deposited in a large, complex intracontinental basin. Traditionally, the Windsor Group has been subdivided into five subzones, named “A” through “E” in ascending order. Giles (1981) reinterpreted the depositional history of the Windsor Group and identified five major transgressive–regressive depositional cycles. The cycles correlate with the earlier subzone nomenclature. Each cycle is characterized by one or more transgressive–regressive cycles. Economic gypsum and anhydrite deposits occur in the two lowest cycles. The earliest cycle (the A Subzone) represents a single rapid marine invasion followed by a slow regression of the sea. The A Subzone consists of up to 305 m of anhydrite with a variable thickness of gypsum near the surface. The depth of hydration varies from 0 to 76 m. The B Subzone also represents extensive evaporite deposition but consists of numerous transgressive–regressive sequences, all similar but on a much smaller scale than found in the A Subzone. The B Subzone consists of about 400 m of gypsum interbedded with dolomite, limestone, and siltstone. Gypsum occurs at a depth of up to 100 m.

The gypsum and interbedded waste units have been complexly folded and faulted into a series of anticlines and synclines. The folding is complex and varies from upright to recumbent. The folds have been refolded and truncated by normal and reverse faults.

**Ontario**

Only one company mines natural gypsum in Ontario: Canadian Gypsum Company, Ltd. A subsidiary of USG, it operates an underground mine in the Upper Silurian–age Salina Group near Hagersville, about 100 km southwest of Toronto. The gypsum seam is about 1.1 m thick, and the room-and-pillar mine is situated at a shallow depth (30 to 40 m) beneath the surface. The gypsum is overlain by 3 to 13 m of thinly bedded shale and dolomite and up to 15 m of glacial till. The gypsum has an average purity of about 85% and is beneficiated by heavy-media separation. The G-P Gypsum Corporation also operates a wallboard plant at Caledonia, near the Canadian Gypsum Company operation. Although natural gypsum was used for many years, production from the Caledonia mine has ceased and synthetic gypsum is currently used. The gypsum seam is 2.5 to 3 m thick and is located stratigraphically about 70 m below the Hagersville seam. The inactive and flooded Drumbo mine, formerly operated by Westroc Industries Ltd. (now a part of BPB North America), is about 75 km northwest of the Hagersville area. The Drumbo mine was active from about 1978 until 1993. The gypsum mining seam averages 1.8 m thick and is located 120 m below the surface.

**Western Canada**

Gypsum is produced in the provinces of Alberta, British Columbia, and Manitoba for wallboard-manufacturing plants in Edmonton, Vancouver, and Winnipeg. The quarries are far from the wallboard plants. The deposits in British Columbia are on the western flanks of the Canadian Rocky Mountains in environmentally sensitive areas. The VMSD at Falkland, near Kamloops, is quarried for portland cement rock.

**Mexico**

Mexico has tremendous resources of high-quality gypsum located in many parts of the country. Although Mexico is the second-largest
exporter of gypsum to the United States for the manufacture of wallboard, it has only three wallboard plants in the country. The gypsum industry continues to grow in Mexico as more development occurs in the commercial and institutional sectors. The primary use for gypsum in Mexico is in manufacturing portland cement rock and building plasters. Gypsum wallboard is rarely used in residential construction. A smaller but growing market is industrial plasters used in the manufacture of ceramics (cups and plates) and sanitary ware (sinks and toilets). Numerous yeseras throughout the country supply the construction plaster needs of local markets.

**Baja California del Sur**

In this area, the gypsum occurs in the Miocene Boleo Formation, a marine-clastic sequence that is also the host for copper, zinc, and cobalt mineralization. Gypsum in the Boleo Formation shares similarities with the Miocene Fish Creek Gypsum in California. Up to 110 m of gypsum was deposited on an irregular bedrock surface more than 30 years, and numerous small plaster-calcining plants. This region, and Monterrey is the center for the sanitary ware and ceramic industry in Mexico. Of the three gypsum wallboard plants in this region, and Monterrey is the center for the sanitary ware and ceramic industry in Mexico. Of the three gypsum wallboard plants in Mexico, located in Puebla, for more than 30 years, and numerous small plaster-calcining plants.

**Puebla State**

Deposits of Miocene–Pliocene gypsum occur to the southeast of Mexico City in the southern part of Puebla State. Several thick gypsum beds occur near the village of Izucar de Matamoros extending eastward to the village of Achoiapian. The deposits supply portland cement rock to numerous plants in the Mexico City–Puebla metropolitan areas. Gypsum from this region has also supplied the first wallboard plant in Mexico, located in Puebla, for industrial plasters. Gypsum wallboard is rarely used in residential construction. A smaller but growing market is industrial plasters. Gypsum wallboard is rarely used in residential

**Nuevo Leon and Coahuila States**

The cities of Monterrey and Saltillo, located in Nuevo Leon and Coahuila states, respectively, are areas of tremendous growth in northern Mexico. These cities are only a few hours south of the United States. There are several portland cement plants located in this region, and Monterrey is the center for the sanitary ware and ceramic industry in Mexico. Of the three gypsum wallboard plants in Mexico, two are located just north of the city of Monterrey.

Gypsum deposits in northern Mexico occur in the Cupido Formation (Cretaceous) and Minas Viejas Formation (Upper Jurassic). Near Monterrey, gypsum in the Minas Viejas Formation commonly occurs in the breached cores of complex anticlinal structures of the Coahuila Marginal Fold Belt, such as Portero Grande and Sierra del Fraile. These structures are diapiric structures of rock salt that have pushed upward through Upper Jurassic and Lower Cretaceous strata. An oil well drilled in the Sierra de Minas Viejas fold/diapir structure penetrated approximately 4,000 m of evaporites (Weidie and Martinez 1970). Gypsum occurs as a capping of the rock salt in some of the large fold structures. The gypsum is often contaminated by fragments of rock salt, however, and generally is not used for wallboard manufacturing.

Gypsum of the Cupido Formation is widespread in northern Mexico. The gypsum occurs along the flanks of limestone ridges in Nuevo Leon and Coahuila states. Two unusual occurrences of gypsum outcrop between Monterrey and Monclova. The diapiric masses of Minas Viejas gypsum, elliptical in shape with a major axis up to 1.5 km long, have pushed through the upper crust an estimated distance of about 5 km. The gypsum contains inclusions of igneous rock plucked from the walls of the conduits during its upward migration.

**Other Resources in Mexico**

There are significant occurrences in other parts of Mexico, including Chihuahua, Colima, Oaxaca, San Luis Potosi, Sonora, and other states. The most recently developed gypsum deposits are located in Colima in southwestern Mexico. Gypsum outcrops in a mountainous area covering almost 60 km between the villages of Coquitlal and Ixtlahuacan. The developed gypsum deposits are located near the main transportation artery (autopista) between Guadalajara and the Port of Manzanillo. Quarried gypsum is transported about 70 km to a state-of-the-art, multiple-use, rock-loading facility in the Port of Manzanillo for shipment to the Pacific Northwest.

**TECHNOLOGY**

**Exploration Techniques**

Several direct and indirect methods exist for determining the presence of gypsum. Because gypsum has been used as a building material and artist’s medium for several thousand years, much is known about the worldwide distribution of deposits.

The initial step in exploring for gypsum is a thorough literature search. The U.S. Geological Survey (USGS) published thorough reviews of the gypsum deposits of the United States in 1904 and 1920 (Adams 1904; Stone et al. 1920) and a comprehensive bibliography on gypsum and anhydrite in 1960. Dean and Johnson (1989) compiled a survey of anhydrite and gypsum deposits. Sources of information in North America include numerous state and provincial geological surveys and federal agencies such as USGS, the Instituto Nacional de Estadística Geografía e Informática (INEGI) in Mexico, and the Geological Survey of Canada. Information on foreign resources may be obtained from similar organizations or international organizations such as the United Nations. Other sources of information include unpublished university theses and dissertations and records of water or oil and gas wells. For example, the initial discovery of two large deposits of gypsum in Iowa and Indiana came from water-well records that are required to be submitted to the state geological survey.

The potential for the existence of evaporite minerals can be determined by studying the stratigraphy in regions where sedimentary rocks occur. In North America, most of the significant deposits of gypsum occur in rocks of Silurian, Devonian, Mississippian, Permian, Jurassic, and Miocene age. If shallow evaporite rocks are believed to be present, then further information may be derived by examining outcrops and topographic maps. Deeper deposits can be initially investigated by examining geophysical logs, oil and gas lithologic strip logs, or water-well information. Many state agencies require samples of cuttings or of diamond drill cores for retention in a permanent repository. As the stratigraphic and lithologic details of a target area are developed, the structural conditions should also be ascertained. Primary, regional structural features such as folds and faults expose gypsum-bearing strata or are pathways for the hydration of deeper anhydrite strata. Linear structural features such as joints and fractures also determine the minability of a gypsum deposit.

Gypsum has some unique features that are directly visible or interpreted from the topography or hydrology of an area. For example, outcrops of gypsum are rare in humid environments because of the relatively high solubility in the presence of surface water or groundwater. Although gypsum is important in agriculture as a soil amendment, outcrops of gypsum support only sparse vegetation.

**Stratigraphy**

Gypsum and anhydrite are usually associated with common sedimentary rocks such as shale and dolomite. It is more commonly associated with dolomite than limestone because the formation of gypsum is often associated with dolomitization of micritic tidal-flat sediments. Megascopic fossils are almost universally absent in gypsum and anhydrite deposits because of the high salinity of the water in which the evaporites were deposited (Pettijohn 1975). The
physiochemical characteristics of gypsum generally rule out its preservation in igneous or metamorphic rocks, except for minor occurrences associated with hydrothermal fluids. A significant exception is the gypsum that occurs interbedded with marble and tremolite schist in Riverside County, California. The country rocks encasing several thick beds of gypsum and anhydrite were subjected to regional metamorphism. The uppermost portion of the evaporite seams was hydrated to form gypsum, but anhydrite occurs at depth. Underground mining to a depth of about 35 m was carried out from the 1920s to 1946.

Topography

The high solubility of gypsum results in areas of low topographic relief or highly dissected terrain in humid regions. For example, the gypsum-bearing portion of the Mississippian Maccrady Formation crops out for about 30 km along the footwall of the Saltville Thrust Fault in southwestern Virginia. Tectonically thickened portions of the Maccrady Formation occur as a prominent valley between more competent ridges of sandstone (Price Formation) and dolomite (Honaker Dolomite) in the thrust fault hanging wall. The Mississippian Windsor Group in Nova Scotia consists of about 800 m of gypsum and anhydrite interbedded with limestone, siltstone, and sandstone. Pinnacles of gypsum and anhydrite occur with deep pockets and sinkholes filled with clay and organic material.

Quarryable gypsum occurs as a product of the near-surface hydration of anhydrite by groundwater. The deposits of Kansas, New Mexico, Oklahoma, and Texas occur in semiarid regions. The pattern and degree of hydration of anhydrite to gypsum are a function of: (1) stream drainage patterns; (2) type and thickness of overburden; and (3) structural features such as fractures, joints, and faults. Gypsum typically caps low escarpments in the semiarid environments. In the outcrop area, some of the gypsum has been dissolved and eroded, resulting in locally poor quarrying recovery. Headward erosion of gypsum along structural discontinuities aids in the transmission of groundwater to hydrate anhydrite in the downdip direction, but may also result in poor quality or recovery near the streams. In the downdip direction, the gypsum is overlain by an increasing thickness of overburden, generally consisting of sand, shale, siltstone, or limestone. The type of overburden and its permeability affect the degree of hydration of the underlying seam.

In arid regions, gypsum outcrops are often more resistant than commonly associated beds of mudstone or shale. The Jurassic Arapie Shale in south-central Utah consists of several gypsum intervals that have been complexly folded. The gypsum outcrops as hogback ridges with slopes of mudstone or shale. The Miocene Fish Creek Gypsum Member of the Split Mountain Group in Southern California is well exposed as barren hills along the limb of a syncline and is underlain by fanglomerate and igneous rocks.

Vegetation

Although gypsum provides many benefits in agricultural applications, outcrops of gypsum are relatively hostile to the growth of vegetation. The development of karst topography on gypsum outcrops in humid regions such as in Nova Scotia supports vegetation primarily because of the accumulation of organic material in pockets of clay.

In arid regions of the western United States, outcroppings of gypsum are largely barren or only sparsely covered by vegetation. The uppermost part of the outcropping consists of soft, friable, secondary gypsum (gypsite) derived by the evaporation of capillary water from the underlying rocks. The surface often has the appearance of a wrinkled orange and is called “cryptogamic crust.” The crust, consisting of gypsite, cyanobacteria, lichens, fungi, or mosses, forms when moisture is available.

A distinctive change in the density or type of vegetation often distinguishes gypsum from limestone in interbedded and folded sequences. Juniper shrubs (a conifer) commonly grow sparsely on gypsum outcrops, but grow more abundantly on limestone. Saguaro cactus thrives on some gypsum deposits in southwestern Mexico. In Colima, for example, the upslope contact of gypsum with limestone on steep, colluvium-covered slopes is generally defined at the highest occurrence of saguaro cacti. Beds of clay impurities within a gypsum deposit may support more vegetation, such as creosote bush.

Hydrology

Examining maps may provide a hint about the presence of gypsum. Sulfate-laden groundwater discharging from springs or in streams is often noted as “sweetwater” or agua dulce. For example, gypsum has been mined at Sweetwater, Texas, for almost 100 years. Sweetwater Creek flows across the outcrop area of the Permian-age Blaine Group. The high solubility of gypsum also forms karst terrain, with little to no surface drainage in some regions.

Deposit Evaluation

Drilling and Sampling

The primary method of evaluating a gypsum deposit is by diamond core drilling. Drilling is rarely done, however, on a regular sized or shaped grid. Rather, drill holes are best placed to answer basic or specific questions about the deposit regarding (1) its thickness and lateral extent; (2) the presence, type, and distribution of impurities; and (3) other factors that may affect minability or quality, such as solution zones, erosional cutouts, or an irregular bedrock surface.

The drilling campaigns to initially outline a gypsum deposit are not sufficient for the long-term planning and operation of a mine or quarry. Subsequent programs provide infill drilling information and answer localized questions.

The diamond drill core is generally sampled by splitting the core longitudinally, preserving one half and preparing the other half for quality analyses. The sampling interval is typically 1.5 to 2 m. The core is crushed in a laboratory crusher and ground in a pulverizing mill to about 100 mesh. The testing methods for the chemical analysis of gypsum are defined in ASTM C471M-01.

Testing Procedures

In general, testing gypsum rock for wallboard manufacture involves determining the amount of chemically combined water and soluble salts. The purity of the sample is determined by measuring the loss of weight after heating for a specific period of time and temperature range. Absorbed moisture (free moisture), however, must be removed first by drying the sample to prevent overestimating purity. Overheating the sample can also cause thermal decomposition of impurities such as carbonates and some clays, and can result in an overestimate of purity.

Free-moisture and combined-moisture losses may be measured by weighing samples with laboratory balances before and after heating in ovens. Computerized systems are also available that perform the drying, calcining, and weighing functions using only one analytical instrument.

Soluble salts are leached from the pulverized samples for determining the content of total dissolved solids (TDS) with an electrical conductivity meter and chloride ions with an ion-specific probe.

Whiteness and brightness are important in manufacturing and marketing industrial and ceramic plasters. Although the color of the calcined plaster may not affect the quality of the finished product, it may have an effect on competitive advantage in the marketplace.
Food- and pharmaceutical-grade gypsum is analyzed for the presence of heavy metals, such as lead, arsenic, and selenium, as well as for the presence, type, and amount of bacteria.

**Mining**

Most of the world’s gypsum is produced by surface-mining operations. In North America, only five active underground gypsum mines were in operation in 2004. Two are located in Indiana, and one each in Iowa, Michigan, and Ontario, Canada. Four additional North American underground gypsum mines ceased operations early in the 21st century after extensive periods of operation. Gypsum was mined in southwestern Virginia from about 1830 until 2000—a period of about 170 years. Several long-term, underground mining operations in New York, Kansas, and Ontario ceased operations in the early part of the 21st century.

**Quarrying**

Gypsum is extracted from near-surface deposits by quarrying methods. Overburden consisting of glacial materials (till, sand, clay), shale, mudstone, siltstone, sandstone, sand and gravel, or limestone, is removed from the gypsum by various stripping methods. Stripping is performed by pan scraper, truck and excavator, front-end loader or hydraulic excavator and truck, dragline, and bulldozer. The maximum economic stripping limit (thickness) is about 30 m and depends on the method of stripping and the thickness of the underlying recoverable gypsum.

Final cleanup of the stripped gypsum surface is important, and is determined by the final products to be manufactured. If the quarried rock is to be used as agricultural products, portland cement rock, or wallboard, then much of the impurities can be removed in the finer fractions during crushing and screening. Conversely, gypsum used for high-quality, high-value-added products requires more stringent cleaning. For example, articulated hydraulic excavators with multiple, interchangeable bucket widths scrape clay from the gypsum surface and fractures that extend deep into the gypsum.

Drilling and blasting is the primary method of quarrying gypsum. Quarry benches are generally about 8 m in height. Hydraulic rotary drilling and auger drilling are commonly used. Gypsum is soft and penetration rates up to 7 m/min are possible. Blast holes are generally 50 to 100 mm in diameter and spaced relatively close together to distribute the explosive forces throughout the rock mass. The blasting components used include ammonium nitrate and fuel oil (ANFO) blasting agent, cast boosters, nonelectric blast initiation systems. Bagged emulsion is used in wet holes. About 1 kg of blasting agents per ton of broken gypsum is an average tonnage factor. The elastic nature of gypsum, the presence of solution-enhanced fractures, and the possible presence of water contribute to poor and inefficient rock fragmentation. An incorrectly designed blasting pattern may result in irregular fragmentation, including excessive oversized rock requiring secondary breakage, excessive fines, or irregular floor conditions that are detrimental to the efficiency and maintenance of mobile equipment. Quarry haulage trucks or over-the-road dump trucks transport the quarry-run broken gypsum from the quarry site to the primary crusher.

Another method of extracting gypsum from quarries that is gaining acceptance is the use of a surface miner. This is a adaptation of highway-resurfacing technology in which a horizontally rotating mandrel with cutting teeth chips away at the asphalt and either discharges the broken material in a windrow or directly into a haulage truck. Specialized machinery using this technology is being developed to quarry coal, gypsum, and limestone. The size, spacing, and arrangement of the cutting teeth on the mandrel are important factors in the efficient production of gypsum rock.

Advantages over standard quarrying techniques are the following:

- Elimination of drilling and blasting
- Elimination of primary crushing
- Direct removal of interbedded thin waste beds or low-purity zones
- Increase in recovered gypsum purity by removal of off-specification material from windrows
- Maximization of the overall recovery of the gypsum near structures or utilities

**Underground Mining**

Underground mining of gypsum is far less common than quarrying. There are currently only five active underground gypsum mines in North America. The mines are located at a depth of < 30 m (Hagersville, Ontario, Canada) to about 200 m (Iowa and Indiana). Access to the mine workings for workers, supplies, ventilation and escape, and production is by either vertical shafts or inclined adits (tunnels). The mined interval varies from 1.1 m (Hagersville) to 3.7 m (Iowa, Michigan, and Indiana).

Gypsum is extracted using the room-and-pillar method, in which pillars are left in place to support the roof strata and the
gypsum is removed in a checkerboard pattern. The extraction ratio, which is the proportion of material mined to material left in the supporting pillars, varies from 65% to 80%.

Drilling and blasting of gypsum in underground mines is similar to methods used in gypsum quarries. The blast-hole pattern, however, is drilled horizontally into the advancing face of a mine heading. The number of drill holes, orientation, depth, and sequence of blasting are designed to maximize breakage of the gypsum and to maintain the integrity of the adjacent pillars and immediate mine-roof strata. The roof strata are reinforced by roof-control fixtures, generally epoxy resin-grouted bolts, up to 1.5 m long. The resin-grouted bolts bind the roof strata together to form an integral beam that is stronger than the individual strata.

Underground gypsum mines are generally very stable. Long-term measurements of roof and pillar convergence (vertical closure) at the USG mine at Sperry, Iowa, indicate that the structure should be stable for hundreds of years. An underground gypsum mine near Grand Rapids, Michigan, is currently being used as a computer network security center.

**Processing**

**Wallboard Manufacture**

Figure 1 is a general flow diagram for the manufacture of gypsum wallboard, and Figure 2 is a conceptualized drawing of that process. Three possible sources of raw material are shown: (1) natural gypsum rock delivered from an on-site quarry or underground mine, (2) synthetic gypsum delivered from a nearby power plant or by barge, and (3) off-specification wallboard recycled into the manufacturing stream.

**Quality Assurance and Quality Control Issues**

No single statement can be made about the effects of the presence of impurities in gypsum deposits. The manufacturing processes for wallboard can be adjusted for a wide range of gypsum purity. Wallboard can be made from relatively low-purity (low 80s) or very-high-purity (high 90s) gypsum. The key is that the purity of the gypsum supplied from the mine or quarry, as well as the calcined gypsum stucco, should be consistent. Formulating calcined stucco with air-entraining agents can decrease the weight of the finished wallboard, enhancing its purity.

Most gypsum contains 10% to 15% impurities, although some deposits may be exceptionally pure (i.e., +95%) or somewhat impure (i.e., 80%). In general, the amount of impurity that can be tolerated depends on (1) the type of impurity, (2) the product being manufactured, and (3) the competitive situation.

Impurities are usually separated into three categories, based on their effect on the manufacturing process and finished products:

1. Insoluble or relatively insoluble minerals such as limestone, dolomite, anhydrite, anhydrous clay, silica minerals
2. Soluble evaporite minerals, including chlorides (halite, sylvite, etc.) and sulfates (mirabilite, epsomite, etc.)
3. Hydrous but insoluble minerals (e.g., the montmorillonite group of clays)

**Insoluble Impurities**

Insoluble impurities, especially carbonates, reduce the strength of the rehydrated stucco and increase the weight of the finished plaster or wallboard products. A greater amount of lower-purity stucco is required to obtain a specific strength plaster or wallboard. Wallboard products that are heavier increase both the transportation costs of the finished products and the difficulty of installation. These minerals can also occasionally act as hydration accelerators. Many commercial gypsum deposits contain as much as 10% to 15% insoluble impurities.

Chert is present only in trace amounts in some deposits and does not significantly affect the manufacturing of wallboard. Chert in the feedstock to the calcining mill can result in excessive abrasive wear of grinding equipment.

Dolomite is detrimental in industrial plaster used in the manufacture of sanitary ware such as sinks and toilets or ceramic products such as dishes. It has a higher specific gravity than gypsum and sinks in the stucco slurry, forming projections at the mold-cast interface and surface pits in the cast product.
Soluble Evaporite Impurities
Soluble evaporite impurities affect calcining temperature, fluidity of the stucco slurry, setting or rehydration time, and bonding of paper and core in wallboard. These minerals are usually limited to no more than 0.02% to 0.03% by weight of the gypsum rock and strongly affect vapor pressure, which in turn affects the gypsum hydration–dehydration reactions.

Hydrous, Insoluble Impurities
The principal effect of hydrous, insoluble impurities is in the absorption of moisture in the finished product and on bonding characteristics of the rehydrated stucco core of wallboard to its paper covering. Hydrous clays up to 1.0% to 2.0% may be tolerated.

USES
Gypsum is a very versatile mineral that can be used in the manufacture of several hundred products. Processing methods vary from simply crushing and sizing of quarry-run gypsum to specialized methods of calcination in closed pressure vessels.

Uncalcined Gypsum
Gypsum that has been processed only by grinding and sizing is known as land plaster, portland cement retarder, and Terra Alba. Land plaster is used for agricultural gypsum and a raw feedstock for manufacturing wallboard and plasters. Portland cement retarder is used in the manufacture of portland cement. Terra Alba is used in food and pharmaceutical applications.

Uncalcined gypsum is principally used as a retarder for portland cement, soil conditioner, mineral filler, and in other minor industrial applications. About 25% of the gypsum mined in the United States is used in these markets. In countries where building practices differ from those in the United States and Canada (poured concrete, block, or brick), however, the relative usage of gypsum varies widely.

Although calcium sulfate deposits are the world's largest sulfur resources, only minor quantities of gypsum and anhydrite have been used to produce sulfur or sulfur compounds. This use is accompanied by a unique, site-specific set of economics, because sulfur is generally available from nongypsum sources at lower cost.

Agricultural Gypsum
Gypsum provides several benefits in agriculture. The specifications of agricultural gypsum are primarily related to the degree of fineness (particle size and surface area). As gypsum dissolves, it is a source of elemental calcium (25% by weight) and sulfur (20% by weight). Gypsum has a neutral pH (7.0) and is 150 times more soluble than ground limestone. Finely ground agricultural gypsum permits rapid dissolution and absorption by plants. Long-term availability of these elements during a growing season can be accomplished by applying agricultural gypsum of multiple particle sizes. Finely ground gypsum (100% passing through a 425-mesh screen) can also be dissolved in irrigation water for easy application.

Gypsum loosens and aerates heavy clay and wet soils. The acidity of aluminum-rich lateritic soils is buffered by gypsum. The gypsum particles act as nuclei for the flocculation of clay particles, producing more granular and well-drained soils. Cation replacement of calcium for sodium reduces the alkalinity of soil. Gypsum also combines with potassium-aluminum silicates in soil, releasing potassium as a nutrient. Applying gypsum prevents the formation of a crust in the soil where low electrolyte irrigation water is used or where the soil has a high sodium content. The soil crust contributes to excessive runoff and erosion in sloping terrain or pooling of water on more level ground.

In dairy-farm applications, gypsum can be applied to manure piles to prevent the loss of nitrogen by reacting with nitrogen to produce ammonium sulfate. An additional benefit is reduced ammonia odors.

Gypsum can be applied to bodies of water with high total suspended solids, such as muddy ponds, where it acts as a flocculating agent to settle the suspended clay particles.

Portland Cement Rock
Gypsum, anhydrite, or a mixture of gypsum and anhydrite is used in the manufacture of portland cement. Gypsum and anhydrite are used as a source of SO₃. Adding calcium sulfate also controls the early-strength characteristics of cement and product shrinkage during drying and curing. About 3 to 5 wt % of calcium sulfate compounds are ground with clinker to form portland cement.

Gypsum also aids in the grinding of clinker by reducing the tendency of fine particles to agglomerate and adhere to the walls of the mill and grinding media (Hansen et al. 1988). Gypsum is much softer than clinker, is easier to grind, and has a much greater fineness (surface area) than clinker. Portland cement rock is typically ground to a particle size of 6 to 65 mm. Calcium silicates and aluminates that constitute clinker have negatively charged oxygen ions on the crystal surfaces. The hydrogen ions in the water molecules of the gypsum particles bind to the negatively charged clinker particles. The neutralization of the electrical charges by the attraction of the gypsum to clinker particles reduces the tendency for agglomeration.

Terra Alba
Terra Alba is white, high-purity, uncalcined gypsum that has numerous uses in the food and pharmaceutical industries. It is made by fine grinding and air separation of gypsum with a purity of greater than 97%. Terra Alba has a minimum calcium content of 23% (by weight).

Beer Brewing
This type of gypsum supplies calcium ions to buffer the pH and reduce the hardness of water used in the beer-brewing industry. The yield of the main mash is increased by promoting the proper gelatinization of the starch in the cooker mash, as well as protein degradation and starch conversion. Flocculation and precipitation of undesirable protein complexes is achieved by adding Terra Alba. These effects produce beer with improved stability and shelf life.

Baking
In the baking industry, Terra Alba is used as a source of supplemental calcium. It is used in enriched flour and breads, pasta products, baking powder, yeast foods, and bread conditioners. Calcium enrichment of bakery products, in addition to providing supplemental calcium, also counteracts the effects of excess phosphorous in a person’s diet. Many foods are high in phosphorous, but few foods are good sources of calcium. A deficiency of calcium makes the dough soft and sticky.

Pharmaceuticals
Terra Alba is used as a diluent and inert extender in pharmaceutical products such as aspirin tablets. It also provides a source of dietary calcium.

Other Food Applications
Terra Alba is also used in canned vegetables, cheeses, and artificially sweetened jellies and preserves.
Glass Batch
Relatively pure uncalcined gypsum, depending on glass-batch chemistry, can also substitute for salt cake (sodium sulfate) in glass manufacturing.

Oxidizing Agent
Thermal decomposition of gypsum in the glass melt produces sulfur dioxide as well as oxygen. The oxygen reacts with any free or reduced sulfur to form additional SO₂. Increasing the amount of gypsum in the glass batch decreases the sulfur content in the melt and results in a lighter-colored glass. Iron pyrites and carbon or blast-furnace slag are commonly added to the melt to manufacture amber-colored glass. Green-colored glass has a natural amber hue.

Fining Agent
Adding gypsum provides a source of sulfate in soda-lime glass. Decomposition of gypsum produces sulfur dioxide, which, in low concentrations, removes seeds and forms a clear glass.

Removal of Surface Scum
Surface scum can form on molten glass because of improper flow conditions in the furnace, especially near the bridgewall. The presence of coarse sand and stratification of the raw materials in the batch may result in selective melting and the formation of a surface scum. Gypsum added to the glass melt reacts with sodium carbonate to form sodium sulfate. The sodium sulfate melts and reacts with free silica to form sodium silicate, which in turn separates from the molten glass and floats on the surface.

Calcined Gypsum
Gypsum chemically transformed by heat or pressure to remove three fourths of the water of crystallization is known as calcium sulfate hemihydrate, stucco, and plaster of paris. Different methods of calcination produce two products, beta hemihydrate and alpha hemihydrate, depending on the processing method used. The chemical reaction, however, is the same for both products and is reversible at atmospheric temperatures and pressures:

\[ \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{heat} \rightarrow \text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O} + 1\frac{1}{2}\text{H}_2\text{O} \]

Many different products may be manufactured from alpha or beta hemihydrate or a mixture of both. The products are further mixed with portland cement, fiberglass, plastic resins, and other materials to produce products with high strength and density, fire and water resistance, and other specialized characteristics.

Beta Hemihydrate
Beta hemihydrate is produced by calcining finely ground gypsum (95% –100 mesh) in vertically oriented, cylindrical steel kettles at atmospheric pressure. The calcination can be a continuous process or a batch process. Continuous calcining of land plaster is used predominantly for producing stucco for wallboard. Batch calcining is used predominantly for manufacturing construction and industrial plasters. The beta hemihydrate calcining process produces rough, fractured, fragmented particles.

In the continuous calcining process, land plaster is introduced into the top of the kettle. As the molecular water is removed during calcination, the beta hemihydrate becomes less dense and rises to the top of the kettle. The beta hemihydrate overflows the top of the kettle into a hotpit where calcination is completed and entrapped steam is released. The beta hemihydrate is discharged from the continuous kettle at 140° to 154°C.

In the batch kettle process, the calcining is done on a measured amount of land plaster, and then the entire batch is dumped into a hotpit to complete the calcination and release entrapped steam. Batch calcining produces beta hemihydrate with high plasticity, high strength, and high density. The product from batch calcination is used for construction and some industrial plasters. Batch calcining is performed at 150° to 165°C.

Gypsum Wallboard
Several different types of wallboard are manufactured, including the common variety and specialized varieties, such as fire resistant, water resistant, and plaster lath. Gypsum wallboard is manufactured by mixing beta hemihydrate stucco, water, and other additives to form a slurry. Additives such as asphalt emulsion, vermiculite, chopped fiberglass, and paper fiber impart to the wallboard characteristics such as water resistance, fire resistance, and strength. The slurry is discharged onto a continuous roll of paper, the edges of the paper are folded upward, and another sheet of paper is applied to the top to form a soft gypsum “sandwich.” This sandwich travels along a conveyor until the stucco slurry has recrystallized to gypsum. The continuous stream of wallboard is cut into lengths varying from 2.4 to 4.25 m. It then enters a multideck drying kiln to remove excess water. Upon exiting the kiln, the wallboard is packaged into two-sheet bundles, stacked, warehoused, and shipped to customers.

Pottery and Ceramic Plasters
Plasters used in the manufacturing of pottery and ceramic products may be alpha hemihydrate, beta hemihydrate, or a mixture of both crystal phases. White art plasters used in schools or arts and crafts classes are made from beta hemihydrate.

The process of manufacturing pottery and ceramic products involves several steps from preparation of an initial model to the final product. An original block mold is manufactured from the finished model of the product to be manufactured. Then a case mold is made from the block mold. The case mold becomes a die for fabricating multiple working or production molds. The block and case molds are typically manufactured from alpha hemihydrate. The use of alpha hemihydrate allows for the production of dense, hard, strong, and durable molds which can be intricately detailed. Working molds, which are used for mass production, are manufactured from a blend of alpha and beta hemihydrate or from alpha hemihydrate. Industrial manufacturing processes for pottery and sanitary ware involve three major types of working molds: slip-cast molds, jigger molds, and press molds.

In slip casting, a relatively fluid mixture of clay and other ceramic raw materials, called “slip,” is poured into a mold, which may consist of several individual pieces. The excess water in the slip is absorbed by the plaster mold. Slip-cast molds are generally manufactured from a mixture of 15% to 20% alpha hemihydrate and 80% to 85% beta hemihydrate. Examples of slip casting include the manufacture of sinks and toilets.

In jigger casting, a relatively soft, plastic clay mixture is placed on a rotating bottom mold. As the mold rotates, an upper molding template moves downward and forces the clay to fill the bottom mold. The upper molding template also impresses or cuts the desired design elements into the clay. This method is not very labor intensive and is used to manufacture lower-priced dinnerware items. Jigger cast molds are generally manufactured from a mixture of 70% alpha hemihydrate and 30% beta hemihydrate. The alpha hemihydrate gives the mold durability and hardness for use in longer production runs.

In press casting, the clay mixture is formed into the final product by hydraulically pressing a lump of clay between the halves of a mold. This method is used to produce products such as dishes, ashtrays, some cups, and bud vases. This method of casting
is also relatively fast and low cost. The molds are manufactured entirely from alpha hemihydrate.

**Alpha Hemihydrate**

Alpha hemihydrate is produced by calcining sized gypsum or lump rock in an autoclave at elevated steam pressure in a batch process. This method of calcination produces dense, orderly, well-formed crystals. Alpha hemihydrate can be used alone or mixed with additives such as beta hemihydrate, portland cement, resins, and fiberglass to produce very durable products.

**Industrial Prototypes and Models.** Gypsum-based plaster has been used for pattern, model, and mold making for more than 1,000 years. Alpha hemihydrate cements are used to meet the specialized needs of the aircraft, automotive, foundry, plastics, and other industries. The characteristics of the alpha hemihydrate cements allow for the manufacture of molds and patterns with high accuracy, high strength, high surface hardness, and low expansion during drying and curing. Patterns and molds can be made to close tolerances such as those required by the aircraft industry.

One of the latest innovations in preparing industrial prototypes and models is the development of machineable alpha gypsum cement. USG developed this product in the 1990s to meet the needs of the rapid-prototype tooling industry; it serves as a replacement for preformed polymer-based boards. The castable alpha gypsum cement can be poured into containment vessels or molds of any size and hardened in about 1 hr. Dimensional stability is achieved after 3 hr.

This material is typically used with computer-controlled, numerical-milling (CNC) machinery to produce prototypes and models. The material can also be used to produce forms for vacuum molding of sheet plastics. Milling of cast blocks of this material produces chips rather than dust and does not require lubricating fluids.

**Art and Statuary.** Alpha hemihydrate gypsum cement and plaster are used to manufacture dense, durable, three-dimensional art and statuary products. Art and statuary cement and plaster can be modified by adding polymers and glass fibers to produce resilient, chip-resistant castings. These products can be used to produce solid figurines, lamp bases, and hollow statuary.

**Traffic Surface Repair.** Traffic surfaces such as expressways, bridges, ramps, and commercial concrete floors that carry high volumes of traffic can be repaired with a mixture of alpha hemihydrate, portland cement, and a suitable aggregate. This is a quick and effective method to repair or replace traffic surfaces that cannot be out of service for long periods.

Traffic surface repair cement expands on setting to ensure a tight contact with the surrounding pavement. This characteristic protects reinforcing steel by restricting water and salt seepage. The product sets quickly and rapidly develops relatively high compressive strength. The total process of repairing or replacing sections of pavement can be completed in less than 5 hr. The cement will develop a compressive strength of about 25 MPa within about 1 hr; the compressive strength will reach about 69 MPa after 28 days.

**Architectural Applications.** Fiberglass-reinforced alpha hemihydrate cement (FGR) is used to fabricate highly detailed interior architectural features. Strong, resilient, high-strength architectural details can be produced with a thickness of as little as 0.10 in. Column capitals and covers, light coves, medallions, cornices, coffers, and wall and ceiling moldings are examples of details that can be fabricated from this material. Architectural detail elements can be cast off site from original pieces to exacting detail. Historical architectural elements can be easily replicated with stronger, lightweight, FGR gypsum cement.

**Medical Applications.** Gypsum plasters are used in dental and orthopedic applications. Dentists use the plasters for making impressions of teeth and gums to produce bridges, crowns, and dentures.

Orthopedic plasters are used in bandages and casts to immobilize broken limbs. Newer, more innovative applications include tissue engineering where gypsum is used to promote bone and tissue regrowth. It is used as bone-void filler, in which cast pellets of high-purity gypsum provide a temporary framework for tissue regrowth (Laurencin et al. 1999). Upon setting, the gypsum has a strength of about 24 MPa. The gypsum is biocompatible, stimulates bone regrowth, and is adsorbed by the body in 4 to 8 weeks.

**Deadburned Gypsum**

Gypsum which has been calcined at a temperature above 400°C loses both molecules of water of crystallization, forming a deadburned calcium sulfate (CaSO4). Although it has the same formula as anhydrite, deadburned gypsum is relatively inert and insoluble. Deadburned gypsum is almost anhydrous, with more than 99.6% of water of crystallization removed during calcination. It has a high content of elemental calcium (29% by weight).

There are several high-value-added uses for deadburned gypsum. It is used as an inert filler in plastics. It is also used in agricultural products as a binder or carrier for herbicides and pesticides. Deadburned gypsum is used in pharmaceutical products such as aspirin tablets. It is also used in pizza dough and other bakery products, acting as a desiccant and a source of calcium. The deadburned gypsum absorbs moisture in products, which then can be manufactured and stored for a period of time before use without becoming soggy.

Deadburned gypsum is used as filler in thermoplastics such as polyvinyl chloride (PVC) products: vinyl siding, window frames, moldings, conduit, and pipe. The filler imparts acid resistance and low electrical conductivity. It is also used in food packaging.

**PRODUCT GRADES AND SPECIFICATIONS**

There is no single statement possible on the grades and specifications of gypsum because of the diversity of products produced from the mineral. Gypsum used in construction products and food and pharmaceutical products, however, must meet stringent regulations.

**Construction Products**

ASTM defines the specifications for testing uncalcined gypsum and construction products manufactured from gypsum. ASTM standard C471M-01 defines the testing methods for the chemical analysis of gypsum. ASTM standard C472-99 defines the standard testing methods for the physical properties of gypsum, gypsum plasters, and gypsum-based concrete. In 1999, ASTM began to phase in a new international standard for interior and exterior gypsum wallboard products and veneer plasters that combined nine separate earlier standards. This standard titled C1396, Specification for Gypsum Board, eliminated inadvertent inconsistencies in the separate standards.

**Food and Pharmaceutical Grade**

Gypsum is an approved additive on the Food and Drug Administration (FDA) “Generally Recognized As Safe” (GRAS) listing of food additives. The use of gypsum in specific food products is described in Title 21, Part 184 of the Code of Federal Regulations (21 CFR 184.1230). The permitted amount of gypsum allowable in different types of foods is defined in the Food Chemical Codex in the United States and the National Formulary in the United Kingdom.

**ECONOMIC FACTORS**

**Pricing**

Gypsum is a low unit-value, high place-value industrial mineral, and its ultimate value is based on value-added processing. The lowest prices are for ground gypsum used for portland cement and agricultural gypsum. Calcining gypsum for use in manufacturing
environmental controls on coal-fired electric-power plants, is a significant cement. A blend of gypsum and anhydrite used in the manufacturing of portland cement rock is distributed primarily by bulk truck. Wallboard and plaster products account for 90% of the total consumption of gypsum in the United States. Agricultural gypsum is the most valuable product, followed by synthetic gypsum and finished products manufactured from gypsum. Calcium sulfate hemihydrate weighs only 84.3% as much as uncalcined gypsum.

**Competitive Substitutes**

No competitive substitutes exist for gypsum used in the manufacture of wallboard and industrial plasters. Gypsum wallboard is not a universal manufacturing material. Masonry products such as brick, concrete block, poured concrete, and cement stucco are used throughout the world. There is no practical substitute for gypsum, anhydrite, or a blend of gypsum and anhydrite used in the manufacturing of portland cement.

Synthetic gypsum, produced primarily as a by-product of the environmental controls on coal-fired electric-power plants, is a significant substitute for natural gypsum. Most of the new wallboard plants constructed in the late 1990s and early 2000s are designed to use 100% synthetic gypsum, primarily FGD gypsum. In 2003, synthetic gypsum accounted for 26% of the total domestic gypsum supply (USGS 2004).

**Packaging**

Gypsum is used in more than 400 products, and therefore many different forms of packaging are used for distribution to customers. Raw ground gypsum (land plaster) for agricultural uses and portland cement rock is distributed primarily by bulk truck. Wallboard panels are loaded onto trucks or railroad cars for distribution. Construction and industrial plasters are packaged in bags.

**TRANSPORTATION**

**Truck**

Trucking is the most common method of transportation of gypsum products. It is the most flexible mode of transport, but also the most expensive. In most cases, transport is between the quarry site and the manufacturing plant, using either quarry haul trucks or over-the-road dump trucks. Truck haulage is relatively low capacity (25 t) compared to other transportation modes. The cost of truck transport is in the range of $0.10 to $0.25/st-mile.

**Rail**

Transporting gypsum by rail is relatively rare, except for the delivery of portland cement rock. The BPB North America plant in Vancouver, British Columbia, Canada, however, receives gypsum by rail from sources along the western flank of the Rocky Mountains. It is more efficient to ship the intermediate calcium sulfate hemihydrate or finished products manufactured from gypsum. Calcium sulfate hemihydrate weighs only 84.3% as much as uncalcined gypsum.

Railroad transport of gypsum is limited by factors such as the proximity of manufacturing plants to railroad lines to avoid rehandling, limited routes, and the seasonable availability of hopper rail cars during the harvest season. Capacities of railroad cars are limited to about 100 t and the transportation cost is about $0.04/st-mile.

**Barge**

Most of the new wallboard plants constructed in the United States during the last decade are totally dependent on the use of FGD synthetic gypsum and were constructed adjacent to coal-fired power plants or along navigable rivers or canals to facilitate the transportation of raw materials by barge. All of these plants are located east of the Mississippi River. There is, however, relatively little natural gypsum transported by barge. Gypsum and anhydrite are supplied to portland cement plants along the Mississippi River by a single source in southeastern Iowa.

Barge transportation is relatively slow and has limited distribution capabilities. The end user must be on a waterway or within about 160 km. Transloading from barge to truck dramatically increases overall transportation costs. Climatic conditions such as drought or flooding can interrupt delivery of products by barge. Barge capacities are limited to about 1,200 t in the United States and 1,500 t in Europe. The cost of transportation by barge is in the range of $0.0075 to $0.01/st-mile.

**Ship**

Wallboard plants along the U.S. coasts receive gypsum by ship. Gypsum producers in Nova Scotia, Canada, supply wallboard plants from New Hampshire to Florida. Gypsum is also supplied to a wallboard plant and to portland cement customers on the St. Lawrence Seaway. Fundy Gypsum Company’s Hantsport, Nova Scotia, ship-loading facility is at the upper reach of the Bay of Fundy and has a tidal range of 15 m. Ships with a capacity of up to 36 kt are loaded within a 3-hr period during high tide.

Mexico supplies the western U.S. coast. Large deposits midway down the Baja Peninsula on the western coast of the Sea of Cortez provide gypsum for wallboard plants from Long Beach, California, to Vancouver, British Columbia. A new gypsum quarry and shipping facility near Manzanillo in Colima on the southwestern coast of Mexico began operations in 2001.

Transportation by ship is the least expensive mode of transport for industrial minerals, about $0.001/st-mile. Transport by ship is highly restricted, however, to coastal areas and other large bodies of water such as the Great Lakes, and requires a significant infrastructure for loading, unloading, and storage.

**Import Tariffs and Custom Duties**

The U.S. International Trade Commission’s Harmonized Tariff Schedule of the United States contains information on import tariffs and duties for raw and processed gypsum. There are currently no general or special import duties on raw gypsum, anhydrite, or calcined plater products.

**By-Products and Coproducts**

Wallboard and plaster products account for 90% of the total consumption of gypsum in the United States. Agricultural gypsum

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**Table 6. Prices for gypsum by end use**

<table>
<thead>
<tr>
<th>End Use</th>
<th>Cost per Ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland cement retarder</td>
<td>$12.37</td>
</tr>
<tr>
<td>Agricultural gypsum</td>
<td>$23.65</td>
</tr>
<tr>
<td>Wallboard</td>
<td>$87.02</td>
</tr>
<tr>
<td>Plasters</td>
<td>$150.98</td>
</tr>
</tbody>
</table>

Source: Olson 2002.
and portland cement rock account for most of the remainder of gypsum consumption. Although some operations specifically produce agricultural or portland cement rock, in most cases these are coproducts associated with the mining and crushing of gypsum for wallboard.

Depletion Allowance

The depletion allowance is an annual, taxable-income deduction to allow mining companies to locate and develop additional ore bodies (Peters 1976). The depletion allowance on domestic gypsum production and foreign gypsum imports is 14%. Two methods of computing the depletion allowance are allowable in the United States. In the cost or unit depletion method, the total cost of acquiring a mineral property is prorated into the total tons or units extracted from the property during mining. In the percentage depletion method, the most common method used, a specific percentage of the mine’s gross income is deducted annually. The deduction, however, may not exceed 50% of the before-depletion net income.

REGULATORY AND ENVIRONMENTAL CONSIDERATIONS

Health and Safety

Gypsum mines and quarries are regulated by numerous local, state, and federal agencies regarding health and safety. In the United States, the predominant agency is the Mine Safety and Health Administration (MSHA). Calcining and manufacturing operations are regulated by the Occupational Safety and Health Administration (OSHA) and, in some cases, state agencies such as CalOSHA in California. Explosives are regulated by the federal Bureau of Alcohol, Tobacco, and Firearms (BATF).

Land Use and Zoning

Underground gypsum mining does not generally affect the concurrent use of the overlying surface. In most cases, the overlying land use is agricultural or forest. Gypsum companies that operate underground mines generally own the mineral rights for gypsum and anhydrite, but not the surface rights on a majority of the mined land and reserves.

The gypsum companies usually own the quarried land. As quarrying progresses, the depleted areas can be concurrently reclaimed and converted to pasture. USG’s Alabaster, Michigan, operation has created a significant amount of wetlands in depleted quarry areas.

Mined Land Reclamation

Gypsum mines and quarries tend to be very long-term operations, and some operations in the United States have been continuous for 100 to 150 years. Gypsum quarrying in Nova Scotia began in the 1700s and continues to the present. A large area of the mined lands was disturbed before the promulgation of local, state, or federal reclamation regulations. Modern mining, however, requires a comprehensive reclamation plan and activities to minimize the impact to vegetation, hydrology, slope stability, flora, and fauna, and so forth.

Financial surety is required for the future costs of reclamation. The cost for reclamation is estimated for the fulfillment of the obligations of the approved reclamation plan by a third party. The financial surety covers the government’s cost of hiring a third-party contractor if the mining company goes out of business or is otherwise unable to perform the reclamation activities in the approved plan.

Concurrent reclamation may be possible in some areas. After quarrying, the overburden stripping spoil from another area can be placed in the previous cut, covered with topsoil, regraded, and revegetated. Reclaimed acreage can be released from financial surety upon satisfactory completion of criteria set forth by the regulatory agency.

Pollution Control

Gypsum mining and processing are less environmentally sensitive than many other types of mining industries such as coal, gold, and copper. There is no acid-mine drainage as in a coal mine; chemicals such as sodium cyanide used in heap leaching of gold ore are not used in gypsum processing.

Storm-water management plans are required for the control, storage, and treatment of surface runoff containing fuel, lubricants, antifreeze, etc. Environmental controls are necessary for storing fuel and lubricants, including aboveground storage tanks with secondary containment structures such as berms or metal pans.

Fugitive-dust suppression and control is required for drilling equipment, haulage roads, crushing and screening plants, and load-out facilities in the mining and milling phase. Dust is collected throughout many of the calcining and manufacturing phases of wallboard and plaster production.

Local and state agencies such as a county air-pollution control district or a state department of environmental protection usually enforce air and water quality regulations.

Closure and Decommissioning

Several gypsum wallboard plants and mining operations have been permanently closed and reclaimed in recent years. Dismantling calcining and manufacturing plants is similar to most industrial facilities. The total deactivation of underground mines requires removing mobile equipment (if possible), draining fluids such as fuel and lubricants from mobile and stationary equipment, and removing transformers. These activities reduce the potential contamination of groundwater as pumping ceases and the mine fills with water. All mine entrances are permanently sealed. Subsidence monitoring may be necessary if there are long-term stability issues associated with the mine structure or flooding of the mine.

Surface mining deactivation includes similar activities for removing mobile and stationary equipment, fuel and lubricant storage facilities, and explosives. Access to quarry workings is limited by berms, boulders, fences, and other measures. The angle and height of quarry highwalls are reduced by blasting to form rubble slopes and to reduce the overall final slope.

OUTLOOK AND FUTURE TRENDS

There is no foreseeable shortage of either gypsum or anhydrite resources in the United States or the world. Paradoxically, there are instances where it may be difficult to find gypsum that can be considered economic at a given time and location, a problem that has its roots in place value. The best evidence of this situation is that the United States historically has imported 33% to 36% of its needs from Canada, Mexico, Jamaica, the Dominican Republic, and Spain.

Almost all the imported gypsum (with the exception of a few thousand kilotons of special-grade rock) is used by wallboard plants on the Atlantic, Pacific, and Gulf coasts of the United States. The basic reasons for this situation are as follows: (1) large markets for gypsum products are concentrated in and around the coastal cities, (2) there are no developed and producing gypsum deposits along any of the three U.S. coastlines, and (3) large gypsum deposits exist on or near deep water of the exporting countries. It costs less to ship rock from the exporting countries to these major markets than to ship it from inland deposits in the United States.
It is likely that these conditions will persist into the future. The industry has been built around these facts and has made large investments in offshore deposits, shipping facilities, and domestic port locations with appropriate marine rock-handling equipment. There is no import duty on crude gypsum rock, but duties are placed on processed gypsum, although continuing free-trade agreements and laws may change the duties. Because of its widespread occurrence and huge potential reserves, and also because its uses are such that it is not basic to survival in a national emergency, gypsum is not considered a strategic mineral. This has permitted natural economic factors to prevail in the development of the mineral worldwide, which overall is a healthy situation that should continue to prevail.

Competition between manufacturers of gypsum building products, and from manufacturers of substitute materials, has resulted in a continuing pressure to improve the quality of gypsum products. In turn, mine operators continually strive to reduce the quantity of impurities (increase the gypsum purity) and to maintain a consistent feedstock purity. Wallboard can be manufactured from gypsum with an average purity of about 70% to 100%. Manufacturing processes, however, are designed for consistent gypsum purity, whether low or high; frequent variations in the purity are intolerable. To date, these objectives are accomplished by (1) selective mining techniques, (2) crushing and screening to the proper size-fractions to remove impurities and maximize the average feedstock purity, (3) blending during the mining cycle on quarry benches or mine faces, and (4) blending from crusher-feed stockpiles. In some cases, heavy-media beneficiation is used to remove anhydrite or dolomite impurities.

Processing of gypsum is energy intensive; energy requirements represent the largest single cost in the production of gypsum wallboard. Conserving energy meshes well with using synthetic gypsum from power-plant desulfurization processes, because waste heat from the power plant can be used in gypsum processing.

Gypsum mining does not result in some of the environmental issues that are commonly associated with mining, such as acid-mine drainage, contamination of surface water or groundwater heavy metals, or the use of cyanide in heap leaching. Gypsum mines and quarries are regulated by numerous local, state, and federal agencies for compliance with environmental and safety regulations. Most states require the approval of an operating plan and/or reclamation plan by local, state, and federal agencies for mines and quarries. The approval of the reclamation plan requires the posting of financial surety to ensure that the plan will be implemented by the applicant or by a third party if the applicant abandons the mining site. Storm-water runoff management plans are generally required to control the introduction of potential pollutants, such as oil, grease, fuel, and antifreeze, into the surface water or groundwater aquifers. The transportation, storage, and use of explosives is permitted and controlled by the federal BATF. Undisturbed areas may require baseline studies to determine the presence of threatened or endangered species of flora and fauna, and a plan to mitigate the disturbance of their habitat, if present, during reclamation. Alternatively, acquisition of additional property with suitable habitat conditions might be required. Revegetation of reclaimed areas may be required with periodic monitoring to determine the degree of success in the reestablishment of vegetation. State or federal agencies, such as the U.S. Fish and Wildlife Service, are involved in the evaluation of the biological impacts of mining. The U.S. Army Corps of Engineers and various state departments of natural resources are involved if mining activities potentially affect stream courses or wetlands. Cultural resources are evaluated by archaeologists and reported to state agencies for historical preservation.

**Synthetic Gypsum**

The usage of synthetic gypsum in the United States increased by 156% between 1998 and 2002: about 3 Mt was used in 1998, and the estimated usage in 2002 was 7.7 Mt. In 2003, synthetic gypsum accounted for 26% of the total domestic supply (USGS 2004). Synthetic gypsum is derived primarily from the FGD of high-sulfur-content coal at power plants. Minor amounts are made as a by-product of chemical processes, such as the production of citric acid, sugar from sugar beets, and titanium dioxide. Phosphogypsum, derived from manufacturing fertilizer, is not used in wallboard manufacturing because radionuclides and radon are present. The majority of the new gypsum wallboard capacity constructed in the United States since the late 1990s is dependent on FGD synthetic-gypsum sources, and new plants are close to the power plants or on navigable waterways.

**Recycling**

Waste wallboard is generated from (1) manufacturing, (2) new construction, (3) renovation, and (4) demolition. Manufacturing waste can be recycled into the raw-material stream. The wet wallboard waste can be disaggregated into the board core and paper fiber, both of which are used in manufacturing wallboard. New construction and renovation generate 10% to 12% of wallboard scrap. The disposal costs for new construction and renovation wallboard scrap in solid-waste disposal landfills are increasing. Scrap wallboard waste generated during new construction can also be pulverized for application as a soil amendment. Demolition waste, however, is often mixed with other materials such as lumber, nails, and fiberglass insulation, and therefore cannot be recycled effectively.

**New Products**

The most popular size and type of wallboard will continue to be the paper-clad sheet with dimensions 1.2 m × 2.4 m × 12.7 mm. New types of gypsum wallboard are expected to grow in popularity. For example, fiber gypsum board, a nonpaper face and back board, incorporates a homogeneous blend of gypsum and paper fiber for abuse-resistant wall and floor underlayment applications. Another example is a gypsum wallboard using fiberglass scrim to replace the facing and backing paper, which is gaining acceptance in water-resistant sheathing applications.

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