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Subsidence hazards due to evaporite dissolution in the United States

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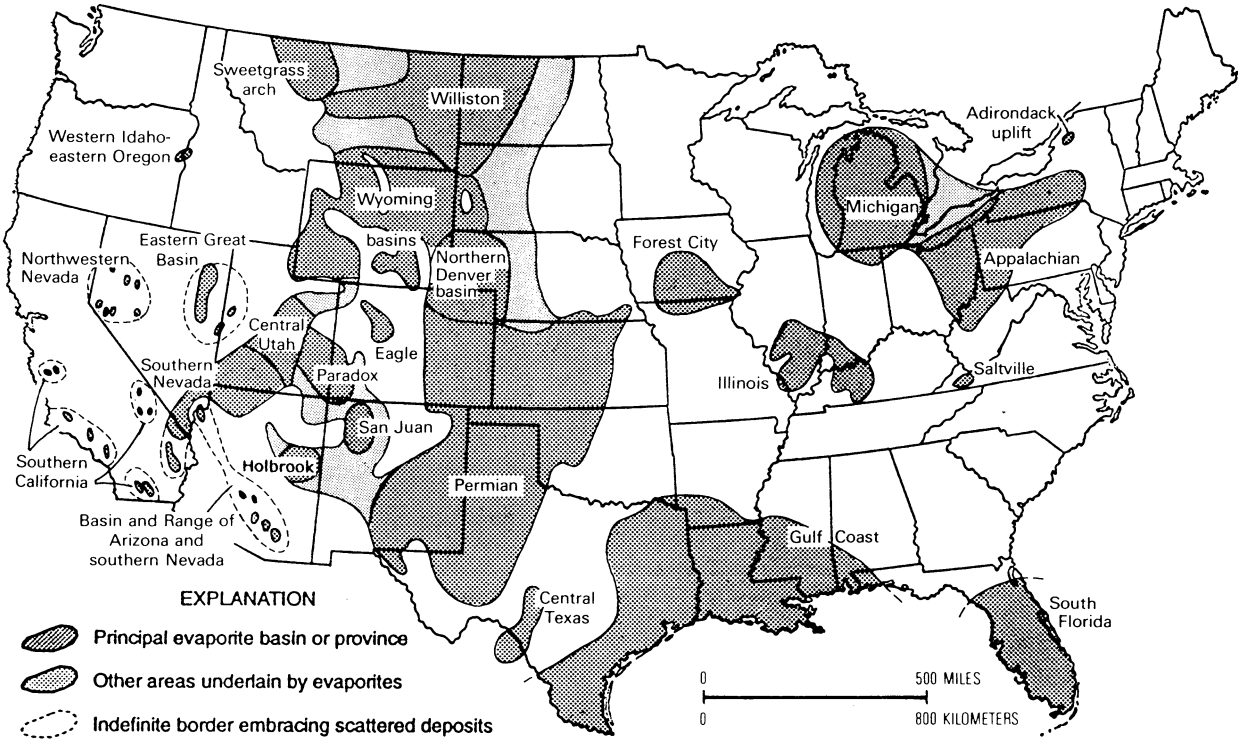
Abstract Evaporites, including gypsum (or anhydrite) and salt, are the most soluble of common rocks; they are dissolved readily to form the same type of karst features that typically are found in limestones and dolomites, and their dissolution can locally result in major subsidence structures. The four basic requirements for evaporite dissolution to occur 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 of the United States, and they underlie about 35–40% of the land area. Karst is known at least locally (and sometimes quite extensively) in almost all areas underlain by evaporites, and some of these karst features involve significant subsidence. The most widespread and pronounced examples of both gypsum and salt karst and subsidence are in the Permian basin of the southwestern United States, but many other areas also are significant. Human activities have caused some evaporite–subsidence 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.

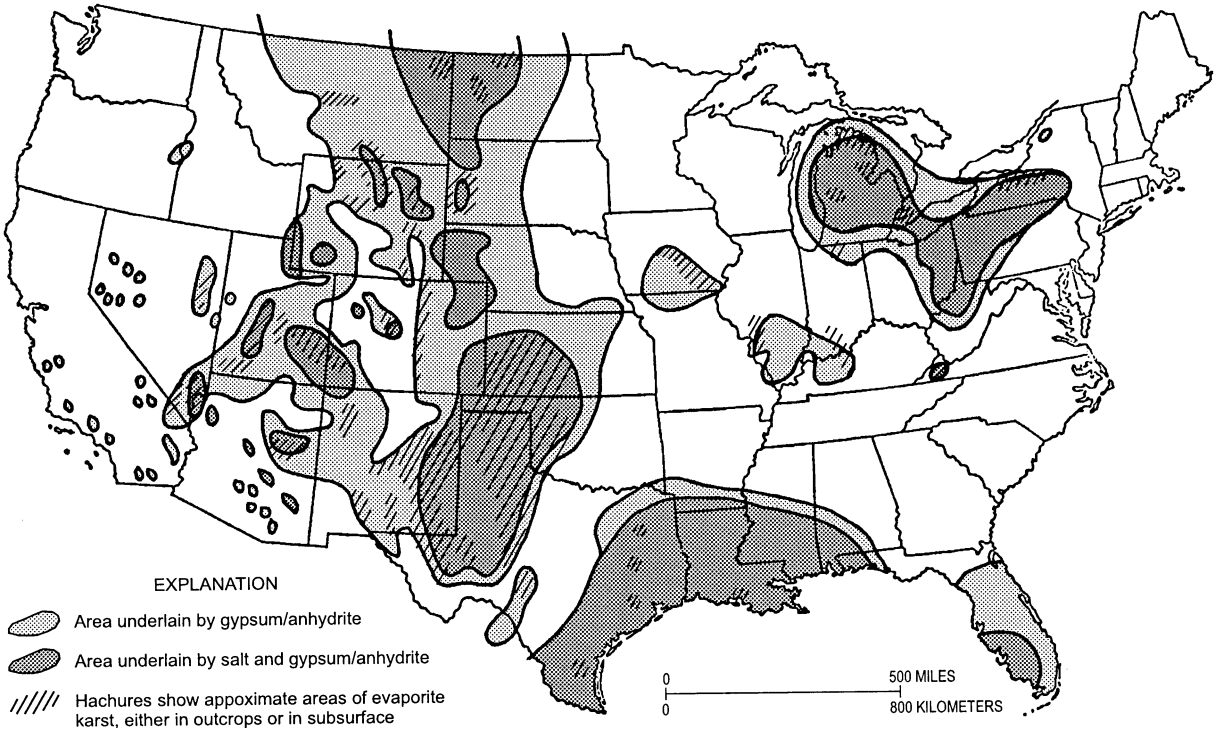
Keywords Evaporite karst · Gypsum karst · Salt karst · Sinkholes · Collapse · Evaporite dissolution · Subsidence hazards · USA

Introduction

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 and subsidence features that typically are found in limestones and dolomites. The principal difference is that evaporite-karst and -subsidence features can form rapidly, in a matter of days, weeks, or years, whereas in carbonate rocks this typically takes years, decades, or centuries to form. Evaporite-karst features include sinkholes, caves, disappearing streams, and springs, and in some areas these features are accompanied by dramatic or catastrophic subsidence. Evaporites are widely distributed in the United States and they contain evidence of karst and subsidence in most areas (Fig. 1).

The current report provides an overview and summary of the general characteristics and distribution of gypsum and salt dissolution in the United States. It is condensed and modified from an article on "Evaporite Karst in the United States," published in *Carbonates and Evaporites* (Johnson 1997), which in turn was based largely upon earlier studies by Johnson and Gonzales (1978), Quinlan and others (1987), and Dean and





Johnson (1989). 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), Ege (1985), Kostick (1994), and Johnson (1996). In addition, there are numerous local or regional studies

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Fig. 1 Maps of the conterminous United States. *Above*; evaporite basins and districts. *Below*; distribution of gypsum/anhydrite and salt deposits, and areas of evaporite karst and subsidence features. From Johnson (1997); modified from Johnson and Gonzales (1978) and Dean and Johnson (1989)

dealing with subsidence due to 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.

Publication of this report is approved by the Director of the Oklahoma Geological Survey.

Processes of evaporite dissolution

Processes for the development of karst and subsidence features in evaporite rocks are identical to those 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, cavities, 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, provided 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 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 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 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-dissolution processes

Gypsum dissolution occurs rapidly because gypsum is highly soluble in water. 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 dissolution and 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 (Fig. 2). 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) and Friedman (1997) provide examples and a summary of this carbonate/sulfate relationship. Gypsum-dissolution 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-dissolution processes

Salt is extremely soluble in ground water. Salt-dissolution features can be present in all parts of the United States that are underlain by salt. The mechanisms for salt dissolution and development of interstratal karst are

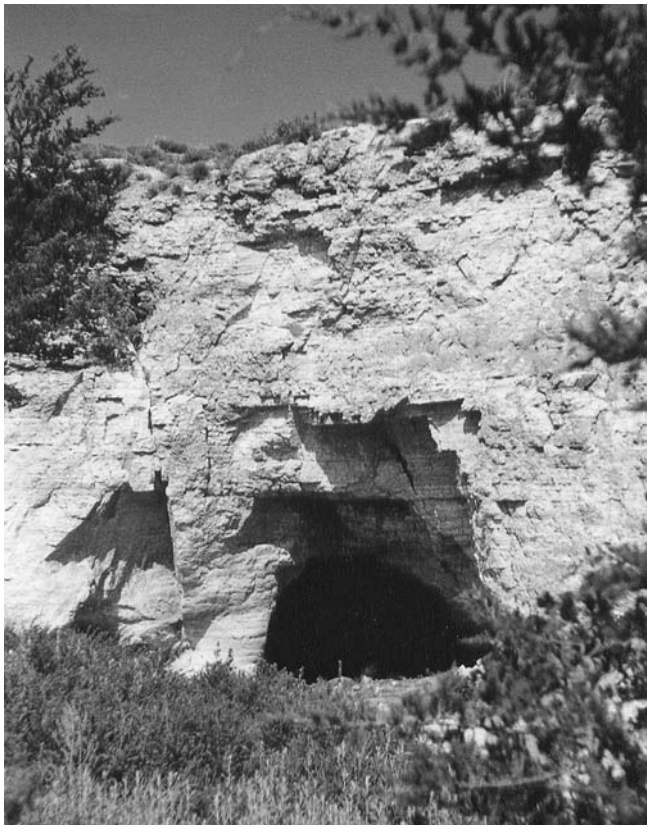


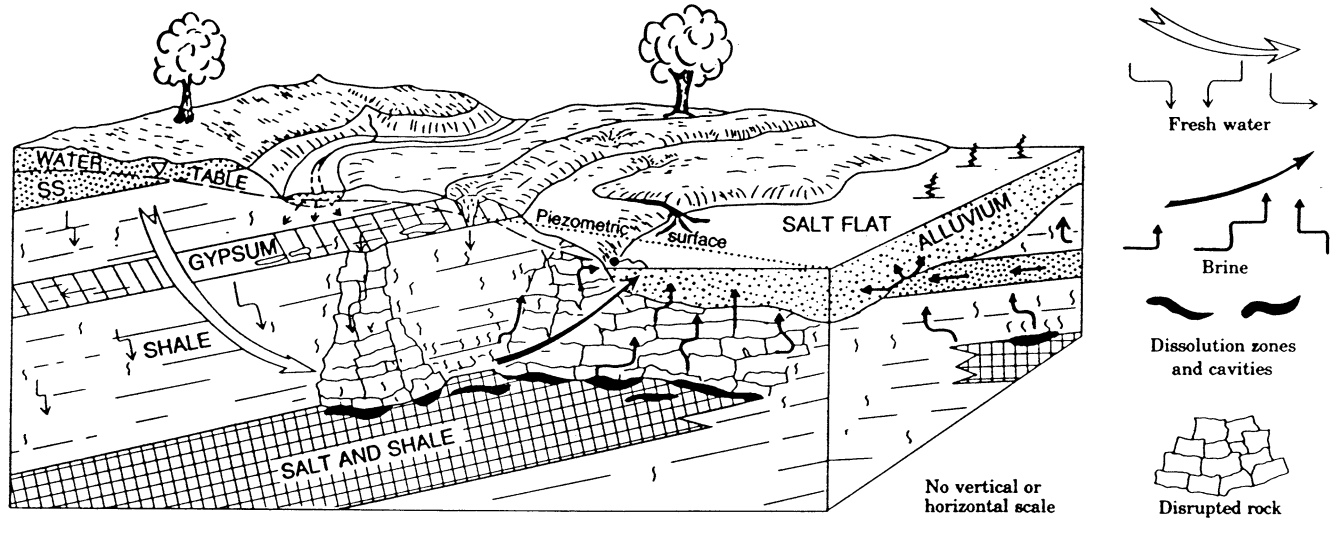
Fig. 2 Entrance to cave in the Permian Chief Gypsum in western Oklahoma. Cave opening is about 3 m wide

described by Johnson (1981) and illustrated in Fig. 3. 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. 3). 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 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 dissolution/karst may be remnant from an earlier hydrogeologic regime (perhaps as early as shortly after the original deposition of the salt unit).

Evidence of salt dissolution includes collapse structures, sinkholes, underground cavities, 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-dissolution 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 northeastern Spain), where typical karst features, such as caves, sinkholes, shafts, and karren, can be documented (White 1988).

Fig. 3 Schematic block diagram of interstratal salt karst in western Oklahoma (from Johnson 1981). The horizontal dimension can vary from 1 km to 15 km; the vertical dimension from 30 m to 300 m



Areas of natural subsidence in evaporites

Gypsum and salt are present in 32 of the 48 contiguous states of the United States, and they underlie about 35–40% 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, and some subsidence, 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.

Natural subsidence in gypsum

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 of the United States. Generally, in areas where gypsum crops out, or is less than 30 m below the land surface, karst and subsidence features are present (at least locally). The most widespread and pronounced examples of gypsum karst and subsidence 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 McGregor and others (1963), Fischer and Hackman (1964), Myers et al. (1969), Kelley (1971), Bozeman (1987), Sares and Wells (1987), Johnson (1990, 1992, 1996, 1998), Belski (1992), Hill (1996), and Forbes and Nance (1997). Quinlan et al. (1987) 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 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, 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 and subsidence 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 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 the 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 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 subsidence 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 (Fig. 2). Among the more important gypsum-karst features of the region are two well-known caves and a major fresh-water aquifer. The D.C. Jester Cave of southwestern Oklahoma has a main passage that is 2,413 m long, but, along with the side passages, the total length is 10,065 m (Bozeman 1987; Johnson 1992); thus making it the longest reported gypsum cave in the western world. The cave, developed in the Blaine Formation, 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 in the Blaine Formation; 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 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 nine 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). In all these areas, collapse structures and subsidence features are locally present above the caves and the aquifer.

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 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). 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 of St. Louis Limestone on the west (Illinois) side of the Illinois basin, and they felt this collapse and subsidence 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). The Forest City basin area of Iowa contains evidence of gypsum karst in Devonian 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).

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 at this site. 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.

Natural subsidence in salt

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 and subsidence are much more widespread 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 (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. A particularly good example is the dissolution trough formed adjacent to the Capitan reef, where several hundred meters of Salado salts have been dissolved (Fig. 4); 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

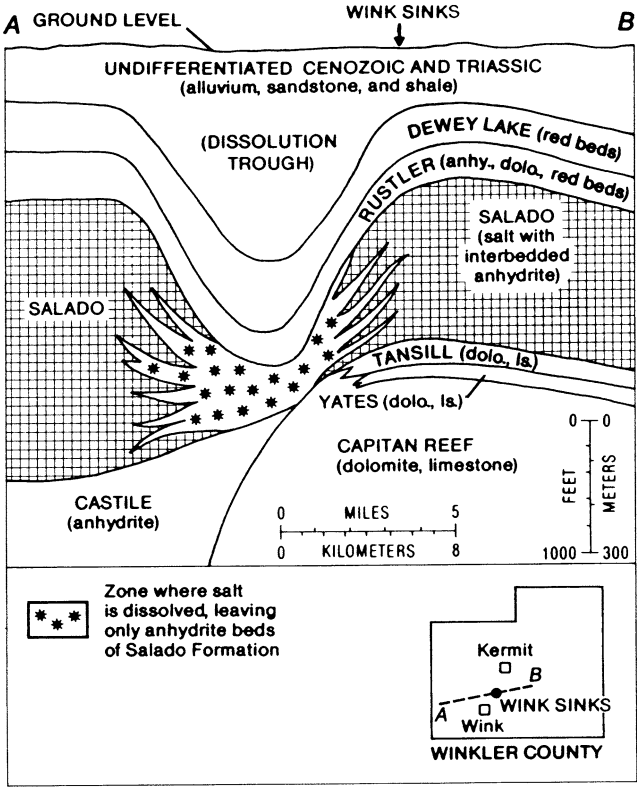


Fig. 4 Schematic cross section in Winkler County, west Texas, showing natural dissolution of Permian Salado Formation salts and basin-fill sedimentation on the east side of the Delaware basin (from Johnson 1987; modified from Baumgardner and others 1982). Also shown is the location of the Wink sink

troughs, breccia pipes, sinks, and other disturbed zones related to salt dissolution.

Permian salt beds are being dissolved at shallow to moderate depths in western Oklahoma and the Texas Panhandle (Fig. 3). 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 (Simpkins others 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 (Fig. 5), fissures,

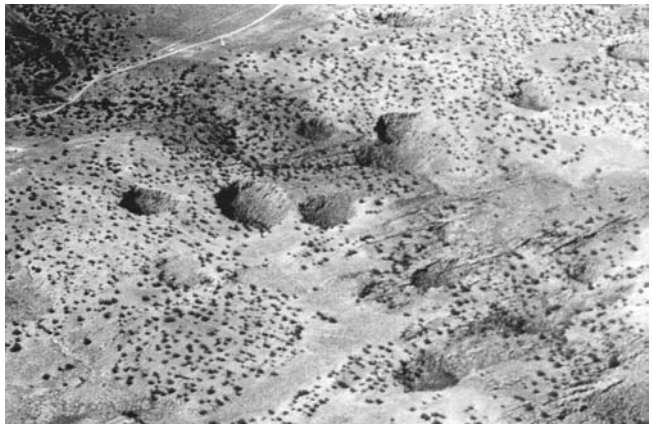


Fig. 5 Aerial photo showing some of the prominent sinkholes and subsidence/collapse features resulting from natural dissolution of salt in the Holbrook basin of northeast Arizona. The sinks are generally 40–50 m wide and 20–30 m deep. Photo courtesy of James T. Neal

depressions, and other karst features that result from ongoing dissolution of salt in the Permian Schnebly Hill Formation (Neal et al. 1998b; Martinez et al. 1998). Natural dissolution of salt 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 subsidence or collapse of overlying strata has occurred in such areas as The Sinks, Dry Lake Valley, and McCauley Sinks (Neal et al. 1998b; Martinez et al. 1998).

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). 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 crests 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, attesting the ongoing dissolution of salt and the undoubted development of cavities and subsidence or collapse features. They estimate that the present-day 33-m-thick cap rock in the salt 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

(Witkind 1994); these anticlines also are believed to have undergone episodes of salt dissolution and collapse.

Salt dissolution has been documented at several places in the Wyoming basins and the Williston basin. Parker (1967) described paleodissolution 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 paleodissolution and subsidence. 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 (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 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 salt dissolution; 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, thus attesting salt dissolution, but evidence of significant subsidence or collapse above salt domes due to natural dissolution of sale is lacking.

Human-induced subsidence in evaporites

Human activities can play a special role in inducing or enhancing dissolution 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 develop 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 only a couple of studies on this problem will be cited in this report; but human-induced salt karst is not as widely understood, and its problems can be very significant.

Human-induced subsidence in gypsum

Gypsum karst and subsidence 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, allowing partially treated sewage to escape the site; and (2) directing runoff into buried gypsum karst has caused several houses to settle and crack, and has 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.

A special case of catastrophic collapse is documented in the failure of the Quail Creek Dike, a 24-m-high structure near St. George, in southwest Utah (Gourley 1992; Payton 1992). The earthen dike was built in 1984 to help contain water in the Quail Creek Reservoir. It was built upon a sequence of thinly interbedded dolomites, siltstones, gypsums, and sandstones of the Triassic Moenkopi Formation. Gypsum, in the form of gypsiferous beds (less than 1 m thick), laminations, nodules, and cement comprised about 25% of the bedrock beneath the dike, and comprised more than 50% of some beds. Upon completion of the main dam in 1985, joints in the bedrock started to allow lake water to pass under the dike, as attested by increased seepage, discolored seepage, and development of small sinkholes, all downstream from the dike. This seepage beneath the dike was caused by: (1) flow through open joints and along bedding planes in the gypsiferous beds; (2) by erosion of clastics (such as clay and silt) or other materials that had partially filled once-open joints; and (3) by further dissolution of gypsiferous bedrock and enlarging of joints and bedding planes. Later studies revealed large openings (up to 15–30 cm across) where

the joints cut across the gypsiferous beds. Eventually, on January 1, 1989, the seepage began eroding unconsolidated earthen materials left between bedrock and the base of the dike, and the structure failed catastrophically. Observation of increased seepage just before the failure caused early evacuation of people, so there were no fatalities; however, the dike collapse and flooding caused millions of dollars in damages and disrupted major highways and bridges.

Human-induced subsidence in salt

Human-induced salt dissolution can have catastrophic effects locally (Walters 1978, 1991; Dunrud and Nevins 1981; Ege 1984; Coates et al. 1985; Johnson 1987, 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 (Fig. 6). Two industries associated with local salt dissolution and subsidence or collapse are the solution-mining and petroleum industries.

Subsidence 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 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 ten 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).



Fig. 6 Aerial photo showing the Cargill sink, which formed as a result of solution mining of salt near Hutchinson, Kansas. The collapse feature (90 m wide and 15 m deep) left railroad tracks suspended in air. Photo courtesy of Deming Studio

The Cargill sink was formed in 1974 as a result of solution mining for salt by Cargill, Inc., near Hutchinson, Kansas (Figs. 6, 7) (Walters 1978; Johnson 1998). 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 and abandoned in 1929.

Grand Saline sink developed in the city of Grand Saline, Texas, in 1976 (Dunrud and Nevins 1981; Johnson 1998). 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 to 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, 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 beds beneath the valley have a cumulative thickness ranging of 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; Kappel 1998).

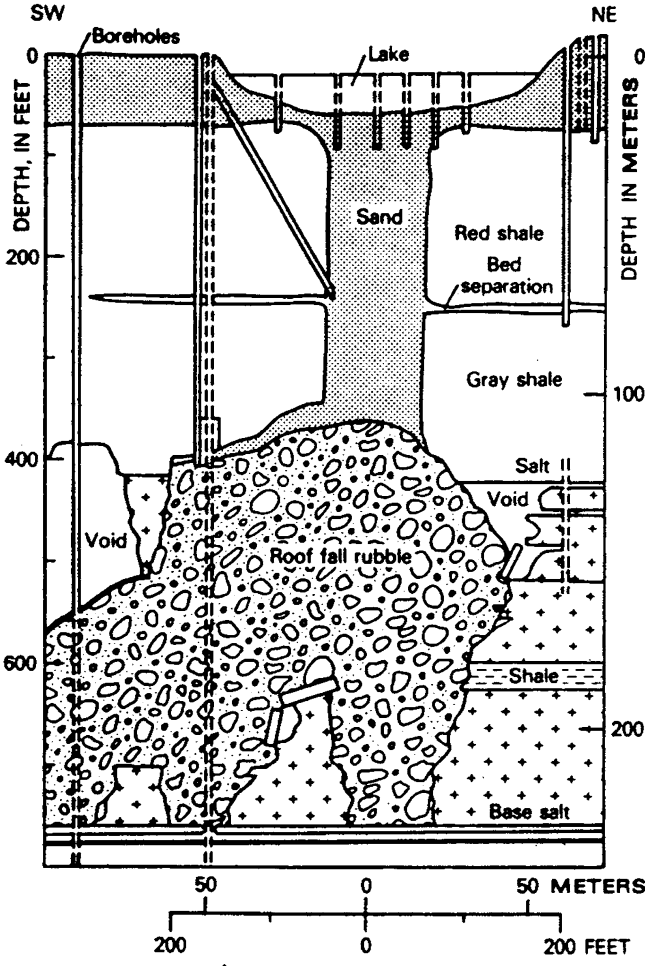


Fig. 7 Cross section through the Cargill sink, near Hutchinson, Kansas; cavity shape is hypothetical. Modified from Walters (1978)

Subsidence over dry salt mines

Sinkholes and subsidence features have formed above dry (room-and-pillar) salt mines at several places where groundwater has entered into the mined-out voids (Martinez et al. 1998). If a leak develops and unsaturated water enters a dry salt mine, the salt can be dissolved rapidly. If large volumes of water are introduced, the mined-out rooms can fill with salt-dissolving water, and the facility behaves like a solution mine. Dissolution can enlarge the rooms, remove salt pillars that support the roof, dissolve salt that remains in the roof, induce collapse of the overburden, and create small to large sinkholes and subsidence features. Three dry salt mines that have been invaded by water and have developed overlying subsidence features are at Jefferson Island (Louisiana), Weeks Island (Louisiana), and Retsof mine (New York). All these mines are now closed.

Jefferson Island salt dome, just west of New Iberia, Louisiana, was the site of a catastrophic sink in 1980 (Martinez 1991; Martinez et al. 1998). The huge sink was apparently caused by accidental penetration of a large, active salt mine (400 m below the surface) by an oil rig that was drilling in a shallow lake. Lake water poured into the mine through the borehole, and more water was drawn through a canal that connected the lake to the Gulf of Mexico. The giant sink consumed the $5-million drilling rig, several barges, a tugboat, and 4 hectares of land. Fortunately there was no loss of life, either of surface personnel or of miners.

Weeks Island salt dome, about 30 km from Jefferson Island, contains an old room-and-pillar salt mine that

was converted in 1981 to storage of crude oil as part of the U.S. Strategic Petroleum Reserve. In 1992 a sinkhole (10 m wide and 10 m deep) was observed above the dome, and this was attributed to increasing dissolution of salt over the mined storage area (Neal and others 1998a; Martinez et al. 1998). In 1995 a second, much smaller sinkhole was discovered. Because 73 million barrels of crude oil were stored in the underground mine, attempts were made to stop the dissolution of salt and protect the facility. Saturated brine was injected into the sinkhole to stop dissolution, and a "freeze curtain" was created to prevent groundwater flow into the mine. The potential dangers caused abandonment of the facility and withdrawal of the crude oil. Total costs of mitigation, removal of oil, and dismantling of facility infrastructure was nearly $100 million.

Retsof mine, a room-and-pillar salt mine operated since 1885, is near Geneseo, in western New York. The mine, about 340 m deep, was the site of a major roof collapse in 1994. The roof failure formed new fractures in overlying rocks, and groundwater flowed into the mine (Nieto and Young 1998; Martinez et al. 1998). Dissolution of salt pillars in the mine (and of parts of overlying salt beds), along with downward slump or piping of thick, near-surface, unconsolidated sediments, caused subsidence of the land above the mine; this resulted in two large sinkholes, with the larger one being about 200 m wide and 20 m deep. The entire 26 km^2 of the mine was flooded and is abandoned. Adverse impacts include: loss of the mine and its economy, disruption of land, abandoning four homes, damage to other homes, loss of a major highway and bridge, and loss of water wells.

Subsidence 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 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 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 (Figs. 4, 8). The sinkhole reached a maximum diameter of 110 m, a depth of 34 m, and an estimated volume of 159,000 m^3 (Baumgardner et al. 1982; Johnson 1987, 1998). One abandoned well that produced oil from 1928 to 1951 was incorporated within the sink itself (Fig. 9). 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, 1998) described the various drilling and well-completion activities that probably led to eventual collapse around the suspect well: (1) fresh groundwater 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.



Fig. 8 Aerial view of the Wink sink in west Texas. The sink, about 110 m wide and 34 m deep, formed in 1980 at the site of an abandoned oil well (the Hendrick well 10–A). Photo courtesy of Robert W. Baumgardner

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 1998). 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 1949 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.

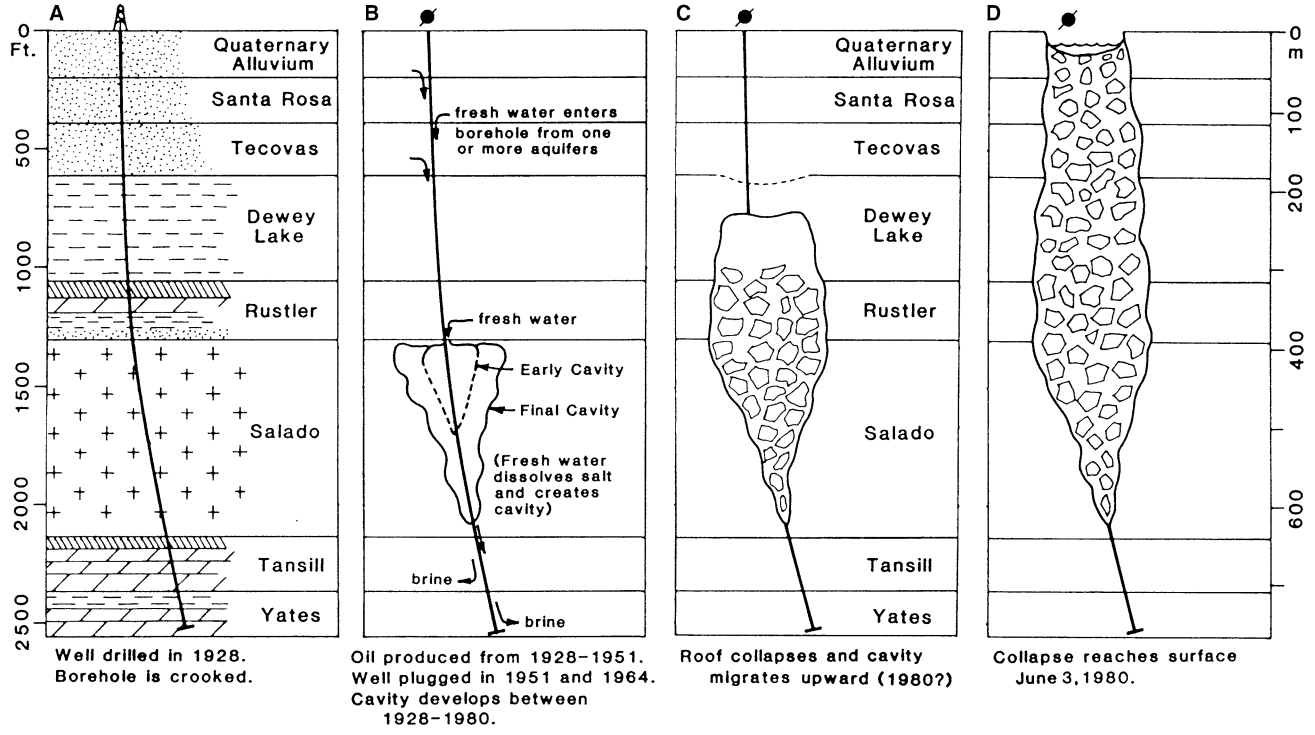


Fig. 9 Schematic cross section through the Hendrick well 10–A, showing possible relationship of this oil well to development of the Wink sink. Fresh water may have circulated down the borehole to dissolve the salt and create a cavity; by successive roof failures, the cavity migrated upward to the land surface. Modified from Johnson (1987)

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-ha 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 dissolution and subsidence hazards in the United States. Caves, sinkholes, cavities, collapse structures, disappearing streams, and other features typical of karst terrains are present in evaporite deposits throughout the nation. Evaporites are present in 32 of the 48 contiguous states, and dissolution and subsidence are known at least locally in almost all of these areas. Evaporite dissolution and karst are, in most respects, identical to those features in carbonate rocks, except that the process is much more rapid. It is much more widespread than is commonly believed.

Gypsum-dissolution features are most conspicuous in gypsum outcrops, but are also 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 subsidence are in the Permian basin of southwestern United States, although other important areas include the Michigan, Forest City, and Illinois basins, and parts of southwest Utah, Texas, South Dakota, Wyoming, and other western states.

Salt dissolution 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 dissolution and subsidence are 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. In addition, impounding water above gypsum deposits containing dissolution features have caused failure of sewage lagoons and an earthen dike.

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