KARST IN EVAPORITE ROCKS OF THE UNITED STATES

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ABSTRACT: Evaporites are the most soluble of common rocks; they are dissolved readily to form the same range of karst features that typically are found in limestones and dolomites. Evaporites, including gypsum (or anhydrite) and salt, are present in 32 of the 48 contiguous United States, and they underlie about 35–40% of the land area. Evaporite outcrops typically contain sinkholes, caves, disappearing streams, and springs. Other evidence of active karst in evaporites includes surface-collapse features and saline springs or saline plumes that result from dissolution of salt. Many evaporites, including some in the deeper subsurface, also contain evidence of paleokarst that is no longer active; this evidence includes dissolution breccias, breccia pipes, slumped beds, and collapse structures. Evaporites occur in 24 separate structural basins or geographic districts in the United States, and either local or extensive evaporite karst is known in almost all of these basins or districts. Human activities also have caused development of evaporite karst, primarily in salt deposits. Boreholes or underground mines may enable (either intentionally or inadvertently) unsaturated water to flow through or against salt deposits, thus allowing development of small to large dissolution cavities. If the dissolution cavity is large enough and shallow enough, successive roof failures can cause land subsidence or catastrophic collapse. Evaporite karst, both natural and human-induced, is far more prevalent than commonly believed.

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. With continued replenishment of the seawater from which these salts were precipitated originally, it is possible for evaporite layers to accumulate to considerable thicknesses, even tens to hundreds of meters thick. These evaporites are widely distributed in the United States and they contain evidence of karst in most areas (Fig. 1). Evaporite rocks are the most soluble of the common rocks throughout the world. Gypsum and salt are dissolved readily to form the same types of karst features that typically are found in limestones and dolomites. The principal difference is that evaporite-karst features can form rapidly, in a matter of days, weeks, or years, whereas carbonate-karst features typically take years, decades, or centuries to form.

The current report is condensed from an article on "Evaporite Karst in the United States," published in *Carbonates and Evaporites* (Johnson 1997), which was based largely upon earlier studies by Johnson and Gonzales (1978), Dean and Johnson (1989), and Quinlan et al. (1986). Other recent comprehensive studies of gypsum and/or salt deposits in the United States were published by Withington and Jaster (1960), Pierce and Rich (1962), Withington (1962), Lefond (1969), Smith et al. (1973), Ege (1985), and Kostick (1994). Publication of this report is approved by the Director of the Oklahoma Geological Survey.

EVAPORITE-KARST PROCESSES

The processes for development of karst features in evaporite rocks 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 or salt 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-flowing passage is created in the evaporite rock, 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 will dissolve some of the rock, providing the water is not already saturated with $CaSO_4$ (or NaCl). For extensive dissolution to occur, it is necessary for the aqueous solution (or brine) thus formed to be removed from the evaporite deposit; otherwise, the water becomes saturated, and the process of dissolution stops. The four basic requirements for dissolution of gypsum (or salt) are: (1) a deposit of gypsum (or salt) against which, or through which, water can flow; (2) a supply of water unsaturated with $CaSO_4$ (or NaCl); (3) an outlet whereby the resulting solution (or brine) 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 (or salt) can be quite rapid, in terms of geologic time.

Evaporite karst is rarely seen at the land surface in eastern United States, where the precipitation is fairly high, but gypsum karst is fairly common in the semi-arid to arid regions of the west. Owing to rapid dissolution of gypsum and (especially) salt, most would-be outcrops in the humid 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 an evaporite unit, 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 Processes

Gypsum karst develops rapidly because gypsum is highly soluble in water. Karst features may be present in gypsum

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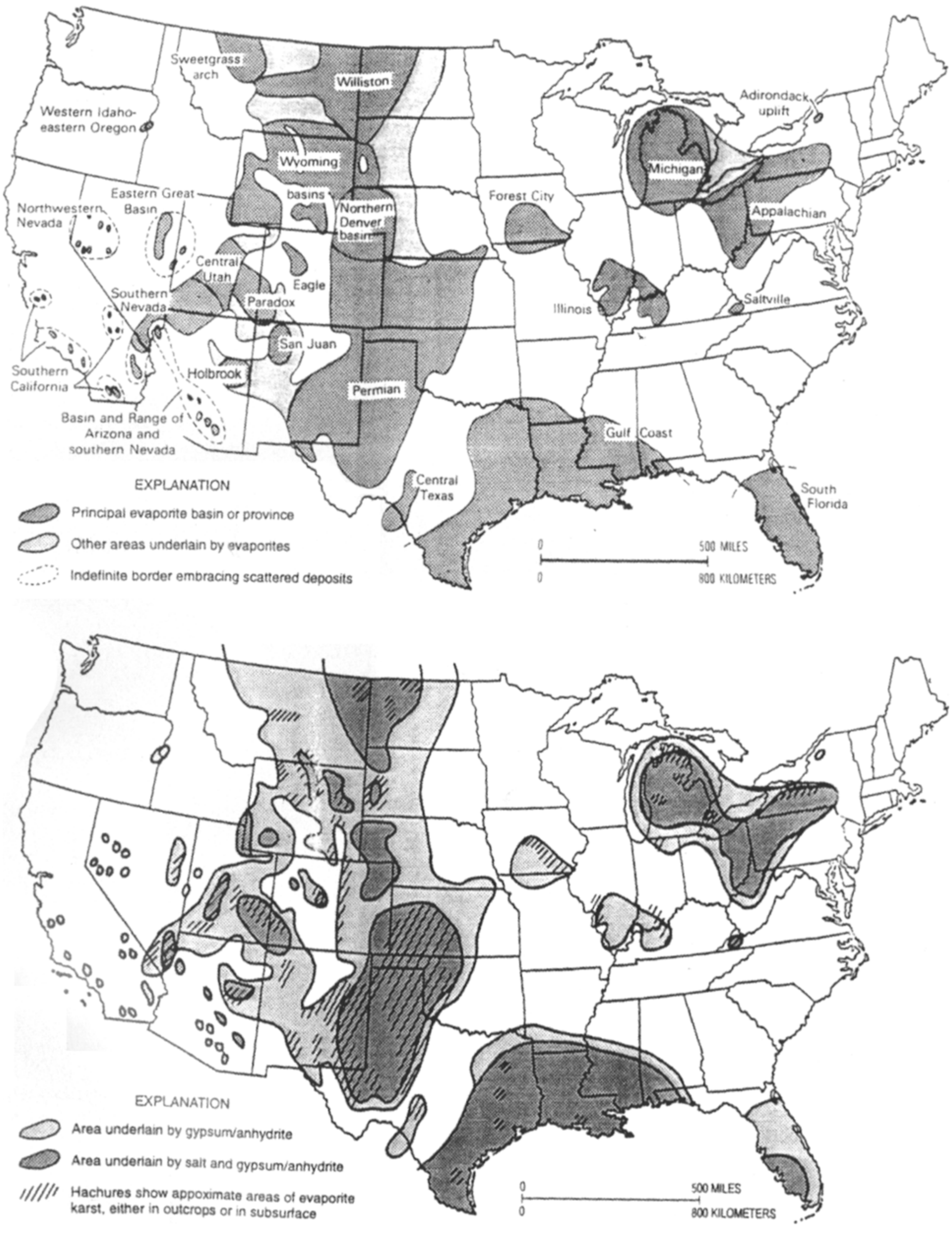

Figure 1. Maps of the conterminous United States: (above) evaporite basins and districts; (below) distribution of gypsum/ anhydrite, salt, and evaporite karst. Modified from Johnson and Gonzales (1978) and Dean and Johnson (1989).

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, 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, in fact, have been initiated by earlier dissolution and karst development in gypsum that is interbedded with the carbonates; Sando (1988), and Friedman (1997) provide examples and a summary of this carbonate/sulfate relationship.

Salt-Karst Processes

Salt is extremely soluble in ground water. Salt-karst features can be present in all parts of the United States that are underlain by salt. The mechanisms for salt dissolution and the development of interstratal karst are described by Johnson (1981) and are illustrated in Figure 2. Fresh ground water can be recharged through sandstone, gypsum, carbonates, alluvium, or other permeable and/or karstic units at or near the land surface (Fig. 2). This water migrates downward and/or laterally to the salt beds, and dissolves the salt to form a brine. The resulting brine is then forced through, and away from, the salt to make room for additional unsaturated ground water. Brine can migrate into an aquifer, or it can be forced back to the land surface in brine springs or salt flats. These mechanisms involve the four basic requirements for the dissolution of salt, as described above.

Salt is so soluble that it survives at the land surface only in arid areas. The two sites in the United States with salt recently at

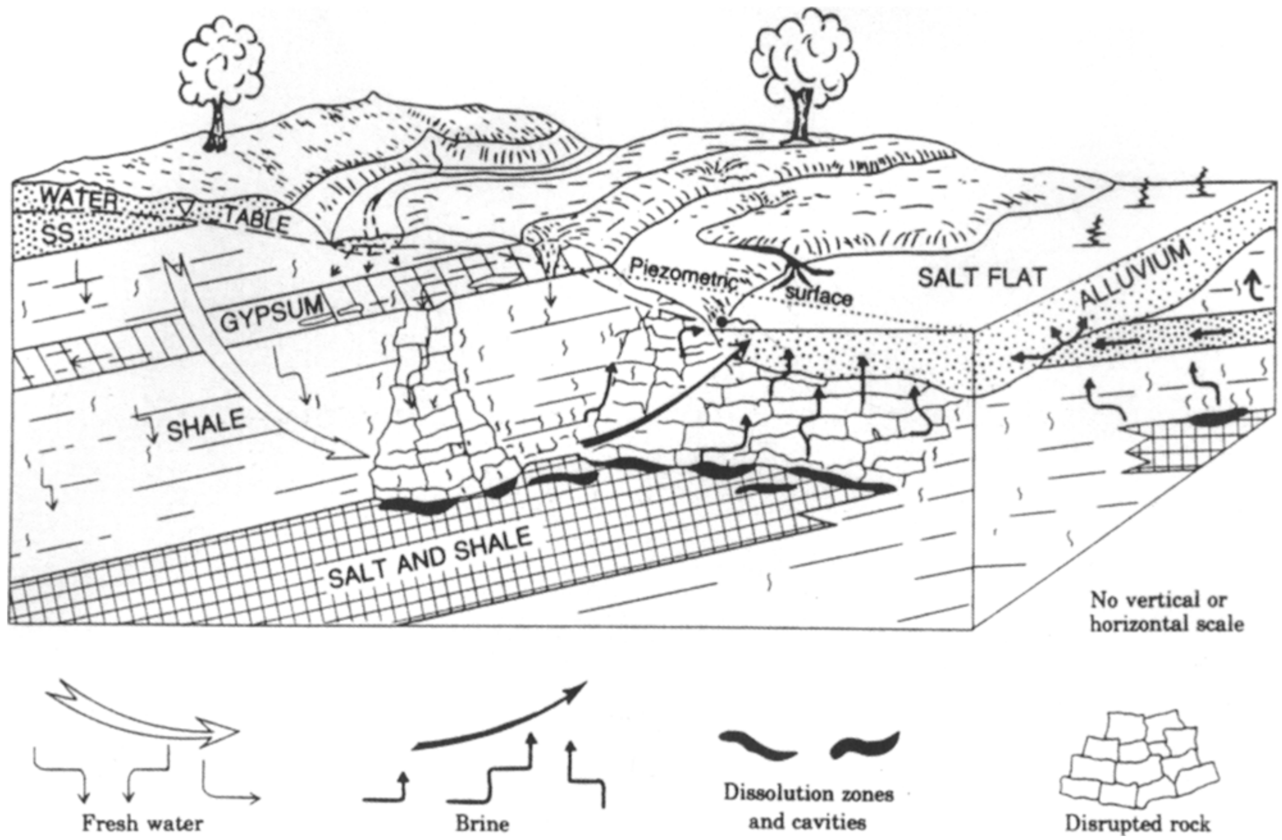

Figure 2. Schematic block diagram of interstratal salt karst in western Oklahoma (from Johnson 1981). The horizontal dimension is 1–15 km; the vertical dimension is 30–300 m.

the surface are Sevier Valley, Utah (where salt is being quarried), and Virgin Valley, in Nevada and Arizona (where the salt outcrops are now inundated by Lake Mead). Elsewhere, salt has been dissolved to depths ranging from tens to hundreds of meters below the present land surface. In many places, it is not easy (or possible) to distinguish between modern dissolution/karst and paleodissolution/paleokarst: some of the salt karst may be remnant from an earlier hydrogeologic regime (perhaps as early as shortly after original deposition of the salt unit).

Evidence of salt karst includes collapse structures, sinkholes, subsidence features, brine springs, salt flats, brecciated zones (in salt beds and overlying rocks), and the dropping of drill bits and loss of drilling fluids while drilling through salt beds. Many salt-karst features are similar to those in carbonate rocks, but there are only a few places in the world with extensive salt outcrops (e.g., Mount Sedom in the Dead Sea Depression of Israel, and Forrat Mico near Cardona in eastern Spain), where typical karst features, such as caves, sinkholes, shafts, and karren, can be documented (White 1988).

DISTRIBUTION OF EVAPORITE KARST

Gypsum and salt are present in 32 of the 48 contiguous states, and they underlie about 35–40 percent of the land area (Fig. 1). These evaporites occur in 24 separate structural basins or geographic districts in the United States, and are reported in rocks of every geologic system from the Precambrian through the Quaternary. Local or extensive evaporite karst is known in almost all of these basins or districts. Below is a discussion of the distribution and selected examples of gypsum karst and of salt karst.

Distribution of Gypsum Karst

Gypsum deposits are more widespread than salt and are a significant part of all evaporite deposits in the United States (Fig. 1). Gypsum crops out or is in the subsurface in 32 of the 48 contiguous states.

Generally, in areas where gypsum crops out, or is less than 30 m below the land surface, karst features are present (at least locally). 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 evaporites 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 areas, typical gypsum-karst features abound. 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. 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 also been affected by subsurface dissolution of some of the salt layers. Gypsum sinkholes, a few meters to 100 m across, are active collapse features in much of the area, and generally they are related to shallow, underground caverns less than 100 m deep.

Another major gypsum-karst area of the Permian basin is along its east flank, in north-central Texas and western Oklahoma. Principal gypsum beds are 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 has a main passage that is 2,413 m long (Bozeman et al. 1987; Johnson 1992), 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. Alabaster Cavern of northwestern Oklahoma, 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). A major fresh-water aquifer is developed in gypsum beds 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 $CaSO_4$); the water is suitable for irrigation, but generally is unsuitable for drinking.

Gypsum karst is indicated, indirectly, along the east and west sides of the Illinois basin in Illinois, Indiana, and Kentucky. Gypsum does not crop out in the area, 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 the collapse of overlying carbonate rocks into cavities. Saxby and Lamar (1957) also recorded the presence of breccia and the absence of gypsum in outcrops 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 and Ostrander 1977). 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 and Ostrander 1977). The Forest City basin area of Iowa contains evidence of gypsum karst in Devonian and Jurassic strata. Devonian strata contain numerous gypsum/anhydrite beds in the subsurface of central and southern Iowa (Witzke et al. 1988). Devonian gypsum does not crop out in Iowa; it is thought that the present limits of some of the evaporite units are dissolutional, and that some of the overlying breccia beds are interpreted as having formed by gypsum dissolution and collapse shortly after evaporite deposition (Witzke et al. 1988). Jurassic gypsum present in central Iowa has an upper surface that is quite irregular, due to partial dissolution before deposition of an overlying Pleistocene till (Cody et al. 1996). 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 gypsum. Other examples of gypsum karst are noted in central Texas, South Dakota, and Wyoming (Johnson 1996, 1997).

Distribution of Salt Karst

Salt deposits underlie a portion of 25 of the 48 contiguous states (Fig. 1). Some of the deposits are extensive, such as the Salina Group salts of the Michigan and Appalachian basins, the Permian salts of the Permian basin, and the Louann salt and salt domes of the Gulf Coast basin. These deposits rank among the greatest salt deposits of the world. Evidence of modern dissolution or paleodissolution of salt has been found in almost every one of the states and districts, and therefore salt karst is much more widespread than commonly suspected.

The Delaware basin area of west Texas and southeast New Mexico contains a great thickness of Permian salt and anhydrite interbeds, and much of the salt has been dissolved from the western half of the basin; hence the stratigraphic position of the salt is marked by brecciated zones of anhydrite that result from collapse and lowering of overlying units (Anderson et al. 1972, 1978). Salt dissolution, resulting in subsidence and increased basin-fill sedimentation, has been observed in various parts of the Delaware basin; most of the dissolution and subsidence occurred during the Cenozoic Era (Maley and Huffington 1953; Bachman 1976, 1984; Lambert 1983), but some of the dissolution occurred during or shortly after deposition of the Permian salts (Powers and Hassinger 1985; Johnson 1993). Salt dissolution is still going on in the Delaware basin area, as attested by the presence of saline seeps along Malaga Bend of the Pecos River in southeast New Mexico. Hill (1996) has provided a good summary of salt-dissolution processes in the Delaware basin, along with discussion of lateral and vertical dissolution features, subsidence troughs, breccia pipes, sinks, and other disturbed zones related to salt karst.

Permian salt beds are being dissolved at shallow to moderate depths in western Oklahoma and the Texas Panhandle. Conspicuous results of this process are collapse and subsidence features that reach to the land surface. Salt dissolution in the area is also accompanied by sediment-filled subsidence basins and fractured rock at the surface (Simpkins et al. 1981; Gustavson and Finley 1985; Johnson 1989). Salt dissolution has also caused formation of a series of breccia pipes in the Lake Meredith area of the Texas Panhandle (Eck and Redfield 1965). Another result of modern salt dissolution is the presence of large, salt-encrusted salt plains that form where high-salinity brines are emitted at the surface (Johnson 1981, 1992); emission of these NaCl-rich brines attests to ongoing salt dissolution and karst development.

The Holbrook basin of northeast Arizona is the site of more than 500 sinkholes, fissures, depressions, and other karst features that result from ongoing dissolution of salt in the Permian Schnebly Hill Formation (Neal et al. 1997). Salt dissolution on the southwest side of the basin, in the vicinity of the Holbrook anticline, has been recognized for many years (Johnson and Gonzales 1978; Neal 1995), and the relationship of the dissolution front to the surface karst features is now well documented. The salt-dissolution front is migrating downdip to the northeast, and collapse of overlying strata has enabled karst to develop in such areas as The Sinks, Dry Lake Valley, and McCauley Sinks (Neal et al. 1997).

Salt deposits of central and southeast Utah have undergone diapiric movement and dissolution. In the Paradox basin of southeast Utah and adjacent southwest Colorado, thick salts have flowed into a series of long and narrow salt anticlines. Past and/or present dissolution of salt in the Paradox basin apparently is limited to the western and southeastern edges of the salt basin, and to the crestal areas of the salt anticlines (Hite and Lohman 1973). Hite and Lohman (1973) point out that rivers draining the Paradox basin increase their load of dissolved sodium chloride by about 610 metric tons per day, while passing through the basin; they also estimate that the present-day 33-m-thick cap rock in the anticlines represents the residue, after dissolution, of about 900 m of halite-bearing rock from the central cores of the anticlines.

Salt dissolution has been documented at several places in the Wyoming basins and the Williston basin. Parker (1967) described dissolution of salt beds of Middle Devonian and Permian age in the deep subsurface of Wyoming, North Dakota, and Montana. Salt removal caused overlying rocks to subside and collapse into the depressions thus formed, with subsidence occurring at various times between the Late Devonian and Late Jurassic. The Michigan basin contains several examples of salt karst. Dissolution of Silurian and

Devonian salts on the northern edge of the Michigan basin occurred by Middle Devonian time; this created a broad area of brecciated and collapsed rocks, referred to as the Mackinac Breccia (Black 1984). In addition, Black (1984, 1997) has shown that a number of modern sinks in the area, and subsurface zones where drilling fluids are lost, are due to paleodissolution and to ongoing dissolution of subsurface salts by ground water circulating in open fault systems.

The Gulf Coast basin is one of the most significant salt-dome provinces in the world (LeFond 1969; Johnson and Gonzales 1978). The Jurassic Louann Salt has flowed (and continues to move) into diapiric structures; more than 260 domes are either known or inferred in the onshore portion of this region. The processes by which salt-dome cap rock forms is a special type of interstratal salt karst; as salt rises in diapirs, ground water dissolves the upper surface of the salt and there is an accumulation of residual, relatively insoluble anhydrite and calcite as the cap rock (Kreitler and Dutton 1983). About half of the known domes have a cap rock, and thus attest salt dissolution.

HUMAN-INDUCED EVAPORITE KARST

Human activities can play a special role in inducing or enhancing karst processes in evaporite rocks, and the results can be catastrophic. Owing to the rapid dissolution of gypsum, and the extremely rapid dissolution of salt, small to large dissolution cavities can be developed in subsurface evaporites by allowing unsaturated water to flow through or against the rock. Human activity that can cause such cavity development typically involves: (1) construction upon, or directing water into or above, outcropping or shallow gypsum deposits; or (2) the drilling of boreholes into or through subsurface salt deposits. Human-induced karst problems in gypsum areas are very much like those that are well known in carbonate-karst areas, but human-induced salt karst can have catastrophic effects locally (Walters 1978, 1991; Dunrud and Nevins 1982; Baumgardner et al. 1982; Ege 1984; Coates et al. 1985; Johnson 1987, 1997, 1998). Drilling of boreholes into or through the salt can enable (either intentionally or inadvertently) unsaturated water to enter the borehole and dissolve the salt. If the dissolution cavity is large enough and shallow enough, successive roof failures can cause the water-filled void to migrate upward; this can result in land subsidence or catastrophic collapse, and the creation of surface sinks up to 100 m wide and tens of meters deep. Two industries associated with local salt dissolution and collapse are the solution-mining and petroleum industries, and the references cited above provide some examples of this human-induced collapse.

Solution mining is the process of extracting soluble minerals, such as salt or potash, by (1) introducing a dissolving fluid (i.e., water) into the subsurface, (2) dissolving the mineral (or rock) and forming a brine, (3) recovering the brine, and (4) extracting the mineral from the brine (usually by evaporation) (Johnson 1997, 1998). Solution mining typically entails creating one or several large underground cavities that are filled with brine; the cavities may be in bedded salts, salt domes, or salt anticlines. Cavities typically are 10–100 m in diameter and are 10–600 m high, both dimensions based largely on the thickness of the salt and the depth to the top of the cavity. At some sites, unfortunately, the cavity becomes too large and the roof collapses. Dunrud and Nevins (1981) reported 10 areas of solution mining and collapse in the United States. Most solution-mining collapses result from cavities formed 50–100 years ago, before modern-day engineering safeguards were developed. Proper, modern design has virtually eliminated this problem in new facilities. Four well-documented subsidence/collapse features resulting from solution mining are Cargill sink (Kansas), Grand Saline sink (Texas), Grosse Ile (Michigan), and Tully Valley (New York) (Johnson 1997, 1998).

Petroleum-industry activities that can produce unintentional dissolution cavities include the drilling of exploration, production, or disposal boreholes into, or through, subsurface salt units (Johnson 1997, 1998). Unintentional dissolution of the salt can create a cavity that is as large and shallow as those created in solution-mining activities. And if the cavity becomes too large for the roof to be self-supporting, successive roof failures may cause a collapse feature to migrate upward and perhaps reach the land surface. The few collapses related to petroleum activity involve boreholes drilled long ago, before development of proper engineering safeguards pertaining to drilling-mud design, casing placement, and salt-tolerant cements. Three well-documented subsidence/collapse features resulting from petroleum activities are the Wink sink (Texas), Panning sink (Kansas), and the Gorham oil field (Kansas) (Johnson 1997, 1998).

CONCLUSIONS

This report provides a brief overview of the processes and distribution of evaporite karst in the United States. Caves, sinkholes, disappearing streams, and other features typical of karst terranes are present in evaporite deposits throughout the nation. Evaporites are present in 32 of the 48 contiguous states, and karst is known at least locally in almost all of these areas. Evaporite 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. Human-induced karst results chiefly from mining of, or drilling into, subsurface evaporite deposits. The most conspicuous problems have developed in salt deposits due to solution mining or petroleum activity. Deep-seated dissolution cavities can result in land subsidence or catastrophic collapse, with surface sinks being up to 100 m wide and tens of meters deep.

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