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Surface Subsidence and Collapse in Relation to Extraction of Salt and Other Soluble Evaporites

By

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ILLLUSTRATIONS

Surface Subsidence and Collapse in Relation to Extraction of Salt and Other Soluble Evaporites

By John R. Ege

Abstract

Extraction of soluble minerals, whether by natural or man-induced processes, can result in localized land-surface subsidence and more rarely sinkhole formation. One process cited by many investigators is that uncontrolled dissolving of salt or other soluble evaporites can create or enlarge underground cavities, thereby increasing the span of the unsupported roof to the strength limit of the overlying rocks. Downwarping results when spans are exceeded, or collapse of the undermined roof leads to upward stoping or chimneying of the overburden rocks. If underground space is available for rock debris to collect, the void can migrate to the surface with the end result being surface subsidence or collapse.

In North America natural solution subsidence and collapse features in rocks ranging in age from Silurian to the present are found in evaporite terranes in the Great Plains from Saskatchewan in the north to Texas and New Mexico in the south, in the Great Lakes area, and in the southeastern States.

Man-induced subsidence and collapse in evaporites are generally associated with conventional or solution mining, oilfield operations, and reservoir and dam construction, and can be especially hazardous in populated or built-up areas.

Introduction

The U.S. Geological Survey conducts earth-science research, including field studies, so as to provide advance recognition and warning of many types of geologic-related hazards. Geologic processes and conditions that could result in harm to people and damage to property include earthquakes, landslides, mudflows, faulting and fissuring of the ground surface, glacial-related phenomena such as release of glacier-dammed lakes and rapid ice surges or retreats, and land subsidence.

Subsidence is a local mass sinking of the ground surface. One current activity in geologic hazards research deals with ground subsidence over underground openings formed by dissolution of soluble rocks such as salt and limestone (Ege 1979a, b). The Solution Subsidence and Collapse project is funded by the Reactor Hazards Research Program, a Geological Survey program directed at expediting the safe siting and design of power reactors in the United States through topical and regional studies of major geological hazards. The program is intended to identify and improve our understanding of geologic processes that may be hazardous to nuclear power reactors and to determine geographic distribution and expected frequency and severity of these processes in order to facilitate the safe siting and design of civilian power reactors.

This report summarizes experience in ground subsidence and collapse over cavities formed by either natural or artificial means in saline rocks. Examples of collapse of naturally formed cavities in saline rocks of the central United States and west-central Canada derived from the literature are cited. In addition, instances of rapid ground subsidence related to man's activities in salt-bearing rocks are described. This information is presented to provide a broad outline of some of the problems that must be faced in the siting of nuclear-powered generating stations in areas of the United States underlain by saline rocks.

Subsidence Processes

It is appropriate here to briefly introduce the viewpoints of several researchers involved in subsidence investigations so as to provide some basis for discussing mechanisms relative to subsidence in saline rocks. When an underground opening is created, the rock strata are disturbed and the initial equilibrium conditions are altered. In discussing the many factors involved in producing subsidence, Stefanko (1973, sec. 13, p. 2) cites the span of the opening as one of the most important. He continues that if the width of the opening is relatively small, the overlying rock strata can bridge across the void and little movement or convergence will take place. However, as the span increases in length, a point is reached where the stress in the overlying rock strata exceeds some strength value of the rock and the roof ruptures. If the span of the opening is limited to some subcritical value, or is at a great depth, a pseudo-arch will form that stabilizes the region around the void before any rupturing reaches the surface. On the other hand, if the width of this opening is increased to some critical value, or the same void is placed at a shallower depth, the overlying rock will progressively fail to the surface resulting in subsidence.

Obert and Duvall (1967, p. 554-581) list at least four subsidence mechanisms related to closure of underground openings and identify them as trough subsidence, subsurface caving, plug caving, and chimneying. These processes, according to the authors, depend on both the time-dependent and time-independent characteristics of the rock and on the stress conditions created in the rock by the geometry of the opening.

Trough subsidence, the most commonly observed type of surface subsidence, generally occurs over openings in relatively horizontal thin-bedded deposits overlain by stratified sedimentary rocks. If the opening is enlarged and is accompanied by roof and floor convergence, then surface subsidence manifested by vertical and lateral surface displacements will occur almost immediately. An idealized profile of a subsidence trough and pattern of vertical and horizontal displacements and horizontal strains over an infinite opening perpendicular to the page was described by Rellensmann in 1957 (fig. 1). Vertical displacement is maximum over the center of the excavation (point F) and extends beyond the lateral limits of the excavation. The lateral surface strain is tensile outside the limits of the opening and compressive within the limits. Lateral strain is zero at point D and corresponds to the surface displacement inflection point (B). Maximum horizontal strain appears at C and surface tension cracks would be expected to form at A. The angle of break (α) is the angle between the horizontal and the line connecting the edge of the opening with the point of maximum surface tensile strain (A). The plane of break passes through the point of maximum tensile strain on the surface of all subsurface strata and coincides with the line defining the angle of break. If the strains are large enough, rock fractures would tend to form along the plane of break.

Under certain conditions caving, or continuous failure of rock overlying an underground opening, can be sustained such that the broken zone progresses toward the surface. If the caving process breaches the surface, a circular depression or sinkhole can form, sometimes catastrophically. In certain mining operations rock failure of this type is deliberately induced and can serve as an illustration of the caving process. In the block-caving method of mining, caving is initiated by removing support and increasing the span in the

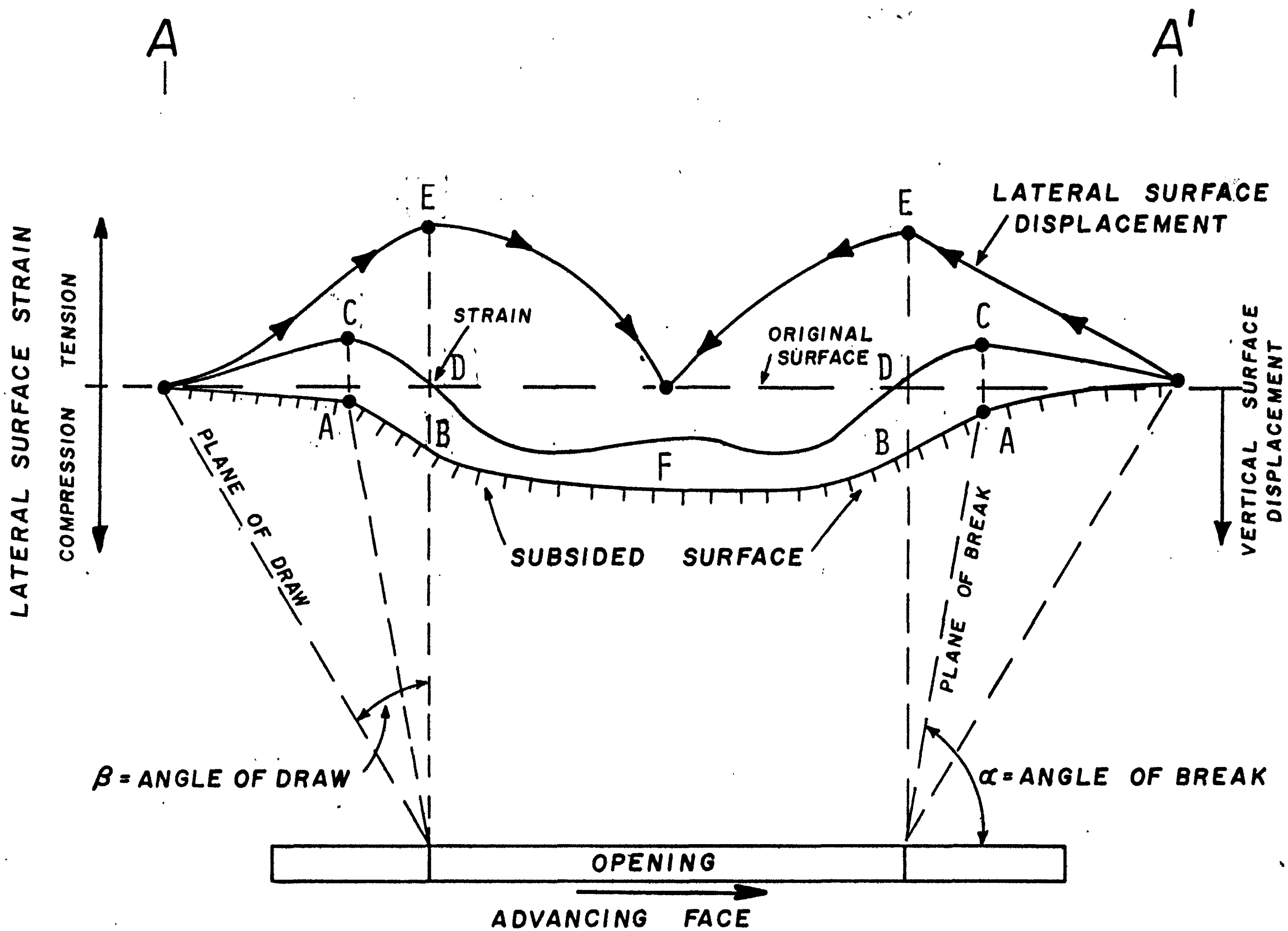

Figure 1.--Idealized representation of trough subsidence showing shift of surface points with excavation (modified from Rellensmann, 1957).

ore (fig. 2). At some width of span the caving will sustain itself and continue until the void is filled with broken rock. As ore is drawn from the block, the overlying broken ore and rock will subside, creating a void into which additional rock can fall. The cave will thus migrate toward the surface at a rate determined largely by the rate at which the ore is drawn.

Chimneying is a type of cave that initiates over a relatively small area and progresses rapidly, sometimes in a matter of days, to the surface by a succession of failures or sloughs. The cross-sectional area over the length of the hole formed is usually constant and of small diameter. Although the mechanism that causes chimneying may be similar to that of progressive caving, the fact that its formation is so rapid and unpredictable, and that it affects a small area seems to make this procedure unique.

Plug caving is characterized by a sudden lowering en masse of the overburden covering an unsupported opening and is usually accompanied at the surface by venting and a dust cloud. The subsidence plug seems to involve a distinctly unique mechanism and Obert and Duvall (1967) offer no theory for this type of failure.

Sowers (1976), in discussing mechanisms of subsidence resulting from underground openings, lists solution channels or voids in soluble rocks as one of the focal points of surface subsidence. Two of the subsidence mechanisms perceived by Sowers as pertinent to solution cavities are loss of support caused by support not adequate to prevent continuing shear failure, and collapse or sudden roof and ground failure caused by enlargement of an underground opening beyond the ability of the materials above to bridge it. Sowers attributes ultimate failure development to some change in the total environment--ground water, stress, or change in the materials involved.

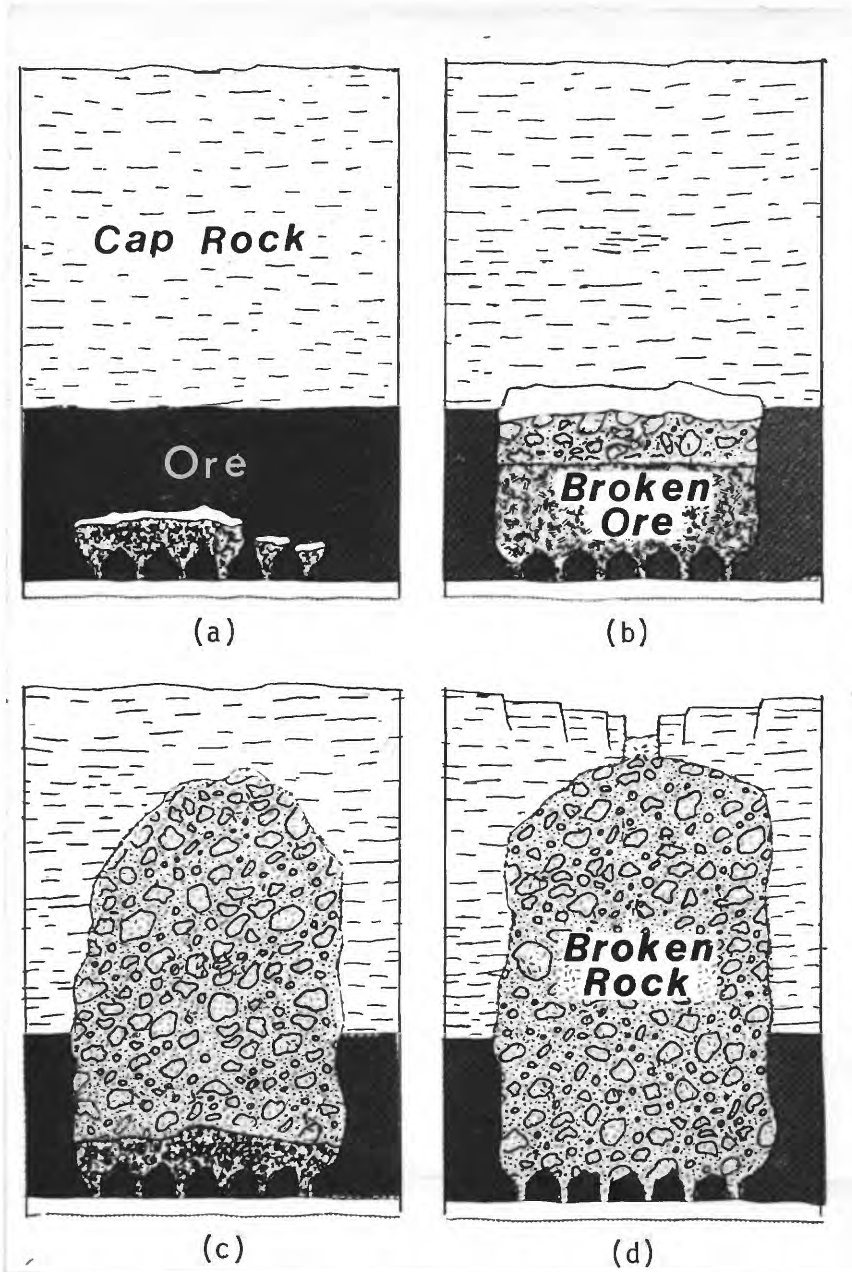

Figure 2.--Progress of subsurface subsidence induced by the block caving mining method. Caving is initiated by removing support (a) and exceeding the span (b). Removing ore creates void into which additional rock can fall (c) and if unchecked the broken zone can breach the surface (d). (Modified from Obert and Duvall, 1967.)

Subsidence over saline rocks

More than one-third of the United States is underlain by marine evaporites (fig. 3), all of which have varying degrees of solubility in permeating freshwater or undersaturated brine. If geologic conditions are such that a continuous flow of water is in contact with an evaporite deposit, then soluble minerals in the deposit can go into solution and be removed, resulting in surface brines, salt caves, and collapse features (Landes, 1963). If, in the case of a salt cave, continued uncontrolled dissolving of the soluble minerals enlarges the opening and increases the span of the unsupported roof to the strength limit of the overlying rocks, then either downwarping of the overlying beds can take place resulting in surface subsidence, or collapse of the undermined roof can occur, leading to upward stoping or chimneying of the overburden rock. If space is available underground to accept falling rock and the stoping process reaches the surface, the resulting ground failure can produce the familiar sinkhole or collapse doline.

Natural subsidence

There are many examples of natural dissolving of evaporite rocks and resultant subsidence structures throughout the world. In North America salt deposits of the Middle Devonian Prairie Formation, extending from North Dakota and Montana through Saskatchewan and Alberta to the Northwest Territories, contain structural lows that were formed through removal of salt by subsurface leaching while the salt bed was buried under hundreds of meters of sediments. Dissolving has been taking place from Late Devonian to present (De Mille and others, 1964). Gendzwill (1978) notes that in southern Saskatchewan, the Prairie Formation is underlain by reeflike carbonate

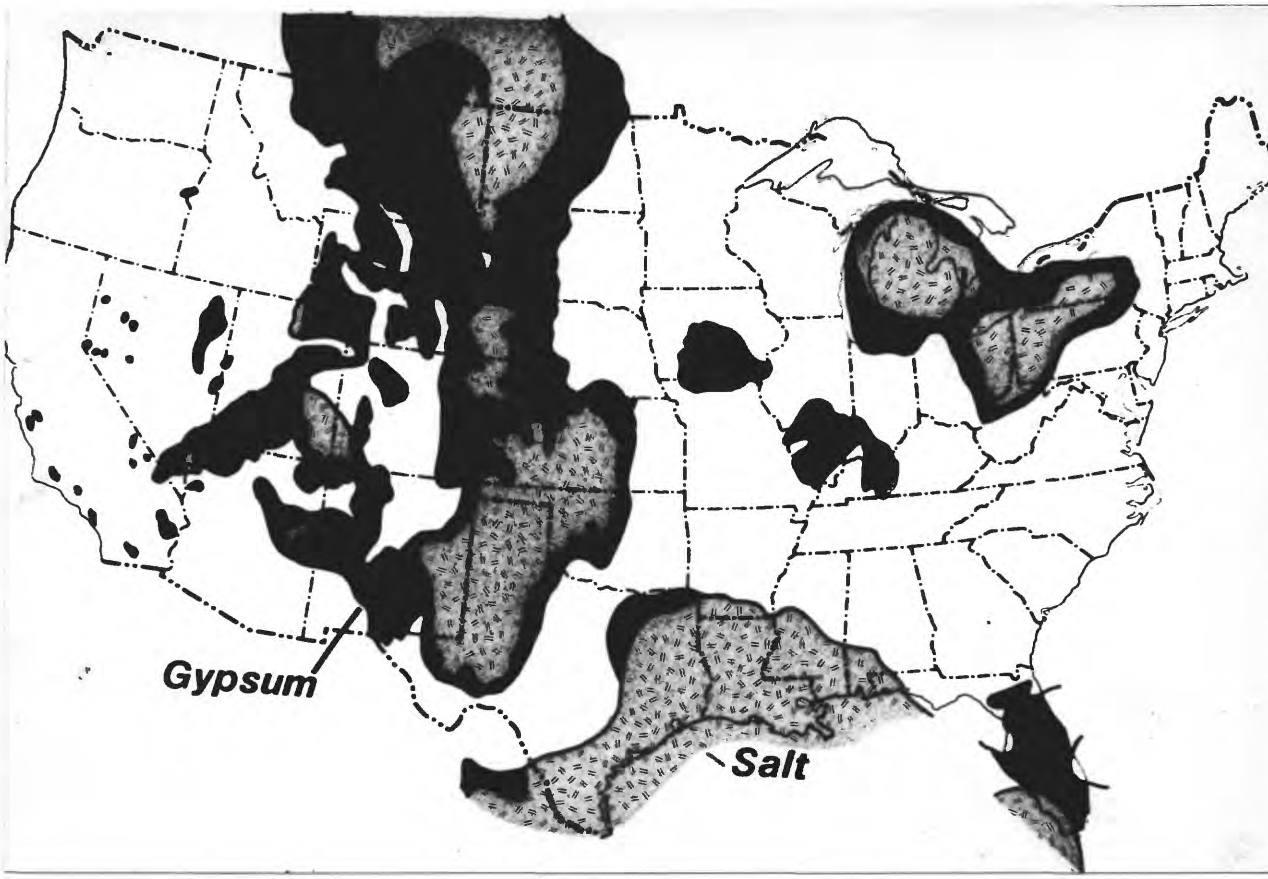

Figure 3.--Distribution of marine evaporites in the United States (modified from Smith and others, 1973).

mounds. Ground water moving through the mounds during Devonian times removed some of the salt above them causing subsidence of the younger beds as much as 30 m deep.

A structural depression, the "Saskatoon low," south of Saskatoon, Saskatchewan, formed by collapse resulting from removal of salt from the Prairie Formation. It began forming during the Late Cretaceous and continued until at least late Pleistocene time. The continuity of the collapse mechanism suggests that the dissolution of salt has been a continuing process and may be going on at the present time with possible future collapses (Christiansen, 1967). In the same area Christiansen (1971) reports that a large water-filled depression, Crater Lake, is a surface expression of a collapse formed from ground-water removal of Prairie Formation salt. The depression is 244 m in diameter and 6 m deep and comprises two main concentric fault zones. The inner cylinder was downfaulted periodically in Late Cretaceous-Tertiary-early Pleistocene time and the outer cylinder during the last deglaciation (13,600 years ago).

Parker (1967) reports that Middle Devonian and Permian salt beds underlying North Dakota, Montana, and Wyoming vary in thickness from a little over 1 m to 200 m. He attributes the salt thickness changes to postdepositional salt removal through dissolving by ground water ascending through local and regional fractures from aquifers below the salt beds.

Landes (1945) describes limestone and dolomite breccias of the Mackinac breccia located in the Mackinac Straits region of Michigan as forming from collapse of cavities dissolved out of salt beds of the Salina Formation (Silurian). There is stratigraphic evidence that some of the blocks fell as much as 200 m, indicating the presence of huge caverns. Collapse took place during Silurian and Devonian times creating breccia thicknesses as great as 1000 m.

Meade County located in the southwestern corner of Kansas has numerous hollows and sinks, some of which can be attributed to solution collapse of overlying strata into cavities dissolved from Permian salt beds. The sudden appearance of a large sink named the Meade Salt Well historically dates from March 1879. Johnson (1901, p. 702-712) quotes an article taken from the May 15, 1879, issue of a local newspaper which describes how a water-filled sinkhole suddenly formed along a well-traveled cattle trail leading from northern Texas to Dodge, Kans. (figs. 4). The sink measured 52 m in diameter and the water level was 4.3 m below land surface. Soundings indicated water depths ranging between 8.5 and 23 m in depth. Frye and Schoff (1942), in postulating the origin of the Meade County solution sinkholes, have shown that faults cut Permian strata containing salt beds and overlying Pliocene-Pleistocene sediments which contain freshwater under hydrostatic pressure (fig. 5). The local structure allows fresh artesian water to circulate down the fault zones into permeable Permian rocks at depth. The ground water flows down-gradient eastward dissolving pockets in the salt into which overlying strata collapse. Evidence of the dissolution appears as salt springs emerging at lower elevations to the east.

A more recent collapse described by Bass (1931) and Landes (1931) took place in Hamilton County, Kans., just east of the Colorado-Kansas line. A sinkhole measured to be about 30 m wide and 12-15 m deep formed on December 18, 1929. The cause was believed to be collapse of a cavern dissolved from salt or gypsum.

San Simeon Swale, a large southeastward-trending depression in Lea County, southeastern New Mexico, covers an area of about 260 km^2. The lowest part of the swale contains a collapse feature, the San Simeon Sink, which is about 30 m deep from the rim to the bottom and approximately 1.3 km^2 in

Figure 4.--View of the Meade Salt Well, a sinkhole formed from dissolution of underlying salt beds, Meade County, Kans. (Johnson, 1901).

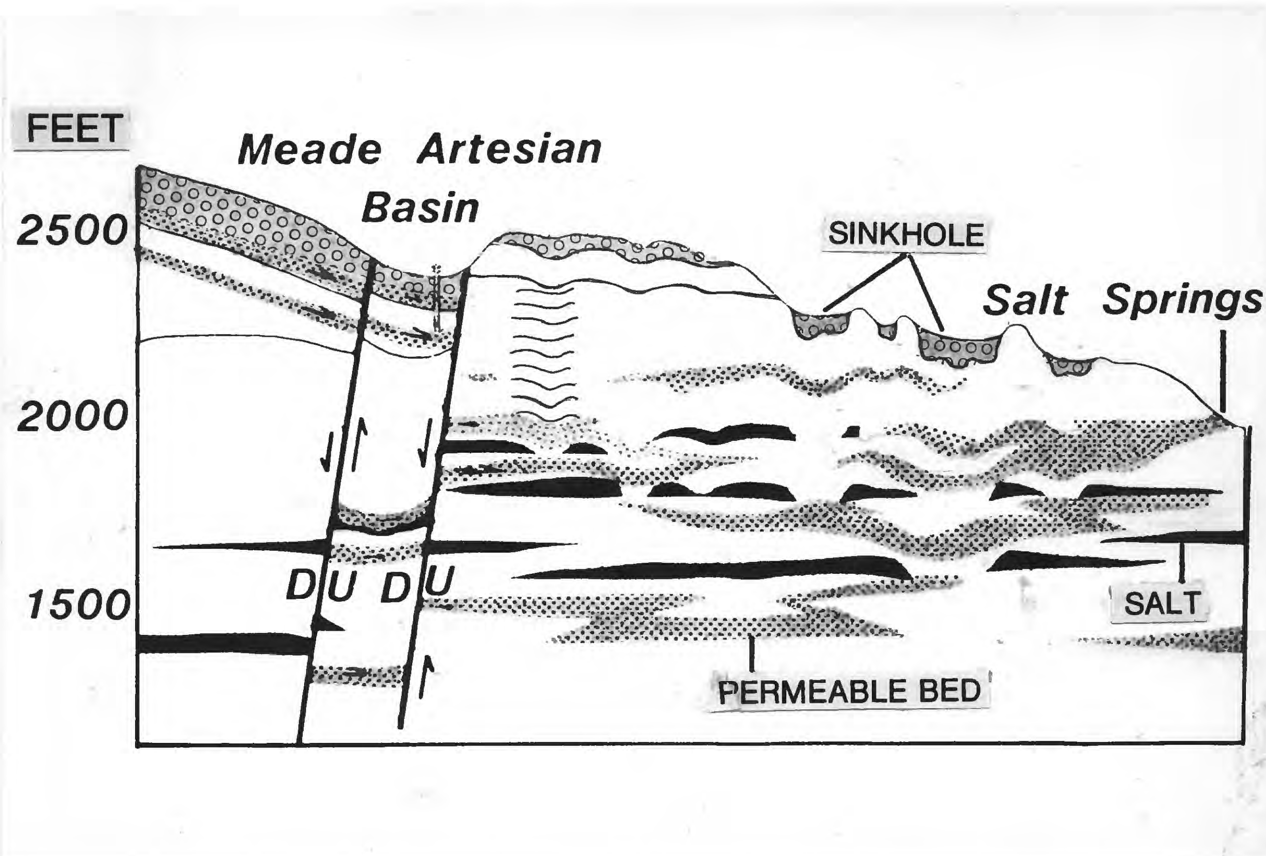

Figure 5.--Generalized section through Meade Basin showing postulated ground-water circulation down fault planes and laterally along permeable beds where adjacent salt beds are dissolved causing development of solution subsidence features (modified from Frye and Schoff, 1942).

area. Within the sink is a secondary collapse about 6.8-8.6 m deep. A great thickness of Permian salt beds underlies the southern Lea County area, and surface features such as the San Simeon structures were formed by the removal of salt by solution and collapse of the overlying beds. It seems that the swale was initially formed by a very large collapse in the vicinity of present San Simeon Sink. Based on the numerous ring fractures around San Simeon Sink, it is apparent that the sink has had a long history of successive collapse events. Subsidence as recently as 1922 took place with the development of a fissure along the western side of the sink (Nicholson and Clebsch, 1961, p. 13-17, 46-47; Bachman and Johnson, 1973, p. 25-34).

Man-induced subsidence

Subsidence related to man's activities in evaporite rocks is usually a result of some form of mining or drilling operation or construction activity. Conventional mining of bedded salt and potash deposits is similar to coal mining and the subsidence mechanisms of these mining methods are likewise similar (Obert and Duvall, 1967, p. 555). Solution extraction of salt and other soluble evaporites is a specialized mining technique and subsidence produced by this procedure has its unique problems (Marsden and Lucas, 1973). Drilling through aquifers and salt beds in search of oil, gas, and water has occasionally resulted in induced salt dissolution and subsequent subsidence (Fader, 1975). Construction of highways, dams, and reservoirs over saline or gypsiferous rock has resulted in subsidence, water loss, and dam failures (Burgat and Taylor, 1972; Sill and Baker, 1945).

Subsidence related to solution mining is currently being studied by the U.S. Geological Survey, especially in terms of geologic and hydrologic controls and mechanical properties of the soils and rock involved in the subsided area. An on-going field program is investigating the cause of subsidence at the Grosse Ile brine fields operated by the BASF Wyandotte Corporation located south of Detroit in Wyandotte, Mich. The study is being made in cooperation with the Solution Mining Research Institute (SMRI) and the University of Illinois. Studying the subsidence process in an active brining operation has the advantage of gaining access to extraction rates and volumes, cavity geometry, geologic and engineering properties of the involved rocks, and hydrologic information, all of which can be related to observed ground behavior. Permission by the BASF Wyandotte Corporation for access to its property and files is hereby acknowledged.

The basic method of solution mining consists of drilling holes to the salt or evaporite deposit, injecting freshwater or undersaturated brine down the hole in order to dissolve the soluble minerals, and then removing the resulting brine through a return conduit to the surface. There are several variations of the solution mining method which are employed according to local conditions and company policy (Quiero, 1977). Three techniques are discussed below.

The top injection single-well method (fig. 6) pumps freshwater or undersaturated brine down the annular space between the well casing and central tube. The soluble minerals, salt in the example, are dissolved and the heavier brine sinks to the bottom of the cavity and is drawn out through the central tube. This method tends to form a cone or "morning glory-shaped" cavity and control of the geometry of the opening is limited. Top injection is an older technique that is often associated with some of the uncontrolled subsidences that have occurred in brine fields, and has largely been replaced by more sophisticated techniques. The air or oil pad method (fig. 7) involves pumping air or hydrocarbon down the hole with water. The air or hydrocarbon floats on the water forming an impermeable barrier or "pad" which retards

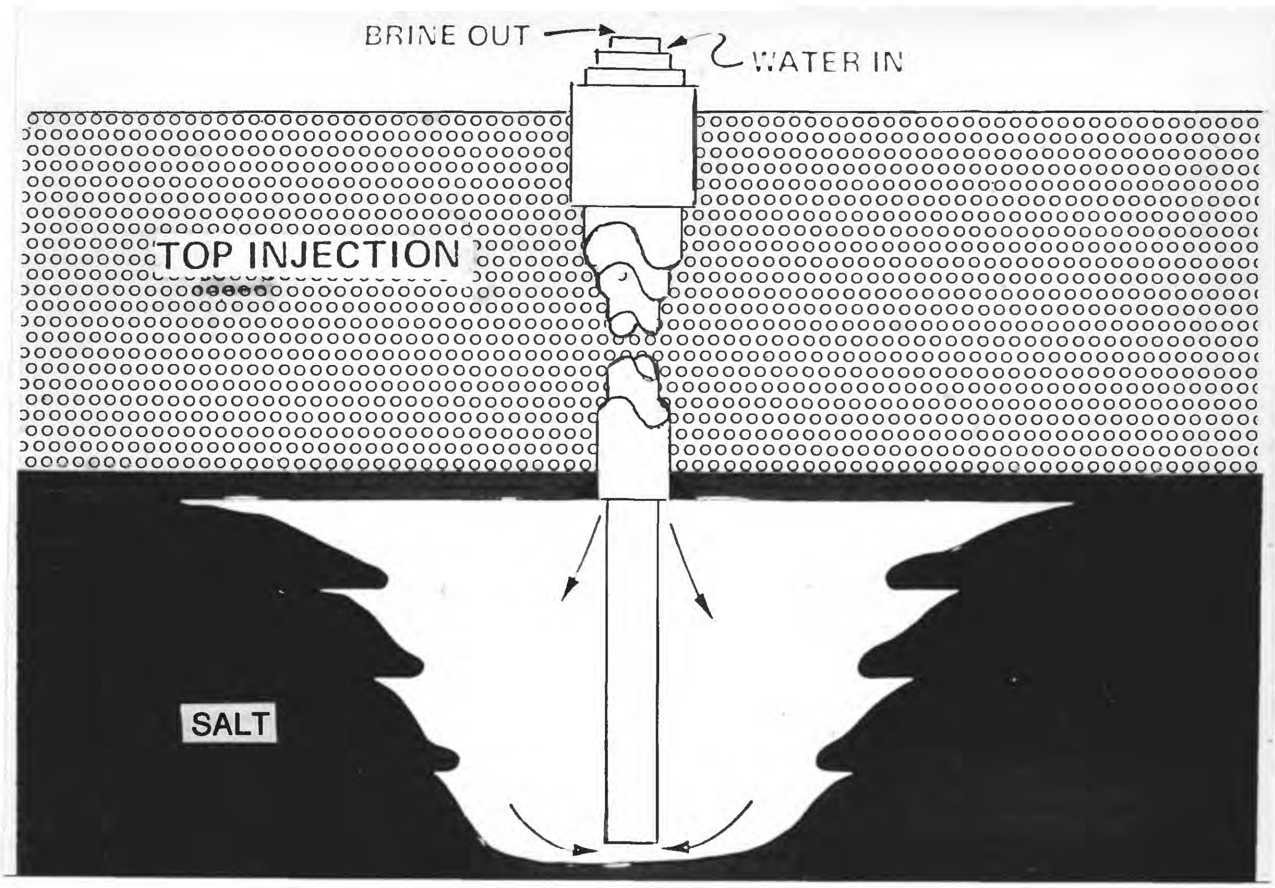

Figure 6.--Solution mining by top (annular) injection single well method. Freshwater is injected down annulus emplaced near top of salt bed. Heavier brine is pumped up tubing emplaced near base of salt bed. Top injection method tends to form "morning glory" cavity (modified from Quiero, 1977).

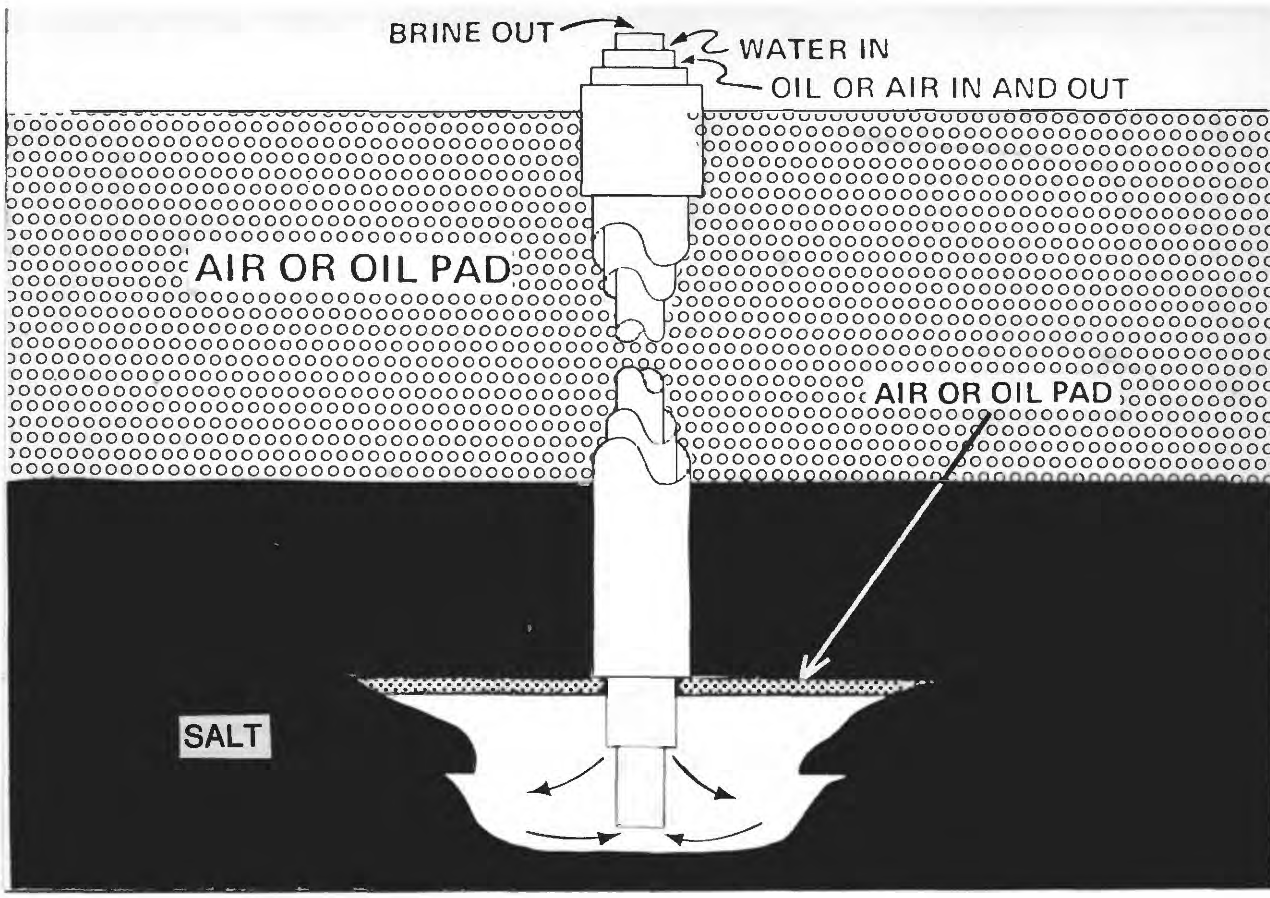

Figure 7.--Solution mining by the air or hydrocarbon pad method. Gas or hydrocarbon padding material is carried down outer annulus. The lighter pad floats on the injected freshwater forming an impermeable barrier between the salt and the dissolving water. This method is used to control the level at which salt solution occurs and a variety of techniques are used to determine the location and maintenance of the pad-solvent interface. Improved cavity shape is one advantage of the pad method. (Modified from Quiero, 1977.)

dissolution of material from the roof of the cavity. In this manner control is maintained of the cavity geometry particularly in keeping a predetermined thickness of salt or evaporite between the cavity roof and overlying geologic materials. In many cases the evaporite is a more competent structural member than the immediate overlying rock which may be a weak shale or sandstone interbedded with soluble materials.

The hydrofracture technique (fig. 8) is a relatively new method adopted from oilfield practice that prepares an area for solution mining. Two holes are drilled at a precalculated spacing. One hole is sealed off with packers within the evaporite deposit and water is injected under pressure until the rock fails in tension and a crack is formed, hopefully horizontally. Continued application of pressurized water advances the crack until it intersects the companion boring. An open hydraulic system is thereby established comprising an injection well and an extraction well. With the addition of an air or hydrocarbon pad, the solution mining can proceed with maximum control of extraction rates and cavity geometry. According to an industry spokesman, this technique allows better control of location, orientation, and size of the solution gallery and minimizes undesirable ground subsidence and collapse.

Walters (1977) discusses land subsidence occurring in central Kansas associated with conventional and solution salt mining and oil and gas operations. He describes 13 subsidence areas, five induced by mining of salt and eight resulting from oil and gas activities. One illustrative case involved a rather dramatic ground subsidence that took place in October 1974 at a brine field in Hutchinson, Kans., as a result of solution mining. South of the Cargill plant, a sinkhole some 90 m in diameter formed over a period of 3 days and left railroad tracks suspended in air (figs. 9, 10). Locally salt

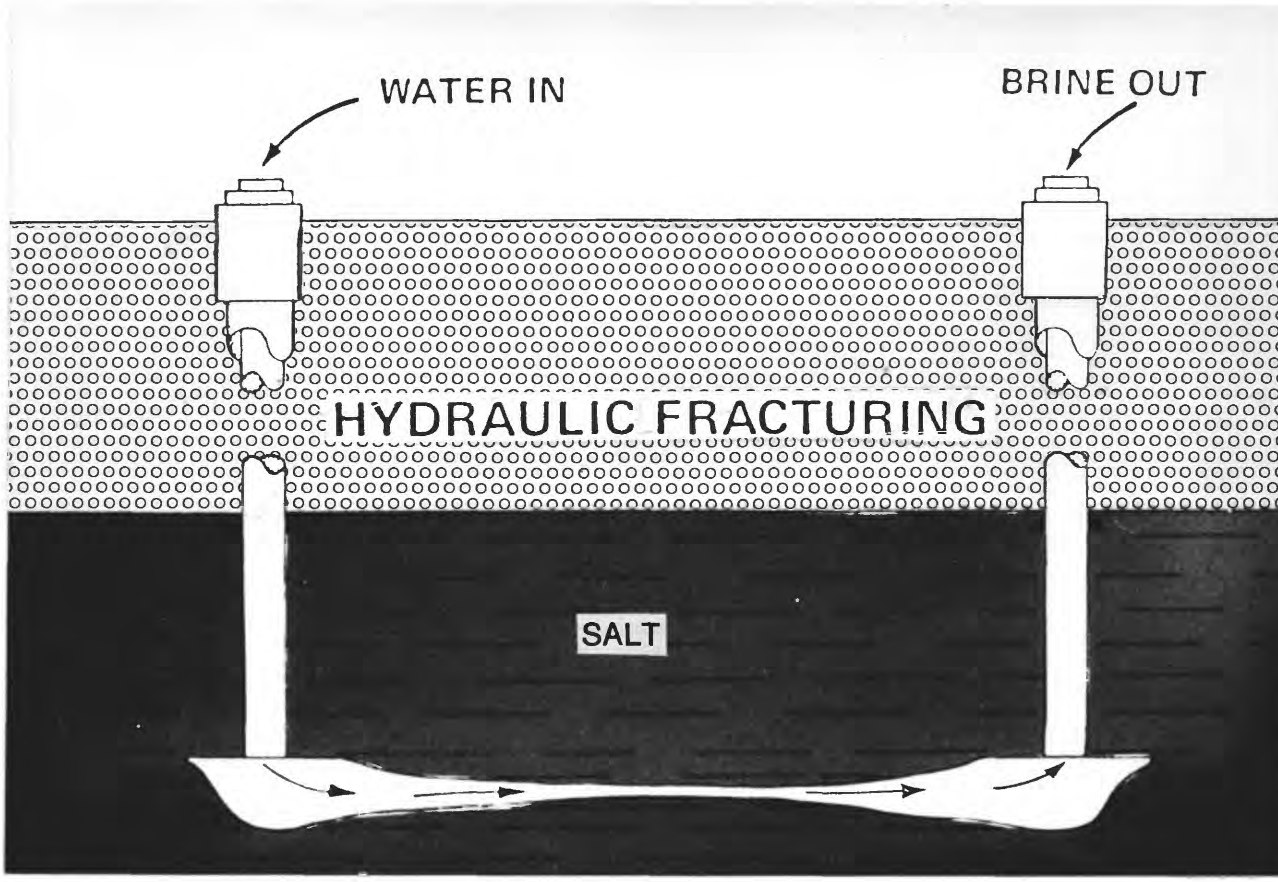

Figure 8.--Hydrofracture technique between two brining wells. Hydrofracturing is used to coalesce a system of wells into a gallery. The rock is split at the desired depth by application of pressured water in a sealed interval of the boring. Once a fracture is initiated pressure is maintained until it intersects an adjacent target well. Solutioning along the induced fracture commences brine productions (modified from Quiero, 1977).

is extracted from the approximately 105-m-thick Hutchinson Salt Member of the Permian Wellington Formation, which is encountered at a depth of about 120 m below ground surface. Overlying the salt is Permian shale capped by unconsolidated Pleistocene sands and gravels and loess-like soil. Salt has been produced at this location since 1888, and the locations of many of the earlier wells are not known. The older solution methods used were often uncontrolled and because of the free-dissolving nature of the former techniques the extent of many of the solution cavities in the area is largely unknown. The sinkhole formed in an active brine field which included both operating and abandoned wells and cavities of unknown geometries.

Post-subsidence drilling of the collapse area as part of an SMRI-Cargill investigation indicated that an elongate northeast-southwest cavity lay beneath the sinkhole which paralleled northeast-southwest trending producing wells that were hydraulically connected (fig. 11). The long dimension of the gallery may be more than 400 m in length (Walters, 1977), which apparently exceeded the span capabilities of the overlying rock layers. This, in turn, caused roof-rock failure which progressed by sequential collapse of the overlying rock layers until the uppermost rock layer was breached.

Several examples of land subsidence associated with oil and gas operations in central Kansas are described by Walters (1977, p. 31-75). Underground oil in central Kansas is associated with gas- and water-driven brine aquifer reservoirs. The oil is separated from the brine and the undersaturated salt water is disposed of underground in brine disposal wells that penetrate a permeable formation, dolomite of the Arbuckle Group, able to receive and store the waste liquid. In a few instances, particularly in salt disposal wells, improperly sealed casing or casing that has been corroded and breached has allowed undersaturated saltwater to come in contact with salt

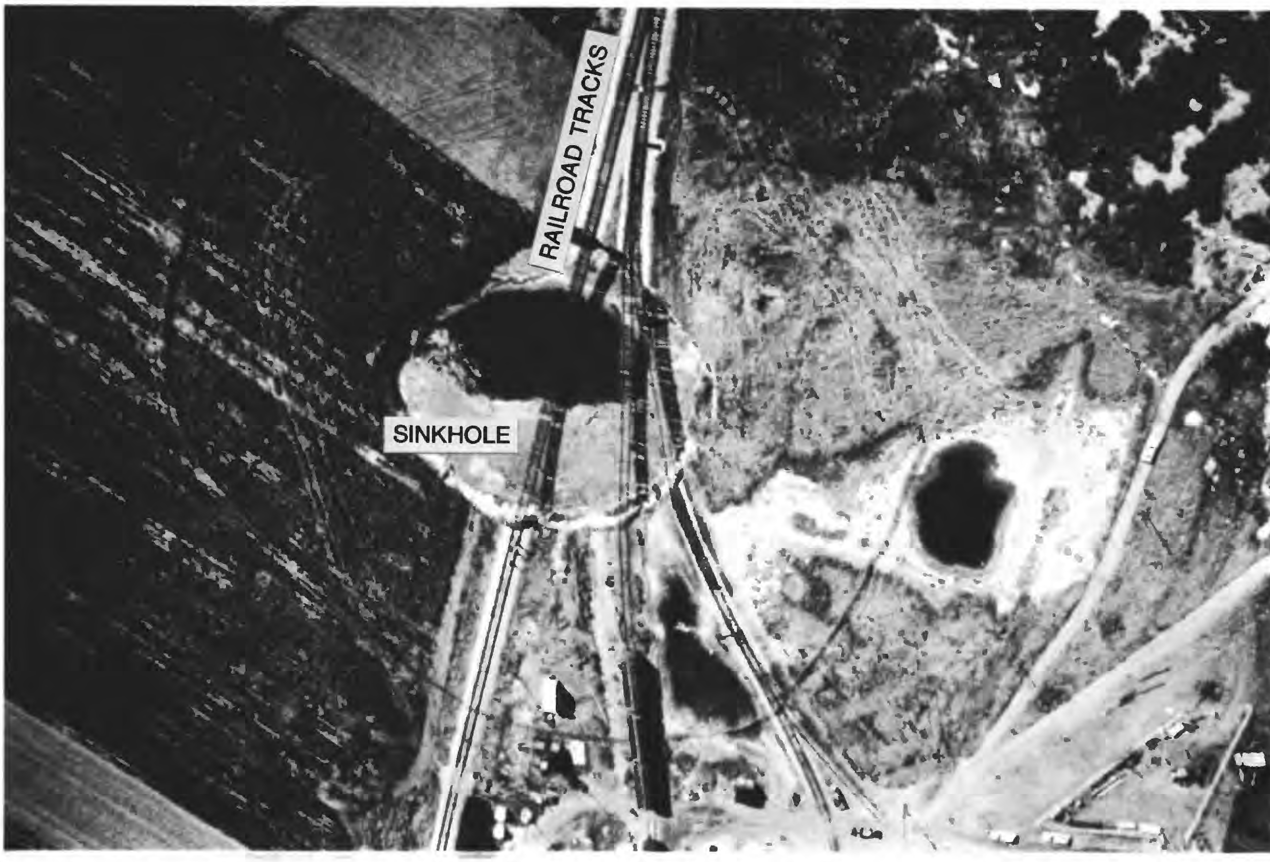

Figure 9 .--Overhead view of sinkhole at Cargill, Inc., plant site in 1974, Hutchinson, Kans. Sinkhole formed beneath railroad tracks seen here suspended in midair. (Walters, 1977.)

Figure 10.--View of sinkhole at Cargill, Inc., plant in 1978, Hutchinson, Kans. Photograph taken by J. R. Ege.

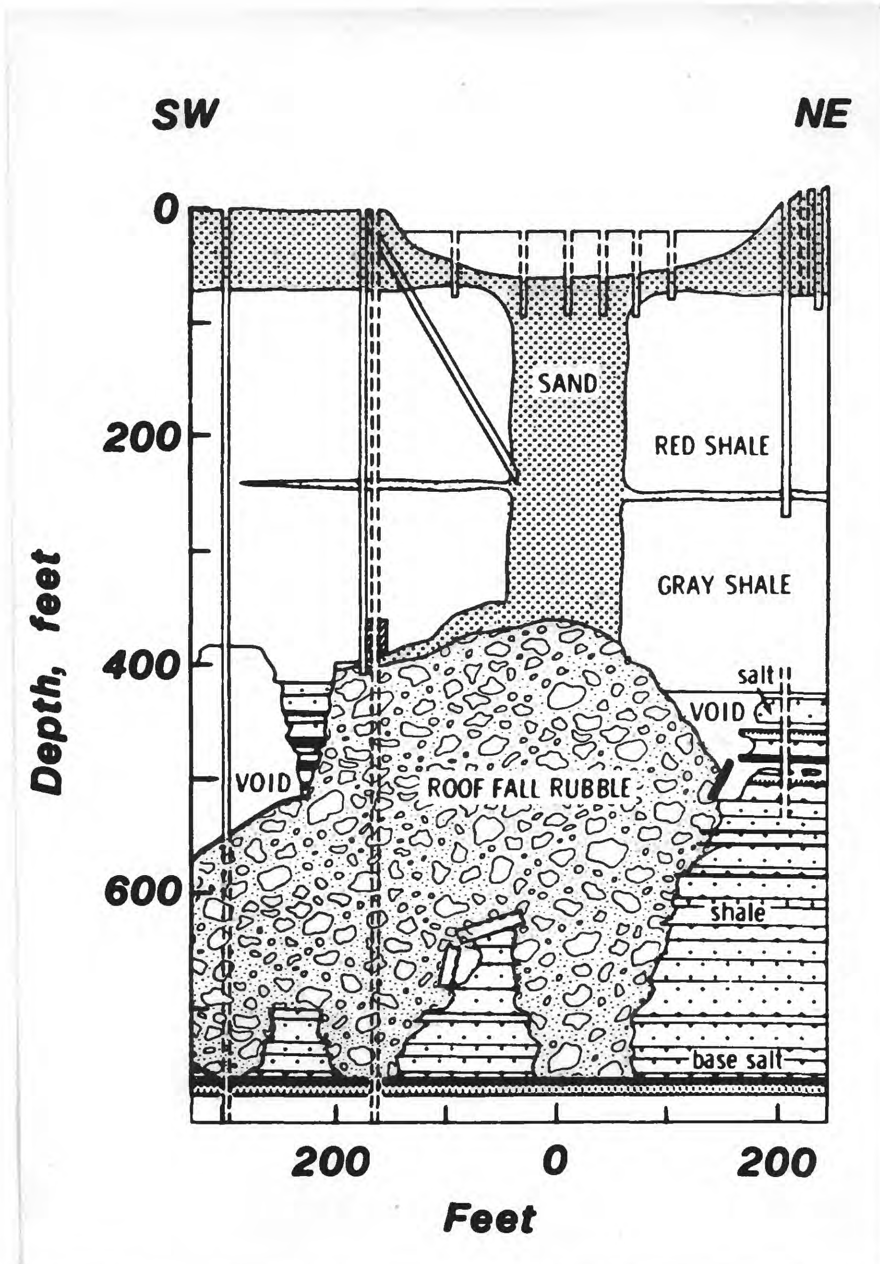

Figure 11.--Cross section and interpretation of the Cargill sinkhole based on post-collapse borings, Hutchinson, Kans. (modified from Walters, 1977).

strata overlying the dolomite and dissolve out voids in the salt beds. Undersaturated brine input extending over many years has in these cases permitted dissolution of sufficiently large quantities of salt to cause progressive upward caving of the salt layers culminating in surface collapse.

On April 24, 1959, rapid subsidence developed around an oil well known as the Panning 11-A located in Barton County, Kans., then in the process of abandonment after extensive use as a saltwater disposal well. Continuing subsidence over a 12-hour period developed a water-filled circular crater nearly 90 m in diameter with the water level 15-18 m below the ground surface, after which major vertical movement ceased. Walters (1977) postulates that during initial drilling of the Panning 11-A in 1938, freshwater drilling fluid dissolved salt to a diameter of 137 cm in a 35-m section that never had cement emplaced around the casing over this interval. The top of the salt section was at a depth of 297 m. In 1946 the boring was converted from an oil well to a saltwater disposal well. Brine was disposed through tubing by gravity flow into dolomite of the Arbuckle Group some 920 m below the surface. In 1949 the tubing was removed and brine was disposed directly down the casing. Inspection showed that corrosion of casing resulted in leaks permitting undersaturated brine to circulate across the salt face, then downward into the dolomite aquifer. A huge cavern, larger than 90 m in diameter, was dissolved in the salt. Successive roof falls of the cavity caused progressive migrating of the void upward resulting in surface subsidence. The well was abandoned in January 1959. On April 24, 1959, the upper rock layer failed and the void breached the surface creating the 90 m sink.

On April 27, 1976, a large sinkhole appeared suddenly in the city of Grand Saline, Tex. (Grand Saline Sun, 1976). Failure occurred in two stages. First, a hole 4-6 m in diameter and more than 15 m deep formed on

Tremont Street. Second, the hole widened rapidly as rim material moved down the hole by slabbing and toppling failure (C. R. Dunrud and B. B. Nevins, unpub. mapping, 1979). Grand Saline is the site of a salt-producing region where salt was mined from the Grand Saline dome by solution methods between 1924 and 1949. A similar collapse took place in 1948 just east of the present sink according to the Grand Saline Sun (1976).

Early in 1971 two sinkholes, designated North and Central sinkholes, formed on the Grosse Ile brine field of BASF Wyandotte Corporation as a result of solution mining over a period of almost 20 years (fig. 12). A similar collapse in 1954 took place at a brine field operation nearby in Windsor, Ontario (Terzaghi, 1970). Two studies on the Grosse Ile events were commissioned and published by the SMRI. Landes and Piper (1972) reported on the environmental effects of the subsidence, and Nieto-Pescetto and Hendron (1977) discussed mechanisms of the collapse. The following summary is based on these two reports.

Grosse Ile Island in the Detroit River is composed of moraine consisting of about 18 m of clay with scattered boulders deposited on dolomite bedrock (fig. 13). Between the top of the bedrock and the top of the salt beds is 150 m of nearly horizontal stratified rock consisting of impure dolomite underlain by sandstone and more impure dolomite. The rock section containing the salt is about 220 m in thickness; the more massive salt beds that are solution-mined lie toward the base at depths between 340 and 400 m.

In November 1969 concentric cracks were first observed in the ground above the North Gallery (fig. 12). Solution mining in this area had been in operation for nearly 20 years. One year later a depression was observed in the same area around which concentric cracks showed vertical displacements of several inches. On January 9, 1971, a depression about 7X9 m appeared and

Figure 12.--Aerial view of the sinkholes formed at Grosse Ile, Mich., on the BASF Wyandotte Corporation property (Landes and Piper, 1972).

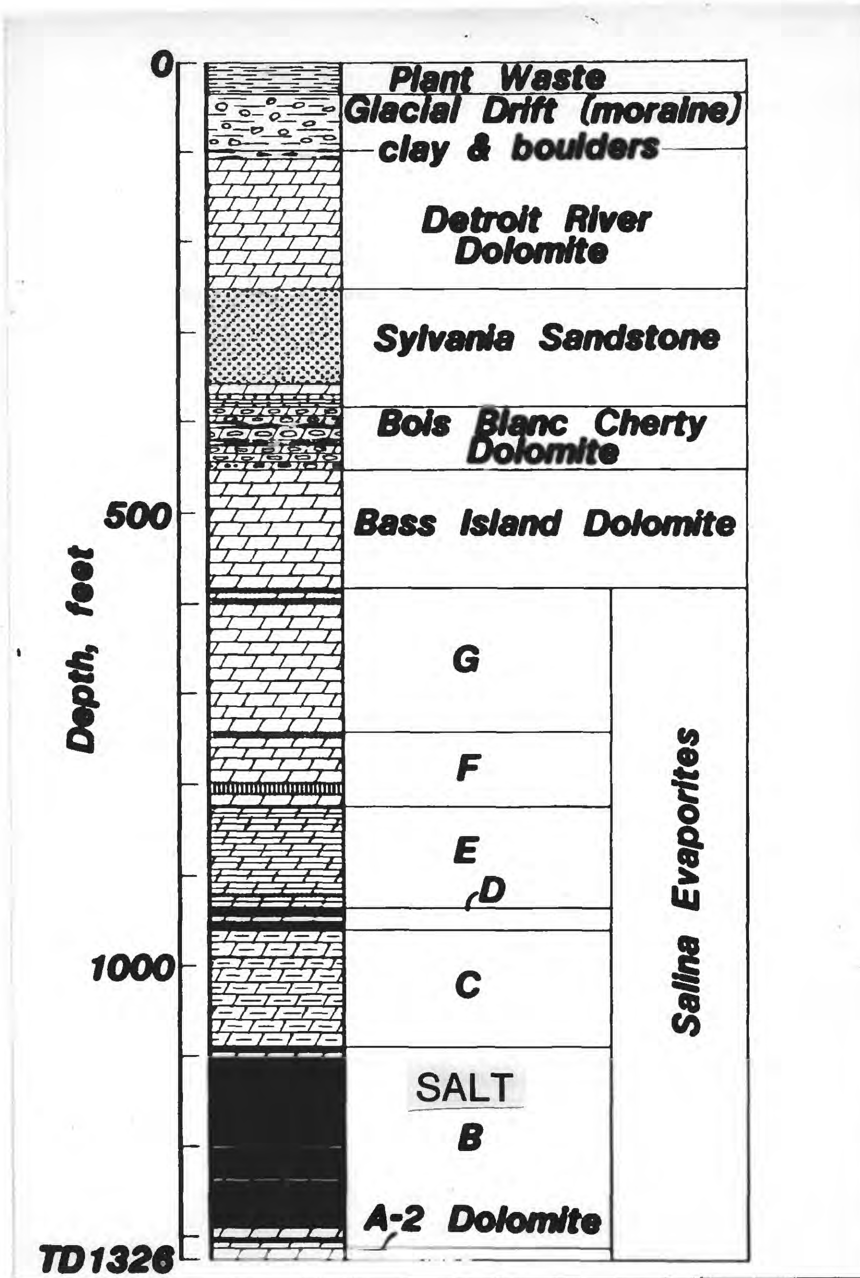

Figure 13.--Stratigraphic column of rocks under Grosse Ile, Mich. (Landes and Piper, 1972).

progressively enlarged over a period of several months into a sink about 60 m in diameter. The sink has stabilized at the configuration. On April 28, 1971, collapse started above the Central Gallery (fig. 12) which is about 800 m south of the North Gallery. No extensive subsidence or cracking of the surface preceded the Central sinkhole formation as experienced with the North sinkhole. The Central sinkhole progressively enlarged over a period of months attaining a diameter of about 135 m and stabilized at this configuration. A smaller sink (62 m diameter) formed adjacent to the Central sinkhole but lies within the bounds of the concentric cracks delimiting the central collapse zone.

Various factors proposed by Nieto-Pescetto and Hendron (1977) are considered to have been contributary to the formation of the Grosse Ile sinkholes. The initial development of the brine field by using older single cavity injection wells was probably instrumental in removing large areas of roof support in the salt section because of the tendency to form morning glory- or V-shaped cavities. A local thinning of salt in the brine field formed an axis of pinchout that served to concentrate extraction and to create large cavities adjacent to the axis that underlay the future sinkholes. The sloping roof due to the pinchout allowed the less dense freshwater to dissolve more salt updip away from the pinchout axis, thereby enlarging the openings on either side of the axis. Continued extraction of salt and enlargement and coalescence of several cavities may have increased the span of the gallery beyond the strength of the roof rock resulting in downwarping or failure of the overlying rock.

The U.S. Geological Survey, University of Illinois, Solution Mining Research Institute, and BASF Wyandotte Corporation are continuing the investigation of the mechanisms and causes of the subsidence and sinkhole occurrences in the Detroit area.

Conclusions

The visual effect of subsidence at the ground surface as a result of the collapse of natural or man-made cavities is usually a bowl-shaped depression resulting from downward vertical movements. Extraction or removal of salt and other soluble evaporites from underground deposits can cause subsidence. Sinkholes, both natural and man-induced, have formed many times in the past over soluble rocks and are a consequence of removal of support. A key factor in the subsidence process is the character and nature of the geologic materials overlying the underground void.

In order for salt and other soluble evaporites to be removed and for cavities to form, an open hydraulic system is required where freshwater or undersaturated brine is introduced to the soluble material, dissolves it, and removes the minerals in solution. Conversely, dissolving of salt would soon cease if water remained inplace and was allowed to become saturated and in equilibrium with the surrounding rock.

More than one-third of the United States is underlain by marine evaporites. Naturally induced subsidence and collapse structures have been reported on in North America from such diverse areas as Saskatchewan, North Dakota, Montana, Wyoming, Kansas, Oklahoma, New Mexico, Virginia, West Virginia, and Michigan. The time range of formation of these structures extends from the Silurian to the present.

Subsidence has occurred over cavities that were created artificially in evaporites in association with mining, drilling, and dam and highway construction activities. Often man-related subsidence occurs in populated or built-up areas where lowering or collapse of the ground surface can be hazardous to property and lives. Some of the more spectacular cases of subsidence have resulted from solution mining of salt beds and oil production activities in fields associated with salt deposits.

Voids formed in soluble beds through dissolution by freshwater or undersaturated brine introduced through brine or oil wells, if uncontrolled, can enlarge until the spans exceed the roof-rock strength causing downwarping or collapse of the overburden rocks. The cavity thus formed can, over periods of months or years, migrate toward the surface as the cavity roof collapses and rock debris falls onto the cavity floor. If the void breaches the surface, a sinkhole is the result.

Additional study is needed in understanding the alteration of the in situ stress field caused by cavity formation, the effect of ground water on the subsidence process, and especially the behavior of the geologic materials overlying the solution cavity when they are subjected to downwarping and subsequent displacements and stress changes.

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