Chapter II.2

GYPSUM KARST IN THE UNITED STATES

Kenneth S. Johnson

Abstract

Gypsum is one of the most soluble of common rocks; it is dissolved readily to form caves, sinkholes, disappearing streams, and other karst features that typically are found in limestones and dolomites. The four basic requirements for gypsum karst to develop are: (1) a deposit of gypsum; (2) water, unsaturated with $CaSO_4$; (3) an outlet for escape of dissolving water; and (4) energy to cause water to flow through the system. Gypsum deposits are present in 32 of the 48 conterminous United States, and they underlie about 35–40% of the land area; they are reported in rocks of every geologic system from the Precambrian through the Quaternary. Gypsum karst is known at least locally (and sometimes quite extensively) in almost all areas underlain by gypsum, and commonly extends down to depths of at least 30 m below the land surface. The most widespread and pronounced examples of gypsum karst are in the Permian basin of southwestern United States, but many other areas also are significant. Human activities may also cause, or accelerate, development of gypsum karst.

Introduction

Evaporite deposits are those sediments that form due to precipitation of various salts out of evaporating water, mainly sea water. Principal evaporite rocks are gypsum (or anhydrite) and salt (halite), although potash salts and other rarer salts also are locally important. (Note: The term gypsum is used in this report, although anhydrite is the common form of calcium sulfate in the deeper subsurface.) Gypsum deposits locally have accumulated to considerable thicknesses, even tens to hundreds of meters thick, where there was continued replenishment of the water from which calcium sulfate was originally precipitated. Thick gypsum deposits are widely distributed in the United States (Fig. 1) and they contain evidence of karst in most areas. Gypsum is one of the most soluble of the common rocks throughout the world, and it is dissolved readily to form the same types of karst features that typically are found in limestones and dolomites. The principal difference is that gypsum-karst features can form rapidly, in a matter of weeks or years, whereas carbonate-karst features typically take years, decades, or centuries to form.

The current chapter provides an overview and summary of the general characteristics and distribution of gypsum karst in the United States. It is based largely upon earlier studies by Quinlan et al. (1986), Dean and Johnson (1989), and Johnson (1997). Other recent comprehensive studies of gypsum in the United States were published by Withington & Jaster (1960), Withington (1962), and Smith et al. (1973). In addition, there are numerous local or regional studies dealing with karst development in the various gypsum deposits: contact with the appropriate

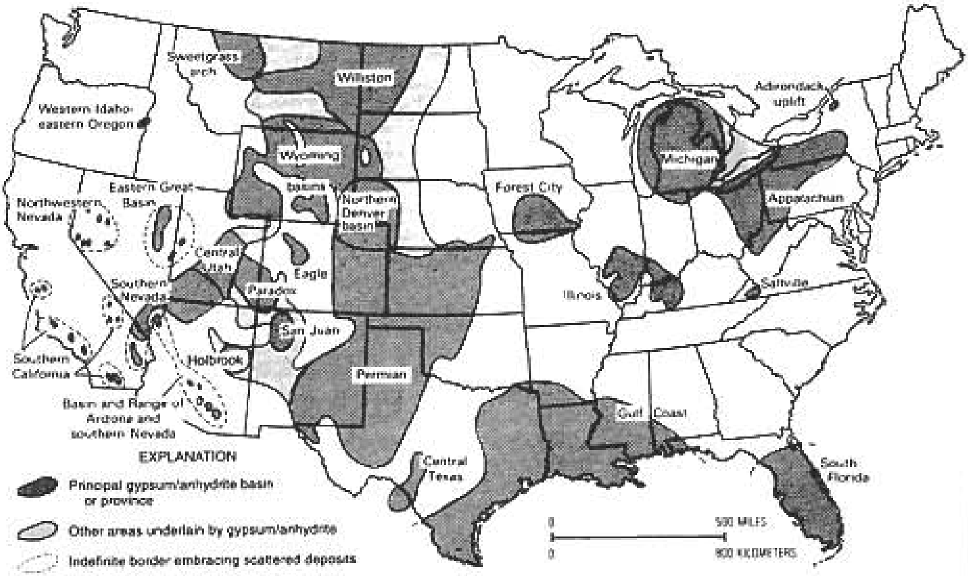

Fig. 1. Gypsum/anhydrite deposits in the conterminous United States (After Dean & Johnson, 1989).

State Geological Survey, and the local cave-exploration groups, is usually the best way to begin a search for such published or unpublished data.

Hundreds of areas or districts in the United States contain karst features that have developed in gypsum rocks, but it is beyond the scope of this summary report to document them all. Therefore, I will discuss the following: (1) the general characteristics of gypsum-karst processes; (2) the general distribution of gypsum karst, and cite several examples that have been well documented; and (3) human-induced gypsum karst that can cause local problems.

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1. Gypsum karst processes

The processes for development of karst features in gypsum are identical to those that form karst features in limestone and dolomite, except that the processes are much more rapid. Water percolates over or through gypsum and dissolves the highly soluble rock; typically, this causes formation of a series of sinkholes, caves, natural bridges, disappearing streams, and springs. Once a through-flow passage is created in the gypsum, enlargement results from further dissolution and from abrasion, as water-borne particles are transported through the cavity.

The process for dissolution of evaporites was described earlier by Johnson (1981), with particular reference to salt; but it clearly applies to dissolution of gypsum as well. He pointed out that ground water in contact with an evaporite deposit (a gypsum deposit, in the current report) will dissolve some of the rock, providing the water is not already saturated with $CaSO_4$. For extensive dissolution to occur, it is necessary for the aqueous solution thus formed to be removed from the gypsum deposit; otherwise, the water becomes saturated, and the process of dissolution stops. The four basic requirements for dissolution of gypsum are:

(1) a deposit of gypsum against which, or through which, water can flow;

(2) a supply of water unsaturated with $CaSO_4$;

(3) an outlet whereby the resulting gypsiferous water can escape; and

(4) energy (such as a hydrostatic head or density gradient) to cause the flow of water through the system.

When all four of these requirements are met, dissolution of gypsum can be quite rapid, in terms of geologic time.

Gypsum karst is rarely seen at the land surface in eastern United States, but it is fairly common in the semi-arid to arid regions of the west. Owing to rapid dissolution of gypsum, most would-be outcrops in the east are quickly destroyed, and the rock and its dissolution features are observable only in excavations, mines, tunnels, and boreholes. Abrupt thinning or termination of a gypsum deposit, particularly where overlying strata are brecciated, commonly marks a dissolution front (either ancient or modern) where karst processes are, or have been, occurring.

Gypsum karst develops rapidly because gypsum is highly soluble in water. The solubility of $CaSO_4 \cdot 2H_2O$ ranges from about 2,200–2,600 ppm in the temperature range of 0–40°C (Hardie, 1967; Blount and Dickson, 1973). Gypsum-karst development can even be accelerated when accompanied by dedolomitization (Raines & Dewers, 1997). Karst features may be present in gypsum deposits in all parts of the United States, whether the gypsum crops out or is in the deep subsurface; the karst may result from climatic and hydrologic conditions of today, or it may be a relict from an earlier, wetter climate and/or hydrogeologic regime of the Pleistocene or pre-Pleistocene epochs.

In the eastern United States, where average annual precipitation commonly is greater than 75 cm, gypsum deposits generally are eroded or dissolved to depths of at least several meters or tens of meters below the land surface. In the west, however, in areas where the average annual precipitation commonly is less than about 75 cm, gypsum tends to resist erosion and typically caps ridges, mesas, and buttes; in spite of its resistance to erosion in the west, gypsum commonly contains karst features, such as cavities, caves, and sinkholes, attesting the importance of ground-water movement, even in low-rainfall areas.

Evidence of gypsum karst includes surface and shallow-subsurface features, such as caves, sinkholes (dolines), karren, disappearing streams (swallow holes), springs, collapse structures, and the dropping of drill bits and/or loss of drilling fluids while drilling through gypsum beds. All these karst features (Plates 2 & 3), and many more, are identical in character and genesis to those found in carbonate rocks. In fact, paleokarst, becciated zones, and other karst features found in some carbonates may have been initiated by earlier dissolution and karst development in gypsum that is interbedded with the carbonates; Sando (1988), Friedman (1997), and Palmer & Palmer (1997) provide examples and a summary of this carbonate/sulfate relationship. Gypsum-karst features commonly have a linear orientation, and these appear to be controlled by joints or fractures

Plate 1. Cave in Permian Cloud Chief Gypsum in western Oklahoma. Cave opening is about 3 m wide.

in the rock; however, some karst features have a seemingly random orientation, wherein the controls are not understood.

2. Distribution of gypsum karst

Gypsum deposits are present in 32 of the 48 conterminous United States, and they underlie about 35–40 percent of the land area (Fig. 1). Gypsum occurs in 24 separate structural basins or geographic districts in the United States, and is reported in rocks of every geologic system from the Precambrian through the Quaternary. Generally, karst features are present (at least locally) in areas where gypsum crops out, or is less than 30 m below the land surface. The most widespread and pronounced examples of gypsum karst are in the Permian basin of southwestern United States. Other significant examples are in the Illinois basin, Michigan basin, Forest City basin, the Black Hills area of South Dakota, and parts of Texas, Wyoming, and other western states.

The Permian basin contains a thick sequence of Permian gypsum, salt, and red beds that extend from west Texas and southeast New Mexico into western Oklahoma, western Kansas, and southeast Colorado (Fig. 1). Individual gypsum beds typically are 3–10 m thick in most Permian basin formations, but are 20–200 m thick in the Castile Formation of the Delaware basin part of the Permian basin (Dean and Johnson, 1989). Low rainfall in the region permits extensive outcrops of gypsum; particularly in the Delaware basin, to the south, and along the Permian basin's west flank (eastern New Mexico) and east flank (north-central Texas and western Oklahoma). In these

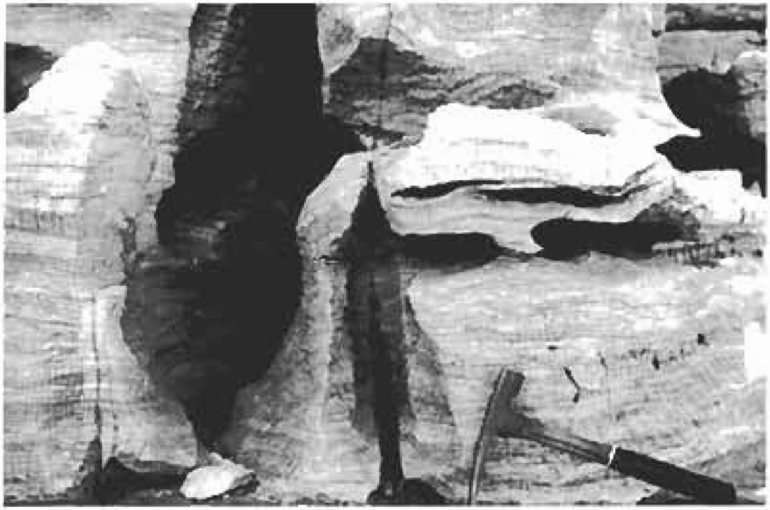

Plate 2. Karst development in Permian Cloud Chief Gypsum in western Oklahoma. Dissolution is most pronounced along joints and bedding planes.

areas, typical gypsum-karst features abound, and are described by Olive (1957), McGregor et al. (1963), Fischer & Hackman (1964), Myers et al. (1969), Kelley (1971), Quinlan (1978), Bozeman et al. (1987), Sares & Wells (1987), Johnson (1990, 1992, 1997), Belski (1992), Hill (1996), and Forbes & Nance (1997). Quinlan et al. (1986) report that there are more than 500 gypsum caves in the United States, and that most of them are in the Permian basin; most of the literature on these caves has been published by local cave-exploration groups.

The Delaware basin of west Texas and southeast New Mexico, in the southwest part of the Permian basin, contains one of the greatest accumulations of evaporites in the United States (Dean & Johnson, 1989). Evaporites (gypsum/anhydrite and salt) of the Late Permian Castile, Salado, and Rustler Formations typically are 500 m to more than 1,500 m thick within the Delaware basin, and are more than 450 m thick where these deposits extend north and east of the basin. Outcrops of these three formations constitute the most extensive examples of gypsum karst in the nation. The area referred to as the Gypsum Plain comprises about 2,600 km^2 of outcropping gypsum of the Castile and Salado Formations (Kirkland & Evans 1980), and additional gypsum outcrops are present just to the east in the Rustler Hills and into Reeves County, Texas.

The Delaware basin gypsum deposits contain abundant sinkholes, caves, closed depressions, collapse sinks, and underground drainage; an excellent summary is provided by Hill (1996). Much of the area has been affected by subsurface dissolution of some of the salt layers, and most of the outcrops consist of massive beds of gypsum. Four principal areas of gypsum karst are Gypsum Plain, Nash Draw, Burton Flat, and the Pecos River Valley (Hill, 1996). Sinkholes, a few meters to 100 m across, are active collapse features in all four areas, and generally they are related to shallow, underground caverns less than 100 m deep. One sinkhole, formed during a storm in 1918, collapsed suddenly to form a gaping hole about 25 m across and 20 m deep (Hill, 1996). Caves are prominent and abundant on Gypsum Plain and Burton Flat (Sares & Wells, 1987; Belski, 1992). The longest gypsum cave in the Delaware basin occurs on Gypsum Plain; Parks Ranch Cave is more than 5,200 m long and it has two sinkhole entrances (Hill, 1996). Other caves in the area are White Horned Owl Cave (about 760 m long) and Skylight and Resurgence Caves (each about 600 m long). Burton Flat consists of more than 275 km^2 of rolling karst plain on which more than 60 caves have been found (Belski, 1992; Hill, 1996); almost all the cave entrances are in gypsum units, although interbedded dolomite beds locally are exposed in the walls of some of the caves.

Along the west flank of the Permian basin, in eastern New Mexico, gypsum crops out extensively along parts of the Pecos River Valley. Various gypsum and carbonate units are present in the Permian Artesia Group, San Andres Formation, and Yeso Formation, and they contain a large number of caves, sinkholes, and other karst features in the Vaughn–Roswell area (Fischer & Hackman, 1964; Kelley, 1971; Forbes and Nance, 1997). Several of the caves in this area are more than 3,200 m long, and the deepest has a vertical extent of more than 120 m (Forbes & Nance, 1997). Individual sinkholes commonly are 7–300 m in diameter, and the larger, coalesced sinkholes are as much as 3–5 km across and up to 60 m deep (Quinlan et al., 1986). Gypsum is preferentially dissolved here by interstratal karstification, and the less-soluble interbeds of carbonates and siliciclastics are thus undermined and now dip down (or drape) toward the center of some of the dolines and subsidence synclines (Fischer & Hackman, 1964). Quinlan et al. (1986) report that Bottomless Lakes State Park, near Roswell, contains the most spectacular group of collapse sinkholes in a gypsum-karst terrane; here, a series of deep, water-filled sinkholes developed in the San Andres Formation as a result of dissolution of gypsum and salt by artesian waters.

Another major gypsum-karst area of the Permian basin is along its east flank, in north-central Texas and western Oklahoma. Principal gypsum units are the Permian Blaine and Cloud Chief Formations, with gypsum beds 3–30 m thick. Among the more important gypsum-karst features of the region are two well-known caves and a major fresh-water aquifer. The J. C. Jester Cave of southwestern Oklahoma (Fig. 4) was surveyed between 1983 and 1987 (Bozeman et al. , 1987; Johnson, 1992); the main passage is 2,413 m long, but, along with the side passages, the total length is 10,065 m, making it the longest reported gypsum cave in the western world. The cave has passageways that typically are 1–5 m in diameter, and locally are up to 20 m wide; it occurs mainly in a 5-m-thick gypsum bed of the Blaine Formation. Alabaster Cavern of northwestern Oklahoma (Fig. 4), now developed as a tourist cave, has a main passage about 700 m long; it has a maximum width of 18 m and a maximum height of 15 m (Myers et al., 1969; Johnson, 1992). The cave is developed mainly in the 10-m-thick, basal gypsum bed of the Blaine Formation. Other gypsum caves are described by McGregor and others (1963), and in various issues of Oklahoma Underground, the journal of the Central Oklahoma Grotto.

A major fresh-water aquifer is developed in the Blaine Formation of southwestern Oklahoma and north-central Texas (Johnson, 1990, 1992). Water is produced from the karstic and cavernous gypsum and dolomite beds of the Blaine aquifer. The aquifer is 50–65 m thick and consists of 9 thick gypsum beds (each 3–8 m thick) interbedded with thinner dolomite beds (0.1–1.5 m thick) and shale beds (0.3–8.0 m thick). Irrigation wells typically are 15–100 m deep and commonly yield 1,000–8,000 L/min. The water is a calcium-sulfate type; total dissolved solids average about 3,100 mg/L (of which about 90% is $CaSO_4$), and the water is suitable for irrigation but generally is unsuitable for drinking.

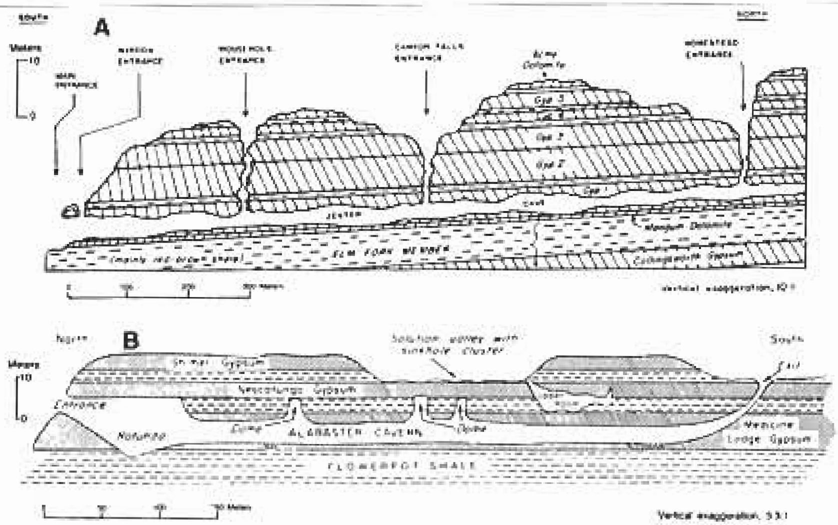

Fig. 2. Schematic cross sections through major gypsum caves in the Permian Blaine Formation of western Oklahoma: (above, A) J. C. Jester Cave; (below, B) Alabaster Cavern. After Myers et al. (1969), Bozeman et al. (1987), and Johnson (1992).

Gypsum karst is indicated, indirectly, along the east and west sides of the Illinois basin in Illinois, Indiana, and Kentucky. The St. Louis Limestone (Late Mississippian) contains several gypsum beds, 1–15 m thick, in the subsurface (McGregor, 1954; Saxby & Lamar, 1957; McGrain & Helton, 1964). Gypsum does not crop out in Indiana and Kentucky, however, because interstratal karstification is dissolving the evaporites and producing ground water with a high concentration of dissolved sulfates along the eastern boundary of the subsurface gypsum deposits (George, 1977). Chemical analyses of springs and well water shows a sulfate concentration of up to 1,350 mg/L, and a low chloride concentration, usually less than 30 mg/L. Westward (downdip) advance of the gypsum-dissolution front in this region generates the sulfate-rich water and collapse of overlying carbonate rocks into cavities. George (1977) cites an example of the collapsed carbonates in Squire Boone Caverns, Harrison County, Indiana. Jorgensen and Carr (1973) show an abrupt lateral thinning of gypsum (from about 4 m thick to <0.5 m thick, within a distance of 150 m) in the St. Louis Limestone near Shoals, Indiana; these authors, along with French and Rooney (1969), ascribe this thinning to dissolution along the eastern, up-dip limit of the gypsum. Saxby and Lamar (1957) also recorded the presence of breccia and the absence of gypsum in outcrops of St. Louis Limestone on the west (Illinois) side of the Illinois basin, and they felt this may have resulted from dissolution of the gypsum.

The Michigan basin contains gypsum karst in the Mississippian Michigan Formation in the central part of the State (Elowski & Ostrander, 1977). The Michigan Formation contains a series of gypsum beds, 1–10 m thick, interbedded with sandstone and shale; these strata crop out locally or are mantled by glacial drift on the east and west side of the basin. Gypsum caves, sinkholes, and collapse features are described in the Grand Rapids area of Kent County (in the west), and also in parts of Iosco and Arenac Counties (in the east) (Elowski & Ostrander, 1977). These authors describe a 100m-long gypsum cavern (Pellerito Cave) that was encountered in an underground gypsum mine near Grand Rapids; the cave is 3–15 m wide and as much as 3 m high.

The Forest City basin area of Iowa contains evidence of gypsum karst in Devonian and Jurassic strata. The Devonian Wapsipinicon and Cedar Valley Groups contain numerous gypsum beds in central and southern Iowa (Witzke & others, 1988). Devonian gypsum does not crop out in Iowa, and it is thought that the present limits of some of the evaporite units are dissolutional; some of the breccia beds (i.e., the Devonian Davenport breccias) are interpreted as having formed by gypsum dissolution and collapse shortly after evaporite deposition (Witzke et al., 1988). The Fort Dodge Formation is an outlier of Jurassic gypsum present in about 40 km^2 of Webster County, central Iowa. The gypsum is as much as 10 m thick, but the upper surface is quite irregular due to partial dissolution before deposition of an overlying Pleistocene till (Cody et al., 1996). This till commonly is 10–30 m thick, but gypsum is exposed locally in stream cuts and quarry faces. The principal karst features are joint-controlled dissolution channels, about 1 m wide and 1–3 m deep, incised into the upper surface of the Fort Dodge gypsum.

Other examples of gypsum karst are noted in central Texas, South Dakota, and Wyoming. The Cretaceous Kirschberg Evaporite Member of the Terrett Formation contains 10 m of gypsum in a quarry near Fredericksburg, Texas (Warren et al., 1990). Vertical pipes, caves, and collapse breccia are well exposed, and gypsum and calcite speleothems (mainly in the form of popcorn and flowstone) were deposited in the pipes and caves. In the Black Hills area of South Dakota, gypsum in the Triassic Spearfish Formation locally contains sinkholes and caves that have caused environmental problems (Rahn & Davis, 1996; Davis & Rahn, 1997). Gypsum beds up to 5 m thick contain sinkholes and caves, and the karst has resulted in general ground subsidence, foundation cracking and seepage in houses, failure of a sewage lagoon, and problems with a proposed mine-tailings facility and a golf-course reservoir. In Wyoming, Sando (1988) describes widespread paleokarst in the Madison Limestone of Mississippian age. He notes that dissolution of gypsum beds within the predominantly limestone sequence during Late Mississippian–Early Pennsylvanian time enhanced contemporaneous development of sinkholes, caves, dissolution-enlarged joints, and breccia zones.

3. Human-induced gypsum karst

Gypsum karst can be accelerated by human activity. Gypsum-karst problems are caused by the same activities that cause problems in carbonate terranes: (1) building structures that induce differential compaction of soils above an irregular gypsum-bedrock surface; (2) building structures directly upon gypsum-collapse features; and (3) impounding water above, or directing water into, a gypsum unit where soil piping can divert water (and soil) into underground gypsum cavities. These human activities can cause land subsidence, or can cause new or concealed sinkholes and cave systems to open up; this can result in settling or catastrophic collapse of the ground.

Specific human activities that have accelerated gypsum karst in the Black Hills area of South

Dakota include (Rahn & Davis, 1996; Davis & Rahn, 1997): (1) sewage lagoons, built on alluvium above a karstic gypsum layer, began leaking badly within one year, and finally failed with partially treated sewage escaping the site; and (2) directing runoff into buried gypsum karst caused several houses to settle and crack, and produced sinkholes in urban/suburban areas. Cooper (1995) also pointed out that (because gypsum dissolution is so rapid) pumping large volumes of gypsiferous water from wells means that subsurface gypsum will be dissolved at an accelerated rate, and this can cause increased subsidence and possible collapse.

Conclusions

This report provides a brief overview of the processes and distribution of gypsum karst in the United States. Caves, sinkholes, disappearing streams, and other features typical of karst terranes are present in gypsum deposits throughout the nation. Gypsum deposits are present in 32 of the 48 conterminous states, and karst is known at least locally in almost all of these areas. Gypsum karst is, in most respects, identical to karst in carbonate rocks, except that the process is much more rapid. It is much more widespread than is commonly believed.

Gypsum karst is most conspicuous in gypsum outcrops, but it also is likely to be found in many areas where the gypsum is up to 30 m below the land surface. The most pronounced areas of gypsum karst are in the Permian basin of southwestern United States, although other important areas include the Michigan, Forest City, and Illinois basins, and parts of Texas, South Dakota, Wyoming, and other western states. Human-induced gypsum karst results chiefly from construction upon, or directing water into or above, outcropping or shallow gypsum deposits.

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