EVAPORITE KARST IN THE UNITED STATES

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ABSTRACT: Evaporites, including gypsum (or anhydrite) and salt, are the most soluble of common rocks; they are 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 evaporite karst to develop are: (1) a deposit of gypsum or salt; (2) water, unsaturated with $CaSO_4$ or NaCl; (3) an outlet for escape of dissolving water; and (4) energy to cause water to flow through the system. Evaporites are present in 32 of the 48 contiguous 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. Evaporite karst is known at least locally (and sometimes quite extensively) in almost all areas underlain by evaporites. The most widespread and pronounced examples of both gypsum and salt karst are in the Permian basin of the southwestern United States, but many other areas are also significant. Human activities have caused some evaporite-karst development, primarily in salt deposits. Boreholes 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 above the cavity can cause land subsidence or catastrophic collapse.

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 water from which these salts originally were precipitated, 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 provides an overview and summary of the general characteristics and distribution of gypsum and salt karst in the United States. It is based largely upon earlier studies by Johnson and Gonzales (1978) and Dean and Johnson (1989), and a review paper prepared by Quinlan et al. (1986). Other recent comprehensive studies of gypsum and/or salt in the United States were published by Withington and Jaster (1960), Pierce and Rich (1962), Withington (1962), Lefond (1969), Smith et al. (1973), and Ege (1985). In addition, there are numerous local or regional studies dealing with karst development in the various evaporite deposits: contact with the appropriate 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 evaporite 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 evaporite-karst processes; (2) the general distribution of evaporite karst, and cite several examples that have been well documented; and (3) human-induced evaporite karst that causes collapse structures associated with solution-mining or petroleum activities.

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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.

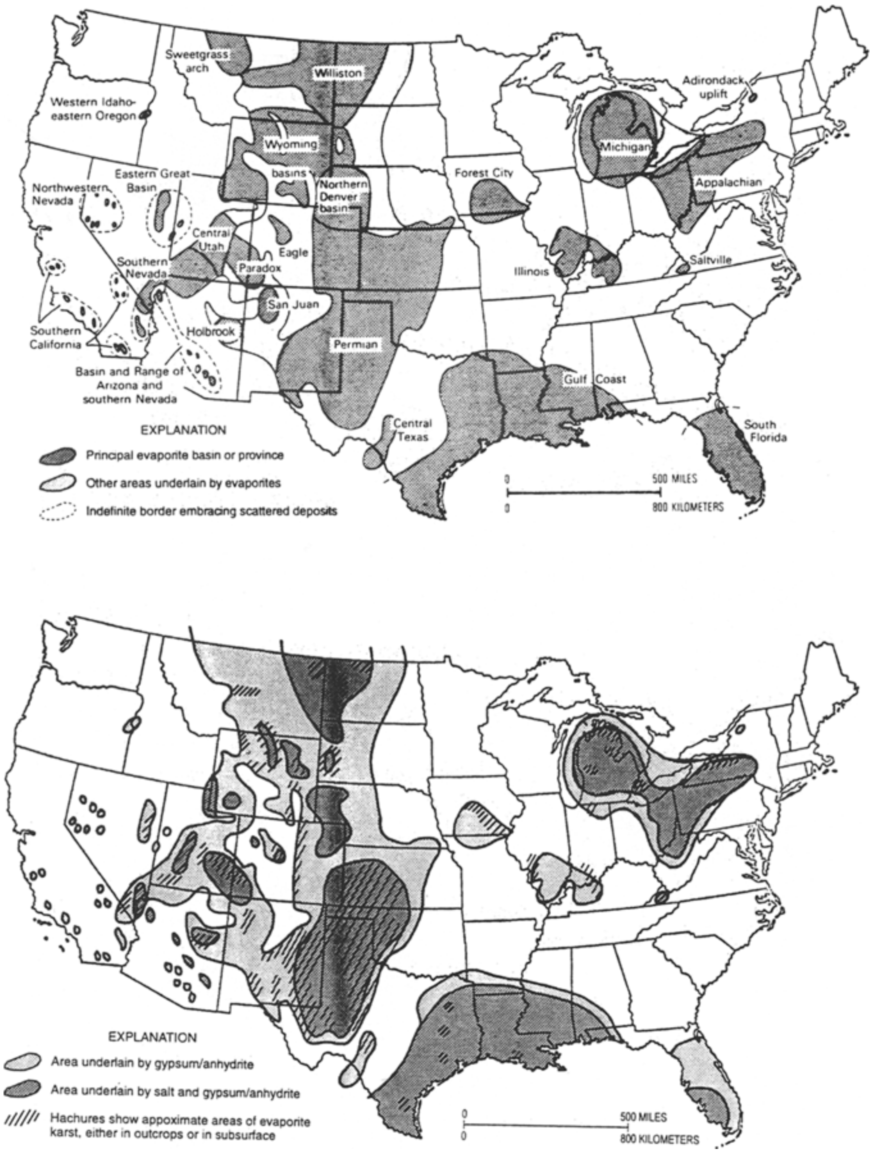

Figure 1. Maps of the conterminous United States: (above) evaporite basins and districts; (below) distribution of gypsum/anhydrite, salt, and evaporite karst. Modified from Johnson and Gonzales (1978) and Dean and Johnson (1989).

Evaporite karst is rarely seen at the land surface in eastern United States, 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 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. 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 and 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

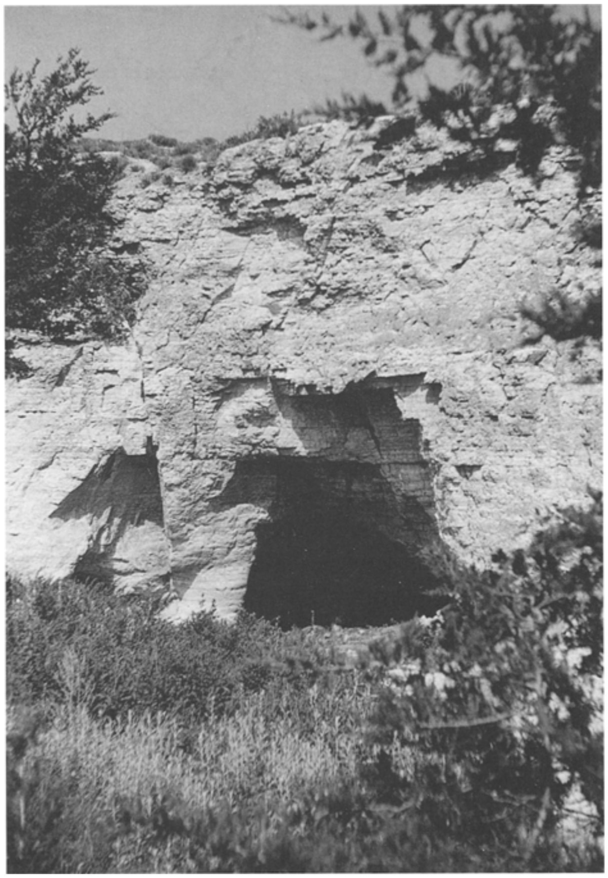

Figure 2. Cave in Permian Cloud Chief Gypsum in western Oklahoma. Cave opening is about 3 m wide.

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 (Figs. 2, 3). In fact, paleokarst, brecciated 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 and Palmer (in preparation) 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 in the rock; however, some karst features have a seemingly random orientation, wherein the controls are not understood.

Salt-Karst Processes

Salt is extremely soluble in ground water. Halite solubility in water is 35.5 percent by weight at 25°C, and it increases at higher temperatures (White 1988). Salt-karst features can be present in any salt in the United States. The mechanisms for salt dissolution and development of interstratal karst are described by Johnson (1981) and illustrated in Figure 4. 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. 4). 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.

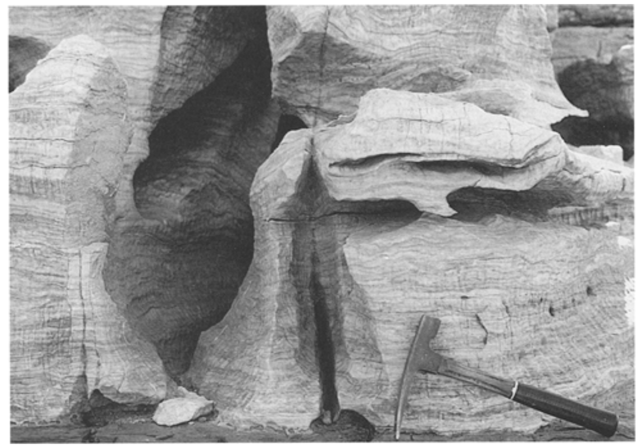

Figure 3. Karst development in Permian Cloud Chief Gypsum in western Oklahoma. Dissolution is most pronounced along joints and bedding planes.

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 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).

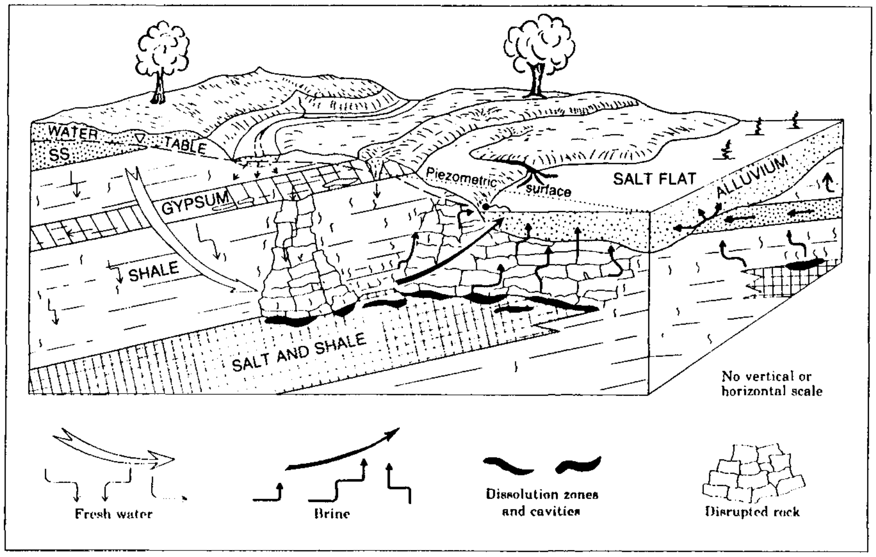

Figure 4. Schematic block diagram of interstratal salt karst in western Oklahoma (from Johnson 1981). The horizontal dimension is 1–15 km; the vertical dimension is 30–300 m.

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, and are described by Olive (1957), McGregor et al. (1963), Fischer and Hackman (1964), Myers et al. (1969), Kelley (1971), Quinlan (1978), Bozeman (1987), Sares and Wells (1987), Johnson (1990, 1992, 1997), Belski (1992), Hill (1996), and Forbes and 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 and 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 (Fig. 5), 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 and Evans 1980), and additional gypsum outcrops are present just to the east in the Rustler Hills and into Reeves County, Texas.

The Delaware basin gyspum 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 (Fig. 5), and most of the outcrops consist of massive beds of gypsum. Four principal areas of gypsum karst are the Gypsum Plain, Nash Draw, Burton Flat, and the Pecos River Valley (Hill 1996).

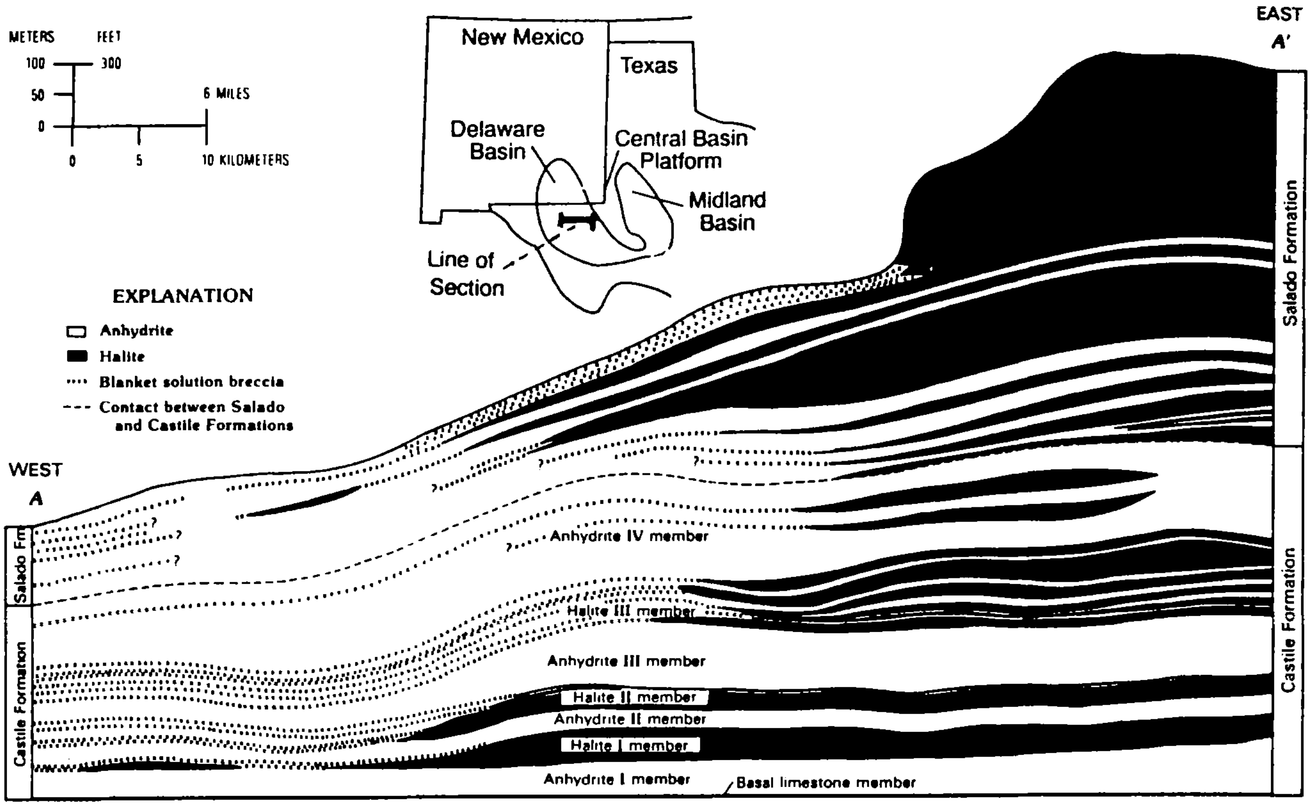

Figure 5. Diagrammatic east–west stratigraphic cross section of Permian Castile and Salado Formations in the Delaware basin of west Texas: section extends from Culberson County (A) to Winkler County (A'). From Anderson et al. (1972).

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 the Gypsum Plain and Burton Flat (Sares and Wells 1987; Belski 1992).

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 and San Andres Formation, and they contain a large number of sinkholes, caves, and other karst features in the Vaughn–Roswell area (Fischer and Hackman 1964; Kelley 1971; Forbes and Nance 1997). Several of the caves in this area are more than 3.2 km long, and the deepest has a vertical extent of more than 120 m (Forbes and Nance 1997).

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. 6) 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 1–5m in diameter, and locally are up to 20 m wide; and it occurs mainly in a 5-m-thick gypsum bed of the Blaine Formation. Alabaster Cavern of northwestern Oklahoma (Fig. 6), 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. 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.

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/anhydrite beds, 1–15 m thick, in the subsurface (McGregor 1954; Saxby and Lamar 1957; McGrain and Helton 1964). Gypsum does not crop out in Indiana and Kentucky, however, because interstratal

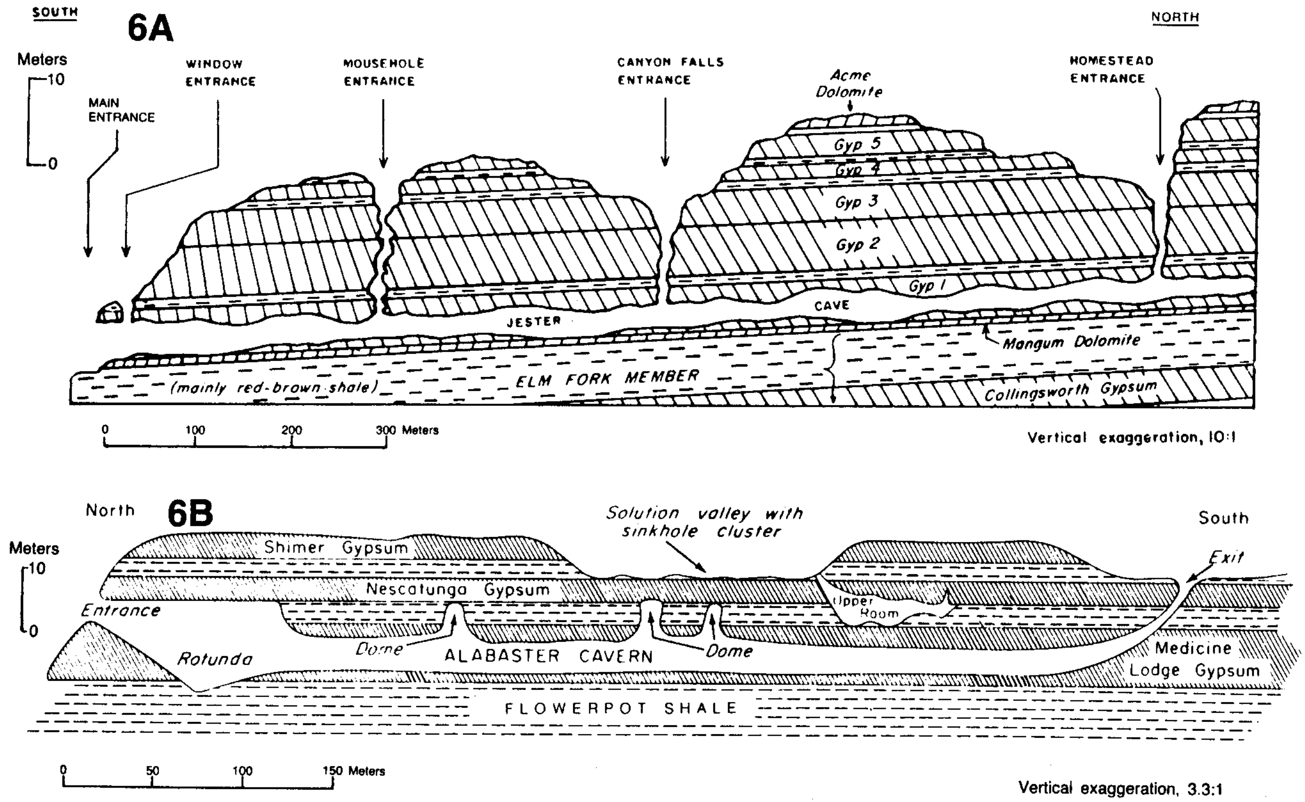

Figure 6. Schematic cross sections through major gypsum caves in the Permian Blaine Formation of western Oklahoma: (above, A) J. C. Jester Cave; (below, B) Alabaster Cavern. From Myers et al. (1969), Bozeman et al. (1987), and Johnson (1992).

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; those 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 and 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 and Ostrander 1977).

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/anhydrite beds in central and southern Iowa (Witzke et al. 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, and 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 and Davis 1996; Davis and 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.

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. Data on salt deposits of the United States were compiled by Pierce and Rich (1962), Lefond (1969), and Johnson and Gonzales (1978). 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 a much more widespread phenomenon than commonly suspected.

The Delaware basin area of west Texas and southeast New Mexico contains a great thickness of Permian salts in the Castile and Salado Formations. Castile salt beds have been dissolved from the western half of the basin, and hence their stratigraphic position is marked by brecciated zones of anhydrite that result from collapse and lowering of overlying units (Fig. 5) (Anderson et al. 1972, 1978; Anderson 1982). 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; Motts in preparation), 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 (Fig. 4). Conspicuous results of this process are collapse and subsidence features that reach to the land surface; for example, the High Plains Escarpment coincides with, and is above, the salt-dissolution front that is advancing westward beneath the Texas Panhandle (Gustavson et al. 1980, 1982). Salt dissolution in the area is also accompanied by sediment-filled subsidence basins and fractured rock at the surface (Irwin and Morton 1969; 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). Hovorka (1983) conducted petrographic studies of the deep-seated evaporites in the area and recognized criteria for post-Permian dissolution of the salt beds. 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 (Baker 1977; 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 (Bahr 1962; Johnson and Gonzales 1978; Neal 1995), and the relationship of the dissolution front to the surface karst features is now well documented (Fig. 7). 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). Evaporite-karst development at other sites in the Holbrook basin is reported by Colpitts and Neal (in preparation) and Neal and Colpitts (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 of the Pennsylvanian Paradox Member of the Hermosa Formation have flowed into a series of long and narrow salt anticlines (Hite and Lohman 1973; Doelling 1988). 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, and 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. In central Utah, the Jurassic Arapien Shale and its thick interbeds of salt have flowed into several major salt-cored anticlines similar to those of the Paradox basin (Willis 1986; Witkind 1994); these anticlines also are believed to

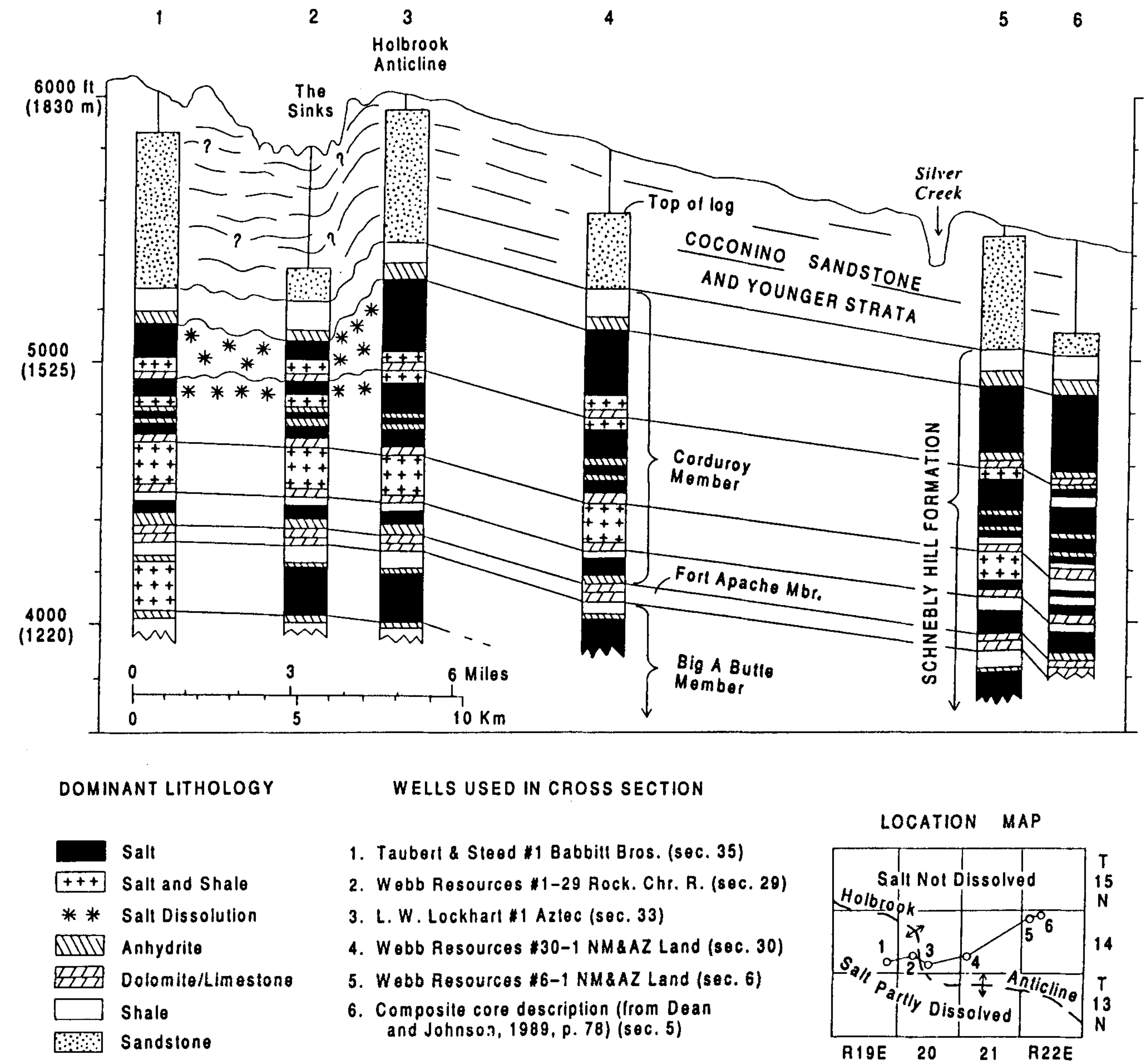

Figure 7. East-west cross section showing natural salt dissolution and collapse on the southwest side of the Holbrook basin, Arizona. From Neal et al. (1997).

have undergone episodes of salt dissolution and collapse. Rock salt is now exposed and is surface-mined in several small areas of the Sevier River Valley along the Sevier–Sanpete County line.

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. Orchard (1987) showed that beds of salt in the Mississippian Charles Formation pinch out abruptly over the Poplar dome, at a depth of 1,700 m in northeast Montana; salt dissolution probably occurred during the Tertiary, and salt removal was a major factor in creation of the large oil field at Poplar dome. Rasmussen and Bean (1984) described salt dissolution and subsidence of overlying strata in the Powder River basin of Wyoming; Late Permian salts of the Goose Egg Formation (Ervay Member) were dissolved mainly during the Late Jurassic and Early Cretaceous, and the dissolution zone now is about 3,000 m below the surface.

The Michigan basin contains several examples of salt karst. Dissolution of salts in the Salina Group (Silurian) and Detroit River Group (Devonian) across the northern edge of the Michigan basin by Middle Devonian time created a broad area of collapsed rocks, referred to as the Mackinac Breccia (Landes 1959; Black 1984). In addition, Black (1983, 1984, and 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 ongoing dissolution of the Detroit River Group 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 (Halbouty 1967; 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 (Walker 1974; 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, and I will cite only a couple of studies on this problem; but human-induced salt karst is not as widely understood, and its problems can be very significant.

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; and 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 and Davis 1996; Davis and Rahn 1997): (1) sewage lagoons, built on alluvium above a karstic gypsum layer, began leaking badly within one year, and then 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.

Human-Induced Salt Karst

Human-induced salt dissolution can have catastrophic effects locally (Walters 1978, 1991; Dunrud and Nevins 1982; Ege 1984; Coates et al. 1985; Johnson 1987, 1997). 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 (Fig. 8). Two industries associated with local salt dissolution and collapse are the solution-mining and petroleum industries.

Collapse due to solution mining.--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). 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).

The Cargill sink formed in 1974 as a result of solution mining for salt by Cargill, Inc., near Hutchinson, Kansas (Fig. 9) (Walters 1978; Johnson 1997). The surface crater reached a diameter of 60 m within 4 hours and stabilized with a diameter of 90 m and a maximum depth of about 15 m; the volume of the crater was calculated to be about 70,000 m^3. Salt was solution mined in the area since 1888. The Permian Hutchinson salt is about 105 m thick and occurs at a depth of about 130 m. The sink developed in an active brine field that included both operating and abandoned wells. Embraced within the sinkhole was a brine well that was drilled in 1908

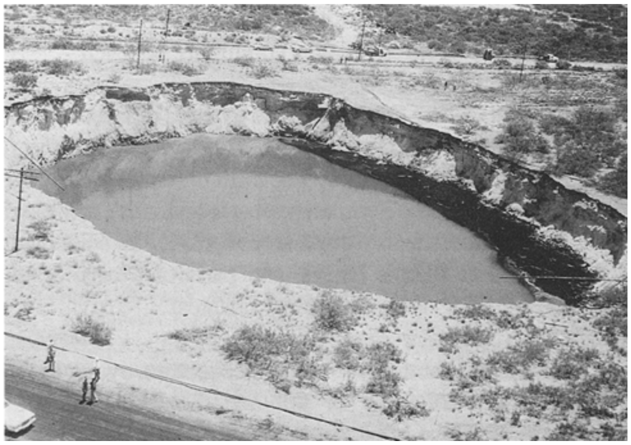

Figure 8. Aerial view of Wink sink in west Texas. The sink, with a diameter of 110 m, formed in 1980 at the site of an abandoned oil well. Photo courtesy of R.W. Baumgardner, Jr.

and abandoned in 1929.

Grand Saline sink developed in the city of Grand Saline, Texas, in 1976 (Fig. 9) (Dunrud and Nevins 1981; Johnson 1997). The sink occurred at the site of a brine well that penetrated the top of the Grand Saline salt dome at a depth of 60 m and had produced brine from 1924 through 1949. The sink eventually grew to a diameter in excess of 15 m, and a total of 8,500 m^3 of silt and clay was displaced into the underground cavity.

On Grosse Ile, located in the Detroit River near Detroit, Michigan, several sinkholes developed in 1971 as a result of 30 years of solution mining the Silurian Salina Group salts at a depth of 325 m below the surface (Nieto-Pescetto and Hendron 1977; Ege 1984). Dunrud and Nevins (1981) estimated that the area affected by subsidence was 37,000 m^2 and the volume of subsidence was 1,200,000 m^3.

In Tully Valley of central New York, the top of the Silurian Salina Group salt ranges from 335–485 m below the surface. The Salina is about 300 m of interbedded shale, dolomite, halite, and gypsum/anhydrite; salt has a cumulative thickness ranging from about 8–100 m (Getchell 1995). These salts have been solution mined from the late 1800s until the mid 1980s, and removal of the salt has resulted in land-subsidence features that generally are closed depressions with vertical displacements of 10–20 m and diameters greater than 60 m (Getchell 1995).

Collapse due to petroleum activity.--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). 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 the collapse 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).

The Wink sink formed in 1980 in an oil field near the town of Wink, in west Texas (Fig. 8). The sinkhole reached a maximum diameter of 110 m, a depth of 34 m, and an

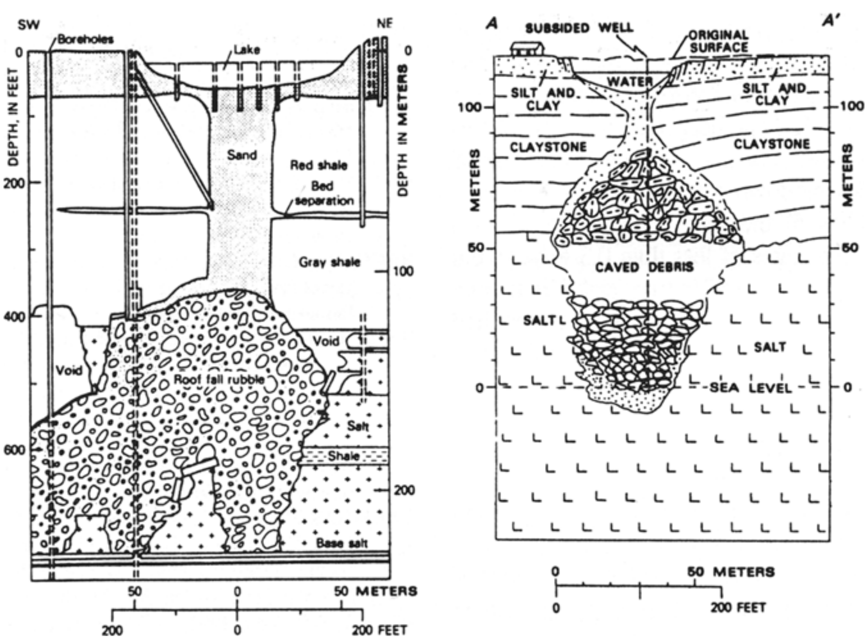

Figure 9. On left is cross section through Cargill sink, Kansas (modified from Walters 1978); cavity shape is hypothetical. On right is cross section through Grand Saline sink in Grand Saline salt dome, Texas (modified from Dunrud and Nevins 1981).

estimated volume of 159,000 m^3 (Baumgardner et al. 1982; Johnson 1987, 1997). One abandoned well that produced oil from 1928 to 1951 was incorporated within the sink itself. This suspect well was drilled through 260 m of salt in the Permian Salado Formation, with the top of the salt about 400 m deep. Johnson (1987, 1997) described the various drilling and well-completion activities that probably led to eventual collapse around the suspect well: (1) fresh ground water unintentionally reached the salt and created a large dissolution cavity around the well; (2) collapse of the non-salt roof into the cavity; and (3) by successive roof failures, the cavity migrated upward until it finally reached the land surface to create the Wink sink.

Panning sink was formed in 1959 by subsidence and collapse around a salt-water-disposal (SWD) well on the Panning lease in Barton County, Kansas (Walters 1978; Johnson 1997). The sinkhole reached a diameter of 90 m and was at least 18 m deep. The suspect well, drilled originally as a producing oil well in 1938, penetrated 91 m of Permian Hutchinson salt at a depth of 298 m. Fresh-water drilling fluids dissolved the salt in the borehole to an excessive diameter (1.4 m), and this washed-out zone was not cemented behind the 15.2-cm-diameter casing. Conversion of the borehole to a SWD well from 1946 to 1958 caused a large quantity of unsaturated oil-field brines (about 28,000 ppm NaCl) to be pumped into the well and inadvertently encounter, and further dissolve, the salt. A large cavern was formed, and with successive roof falls the water-filled void migrated upward to cause surface subsidence, tilting of an oil-field derrick, and eventual collapse.

Gorham oil field, in Russell County, Kansas, is the site of slow subsidence of a major highway (Interstate 70) above salt-dissolution zones in the Permian Hutchinson salt (Walters 1991). A series of oil wells, drilled on 4-hectare spacing in 1936–1937, penetrated 75 m of salt at a depth of 390 m. The wells are now plugged and abandoned, but some of them contain corroded casing that has been left in the boreholes above, within, and below the salt unit. As a result, unsaturated water probably has flowed down some of the boreholes and dissolved large volumes of the salt. Subsidence of I–70 pavement has occurred at rates of less than 0.3 m/year, but cumulative subsidence through 1987 in two "sinks" is about 4 m and in a third "sink" is about 0.3 m; this has required rebuilding parts of I–70 in 1971 and again in 1986 (Walters 1991).

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.

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.

Salt karst is almost entirely a subsurface feature, owing to the extremely high solubility of salt and the virtual lack of outcrops in the United States. Salt karst is most conspicuous and widespread in the Permian basin region; several major salt units have been extensively dissolved here to produce collapse features and sediment-filled subsidence troughs. Other areas of significant salt karst are the Holbrook, Paradox, Michigan, and Gulf Coast basins.

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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