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GEOLOGICAL SURVEY CIRCULAR 897

Formation of Solution-Subsidence Sinkholes Above Salt Beds

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CONTENTS

ILLUSTRATIONS

FORMATION OF SOLUTION-SUBSIDENCE SINKHOLES ABOVE SALT BEDS

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INTRODUCTION

More than one-third of the United States is underlain by marine evaporites (fig. 1), all of which have varying degrees of solubility in permeating fresh water or unsaturated brine (Johnson and Gonzales, 1978; Landes, 1963b; Smith and others, 1973, p. 197–216). Research supported by the U.S. Geological Survey has investigated mechanisms of subsidence over soluble rocks, in particular salt deposits (Ege, 1979; Savage, 1981). The research is directed toward a better understanding of the geologic environment and processes of subsidence, and toward formulating measures to avoid or mitigate the effects of ground collapse resulting from dissolution of underlying soluble rocks. This report discusses various mechanisms of surface subsidence above underground openings formed in salt terranes. Both natural and man-induced (artificial) processes are considered.

SUBSIDENCE OVER SALINE ROCKS

Subsidence is a sinking of the ground surface (Allen, 1969; Landes, 1963b; Obert and Duvall, 1967, p 554–581; Rellensmann, 1957, p. 35–49; Sowers, 1976, p. 2–8; and Stefanko, 1973, v. 1, p. 13–2 to 13–9). Many sedimentary basins, worldwide, contain great thicknesses of bedded salt in which extraction of the soluble minerals, whether by natural or man-induced processes, can result in localized land-surface subsidence. The contact of a salt bed with flowing water or unsaturated brine produces cavities in the salt through the leaching of soluble minerals. Density layering (saturation decreasing upward) of the brine tends to concentrate solutioning along the roof of the void, often resulting in a "V"-shaped cavity. If, for example, continued, uncontrolled dissolving of the soluble minerals in a salt cavity increases the width of the roof arch to the point of failure, 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 of the overburden rock. If space is available underground to accept falling rock and the stoping process breaches the surface, the resulting ground failure can produce a sinkhole.

The stoping process (fig. 2) can be visualized by examining the block-caving method used in mining operations where roof failure is deliberately induced by removing support through increasing the width of a mined opening in an ore body (Obert and Duvall, 1967, p. 554–581). At mine level, ore is withdrawn creating a space into which the overlying broken ore and rock can subside. A void is thus formed where the moving ore and rock separate from solid rock. Additional rock can now fall into the newly formed void and, at some critical width, the caving process will sustain itself and continue until the opening is filled with broken rock. The cave, in this manner, will migrate toward the surface at a rate determined largely by the rate at which the ore is removed. If the cave breaches the surface, a sinkhole will form.

Another mechanism, subsurface mechanical erosion of sedimentary beds overlying salt, may be an important component of the subsidence process. Mechanical transport of sediment by ground water from overlying granular beds into deeper salt cavities may form voids in the overlying sediments that are then subject to collapse. Subsidence also can be induced by artificial processes such as solution mining of salt or potash, oil- and

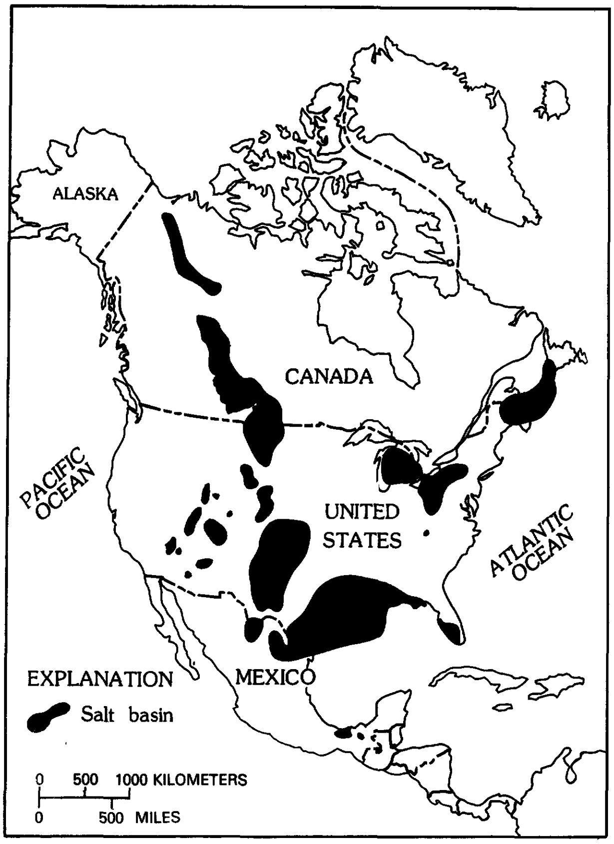

FIGURE 1.—Major salt basins of North America. (Modified from Johnson and Gonzales, 1978; Landes, 1963a.)

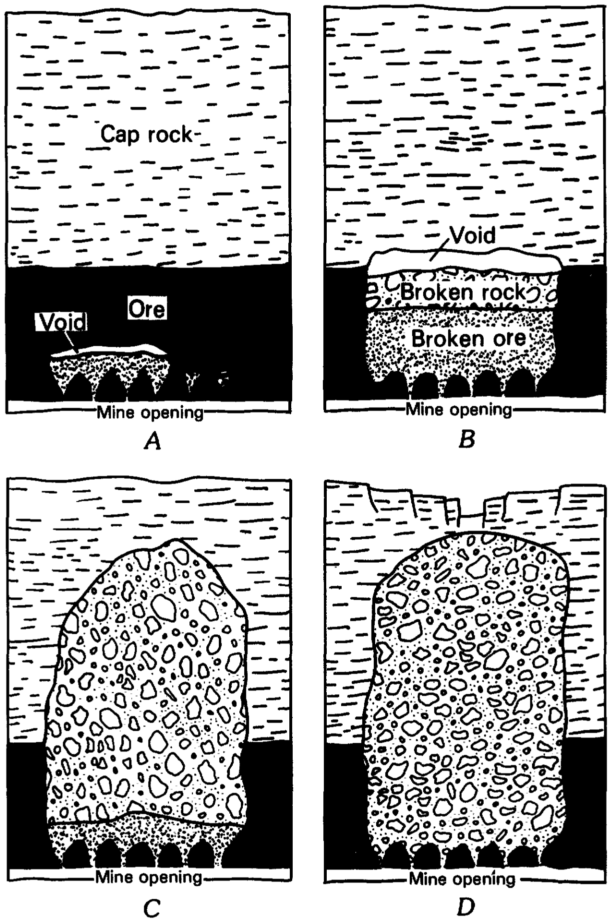

FIGURE 2.—Progress of subsurface subsidence induced by the block-caving mining method. Ore is mined, forming a void. *A*, Caving begins, removing support under roof until, *B*, width of span exceeds capability of roof rock to stand. *C*, Continuous removal of ore enlarges void into which additional rock can fall. *D*, If roof support is not reestablished by void being sufficiently filled with falling rock, then broken zone can progress upward until it breaches the surface. (Modified from Obert and Duvall, 1967 (used with permission of the publisher).)

water-well drilling through salt beds, and construction activities above saline rocks.

NATURAL SUBSIDENCE

In natural subsidence, cavities form in salt by the dissolving action of fresh ground water or unsaturated brine that flows through enclosing permeable beds and along faults or other discontinuities in surrounding rocks, or by the leaching of caves exposed in salt beds adjacent to lakes and streams. Subsidence features ranging in area between 100 and 1,000 m^2 have resulted from natural solutioning. Many examples occur throughout the world of natural dissolving of evaporite rocks and resultant subsidence structures.

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 sediment. Dissolving has been taking place from Late Devonian to the present (DeMille and others, 1964). Gendzwill (1978) noted that in southern Saskatchewan, the Prairie Formation is underlain by reeflike carbonate mounds. Ground water moving through these mounds during Devonian time removed some of the overlying salt deposits, causing subsidence of the younger beds of as much as 30 m.

A structural depression, the "Saskatoon low," south of Saskatoon, Saskatchewan, formed by collapse resulting from removal of salt from the

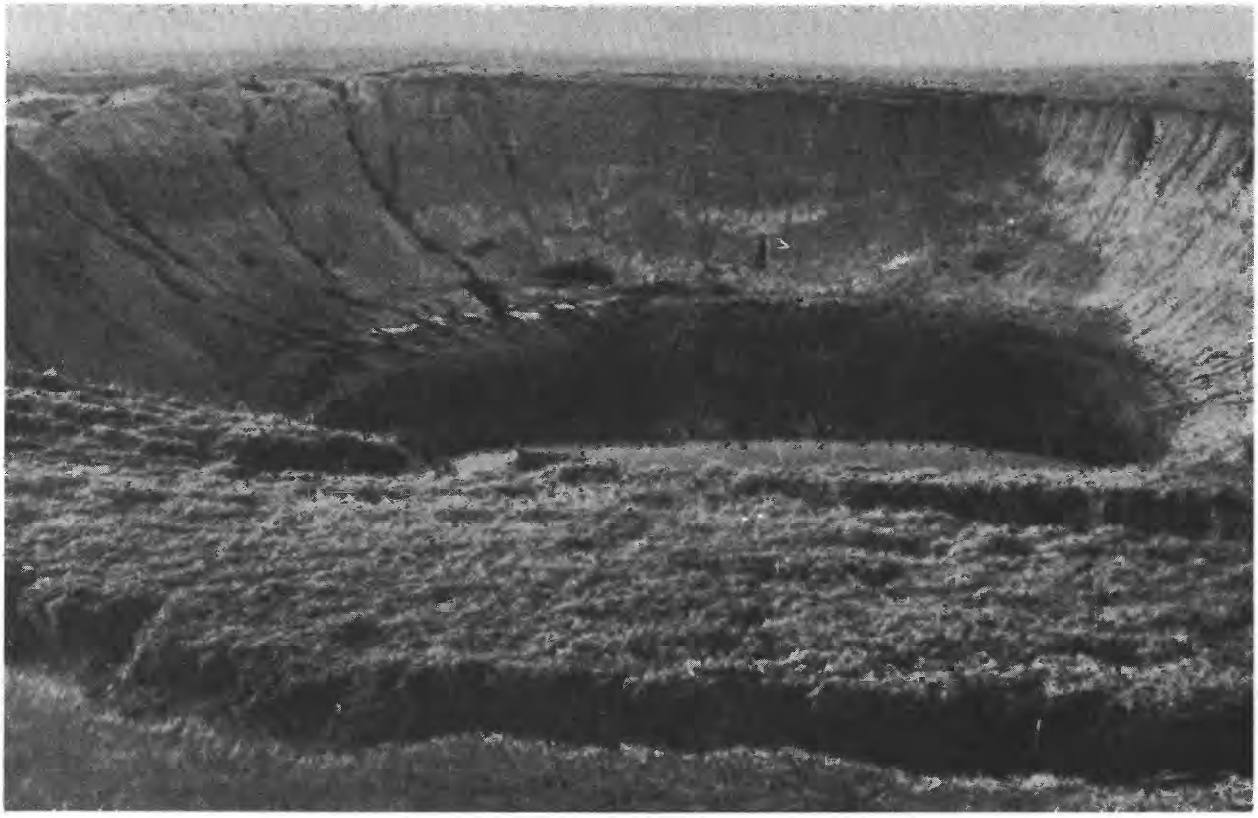

FIGURE 3.—The Meade Salt Well, a sinkhole formed from dissolution of underlying salt beds, Meade County, Kans. (Johnson, 1901). Note man standing at base of sinkhole for scale.

Prairie Formation. This depression began forming during the Late Cretaceous, and removal of salt 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 present, raising the possibility of forming collapse features at some future time (Christiansen, 1967). In the same area, Christiansen (1971) reported that a large water-filled depression, Crater Lake, is a surface expression of a collapse formed by ground-water removal of Prairie Formation salt. The depression is 244 m in diameter, 6 m deep, and comprises two main concentric fault zones. The inner zone was downfaulted periodically in Late Cretaceous-Tertiary-early Pleistocene time and the outer zone was downfaulted during the last (13,600 B.P.) deglaciation of the area.

Parker (1967) reported that Middle Devonian and Permian salt beds underlying North Dakota, Montana, and Wyoming, vary in thickness from a little more than 1 to 200 m. He attributed the salt thickness changes to postdepositional salt removal that was dissolved by ground water that ascended through local and regional fractures from aquifers below the salt beds.

Landes (1945) described 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). Stratigraphic evidence shows 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 1,000 m.

The ground surface in Meade County, located in the southwest 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. A large sink, named the Meade Salt Well, formed suddenly in March 1879. Johnson (1901, p. 702–712) quoted an article taken from the May 15, 1879, issue of a local newspaper that described how a water-filled sinkhole suddenly formed along a well-traveled

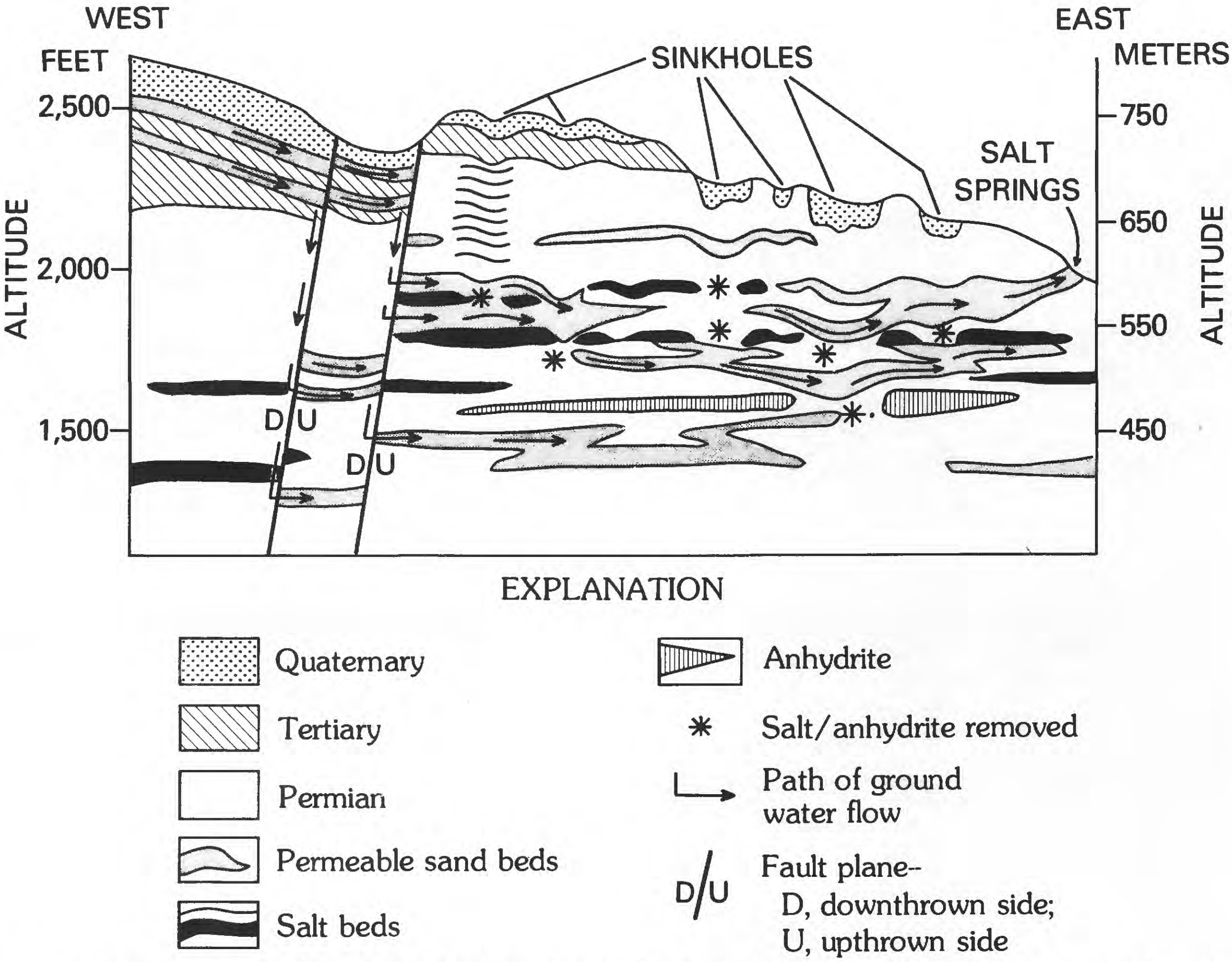

FIGURE 4.—Generalized section through Meade Basin showing postulated ground-water circulation down fault planes and laterally along permeable beds where adjacent salt beds are dissolved causing formation of solution-subsidence features. (Modified from Frye and Schoff, 1942.)

cattle trail, leading from northern Texas to Dodge City, Kans. (fig. 3). 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. Frye and Schoff (1942), in postulating the origin of the Meade County solution sinkholes, showed that faults cut Permian strata containing salt beds and overlying Pliocene-Pleistocene sediments that contain fresh water under hydrostatic pressure (fig. 4). The local structure allows fresh artesian water to circulate down the fault zones into permeable Permian rocks at depth. The ground water, flowing down gradient through the permeable layers in contact with the salt beds, dissolves openings in the salt into which overlying strata collapse. Evidence of the dissolution appears as salt springs emerging at lower altitudes to the east of the sinkholes.

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 measuring about 30 m wide and 12 to 15 m deep formed on December 18, 1929. The cause was believed to be collapse of a cavern dissolved from salt or gypsum.

San Simon 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 Simon sink, that is about 30 m deep and approximately 1.3 km^2 in area. Within the sink is a secondary collapse feature about 6.8 to 8.6 m deep. Thick Permian salt beds underlie the southern Lea County area, and surface features such as the San Simon swale were formed by the removal of salt by solution and collapse of the

FIGURE 5.—Aerial photograph of sinkhole at a local solution-mining plant site, Hutchinson, Kans., in 1974 (Walters, 1977 (reproduced with permission of the publisher)). Sinkhole is about 100 m in diameter.

overlying beds. It seems that the swale was initially formed by a large collapse in the vicinity of the present San Simon sink. On the basis of the numerous ring fractures around San Simon sink, it is apparent that the sink has had a long history of successive collapse events. Subsidence took place as recently as 1922, with the development of a fissure along the west 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 affecting 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 that can produce subsidence (Querio, 1977; 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 infiltration and consequent subsidence, water loss, and dam failures (Burgat and Taylor, 1972; Sill and Baker, 1945).

Walters (1977) discussed land subsidence occurring in central Kansas that was associated with conventional and solution salt mining and oil and gas operations. He described 13 subsidence areas, 5 induced by mining of salt and 8 resulting from oil and gas activities. One illustrative case involved a ground collapse that took place in October 1974, at a brine field in Hutchinson, Kans., as a result of solution mining. South of the local solution-mining plant, a sinkhole some 90 m in diameter formed over a period of 3 days and left railroad tracks suspended in air (fig. 5). Locally, salt is extracted from the approximately 105-m-

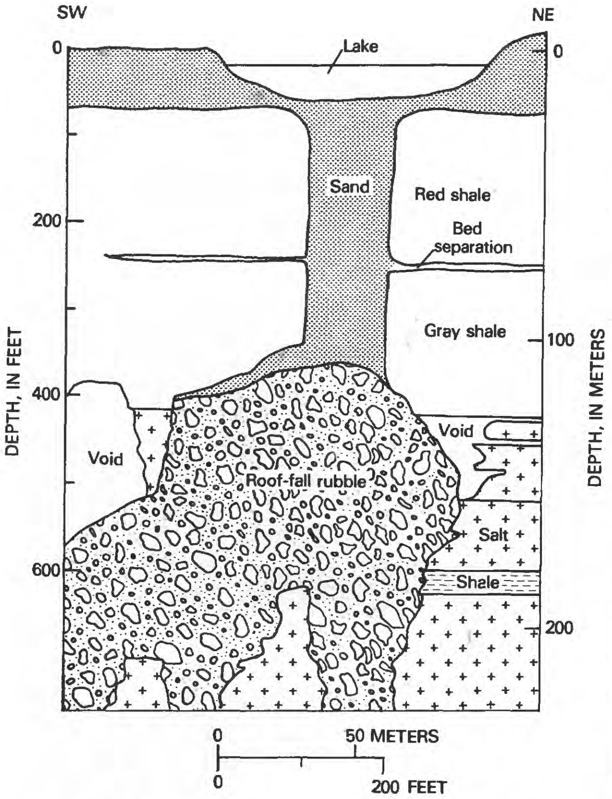

FIGURE 6.—Cross section of sinkhole, Hutchinson, Kans., based on postcollapse borings (not shown). (Modified from Walters, 1977, p. 79–82.)

thick Hutchinson Salt Member of the Permian Wellington Formation, which occurs at a depth of 120 m below ground surface. Overlying the salt is Permian shale capped by unconsolidated Pleistocene sands and gravels and loesslike soil. Salt has been produced at this location since 1888, and the locations of many of the earlier wells are not recorded. The older solution methods often allowed uncontrolled dissolving of salt with the result that the extent of many of the solution cavities in the area is not known. This sinkhole formed in an active brine field, which included both operating and abandoned wells and cavities of unknown geometries.

Postsubsidence drilling of the collapse area as part of a Solution Mining Research Institute (SMRI) investigation indicated that an elongate northeast-southwest cavity lay beneath the sinkhole. The subsurface cavity also paralleled a northeast-southwest-trending line of producing wells that were hydraulically connected (fig. 6). The long dimension of the cavity may be more than 400 m (Walters, 1977), which apparently exceeded the span capabilities of the overlying rock layers. This, in turn, caused roof-rock failure that progressed by sequential collapse of the overlying beds until the surface 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 crude oil in central Kansas is associated with gas- and water-driven brine-aquifer reservoirs. The oil is separated from the brine that then is disposed of underground in brine disposal wells that penetrate a permeable dolomite of the Arbuckle Group, which is 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 unsaturated saltwater to come in contact with salt strata overlying the dolomite, and dissolve voids in the salt beds. Input of unsaturated brine extending over many years has, in these cases, permitted upward caving of the salt layers, culminating in surface collapse.

On April 24, 1959, rapid subsidence occurred around a depleted oil well located in Barton County, Kans., which was in the process of abandonment after long-term use as a saltwater disposal well. Continuing subsidence over a 12-hour period formed a water-filled circular sink nearly 90 m in diameter with the water level 15 to 18 m below the ground surface, after which major vertical movement ceased. Walters (1977) postulated that during initial drilling of an oil well in 1938, fresh-water drilling fluid dissolved salt to a diameter of 137 cm in a 35-m section that never had cement emplaced around the casing. 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 unsaturated brine to move 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 migration of the void upward, resulting in surface subsidence. The well was abandoned in Janurary 1959. On April 24, 1959, the upper rock layer failed, and the void breached the surface, creating the 90-m sink.

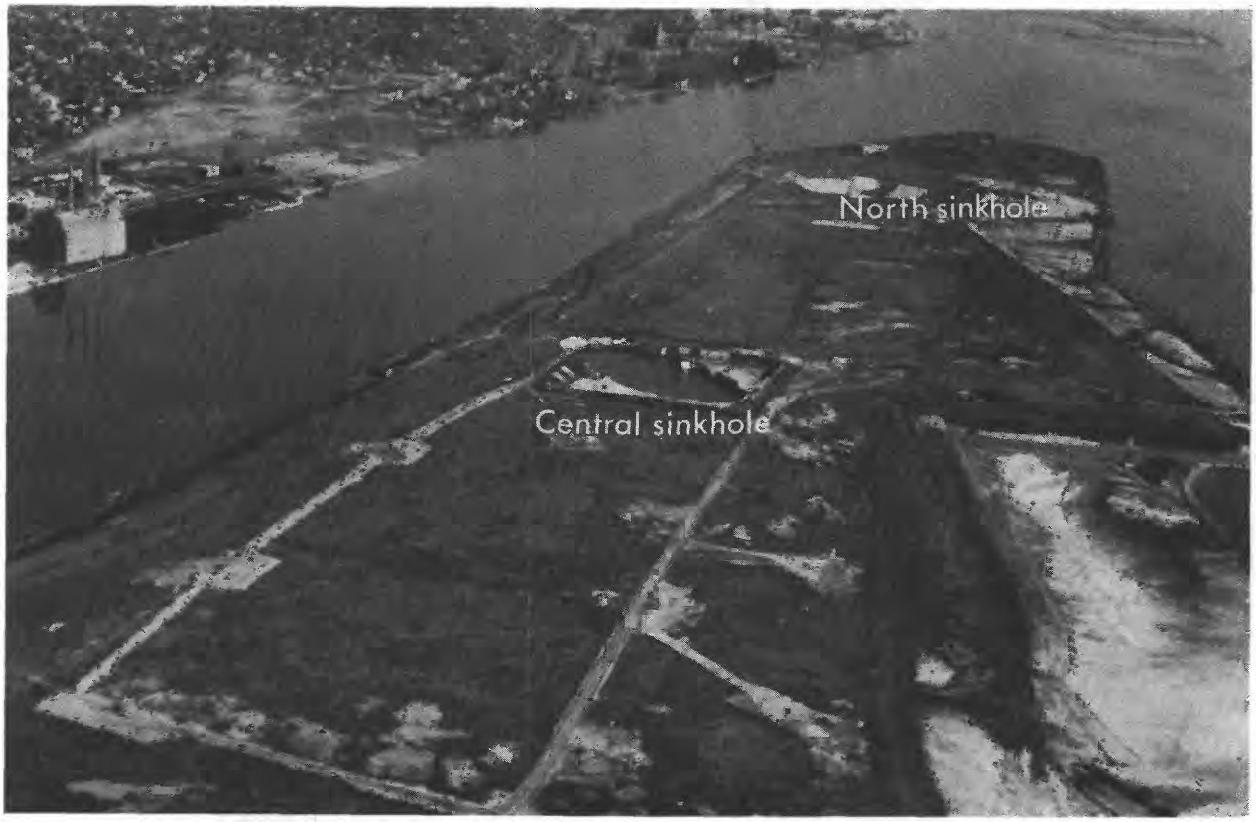

FIGURE 7.—Aerial view of the sinkholes formed at Grosse Ile, Mich., on the BASF Wyandotte Corporation property (Landes and Piper, 1972 (reproducted with permission of the publisher)). Width of channel between mainland and Grosse Ile is approximately 265 m.

On April 27, 1976, 27 years after cessation of solution mining, a large sinkhole formed in the city of Grand Saline, Tex. Grand Saline is a salt-producing region where salt was mined from the Grand Saline dome by solution methods between 1924 and 1949. Failure occurred in two stages. First, a hole 4 to 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. A similar collapse took place in 1948 just east of the present sink (Dunrud and Nevins, 1981).

Subsidence and sink formation resulting from brining operations in the Windsor-Detroit area include the 1954 sink at the Canadian Salt Company brine field near Windsor, Ontario (Terzaghi, 1970), and the 1971 sinks at the BASF Wyandotte Corporation brine field on Grosse Ile, Mich. (Landes and Piper, 1972) (fig. 7). Early investigations into both occurrences hypothesized that the mechanism of sink formation consisted of the gradual stoping of poorly supported brine-gallery roof rock to the near surface followed by surface collapse. A later study proposed a mechanism of sink formation on the basis of the geometry of a cylindrical chimney that formed by stoping of roof rock. The geometric factors consisted of the height of a cavity in salt at depth, the thickness of overlying rock, and the bulking ratio of the rubble formed during stoping (Nieto-Pescetto and Hendron, 1977).

Persons with extensive experience in solution mining in the Windsor-Detroit area have expressed doubt that the stoping mechanism could fully explain the formation of these sinks. Exploratory drilling at the site just before collapse indicated that no open cavity large enough to account for the sinkholes that were formed at the surface existed in the salt bed 335 m below the surface. It was then suggested that the shallow Sylvania Sandstone (fig. 8) might be responsible for the sinks by a secondary undermining mechanism because of its reputation as a "caving" formation when drilled or mined through.

A study initiated to examine the possible role

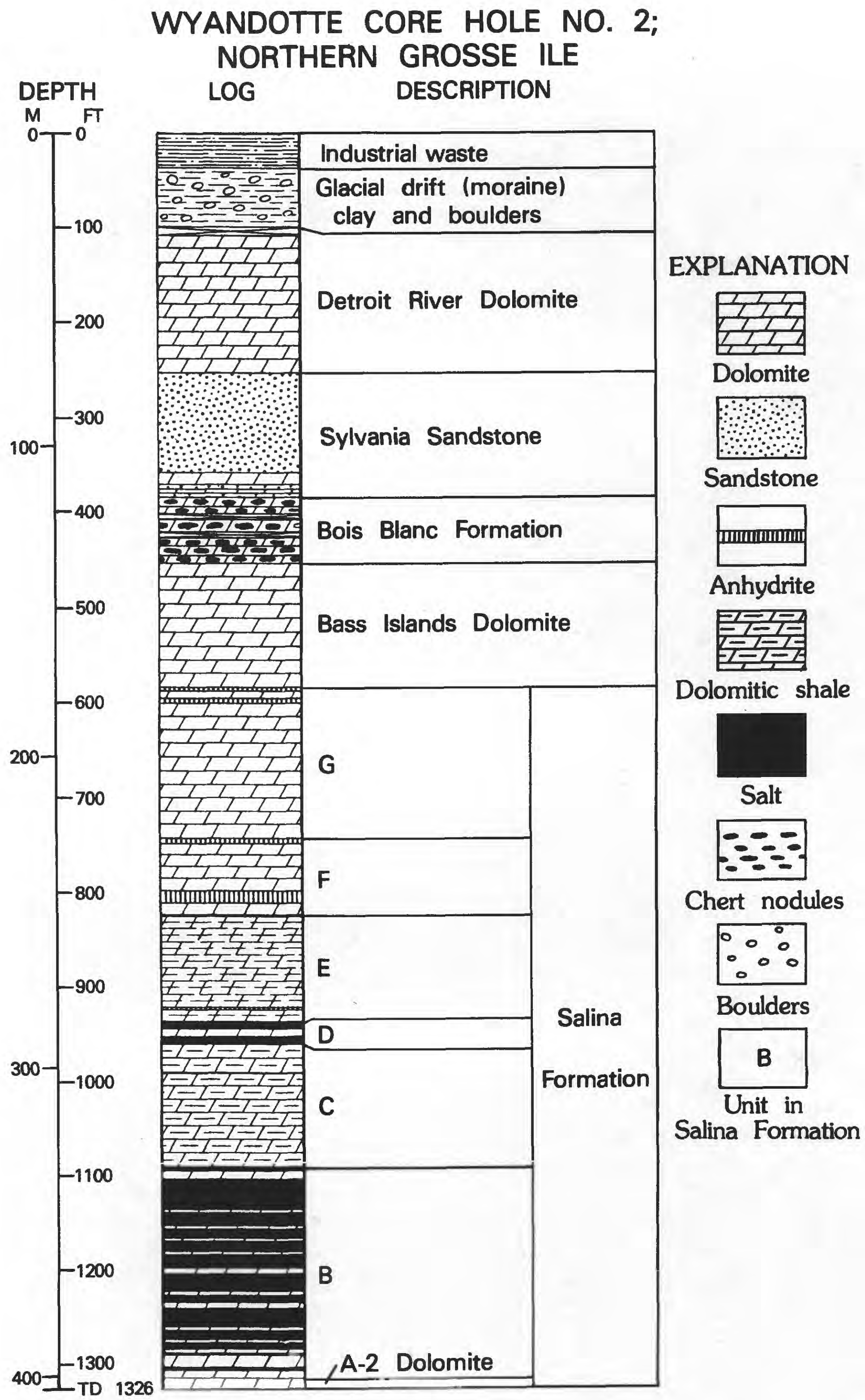

FIGURE 8.—Typical core log from Grosse Ile brine field. (Modified from Landes and Piper, 1972.)

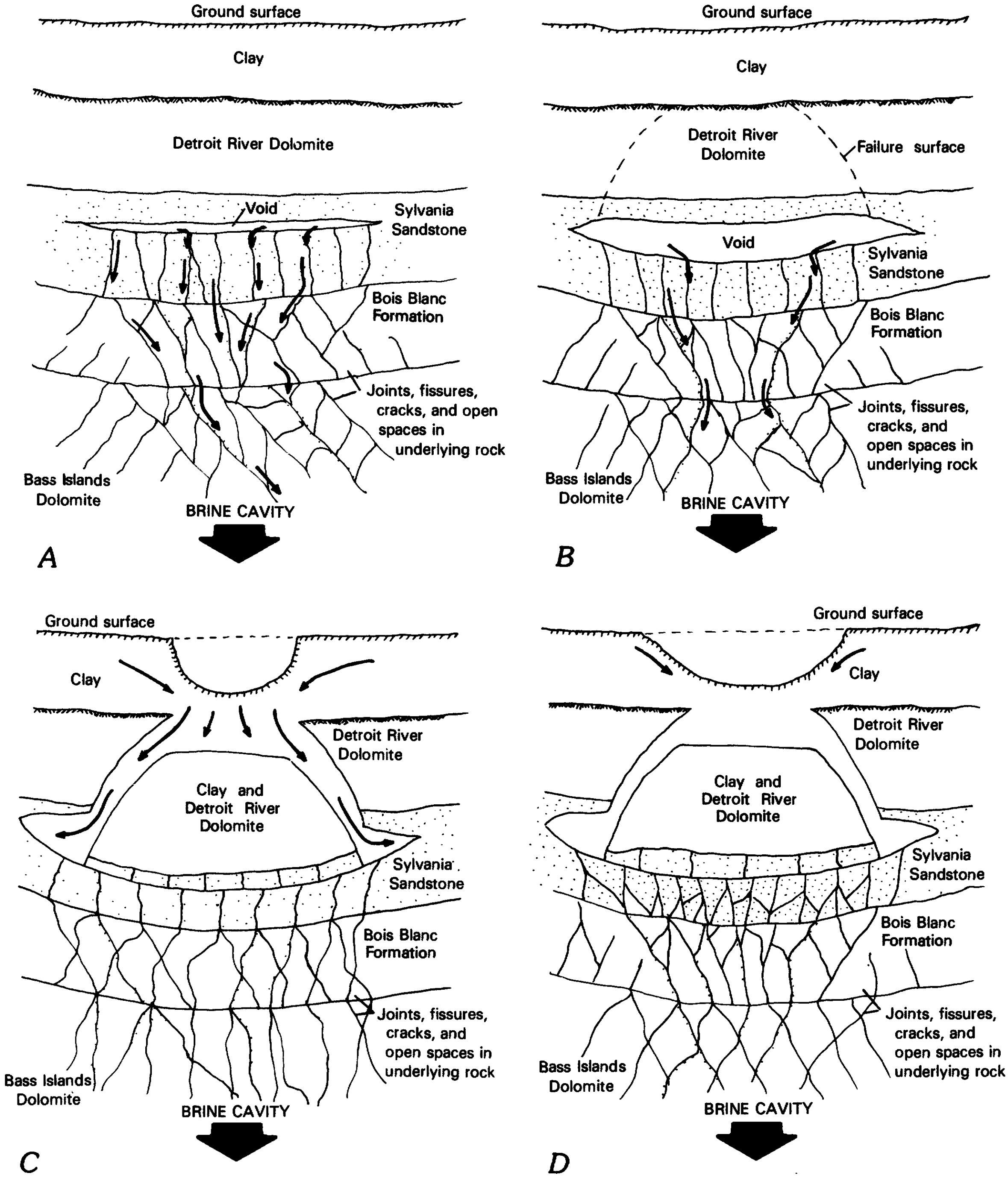

FIGURE 9.—Progress of sinkhole formation resulting from collapse of void formed in the Sylvania Sandstone. *A*, Initial sagging of Sylvania Sandstone occurs in response to sagging of lower dolomites into salt cavity. Separation takes place along a weak zone in sandstone. Loose sand grains are transported as a sand-water slurry (arrows) down through cracks in underlying rock. *B*, Increased sagging of Sylvania Sandstone intensifies crushing of the weak zone in the sandstone. Sand slurry migrates downward (arrows) into joints and voids in lower rock units, increasing size of opening in sandstone. Incipient failure of roof of cavity occurs within Sylvania Sandstone. Dashed lines show projected failure surface. *C*, Failure occurs in overlying highly jointed and fractured dolomite. Sinkhole forms when void breaches ground surface, allowing unconsolidated clay to flow (arrows) into voids below. *D*, Sinkhole enlarges laterally and decreases in depth through slabbing and settling of material from walls of sink. Sinkhole is now subjected to weathering processes. (Modified from Stump and others, 1982.)

of the Sylvania Sandstone in sinkhole formation concluded that the Sylvania Sandstone can lose its cohesion under high horizontal stresses (Stump and others, 1982). These stresses could be the result of deformation that accompanies general subsidence and (or) of past geologic processes. A mechanism advanced by the investigators proposed normal downwarping of beds overlying a rubble-filled salt cavity that induces high horizontal stresses, disintegration of the Sylvania Sandstone, mixing of sand grains with ground water to form a slurry, and flow of the sand slurry through openings in the disturbed rock to voids in the underlying dolomite and salt. A cavity, if formed in the shallower Sylvania Sandstone by this process, could then collapse, resulting in rapid stoping through the remaining 90 m of rock to the surface and formation of a sinkhole (fig. 9).

CONCLUSIONS

Ground failure over voids formed in salt terranes has occurred many times in the past as a result of natural or man-induced processes. If overlying beds merely flex downward into a rubble-filled cavity, then the effect at the surface may be a shallow-bowl- or trough-shaped depression. On the other hand, if the roof of a void collapses and sufficient space is available in the cavity to store rock debris, then continuous upward stoping through overlying rocks can breach the surface and form a sinkhole. Ground failure can occur above salt beds as the result of roof collapse of a cavity formed in salt by dissolution and removal of soluble minerals by ground water. Ground failure may also occur as the result of roof collapse of a cavity formed in granular sediments overlying salt beds by subsurface mechanical erosion and removal of sediment grains by ground water (piping).

REFERENCES CITED

Allen, A. S., 1969, Geologic settings of subsidence, *in* Reviews in engineering geology, v. 2: Geological Society of America, p. 305–342.

Bachman, G. O., and Johnson, R. B., 1973, Stability of salt in the Permian Salt Basin of Kansas, Oklahoma, Texas, and New Mexico, *with a section on* dissolved salts in surface water, by F. A. Swenson: U.S. Geological Survey Open-File Report 73–14, 62 p.

Bass, N. W., 1931, Recent subsidence in Hamilton County, Kansas: American Association of Petroleum Geologists Bulletin, v. 15, no. 2, p. 201–205.

Burgat, V. A., and Taylor, W. K., 1972, Highway subsidence caused by salt solutioning [abs.]: Association of Engineering Geologists Annual Meeting, Kansas City, Missouri, Program and Abstracts, no. 15, p. 20.

Christiansen, E. A., 1967, Collapse structures near Saskatoon, Saskatchewan, Canada: Canadian Journal of Earth Sciences, v. 4, p. 757–767.

———1971, Geology of the Crater Lake collapse structure in southeastern Saskatchewan: Canadian Journal of Earth Sciences, v. 8, no. 12, p. 1505–1513.

DeMille, G., Shouldice, J. R., and Nelson, H. W., 1964, Collapse structures related to evaporites of the Prairie Formation, Saskatchewan: Geological Society of America Bulletin, v. 75, p. 307–316.

Dunrud, C. R., and Nevins, B. B., 1981, Solution mining and subsidence in evaporite rocks in the United States: U.S. Geological Survey Miscellaneous Investigations Map I–1298, scale 1:5,000,000.

Ege, J. R., 1979, Selected bibliography on ground subsidence caused by dissolution and removal of salt and other soluble evaporites: U.S. Geological Survey Open-File Report 79–1133, 26 p.

Fader, S. W., 1975, Land subsidence caused by dissolution of salt near four oil and gas wells in central Kansas: U.S. Geological Survey Water-Resources Investigations WRI–27–75; available only from U.S. Department of Commerce, National Technical Information Service, Springfield, VA 22161, as Report PB–250 979/AS, 33 p.

Frye, J. C., and Schoff, S. L., 1942, Deep-seated solution in the Meade Basin and vicinity, Kansas and Oklahoma: American Geophysical Union Transactions, v. 23, pt. 1, p. 35–39.

Gendzwill, D. L., 1978, Winnipegosis mounds and Prairie Evaporite Formation of Saskatchewan—seismic study: American Association of Petroleum Geologists Bulletin, v. 62, no. 1, p. 73–86.

Johnson, K. S., and Gonzales, Serge, 1978, Salt deposits in the United States and regional geologic characteristics important for storage of radioactive waste: U.S. Department of Energy, Office of Waste Isolation, Y/OWI/SUB–7414/1, 188 p.

Johnson, W. D., 1901, The high plains and their utilization: U.S. Geological Survey 21st Annual Report, p. 601–741.

Landes, K. K., 1931, Recent subsidence, Hamilton County, Kansas: American Association of Petroleum Geologists Bulletin, v. 15, no. 6, p. 708.

———1945, Mackinac breccia, *in* Geology of the Mackinac Straits region: Michigan Geological Survey Publication 44, p. 123–154.

———1963a, Origin of salt deposits, *in* Bersticker, A. C., ed., First symposium on salt, Cleveland, 1962, Proceedings: Northern Ohio Geological Society, p. 3–9.

———1963b, Effects of solution of bedrock salt in the Earth's crust, *in* Bersticker, A. C., ed., First symposium on salt, Cleveland, 1962, Proceedings: Northern Ohio Geological Society, p. 64–73.

Landes, K. K., and Piper, T. B., 1972, Effect upon environment of brine cavity subsidence at Grosse Ile, Michigan—1971: Solution Mining Research Institute open-file report, 812 Muriel Street, Woodstock, Illinois 60098, 52 p.

Marsden, R. W., and Lucas, J. R., coordinating eds., 1973, Specialized underground extraction systems, *in* Cummins,

A. B., and Given, I. A., eds., SME mining engineering handbook: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 2, p. 21–1 to 21–118.

Nicholson, Alexander, Jr., and Clebsch, Alfred, Jr., 1961, Geology and ground-water conditions in southern Lea County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Report 6, 123 p.

Nieto-Pescetto, A. S. and Hendron, A. J., Jr., 1977, Study of sinkholes related to salt production in the area of Detroit, Michigan: Solution Mining Research Institue open-file report, 812 Muriel Street, Woodstock, Illinois 60098, 49 p.

Obert, Leonard, and Duvall, W. I., 1967, Rock mechanics and the design of structures in rocks: New York, John Wiley & Sons, 650 p.

Parker, J. H., 1967, Salt solution and subsidence structures, Wyoming, North Dakota, and Montana: American Association of Petroleum Geologists Bulletin, v. 51, no. 10, p. 1929–1947.

Querio, C. W., 1977, Current practices in solution mining of salt, *in* Martinez, J. D., and Thoms, R. L., eds., Symposium on salt dome utilization and environmental considerations, Baton Rounge, 1976, Proceedings: Institute for Environmental Studies, Louisiana State University, p. 3–41.

Rellensmann, Otto, 1957, Rock mechanics in regard to static loading caused by mining excavation, *in* Behavior of materials of the Earth's crust, Second Annual Symposium on Rock Mechanics: Colorado School of Mines Quarterly, v. 52, no. 3, p. 35–49.

Savage, W. Z., 1981, Prediction of vertical displacements in a subsiding elastic layer: Geophysical Research Letters, v. 8, no. 5, p. 195–198.

Sill, R. T., and Baker, D. M., 1945, Prevention of seepage in foundations for dams: American Geophysical Union Transactions, v. 26, no 2, p. 169–273.

Smith, G. I., Jones, C. L., Culbertson, W. C., Ericksen, G. E., and Dyni, J. R., 1973, Evaporites and brines, *in* Brobst, D. A., and Pratt, W. P., eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 197–216.

Sowers, G. F., 1976, Mechanisms of subsidence due to underground openings *in* Subsidence over mines and caverns, moisture and frost actions, and classification: Washington, D.C., Transportation Research Board Record 612, p. 2–8.

Stefanko, Robert, 1973, Roof and ground control—subsidence and ground movement, *in* Cummings, A. B., and Given, I. A., eds., SME mining engineering handbook: Society of Mining Engineers of American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 1, p. 13–2 to 13–9.

Stump, Daniel, Nieto, A. S., and Ege, J. R., 1982, An alternative hypothesis for sink development above salt cavities in the Detroit area: U.S. Geological Survey Open-File Report 82–297, 61 p.

Terzaghi, R. D., 1970, Brine field subsidence at Windsor, Ontario, *in* Rau, J. L., and Dellwig, L. F., eds., Third symposium on salt, Cleveland, 1969, Proceedings: Northern Ohio Geological Society, v. 2, p. 298–307.

Walters, R. F., 1977, Land subsidence in central Kansas related to salt dissolution: Kansas Geological Survey Bulletin 214, 82 p.

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