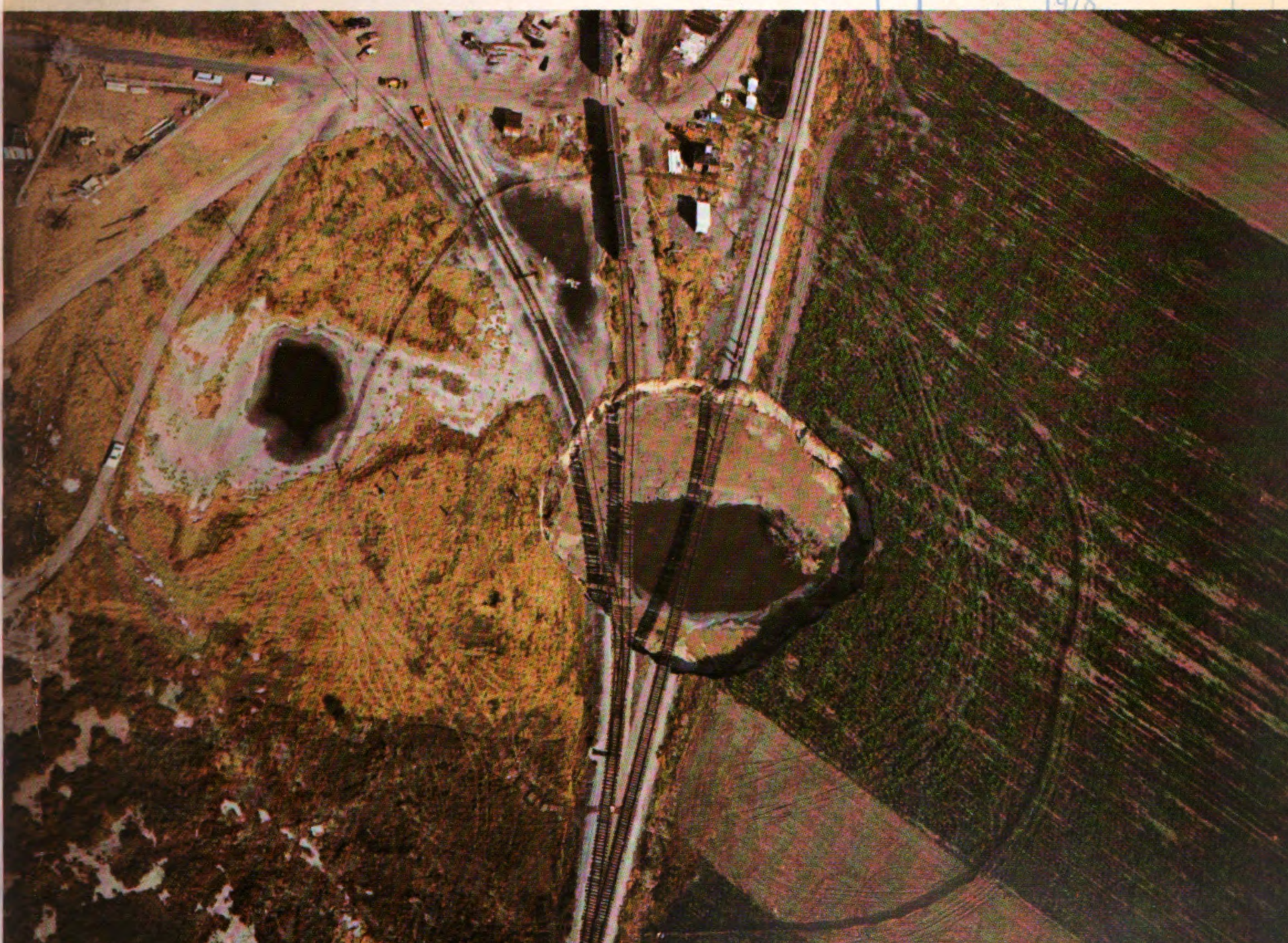
Robert F. Walters

LAND SUBSIDENCE IN CENTRAL KANSAS RELATED TO SALT DISSOLUTION



KANSAS GEOLOGICAL SURVEY
BULLETIN 214
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Cover: Sinkhole, Hutchinson, Kansas, October 22, 1974. View north toward Cargill, Inc. salt plant. The Missouri-Pacific Railroad tracks are suspended 21 feet above the water level in the still enlarging sinkhole. Circular shadow marks protective fence. Abandoned brine wells are located between and west (left) of the railroad tracks. Well 35, airlift brine return well, is near the left margin (building and derrick). Well 62, connected underground with the sinkhole, is located (small square) in the bottom left-hand corner. Photograph courtesy Deming Studio, Hutchinson.

BULLETIN 214

Land Subsidence in Central Kansas Related to Salt Dissolution

By

Robert F. Walters

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Executive Summary

The Hutchinson Salt Member of the Permian Wellington Formation underlies 27,000 square miles in central and south-central Kansas. Near the city of Hutchinson, the salt has a gross thickness of 350 feet, including shale and anhydrite interbeds totaling 20 percent of the section, or a net of 280 feet of rock salt (mineralogically halite, chemically NaCl) of variable purity. It is there encountered near 400 feet, but elsewhere at depths ranging from 200 feet to over 2500 feet. Within Kansas, the margins of the Hutchinson Salt are depositional edges except for the updip east edge which is solution eroded due to access to the Pleistocene and present water tables. West of this natural erosion border, there are no instances of dissolution of the Hutchinson Salt prior to man's drilling test holes for oil or salt during the past 88 years, the inadvertent effects of which are the 13 subsidence areas described in this paper, five associated with the mining of salt and eight resulting from oil and gas operations.

In 1914, subsidence within the salt works of the Joy Morton Salt Company southwest of Hutchinson affected an area 150 feet in diameter with a vertical depression of 15 feet, demolishing part of the plant. In 1925, the operation of Carey Salt Company's brine wells in downtown Hutchinson resulted in vertical subsidence of a few inches within a circular area, diameter 600 feet, and horizontal movement of 2½ inches affecting the east end of the court house. In 1952, ground north of the Barton Salt Company plant (now Cargill, Inc.) in the southeastern portion of Hutchinson subsided. In 1974, a sinkhole 300 feet in diameter formed in three days time south of the same plant, leaving railroad tracks suspended in air. Volume of the sinkhole is 90,000 cubic yards, with water level 21.5 feet below the ground surface and maximum water depth of 39 feet. A research project of the Solution Mining Research Institute, Inc. in which eight shallow holes were drilled within the sinkhole from a barge one year later, indicated nearly flat bedrock at a depth of 70 feet, except for a central area about 100 feet in diameter down which displaced sand and gravel moved into void space associated with the removal of salt. Near Ellsworth, Kansas in 1972, collapse of the material filling the shaft of an abandoned dry salt mine resulted in a surface crater 129 feet by 95 feet, 60 feet deep, with a volume equal to four times that of the original mine shaft 790 feet deep.

The most intensely studied subsidence areas associated with oil operations are the Crawford and Witt Sinks in the Gorham Oilfield west of Russell, Kansas. Subsidence during a 20-year period of more than 26 feet and 17 feet at three abandoned oil wells affected 1000 feet of U.S. Interstate Highway 70 at each location, necessitating costly repairs. A research test hole drilled through the salt, depth near 1300 feet, demonstrated conclusively that subsidence—which is still continuing at a rate of one-half foot per year—is caused by dissolution of the Hutchinson Salt. In contrast, rapid subsidence occurred at the Panning Sinkhole in the Chase-Silica Oilfield near Ellinwood, Kansas, on April 24, 1959 as photographed by Larry Panning. A circular pit 300 feet in diameter and 85 feet deep developed in a few hours around a plugged and abandoned salt water disposal well 3850 feet deep in which the Hutchinson Salt was penetrated from 975 feet to 1275 feet. Two miles east, the land subsided slowly for 15 feet vertically from 1972 to 1976 around the Berscheit salt water disposal well, causing a pond to form 375 feet in diameter. Events leading to this sinkhole are similar to the history of the nearby Panning Sinkhole, but the final event, rapid collapse resulting from inflow of loose sand and gravel, could not occur because alluvial fill is absent at the Berscheit location. A similar sinkhole developed slowly near Chase, Kansas before 1964 around twin salt water disposal wells, the Hilton No. 6 and No. 7, where a pond 350 feet in diameter formed due to 18 feet of vertical subsidence.

Evidence is presented that solution of salt during modern rapid rotary drilling using fresh water results in borehole enlargement to about three times the

diameter of the drilled hole, and that early rotary drilling in the 1930s resulted in borehole enlargement to five feet or more in diameter through the Hutchinson Salt. Both amounts are too small to cause surface subsidence.

Ordinarily, no salt dissolution occurs after drilling ceases. This important principle is valid if shallow aquifers above the salt are adequately isolated by surface casing and/or by proper hole plugging as required by regulations of the Kansas Corporation Commission. This is the normal situation in the broad ten-county study area. The subject was investigated by a study of the ten principal aquifers, depths to 4000 feet, which are oil reservoirs wherever hydrocarbon trapping conditions exist. In boreholes with properly isolated shallow aquifers above the salt, the deeper aquifers below the salt—although possessing static fill-up levels higher than the top of the salt—will equalize pressure by flowing up or down the borehole from one aquifer into another without flow across the salt face, hence without dissolving the salt. This is true for all such oil and gas test holes regardless of how else the borehole is plugged, if at all. This is a fundamental reason oilfield-related subsidence areas are rare and are confined to situations where aquifers above the salt are not isolated by surface casing (Gorham Oilfield, Witt and Crawford Sinks), or where casing failures in salt water disposal wells permitted extensive flow of unsaturated brine across the salt (Chase-Silica Oilfield, Panning, Berscheit, and Hilton Sinkholes).

It is a conclusion of this extensive search for, and report on, land subsidence areas in central Kansas associated with rock salt dissolution that such subsidence areas attributable to man's activities are rare and unusual features. Oil-related subsidence areas occur in a ratio of one to each 10,000 holes drilled through the Hutchinson Salt. Subsidence areas related to the mining of salt average only one for each 17 years for 88 years of continuous salt production.

It is an important observation of this investigation that all surface subsidence areas in Kansas related to salt removal have a common history of slow development in a time frame of months and years, but where near-surface materials consist of water saturated unconsolidated sands and gravels, and the underlying bedrock layers are breached, a surface sinkhole formed in a few hours or days.

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ROBERT F. WALTERS[1]

Land Subsidence in Central Kansas Related to Salt Dissolution

FOREWORD

This bulletin, number 214 of the Kansas Geological Survey, is unusual in that it makes public in permanent form a report by a consulting geologist prepared for an industrial client based on prior original research work by the author for a federal agency. The industrial client, the Solution Mining Research Institute (SMRI), is described more fully on page 2 in the original "FOREWORD" by its editor, Thomas B. Piper. The federal agency involved is the former Atomic Energy Commission (AEC), now succeeded by the Department of Energy (DOE). These organizations have generously cooperated by releasing this material for publication.

The author, Dr. Robert F. Walters, has actively engaged in prospecting for oil and gas within the State of Kansas, through his own company, Walters Drilling Co., Wichita, Kansas for more than 25 years. He is a graduate of the University of Rochester, New York, B.Sc. cum laude and M.Sc. in Geology, and of The Johns Hopkins University, Baltimore, Maryland, Ph.D. His long and distinguished career in the geology of Kansas began with his Ph.D. dissertation, "Buried Pre-Cambrian Hills in Northeastern Barton County, Central Kansas," which appeared as an award winning article in the *Bulletin* of the American Association of Petroleum Geologists in 1946. Dr. Walters is also past president and an honorary member of the Kansas Geological Society, a Fellow of the Geological Society of America, and holds membership in the American Geophysical Union (AGU) and the Society of Economic Geologists (SEG). He gave greatly of his time and energy while serving on the Advisory Council of the Kansas Geological Survey for 10 years from 1963 to 1973, including five years as chairman. The quality and thoroughness of his work are evident in this report.

On behalf of the Kansas Geological Survey, thanks are extended to SMRI and DOE for permission to publish the material in this bulletin in essentially its original form, as it was submitted to SMRI in June 1976. In addition, SMRI has kindly released data from its 1977 drilling program at the Cargill sinkhole which is included as Appendix D, pages 79-82 of this bulletin. Readers interested in the subsurface conditions beneath the sinkhole pictured on the cover will find that Figure 39, page 82, incorporates information from early brine wells with information from two later research drilling programs to give a comprehensive interpretation of the subsurface anatomy of a spectacular surface sinkhole.

William J. Ebanks, Jr.
Subsurface Geology Section
Kansas Geological Survey
University of Kansas
Lawrence, Kansas 66044

[1] Consulting Geologist, 400 Insurance Building, Wichita, Kansas 67202.

FOREWORD, 1976
(Solution Mining Research Institute)

Pictured on the cover of this report is a surface crater which formed near the Hutchinson, Kansas plant of the Cargill Salt Company in November 1974. Craters of this type are recognized to be the end result of a long-term sequence of activities related to production of salt under methods largely replaced by modern techniques—the crater, or sinkhole as these occurrences are known, is the last of a chain of events starting with salt extraction and requiring a special set of conditions to culminate in a surface collapse. Because these happenings present risk to safety and security of surface installations, interrupt operations of the plant involved, and in that their occurrence is not planned, they are evidence that salt well operators are not in full control of their extractive technology. This report is directed to an investigation into the causes which contributed to the Hutchinson 1974 crater with the long-term objective of developing salt production technology which will preclude their occurrence. Included also are descriptions of other examples of subsidence in Kansas having similar origin related to oil well operations—since they are also the result of salt dissolution, their occurrence and a proposed explanation for their cause will also be discussed.

This investigation was sponsored by the Solution Mining Research Institute, Inc. The Solution Mining Research Institute is a technical association of companies engaged in production of salt by the solution mining method. Sinkholes and subsidence related to extraction of salt by dissolution are a topic of considerable concern to the Institute because of the adverse reactions these events create at the time they happen—a response common to all geological events of this magnitude. The Institute has as one of its objectives the study of various aspects of salt extraction —this report is part of the Institute's continuing effort directed to further expanding our knowledge in this sensitive area.

The Hutchinson 1974 portion of this report was originally prepared by Ralph E. O'Connor for the State of Kansas Department of Health and Environment; in its present form the subject has been expanded upon by Dr. Walters to include material based on his experience with salt in Kansas. Cooperation of the Cargill Salt Company in releasing information in this report and in permitting subsequent investigation into the sinkhole mechanism at the Hutchinson site is noted with appreciation as is the cooperation of Mr. O'Connor and the State of Kansas Department of Health and Environment in allowing use of much of the material in their publication.

The Institute is fortunate in having the services of Dr. Walters, who is an authority on oil and gas operations in Kansas, and also has extensive experience with Kansas salt probably because of its close association with petroleum but also because of his personal interest.

Thomas B. Piper[2]
Chairman (1976) Technical Committees
Solution Mining Research Institute

INTRODUCTION

The surface crater, or sinkhole, pictured on the front cover formed in a few hours, during which the surface slowly subsided, leaving the railroad tracks suspended in midair. Subsidences of this type are not without warning, and investigation indicates that they are only the end result of a special sequence related to removal of subsurface support—in this case, rock salt, by dissolving methods employing brine wells. Other evidence of subsidence resulting from dissolution of rock salt caused by man's activities are available for study. In all, thirteen examples known to the author are discussed, five of which are related to solution mining of salt, and eight of which are related to oil and gas operations.

This report begins with a summary of the regional geology of salt deposits in Kansas. Such information is not concisely available elsewhere. Readers interested only in subsidence features due to salt dissolution may wish to proceed directly to Part II, page 13.

It is the author's conclusion that these rare and unusual instances of surface settlement related to salt extraction have a common history of slow surface downwarping involving an area of several acres and a time frame of many months or years, but in cases where surface materials are water-saturated sands and gravels, and the underlying bedrock layers are breached, a surface sinkhole forms in a few hours or days.

[2] Manager of Wells, BASF Wyandotte Corporation, Wyandotte, Michigan 48192.

PART I: SALT DEPOSITS OF KANSAS

REGIONAL GEOLOGY

HUTCHINSON SALT MEMBER OF THE WELLINGTON FORMATION

Extent. The Hutchinson Salt Member of the Permian Wellington Formation is present in the subsurface under much of central and southcentral Kansas, as is depicted in Figure 1. Thickness of the salt reaches a maximum of 555 feet in northwestern Oklahoma; the increased thickness of the unit is supplied by increased thickness of the salt beds and also by an increase in number and thickness of anhydrite interbeds. The zero thickness line marks a depositional edge to the west, the northwest, the north, and the northeast. The east edge of the salt, where the contours are close together, is an erosional edge. On the southwest the Hutchinson Salt Member undergoes a facies change to anhydrite and dolomite.

Figure 2 is a northwest to southeast cross section representative of a section 150 miles long, which illustrates the westward dip of the salt, the westward gentle rise in the elevation of the land surface, and shows the natural solution truncated eastern updip edge of the salt. Commercial salt operations in Kansas traditionally have been located as far east as possible to minimize the depth to the salt, yet still encounter the salt section intact and unaffected by the eastern natural dissolution edge. This explanation accounts for the concentration of salt mines at Hutchinson, known since the turn of the century as "The Salt City." The more modern concentration of salt cavity liquefied petroleum gas (LPG) storage operations at Hutchinson, at Conway just west of McPherson, Kansas, and elsewhere (mapped in Fig. 3) are sited at locations which will provide adequate depth confinement to contain the products under pressure in liquid phase.

Appendix A provides a descriptive listing of subsidence areas, salt test holes, underground salt mines, solution mining sites, and LPG storage installations in salt, the approximate locations of which are mapped in Figure 3. Appendix B lists the borings—oil test holes, salt test wells, water wells used in the construction of Cross Section A-B—through locations mapped in Figure 3, and lists the locations of test holes illustrated in other cross sections.

Figure 4 is a natural scale cross section (no vertical exaggeration), length represented 1.7 miles, near Lyons, Kansas, about midway of the regional Cross Section A-B, Figure 2. Figure 4 shows the Hutchinson

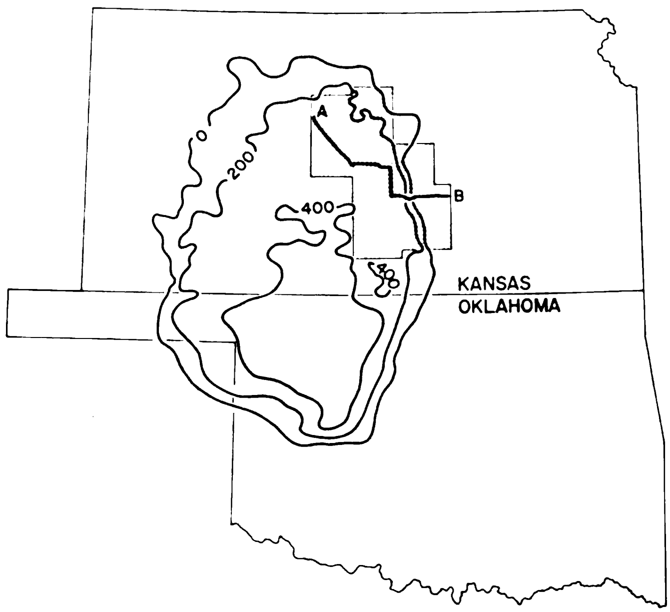

FIGURE 1.—Extent and thickness in feet of the Hutchinson Salt Member of the Wellington Formation, Permian System. Kansas portion modified from Schumaker (1966). Oklahoma portion by Johnson (1976). The location of Cross Section A-B (Fig. 2) is indicated within the shaded study area (Fig. 3).

Salt, the Carey Salt Company mine at Lyons, Kansas, the relation of the salt to the deeper and shallower rocks, and to the water-bearing zones ("W") or aquifers. Depth from ground surface to mine floor is 1024 feet. Wells and shafts numbered 1 to 9 are listed in Appendix B.

Overview. Viewed in the perspective of the regional index map (Fig. 1) the Hutchinson Salt is seen as a laterally persistent but thin rock unit covering 27,000 square miles within the State of Kansas. The ten-county study area is marginal to the Kansas salt basin, and viewed even more broadly the entire Hutchinson Salt area is marginal to the great Permian Basin salt deposits of Oklahoma, Texas Panhandle, and southeastern New Mexico (Bachman and Johnson, 1973) which covers an area of about 100,000 square miles.

It has long been recognized that the west, northwest, north, and northeast edges of the Hutchinson Salt (Fig. 1) are depositional edges (Bass, 1926), and that the updip east edge was solution-eroded due to natural access to the water table. This has been con-

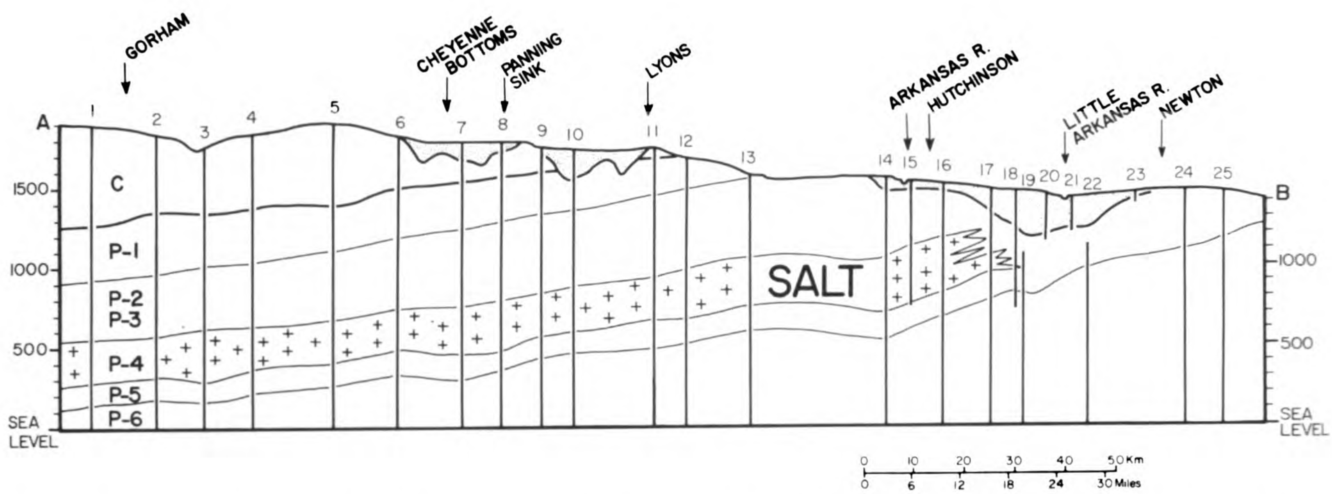

FIGURE 2.—Cross Section A-B. Length of section depicted is 150 miles. Vertical exaggeration × 100. Figures indicate elevation in feet above mean sea level. Location of cross section indicated in Figures 1 and 3. Control borings drilled for oil, gas, salt, or water, numbered 1 to 25, are listed in Appendix B. Stippled areas = unconsolidated beds, water-bearing; R = river.

STRATA			
C			Cretaceous
P			Permian
	P-1		Nippewalla Group
	P-2 to P-5		Sumner Group
		P-2	Ninnescah Shale
		P-3	Wellington Shale
		P-4	Hutchinson Salt Member
		P-5	Wellington Shale-Anhydrite
	P-6		Chase Group

firmed in general by Kulstad's (1959) map of the salt beds in Kansas, prepared in the middle 1950s but not published until 1959, and by Schumaker's map (1966). It has been further verified by Dellwig (1963 and 1971) in detailed studies of salt mines and cores. Considering the shoal water and basin margin environment of salt deposition, the lateral persistence of the Hutchinson Salt as a unit is remarkable. Within the outline of the salt area in Figure 1, no boreholes failed to penetrate salt, although thickness and quality vary. The fact that the salt is everywhere present is well recognized by the oil and gas drilling industry in Kansas. The salt beds are characterized by very rapid drilling penetration rate, commonly as much as 180 feet an hour with modern rotary tools. In oil and gas well drilling, the salt beds are routinely drilled with fresh water which is readily available (salt water is not as cheap or easily obtained). Drilling mud programs are engineered for salt brine mud systems with the salt provided by dissolution of the Hutchinson Salt during drilling.

Although the Hutchinson Salt Member is remarkable for its wide lateral continuity as a unit, individual salt beds, separated by shale interbeds and with shaly partings, commonly are continuous only a few miles. Dellwig (1971) states, "the salt consists of a succession of layers. The area underlain by any single bed is small compared to the area underlain by the entire salt unit, indicating a continual shifting of the locus of deposition. Correlation (based entirely on logs) also indicates that individual strata are imbricate and have an oblique relationship to the upper and lower boundaries of the salt unit as a whole. Key beds can be correlated only for short distances. In studies of mine areas, correlation of key beds offers no problem but it is important to note that one should not expect to project local stratigraphic units from marginal areas (Hutchinson, Lyons, and Kanopolis mines; AEC holes) toward the basin center and anticipate an increase in thickness or improvement in quality of a salt unit. . . ."

Perhaps even more remarkable than the lateral depositional extent of the Hutchinson Salt is the intact preservation of these water-soluble halite beds over the time period of about 250 million years since the Leonardian Stage of the Permian Period. This preservation is due to the seal afforded by the impermeable Permian redbeds, shale and silty shale, immediately overlying the salt and to the Kansas locality in the geologically stable heart of the North American continent. These salt beds have been subject to no intense tectonic forces but only to gentle,

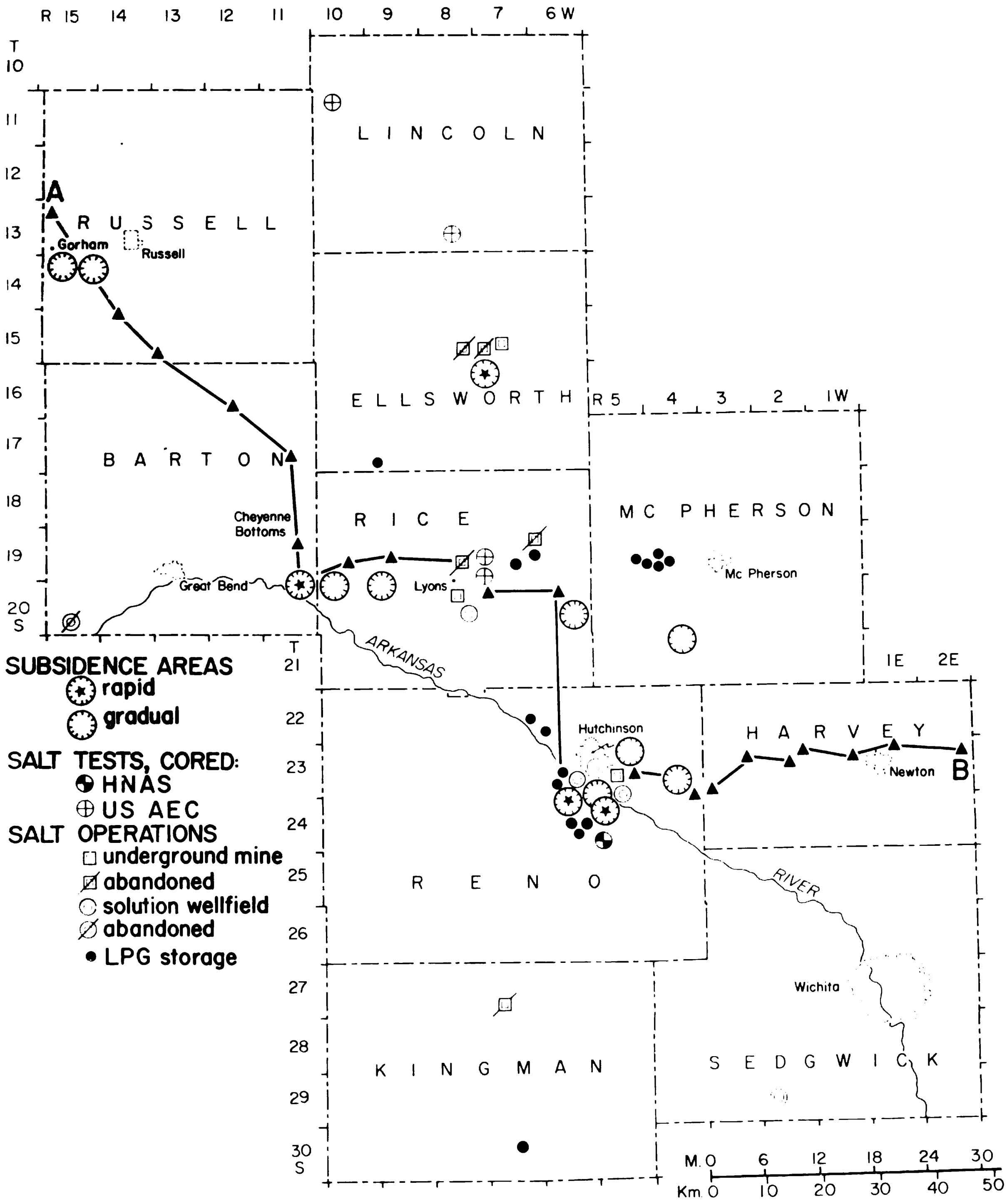

FIGURE 3.—Index map, ten counties in central Kansas. Indicates location of (a) Cross Section A-B, (b) subsidence areas, and (c) salt mines, etc. Abbreviations: Hutchinson Naval Air Station (HNAS); U.S. Atomic Energy Commission (AEC); Liquefied Petroleum Gas (LPG).

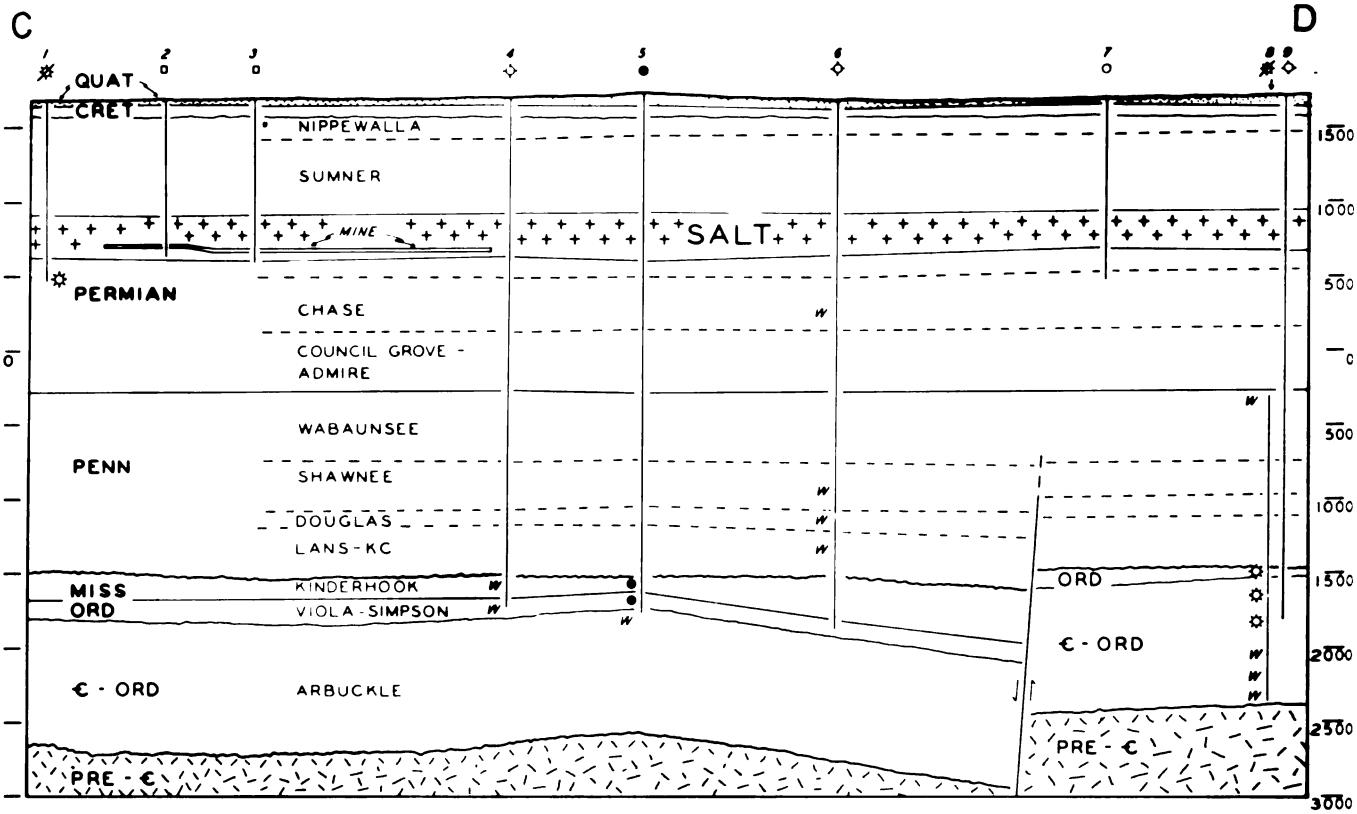

FIGURE 4.—Cross Section C-D, natural scale, near Lyons, Kansas. Length of section depicted is 1.7 miles. Wells and shafts are listed in Appendix C. Also shown is the Lyons, Kansas mine of the Carey Salt Company in the Hutchinson Salt Member. Abbreviations used:

W	water	MISS	Mississippian
QUAT	Quaternary, unconsolidated deposits	ORD	Ordovician
CRET	Cretaceous	€-ORD	Cambro-Ordovician
PENN	Pennsylvanian	PRE-€	Precambrian basement rocks
LANS-KC	Lansing-Kansas City Group		

Figures indicate distance in feet above or below mean sea level, indicated by zero.

vertical, epeirogenic movements for that time period. The redbeds can be quite thin and still preserve the salt beds. Dellwig (1963) has published a detailed cross section based on cores of salt encountered in Sedgwick County at depths just below 200 feet showing undissolved halite beds truncated by the overlying Permian shales, but "the contact between the salt and the overlying shale is clean and sharp and there is no indication of post shale-deposition solution of the salt and collapse of the overlying shale unit."

Natural dissolution. Just east of the area where salt occurs at depths as shallow as 200 feet is the area shown on Figure 1 by the parallelism and convergence of the 200-foot and zero salt thickness lines which mark the updip east edge of the Hutchinson Salt. For over 100 miles, the active dissolution front in which the Hutchinson Salt is being dissolved by ground water on its updip east edge is marked by the erratic and poorly mapped "Wellington lost circulation zone" of oil well drillers. This is a zone of partial to total dissolution of rock salt due to natural causes in which the void space created by salt removal has only partially been closed by collapse and gravity slumping, leaving cavernous void space forming a brine-filled conduit which is capable of either yielding large quantities of brine when pumped or of taking large quantities of fluid such as drilling mud. Penetration of this zone while drilling can cause lost circulation problems which at times can lead to the loss of the hole. Redrilling sometimes only 50 feet distant may miss the zone. The circulation path of this narrow zone extends along the salt front from near Wellington, in Sumner County, over 100 miles north to the proximity of Salina, Kansas. It has been investigated by O. S. Fent (personal communication) whose work is acknowledged here, and by Lane and Miller (1965, pp. 15-21).

The only natural dissolution of the Hutchinson Salt

FIGURE 5.—Carey Salt Company mine, Hutchinson, Kansas, showing light and dark banding in the Hutchinson Salt. Photograph courtesy of Underground Vaults and Storage, Inc., P.O. Box 1723, Hutchinson, Kansas 67501.

occurs along this updip east salt face. In Pleistocene time and continuing to the present, surface subsidence above the solution front resulted in sink and valley formation. A succession of such subparallel north-south valleys, now sediment filled, formed as the salt dissolved and the salt front receded westward. The study of these valleys which have extensive "closed lows" indicative of solution origin and the dating of the Pleistocene to Recent sediments filling them which are important fresh water aquifers has enabled Fent to conclude that the westward retreat of the salt front due to natural dissolution occurred at an average rate of four miles a million years during early Pleistocene time and at a rate of about two miles a million years in late Pleistocene time, continuing to the present.

In Cross Section A-B, Figure 2, near the Little Arkansas River (Well Nos. 20 and 21), the cross section transects a portion of the extensive well field developed for the municipal water supply of Wichita, Kansas. In the deepest part of the solution-slump valleys, formed as a result of the removal of 300 feet or more of salt, the water-bearing sand and gravel fill of Pleistocene age reaches a thickness of 275 feet.

Except for natural dissolution along the updip east edge of the Hutchinson Salt there are no instances of dissolution within the salt mass over hundreds of square miles prior to the advent of man's drilling oil and gas tests during the past 50 years and mining salt during the past 88 years, the effects of which are the subject of this investigation. In short, no natural dissolution (or subrosion) of the Hutchinson Salt from its top downward has been detected to the knowledge of the author.

Lithology. Because an evaporite sequence such as the Hutchinson Salt and the associated underlying massive anhydrites does not crop out at the surface in a humid climate such as Kansas had in Pleistocene time, there is no "type locality" for the Hutchinson Salt in the usual sense. The salt is named from the mines at Hutchinson, Kansas (Fig. 5). Although salt has been produced continuously at Hutchinson since 1888, the mines themselves provide a poor type section because underground mining of salt is usually confined to a single bed (thought to be approximately the same bed in all mines) selected for its high purity. Commonly the shaft which provides the only penetration of the entire salt section is cemented over, and the shafts frequently are not dug as deep as the base of the salt. Wells drilled with cable tool type drilling rigs for salt and/or oil or gas from 1888 to the 1930s yielded samples in the form of cuttings representing a 10 foot drilling run; hence details of the salt beds are obscured. Excellent suites of wire line geophysical logs of holes drilled more recently with rotary tools provide detailed information, but the best information concerning the Hutchinson Salt is provided by actual cores of the salt itself. In 1958 a test hole located south of Hutchinson was cored through the entire Hutchinson Salt. The site was the former Hutchinson Naval Air Station; hence the test hole is known as HNAS Core Hole No. 1. Its location is in the SE/4 NE/4 of Section 29, Township 24 South, Range 5 West, Reno County, Kansas (Fig. 3). Its core description now serves as a reference locality for the Hutchinson Salt.

C. L. Jones (1965) published a detailed lithologic and petrographic description of the 286 feet of salt section and interbedded rocks present in the cores from HNAS Core Hole No. 1 from 426 feet to 712 feet, together with gamma-ray and neutron logs of the hole. Because of the importance of HNAS Core Hole No. 1 as a reference section for the Hutchinson Salt Member, and because the USGS Bulletin by C. L. Jones provides the only published details concerning lithology and mineralogy of a complete section of the Hutchinson Salt in Kansas, an error of omission in his published lithologic description is hereby corrected by use of photocopies he furnished of his original core description notes (C. L. Jones, personal communication, July 9, 1974) from which the following additions (marked by asterisks) are abridged:

The Geotechnical Corporation
HNAS Core Hole No. 1
SE/4 NE/4 of Section 29, Township 24 South, Range 5 West
Reno County, Kansas

Addenda to core description by C. L. Jones (USGS Bulletin 1201-A, 1965):

520′-2″	525′-7″	5′-5″	Halite rock, description correct as published on page A-58
*525′-7″	526′-9″	1′-2″	Clay shale, medium bluish gray cut by veins of orange halite
*526′-9″	527′-4″	7″	Anhydrite rock; has a 2-inch clay shale seam with orange halite veinlets
*527′-4″	528′-5″	1′-1″	Halite rock, anhydritic and argillaceous; coarse grained (¼″ to ⅜″), grayish color
*528′-5″	531′-0″	2′-7″	Clay shale; interlaminated medium bluish gray and gray; prominent veins of amber halite, in part cut by anhydrite nodules
*531′-0″	532′-0″	1′-0″	Halite rock; interval incorrectly published but description correctly published at top of page A-59
532′-0″	534′-2″	2′-2″	Halite rock; description and interval correctly published on page A-59

Jones (1965) determined from complete lithologic and petrographic examination, using rock units as thin as one inch, that the 286-foot thick Hutchinson Salt Member in the reference locality, HNAS Core Hole No. 1, included 82 percent halite, 3 percent anhydrite, 4 percent carbonate—either magnesite or dolomite, and 11 percent shale including minor amounts of siltstone.

C. L. Jones (personal communication, July 9, 1974) correlates a 7-inch anhydrite seam near 647 feet with a similar anhydrite bed one to four feet below the mine floor in the Carey Salt Company underground mine at Hutchinson, and considers the salt cored from about 635 feet to 645 feet to be the bed mined. Likewise he considers the fossiliferous layer at depth of 698 feet as very similar to a fossiliferous layer at the base of the salt 44 feet below the mine floor in the Carey underground salt mine at Lyons, Kansas.

When the U.S. Atomic Energy Commission (AEC) undertook an investigation of the area surrounding the Carey Salt Mine at Lyons, Kansas in which they had been conducting experiments for almost a decade, it was found that specific information concerning the subsurface salt (other than the one 9-foot bed mined), the Permian redbeds above the salt, and the anhydrites below, was almost nonexistent. The AEC contracted the coring of two holes at Lyons in 1970, designated as AEC Test Holes No. 1 and No. 2. Not until cores were recovered in 1970 was it relearned why miners laboriously hand digging a mine shaft in 1889 in search of salt had continued their shaft more than 200 feet below the top of the salt. Cores from AEC Test Hole No. 1 showed that the first 100 feet of salt section included 25 percent shale, measuring only beds one foot in thickness or more. In addition, thin shale partings were present in the dirty (clayey) salt. These cores confirmed what the old miners knew, that the mined bed near the base of the salt, depth 1013 feet to 1024 feet in the Carey Salt Mine, was the cleanest and most minable bed (free of shale partings) encountered. The same bed, and no other, is still being mined underground at the American Salt Company mine at Lyons (Lomenick, 1972), and is believed to be the same bed mined 30 miles north in Ellsworth County. Even the bed which is mined because it is the "clean-

* Indicates additions to core log as published by C. L. Jones (1965).

est" salt often shows light and dark banding or laminae ("Jahresringe"—Dellwig, 1963) of clay or anhydrite spaced 0.25 inches or more apart, with no regular spacing of the laminae, and the salt crystals show considerable variance in size. This is illustrated in Figure 5.

The gross lithology of the Hutchinson Salt and the beds directly above and below it, plotted from field descriptions of cores recovered from AEC Test Hole No. 1, Section 26, Township 19 South, Range 8 West, Rice County, Kansas, is illustrated in both Figure 6 and Figure 7 as the center lithology column. The various wire line geophysical logs, and their usefulness for delineating salt are discussed on page 13. Appendix A lists the five holes in Kansas from which cores of the entire salt section were recovered for the U.S. Atomic Energy Commission, and states the repository of each of the cores. No detailed lithologic or petrographic study comparable to that of Jones from the HNAS Core Hole No. 1 was made.

Thickness. The generalized thickness of the Hutchinson Salt Member is mapped in Figure 1 with a contour interval of 200 feet, and is illustrated in the regional cross section (Fig. 2). The maximum gross thickness of the Hutchinson Salt Member in Kansas is 515 feet (Schumaker, 1965). By selective use of quality-controlled well logs, the principle was established by the author that the salt is locally thinner over anticlinal structures and locally thicker in the intervening gentle synclines. The mapped areas of thin salt coincide with most of the major oilfields in the central portion of the map. The thick salt areas overlie synclines separating oilfields. Examples illustrated on Cross Section A-B, Figure 2, are Well Nos. 2 and 6 (anticlines with thin salt) and Well Nos. 3 and 7 (synclines with thick salt). Although exact bed-by-bed correlations cannot be carried across the several hundred square miles of area from log study, it can be shown that the salt thickness varies due to some combination of:

a. Loss of salt beds at base of salt section;
b. Absence of salt beds in upper middle portion of the salt section;
c. Loss of salt beds at the top of the salt section.

From available well logs it is relatively easy to accurately determine the top of the salt, but relatively difficult (and often impossible) to accurately determine the base of the salt section because a transition zone is present at the base of the salt section. For example, Dellwig (1971) identified fifteen lithological units, largely salt, in nine feet of core from 1077 feet to 1086 feet (base of the salt section 1084 feet) from AEC Test Hole No. 1 (Fig. 6) and specifically correlated each of the fifteen equivalent beds (largely devoid of salt) as all present in four feet of core from 1002 feet to 1006 feet from AEC Test Hole No. 2 (1¼ miles distant) in which the base of the salt was 1004.5 feet. Such fine discrimination requires cores studied by experts and is beyond the resolving power of even the best geophysical log suites. This example confirms the presence, recognized on a broader scale in log studies, of a basal transition zone sometimes salt-bearing, sometimes not, with a thickness varying from zero to over 40 feet. This basal transition zone indicates that anticlinal areas which were also gentle topographic highs were present in mid-Permian time during the deposition of salt in Kansas, with more and thicker salt beds deposited in the lows than on the highs.

The absence of salt beds in the upper middle portion of the salt section is associated with one or more disconformities marked by shale beds with a thickness from 1 to 10 feet. In the upper 100 feet of the salt section, shale beds, each more than one foot thick, constitute 25 percent of the interval thickness. The depositional environment of the Hutchinson Salt was a broad shallow embayment, perhaps with extensive tidal mud flats. Desiccation cracks, large-scale polygons, and salt hopper crystals confirm the very shallow

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LEGEND FOR FIGURES 6 AND 7

shale — salt
siltstone — anhydrite

AEC TEST HOLE NO. 1—Sec. 26, T. 19S, R. 8W, Rice County, Kansas
WIRE LINE GEOPHYSICAL LOGS
(depths in feet from ground surface)

Gamma	Gamma-Ray Log in API units. Radioactivity increases to the right.
Density	Gamma-Gamma Log or Formation Density Log compensated for variations in hole diameter. Scale indicates bulk density in grams/cc. Commonly printed on the right side of multi-log prints, but here placed on the left near the gamma log to emphasize the similarity of the two logs (in shale and salt) and the dissimilarity (in anhydrite). Anhydrite commonly records as 2.9, halite as a little over 2.0 units.
Caliper	Measures the diameter of the hole in inches within limits of the "reach" of the logging tool.
Neutron	Neutron Log in API units. This log is highly sensitive to hole size and is only effective in nearly out-to-gauge holes through the salt section. In enlarged holes this log loses character.
Resistivity	A resistivity log made with current focused. Measures electrical resistivity in ohms per square meter per meter (m^2m), recorded on a logarithmic scale.
BHC Sonic	Borehole Compensated Sonic Log, corrected for variations in hole size with interval transit time of sound recorded in microseconds per foot. Ideal travel time in halite is 67, and in anhydrite is 50 units. Also termed "Compensated Acoustic Velocity Log."

FIGURE 6 (Legend, p. 9)

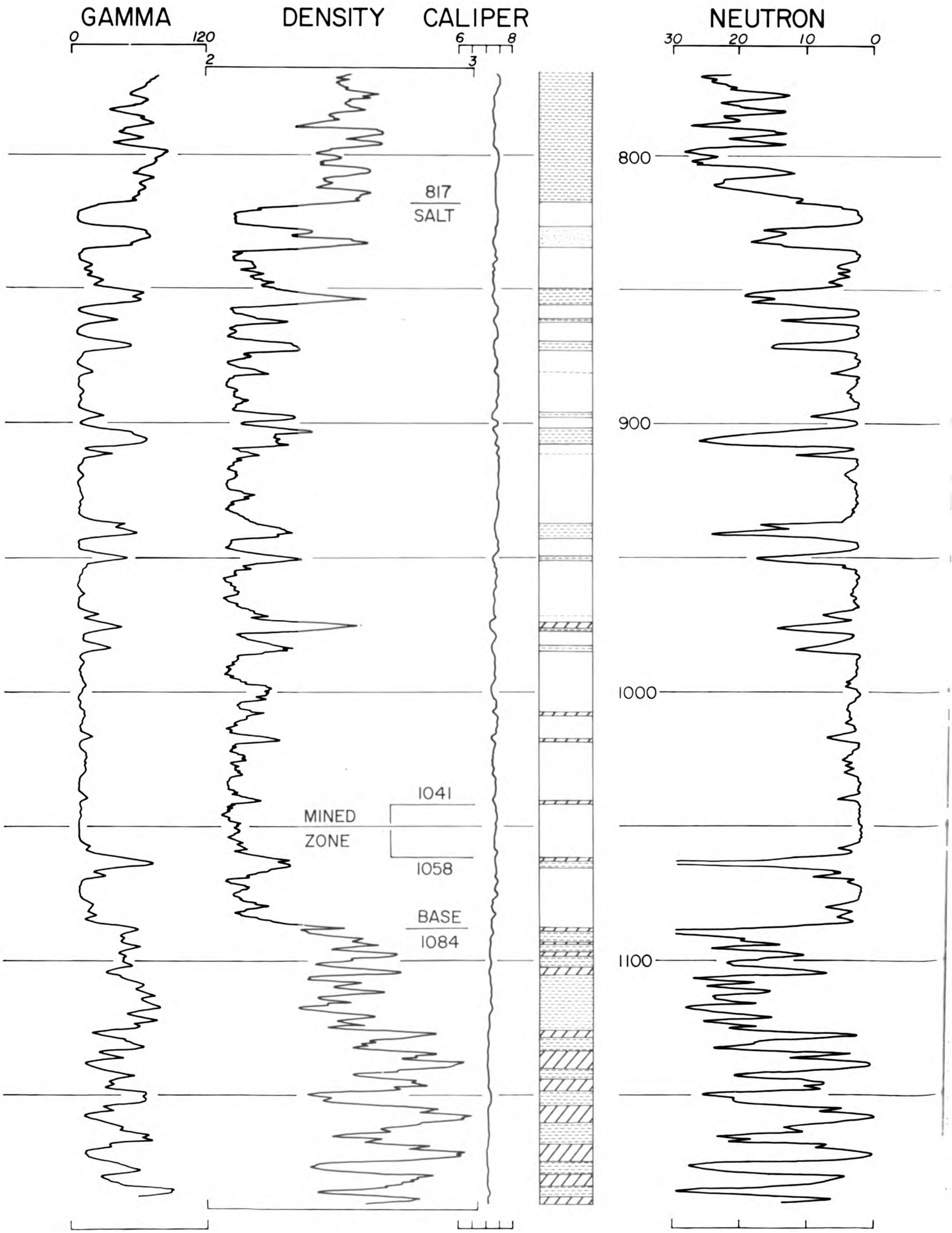
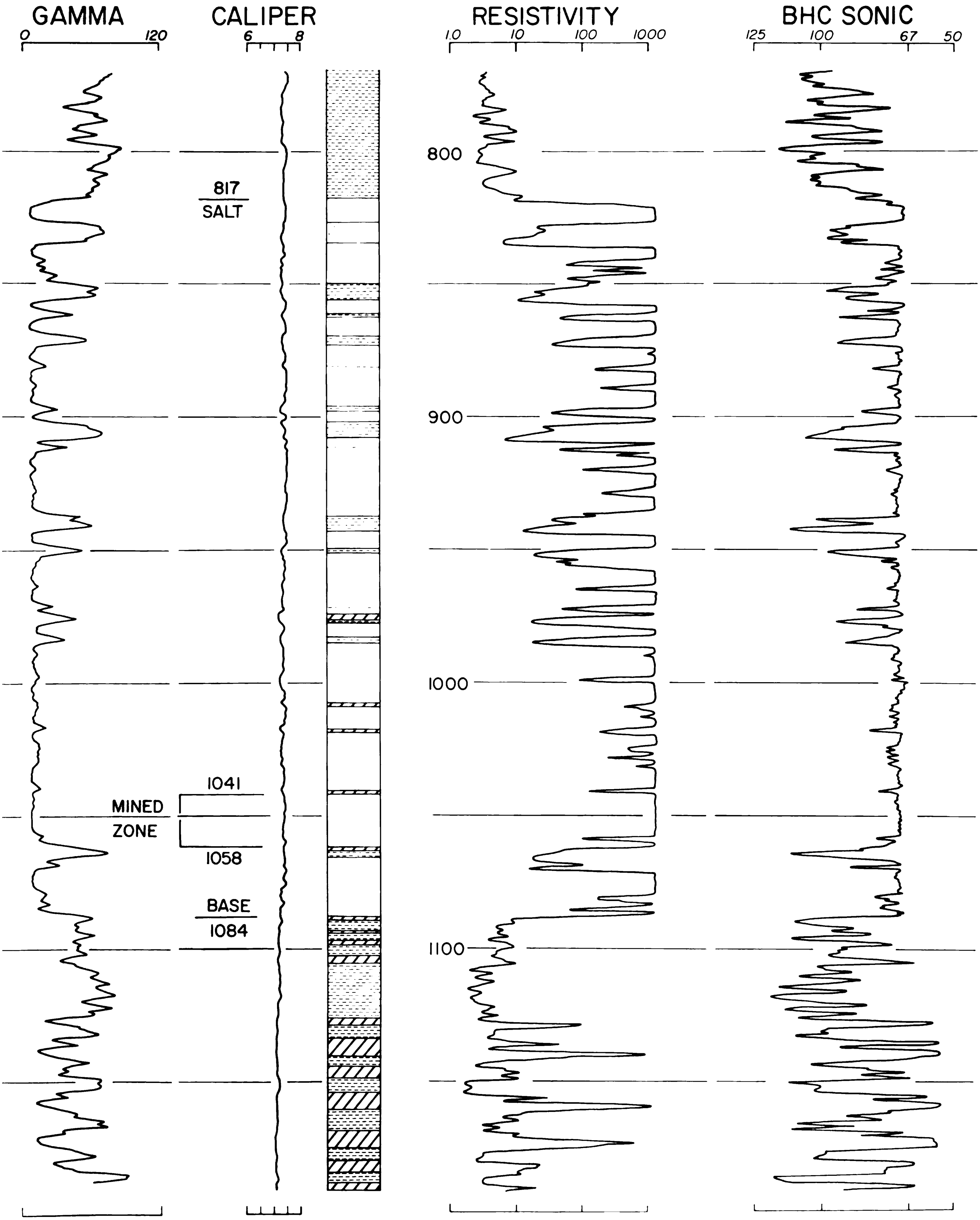


FIGURE 7 (Legend, p. 9)



water environment (Dellwig, 1971). The absence of salt beds, locally, in this part of the section may be due to redissolution of the salt by incursions of muddy fresh water depositing the shale interbeds. Shale-filled channels can be seen exposed in the walls of the Carey Salt Mine at Lyons.

The local loss of salt beds at the top of the section may be due to nondeposition, but has been shown by Dellwig (1971) to be in part due to early post-depositional truncation in Permian time, based on three core holes near Clearwater, Sedgwick County, Kansas. This may also be the situation at Hutchinson. Cargill, Inc.'s Core Hole No. H-9, drilled in 1976 in the E/2 SW/4 of Section 19, Township 23 South, Range 5 West, penetrated 355 feet of salt from 409 feet to 764 feet. This is 69 feet, or 24 percent, more salt than the 286 feet present seven miles south in the reference locality, the HNAS No. 1, described by Jones (1965). The additional salt section consists of massive salt beds at the top of the section in the No. H-9 core hole. They may have been removed by erosion in Permian time in the vicinity of the HNAS Core Hole No. 1. Jones describes contact of the salt and the overlying Permian shale as "sharp but somewhat sinuous" in cores from the HNAS Core Hole No. 1.

There is no direct evidence of thickening and/or thinning of salt beds by salt flowage. The beds are nearly horizontal with regional dips of only about 30 feet per mile (⅓ of 1°). It is thought that the maximum depth of burial in the 200+ million years since deposition of the salt is less than 4000 feet. The present overburden thickness ranges from 400 feet to 2500 feet within the study area. These observations provide indirect evidence of the absence of thickness variations due to salt flowage. The stable continental position and the depth of burial too shallow to mobilize salt flowage on a regional basis (Gera, 1972) confirm this conclusion.

YOUNGER PERMIAN SALTS IN KANSAS

Lower Cimarron Salt. This salt, named from the Cimarron River area of Oklahoma, is developed under the Cimarron Anhydrite (Stone Corral of Kansas) and is mapped by Schumaker (1965) as present in five counties in southern Kansas, adjacent to the Oklahoma border. Jordan and Vosburg (1963) have described and mapped the extent of this salt plus the upper Cimarron Salt (absent in Kansas) and two younger salts in an excellent brief publication, "Permian Salt and Associated Evaporites in the Anadarko Basin of the Western Oklahoma-Texas Panhandle Region." No comparable publication exists summarizing Permian salts in Kansas.

Blaine Salt. This salt is present in western Kansas west of the area of the Hutchinson Salt Member of the Permian Wellington Formation, and in eastern Colorado. Bayne (1972) reproduces a map prepared in the 1950s by Robert O. Kulstad for the State Geological Survey of Kansas showing a maximum thickness of 600 feet. The equivalent salt in the Oklahoma and Texas Panhandle is termed the Flowerpot Salt (Jordan and Vosburg, 1963).

In 1972, the Blaine Salt was cored in AEC Test Hole No. 5 near the center of Section 22, Township 19 South, Range 37 West, Wichita County, Kansas. This is believed to be the only hole cored entirely through this salt. The rocks recovered included 253 feet of salt with discrete large (¼"-1") halite crystals mostly free of inclusions but separated by intercrystalline red clay. Holdoway (1978) attributes the origin of this unusual and thick salt to mud flat conditions in a continental basin which was subject to occasional flooding by the sea.

Commercial development. With the exception of one LPG storage area operated by Amoco in Grant County, there is no commercial development of the Lower Cimarron Salt and the Blaine Salt in Kansas.

Land subsidence. Both the Lower Cimarron Salt and the Blaine Salt are associated with lost circulation zones caused by natural dissolution of salt and with areas of land subsidence which have been called solution-collapse basins. These include, in Clark County, Big Basin measuring one mile from rim to rim, and the adjacent Little Basin, one-fourth mile from rim to rim, which in its lowermost portion breaches the water table in what is known as Saint Jacob's Well (Shumard, 1974). In Meade County, the Meade Salt Sink (Frye, 1940), the Jones Ranch Sink, and others (Frye, 1950), have been described by Frye and by Frye and Schoff (1942). All examples are natural occurrences. There are no known areas of land subsidence in Kansas associated with the dissolution of these younger salts due to man's activity.

PART II: LAND SUBSIDENCE AREAS ASSOCIATED WITH SALT MINING

HUTCHINSON, KANSAS: LOCAL GEOLOGY-SALT RESOURCES

Unconsolidated Pleistocene beds. Underlying the city of Hutchinson, Kansas, below eight feet of loess-like soil, are coarse crossbedded loose sands and gravels having a thickness of 50 feet or more. These alluvial sands of the McPherson Formation (formerly called the McPherson Equus Beds) were deposited as stream-channel filling during various epochs of the Pleistocene. They have been extensively drilled to provide the municipal water supply for the city of Hutchinson (Williams, 1946; Bayne, 1956) and, further east, for the city of Wichita (Williams and Lohman, 1949). The presence of an abundant supply of fresh water was and is an important factor in salt mining by solution. At the Cargill plant, three water supply wells, each capable of supplying 1,000 gallons per minute with very little drawdown, are typical of water wells in the vicinity. These shallow beds are designated by stippling in Cross Section A-B, Figure 2.

Bedrock; Permian formations. Bedrock is Permian shale, commonly reddish brown. This extends to depths near 400 feet east of Hutchinson, or 500 feet southwest of the city. Beneath the Permian shales are salt beds with a thickness of about 350 feet. Under the salt beds are massive anhydrites interbedded with clay shales which extend to the top of the Chase Group marked by the presence of normal marine beds of the Nolans limestone. With reference to the regional Cross Section A-B, Figure 2, all Permian rocks are designated "P." The Chase Group is designated P-6. Beds designated P-5, P-4, P-3, and P-2 constitute the Sumner Group. Within this group the Wellington Formation includes P-5, the shale and anhydrite beds below the salt, P-4, the Hutchinson Salt Member of the Permian Wellington Formation, and P-3, the shales above the salt. Elsewhere the top of the Wellington Formation is marked by the Milan limestone which is absent in the Hutchinson area, making it difficult to distinguish shale beds of the Wellington Formation which are dark colored in the lower portion just above the salt but which are reddish in the upper beds from the overlying red shales and siltstones, P-2, of the Ninnescah shale. The uppermost bed of the Ninnescah Formation, and of the Sumner Group, is the Stone Corral Formation (dolomite-anhydrite) which crops out between Hutchinson and Lyons, Kansas. The uppermost Permian beds in the area of Cross Section A-B, designated P-1, include redbeds of the Nippewalla Group which are unconformably truncated by Cretaceous beds, undifferentiated in Figure 2 but designated "C."

Salt resources. The local salt resources of the Hutchinson area are excellent and include 350 feet of horizontally bedded salt with interbeds of dark shale, and with a few thin anhydrite layers. The salt section is well shown in logs of the newly drilled Cargill brine wells in the E/2 SW/4 of Section 19, Township 23 South, Range 5 West. There the Hutchinson Salt Member is 80 percent salt (halite) and 20 percent insoluble nonsalt beds, shale, anhydrite, and dolomite. The resolving power of the available gamma-neutron logs is about one foot, the thinnest unit used, as contrasted with one inch minimum unit measured by Jones (1965) when he determined the content of the 282-foot thick Hutchinson Salt in the HNAS No. 1, seven miles south, to be 82 percent halite, 3 percent anhydrite, 4 percent dolomite-magnesite, and 11 percent shale and siltstone.

Wire line geophysical logs. Reasonably accurate salt resource determinations can be made from wire line geophysical logs if sufficient logs are recorded and if basic core examination work such as that of Jones has been recorded. A few comments are included here on the characteristics and usefulness for salt evaluation of wire line geophysical logs. It is suggested that the reader refer to Figure 6 and Figure 7 showing logs from AEC Test Hole No. 1 in the Lyons area used here because no comparable suite of logs is known to be recorded in connection with salt operations in the Hutchinson area.

The gamma-ray log (Fig. 6, "gamma") is by far the single most useful log in Kansas where halite beds are interbedded with shale. The gamma-ray radioactivity log can be recorded in both open holes and through casing. It discriminates readily between nonradioactive halite (left) and radioactive shale (right). In areas such as New Mexico, it can be used to distinguish radioactive potash salts. The neutron log (Fig. 6, "neutron") is everywhere quite useful in salt studies. It can be recorded in either open hole or cased holes. In areas such as Michigan, where shales are rare in the evaporite section, the neutron log is the single most useful log as it distinguishes readily between porous formations such as dolomite (left) versus nonporous salt (right). The neutron log is extremely sensitive to variations in borehole diameter and fails to record in enlarged holes, a factor which in itself aids in recognition of salt in rotary drilled oil and gas holes, and which is useful to indicate cavernous conditions behind casing in brine wells. The particularly sensitive neutron log depicted in Figure 6 is designed for open hole logging and minimizes borehole effects because it is a sidewall device mounted on a skid pressed against the side of the hole. The density log, Figure 6, like the gamma and neutron logs, records radioactivity increasing to the right. It is an open hole log useful both as a porosity logging tool and in identification of minerals in evaporite deposits, but is used much less frequently. The density log is commonly plotted to the right of the lithology column but this less familiar log is here moved to the left side of the lithology column to show its similarity to the gamma log in salt and shale, and its discriminating dissimilarity in anhydrites. The various resistivity logs (Fig. 7) are open hole logs abundantly recorded in oil and gas operations as porosity tools and hydrocarbon-sensitive indicators. Resistivity logs are useful in salt studies because bedded evaporites are essentially nonporous and electrically nonconductive, hence are characterized by extremely high readings on resistivity logs. The laterolog illustrated in Figure 7 has special shielding to minimize the influence of borehole size and to permit recording of resistivity through salty muds. The sonic log (Fig. 7, "BHC Sonic") is also extremely sensitive to borehole size, hence is "BHC" or "borehole corrected" using the simultaneously recorded caliper log, showing hole size in inches, for corrections. A cross plot of sonic and neutron logs permits the determination of several nonradioactive evaporite minerals. Moreover some evaporites can be identified specifically from the sonic log alone by their sound travel times or velocities, for example, halite 15,000 ft/sec = Δt of 67 on the log and anhydrite 10,000 ft/sec = Δt of 50 on the log where the formations have sufficient thickness to record. In New Mexico, where natural salt dissolution (subrosion) has occurred from the surface downward, not just at the salt edge as in Kansas, the dissolution of a salt bed may leave an airfilled porous zone affecting the travel time of sound waves; hence sonic (sometimes called acoustic) logs have indicated the position within the section of a missing salt bed. Other sonic logs also recorded in AEC Test Hole No. 1, but not here illustrated, record acoustic amplitude variations in the compressional or in the shear waves and have applications in determining cement bonding, cement compressive strength, abnormal formation pressures, and in combination with precise caliper logs and density logs can be read and computer-calculated to yield data on shear modulus, Young's modulus, and Poisson ratio. These more exotic sound wave logs ("variable density log," "frac finder log," "3-D velocity log," etc.) are not now used in salt-related drilling but in the future may become more widely applied for rock mechanics studies, particularly for the in situ evaluation of the strength of roof rocks overlying salt cavities.

Roof rocks above the Hutchinson Salt. Any discussion of the salt resources of the Hutchinson area must include a consideration of the roof rocks above the salt beds. The Permian Wellington shales, thickness 340 feet or more, just above the salt section, provide a poor roof rock which has failed repeatedly when sufficiently undermined leading to surface subsidence over salt cavities. The basal dark-colored shales, 20 feet or so in thickness, immediately overlying the uppermost salt bed have joint and bedding cracks filled with one-fourth inch bands of red halite. These shales were deposited as muds in an evaporite environment. Their halite-filled mud cracks and their illite clay minerals indicate equilibrium with salt brines, but these shales slake, slough, and cave readily when exposed to air or to fresh water. In old brine wells, where casing was set at the top of the salt or above the salt in the shale beds themselves, cavernous conditions behind the casing are common as recorded on cased hole neutron logs, indicating roof rock collapse of these shale beds.

Shallower red shales and reddish-brown siltstones of the Wellington Formation, termed "redbeds," likewise are unstable when exposed to fresh water and make a poor roof rock susceptible to sloughing and collapse. The clay minerals (Swineford, 1955) in these redbeds are largely illite and chlorite, not kaolinite, indicating deposition under water in a broad saline basin. The Permian redbeds are about as impermeable to water as any formation, a factor vital in preserving the Wellington Salt, but such redbeds "cave" readily in boreholes when drilled with fresh water and form poor quality roof rock, with the result that surface subsidence as described in this report has occurred due to dissolution of salt at depths greater than 1000 feet in oil and gas test holes in central Kansas as a result of roof failure in the Wellington shales.

Relation of roof rock failure to method of salt mining. Land subsidence is found to be directly related to roof rock failure caused by the formerly used method of solution mining of salt through single boreholes with casing set in the shales above the salt and tubing extending into the salt section. Maximum salt dissolution occurred in the most shallow salt beds, with the cavity often developing a "morning glory" shape broadest at the top. Extended operation of these wells or groups of wells (galleries) undermined large areas, often beyond the structural competence of the shale roof rocks. Modern methods are directed to minimizing this roof span or limiting it to the competence of the rocks for the spans developed. The relation of each of four mining methods to roof rock failure is summarized as follows:

Mining Method	Portion of Salt Mined	Associated Surface Subsidence
Underground Mines	One bed 8′ to 15′ thick in lower salt; room and pillar with 75% of salt removed.	None known
Solution Mining 1888-1960s	Predominately the uppermost salt decreasing downward.	Known surface subsidences in 1914, 1915, 1952, 1974
Solution Mining 1960s-1970s	Predominately the lowermost salt decreasing upward. Void space is a narrow corridor.	None known
Solution Mining for storage of Liquefied Petroleum Gas	Lower salt below "shale" marker; 100′ ± vertically, 40′ ± diameter.	None known

Where underground mining of a single salt bed was done by the "dry" method, or room and pillar mining, leaving 40 percent to 25 percent of the salt as pillars, no known surface subsidence has resulted in Kansas. With the passage of a few years' time, the inactive areas of underground mines tend to close by flowage of rock salt in the pillars as described by Dellwig (1958), but with mine ceiling of only 8 to 11 feet, and mine floor depths of 645 feet (Hutchinson area) to 1024 feet (Lyons area), no surface subsidence has been noticed. Likewise, no surface subsidence has been recorded in connection with the operation of hundreds of LPG storage cavities dissolved in salt. Commonly, these are dissolved through a vertical range of 100 feet in the lower portion of the salt, leaving perhaps 200 feet of salt roof rock. Moreover, most LPG storage cavities are about 40 feet in diameter spaced on 100-foot centers, leaving about 88 percent of the salt unmined throughout their average height of 100 feet.

Brine production by operation of single individual wells, termed "conventional wells" by Landes and Piper (1972), was the system extensively used from 1888 until the 1960s, and cases are known of present-day, single-well operations. In this method of operation, casing was set at the top of the salt and a string of tubing lowered to the bottom of the salt section to be brined. Water pressure at the surface provides the energy to lift the resulting saturated brine back to the surface.

A pressure tight cavity is required, a condition usually prevailing in the early life of a well. By this method of operation, salt was dissolved *upward* in the salt zone with extended operation due to the buoyant rise of fresh water (or weak recycle brine). This in turn caused the tubing to be broken as the result of the falling of undermined ledges (shale, anhydrite) which then exposed shallower salt beds, the dissolving of which allowed water direct access to the roof; dissolving concentrated at the top of the cavity which in near horizontal beds developed a conical or morning glory shape. Ultimately, cavities merged with those of adjacent brine wells to form a common cavity known as a gallery, thus tremendously increasing the span of the unsupported roof. Carried to the strength limit of the overlying rocks, the cavity roof then sagged downward. Translated to the surface as downwarp, the effect initially was barely detectable. Under proper conditions, it affected surface drainage causing ponding. Action sometimes terminated at this point, or if dissolution continued and the gallery enlarged further, the undermined roof rock collapsed into the cavity layer-by-layer in a mechanism known as stoping. The end result of this former method of cavity operation is thus considered to be directly related to roof collapse and ultimately to localized surface subsidence including sinkhole formation.

Modern brine well systems are designed to assure surface stability by limiting roof spans. In the Hutchinson area for example, wells for salt production are often drilled in pairs on 400-foot centers. At least two pairs of wells on 1000-foot centers have been in operation since 1967. In one pair of these wells, 10 million cubic feet of salt have been dissolved in each of the wells, or a total of 20 million cubic feet (Mauritz J. Kallerud, personal communication, July 10, 1976). Wells in each pair have been connected at the base of the salt section by an undercutting technique known as hydraulic fracturing. By this method, water pumped into one well dissolves salt as it moves laterally toward the second well through the undercut or fracture zone. The resulting brine is returned to the surface through the second well. Dissolution continues; eventually enough salt is removed from the bed containing the cross connection that the overlying layer falls by undermining, and the water has access to the next higher salt bed. This is repeated as mining progresses; a channel or corridor is dissolved between the two wells. Structural stability depends on the competence of the roof rock and roof salt. The narrow span of the width dimension of a cavity provides the needed structural stability.

HUTCHINSON, KANSAS: EARLY LAND SUBSIDENCE AREAS

Three known areas. In and near the city of Hutchson, where salt has been mined continuously since 1888, only three areas of land subsidence earlier than the 1974 event pictured on the front cover are known to the author. All three are associated with salt mining by the former method of solution mining using casing set near or above the top of the salt, with resulting uncontrolled dissolution. The areas are listed in order as to time of subsidence:

Year	Company	Area	Remarks
1914	Morton Salt Company	Southwest of city	Rapid surface cratering
1925	Carey Salt Company	Downtown	Slow subsidence of only few inches
1952	Barton Salt Company	Southeast of city, north of plant	Ground subsidence with water coming in the hole

It is quite possible that there are other areas. Old records become lost, the unrecorded locations of old brine wells are forgotten, and even land subsidence areas, which characteristically stabilize when mining ceases, are not remembered. On the other hand, the total amount of salt mined was much less than the 4,000 short tons per day mined in the State of Kansas in 1974 (Berendsen, 1975). Calculations from figures recorded by Taft (1946) for annual salt production for the entire State of Kansas (separate figures for the Hutchinson area are not given) indicate that the average daily salt production at the time of the 1914 subsidence was approximately 1,000 tons per day, and at the time of the 1925 subsidence was about 2,000 tons per day. It is estimated that at the time of the 1952 subsidence the figure was less than 3,000 tons per day. The three known areas are described in chronological sequence.

Morton Plant, 1914. On May 15, 1914, subsidence took place within the plant of the Joy Morton Salt Company southwest of Hutchinson. The company's plant and solution mining operations are located just south of the Arkansas River in Section 23, Township 23 South, Range 6 West (Fig. 2—near Well 14). Conditions are comparable to those at the Cargill plant (Fig. 2—Well 15) except that the salt is somewhat deeper, being encountered near 500 feet.

According to a contemporary report dated May 25, 1914, by Erasmus Haworth, State Geologist for Kansas (from the Morton Company files, Mauritz J. Kallerud, personal communication, June 8, 1976), "On the morning of the 15th inst., at about seven o'clock, a depression became noticeable in the surface of the ground within the works. By ten or eleven o'clock, the depression had reached a maximum (vertical depth) of fifteen feet, carrying with it and demolishing certain parts of the plant. . . . The border of the sunken area approximates a circle of about 150 feet in diameter. Wells No. 1, No. 2 and No. 3 are close to the border of the sink, and each one was affected. . . . Well No. 1 had both casing and tubing broken off at 287 feet. . . . After the sinking, a sand bucket was let down into No. 2 175 feet but would go no further, and a like sand bucket could be sunk 185 feet in No. 3. The ground sank enough to carry top of drive pipe 8 feet below original surface, with the casing pulled down four feet further than the drive pipe, although the space between the two was thoroughly packed with rope packing to make a water tight joint."

After the initial rapid subsidence, the sinkhole was filled and leveled with sand, and the affected brine wells were abandoned and plugged. The ground has stabilized as indicated by over 50 years of close monitoring by surveying the position of the tall brick smoke stack located immediately adjacent (25 feet ±) to the ground affected by the sinkhole.

Carey Salt Company, 1925. An excellent account by C. M. Young (1926) entitled "Subsidence Around a Salt Well" provides information and precise settlement measurements of gentle early subsidence in downtown Hutchinson in 1925, centering around Well 2 of the Carey Salt Company. Maximum subsidence reported by Young was about two and one-half feet vertically and one-fourth foot horizontally. Raymond C. Moore (1925) states in an open-file report dated March 25, 1925: "except for its occurrence in the city where paving and large buildings have shown the effects of the movement, it would have been certainly quite unnoted." Measurements by the city and county engineers showed a series of cracks in the pavements of streets and alleys outlining a circle about 600 feet in diameter. Most serious damage concerned the former court house which stood upon a line of surface cracks indicating tension. The east end of the court house moved horizontally away from the undisturbed west end by about 2½ inches. The cement collar of the abandoned Well 2 may still be seen at the southwest corner of the intersection of Walnut Street and the paved alley midway between Avenue B and Avenue C, but the obsolete court house and other structures have been razed. The area has stabilized and is presently the site of a supermarket. Well 2, first used as a brine production well, was later used as a fresh water input well supplying brine Well 1, 246 feet west, and brine Well 3, 254 feet east, with which it was connected presumably in a common cavity or gallery. All wells were abandoned at the time of the settlement, and the Carey Salt Company continued the gradual transfer of its salt well operations to its present location east of the city. There had been a growing recognition in Hutchinson since the 1914 Morton subsidence, that the extraction of large quantities of salt posed a risk of surface subsidence, and hence that the downtown urban area was an undesirable place for salt mining. The early detection of the initial land subsidence in downtown Hutchinson in 1925, the careful monitoring work reported by Young, and the publicity discussed above caused the immediate cessation of solution mining in this area. This work by Young serves as a documented example of early detection of subsidence by detailed surveying. Cessation of operations no doubt precluded further subsidence which might have caused damage to valuable urban property.

Barton Salt Company plant, 1952. In June 1952, the ground north of the Barton Salt Company plant in the NW/4 of Section 19, Township 23 South, Range 5 West, began subsiding around an old G&H Salt Company well. Remnants of this subsidence may be seen in the abandoned spur of railroad track and the nearby steep crater wall still showing more than ten feet of relief. At the time of the sinking it was noticed that Barton Salt Company's Well 60, south of the plant (Figs. 8 and 9), more than 1,000 feet distant, was associated with the caving north of the plant where water was seen to be coming in the bottom of the hole, until Well 60 was cut off. The operators suspected that their Wells 7, 8, 58, and 59 were also associated with the dissolution gallery connecting the G&H subsidence area with Well 60. The old G&H Salt Company well (the exact location is not known to the author) may have been drilled in 1888 as one of the wells of the firm of Dr. W. C. Gouinlock and C. H. Humphrey. Their firm was the first to begin salt operations at Hutchinson, according to Eskew (1948). When the G&H brine well was re-entered and plugged in June 1952, it is reported that at 150 feet the tools dropped to 252 feet, indicating a sizable cavernous chimney due to successive roof falls above the gallery formed by dissolving the salt formerly present below 400 feet.

In 1972, the Barton Salt Company plant was purchased by Cargill, Inc. Slow subsidence of the area north of the plant was still continuing in 1974, as indicated by the westward tilt of the cement floor of the truck loading dock on the north side of the plant, by the misfit of the sliding doors, and by sandfill required in the driveway from time to time. Wells 58, 59, and 70 have not yet been abandoned (1976).

SUBSIDENCE: CARGILL PLANT SITE, 1974

Sequence of events. On the morning of October 21, 1974 at about 8:00 a.m. it was observed that the surface was subsiding in an area south of the salt plant. As subsidence continued, railroad tracks crossing the site were left suspended in midair. By noon the growing basinlike crater had a diameter of about 200 feet, and had filled with ground water as shown in the photograph, Figure 10. Settlement continued until the afternoon of October 23, 1974 when the crater stabilized at a diameter of about 300 feet, with walls in the soil and alluvium nearly vertical. Water surface in the crater was 21.5 feet below ground level. Water depth was later determined to be 37.5 feet at the deepest level. The volume of the crater was calculated to be 90,000 cubic yards. Figure 11, photographed by the Wichita Eagle and Beacon, November 12, 1974, shows the stabilized sinkhole site after the railroad tracks had been relocated.

Area affected. The 1974 sinkhole developed within a portion of the plant yards and brine well field of the Cargill salt processing plant near the southeast city limits of Hutchinson, Kansas, in the NW/4 of Section 19, Township 23 South, Range 5 West, Reno County, Kansas. Within the area of the crater were two railroad sidings which serve the plant, the main line of the Missouri-Pacific Railroad, and probably one or more abandoned salt wells as shown on the map (Fig. 9). The exact location of many of the abandoned salt wells is uncertain or unknown. Figure 9 was prepared by the author utilizing a surveyed base map on which were plotted the approximate location of abandoned salt wells from surviving well records, often vague or ambiguous. Records exist for 72 brine wells numbered consecutively in order by date of drilling. Abandoned Wells 1 and 2, located in the area now occupied by the present plant buildings, are known to have been in use as late as 1906. No records exist for many of the still earlier salt wells operated by the former Barton Salt Company, beginning in 1892.

Much difficulty was experienced in constructing the map showing well locations (Fig. 9). In addition to the lack of records, a base map showing well locations furnished to Cargill at the time of purchase of the properties in 1972 was found to be incorrectly plotted. The base map was drawn assuring a standard size land section. It was determined that Section 19 is an irregular short section with the correction being made in the W/2 of Section 19, as shown in Figure 9, with the result that the W/2 NW/4 on which the plant, the sinkhole, and the abandoned wells in question are located measured 1275.40 feet (not 1320 feet) along its north line, 1281.02 feet (not 1320 feet) along its south line, but is nearly normal along its east line, 2645.13 feet (not 2640 feet). By using an erroneous base map for plotting well locations, it was thought that Well 9

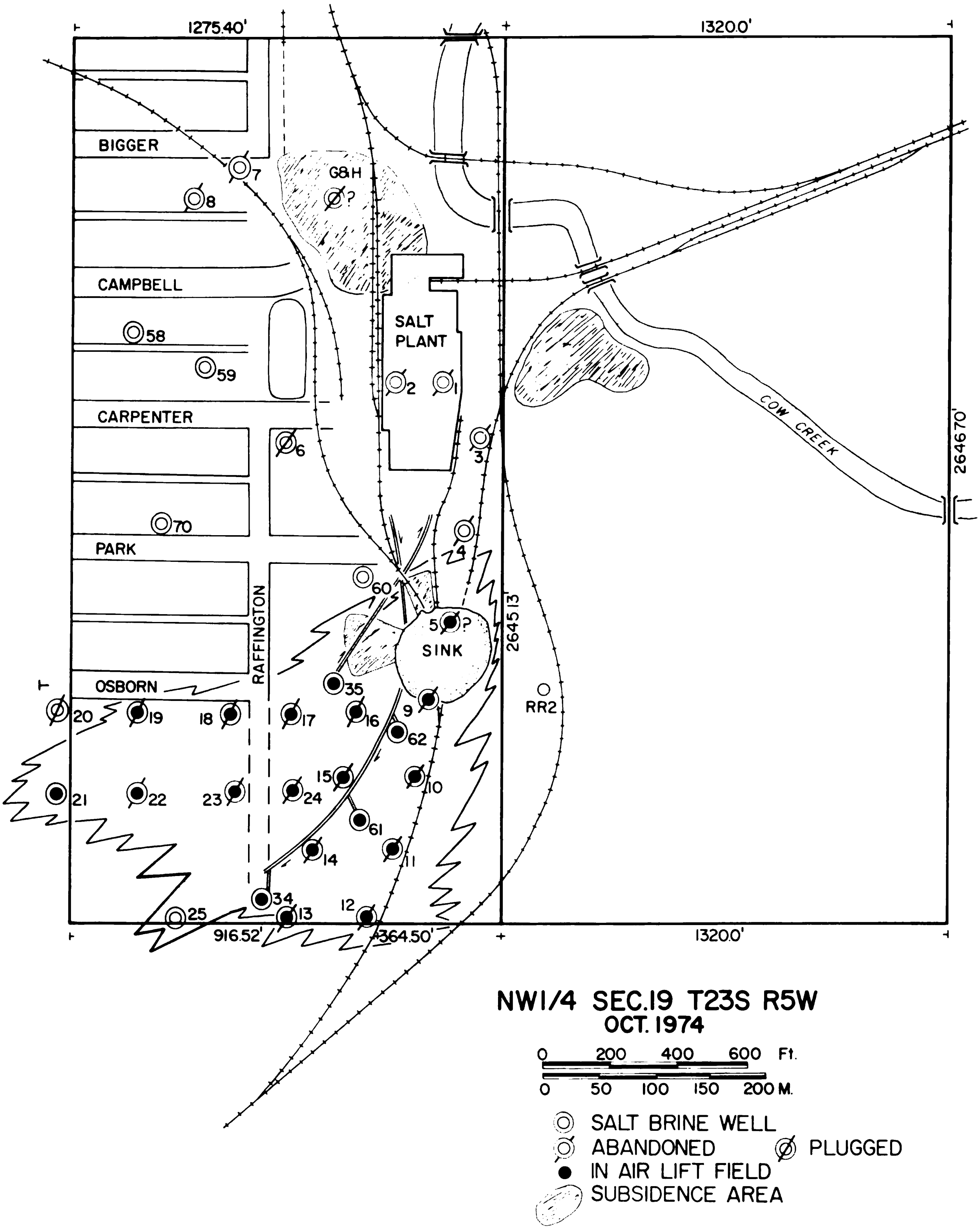


FIGURE 8.—Interpretative map showing the Cargill salt plant, subsidence areas, sinkhole, "Airlift Field," and brine wells in the NW/4 of Section 19, Township 23 South, Range 5 West.

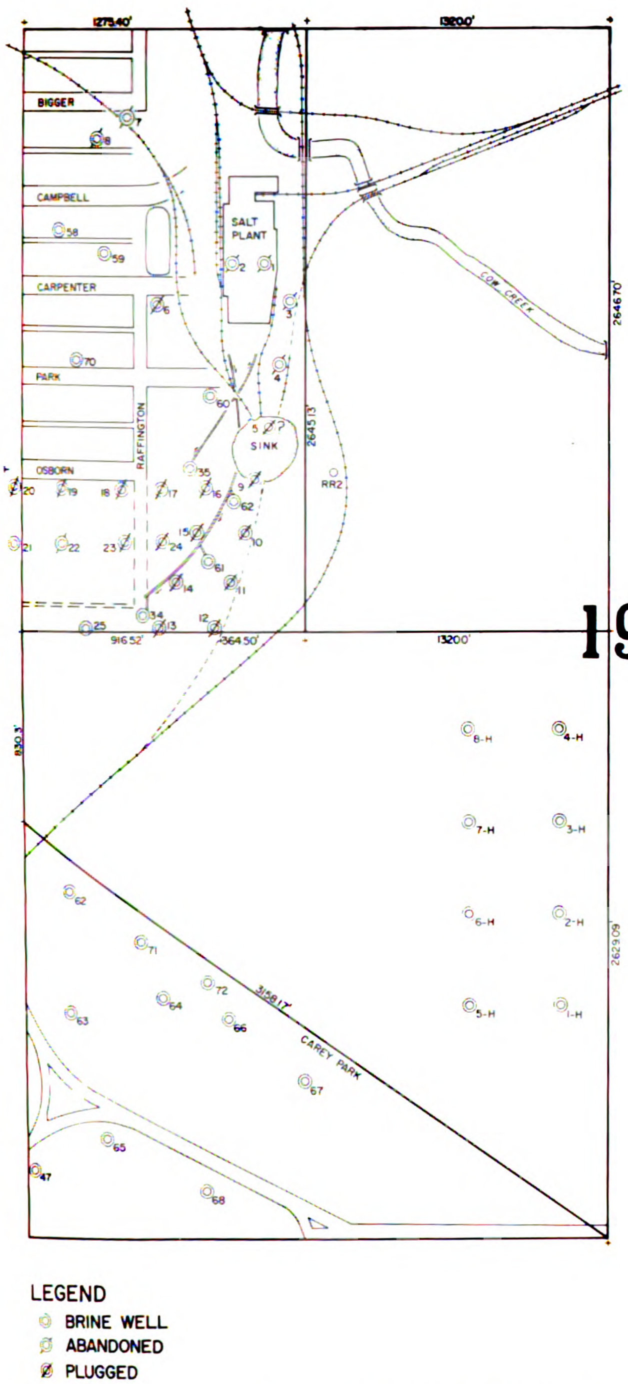


FIGURE 9.—Base map, W/2 Sec. 19, T. 23S, R. 5W, Hutchinson, Kansas.

might be located within the crater, but during a visit on November 21, 1975, the author found the casing of an abandoned salt well in the nearly vertical south wall of the pit where it had become exposed by slumping of the crater walls in the 13-month interval since the collapse. Its location fits the word description of Well 9 (drilled in 1914 and plugged November 17, 1928) "located in the southwest corner of the intersection of (the projection of) Osborne Street and Missouri-Pacific tracks." Word descriptions for other abandoned wells do not provide mappable locations. For example, Well 5 mapped by the author in Figure 9 as within the crater is described only as "located between Park and Osborne Streets between the Missouri-Pacific tracks." There is no visible evidence for the existence of Well 5 either within the crater or adjacent to it. Well 5 was drilled in 1908, and required one month's work to plug in July 1929 as follows:

> Plug set at 415 feet, filled with brick to 395 feet, mud to 320 feet, and stone to 295 feet. Bailed hole dry and filled with concrete to top.

Sources of information. Much of the data pertinent to understanding of the sinkhole, and how and why it occurred when and where it did, consists of subsurface information, chemical analyses, flow pressures, etc., available through informed personnel such as plant employees of Cargill, geologists and engineers associated with the State of Kansas Department of Health and Environment, railroad personnel, or through the author's own observations. The author visited and photographed the site on various dates in 1974 and 1975, witnessed the drilling operations within the crater in November 1975, and has had the cooperation of the executives and staff of Cargill. This portion of the report makes extensive use of the unpublished investigation by Ralph E. O'Connor, Area Geologist, prepared for internal use by the State of Kansas Department of Health and Environment in March 1975, and released for this use. The present report makes extensive use of data from these sources.

Cargill personnel reported that at the time the settlement was first observed there was a rolling motion associated with the water contained within the sinkhole. Nearby wells being operated by the airlift method were shut down; thereafter, the rolling motion in the sinkhole quieted. Communication is thus indicated between the water-filled crater and wells in the "Airlift Field." Samples of the water in the sinkhole, taken October 22, 1974 during active sinkhole collapse, had a chloride content of 89,000 parts per million (ppm). Salt saturation is 226,000 ppm or 311,300 milligrams per liter (mg/l). Two weeks later, on December 5, 1974, the chloride content within the crater was 1,525 ppm. This indicates that a slug of diluted brine was displaced into the sinkhole at the time of active collapse, but substantially dissipated within two weeks.

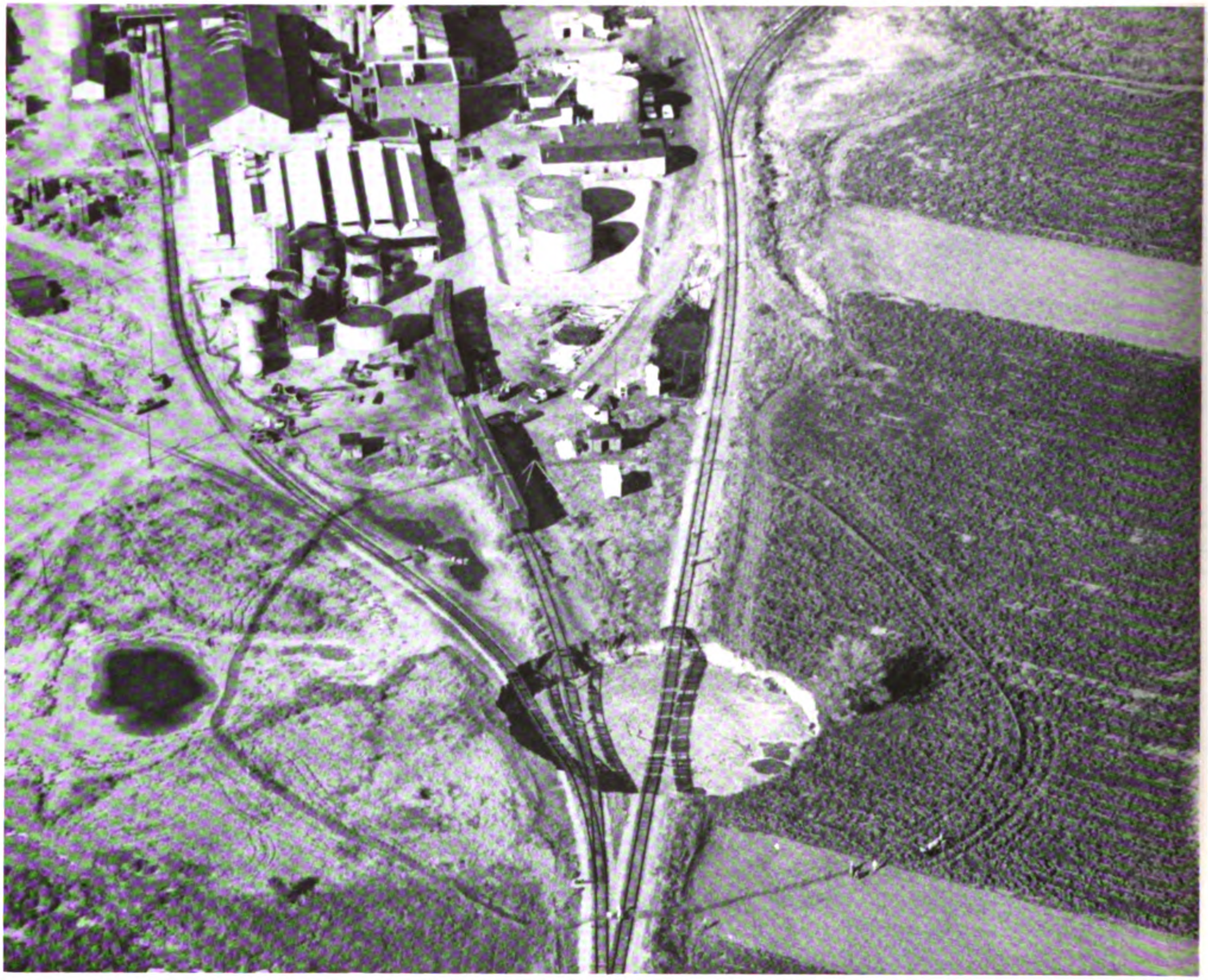


FIGURE 10.—Photograph by The Hutchinson News, October 21, 1974. Diameter of the sinkhole after 14 hours is about 200 feet. View toward the north, with the Cargill salt processing plant in the background. Note the tree on the east (right) bank. Dark circle around perimeter is a temporary fence being erected to restrain spectators.

Airlift Field. Because of the free migration of dissolving fluids in the wells, the actual outline of a mature salt well gallery cannot be precisely defined. The hypothetical outline depicted in Figure 8 includes the operating wells, excludes others, and is thus the approximate outline as well as can be defined. At the time the crater started to form, Wells 34, 61, and 62 were being run as a gallery with Well 35. The term "gallery" is used to indicate that these wells are part of a group of wells known to be hydraulically connected, presumably in a common salt cavity. Locations of these wells are shown in Figure 8. Wells 34, 61, and 62 are spaced on 300-foot centers on a line bearing northeastward, the projection of which intersects the crater. Well 62 is 125 feet from the abandoned well exposed in the bank of the crater, thought to be Well 9. Wells 34, 61, and 62 were being used for access to the salt cavity for disposal of waste solids from the plant. These waste solids were being transported in waste brines which are reported to vary widely in chloride content from saturated to 22,500 ppm as measured at the time of cratering. The waste brine stream was being injected at pressures varying from zero (vacuum or gravity flow) to 150 psi at the time of collapse. Well 62, the disposal well closest to the crater, was equipped with 705 feet of 2-inch tubing in July 1970, of which 26 joints, or about 550 feet, of the 2-inch tubing were recovered when it and Wells 34, 35, and 61 were abandoned in November 1974. These waste-bearing brines carried solid wastes (precipitates of calcium sulfate, magnesium chloride, and other minerals) in amounts approximating three-fourths ton per day. The solids settle in the salt cavity during slow flow through the gallery. Upper flow water from

FIGURE 11.—Photograph by The Wichita Eagle and Beacon, November 12, 1974. Diameter of the stabilized sinkhole is 300 feet. View toward the south, with the Cargill salt processing plant in the foreground. Note that the tree mentioned in Figure 10 now stands in 18 feet of water within the crater near the east (left) bank. Missouri-Pacific railroad tracks have been relocated around the sinkhole.

which the solids had settled by gravity was withdrawn through Well 35 (300 feet northwest of Well 62) by the airlift method, hence the term "Airlift Field." Airlift is a system of producing fluids from a well wherein a small tube is injected part way down the well and air introduced under sufficient pressure to escape beneath the end of the tube and rise in the well fluid. The rising air lightens the fluid column sufficiently to cause the well to flow in an erupting fashion. Well 35 was equipped with 17 joints, or about 357 feet, of one inch tubing down which compressed air was forced to accomplish the airlift. Although injection of solid waste-bearing brines were being made only into Wells 62, 61, and 34, most of the abandoned salt wells near the collapse area are known to be connected in the subsurface with this gallery. For example, fresh water was formerly put in Well 13 for the purpose of dissolving the salt with return brine to be taken out of Well 9, a distance of 800 feet. By study of the records of well histories showing interconnections of wells, the author has indicated on the interpretative map, Figure 8, the approximate extent of this gallery. Well 9, on the south bank of the collapse area and connected to the airlift gallery, served as an individual brine production well for ten years from 1914 to 1924, after which it was used as a brine production well for a gallery including other injection wells in addition to Well 13 on the south edge of the property.

It should be noted that the injection of weak disposal brine in one well in a gallery does not affirm that saturated brine produced elsewhere is derived from the disposal brine. In the case of a gallery which is not pressure tight, fresh water can be induced through unsealed casings or through leakage around the outside of uncemented casings. In either case, the introduced water dissolves additional salt resulting in cavity extension by enlarging the gallery an indeterminate area. It is reported that Well 13, a water injection well connected with brine production Well 16, "blew up," meaning the pressure of the injected fresh water broke the mud seal on the outside of the uncemented four-inch casing set at 355 feet. This occurred in 1931 at which time the well was plugged. A similar incident occurred in Well 16, the connected brine production well, in which uncemented four-inch casing had been set at 345 feet with a seed bag packer and mud. Swelling of the seeds, commonly flax seed, plus the weight of the mud provided the only seal. In 1931 it too blew out the mud seal around the casing and was patched by repacking around the top of the four-inch casing with hemp to stop the leak. These examples give some idea of the conditions within the airlift gallery (approximate limits, gallery outline Fig. 8) adjacent to and connected with the sinkhole at the Cargill plant.

Early indication of subsidence. In retrospect, probably the most conspicuous advance indications of the 1974 subsidence at the Cargill site were the adjacent flat areas in which water collected located immediately west of the sinkhole and another to the north between the railroad tracks. These areas are visible in the color photograph on the front cover, in Figure 10, and are mapped in Figure 8. Other advance indications are the reports by railroad maintenance personnel that the switch at the south edge of the crater was frequently difficult to throw because of being out of alignment and periodically required realignment. The track was required to be raised at intervals for two years prior to the collapse. The crater affected no buildings, and there are no paved roads; hence no preliminary advance indication in the form of cracks could be observed. The sandy hummocky ground in the plant yard will not preserve and show ground cracks.

Also in retrospect, the general area of the sinkhole could probably be considered to be subsidence prone because of continuous production of salt from the well group in this area for 84 years since 1892, including its recent utilization for plant waste brine recycle and disposal. A poorly drained low area east of the salt plant within the curve of the railroad tracks is faintly visible on the air photograph, Figure 10, upper right, and mapped in Figure 8 by shading. This also appears suspect as a salt-related subsidence area. This site is immediately adjacent to the present salt processing plant under which are the locations of brine supply Wells 1 and 2, in use in 1906, as shown on the interpretative map, Figure 8. The locations of other early brine supply wells utilized in the period from 1892 to 1912 are now unknown. Because the removal of each ton of salt creates a cavity of about 15 cubic feet, or ½ cubic yard, it can be estimated that the cavity created in these first 20 years of operation near Wells 1 and 2 is approximately 150,000 cubic yards, or approximately one and one-half times the measured surface volume of the 1974 sinkhole south of the plant.

A third area of prior subsidence is briefly described on page 17 as the June 1952 subsidence area at the then Barton Salt Company plant. It involves the northwest corner of the present main plant building, the driveway, and an area west of the railroad tracks as mapped in Figure 8. Subsidence here is definitely salt related, and was still active in 1974 as shown by the westward tilt of the cement floor and the closure difficulties experienced with the large sliding doors of the truck loading dock. Together, these three areas of prior surface subsidence adjacent to the old Barton Salt Company plant affirm that the salt in the vicinity has been extensively removed by solution mining.

Historical background—Cargill plant. When rock salt was discovered at Hutchinson in 1887 (Cowan, 1940), it was speculated that the city would develop into one of the largest salt manufacturing cities in the west. In 1890 there were 23 Kansas plants producing salt (Taft, 1946, p. 265), but the financial panic of 1893 put many of the new plants out of business. When Cow Creek, which flows into the Arkansas River at Hutchinson, flooded the countryside in 1894, many others were forced to shut down. By 1900 there were only eight plants producing salt in Kansas (Taft, 1946). The salt brine wells used in these short-lived operations were commonly abandoned and left without any plugging and with no known surviving well records.

The Barton Salt Company, now Cargill, Inc., is the oldest of the three presently operating companies active in the Hutchinson area. The Barton Salt Company was founded in 1892, and began operating with three open grainer pans. Its original capacity was rated at about 40 tons of salt per day. In 1913, the Barton Salt Company passed to new owners, C. H. Humphrey and E. T. Guyman. C. H. Humphrey, an experienced chemist, took over active direction of the company and began a broad sweeping modernization and expansion program that was to literally remake the original company. He installed vacuum pans, rotary vacuum filter wheels and dryers, new grainer pans, complete packaging equipment, and new salt block presses. Cargill succeeded the Barton Salt Company in 1972 and continued its operations making changes and improvements, but essentially continuing the salt production practices of the Barton Salt Company.

The Cargill plant produces salt by evaporation of brine. Because of the nature of the manufacture of salt by evaporation, these operations are required to be carried out on a continuous 24-hour basis. The brine is produced by dissolving of the salt deposit by the introduction of water through wells drilled for this purpose. Brine is produced when the feed water contacts and dissolves the salt; the resulting brine is produced from the same well by an annular tubing/casing arrangement, or from a nearby well when their cavities have coalesced to form a gallery. Water input wells are known as feed wells—brine is produced by pressure (forcing) in the case of pressure-tight cavities, or by pumping using airlift or well pumps—in more mature systems which have ceased to be pressure-tight.

Water for supplying the brine wells is derived from three water supply wells completed in the alluvial sands and gravels, and also from the plant cooling tower, with total water use at an average rate of 250 to 300 gallons per minute.

A typical brine well employs 150 to 170 feet of surface casing which is cemented in place, and producing casing which is set at approximately 480 feet; tubing is run inside the production casing to the base of the salt section which averages 770 feet in depth. In the pressure or forcing system, water is pumped down the tubing under sufficient pressure to force the resulting brine up the annular space between the tubing and the production casing. The brine then flows to surface collecting tanks. In the case where cavities of wells have dissolved together ("coalesced"), or have ceased to be pressure-tight, it becomes necessary to use either airlift or one of several types of well pumps.

Because of the free dissolving nature of this process, the extent of the solution cavities was largely unknown other than those encountered in drilling or by reported coalescences. Modern well logging and cavity survey techniques had not been developed. Cavities often merged with one another by free dissolving, and no particular stress was put upon attempts to prevent cavity coalescence. New wells were started at a rate averaging one every two to two and one-half years. Salt saturation of the produced brine was nominally 100 percent.

Figure 9 depicts the approximate locations of the earlier wells for which records exist. The reader will recall that, as mentioned above, well operations date back over 80 years—in early days no records were kept; wells were abandoned or "lost." Modern casing, cementing, and abandonment techniques have only recently become employed. From the position of the subsidence basin and sinkhole crater, as shown on Figure 8, it will be seen that the crater location is related to the old brine wells of the Airlift Field, being sited among the wells. Not shown on either Figure 8 or 9 are 27 other active brine supply wells supplying most of the brine to the plant in 1974. These wells are located as much as one mile south of the plant in an area along the Arkansas River, under Carey Park and the Hutchinson municipal zoo. All but four of the brine wells mapped in Figure 9, in operation close to the plant in 1974, have since been plugged and abandoned, and replaced with a new supply field about one-half mile southeast of the plant, Wells 1-H to 8-H, Figure 9. Average salt production was approximately 500 tons a day in October 1974, but at that time the plant was in the process of extensive remodeling to expand its daily capacity to about 750 tons of salt per day.

POST-SUBSIDENCE ACTIVITIES AND INVESTIGATIONS

Cargill, Inc. When the ground collapse was observed on Monday morning, October 21, 1974, an emergency fence was erected and guards were retained to restrain curious spectators who had seen and heard the news and television coverage of the developing sinkhole. Freight cars were moved from the edge of the pit. The use of Wells 34, 35, 61, and 62 in the Airlift Field was immediately discontinued. Later, tubing was pulled from all four wells and efforts were made to log the wells before abandonment. Because no buildings and no principal brine or fresh water lines were involved in the growing sinkhole, plant operations were not interrupted by the settlement. Subsequently, a new eight-well brine field has been developed 2,000 feet southeast of the plant in the E/2 SW/4 of Section 19. In the new field, wells on 400-foot spacing are operated as four fresh water input wells each connected by fracturing to one of the four brine production wells, making four pairs of wells. These new wells are designated 1-H to 8-H, Figure 9.

Missouri-Pacific Railroad. At the time of the settlement, immediate steps were taken by the Missouri-Pacific Railroad to relocate its main line tracks which were intercepted by the crater. On October 23, while subsidence was still active, work was underway for the railroad bypass, mapped in Figure 9, just east of the sinkhole. In order to verify the competence of this route, three test holes were drilled. Two holes, drilled to 250-foot depth by Darling Drilling Company of Hutchinson, encountered shale bedrock at a normal depth of 68 feet. A third hole, designated on Figure 9 as "RR 2," was drilled by the Engineering Testing Company of Wichita, Kansas, to 519 feet total depth in salt without encountering cavernous conditions. The top of the salt, expected near 400 feet, was not determined because the hole was neither cored nor logged with wire line logs. At the request of the Missouri-Pacific Railroad, the hole was used by Wichita Testing Laboratories for a limited refraction seismic survey program employing 12 geophones. Two sets of fan shots were recorded by detonating explosives at depths of 506 and 425 feet in RR 2 hole. The 12 geophones were spaced in two arcs equal distant from the shot point. If all substrata traversed are uniform in depth and thickness, the travel time through the rocks to each geophone will be the same. By this method, any significant abnormal condition such as a subsurface void between shot point and geophones will be recorded by a difference in time delay to the geophones affected. The fan spread toward the north and east from RR 2 recorded such delay in an arc including the shaded subsidence area east of the plant in Figure 8, inferring cavernous void space due to salt dissolution. The second fan spread toward the west from RR 2 gave a similar indication through the area of the sinkhole and the Airlift Field, Figure 8, but of more significance to the railroad, indicated normal travel times in the area east of Wells 10, 11, and 12, confirming the absence of cavernous conditions and verified the feasibility of construction of the new railroad tracks. The very limited emergency refraction seismic program was discontinued after the two fan spreads. The specific location of the railroad bypass was made on the basis of tolerable curvatures.

State of Kansas Department of Health and Environment. While the crater was still actively forming, Melville W. Gray, Director of Environment, State of Kansas Department of Health and Environment, was present at the location and immediately organized an investigation directed to determine the environmental impact of the formation of the crater. The investigation included a drilling program for ground-water monitoring to which he assigned Ralph E. O'Connor, Area Geologist, whose written interim report of March 17, 1975 records basic factual data. Water samples were collected October 24-25, 1974, just after active cratering ceased, from 39 water wells in the vicinity, and were analyzed for chlorides, showing an average of 367 mg/l chlorides. Twelve observation water wells were drilled by the State of Kansas Department of Health and Environment to permit sampling of ground water in the area. Average depth of the wells was 65 feet; shale bedrock was encountered near 60 feet. Complete analyses of water samples from these wells, taken in November 1974, about one month after the sinkhole collapse, showed results which varied widely from 3,130 mg/l to 90,300 mg/l total solids and 488 mg/l to 52,000 mg/l chlorides. The depth to the water surface within the sinkhole was measured as 21.5 feet below average ground level. Water depths within the sinkhole were measured and ranged from 18 feet to 33 feet. Monitoring of ground-water quality in the 12 holes drilled for that purpose is continuing. No chloride contamination other than that initially present had been detected to February 1976; the State of Kansas Department of Health and Environment continues its surveillance of well plugging, drilling of new wells, and the management of plant waste waters.

Solution Mining Research Institute, Inc. Investigation. Because unplanned subsidence is a major hazard of the solution mining industry, a considerable portion of the research effort of the Solution Mining Research Institute (SMRI) is directed toward an understanding of the mechanism and establishment of the time framework of ground subsidence resulting from salt mining by dissolution. Accordingly, SMRI requested permission of Cargill, one of the corporate members of the Institute, to conduct a test drilling program adjacent to and within the sinkhole. In November 1975, one year after the ground collapse, SMRI engaged Wichita Testing Laboratories (WTL) to drill ten holes, two on opposite banks of the 300-foot diameter sinkhole and eight from a barge on the pond within the sinkhole. Location of the test holes is mapped in Figure 12. A geological cross section through eight of the holes is presented in Figure 13. Both figures are from the WTL report.

Holes B-1 and B-2 outside the sinkhole were drilled using a truck-mounted Mobil B-40 drilling rig, equipped with 7-inch diameter continuous flight auger. Borings within the sinkhole were made with a smaller raft-mounted drilling rig, equipped with 70 feet of 4-inch diameter continuous flight auger. The nearly flat surface of the bedrock, reddish-brown Permian shale, was reached by seven of the wells at depths near 70 feet in holes B-1 and B-2, or near 50 feet for barge-drilled holes. The water surface, elevation 1502.5 feet, is 21 feet below the average ground level. Three holes near the center of the pond in the deepest water failed to encounter shale bedrock at total depth of 70 feet (the limit of drilling equipment on the barge). This infers the presence of a restricted area of bedrock collapse, approximately coinciding with the 30-foot water depth contour of Figure 12 which defines an elliptical area with axes of 130 and 90 feet, or an average diameter of 110 feet, as compared to the 300-foot average diameter of the nearly circular sink.

The results of this drilling indicate (1) that the surface sinkhole is developed in loose sand and gravel, (2) that only 20 percent of the material removed from the sinkhole was in a position to move directly downward, and (3) that 80 percent of the material removed

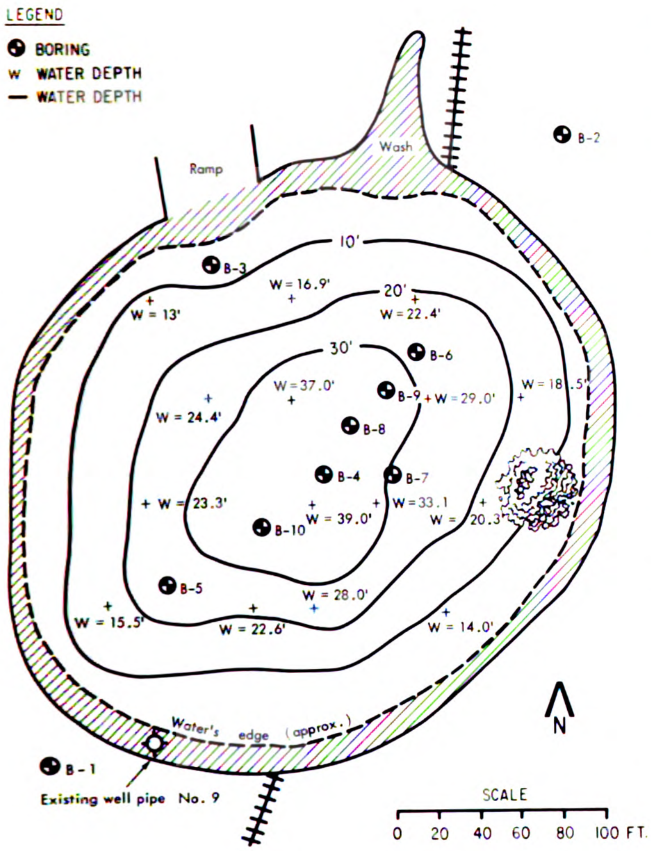


FIGURE 12.—Test Location Plot, Sinkhole, Cargill Salt Property, Hutchinson, Kansas.

Borehole	Water Depth	Shale Depth
B-1	----	----
B-2	----	----
B-3	3	45
B-4	37	----*
B-5	25	45
B-6	27	47
B-7	30	46
B-8	36	----*
B-9	34	59
B-10	37	----*

* Not reached at 70′ maximum depth.

required some lateral component in order to move down the hole in the bedrock. This is interpreted as evidence for extensive "piping" of an aqueous sand-gravel slurry down a restricted opening into the void space created by dissolution of salt formerly present from 400 to 750 feet. Estimates and calculations are as follows:

1. Volume of sinkhole, estimated
   - Above water level .... 50,000 cubic yards
   - Below water level .... 40,000 cubic yards
   - Total .... 90,000 cubic yards
2. Volume of central area of sinkhole bounded by 30-foot water depth contour, Fig. 8
   - Above water level .... 7,000 cubic yards
   - Below water level .... 11,000 cubic yards
   - Total .... 18,000 cubic yards
3. Ratio of volumes .... $\frac{18,000}{90,000} = .20 = 20\%$

These volume figures were calculated from the average ground surface to the bottom of the water, as mapped in Figure 12, but not to the top of the sand. The interval labeled "silty sand (muck)" consisted of water saturated fine sediment which could be penetrated by pushing the drill through it. In contrast, the sand required drilling, and the firm bedrock, the Permian shale, was so resistant that it could be penetrated only a foot or so with this type of equipment.

In addition to the sinkhole drilling project, SMRI cooperated with Cargill in coring and wire logging the salt section in one of the new brine wells being drilled in the SW/4 of Section 19, and contributed to preparation of a descriptive log of the salt cores under the direction of Dr. A. J. Hendron, University of Illinois, consultant to SMRI on rock mechanics and salt cavity design.

CAUSE, MECHANISM, AND TIME FRAMEWORK: 1974 SINKHOLE

Cause. It appears at this time that the 1974 sinkhole was the result of the removal of salt in a cavity configuration which 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 bedrock ledge was breached, permitting 90,000 cubic yards of sand and gravel to move down the bedrock opening. In developing this explanation, Donald S. Robinson, plant manager (personal communication), thinks it possible that brine pumped from Well 35 in the Airlift Field gallery exceeded the amount of recycle brine returned to the gallery, thus permitting induction of makeup fluid (fresh water) through leaks from improperly plugged, or entirely unplugged, abandoned brine wells for which insufficient records, or no records, exist. The resulting movement of fresh water was downward from the shallow aquifer by way of the abandoned brine wells which provided connections with the water-saturated overburden. Lateral movement of fresh water or unsaturated brine through the gallery at the roof dissolved additional salt causing cavity enlargement over a large area by removing critical roof support resulting in broad areal subsidence or downwarping prior to sinkhole formation.

It is recognized that many factors combined to cause the surface subsidence at the Cargill plant, and must be given consideration. Salt had been produced at this location for a long time, from perhaps as early as 1888 until October 1974, by the method of uncontrolled dissolution in the Airlift Field gallery. Underground conditions are unknown, and largely unknowable, due to the abandonment of many former

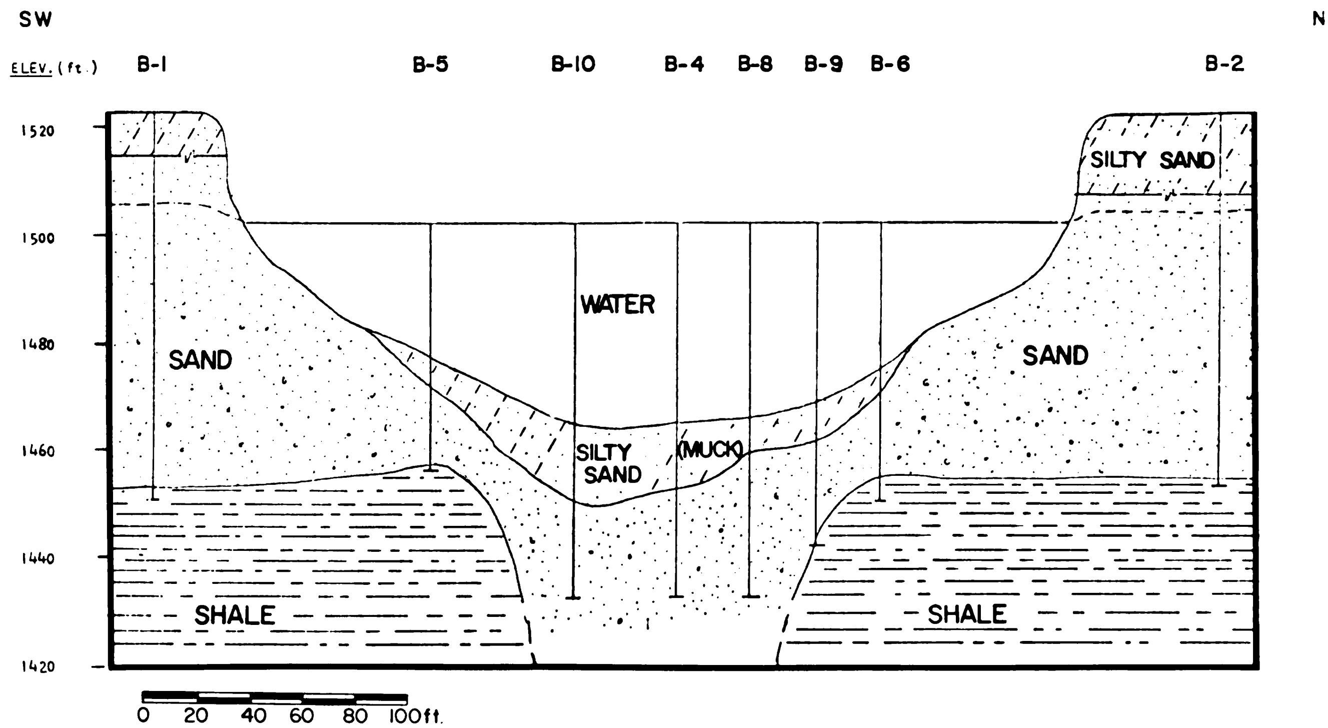


FIGURE 13.—Geological cross section, sinkhole, Cargill property, Hutchinson, Kansas. Vertical exaggeration × 2. Prepared by Wichita Testing Laboratories for the Solution Mining Research Institute, November, 1975. "Shale" is bedrock. For location see Figure 12.

brine wells often with no surviving well records. Moreover, production in this area is at relatively shallow depths, from 400 to 750 feet, with structurally weak Permian shales and siltstones overlying the salt. Also, all production takes place under a shallow and prolific fresh water aquifer in unconsolidated sand and gravel. It is recognized as a causative factor that the operation of brine pumps in the Airlift Field gallery for all the years of salt production and of waste brine recycling provided the needed energy input into the system. The surface sinkhole is located within the brine production gallery limits and directly under the main line of the Missouri-Pacific railroad tracks. Periodic ground vibration with the passage of long freight trains may be a contributing cause in the localization of the surface sinkhole. Although the exact combination of factors contributing to cause the sinkhole formation in October 1974 at the Cargill plant is unknown, it is recognized that the most visible phase of sinkhole development—when 90,000 cubic yards of loose sand and gravel moved downward in three days time leaving a crater 300 feet in diameter—was not itself the cause of land subsidence but was, rather, the end result of a sequence of events originating with gallery operation.

Mechanism and time factors. In view of the factors outlined above, knowledge of the time frame and mechanism involved ultimately in collapse of the land surface remains to be developed. It is not known, for example, whether the crater is situated above a narrow vertical chimney-shaped bedrock void localized in a small area by contributing factors such as the presence of an unknown old brine well, or the daily vibrations from passing freight trains. If so, then the mechanism involved can be interpreted as chimneying, as described by Landes and Piper (1972), and the implications are that solid roof rock, perhaps in its full original thickness, remains over the rest of the mined area of the Airlift Field gallery, and that the 90,000 cubic yards of sand and gravel was transported downward and deposited at depths below 400 feet within void space from which salt had been dissolved. This could be tested by a suitable drilling program. An alternative interpretation is that the circular sinkhole is located above a wide cone of underground roof collapse over the Airlift Field gallery with only relatively thin undisturbed bedrock remaining in place over a large area. In this case, the bedrock collapse can be attributed to stoping and the relatively small opening through which sand and gravel moved downward might be localized at the apex of the broad cone of roof rock failure. This, too, could be investigated by a drilling program. If correct, test holes should encounter the transported sand and gravel at shallow depths, perhaps 150 to 250 feet, and should find roof-fall shale material at depths below 400 feet filling former void space from which salt was dissolved.

Other investigations which might contribute knowledge of the mechanism involved include extensive recording of wire line geophysical logs in any future holes drilled, additional seismic refraction work, diamond coring of both bedrock and collapse breccia, and fluid injection, or withdrawal, tests. Fortunately, it is well recognized that when the energy input into the system ceases (in this case, when the brine pumps are shut off), then cavity enlargement ceases, subsidence terminates except for minor compaction, and sinkhole areas tend to stabilize. Beyond that, little else is established concerning the actual mechanism of ground subsidence due to salt dissolution and the time frame involved. Research investigations under actual field conditions are much needed.

KANOPOLIS, KANSAS: LAND SUBSIDENCE DUE TO CRATERING OF SALT MINE SHAFT

Subsidence sequence. In 1949, the shaft of the abandoned Crystal Salt Mine at Kanopolis, Ellsworth County, Kansas, was plugged and filled to the surface with rock and dirt. Twenty-three years later, on January 12, 1972, W. Holms, plant superintendent of the Acme Brick Company, then owners of the property, was surprised to find the formerly filled shaft open and empty. He lowered a brick on a long rope to a depth of 700 feet indicating only 90 feet of rubble fill in the shaft at that time. The abandoned shaft was constructed in 1923, with dimensions 17 feet by 9 feet by 790 feet deep, and hence had an original volume of 4,500 cubic yards. Figure 14 depicts cross sections through the upper shaft on various dates. Profile "A" indicates conditions on January 11, 1972. Note the presence of unconsolidated Quaternary water sands ("W") near 35 feet, and the presence of Cretaceous sandstones near 80 and 140 feet. Profile "B," March 6, 1972, and Profile "C," March 8, 1972, show how the surface around the mine shaft cratered, forming a steep-sided pit having a final volume approximately four times the volume of the mine shaft. The cratering of the surface was relatively rapid. The first two days were witnessed by N. W. Biegler (personal communication) of the State of Kansas Department of Health and Environment.

Surface subsidence began at the Crystal Mine shaft on the morning of March 7, 1972. By that afternoon, Biegler estimated that the dimensions of the cone shaped hole were about 40 feet north-south and 30 feet east-west, indicating the dropping into the shaft of a volume of about 150 cubic yards of unconsolidated soil, sand, and shale (assuming the cone shaped hole was then 25 feet deep). Twenty-four hours later at 3:00 p.m., March 8, 1972, Biegler measured the cone shaped opening as 65 feet by 40 feet, Figure 14, Profile "C." At a depth of 31 feet, the opening narrowed to about 25 feet north-south and about 15 feet east-west due to a ledge of Cretaceous Dakota sandstone below the unconsolidated Quaternary Grand Island Formation. It is calculated that another 666 cubic yards of each material had dropped down the shaft. The shaft was then partially filled and blocked at the bottom by the 90 feet of fill, measured on January 12, plus the material dropped in forming Profile "C." Evidence of blocking is provided by the fact that the formerly dry shaft had filled with water to a depth of 110 feet below the surface on March 8. No other measurements were recorded until several days after the cave-in had stabilized. When surveyed on March 28, 1972, by Brady and Wilson of the Kansas State Geological Survey (Frank Wilson, personal communication, October 29, 1974), the steep-sided pit measured 129 feet by 95 feet. Water level was 23.3 feet below the surface. The depression was flat bottomed at an average depth of 60 feet below ground level as determined by 28 soundings. The position of the former shaft could not be ascertained, presumably because it was filled and plugged with slump material. Measurements from the soundings are diagrammed as the stabilized Profile "D," Figure 14. Brady and Wilson estimated that it would require about 20,000 cubic yards to fill the pit level with the ground. This is more than four times the volume of the original shaft. About 95 percent of the material from the crater moved down the shaft after March 8, and in so doing, moved into a water-filled shaft which was partially filled and blocked with rock debris prior to the settlement of the great bulk of the material. These observations and calculations provide the basis for speculation as to how a rapidly forming cave-in could move a volume of sand, shale, and rock debris several times the original shaft volume down that same water-filled shaft, leaving it plugged to within 60 feet of the top.

Mine history; Crystal Salt Mine. The crater formed in the abandoned shaft of the Crystal Salt Company mine located at the east edge of the city of Kanopolis, in Section 25, Township 15 South, Range 8 West, Ellsworth County, Kansas. The mine was a room and pillar mine, ceiling 9 feet for the most part, with a maximum ceiling of 11 feet, and with a salt removal ratio of 70 percent. It connected underground with the adjacent Royal Mine. In 1941, the Crystal Mine was sold to the Morton Salt Company, who operated it until 1947 when operations were terminated because sloughing of shale between 200 and 300 feet

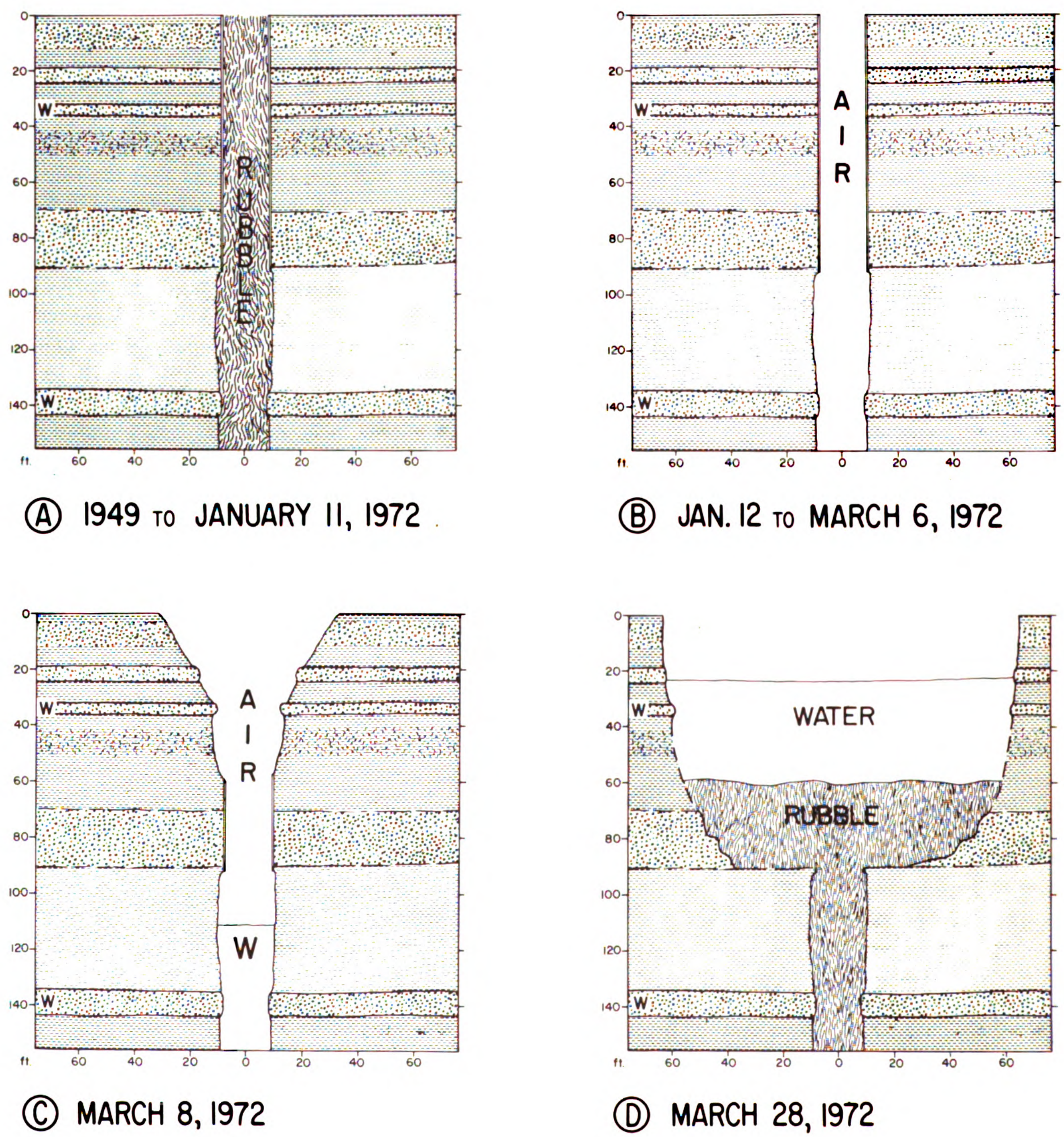


FIGURE 14.—Shaft profiles, abandoned Crystal Salt Mine, Ellsworth County, Kansas. Sandstones are stippled, shales are patterned; "W," water. Measurements are in feet.

depth caused alignment of the cribbing in the shaft to shift sufficiently to affect the operation of the hoisting equipment. It was reported in 1949, when the shaft was plugged, "that a large concrete block lodged at 126 feet below the surface and the shaft was filled to the surface." (N. W. Biegler, personal communication, April 12, 1972). It is possible that the timbers supporting the concrete plug at 126 feet gave way causing the concrete block to fall through air to the bottom of the shaft in November 1971, at which time residents of Kanopolis reported feeling a sonic boom. Later, the remainder of the 126 feet of fill fell to the bottom of the shaft, leaving it open and air-filled as discovered by W. Holms on January 12, 1972.

No direct observations could be made concerning conditions in the lower shaft of the abandoned Crystal Salt Mine during and preceding the sequence of events depicted in Figure 14. Such information is available, however, from another abandoned salt mine, the Little River Salt Mine in Rice County, which is discussed next because of the applicability of the information as part of the explanation for rapid land subsidence at the Crystal Salt Mine shaft.

Information, shaft and mine deterioration, Little River Salt Mine shaft. Data accumulated in 1963, and confirmed in 1975, in connection with the sealing of the shaft of the abandoned Little River Salt Mine in the NE/4 NE/4 of Section 18, Township 19 South, Range 6 West, Rice County, Kansas, provide information as to shaft and mine deterioration. Active mining of salt in this 40-acre room and pillar underground salt mine ceased in 1926. The mine was kept open until 1938, then abandoned with the shaft left open and unsealed. Depth to the mine floor was 796 feet at the shaft, the mine ceiling was 11 feet high, and 75 percent of the salt was mined, leaving 25 percent as pillars. The shaft, which originally measured 7 feet by 17 feet (Jewett, 1956), deteriorated due to fresh water seepage for 25 years until 1963. Figure 15 depicts the position of the top of the rubble pile, and the foot-by-foot volume of the shaft as determined by a sonar survey from which the shaft cross-section diagram was constructed. N. W. Biegler (personal communication April 25, 1975) reported that 12 years later, in 1975, when new owners conducted an investigation as to the feasibility of using the mine for propane storage, it was confirmed that the shaft was not hydraulically tight. In the course of further investigation, one hole was drilled down the center of the filled shaft to 655 feet. Two additional holes were drilled through the bedrock adjacent to the shaft. Both of these holes drilled out of bedrock into areas of shaft enlargement near 540 to 560 feet, confirming the accuracy of the sonar survey. Note that considerable shaft enlargement occurred in shales immediately above the salt. These shales, present at depths from 540 to 560 feet, are dark gray to black with vertical joints filled with red halite. The shales were deposited in equilibrium conditions with the halite crack filling, and are quite unstable in the presence of fresh water or air. The rubble is built up about 50 feet above the original mine floor. Note also the extensive mine roof collapse and the extensive bedding-controlled collapse of salt near 740 feet, or about 60 feet above the original mine floor. The mine shaft was sealed by grouting in 1975, and the mine is being operated as LPG storage for propane, using bottom hole pumps set in large diameter drilled shafts for product removal.

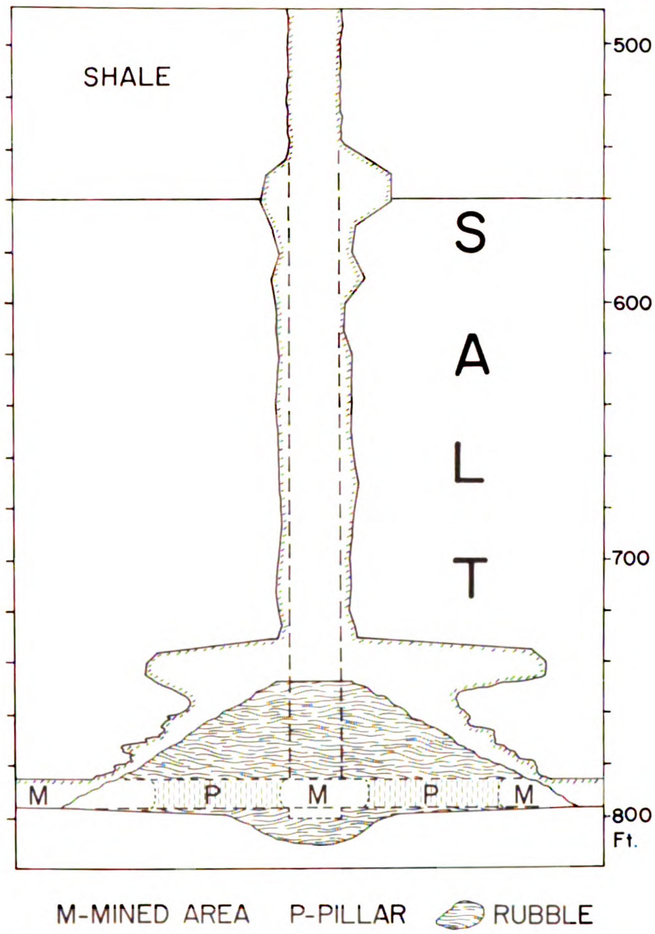


FIGURE 15.—Lower shaft, abandoned Little River Salt Mine, Rice County, Kansas. Constructed from a sonar survey to the top of the rubble at 750 feet. Dashed lines indicate position of shaft as constructed. Measurements are in feet.

Volumetric data, Little River Mine. It is noteworthy that the extensive void space developed by roof collapse and salt dissolution in the 25-foot interval from 725 feet to the top of the rubble at 750 feet was measured by sonar as a volume of 13,100 cubic yards, or four times the volume of the original shaft to 750 feet (3,305 cubic yards). The calculated average diameter for the 25 feet from 725 feet to 750 feet is

134 feet. The volume of salt which was originally mined from an underlying area 134 feet in diameter with an 11-foot ceiling, was only one-third as much as the sonar measured void space from 725 to 750 feet, indicating considerable dissolution of salt in place or by fresh water falling on the collapsed rubble pile.

Application to the Crystal Mine, Kanopolis, Ellsworth County. This volumetric information concerning shaft bottom conditions in the Little River Salt Mine is considered to have application to the Crystal Salt Mine in Ellsworth County. Rubble from the surface subsidence crater at the Crystal Mine in the amount of four times the original shaft volume may have filled a collapsed lower shaft area rather than being displaced into the low ceiling abandoned mine through two narrow portals. In conclusion, the Crystal Mine shaft cave-in crater is another example associated with the removal of salt in which land subsidence occurred rapidly (in a few days) because of the presence of a near surface aquifer in unconsolidated sand and gravel.

PART III: LAND SUBSIDENCE AREAS ASSOCIATED WITH OIL AND GAS OPERATIONS IN KANSAS

GENERAL STATEMENTS

Land subsidence: a rare event. Eight areas of land subsidence associated with salt dissolution due to oil and gas operations in Kansas are known to the author. They are mapped in Figure 3. Within the State of Kansas, an estimated 80,000 oil and gas test holes have been drilled through the Hutchinson Salt Member of the Permian Wellington Formation. Over several years, a thorough search for subsidence areas caused by dissolving salt in connection with oil operations disclosed only these eight examples. This is a ratio of one land subsidence area for each 10,000 oil and gas test holes penetrating the Hutchinson Salt. Land subsidence due to this cause may, therefore, be considered as a rare event related to oil and gas operations. Its severity, however, under proper geological conditions must not be discounted.

Similarity to subsidence areas due to salt mining. In appearance, size, and variation in time frame, the oil-related subsidence areas closely resemble the five previously described surface subsidence areas associated with solution mining of salt. The most conspicuous difference is that in the oil and gas related land subsidence areas all dissolved salt is transported downward to a suitable permeable zone. Because the dissolved salt is not produced at the surface, as in salt operations, we thus have no directly visible evidence of salt, or of saturated brine resulting from the dissolution of the rock salt.

Related to salt water disposal systems. Although some salt dissolution does occur during the drilling of wells, it is of limited extent and, because of limited volume, is not expected to have caused land subsidence. Likewise, after drilling ceases, whether the hole is abandoned as "dry" or completed as an oil well, little or no additional dissolution of salt occurs if the hole has adequate casing cemented in place opposite fresh water zones. This practice was adopted by the industry and has been required since 1935 by state regulations. The rare instances of land subsidence due to salt dissolution associated with oil and gas activity have all been caused by the disposal of produced oilfield brines, undersaturated as to sodium chloride, by reinjecting them into deep aquifers through salt water disposal wells with corroded or faulty casing allowing uncontrolled dissolution of salt. To aid in understanding this situation, oil production practices employed in central Kansas are briefly discussed in general terms, particularly as regards disposal of brines produced with the oil.

Oil production, central Kansas. Oil production in the study area (Figs. 1 and 3, shaded area of 10 counties) dates from the discovery of the Fairport Oilfield in western Russell County in 1923. The underground reservoirs from which vast quantities of oil were produced in the central Kansas oilfields over this 53-year period are all brine aquifers. Oil in them is associated with reservoir brines which are produced in decreasing amounts in the dissolved gas-drive oil reservoirs, and in increasing amounts in the water-drive reservoirs as the oil wells become older. The Arbuckle dolomite, reservoir for perhaps 75 percent of the oil produced in the study area, is an enormously large aquifer; hence Arbuckle oil reservoirs have a strong water drive. Wells producing from the Arbuckle Group (Walters, 1958) are seldom abandoned because they run out of oil, only because it becomes no longer profitable to pump and dispose of so much brine. Scores of Arbuckle wells in the Chase-Silica Oilfield each produced 500 barrels or more of salt water each day, along with oil in amounts decreasing to one percent for years prior to abandonment.

The State of Kansas Department of Health and Environment, the state agency charged with supervision of waste brine disposal operations, has long-established requirements that brines be disposed underground in salt water disposal wells. These wells are commonly completed in the Arbuckle dolomite, and frequently take large volumes of brine by gravity flow. A single Arbuckle salt water disposal well in the Tobias Oilfield of eastern Rice County, for example, disposes brine pumped by 50 Arbuckle oil wells, most producing over 100 barrels of brine each, or over 5,000 barrels of brine per day. The well takes the brine by gravity flow through approximately 3500 feet of plastic-coated 5½-inch casing used as tubing. One can hear the roar of the falling water while standing many feet distant from the disposal well. The energy input into such a salt water system is enormous. Here, 50 large motor-driven pumps lift oil and brine from 3350 feet, then the separated brine flows horizontally in a gathering system, followed by gravity drop of the brine through the same 3500 feet.

The disposed brine is unsaturated as to chlorides. The average of 33 Arbuckle brine analyses from the Chase-Silica Oilfield (Martin, 1968) is 13,870 ppm chlorides. This figure is quite low as compared with 98,000 ppm chlorides for a ten percent salt solution (common in drilling mud), or 260,000 ppm chlorides in a saturated solution. There is tremendous capacity for this disposed brine to dissolve more salt. Here then in the disposal wells is the potential for appreciable salt dissolution—high energy input, large volumes of water undersaturated as to chlorides, and an enormous brine outlet in the Arbuckle dolomite. Moreover, the waste brines are corrosive to metals; the Arbuckle brines characteristically contain dissolved H_2S.

The undetected corrosion of the casing opposite the salt section has in a few instances permitted the downward flowing undersaturated brines to gain access to the salt. The high energy input extending over many years of disposal well operation has in these cases permitted dissolution of sufficiently large quantities of salt to cause progressive upward collapse of the rock layers culminating in surface subsidence. This process is described in connection with the Panning Sinkhole. Generally, with the abandonment of all of the oil wells in the oilfield, and the plugging and abandonment of the disposal wells, the energy input is curtailed, circulation is terminated, dissolution ceases, and subsidence at the land surface declines, eventually to zero. Important exceptions occur in western Kansas, where brine-bearing aquifers (Cretaceous Cheyenne sandstone and Permian Cedar Hills sandstone) are present above the salt. These aquifers are not required by state regulation to be isolated by surface casing as are fresh water aquifers. They were utilized for many years as shallow salt water disposal zones. Undersaturated brines from these aquifers flow downward across the salt through old improperly plugged boreholes. Gravity provided, and continues to provide, the energy input into such a dissolution system; hence surface subsidence continues at the Crawford and Witt Sinks even though most of the oil wells have been plugged and abandoned.

In the case of the two easternmost sinks (Fig. 3), the Lovett and Pierce Sinks, surface subsidence was caused by disposal of oilfield brines at shallow depths (now illegal) into the Hutchinson Salt itself within the natural dissolution zone, or "Wellington lost circulation zone" of drillers, described on page 6. The disposed undersaturated brine dissolved additional salt, resulting in surface subsidence.

Oilfield subsidence areas. The eight subsidence areas are listed in Table 1. Considerable information is recorded for the Crawford and Witt Sinks in the Gorham Oilfield, which affect U.S. Interstate Highway 70, west of Russell, Kansas. Subsidence has been precisely measured by detailed surveying for the eleven years since the highway was built in 1965-66, and is known from prehighway vertical aerial photographs taken in 1957, or a time span of 20 years. Because of extensive subsidence, it was necessary to rebuild one mile of both lanes of the highway in 1957, at a cost of about $250,000, or an average maintenance cost of about $1,000 a week. Subsidence is continuing, but at a diminishing rate.

The Panning Sinkhole, located in the Barton County portion of the extensive Chase-Silica Oilfield, received much publicity in 1959. It closely resembles the 1974 Cargill Sinkhole in size and geological setting. Both developed rapidly and dramatically in a matter of hours, receiving widespread news coverage. It is described in some detail with quantitative data on fluid movements.

The remaining five land subsidence areas related to oil and gas operations subsided slowly, and had but minimal economic and environmental impact, and hence only the relatively meager facts of their occurrence are preserved.

Possible undetected oil-related subsidence areas. It is possible, but unlikely, that there are undetected oil-related subsidence areas in central Kansas, other than the eight listed in Table 1. Surface indications of salt dissolution at depth may go unnoticed. Even leaks in the casing in salt water disposal wells opposite the salt section may be undetected if the well continues to take brine in undiminished amounts. Ground cracks, an early indication of subsidence, show best in paving or solid material, but not at all in plowed ground. In central Kansas, precise level surveys are lacking; routine oil well elevations are accurate only to plus or minus one foot. The oilfields are typically located in agricultural areas where the possibility of detection of subsidence is minimal. This is in contrast to the urban situation described by Landes and Piper (1972) where salt is produced near the City of Detroit. There, many precise reference point elevations were surveyed in units of 1/1000ths of a foot, recorded, mapped, and graphed semi-annually or annually. Subsidences of one-fourth inch (0.021 feet) per year were recognized and considered acceptable in that area. In agricultural areas in central Kansas, slow subsidence of one foot may easily go entirely unnoticed. It is, however, unlikely that subsidence of two feet or more will go unnoticed because of interference with agriculture by ponding of water in the low spots, and because officials of the state regulatory agencies systematically inspect oil leases checking for infractions in water disposal, surface casing, and hole plugging.

TABLE 1.—List of Land Subsidence Areas Associated with Inadvertent Salt Dissolution in Oil and Gas Test Holes, Central Kansas.

Crawford No. 12 Crawford No. 16 Sec. 2, T.14S, R.15W Twin wells in C NW/4 NW/4 SW/4 Gorham Oilfield Russell County, Kansas	These twin wells, 50 feet apart, are the site of more than 26 feet of settling affecting both lanes of Interstate Highway I-70. The Kansas Highway Commission drilled a test hole between these wells. The area is precisely surveyed, intensely studied (Burgat and Taylor, 1972), and affords conclusive evidence that subsidence is due to dissolution of salt in old oil and gas test holes. See pages 68 to 71.
Witt No. 1 Sec. 3, T.14S, R.15W C NW/4 NW/4 SE/4 Gorham Oilfield Russell County, Kansas	The Witt No. 1 is next to the south right-of-way fence of U.S. I-70. Subsidence of 17+ feet around the well makes a gathering basin for rainwater which drains directly off the highway into the well bore, exposed in a gully. See pages 71 to 73.
Hodge No. 2 Sec. 25, T.20S, R.6W C S/2 NW/4 NE/4 Welch-Bornholdt Oilfield Rice County, Kansas	There is a mature shallow dished depression with a small pond at this location. Gilbert Toman (personal communication) said this was due to settling of the ground around the old disposal well.
Hilton No. 6 Hilton No. 7 Sec. 6, T.20S, R.9W C NW/4 NE/4 SW/4 Chase-Silica Oilfield Rice County, Kansas	Abandoned oilfield brine disposal wells 200 feet apart. Well 6 was used until Oct. 1951, and Well 7 until June 1965. The subsidence area around these holes appears stabilized. There is a shallow fresh water lake in the gentle depression. See pages 59 to 60.
Berscheit Heirs No. 14 Sec. 6, T.20S, R.10W C SW/4 SW/4 NW/4 Chase-Silica Oilfield	N. W. Biegler (personal communication) was present at the site during plugging of this Arbuckle disposal well in April 1972. The ground was then sinking. See pages 57 to 59.
W. M. Panning No. 11 Sec. 2, T.20S, R.11W C SW/4 SE/4 SE/4 Chase-Silica Oilfield Barton County, Kansas	On April 24, 1959 at 9:00 a.m., the landowners observed a cavity forming around this well. It developed into a pit 300 feet in diameter within a few hours time. At present the site is a fenced fresh water lake used as a game preserve. See pages 52 to 57.
Daisy E. Pierce No. 5 Sec. 33, T.23S, R.4W C NE/4 SE/4 NE/4 Burrton Oilfield Reno County, Kansas	Gilbert Toman (personal communication) reports disposal into this shallow well in 1968 caused about four feet of settling of the section line road. The well is 10 miles east and south of Hutchinson, Kansas, near Well 17 of Figure 2, within the zone of natural salt dissolution. Depth to salt is about 400 feet. Well abandoned. Road rebuilt. Appears stable.
Lovett SWD No. 2 Sec. 14, T.20S, R.4W C SW/4 SW/4 SW/4 Groveland South Oilfield McPherson County, Kansas	This shallow brine disposal well, drilled in 1958, encountered salt at 489 feet total depth, with 7-inch casing set at 487 feet. Brine was introduced directly into the salt section within the zone of natural salt dissolution. Subsidence area, about 100 feet in diameter, is east of the section line road and north of the creek. The disposal well and all adjacent oil wells are now abandoned. N. W. Biegler (personal communication) considers the area stabilized.

SALT DISSOLUTION IN OIL AND GAS TEST HOLES DURING DRILLING

Methods of investigation. Salt dissolution in oil and gas test holes during drilling can be measured by (1) study of caliper logs, (2) calculation of cement volume in holes in which casing is cemented through the salt section, or in the few unusual holes plugged with cement through the salt section, (3) by study of recorded geophysical logs, especially the neutron log which is highly sensitive to hole size and "washes out" (loses character) in enlarged sections of the hole, (4) by information from "fishing" operations opposite the salt, and (5) by recording and calculating volume and the increased salinity of the drilling fluid.

Caliper logs. The first method, use of caliper logs, is by far the most important. In Figure 16, caliper logs from four holes drilled through the Hutchinson Salt with rotary tools were reproduced. The wells are identified in Table 2. These four logs provide examples of:

A. Hole out-to-gauge with near zero alteration of the borehole by drilling;
B. Carrot-shaped hole due to mechanical abrasion, no dissolution;
C. Hole moderately enlarged by abrasion and by dissolution of salt;
D. Extensive hole enlargement by dissolution of salt.

For Borehole "C" an approximate calculation of hole enlargement during drilling can be made from the caliper log. The hole was drilled with a 7⅞-inch bit. The average hole diameter above and below the salt measured about 10½ inches. The average hole diameter through the salt section measures approximately 12½ inches (maximum 13½ inches). We may, therefore, calculate for the 277 feet of salt section a

TABLE 2.—Index to Boreholes "A," "B," "C," "D" of Figure 16. All are in Rice County, Kansas.

Borehole "A"
- USAEC Test Hole No. 2
- Section 35, T.19S, R.8W
- Drilled and cored by the U.S. Corps of Engineers 1970
- Hutchinson Salt — 755.0 feet to 1002.5 feet
- Cored from 737.9 feet to 1099.6 feet
- Diameter of cores = 4″ — Reamed to 6¾″
- Caliper Log shows borehole out-to-gauge
- Salt-saturated brine and low-water-loss starch mud
- Nine days spent coring and/or reaming from base of 8⅝″ surface pipe at 247.5′ to 1216′ T.D.

Borehole "B"
- USAEC Test Hole No. 1
- Section 26, T.19S, R.8W
- Drilled and cored by the U.S. Corps of Engineers 1970
- Hutchinson Salt — 815.1 feet to 1084.1 feet
- Cored from 0 feet to 1300.8 feet
- Diameter of cores = 6″ — Cored with 7¾″ core bit
- Salt-saturated brine and low-water-loss starch mud
- Caliper Log shows hole is carrot-shaped due to abrasion
- Twenty-five coring days from base of 8⅝″ surface pipe at 309.5′ to 1300.8′ T.D.

Borehole "C"
- Barnett Oil Company, No. 1 Wright
- Section 35, T.19S, R.8W
- Drilled and cored in Oct. 1971
- Hutchinson Salt — 758 feet to 1036 feet
- Four cores and four drill stem tests of fluid
- Drilled with 7⅞″ bit
- Caliper Log shows maximum hole size 13½″
- Fresh water and starch mud
- Fourteen drilling days from base of 8⅝″ surface pipe at 223′ to 3583′ T.D.

Borehole "D"
- Woodman & Iannitti, No. 2 Stockham
- Section 34, T.19S, R.8W
- Drilled in Nov. 1970
- Hutchinson Salt — 775 feet to 1062 feet
- No cores. No drill stem tests
- Drilled with 7⅞″ bit
- Caliper tool fully extended at 15 inches
- Clear fresh water and no mud additives
- Six drilling days from base of 8⅝″ surface pipe at 179′ to 3466′ T.D.

measured hole volume of 236 cubic feet, of which 94 cubic feet were cut away by the bit, 70 cubic feet of rock removed by mechanical abrasion including mud flow erosion, and the remaining 72 cubic feet removed by dissolution of the salt by the fresh water drilling mud. The measured hole is 2½ times (251%) the volume of the cylinder drilled by the 7⅞-inch bit. A total of 142 cubic feet of rock salt (or 60% of the measured hole volume) was removed by dissolution and/or abrasion. Borehole "C" is not a typical borehole. It was drilled with a bentonite mud program (rather than clear water and native muds) which partially inhibited salt dissolution. Borehole "C" is also illustrated in Figure 17.

Borehole "D" is representative of the usual borehole enlargement due to rotary drilling of the Hutchinson Salt with fresh water. This hole was drilled with a 7⅞-inch bit. Average hole size above and below the salt is nine inches. The caliper log illustrated recorded a maximum diameter of 15 inches. We may, therefore, calculate for the 287 feet of salt section a minimum hole volume of 333 cubic feet, of which 97 cubic feet were cut away by the bit, 29 cubic feet of rock removed by mechanical abrasion, and the remaining 207 cubic feet removed by dissolution of the salt by the fresh water drilling mud. This figure is too low by an unknown amount, but some order-of-magnitude approximations can be made. First, this log shows, midway through the salt section, two constrictions due to thin anhydrite beds. Second, a repeat caliper log with a maximum diameter of 16 inches (not shown) was run in connection with a density log. It confirmed the two anhydrite beds and indicated the tips of our additional thin shales and/or anhydrite beds in the extra inch of diameter measured, from which it may be inferred that the hole is only a few inches larger in diameter. Recalculation of the minimum volume on the basis of 16 inches maximum recording gives a hole enlargement of more than two diameters and a minimum volume of 372 cubic feet, or a hole enlargement of nearly four times the drilled volume (383 %) which is still too low by an unknown amount.

Occasionally older caliper logs recording to 36 inches maximum diameter are available. These logs were recorded with four independent legs probing the borehole, but with only the maximum reading recorded. Such logs dating in the 1960s to 1970s seldom record off-scale measurements in normally drilled holes, but show frequent occurrences of holes in the 24- to 36-inch diameter range. The logs, rare in library collections because customers were loath to pay an extra log charge, were abundantly recorded quietly by the log engineers for their own personal use as they became aware of the sensitivity of the early neutron logs (the most common porosity tool then and now) to hole size corrections. Such logs indicate a common hole enlargement during rotary drilling of 7⅞-inch holes or 9-inch holes to the 24- to 36-inch diameter range, or about three times the drilled diameter.

Cementing experience. A second line of evidence comes from oil well cementing experience. When cementing oil string casing through a salt section drilled with fresh water, an uncommon operation, cementers expect to use an additional 300 to 500 sacks of cement. Slurry volumes vary with types of cement and additives. Portland cement yields 1.18 cubic feet per sack, but with four percent bentonite (commonly used) yields 1.55 cubic feet per sack, or with eight percent bentonite (the maximum commonly used) yields 1.92 cubic feet per sack. For Borehole "D" as a theoretical example, it can be assumed that the "additional" cement will be required for that part of the hole in excess of nine inches in diameter through the salt section. It can then be calculated that the hole

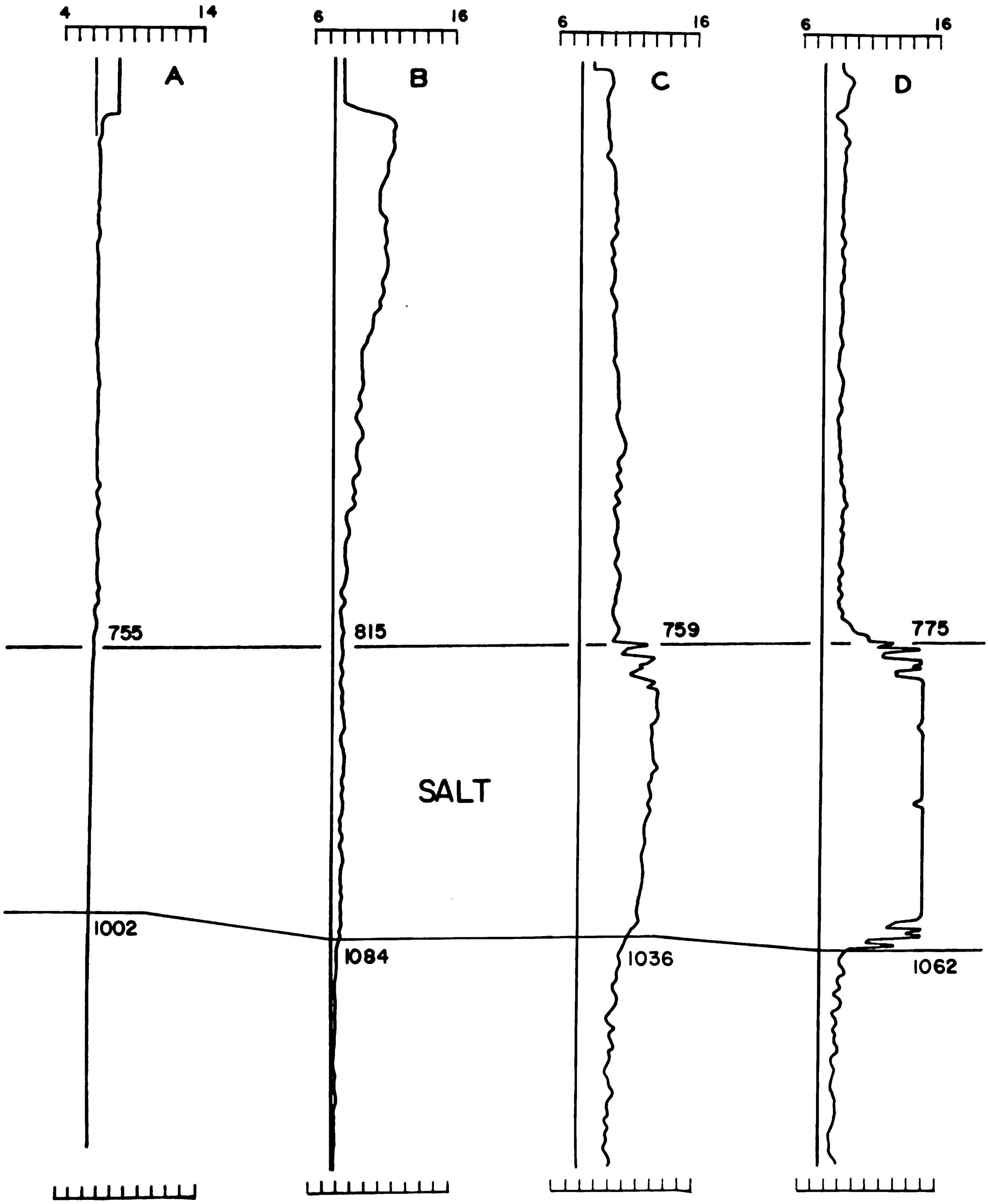


FIGURE 16.—Caliper logs from four holes in Rice County, Kansas. Figures indicate hole diameter in inches and well depth in feet. Top and base of Hutchinson Salt indicated. Wells are identified in Table 2.

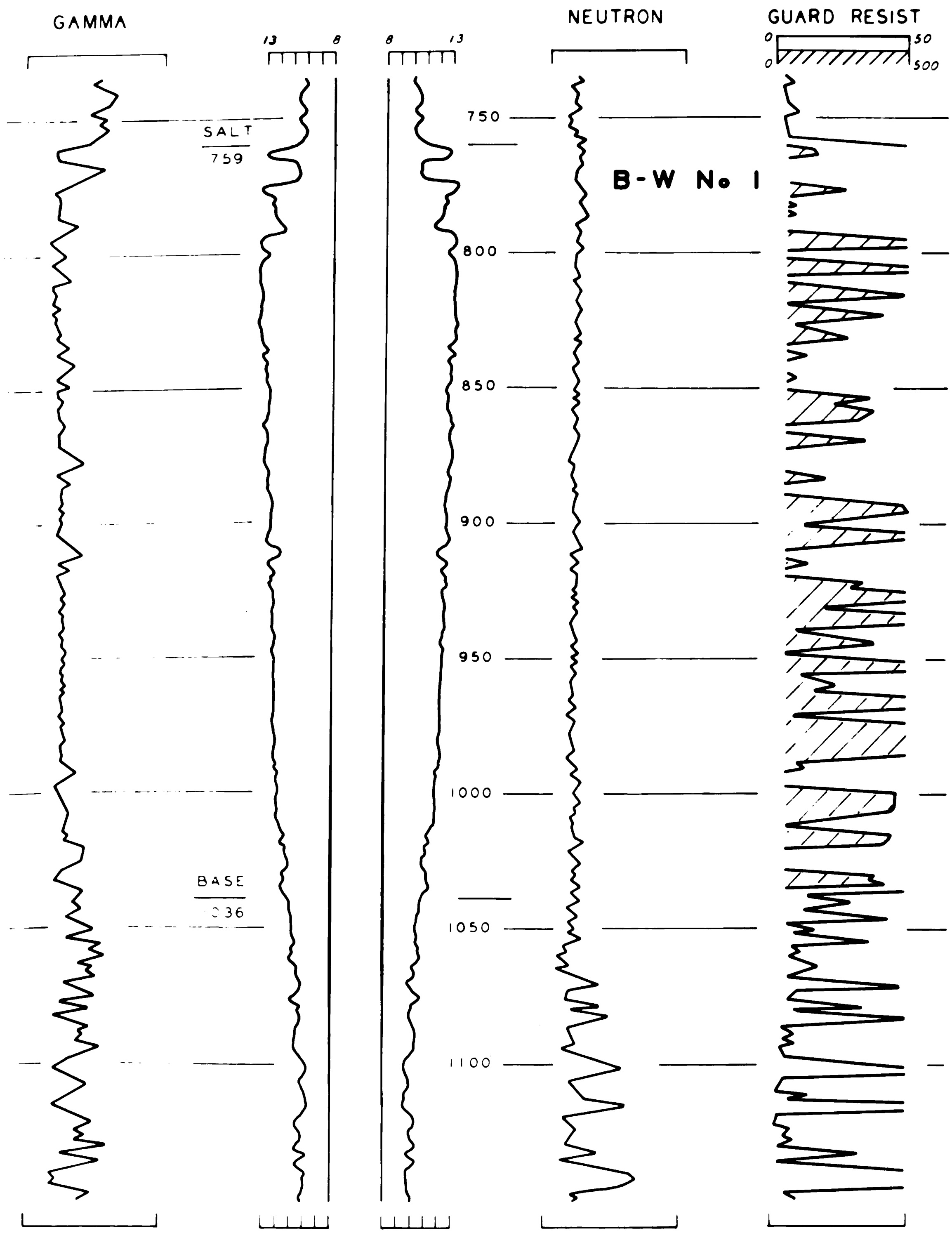


FIGURE 17.—Wire line geophysical logs from Wright No. 1, Well "C" of Figure 16 and Table 2. Caliper log repeated in mirror image to indicate shape of hole through the Hutchinson Salt, depth 759 to 1036 ft.

size is within the following range; based on cementer's practical experience:

if filled with 300 extra sacks
cement with 4% bentonite .... 19¼″ diameter;
if filled with 300 extra sacks
cement with 8% bentonite .... 21¼″ diameter;
if filled with 500 extra sacks
cement with 4% bentonite .... 24″ diameter;
if filled with 500 extra sacks
cement with 8% bentonite .... 26″ diameter.

Similar calculations can be made for cement with salt added in varying amounts.

From these order-of-magnitude figures, it may be estimated that the probable hole size in the salt section in Borehole "D" is near 24 inches. If correct, this calculates as 902 cubic feet of salt removed, only 97 cubic feet of which were cut away by the bit, or a volumetric hole enlargement to about nine times the drilled hole volume due essentially to salt dissolution while drilling with fresh water during which the hole became enlarged to a diameter about three times the bit size (7⅞-inch bit × 3.05 = 24 inches). These deduced figures are the right order of magnitude and give a good approximation of the usual hole enlargement by salt dissolution during modern rapid drilling with rotary tools in the 1960s and 1970s using fresh water and no mud additives as is the common practice in the study area.

An example of a hole plugged with cement through the salt section is the Cook No. 1, dry hole, in Section 27, Township 19 South, Range 8 West, Rice County, Kansas, illustrated in the reentry diagram, Figure 18. The hole diameter is calculated as 19.3 inches through the salt section, or two and one-half times the drilled size of 7⅞ inches.

Neutron logs. The sensitivity of neutron logs to hole size provides a third line of evidence of hole enlargement during drilling of the salt section. An example is Borehole "C" of Figures 16 and 17. The caliper curve is drawn in mirror image to give a visual impression of the shape of the hole. Even the measured small amount of hole enlargement from 7⅞ inches to a maximum of 13½ inches was sufficient to cause the neutron log to lose character through the salt section. This combination of gamma-ray, neutron, and resistivity logs, but without the caliper log, is the most commonly recorded log suite in oil and gas test holes in the study area. The flattening of the neutron curve in conjunction with low gamma and high resistivity readings on such logs provides evidence that salt was drilled and partially dissolved, but does not provide useful quantitative evidence of the amount of hole enlargement due to dissolution of salt. See Figure 6 for an example of a neutron log in salt in an out-to-gauge hole.

On occasion, logging engineers running logs in hole after hole, as for example in a salt solution well field, are able to approximately calibrate the sensitivity of their neutron log by comparison with known hole sizes from caliper or sonar surveys. One logging engineer has determined that his 34-inch scintillometer-recorded neutron curve "washed out" completely at a hole diameter of 34 inches, and his similarly recorded gamma-ray log "washes out" in holes larger than 36 inches in diameter. His experience with older Geiger-Muller counter tools indicated figures a little larger. He sometimes applies this aspect of log failure to locate "cavities" in cased salt solution holes. The neutron logs usually available to the writer do not permit quantitative hole measurement but record hole enlargement by salt dissolution.

Recovery of objects, or tools, termed "fishing." "Fishing" operations give a fourth method of approximating hole diameter due to salt dissolution while drilling. During the period of slower drilling by rotaries, and less or no use of commercial mud additives, there are instances of great hole enlargement during drilling. Holes drilled by rotary in the 1940s had many "fishing jobs" to recover twisted-off drill pipe. Drill pipe parted opposite the salt section (a common position) was difficult to recover because the "fish" fell to the side of the hole back in the solution cavern under shale ledges, and, thus concealed, could not be retrieved. Fishing tools such as a "knuckle joint" which extended outward as much as five feet were slowly rotated to sweep the salt cavern in a sometimes successful effort to connect with the pipe and move it to a position centered in the well bore for recovery. Some salt washouts where the knuckle joint tool touched no iron were believed to be enlarged to more than 10 feet in diameter during drilling, an enlargement of over 13.3 diameters (9-inch bit) with a volume increase to over 178 times that of the cylinder cut by the bit.

Calculation of salinity of the drilling fluid. While method five, calculation of volume and salinity of the circulating fluid, is routine in solution mining of salt, it is of limited applicability to oil and gas well drilling. Commonly the hole is started with fresh water which becomes salt saturated during drilling but which is not then replaced with fresh water. Rather, as the hole is deepened and hole volume increases, more fresh water is added which in turn becomes salt saturated. An approximation of the amount of salt dissolved during drilling could be made if the volume of fresh water was accurately known. Such data is difficult to obtain, however, because water trucked to rotary rigs is billed on a trucking time basis, not a water volume basis.

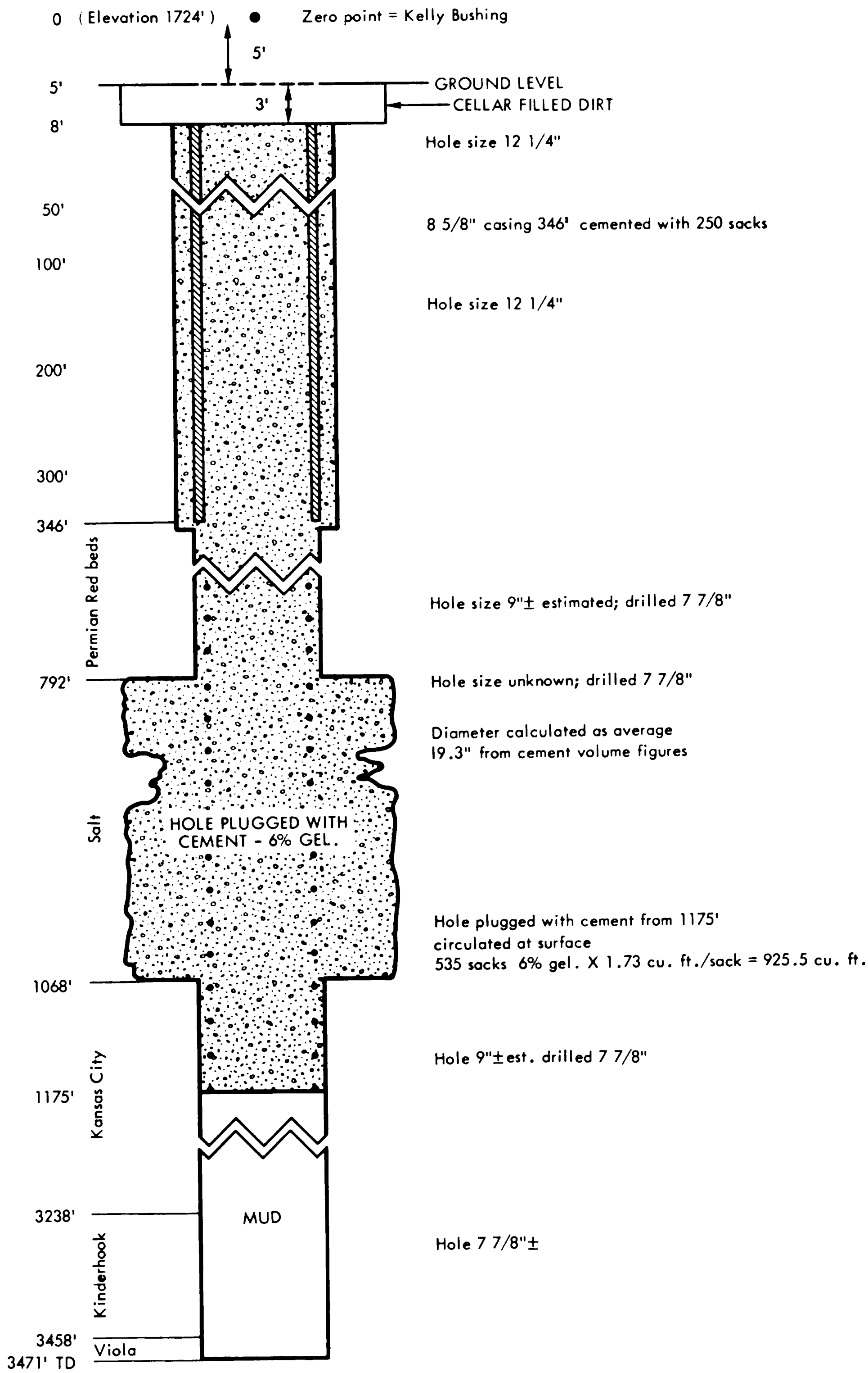


FIGURE 18.—Reentry diagram. Imperial Oil Co., Cook No. 1, Sec. 27 T.19S R.8W, Rice County, Kansas.

Often the water hauler will substitute a load of salt water (oilfield brine) if more easily available when roads are muddy, etc.; hence this is not a meaningful source of data.

Holes drilled with cable tools. Instances of zero or near zero hole enlargement by salt dissolution during drilling are limited to the rare salt test holes drilled with brine saturated as to sodium chloride and to old-time cable tool holes. The latter, though often of large drilled diameter in the salt section (18 inches or more), used small amounts of drilling water. Actual samples of the salt itself were recovered and the holes were not appreciably enlarged by salt dissolution during drilling.

In conclusion, salt dissolution in oil and gas test holes during drilling may range from no dissolution (brine drilled rotary holes and cable tool holes) to extensive dissolution (more than 10 feet in diameter), but in modern rotary drilled holes such enlargement is commonly of the order of magnitude of three times the diameter of the drill bit or nine plus times the volume of the drilled hole as derived by the direct and indirect measurements discussed.

SALT DISSOLUTION IN OIL AND GAS TEST HOLES AFTER DRILLING

Method of investigation. The subject is less difficult to investigate than one might assume on first impression. When information from abandoned holes reentered years later (Fig. 19), plus information from cased hole logs, is combined with knowledge of the hydrological principles involved, the conclusion is reached that, most commonly, no salt dissolution occurs after drilling ceases, shutting off that source of energy input. To understand why this is so, we must consider the four essential components—salt, water, energy, brine outlet—with the added factor of a 50-year time interval for extensive oil and gas test well drilling in the study area.

The salt itself has not changed—it is still in place where it has been for over 200 million years, but now with its protective shale envelope pierced by boreholes. Water, including fresh water, is usually present in Kansas in aquifers penetrated by the drill at depths more shallow than the salt. A constant natural energy source, gravity, is available to move the fresh water down the drilled hole past the salt section, unless impeded by the well plugging materials or by cemented surface casing left in the hole (required in Kansas oil and gas test holes since 1935). Other aquifers (sometimes termed "salifers") below the salt contain brine in varying concentrations, but unsaturated as regards sodium chloride. Absent in most cases is the critical factor of a brine outlet; hence post-drilling salt dissolution usually does not occur. Exceptions are old test holes with no surface pipe cemented through the shallow fresh water aquifers and eight instances of salt water disposal wells (high energy input, high volume of fluid flow) with corroded leaky casing where inadvertent extensive salt dissolution has resulted in subsidence at the surface. Also excepted is approximately ten percent of the study area including the Gorham Oilfield, site of the Witt and Crawford Sinks, where limited post-drilling salt dissolution is believed to be continuing at the present time.

To investigate post-drilling salt dissolution in oil and gas test holes we must briefly consider the hydrology of the aquifers drilled and their ability to flow from one to the other across the salt face through man-made boreholes with only gravity as an energy source.

Hydrology. To summarize the hydrology of multiple aquifers in a 4,000-square mile study area in Russell, Lincoln, Barton, Ellsworth and Rice Counties (Fig. 3) penetrated by 22,200 oil and gas test holes in a brief but meaningful way, we begin with a specific example, applicable in principle to 90± percent of the area, then discuss the difference in the other 10± percent of the area. In general, the aquifers drilled at depths less shallow than the salt are fresh-water-bearing; in general, the redbeds above and below the salt and the salt itself are nonaquifers or aquitards with very low transmissibility; and, in general, the multiple aquifers below the salt (some of which are oil and gas reservoirs) are brine-bearing, but all brines are unsaturated as to sodium chloride at reservoir temperatures and pressures.

Cross Section C-D, Figure 4 (list of wells and shaft, Appendix B, pages 77 to 78), in Rice County, Kansas shows in natural scale (vertical and horizontal scales equal) the relative position of the aquifers (indicated by the letter "W" on the cross section) here discussed as a specific example. Omitted from the cross section are the many shallow fresh water test wells drilled by the Kansas Geological Survey (Bayne and Ward, 1971). Drill stem test data from Wells 6 and 9, cable tool water information from Well 8, and potentiometric surface data from shallow wells are combined in Table 3.

Aquifer 1 of that table, "rain," was not entered to be facetious. In the Gorham Oilfield one abandoned oil well serves directly as a storm sewer for rainwater runoff from Interstate Highway 70, draining a closed subsidence basin caused by salt dissolution at the Witt Sinkhole. Aquifer 3, the Dakota sandstone, is absent in the cross section but widely present to the west as a shallow fresh water aquifer protected by surface casing. For the other shallow Quaternary and Cretaceous fresh water aquifers (Aquifers 2 and 4 in Table 3) the

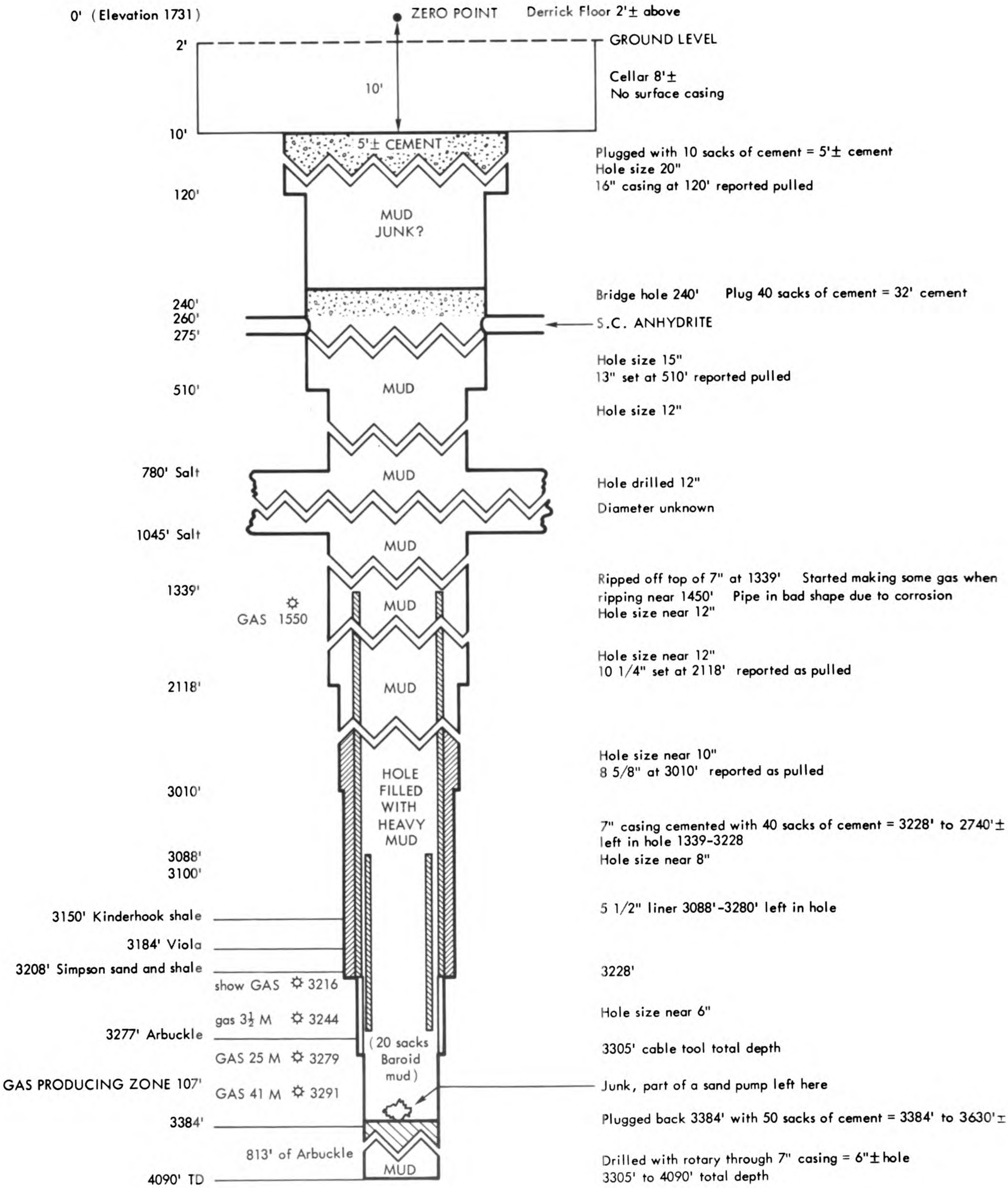


FIGURE 19.—Reentry diagram. Imperial Oil Co., Pulliam No. A-1, Sec. 35 T.19S, R.8W, Rice County, Kansas.

TABLE 3.—Aquifer Data—Rice County, Kansas.

	Aquifer Number	Depth (Base) Feet	Sea Level Datum	BHP psi	Pot. Surface	Sp.Gr.	Water Quality (ppm) Chlorides	Total Solids
Surface water — rain	1	0	+1694	....	+1694	1.000	0±	0±
Quaternary								
Pleistocene — sand, gravel	2	50	+1644	....	+1680	....	71	445
Cretaceous								
Dakota — sandstone lenses	3	absent						
Kiowa — sandstone lenses	4	170	+1524	....	+1680	....	78	488
Permian								
Nippewalla Group "redbeds"	aquitard							
Sumner Group "redbeds"	aquitard							
Hutchinson Salt Member	aquitard							
Chase Group								
Florence dolomitic limestone	5	1451	+ 243	435	+1249	1.162	155,000	270,000
Pennsylvanian								
Wabaunsee Group limestone	6	2075	— 344	....	+1350 Est.	....	....	....
Shawnee Group								
Lecompton limestone	7	2604	— 910	1035	+1480	1.146	132,000	237,000
Douglas Group sandstone	8	2823	—1129	1150	+1527	1.145	132,000	234,000
Lansing-Kansas City Group limestone	9	3043	—1349	1167	+1346	1.135	127,000	195,000
Cambro-Ordovician								
Arbuckle Group dolomite	10	3526	—1783	1221	+1037	1.033	24,000	41,000

potentiometric surface was measured directly in water wells drilled for that purpose by simply measuring the depth to water in the open hole and correcting for well elevation. For Aquifer 6, the cable tool drillers' log of Well 8 recorded "three bailers of water per hour at 2075 feet." All other aquifer data for brines below the salt section is derived from fluid recoveries and charts of bottom hole pressures recorded while using the drill pipe with one or more packers as temporary casing isolating the zone. Such a test, called a drill stem test (DST), gives accurate pressure information and provides recovery of the actual formation fluid, although in part contaminated by drilling fluid. DST bottom hole pressures (BHP) are here converted to the potentiometric surface figure of hydrologists by dividing the BHP by .433 psi per lineal foot, the weight of a column of fresh water specific gravity 1.000; and correcting the answer to a sea level datum. For example:

A. Chase Group, Florence Limestone, Aquifer 5

From an elevation of	1694 feet above sea level
at a depth of	1451 feet in the well bore
or a datum of	+243 feet above sea level
the BHP will support	1006-foot column of fresh water (435 psi/.433)
or a potentiometric surface of	+1249 feet above sea level.

B. Shawnee Limestone

From an elevation of	1694 feet above sea level
at a depth of	2604 feet in the well bore
or a datum of	—910 feet below sea level
the BHP will support	2390-foot column of fresh water (1035 psi/.433)
or a potentiometric surface of	+1480 feet above sea level.

The resulting derived and measured potentiometric surface figures are graphed in Figure 20. Hydrologists who are accustomed to working with fresh water in unconfined reservoirs find the simple concept of potentiometric surface adequate for much of their work as it is axiometric that flow (by gravity downward) is from higher to lower values on the potentiometric surface. By simple inspection of Figure 20, it is apparent that Aquifers 1, 2, and 4, all fresh-water-bearing and located above the salt, will flow into any or all of Aquifers 5 through 10, if a suitable borehole is available, with a "head" difference obtained by subtracting the potentiometric surface figures and such flow will be across the salt face if borehole conditions permit.

But as regards actual flow from one deeper aquifer to the other, the potentiometric surface can be misleading. Hydrologists working in the future with confined aquifers (or "salifers") of varying salinity, will have to rely more on pressure data because in confined reservoirs the flow direction may be up, down, or sideways. For example, Aquifer 9, Kansas City, has a higher potentiometric surface (+1346) than Aquifer 5, Chase Group (+1249), but the actual flow direction is the opposite of that indicated by the potentiometric surface figures due to differences in the specific gravity of the contained brines.

The potential flow directions for Aquifers 1 through 10, if interconnected, may be derived graphically. The construction of such a graph is shown in four steps. Figure 21 shows a graph of a DST of Aquifer 5, Chase Group dolomitic limestone, with depths in feet and position relative to sea level as ordinate and BHP in psi as abscissa. The actual fluid fillup data is recalculated as a static fillup of brine (not rotary mud). The pressure gradient is then drawn. In the graph, Figure 22, the subsurface position of the salt is plotted and the position of three deeper aquifers is shown.

Figure 23 graphs the fillup data and pressure gra-

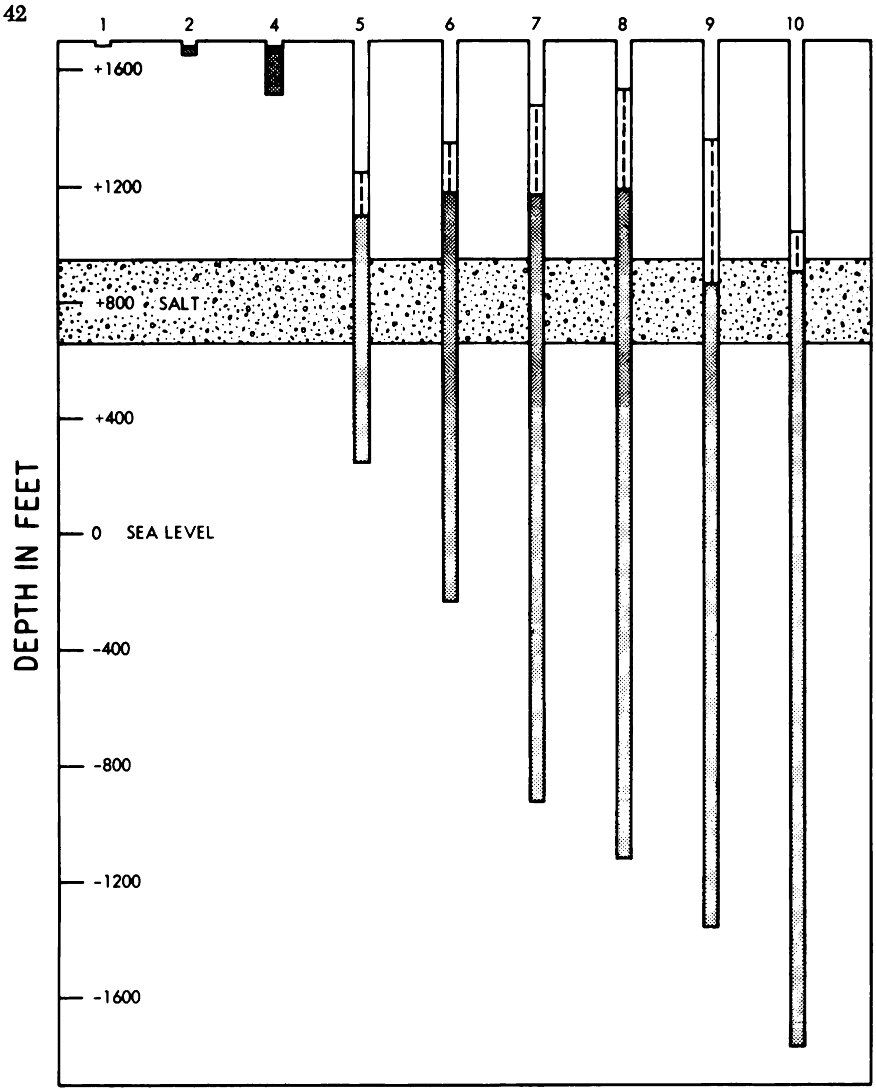


FIGURE 20.—Static fluid levels in Aquifers 1 to 20 of Table 3, and Cross Section C-D, Fig. 4. Each column depicts a hypothetical well with casing bottomed in an individual aquifer. Shading indicates static fluid level, dashes depict higher level (potentiometric surface) to which fresh water would rise.

other), had equalized with the brine in the Kansas City, Aquifer 9. Common static level for all aquifers below the salt, 5, 6 (not shown), 7, 8, and 9, will be slightly higher than +864. Note that flow from zone to zone among these aquifers to equalize pressures does not involve flow across the salt face itself; hence no dissolution occurs even with borehole communication between all aquifers below the salt and above the Cambro-Ordovician Arbuckle dolomite, Aquifer 10, which has by far the greatest capacity to either yield or take fluid.

The graph in Figure 24 repeats the previous four pressure gradients and adds a pressure gradient from four DST pressures in the Cambro-Ordovician Arbuckle dolomite in a nearby well, No. 9 (Fig. 4).

For all aquifers interconnected by a suitable borehole, flow direction can be read on the graph and will be from higher pressure (right) to lower pressure (left) until a common static level is reached. Flow from zone to zone to reach equalized static will occur at the aquifer depth level and there will be **no flow across the salt face, hence no dissolution of salt.**

dients for all four aquifers. Note that the four static fluid levels are all above or within the salt interval which means that if an underground salt operation inadvertently mined into an unknown abandoned and unplugged oil and gas test hole, the mine would be flooded (Lomenick, 1972). Flow from one zone to another, if interconnected by a suitable borehole, will be from higher pressure to lower pressure. Thus at the depth of the Florence Flint, Aquifer 5, brine will flow from it into the borehole, down and into the Kansas City, Aquifer 9. This flow is the opposite of that indicated by the simplistic potentiometric surface data, Table 3, used by hydrologists. Such flow, however, would occur only after flow from the Lecompton and Douglas aquifers, 7 and 8 (in equilibrium with each

Note that the pressure data developed in the graphs, Figures 21-24, assume interconnected zones in an open borehole. They are, therefore, valid for all oil and gas test holes in the study area which have properly set surface casing "protecting" (isolating) fresh water aquifers as required by ruling of the Kansas Corporation Commission. This permits the conclusion for **all oil and gas test holes**, whether "dry holes" in which only surface pipe has been set, or oil wells cased to the pay zone, or abandoned oil wells with a casing stub left in the hole, or salt water disposal wells, that FLUID WILL EQUALIZE IN HOLES HOWEVER PLUGGED OR EVEN NOT PLUGGED AT ALL, WITH NO FLOW ACROSS THE SALT FACE, HENCE WITH NO SALT DISSOLUTION in oil and gas test holes after drilling, provided adequate surface

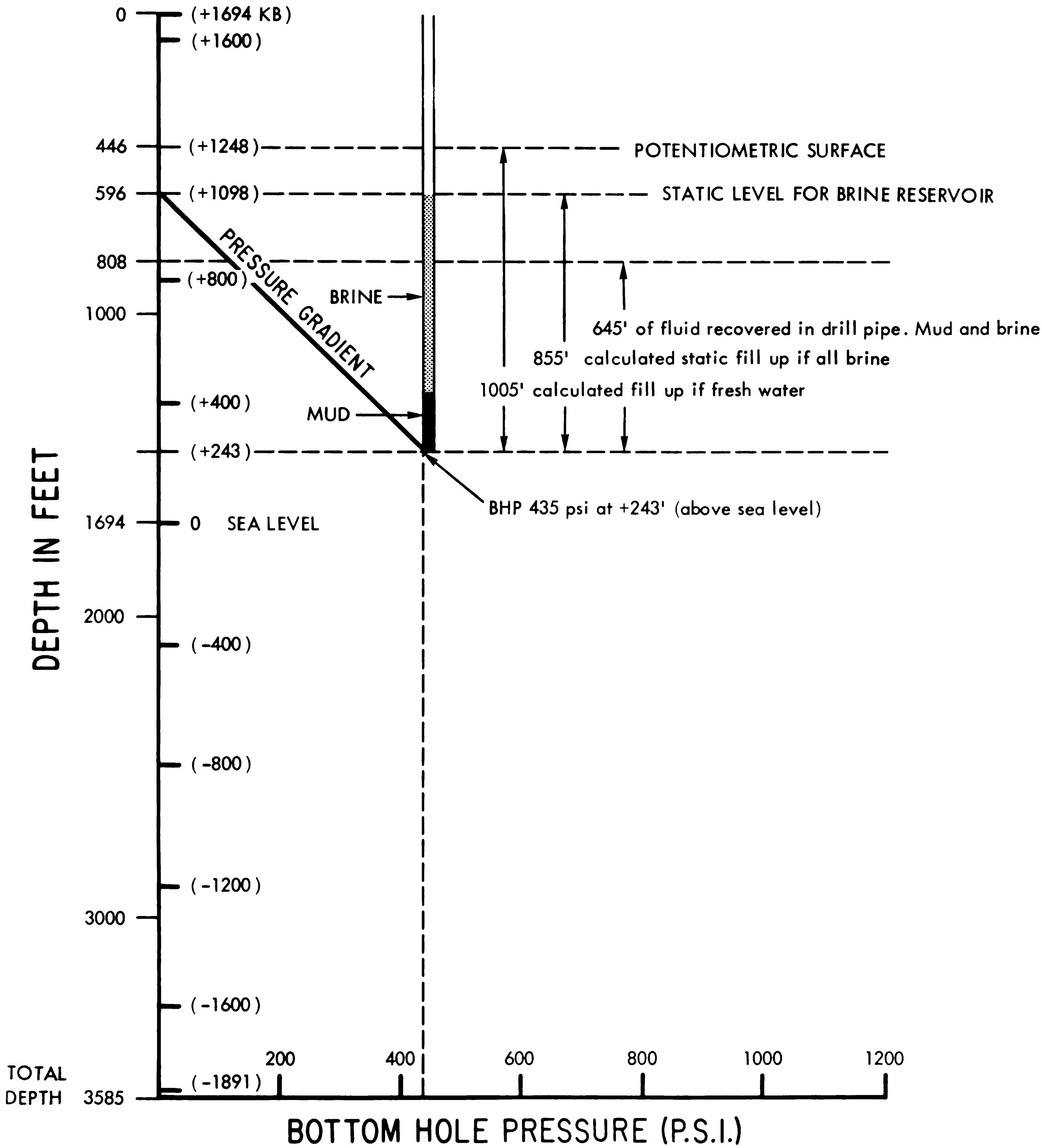


FIGURE 21.—Graph of drill stem test data, Chase Group.

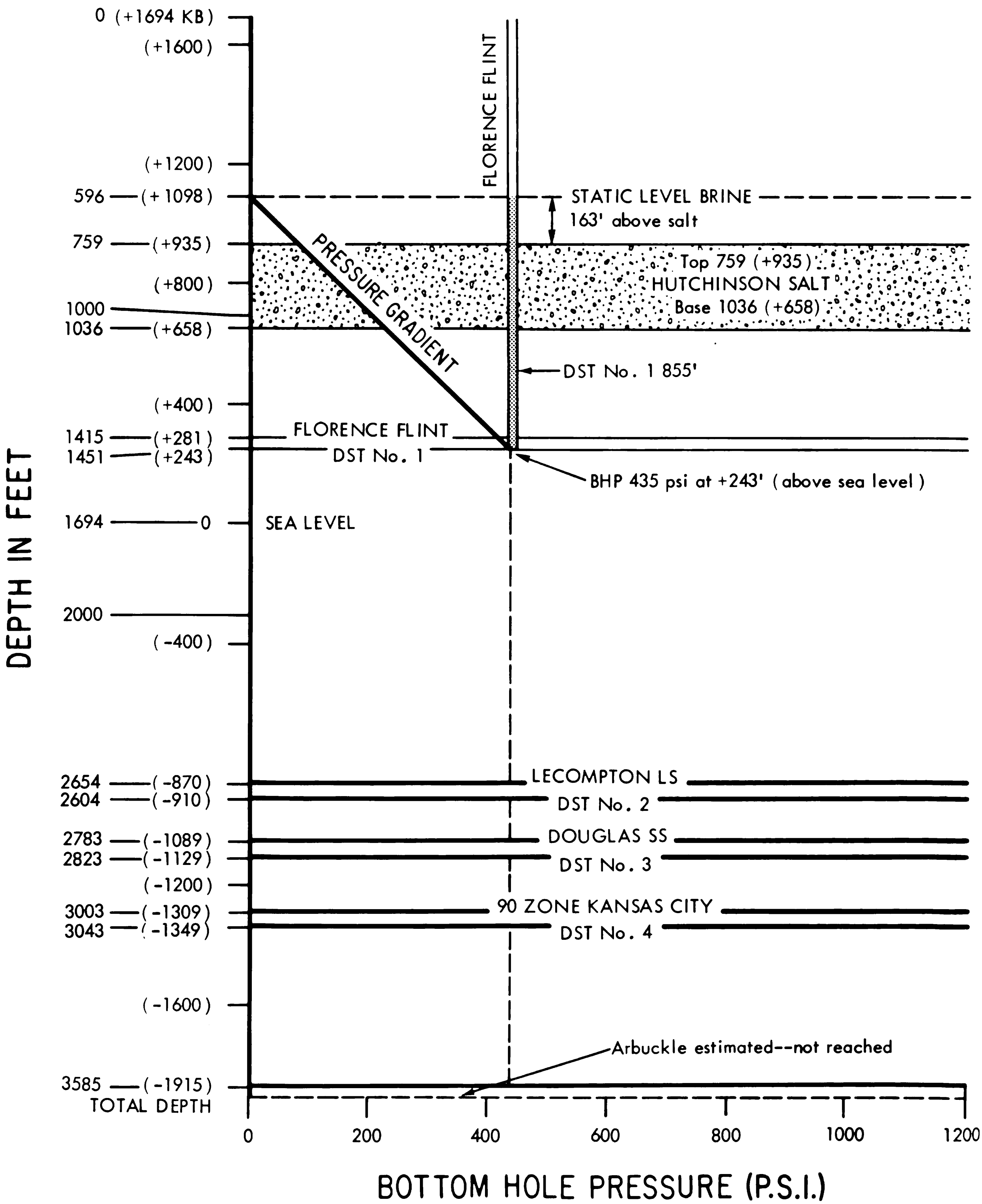


FIGURE 22.—Graph showing position of Hutchinson Salt relative to four aquifers.

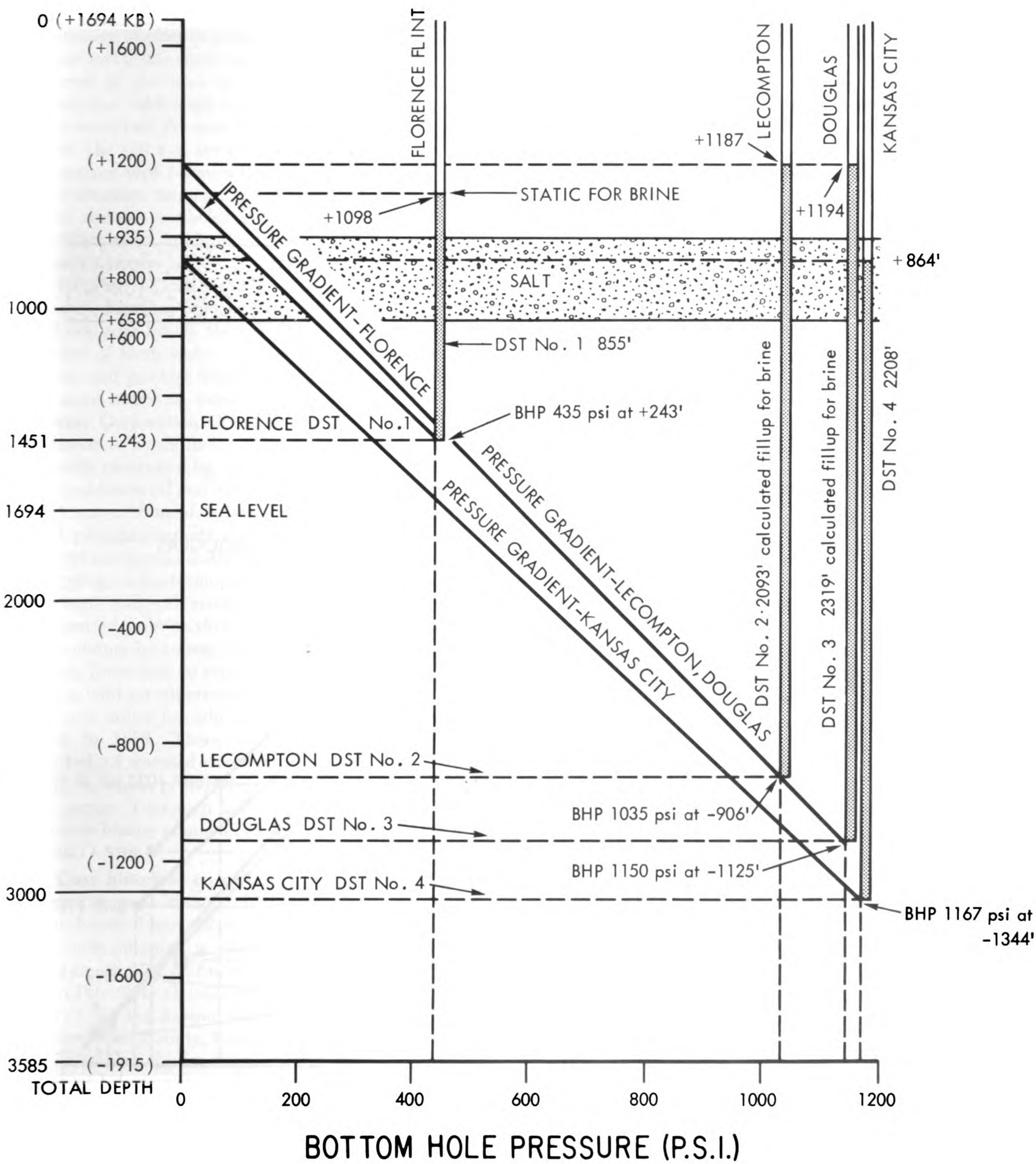


FIGURE 23.—Graph showing derivation of pressure gradients for four aquifers.

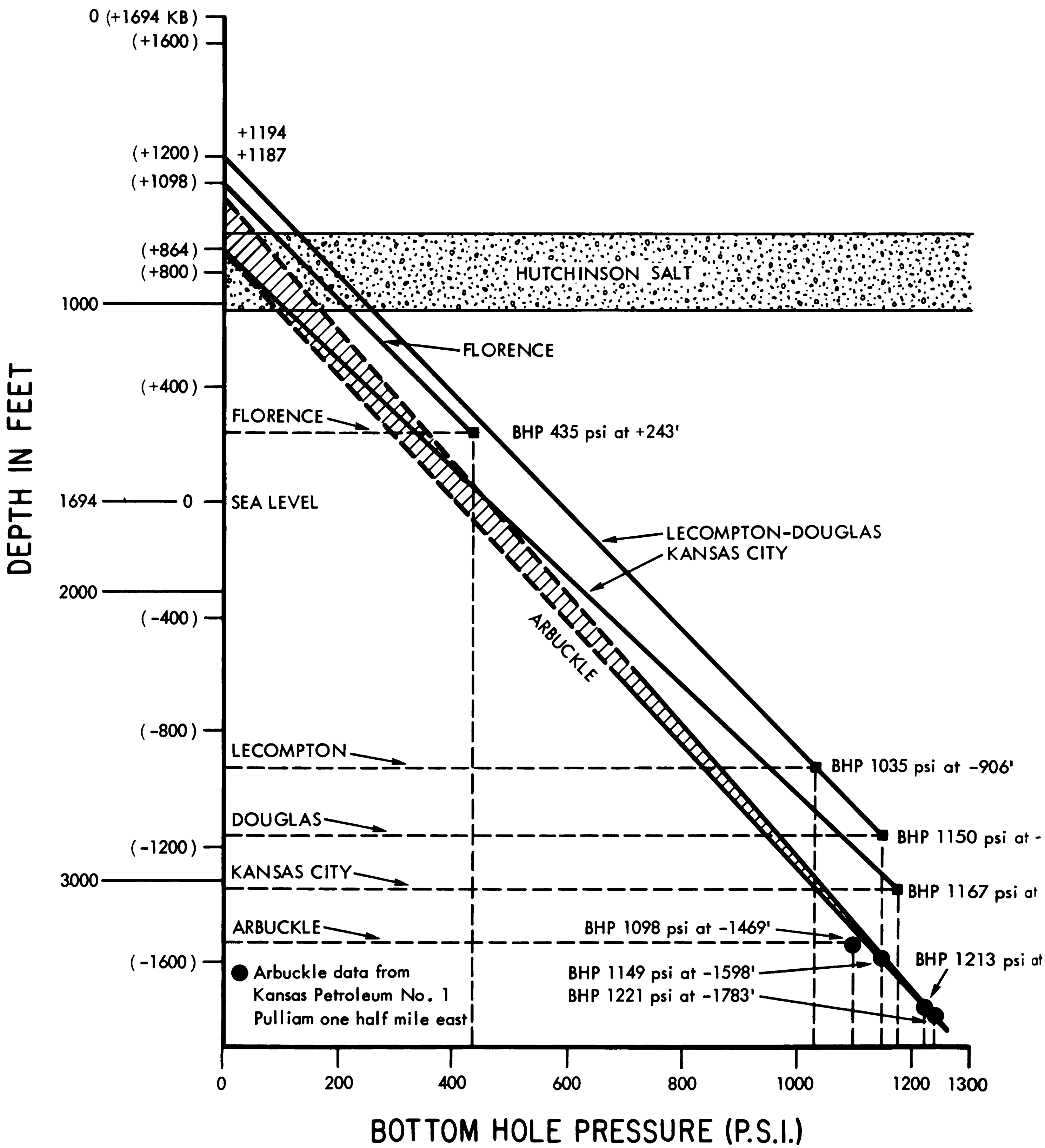


FIGURE 24.—Graph of aquifer pressure gradients, Rice County, central Kansas.

pipe, internally plugged, is cemented in place through the near surface fresh water aquifers. This important conclusion applies to geological conditions over about 90 percent of the study area. It does not apply to 10± percent of the area including the Gorham Oilfield where two additional aquifers, Cretaceous Cheyenne sandstone and Permian Cedar Hills sandstone, occur above the salt and are not required to be "protected" by surface pipe because their contained fluid is brine. This situation can, has, and will cause salt dissolution in oil and gas test holes as discussed in the section on the Witt and Crawford Sinks in the Gorham Oilfield, Russell County.

Because of the critical importance of properly cemented surface pipe, as required of all operators, we will consider briefly the regulations covering the protection of fresh water. Surface casing is required for all oil and gas test holes, its amount is specified, and advance notice of intent to drill is required by the Kansas Corporation Commission. Violations are uncommon to nonexistent. The presence of surface pipe is easily monitored by cased hole logs. Final plugging of abandoned oil and gas test holes is under the direct field supervision of a "state plugger," and notarized well plugging reports showing surface casing are required and permanently filed. Such regulation of hole plugging, and concomitant surface pipe supervision by the state and well record file goes back to 1935. For the period prior to that there was limited supervision on a county-by-county basis from about 1930, prior to which there was no regulation, no protection of fresh water, and no supervised hole plugging. Drilling for oil, and earlier for salt, within the study area extends back to 1888. There are instances, seldom documented, of uncased unplugged early oil and gas test wells in which post-drilling salt dissolution could and did occur. Two such holes are described along with the case history of one other adjacent partially plugged hole.

Case histories—no surface casing. An example of extensive post-drilling salt dissolution in an old test hole due to absence of surface pipe and lack of proper borehole plugging is provided by the Taylor No. 1, total depth 3552 feet in the Arbuckle dolomite, drilled from July 28 to October 10, 1934, in the Center of the NW/4 SE/4 of Section 25, Township 19 South, Range 8 West, Rice County, Kansas. This cable tool dry hole was abandoned prior to state regulation of well plugging and protection of fresh water by surface casing. It is located just east of the abandoned Lyons Arbuckle gas field which Northern Natural Gas Company redrilled for use as an underground natural gas storage reservoir. To ensure proper plugging of old test holes to avoid leakage of valuable stored gas from the Arbuckle reservoir, several abandoned holes were reentered in 1974, including the Taylor No. 1 on the south side of U.S. Highway 56 which was located without difficulty by use of 1938 aerial photographs. Discolored soil marked the location. Bulldozer excavation revealed the old cellar 12-feet deep filled with large concrete rig foundation blocks between which black topsoil was tamped. No surface casing was present. When the bulldozer was 17 feet below the surface, it found a 48-inch hole empty and open. To reenter the hole it was necessary to set 18 feet of 48-inch conductor pipe, then to set 8⅝-inch surface pipe at 134 feet. Even so, drilling was made more difficult by the presence of Cretaceous sand from 170 to 190 feet, a fresh water aquifer (4 of Table 3). At a total depth of 3495 feet, 5½ hours were required to circulate a sample of cuttings from the bottom. Using this information, Bill Luck (personal communication), field superintendent for Northern, calculated that it required the pumping of 11,000 barrels of fluid to bring the cuttings to the surface. Using this as a minimum estimate of the volume of the old hole, the author calculated an average hole diameter in the salt section from 800 feet to 1060 feet to be 8.43 feet, due to solution removal of salt. Any hole enlargement due to caving of an upper part of the hole would be compensated by filling a lower portion. This is a documented example of an old hole with no surface casing, and no plugging.

The salt section in the Taylor No. 1 was drilled with a 15-inch cable tool bit; hence there was little or no solution enlargement during drilling. The estimated minimum diameter at reentry, 8.43 feet, represents a post-drilling hole enlargement of about seven diameters, or of a removal of about 12,000 cubic feet of salt by post-drilling dissolution due to gravity flow from a fresh water aquifer down the borehole of an uncased unplugged oil and gas test hole into the permeable Arbuckle dolomite which provided the needed brine outlet. It is thought that the hole partially plugged itself by bridging as a larger amount of dissolution could be expected in 40-years time with the available abundant fresh water supply.

A second example in the same area is the Pulliam No. A-1 in the Center of the S/2 N/2 NE/4 of Section 35, Township 19 South, Range 8 West, Rice County, Kansas, reentered by Northern Natural Gas Company in 1974. The reentry diagram, Figure 19, of this well illustrates the complex subsurface conditions in old holes—here a 1936 cable tool hole completed with rotary tools below 3305 feet. Note the complete lack of surface pipe left in place in this abandoned gas well. This provided the first minor problem in reentry for the reason that the well could not be located by magnetic survey. After considerable bulldozer work, the old 6 ft × 6 ft cellar ten feet deep was located considerably south of its reported location. As excavation proceeded, the old sills and blocks were found to be in place at the bottom of the cellar. Below them was an open unfilled hole 48 inches in diameter to a depth of 28 feet. When this gas well was abandoned in 1945, it was plugged in the Simpson and Arbuckle near 3200 feet, but all casing which could be removed was salvaged leaving no surface pipe at all, and apparently no plugging of the hole above the Arbuckle reservoir. No information is available as to the diameter of this hole in the salt section at reentry in 1974, but it may have been enlarged as much as, or more than, the adjacent hole just 150 feet south, next discussed.

A test hole in the same section only 150 feet south, in the Center of the NE/4 of Section 35, Township 19 South, Range 8 West, Rice County, Kansas, the Pulliam No. 1, reentered by Northern Natural Gas Company, provides some information on hole enlargement in the salt, presumably in part due to post-drilling dissolution. The Pulliam No. 1, a dry hole, had surface pipe set at 204 feet with no casing below that point. It was drilled in 1962, fifteen years after the abandonment of the nearest gas wells. It was an easy hole to reenter and had a deep penetration, 102 feet, in the Arbuckle (see Figure 4, cross section, Well 9, and Table 3, Aquifer 10). The author studied pressure and fluid recovery information from the drill stem tests and calculated equivalent specific gravity figures for three intervals. Figures were 0.996 (fresh water), 1.033 (equivalent 41,000 ppm), and 1.047 (equivalent 65,200 ppm). These calculations suggested dilution of normal Arbuckle brine by leakage of fresh water into the Arbuckle dolomite through older abandoned gas wells improperly plugged. This test hole was, itself, left unplugged (except for "heavy mud") below the surface casing in 1962. Northern set a new string of casing in the reentered hole in 1974 for use as an input-withdrawal gas storage well. From cementing information, the author calculated the average hole size in the salt section, depth 777 feet to 1042 feet, as 37 inches average diameter. This amount is approximately 50 percent more hole enlargement than would be expected due to normal rotary drilling with fresh water.

These examples confirm the premise that absence of surface pipe isolating fresh water aquifers can cause post-drilling salt dissolution in unplugged, or poorly plugged, holes. Older holes drilled before 1935 are most suspect. Apparently, these holes plug, or partially plug, themselves by bridging as there are no known examples of surface subsidence associated with these 40- to 50-year old holes.

Recognition of salt dissolution. At best, the subsurface measurement of salt dissolution in a borehole is an evasive and difficult subject. Once the hole is closed by abandonment and/or plugging, there are very few methods of monitoring subsurface conditions. Although many abandoned "dry holes" are routinely reentered each year in central Kansas in search for overlooked hydrocarbons, such borehole reentry work is done as quickly and cheaply as possible with little regard for the salt section. Only rarely is there a major reentry program like that of Northern Natural Gas Company in the Lyons Gas Field where 18 holes were reentered and carefully replugged at a cost of over $600,000 in 1974. Three of the reentered holes provided salt dissolution case histories for this study, the Taylor No. 1, Pulliam No. A-1, and Pulliam No. 1.

The presence of these now confirmed unplugged oil and gas test holes was suspected correctly by Charles K. Bayne (Bayne and Ward, 1971) who directed a detailed subsurface hydrological investigation of shallow aquifers in and near the immediate vicinity in 1970-71. At that time, the area was undergoing intensive investigation as to its suitability for long-term (200,000 years) use as a repository for high level radioactive wastes. The groundwater study, funded by the United States Atomic Energy Commission, included the drilling by the Kansas Geological Survey of 36 shallow (100 feet ±) water wells with its own drilling rig, plus four deeper (300 feet) holes for hydrologic testing. The Survey's groundwater investigation disclosed a "pressure sink" in the potentiometric surface of the Cretaceous Kiowa aquifer (Table 3, Aquifer 4) about which Bayne wrote with regard to their hole 2-S, ". . . the anomalous hydraulic potential in this test hole can only occur if water is being or has been withdrawn either through a well pumping from the aquifer, or being discharged downward through an old drill hole or fracture. There is no record present or past of water being pumped from this zone . . . there is a strong argument for downward leakage of water. Several oil and gas test holes have been drilled within a few hundred yards of the site of test hole 2-S." This example indicates that when special needs justify funding the costly and time consuming effort, a detailed subsurface hydrological investigation of shallow aquifers by drilling and testing may provide pertinent information on uncased, unplugged oil and gas test wells which by inference may be the locus of salt dissolution.

Methods of detecting salt dissolution at depth after drilling ceases include: (1) changes in, or redirection of, drainage patterns, (2) presence of unusual drainage patterns foreign to the geomorphology, (3) ponding of water under certain soil conditions, (4) minor downwarping detectable by precise level surveys, (5)

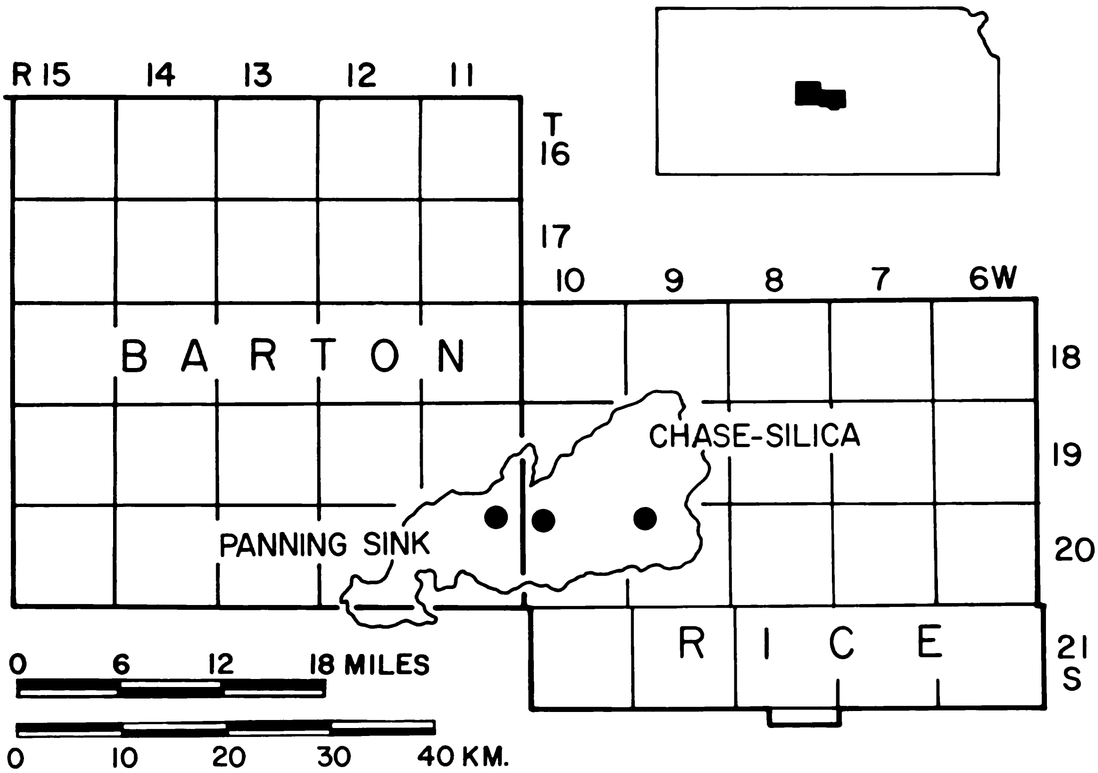


FIGURE 25.—Index map: Chase-Silica Oilfield, central Kansas. Shows location of three subsidence areas: (1) Panning Sink in Barton County, (2) Berscheit Heirs (T.20S, R.10W), and (3) Hilton (T.20S, R.9W) in Rice County.

cracks in the ground surface or roads, (6) cracks in the walls of buildings, (7) tilting of structures such as derricks, (8) casing leaks opposite the salt section, (9) casing failures at progressively shallower depths with the passage of time, (10) contamination of fresh water aquifers by brine from subsurface sources. Often, however, salt dissolution at depth may be undetected.

HUTCHINSON SALT IN THE CHASE-SILICA OILFIELD

Chase-Silica Oilfield. The Chase-Silica Oilfield (Fig. 25) is a major oilfield in Barton and Rice Counties, covering 135.3 square miles as redefined through the years since its discovery in 1929. Within it are three subsidence areas related to oil activity, the best known of which is the Panning Sinkhole described and illustrated in pages 52 to 58. The official field boundaries, as defined by the Kansas Corporation Commission, include 4845 oil and gas test holes of which 3738 produced oil, 19 produced gas, and 1088 were nonproductive "dry holes" encountering salt water in porosity zones. As of January 1, 1975, there were 694 active oil wells by field count. The wells are nearly all "stripper" oil wells (definition less than 10 BOPD for one year) averaging 4.68 barrels of oil per day per well (BOPDPW). During the year 1974, oil production was 1,185,331 barrels. Cumulative production from this giant oilfield is over 250 million barrels of oil.

In defining the field limits and regulating allowed oil production, the Kansas Corporation Commission has had the advice of many industry geologists serving on the Kansas Nomenclature Committee. In recent years the "lumpers" have won over the "splitters" with the resulting sprawling oilfield held loosely together by its official boundary, and by the common production of oil from the Cambro-Ordovician Arbuckle dolomite reservoir at depths near 3200 and 3300 feet. There is evidence of an original common oil-water contact near subsea —1585 feet in the enormous water-drive Arbuckle reservoir over much of the field, justifying the position of the "lumpers." Merged into the Chase-Silica Oilfield are 35 former oilfields. The author estimates that 85 percent of the total oil was produced from the Arbuckle dolomite.

The name "Chase-Silica" is derived from the town of Chase, Kansas in Sections 31 and 32, Township 19 South, Range 9 West, where a townsite oil play with the last of the wooden derricks occurred with prolific wells (100,000 barrels each) on five-acre spacing (Clark, Tomlinson, Royds, 1944), and from grain elevators at the former settlement of Silica, Kansas in Section 32, Township 19 South, Range 10 West.

The field was a learning ground for the oil operators. Early wells drilled with steam-powered cable tools required 30 to 60 days to drill. Then, in the 1930s, the first of the rotary rigs with derricks (not masts) moved into Chase-Silica. Geologists found the transition from excellent rock samples and fluid measurements of cable tools to the scrambled cavings of the rotary very difficult, and many logs and records of the 1930s are practically worthless. Rotary holes to 3250 feet, now commonly drilled in five days, took up to 24 days to drill. Drilling methods of the 1930s with no mud except native clays, with an abundance of easily available fresh water, with ram and cram drilling, with no drill collars, and with the drill pipe slapping the caving redbeds, resulted in hole enlargement to about five feet in diameter in the 300-foot thick salt section with many twistoffs and pipe recovery or "fishing" jobs. Here, too, is where geologists learned that the unconformity surface at the top of the Cambro-Ordovician Arbuckle was a carbonate karst plain with unpredictable "sinkholes" of limited extent (Walters, 1946) and here, too, the unexpected Precambrian quartzite monadnocks were encountered (Walters, 1953).

All early regulation of oil wells by the Kansas Corporation Commission in the 1930s was based on actual physical pump tests for 24 hours, with big machinery, everything bolted down, and the wheels flying. These physical tests (we now believe) coned bottom water upward in the first 24 hours. Rapid depletion of reservoirs in the 1930s when all the wells in the field averaged over 100 BOPDPW, is thought to have caused reservoir damage. This resulted in the handling of vast quantities of Arbuckle water, as much as 500 BWPDPW or more. At first, this was dumped wherever convenient (1920s), then vast "evaporation ponds" were built on the leases (1930s). In the 1940s, subsurface disposal in wells designated as salt water disposal (SWD) wells was required. These SWD wells commonly handled over 100 BW per hour by gravity flow into the porous lower Arbuckle dolomites. There have been a total of 154 SWD wells in the Chase-Silica Oilfield, converted for this use from 86 former oil wells and 68 former dry holes. In connection with the operation of these 154 SWD wells over a 30-year period, in only three SWD wells has casing corrosion caused excessive salt dissolution leading to surface subsidence, which may be viewed, therefore, as a relatively rare and unusual event.

Thickness and quality of salt. The Hutchinson Salt Member of the Permian Wellington Formation was penetrated by all of the 4845 oil and gas test wells drilled in the Chase-Silica Oilfield. As mapped in Figure 26, the salt has a thickness of 250 feet in its thinnest areas, across the summits of buried Precambrian hills in Township 19 South, Range 10 West. Over much of the Chase-Silica Oilfield the salt has a thickness of approximately 300 feet. In synclinal areas and regionally along the south portion of the maps, the salt thickness exceeds 350 feet. The depth to the top of the salt is approximately 900 feet in the east portion of the field and 1000 feet in the west, or Barton County, portion of the oilfield. The thickness map was prepared from all surviving available log information. Indicated on the map are the locations of the key wells in which the wire line geophysical logs permit determination not only of the salt thickness but of the quality of the salt. The resolving power of such logs is about one foot. A careful study and tabulation was made of the logs capable of such resolution. Within the Wellington Salt are beds, one foot in thickness or more, of nonevaporite material (principally gray shale) totaling about 25 percent of the total thickness. The figure is derived from the calculation of 109 logs of the salt section in Rice County which averaged 24.09 percent nonevaporite material plus 32 logs in the Barton County portion of the Chase-Silica Oilfield which averaged 30.69 percent nonevaporites, or a composite figure for 141 calculated logs of 24.57 percent nonevaporite beds, one foot or more thick, within the gross salt section. This means that, if the salt sections were dissolved, one-fourth of the total section, or approximately 75 feet, would remain as water insoluble residue. Actually such residue would increase its bulk considerably during the process of falling into the lower portions of the solution cavities. Landes and Piper (1972) term this process "bulking."

Salt dissolution in early tests during drilling. During the drilling of many of the early holes in the Chase-Silica Oilfield in the 1930s, as many as 24 drilling days were required to reach 3250 feet, resulting in hole enlargement of the salt section during drilling to five feet or more. Twistoffs of rotary drill pipe were common, usually occurring opposite the salt section. Experience of operators in fishing for stuck and twisted-off drill pipe provided many instances of evidence for hole size enlargement in the salt section exceeding five feet, and even exceeding ten feet occasionally. Information concerning hole enlargement by salt dissolution during drilling is provided by (a) such fishing experience, (b) calculation of cement volumes in the few holes in which casing was cemented through the salt section, and (c) wire line logs. One hole which was intensely studied, the Panning 11-A, in Section 2, Township 20 South, Range 11 West, had cement placed behind the casing opposite the lower

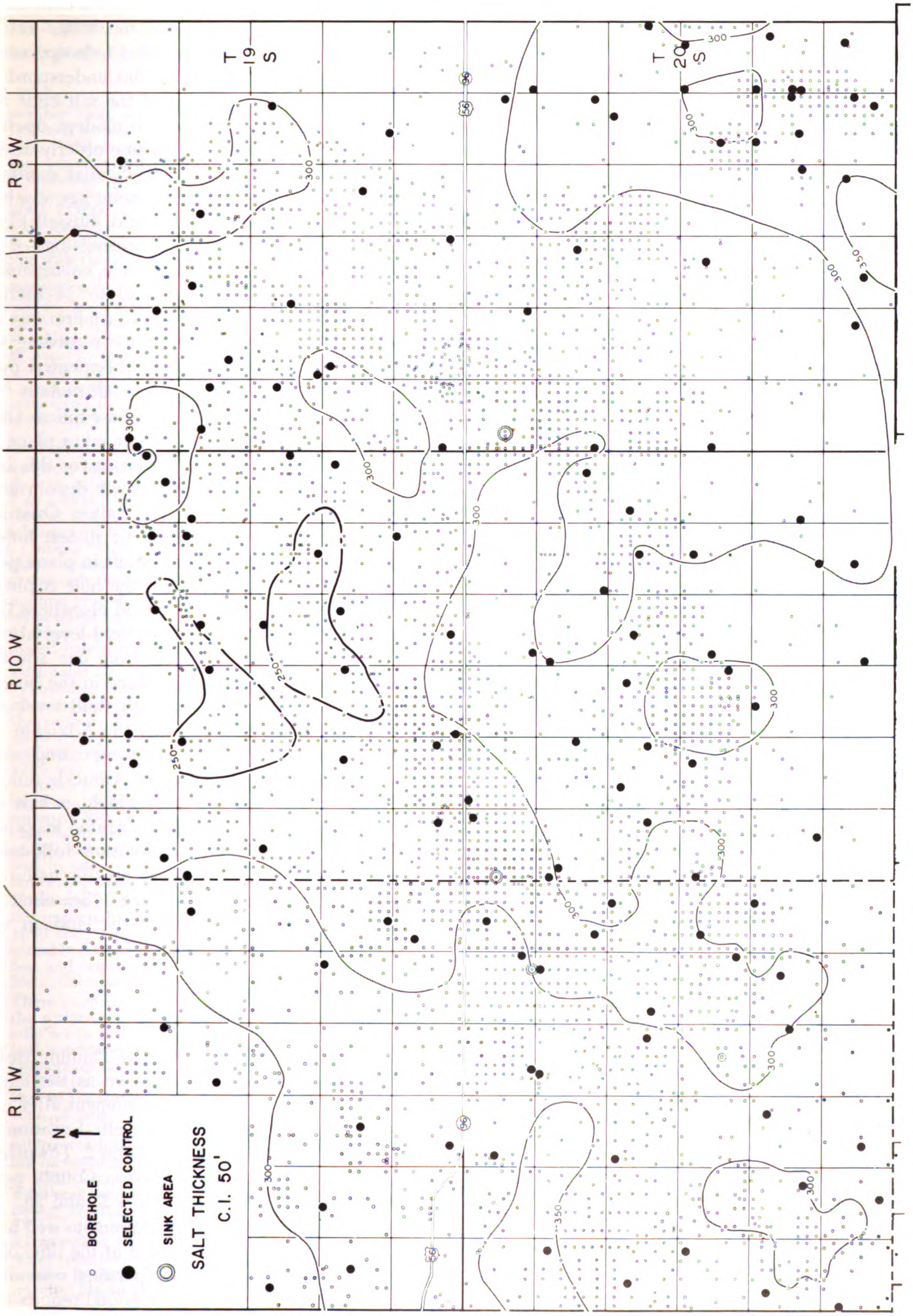


FIGURE 26.—Map; thickness of salt, Chase-Silica Oilfield. Contour interval 50 feet.

portion of the salt section. The author calculated from cement data that the average hole size above and below the salt section was 16 and 17 inches respectively, whereas the hole size within the salt section was calculated from cementing data to be 44 inches and 54 inches. Hole size information from cased hole gamma-neutron logs does not give precise figures but beyond critical limits, usually 36-inch diameter, the curves "wash out" or fail to record. An unusual and peculiar shift in the gamma-ray logs in much enlarged holes, and its meaning, is discussed next.

In the Chase-Silica Oilfield many cased hole gamma-neutron logs were recorded in the 1940s, usually by the Lane Wells Company. The holes were of uncontrolled large diameter—drilled nine inches but washed out to five feet or more in the salt section. Surface pipe, cemented in the Permian redbeds near 200 feet, serves to shut off fresh water aquifers above the salt. Oil string production casing, commonly 7-inch OD, set in the Arbuckle near 3250 feet isolated that reservoir, but commonly only 100 sacks of cement were utilized leaving the casing uncemented except for the bottom 200 feet or so. In log after log there is the usual well-defined shift of the gamma-ray curve to the left (decreased radioactivity) defining the top of the salt, followed by an equally sharp but unexpected gamma-ray shift to the right, here discussed, some 200 to 250 feet lower (example, Fig. 29-C). The lower shift has been read by geologists as the base of the salt leading to errroneous and erratic salt determinations. We now conclude that their shift is not the base of the salt, but that the actual salt base is from 10 to 70 feet lower with the gamma-ray curve giving a shale-like reading for this interval due to packing of former void space behind the casing with fallen shale. The shift occurs opposite the lower salt beds, the cleanest, purest, most easily dissolved portion of the 300-foot salt section. Usually the accompanying neutron log is essentially not recording because of hole enlargement. These two logs are the only cased hole logs available. A secondary characteristic of logs showing the anomalous shift is that the gamma-ray log, reading far to the left (low radioactivity) in the upper salt section lacks character. James Dilts who worked scores of logs for the author, measuring foot-by-foot the salt section recorded on wire line logs, concluded that the gamma-ray log, too, was essentially recording hole enlargement.

When casing is run in the rotary hole, it is floated into place in a fluid-filled hole. With the passage of time (logs usually recorded four to ten years later), the fluid level behind the casing adjusts to the common static level 1000 feet ± lower, removing fluid support from cantilevered shale partings in the Permian redbeds and in the upper salt section which then fall into the water-filled cavity opposite the lower salt, but which bridge above the constricted hole opposite the anhydrites below the salt. With this understanding of the gamma log shift, mapping of the salt beds in the Chase-Silica Oilfield, even though modern open hole multiple curve logs are rare, became orderly and predictable as shown in Figure 26. Similar gamma-ray shifts are present in logs of the same age elsewhere, for example, in the Gorham Oilfield, Russell County, but are not observed in gamma-neutron logs of holes drilled in recent years in which hole enlargement in the salt section is less severe, 20 to 24 inches in diameter. This observation tends to confirm our interpretation that the gamma-ray shift is recording shale-packed solution voids behind the uncemented portion of the oil string casing in the lower salt section.

Salt dissolution within the Chase-Silica Oilfield after drilling. No dissolution of salt takes place ordinarily after drilling ceases. The reason for this is that the four essential requirements for salt dissolution are not present. Fresh water in the shallow Quaternary and Cretaceous beds is cased off in all test holes by cemented surface casing which is left in place permanently and filled internally when the hole is plugged. Aquifers below the salt, as discussed elsewhere in this report, adjust to a common static fluid level above or within the salt section, but flow from one aquifer to the other does not cross the salt face in the borehole. The Arbuckle reservoir has a static fluid level above the salt, but fluids produced from the Arbuckle reservoir were confined within the oil string casing, set and cemented at some point within the Arbuckle dolomite. Rarely, in three holes only, all of which are salt water disposal wells, casing corrosion has caused leaks which have led to extensive salt dissolution followed by surface subsidence. These areas are discussed individually. They are named "Panning," "Berscheit," and "Hilton," after the fee owners of the land on which the disposal wells were drilled.

PANNING SINKHOLE— BARTON COUNTY, KANSAS

Well history, Panning 11-A. The Panning sinkhole developed around an oil well known as the Panning 11-A, then in the process of abandonment after extensive use as a salt water disposal well. Location is in the Center of the S/2 SE/4 of Section 2, Township 20 South, Range 11 West in the Barton County portion of the Chase-Silica Oilfield, Figures 25 and 26.

The following paragraphs pertaining to well history are based largely on data recorded at the time of surface collapse by Bruce F. Latta (personal communication), who submitted intradepartmental reports to the

Director, State Board of Health, dated April 18, 1959 and May 5, 1959, and who generously furnished copies of these reports to the author.

Oil Well

September 1938, drilled with rotary tools. Set 184 feet of 10¾-inch surface casing at 190 feet with 200 sacks of cement. Producing casing 6-inch OD set at 3268 feet in the Arbuckle and cemented with 100 sacks cement. Top of Arbuckle Dolomite 3267 feet (subsea −1502 feet). Completed on September 30, 1938 for a potential of 2001 BOPD. During testing the well swabbed 104 BOPH, natural (without acidizing), pulling swab from 1800 feet off bottom and swabbing through the 6-inch casing with the then total depth of 3276 feet.

Recompletion

Five years later, March 22, 1943, the well was deepened to 3285 feet (subsea −1520 feet) and acidized with 3000 gallons and then pumped 4 barrels fluid per hour (99% water). It was plugged back to 3270 feet (subsea −1505 feet), reacidized with 500 gallons 15% HCl, and again pumped 4 barrels fluid per hour (99% water). An echometer fluid level test showed fluid level 912 feet from the top (+865 feet above sea level).

Conversion to SWD

Three years later, March 23, 1946, the well was deepened with cable tools for use as a salt water disposal well at a total depth of 3850 feet in Precambrian granite, top at 3844 feet (subsea −2079 feet). Inside the 6-inch casing a 5-inch liner was run from 3223 to 3328 feet (subsea −1563 feet). At this time it was planned to place cement behind the oil string casing, but this plan was only partially followed.

Cementing procedures, which have an input bearing on the subsequent failure of the SWD well, were as follows (data from Latta personal communication, except that estimated hole sizes are calculated by the author):

> Perforated at 2500 feet (−735 feet) opposite Wabaunsee Group and circulated to surface i.e. no cement at all then present from 2500 feet to the surface. Pumped 750 sacks cement 2500 to 1240 feet, just above base of the salt which is variously reported as 1245 feet (+520 feet), or 1225 feet (+540 feet), or 1275 feet (+490 feet —author's figure). Average hole diameter calculated as 16 inches. Perforated at 1225 feet and pumped 500 sacks cement to 1150 feet in salt. Calculated hole diameter 44 inches. Perforated at 950 feet and cemented with 500 sacks to 1090 feet in salt section. Calculated average hole diameter 54 inches. See Figure 29 A-D.
>
> There was no cement placed opposite 115 feet of the upper salt section from its top at 975 feet to 1090 feet. Hole size cannot be calculated, presumably 54 inches or larger. Perforated at 1090 feet and cemented with 500 sacks cement to 230 feet. Calculated hole diameter 17 inches.
>
> There is no cement from 230 feet to the base of the surface casing at 190 feet which was reportedly set in bedrock, casing off Cretaceous shales and sandstone 190 feet to 98 feet and loose Quaternary sand and gravel present from 98 feet to 8 feet above which is loess-like clay soil. The base of the surface pipe, commonly a washed out zone of large diameter, was not here supported with cement. A string of 3-inch plastic lined tubing (to inhibit corrosion from the H_2S bearing corrosive Arbuckle brine) was set on a packer at 3320 feet to conduct the waste brine downward and keep it out of contact with the 6-inch casing to avoid corroding it. Completed as a SWD input well May 2, 1946, acidized with 3,000 gallons HCl. The well took 410 barrels of water per hour by gravity flow, or in terms familiar to hydrologists this is 287 gallons per minute. Placed in service as a disposal well.

In Use as SWD

Three years later, in 1949, the tubing was removed "because of inadequate capacity through tubing" (Latta, personal communication). Water was injected directly down the 6-inch casing. The total water injected in this well in 11½ years of use, May 2, 1946 to December 31, 1958, is reported as 11,486,238 barrels of brine. This is an average of 2485 barrels of brine per day, or 103.55 barrels of salt water per hour, day and night, for 11½ years, or 72.6 gpm. The figure is believable because in December 1958 the measured injection rate was 140 barrels water per hour by gravity flow.

Abandonment

The Panning 11-A was abandoned (but not plugged) in January 1959 because "the area around the well started settling causing the derrick to tilt and water to stand around the well" (Latta, personal communication). The derrick was cut down and moved in January 1959. Subsidence was first noted in late 1957, or early 1958, by oilfield workers according to S. W. Fader (1975).

Plugging

After standing idle for four months, the Panning 11-A was plugged April 14, 1959. The 6-inch casing was shot off at 230 feet, but operators could not pull the pipe. Shot off again at 188 feet (inside 10¾-inch surface casing) and recovered 189 feet of 6-inch casing which was laid on the ground at the location. The 188 feet of 10¾ inch surface casing cemented at 190 feet was left in the hole. The official plugging record on file with the Kansas Corporation Commission is somewhat ambiguous in that "the hole was bridged from 3850 feet to 360 feet." Note that the bridging materials, and the amount used are not stated. The Arbuckle at the bottom of the hole was probably plugged with sand or whatever was thrown into the hole. The report states that the hole was plugged back to 190 feet from 3850 feet, and squeezed (grouted) with 150 sacks cement, with cement fill to 110 feet. Filled the surface pipe from 110 feet to 20 feet with clay and rock, then ran 10 sacks of cement from 20 feet to the bottom of the cellar at 8 feet.

Collapse

Ten days later, April 24, 1959, the ground collapsed from 9:00 a.m. until evening (12 hours ±) when vertical movement stopped. At that time, the hole was about 300 feet in diameter with water level 50 to 60 feet below the surface (Latta, personal communication). Four days later when Latta was at the location, the water level was 11.5 feet below the land surface and the vertical walled pit had not increased in size. A week or two later the pond with 6-foot vertical banks above water level was fenced with a 6-foot chain link fence in a square 500 feet on a side.

Observations by witnesses. At 9:05 a.m., April 24, 1959, Larry Panning and his father, Alfred Panning, saw dust, mud, and dirt being blown in the air from the well, a distance of one-fourth mile east of their farmhouse. They drove to the site and photographed the sinkhole forming so rapidly that it drained water from the sand and gravel aquifer (Fig. 27). The rapidly enlarging hole was about 40 feet deep and about 75 feet across. The cone-shaped, or funnel-shaped, hole was forming in loose sand and gravel with large flows of fresh water rushing in, swirling around, and flowing down the hole. Within the first few hours there disappeared down the hole 190 feet of 8⅝-inch surface pipe formerly cemented in place, six joints (189 feet) of 6-inch casing which had been pulled and were lying on the ground beside the well,

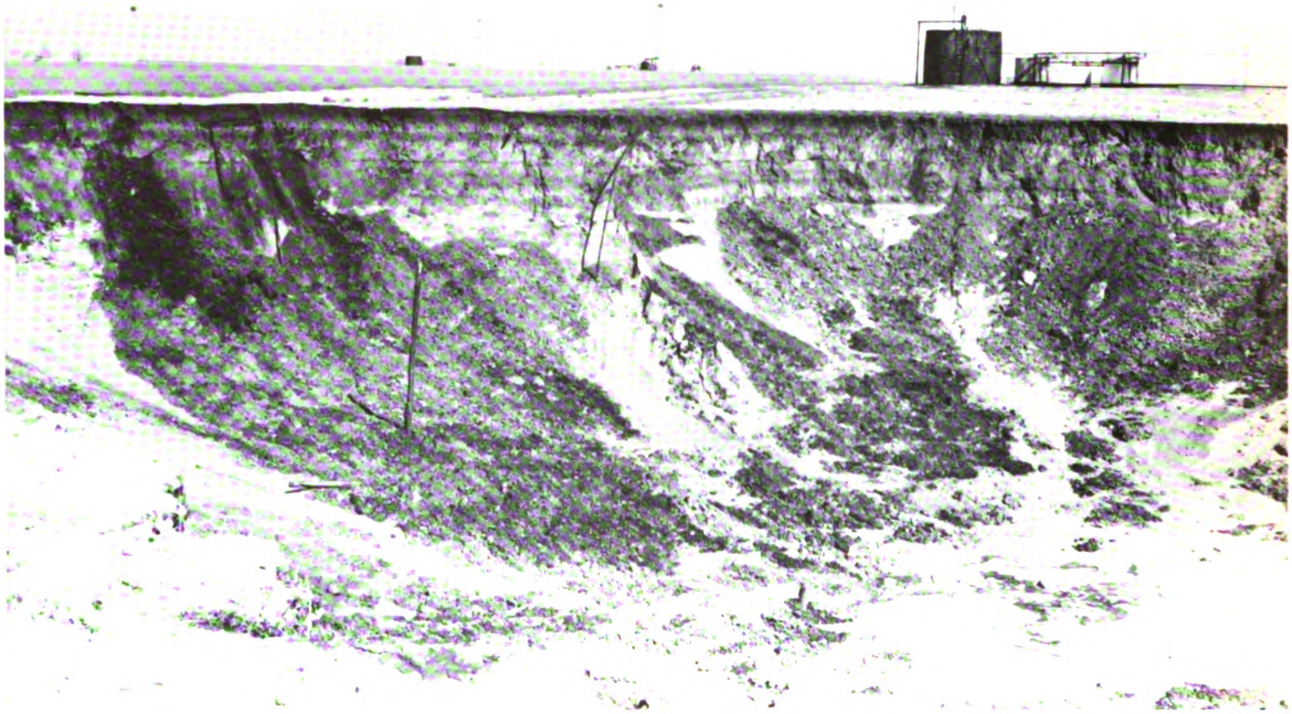


FIGURE 27.—Photograph by Larry Panning, April 24, 1959. Shows Panning Sinkhole after about one hour. View toward northwest. Vertical casing of abandoned water well, left center. Shows large flows of fresh water from breached near-surface aquifer.

debris from a 500-barrel redwood salt water receiving tank (diameter 20 feet, height 10 feet), the concrete well apron, and four concrete derrick corners (each corner 5 by 5 by 6 feet). The Pannings report (personal communication, Alfred Panning, December 17, 1974) that as they arrived at the location there was a sudden burst of dust, clods, and sand. They observed that this was repeated and that each burst, or shower, of dirt clods occurred just after each concrete rig corner block disappeared. The growing cone-shaped pit was a moving slurry of sand, gravel, dirt, and water. The hole grew rapidly to about 200 feet in diameter in three hours. The eyewitnesses estimated that the cone-shaped pit was about 100 feet deep. The pit was then filling rapidly with water with the result that its depth could no longer be estimated. Development of the crater continued until evening (12 hours ±) forming a nearly circular pit 300 feet in diameter (Figure 28), with the water level 50 or 60 feet below the surface, at which time major vertical movement ceased. The water level was 11.5 feet below grade and the pit size unchanged when observed three days later, April 26, 1959 (Latta, personal communication).

May 3, 1959, a fence enclosing an area 500 feet by 500 feet was built on the undisturbed land surrounding the pond, which at that time had vertical banks six feet high. In the subsequent 17 years, there had been little evidence of subsidence. The fence has buckled near the midpoint of each of the four sides as a result of downward movement of about two feet and inward movement of slightly more than two feet at each midpoint relative to the four corners, providing an indication of the downward and inward adjustment movement in that time period. By erosion and readjustment, the pit has dished out and developed gently sloping banks. Maximum depth of water in the pit was reported as 85 feet in May 1959 by Larry Panning (personal communication). In July 1975, the maximum depth was measured by Clark T. Snider and the author as 64 feet. The bottom has a gentle wave cut notch 15 feet wide from depth of zero to three feet, then a fairly uniform steep 30-degree slope to a depth of 50 feet, a gentle slope to a small flat area (40 by 40 feet) depth 62 feet, with a maximum reading of

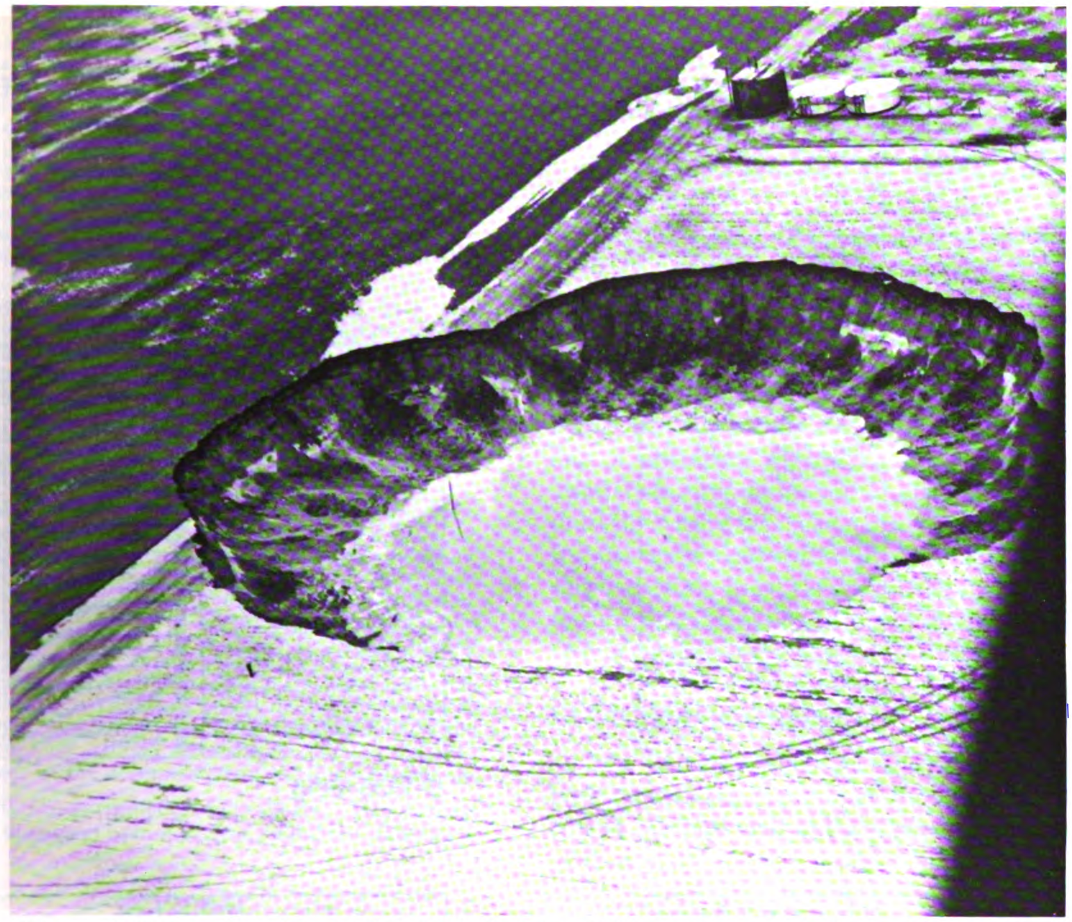


FIGURE 28.—Photograph by Larry Panning, April 24, 1959. Panning Sinkhole, view toward the northwest. Vertical water well casing of Figure 27 at left center. Figure of man, left foreground. The light areas in the sides of the pit are water flows.

64 feet directly above the old well bore. This fenced fresh water pond, now a wildlife preserve, is circular, measuring 370 feet in diameter, with the water level six feet below the general ground level. This is slightly larger than the October 1965 aerial photograph measurements of an approximately circular pond 330 feet in diameter. The enlargement is presumably the result of wave erosion and bank leveling.

Postulated sequence of events. Using these facts, and combining them with knowledge of the hydrology of the Chase-Silica Oilfield aquifers, a sequence of events can be postulated. The reader is cautioned to remember, however, that this reconstruction is made from observations in which the subsidence itself is the principal evidence for salt dissolution: (1) no saturated brine was ever recovered at the surface; (2) there is actually no direct evidence that the salt section was dissolved; (3) the gamma-neutron log (Fig. 29-C) from a nearby well shows normal post-drilling conditions in the salt section; (4) no casing was recovered from the depth of the salt section; hence even the presence of corroded holes in the casing is circumstantial; and (5) there have been no post-subsidence surveys by seismic soundings, or drilling. With these reservations in mind, the postulated sequence of events terminating with the formation of the Panning Sinkhole is as follows:

September 1938 (Fig. 29-A). During the drilling of the Panning 11-A, the fresh water drilling fluid dissolved salt to a diameter of 54 inches. Note that production casing cementing did not proceed up hole this high.

1938-1943 (Fig. 29-B). No dissolution of salt took place while over 100,000 barrels of oil were being produced through tubing. Shale interbeds in the salt section collapsed and fell, accumulating in the void space from 1200 to 1275 feet, just above the constriction in hole size at the first anhydrite bed.

1943-1946 (Fig. 29-C). A cased hole gamma-ray neutron log recorded in a nearby hole showed the static fluid level of the Arbuckle aquifer to be 912 feet from the top of the hole. No salt dissolved in these years during which the well was temporarily abandoned as non-commercial after pumping 99 percent water due to depletion of the oil.

1946-1949 (Fig. 29-D). The well was converted for use as a salt water disposal well ("SWD" in Fig. 29-D) by recementing the casing. Note the presence of cement opposite the lower salt section and the absence of cement opposite the upper salt section. No salt dissolved. Brine was disposed through tubing by gravity flow.

1949-1958 (Fig. 30-A). Tubing was removed from this disposal well and brine was disposed directly down the casing. Corrosion resulted in casing leaks, permitting access for 72 gpm of brine, 14,000 ppm chlorides, to circulate across the salt face, then downward into the

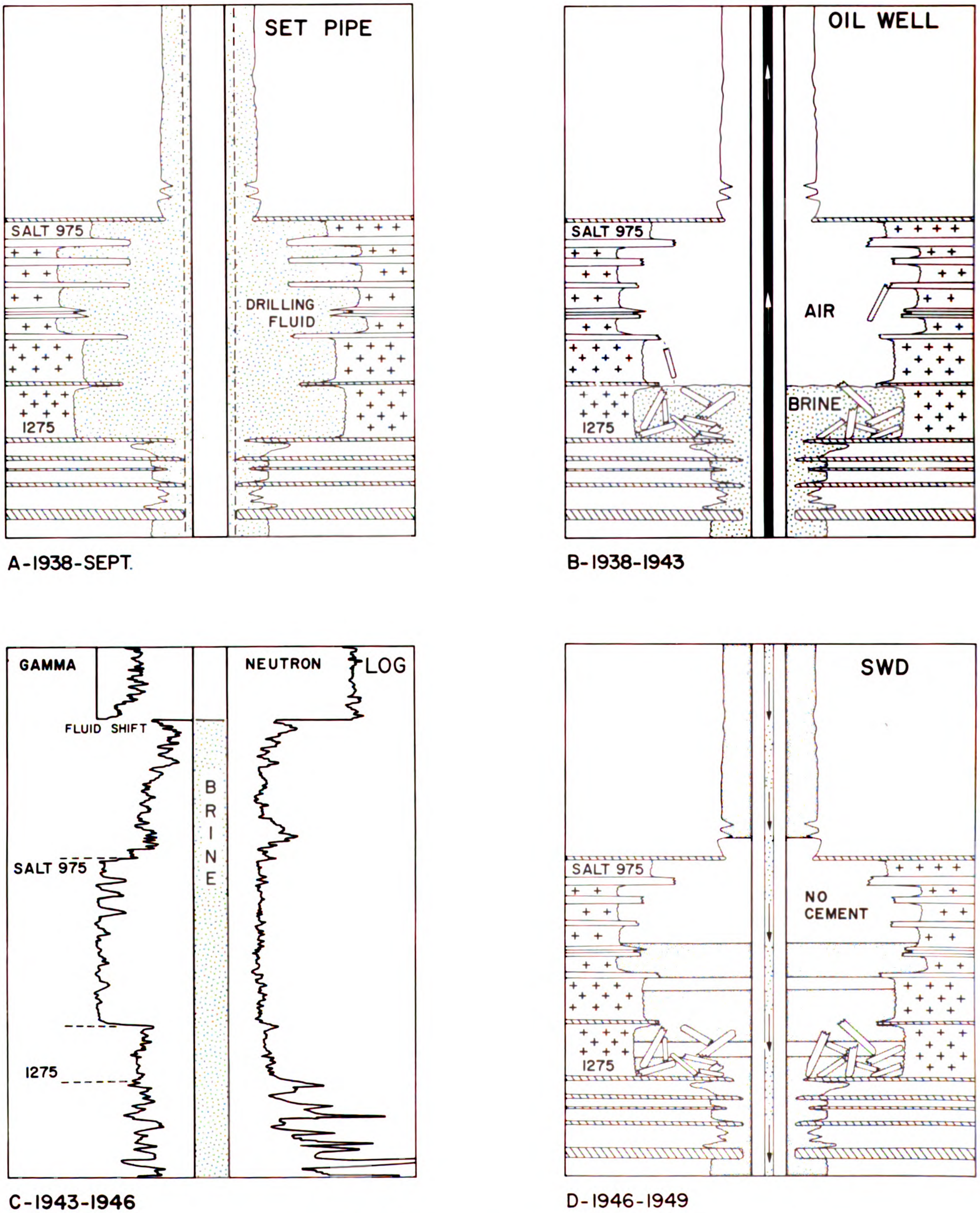


FIGURE 29.—Diagram; salt section in Panning 11-A.
A. After setting 6-inch oil string casing.
B. Oil well. Oil is pumped up 2-inch tubing.
C. Gamma-neutron log; tubing removed.
D. Salt water disposal well (SWD). Waste brine moving down 3-inch plastic-lined tubing.

Arbuckle aquifer. A huge cavern dissolved in the salt, larger than 300 feet in diameter. Progressive falls of shale interbeds and shale roof rocks partially filled the cavern. Successive roof falls caused the void space to gradually migrate upward to near the Stone Corral Anhydrite, depth 465 feet (1300 feet above sea level) causing, in turn, surface subsidence, ponding of water, and tilting of the derrick.

1959-January (Fig. 30-B). The Panning 11-A was abandoned but not plugged. The derrick was removed because surface subsidence caused it to tilt dangerously. With disposal brine flow discontinued, salt dissolution ceased.

1959-April 14 (Fig. 30-C). The Panning 11-A was plugged with 150 sacks of cement in the surface pipe to 190 feet, and the Arbuckle was bridged: There was no other plugging. The underground void space at shallow depth was now isolated from both the near surface and the Arbuckle aquifers. Brine in the void space drained downward gradually to reach equilibrium with intermediate aquifers leaving the near surface void space unsupported by fluid and under vacuum.

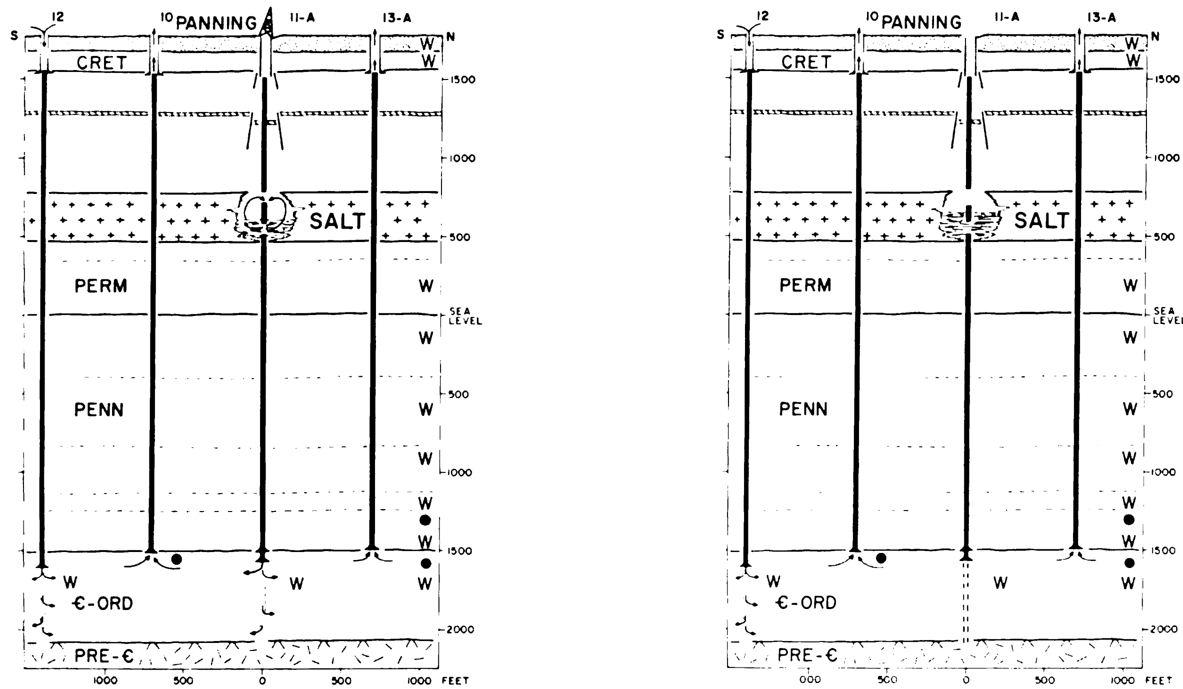
1959-April 24 (Fig. 30-D). When the uppermost "keystone" bedrock at a depth of 106 feet fell into the newly drained shallow void space, the surface sinkhole formed rapidly in three hours from 9:00 a.m. until noon, with some subsidence continuing until about 9:00 p.m. As the shallow void space filled with fresh water and air, falling material such as concrete derrick corner blocks fell into the narrow aperture and compressed, then ejected, the air. The casing collapsed and fell. At first, the loose sand and gravel moved downward in a fresh water slurry at a rate faster than the flow of the aquifer, forming a deep cone shaped pit. As the void space filled, water accumulated in the surface sinkhole.

1959-April 25 to present (Fig. 30-E). The circular sinkhole diameter near 330 feet, stabilized forming a fresh water pond 64 feet deep, volume near 2,000,000 cubic feet. In 17 years, the surrounding fence buckled downward and inward only about two feet on each side, indicating resumption of stable subsurface conditions. Transported sand and gravel fills the shallow space voided by roof falls. The former cavern in the salt is filled and plugged with fallen Permian shale and redbeds; hence it is thought that no further dissolution is occurring.

Larry Panning (personal communication, July 23, 1976) stated that evidence was submitted during litigation in the early 1960s indicating that the surface pipe may have parted during drilling. If correct, fresh water from the shallow aquifer could have drained downward by gravity flow outside the 6-inch casing, across the salt section dissolving salt and flowing into any or all of the several Permian and Pennsylvanian aquifers during the period of oil production from 1938 until the casing was recemented in 1946 in preparation for use as a disposal well. The author's theoretical reconstruction may, therefore, require modification as to time and cause of salt dissolution, but the resulting sequence of events remains the same.

BERSCHEIT SINKHOLE

The Berscheit Sinkhole developed by slow subsidence around the location of the abandoned Berscheit No. 14 disposal well in the Center of the SW/4 SW/4



A-1949-1958

B-1959-JAN.

FIGURE 30.—Cross section through Panning 11-A disposal well.

A. Waste brine moving down inside 6-inch casing (plastic-lined tubing removed) and circulating by Permian salt section through holes in casing.
B. Well abandoned; derrick removed.

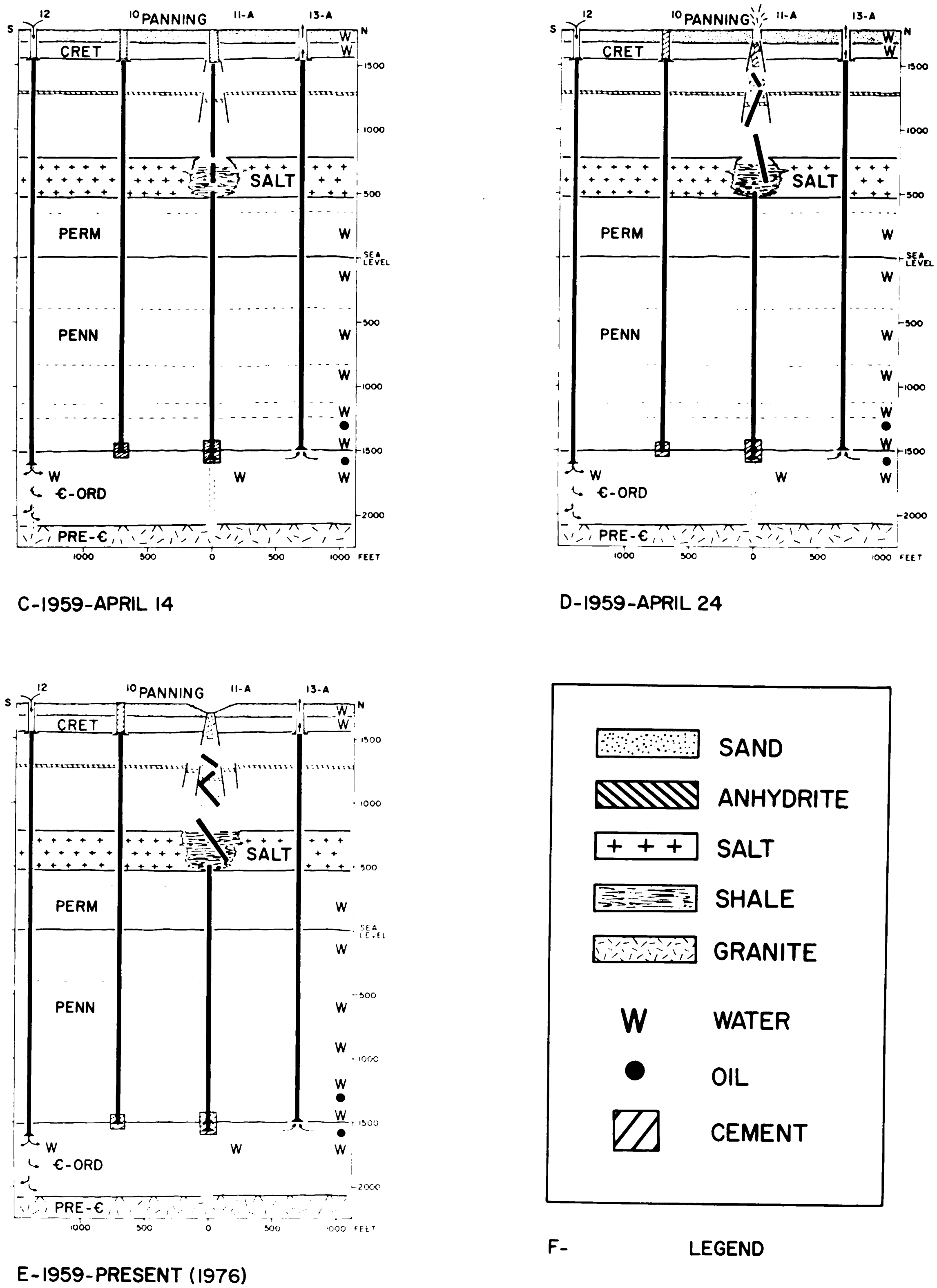


FIGURE 30 (continued).—Cross section through Panning 11-A disposal well.
C. Well plugged with cement in surface pipe, and "bridged" in Cambro-Ordovician Arbuckle Dolomite.
D. Sinkhole forming April 24, 1959.
E. Panning Sinkhole with pond.
F. Legend for Figure 30.

NW/4 of Section 6, Township 20 South, Range 10 West, Rice County, Kansas. At the time of abandonment of the well in March 1972, Norman W. Biegler (personal communication) photographed the pond forming in the subsidence area around the well. At that time, this 160-acre lease, formerly with 16 Arbuckle oil wells, had only one remaining oil well located one-fourth mile east of the disposal well. The tank battery burned to the ground contributing to lease abandonment.

The amount of subsidence is not known because this agricultural land has not been monitored by precise surveys. The well elevation was 1772 feet derrick floor, and 1769 feet ground level. In 1975, unusually heavy precipitation filled the pond in the subsidence area completely to the spill point on the northwest, and in July 1975, the pond had a water surface elevation of 1764 feet (Clark T. Snider, personal communication). Mr. Allen Kelly, the present landowner, said that swimmers report the water to be 10 feet deep. The subsidence is, therefore, estimated at 15 feet. There has been no collapse or sudden drop. Cretaceous bedrock is close to the surface with a Dakota sandstone ledge exposed a few inches above lake level in a gully on the south side. All slopes are very gentle and a small rise in water level increases the inundated area greatly. The pond measured about 450 feet east-west and 375 feet north-south.

The Berscheit No. 14 was drilled with rotary tools in 1936, with only 114 feet of 12½-inch surface pipe. The Arbuckle was drilled at 3264 feet (subsea −1492 feet) and produced oil from open hole below the 7-inch casing set at 3267 feet, with a total depth of 3272½ feet. When deepened in 1942 for use as a disposal well, weathered granite was encountered at 3794 feet (subsea −2022 feet), with a total depth of 3819 feet. A liner of 5½-inch pipe 543 feet long was set within and below the 7-inch casing from 2842 to 3385 feet (subsea −1613 feet). At the time of plugging, April 6, 1972, only 60 feet of 5½-inch and 60 feet of 7-inch casing were recovered, and both were "very badly eaten away" according to official plugging report by Gilbert J. Toman, State Plugging Supervisor, who noted on the report, "location sinking from washed out salt section." Plugging consisted of pumping 400 sacks of cement into the well through a two inch opening in plate welded into 12½-inch surface casing.

The sequence of events leading to the formation of the Berscheit Sinkhole is thought to be similar to the nearby Panning Sinkhole. The final event, the rapid collapse resulting from inflow of loose sand and gravel, could not occur because alluvial fill is absent at the Berscheit location. Corrosion of the casing causing large leaks was inferred in the Panning 11-A, but is a certainty in the Berscheit No. 14. Photographs by N. W. Biegler (personal communication) of the 120 feet of casing recovered from the Berscheit No. 14, show the pipe "eaten away" with large holes each several square inches in area.

HILTON SUBSIDENCE AREA

An area of slow subsidence due to salt dissolution developed around the location of twin salt water disposal wells, 200 feet apart, in the NW/4 NE/4 SW/4 of Section 6, Township 20 South, Range 9 West, Rice County, Kansas. At the present time, all oil wells in the W/2 of Section 6 have been abandoned and the land restored to agriculture. There is a shallow pond with gentle sloping grassy banks. Well data are as follows:

	Hilton No. 6 **C NW¼ NW¼ SW¼** **Sec. 6, T.20S, R.9W**	**Hilton No. 7** **200′ West of No. 6** **Sec. 6, T.20S, R.9W**
Completed	November 1948	October 1951
Plugged	October 1951	June 1965
Elevation	1731 ground level	1735 rotary bushing 1731 ground level
Surface Casing (8⅝ inch)	198′ with 100 sacks	203′ with 125 sacks
Arbuckle	3278 (−1547)	3278 (−1543)
Total Depth	3542 (−1811)	3564 (−1829)
Production Casing (5½ inch)	3282′ with 25 sacks	3285′
Liner (4 inch)	3336′	None
Plugged	October 10, 1951	June 25, 1965
Casing removed	765′ of 5½ inch	None
Reason for abandonment	Tubing failure. Found top of tubing at 855′—could not fish tubing.	When holes in the 5½-inch casing were squeezed (grouted) with 550 sacks of cement, the collar and surface pipe filled with cement.
Plugging	Rock bridge 175′-185′ and 20 sacks cement.	Pumped 300 sacks cement in the well down the 5½-inch casing.

Data recorded by S. W. Fader (1975) in March 1973 indicate that subsidence at this site was first noted in May 1964 (one year prior to plugging the last disposal well) at which time geologists from the State of Kansas Department of Health and Environment estimated that 13 feet of decline occurred at some time between 1948 (first disposal) and 1964. On the basis of the Chase, Kansas topographic quadrangle prepared from aerial photographs taken in 1968, and field checked in 1970, Fader estimated that total subsidence in 1968 was 18 feet in the center of an area about 500 feet by 600 feet, and he notes that an aerial photograph taken in September 1970 shows a pond with surface dimensions of about 320 feet by 380 feet. The area appears to be stabilized but it has not been surveyed.

The sequence of events leading to the formation of the Hilton subsidence area is thought to be similar to the Berscheit Sinkhole. The observance of sinking at the surface at least a year before abandonment is significant as regards the slow development of such areas. The presence of twin disposal wells 200 feet apart with the earliest hole abandoned, the Hilton No. 6, plugged only as described, may have been a factor. In salt mining by solution, pairs of brine wells are commonly employed to dissolve galleries in the salt which are several hundred feet in length.

HUTCHINSON SALT IN THE GORHAM OILFIELD

Gorham Oilfield. Within the Gorham Oilfield, in western Russell County, central Kansas (Fig. 31), there are two areas of surface subsidence caused by salt dissolution in three abandoned oil wells. These subsidence areas seriously affect Interstate Highway 70; hence they were and are carefully surveyed and studied. In the 44.5 square miles of the Gorham Oilfield, all of the 1593 oil and gas test holes drilled penetrated the Hutchinson Salt Member of the Permian Wellington Formation which was encountered near a depth of 1300 feet.

The 50-year old Gorham Oilfield is localized by a broad gentle anticline overlying a faulted Precambrian basement high. There is a displacement of 300 feet in the Precambrian granite. Faulting accounts for 50 feet of relief on the sub-Pennsylvanian unconformity surface depth near 3250 feet. At the level of the oil producing Lansing-Kansas City limestone, near 3000 feet, faulting is also evident to the extent of 50 feet of the total relief of 100 feet. The Hutchinson Salt has a thickness of less than 250 feet overlying the structurally highest area, as compared with over 300 feet in the surrounding synclinal areas. The Permian Stone

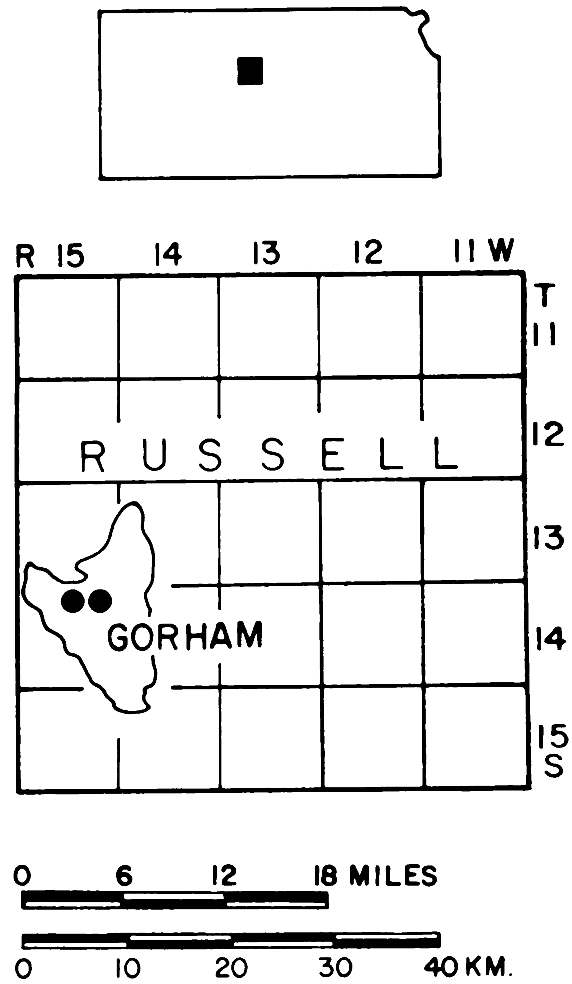


FIGURE 31.—Index map; Gorham Oilfield, Russell County, Kansas.

Corral Anhydrite at the top of the Sumner Group, depth near 900 feet, shows 30 feet of steep dip overlying the fault zone. Careful surface mapping of the outcropping Cretaceous Fence Post Limestone in the early 1920s disclosed 30 feet of closure, leading to the discovery of the oilfield in 1926. The geology of the Gorham Oilfield has been described in detail by Walters (1977), who earlier published a geological cross section through the oilfield (1953).

Cumulative oil production in this major oilfield totals 86,919,723 barrels of oil to January 1, 1975. It is estimated that 69 percent of this is from the truncated Arbuckle dolomites and Cambrian Basal Sandstone, 25 percent from the Pennsylvanian Lansing-Kansas City limestones, and 6 percent from shallower Pennsylvanian and Permian zones, principally from the Shawnee Group. An unusual feature of the oilfield is the presence of a five-mile long fracture zone indicated by the straight line distribution of 20 Topeka (Shawnee Group, Pennsylvanian) limestone oil wells, including two unique giant wells each of which produced over one-half million barrels of oil. The 341 active oil wells, part under secondary recovery by waterflood, averaged 4.55 barrels of oil per day per well during 1974, but these "stripper wells" together accounted for an annual production of 565,991 barrels of oil in 1974. Within the Gorham Oilfield, or immediately adjacent to it, there have been drilled 1593 oil and gas test holes, 1170 oil wells, 386 dry holes, and 37 service wells. In connection with the handling of oilfield brines produced along with the oil, there were 56 deep salt water disposal wells, 17 converted from abandoned oil wells, and 39 converted from former dry holes. In connection with secondary recovery of oil from the Lansing-Kansas City limestones by waterflooding, there are 56 salt water injection (SWI) wells, 19 of which were converted from abandoned oil wells, and 37 of which were drilled specifically for use as injection wells, and hence are classified as service wells.

Wells were drilled in the Gorham Oilfield in the 1920s and 1930s with cable tools (wire line percussion drilling and bailing) requiring 60 days or more for each well (depth 3250 feet ±), and providing excellent rock cuttings (when saved), data on aquifers penetrated, and actual salt cuttings. Wells drilled in the late 1930s and later were among the earliest rotary drilled holes in Kansas, and information on formations penetrated—even oil zones—was meager, with no data on the salt (borehole enlargements to five feet, or even ten feet, in diameter), and almost no useful data on aquifers and the general hydrology of the Gorham anticline. Redrilling of portions of the Gorham Oilfield for secondary recovery of oil by waterflood has provided some modern wire line geophysical logs and fluid data, but most of these logs record only formations below the base of the salt.

Thickness and quality, Hutchinson Salt. The Hutchinson Salt, depth near 1300 feet, is less well known than one would expect in the Gorham Oilfield where it has been penetrated by 1593 oil and gas test holes, or an average hole density of 36 holes per square mile. All that is left from the many early cable tool holes are written drillers' logs which are usually accurate as to the depth of the top of the salt, but which are inaccurate and contradictory as to the base of the salt, and which provide no details, the whole 300-foot section often being described by the one word "salt." Early rotary hole records are worthless as regards information concerning the salt. A thorough review was made of all available log data, and the results are incorporated in Figure 32, a map showing the thickness of the Hutchinson Salt. Only three percent of the total holes drilled, the 47 holes designated as "selected control," had logs of sufficient quality to permit evaluation of the salt beds. These indicate that the salt section (1) is less than 250 feet over the anticlinal crest, (2) thickens to more than 300 feet in the synclinal area, and (3) averages 33.7 percent nonsalt, principally shale, in beds one foot or more in thickness, which is the resolving power of the wire line logs. The salt beds thin over the anticlinal axis principally by the loss of basal beds, indicating the presence of a positive area, perhaps an island, during the early deposition of salt. There is also some thinning of beds in the mid-salt section and some loss of beds at the top of the salt section along the anticlinal axes, indicating differential vertical movement in mid-Permian time when the Hutchinson Salt was being deposited as an evaporite formation in the shallow sea.

Indicated on Figure 32, by double circles, are the two locations where salt dissolution associated with oil operations has been so extensive as to cause surface subsidence. These are the Crawford and Witt Sinks. They are illustrated in greater detail in Figure 33, an index map of two square miles, Sections 2 and 3, Township 14 South, Range 15 West, which shows the location of the two sinkholes, of Interstate Highway 70, and of the many oil and gas test holes drilled through the salt. Contours indicate the amount of surface subsidence due to dissolving the Hutchinson Salt, present at depths below 1300 feet. During a 20-year period, slow subsidence has occurred totaling more than 26 feet (Crawford) and 17 feet (Witt), associated with three abandoned oil wells and three nearby abandoned shallow salt water disposal wells ("SWD" of the legend, Fig. 33). This oil-related subsidence has affected 1000 feet and 750 feet, respectively, of both lanes of Interstate Highway 70 at these locations, necessitating costly repairs. The relation of these two subsidence areas to the subsurface formations and aquifers is illustrated in Cross Section I-J, Figure 34, discussed next.

Cross Section, Gorham Oilfield. Cross Section I-J, Figure 34, is drawn without vertical exaggeration. It illustrates the geological rock column drilled in the Gorham Oilfield, the close well spacing with twin and triple well locations, the multiple porous zones which are oil reservoirs and/or aquifers, and the two areas of salt dissolution and surface subsidence the investigation of which is continued in a following section.

The cross section was compiled by using all available surviving data—plotted cable tool drillers' logs, wire line logs, samples of well cuttings, hydrological data, oil and brine production information, and State Highway Commission surveys. It serves as an introduction to subsurface conditions in undistorted vertical and horizontal relationship.

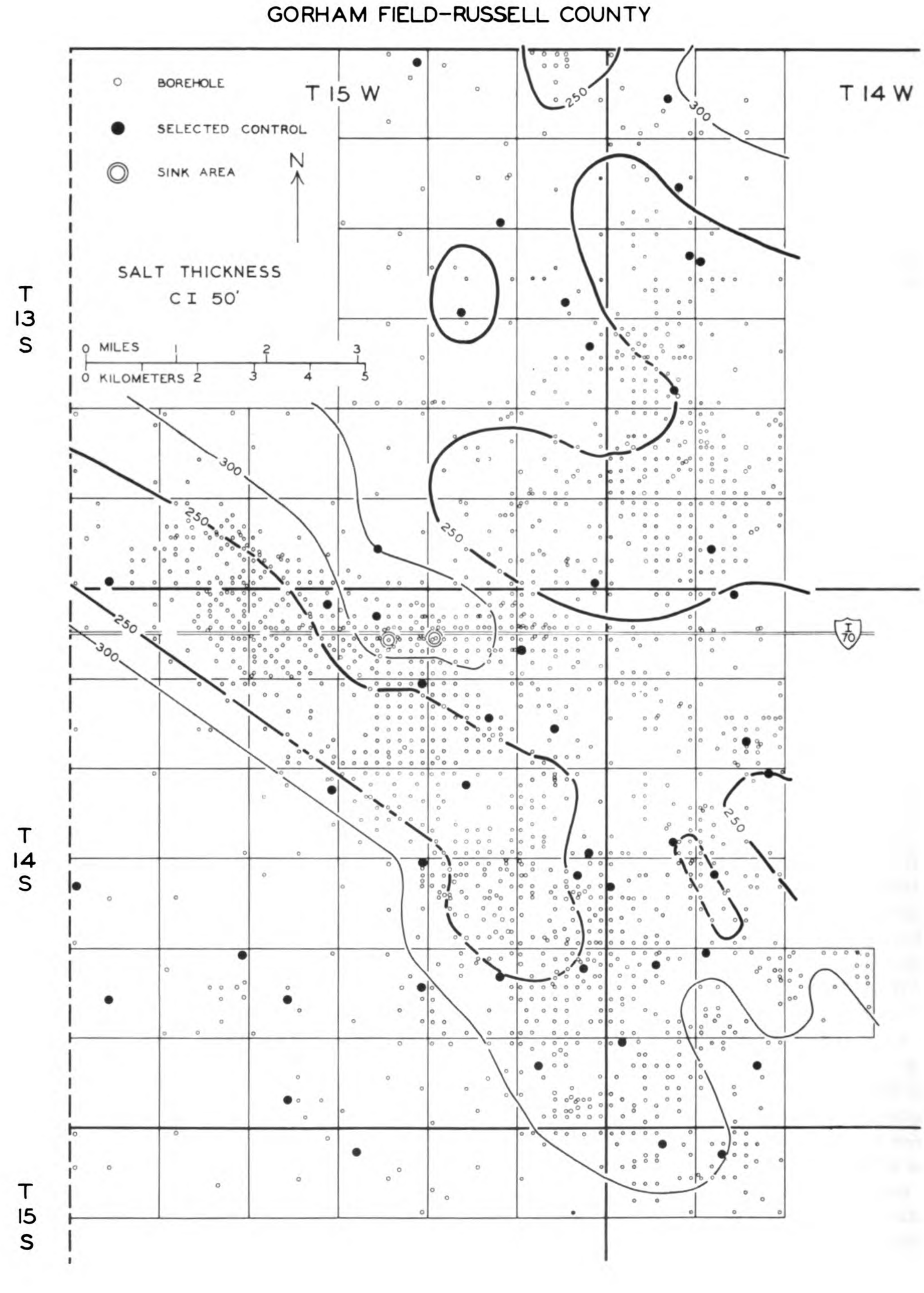


FIGURE 32.—Gorham Oilfield, showing thickness of Hutchinson Salt. Contour interval 50 feet.

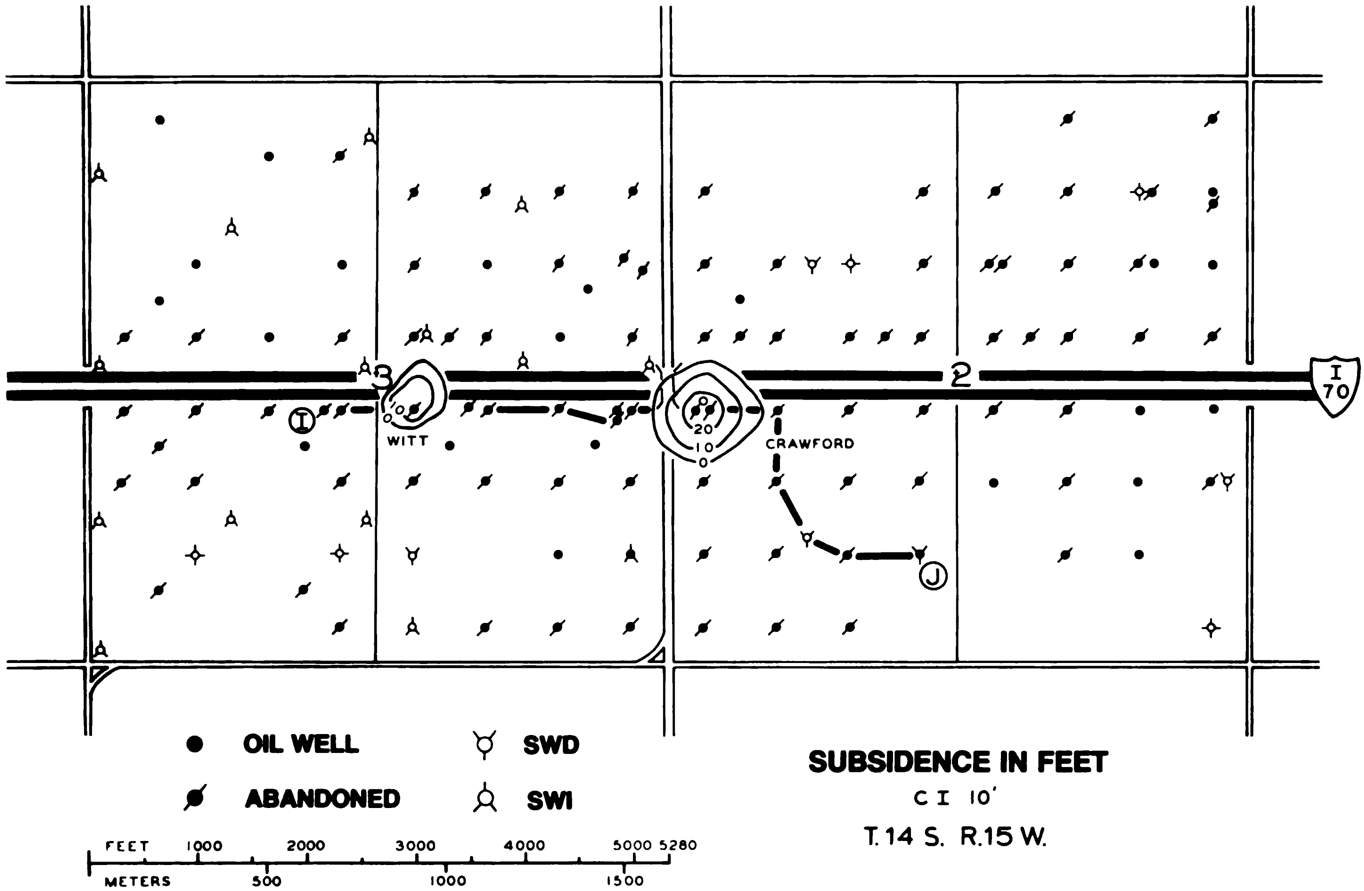


FIGURE 33.—Index map, Gorham Oilfield, Sections 2 and 3, T.14S, R.15W. Contours show the amount of subsidence in the Witt and Crawford Sinks. Contour interval, 10 feet.

The many aquifers are indicated by the symbol "W." Note the complete absence of aquifers in the Permian Sumner Group above, within, and just below the Hutchinson Salt. The Sumner Group is an aquiclude serving as a barrier to vertical fluid migration. Within or above the Sumner Group there are no oil shows, but below it there are oil shows (solid dots, Fig. 34) and/or commercial oil production in all porous zones. Where this natural barrier to vertical fluid movement is breached by drilling, or by the abandonment of improperly plugged boreholes, vertical fluid movement can and has taken place—upward movement of oil by flowing during the drilling of some early cable tool holes, and downward movement of water by gravity flow in abandoned boreholes. The aquifers of the Gorham Oilfield are next discussed.

Aquifers in the Gorham Oilfield. Aquifers in the Gorham Oilfield are illustrated on Cross Section I-J, Figure 34, by the letter "W" plotted in the position where water was reported in holes drilled with cable tools, or by a solid dot indicating oil. The aquifers are also shown graphically in Figure 35, in which the sea level position of the lower limit of the aquifer is plotted as though it were the bottom of a well. Dotted shading indicates the static fluid level for each reservoir for the fluid contained in the reservoir. For reservoirs 1 and 2, which are fresh water aquifers, the level shown is the potentiometric surface. For reservoirs 3 to 10, which are brine-bearing, the potentiometric surface, or height of an equivalent column of fresh water, will be somewhat higher or more shallow. General statements which can be made concerning significant relationships shown graphically in Figure 35 include:

a. Aquifers 1-4 inclusive, if interconnected, would flow from one to the other in numerical sequence with Aquifers 1 and 2, which are fresh-water-bearing, flowing into Aquifers 3 and/or 4, which contain brines undersaturated as to chlorides;
b. All aquifers above the salt, 1-4 inclusive, if connected with any one or all the aquifers below the salt, for example by a well bore, will flow into the lower aquifers because of a "head" difference of 700 feet or more, and in so flowing can dissolve salt;
c. All aquifers below the salt, 5-10 inclusive, are brine-bearing "salifers," but with brines undersaturated as to chlorides and in their original virgin pressure condition, had static fillup levels higher than the salt section, hence were capable, for example, of flooding a hypothetical underground salt mine;

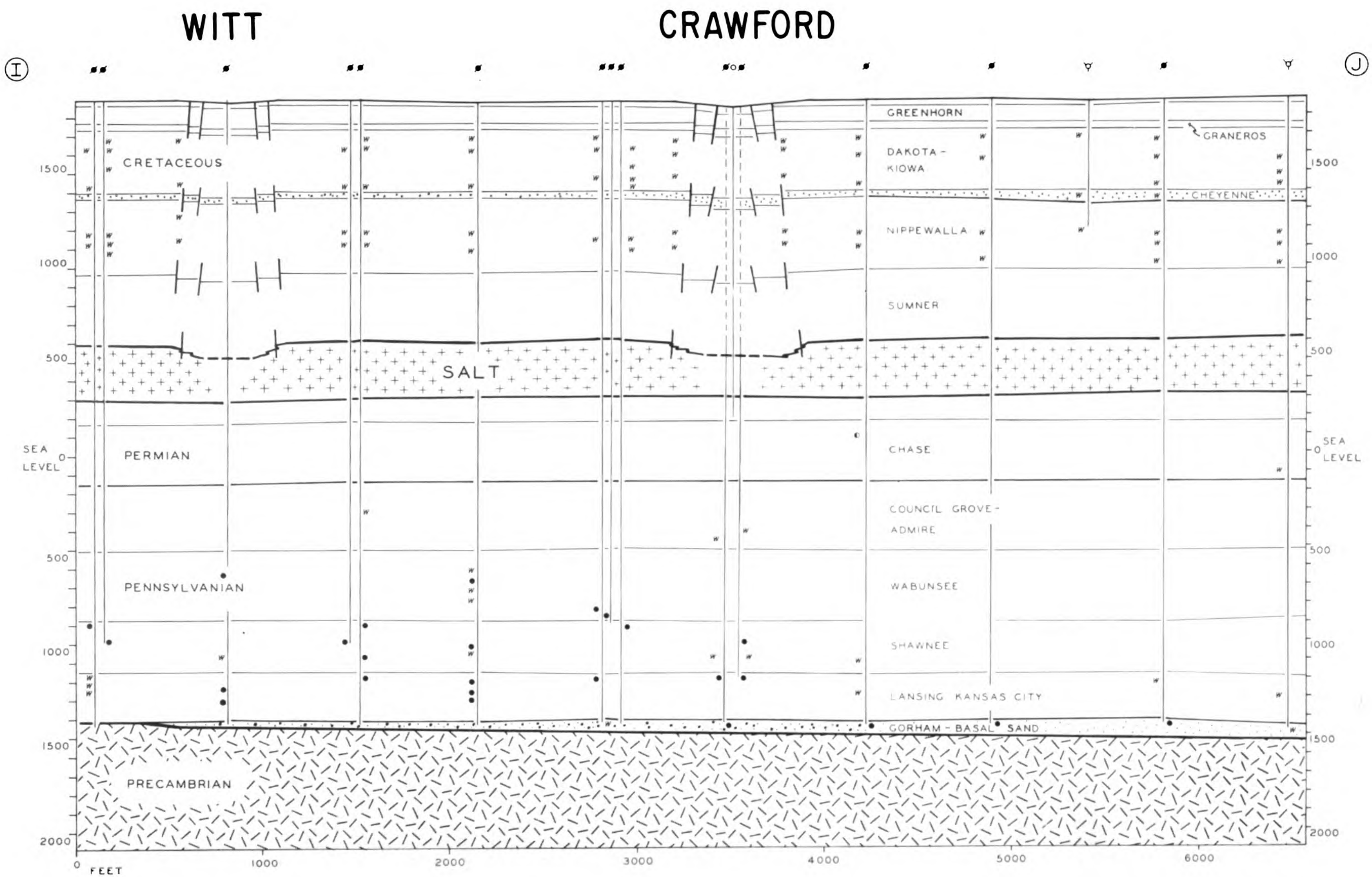


FIGURE 34.—Cross-Section I-J, through the Witt and Crawford Sinks, Gorham Oilfield. Natural scale, no vertical exaggeration. Length of section depicted, 6500 feet.

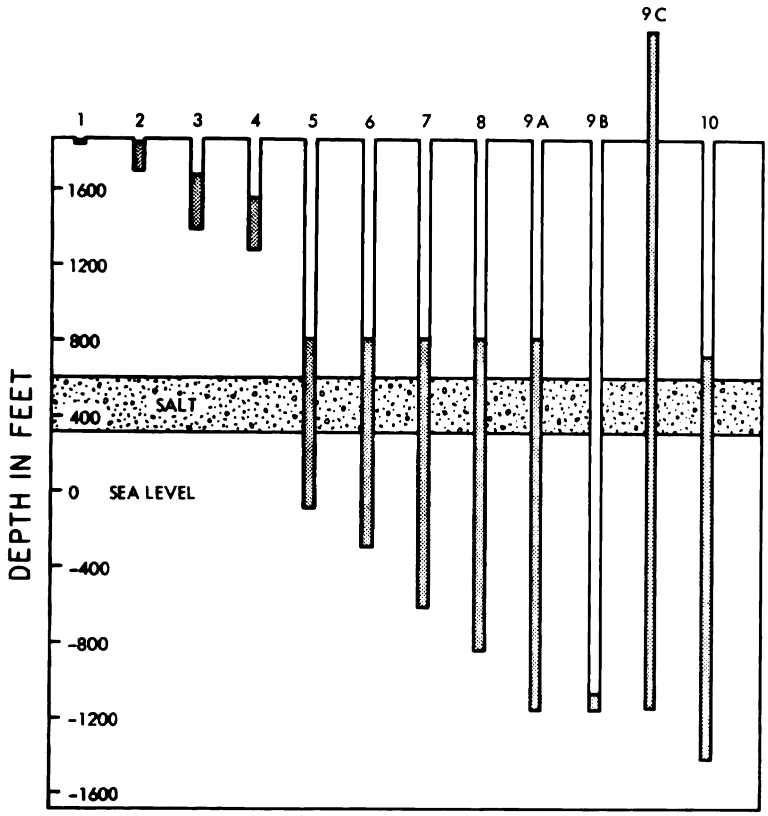


FIGURE 35.—Static fluid level in Aquifers 1 to 10 of Table 4, and Cross Section I-J, Fig. 34, Gorham Oilfield. Each column depicts a hypothetical well with casing bottomed in an individual aquifer.

d. All aquifers below the salt, 5-10 inclusive (except 9-C), if interconnected with each other in any combination, for example by a well bore, will flow from one to another until pressures are equalized, but there will be no flow across the salt section, hence no salt dissolved.

Note that these general statements, which are fundamental principles, can be made without naming the aquifers and without specific figures other than the depths graphed with their implied pressure relationships. The aquifers are summarized in Table 4.

History of brine disposal—Gorham Oilfield. Throughout the 50-year history of the Gorham Oilfield, there have been many changes in the method of handling oilfield brines produced with the oil. During the 1920s and early 1930s, there were no regulations and it was accepted practice to store brine in surface pits. Ultimately the brine either evaporated or seeped into the soil or alluvium, and eventually made its way into the shallow fresh water aquifers, or else washed into the surface stream drainage during storms which eroded out the earthern embankments. Pits continued to be used into the early 1950s, by which time many of the Basal Sandstone oil wells were producing 90 percent salt water in amounts exceeding 100 barrels of water per day per well. Such pits are abundantly visible on 1938 and 1951 photographs studied. This disposal method was beneficial from the point of view of salt dissolution as no dissolution occurred, even though it was most deleterious as regards surface runoff water and the shallow fresh water aquifers.

In 1941, the Kansas Geological Survey conducted a study of oilfield brine disposed in the Gorham Oilfield, and in adjacent parts of Russell and Ellis Counties. Test holes were drilled and water samples collected. This study (Frye and Brazil, 1943) was interrupted before completion, but official approval was given by the Kansas Corporation Commission for disposal of oilfield brines in shallow brine-bearing aquifers, the Cheyenne sandstones (No. 3 of Fig. 35), and the Cedar Hills Sandstone Member of the Permian Nippewalla Group (No. 4 of Fig. 35), at depths near 500 to 800 feet. Frye and Brazil mapped 22 such wells within the present Gorham Oilfield of which four, mapped in Fig. 33 (indicated as "SWD"), affected the Witt and Crawford Sinks. Operations were not always discriminating as to the shallow sandstones used, and it is in this period that the chloride count in the Dakota reached 7,655 ppm, Table 4, as compared with 303 ppm chlorides in non-oilfield areas. This period was disastrous as regards the integrity of the salt. The over-pressured aquifers above the salt transmitted brine laterally for distances of 1500 feet or more to available well bores in oil wells with uncemented casing, or to abandoned oil wells plugged only in the surface pipe (200 to 400 feet). This is the period of initiation of the dissolution of salt beneath the Witt and Crawford Sinks. Nearly all of the shallow disposal wells were abandoned prior to the March 1, 1967 change of regulations, because of the impracticability of operating such shallow wells. Some were redrilled twice because of plugging off at the sand face, leaving three holes, often unplugged, at one location. In short, such wells did not do the job of brine disposal.

Disposing of large quantities of brine produced from Basal Sand wells flanking the Precambrian granite high in the older portion of the Gorham Oilfield was particularly difficult because no Arbuckle dolomite was present in which deep disposal wells could

TABLE 4.—Data: Aquifers, Gorham Oilfield.

Fig. 35 Number	Name	Depth	Depth in feet down to static level	Chlorides in ppm	Total Dissolved Solids (Sp.Gr.)	Remarks
1	Surface runoff and alluvium	0-10′	0	0	0	....
2	CRETACEOUS Dakota-Kiowa Sandstones	175-400′	0	303 7,655	1,041 16,652	Average 4 analyses non-oilfield areas Russell County. Average 4 test holes Gorham Oilfield. Data: Frye and Brazil (1943).
3	CRETACEOUS Cheyenne Sandstone	475-515′	200	16,059	26,000± (Sp.Gr. 1.021)	Used for shallow SWD in 1940s. Contaminated and repressured.
4	PERMIAN Nippewalla Group	515-900′	300	....	....	No analyses available. "Highly mineralized water" (Frye and Brazil, 1943).
5	PERMIAN Chase Group	1700-2000′	Not known	....	....	No analyses.
6	PERMIAN Council Grove and Admire Groups	2000-2350′	Not known	102,016	170,955 (Sp.Gr. 1.117)	Average of two analyses from adjacent Hall-Gurney Oilfield.
7	PENNSYLVANIAN Wabaunsee Group	2350-2700′	Not known	100,930	181,186 (Sp.Gr. 1.111)	Average of 21 analyses from Russell County. None in Gorham Oilfield.
8	PENNSYLVANIAN Shawnee Group	2700-3000′	700	99,502	162,915 (Sp.Gr. 1.107)	Average of seven analyses, six from Gorham Oilfield.
9-A	PENNSYLVANIAN Lansing-Kansas City Group	3000-3300′	700	68,948	132,498 (Sp.Gr. 1.075)	Average of ten analyses from Gorham Oilfield.
9-B	PENNSYLVANIAN Lansing-Kansas City Group	....	3,000	....	....	Depleted condition of oil reservoirs, 1940s.
9-C	PENNSYLVANIAN Lansing-Kansas City Group	....	Up	....	....	600 psi surface pressure, secondary recovery waterflood.
10	ORDOVICIAN AND CAMBRIAN ARBUCKLE DOLOMITE AND BASAL SANDSTONE	3300-3700′	900	26,200	44,793 (Sp.Gr. 1.030)	Chlorides, average of 30 analyses, from Gorham Oilfield.

be completed. During the past 15 years, two extensive oilfield brine-gathering systems were constructed each with a pipeline three miles long to two Arbuckle disposal wells in Section 22, Township 14 South, Range 15 West. Many other Arbuckle disposal wells are also in use. There are no unlined surface brine ponds and no shallow disposal wells licensed for use in the Gorham Oilfield at present (1976). Water produced in secondary recovery waterflood projects is recycled.

History of well plugging. To understand the relationship of the Hutchinson Salt to the aquifers in their present condition, it is necessary to briefly review the history of plugging (or nonplugging) of wells in the Gorham Oilfield. Until 1930, there was no supervision, no regulation, and essentially no hole plugging, just abandonment with the salvage removal of all casing which could be pulled, tossing of available junk in the hole, and use of a fence post or concrete rig corner block as a surface plug. From 1930 to 1935, there was minimal regulation by the county. The first systematic plugging records date from 1935 when the state used county employees for plugging supervision on a fee basis. From 1941 to January 1, 1966, the State Corporation Commission, the regulatory agency, had salaried field plugging supervisors, but still the only plugging requirement, even in these years, was to protect zones of fresh water, defined as zero to 500 ppm chlorides. From January 1, 1966 to March 1, 1967, for the first time a cement plug was required opposite the depleted oil producing zone. At this time, too, "usable water" (500 to 5,000 ppm) was first recognized in plugging requirements. From March 1, 1967 to May 22, 1969, surface pipe regulations to protect fresh and usable water were revised more stringently and in addition, for the first time, it was required that any hole, not just oil and gas test holes, penetrating a salt water formation (over 5,000 ppm chlorides) be plugged so as to prevent migration of salt water into fresh or usable water zones. Previously exempt from plugging regulations were stratigraphic tests, structural core holes, seismic drill holes, salt test holes, water wells, etc.

This brief review shows that only in very recent years has there been any requirement for hole plugging beyond the minimum of protecting shallow fresh and usable water zones. The history of well plugging in the 50-year old Gorham Oilfield is more truly a history of nonplugging.

Present status, aquifers, Gorham Oilfield. The complications introduced by well plugging, or lack of plugging, and by the varied salt water disposal practices, has messed up the aquifers within the Gorham Oilfield to the extent that it is difficult to decipher pressure relationships and zone interconnections. It is also difficult to characterize the chemistry of the individual waters because they have been so badly mixed. Such mixed waters can be particularly corrosive. An example of rapid corrosion is the State Highway Commission test well in the Crawford Sink area in which new 4½-inch casing leaked from corrosion in 18 months. With this background, the ten aquifers, or aquifer zones, recognized in Figure 35, and summarized in Table 4, are discussed as regards their relationship to the Hutchinson Salt in the Gorham Oilfield.

Aquifer 1, **surface runoff water,** is thought to be an important source of fresh water causing salt dissolution in the Witt Sinkhole.

Aquifer 2, the **Dakota-Kiowa** sandstones of Cretaceous age, is an excellent aquifer zone, depth range 175 to 400 feet, and there is no doubt that these sandstones were originally fresh-water-bearing within the Gorham Oilfield. They were never legally utilized for salt water disposal, but there was a prolonged period of use of extensive surface salt water ponds, evident on the 1938 and 1951 vertical air photographs examined, during which contamination of fresh-water-bearing aquifers did occur. Comparison of the two sets of water analyses in Table 4 shows the influence of oilfield operations. In all oil test holes, the Dakota-Kiowa sandstones are "protected" by surface casing. Even the older cable tool holes had 350 to 400 feet of casing through these rocks because of the physical impossibility of efficiently drilling deeper with a hole full of water. The Dakota-Kiowa sandstone aquifer, therefore, does not usually have much effect on salt dissolution.

Aquifer 3, the **Cheyenne Sandstone,** Cretaceous age, depths near 500 feet, thickens from a zero wedge edge east of the Gorham Oilfield in central Russell County to 60 feet within the oilfield limits. This evenly bedded marine sandstone formation apparently has always been brine-bearing, but because of its extensive use in the 1940s as a shallow disposal zone, it is difficult to get a water analysis that is representative. Although the average of five analyses is 16,059 ppm chlorides, the range is from 4,920 to 34,916 ppm chlorides. Information from fluid level measurements in the State Highway Commission's test well in the Crawford Sink indicates a 1967 static level near 200 feet from the surface for the Cheyenne aquifer. Of greatest significance is the presence of an excellent aquifer at shallow depth above the salt, with excess pressure, good permeability, and contained water quite capable of dissolving salt. Note, too, that waste oilfield brines injected into this aquifer for disposal from 1940 to 1961 were all unsaturated as to NaCl.

Aquifer 4, the Permian redbeds of the **Nippewalla** are water-bearing, particularly in the uppermost 80 feet where the Cedar Hills Sandstone Member is developed. This member thins to zero east of the Gorham Oilfield, but thickens appreciably to the west and northwest. Where Cheyenne Sandstone rests directly on Cedar Hills Sandstone, as in the State Highway Commission's test well, the two are difficult to distinguish in modern rotary drilling and on gamma-neutron logs. They were easily distinguished by the cable tool drillers as in the Crawford No. 12 and No. 16 twin wells, depths 515 and 510 feet, by the brownish-red color of the Permian sandstone. Sufficient water was encountered from this zone to require setting 15½-inch casing at 599 feet and 598 feet in these two holes. No analyses are available for the water in the Nippewalla aquifer in the Gorham Oilfield, but Frye and Brazil (1943) state that, "highly mineralized water has been encountered." The static water level of this aquifer was near 300 feet in the State Highway Commission's well after the 4½-inch casing leaked, from March 6, 1969 to July 22, 1970, when the casing broke and hung loose. Because of the skimpy information available concerning the Nippewalla aquifer, before, during, and after its use as a shallow disposal zone, its role in salt dissolution is difficult to assess, but as an aquifer above the salt, it has potential for salt dissolution by gravity flow down old unplugged well bores.

The **Sumner Group** is not an aquifer; it is an aquitard. The top of this 800-foot thick group is marked by the Stone Corral Anhydrite encountered near 900 feet. Below the 40-foot anhydrite members are about 300 feet of impervious shaly silty redbeds above the 300-foot thick Hutchinson Salt Member, below which occur highly impervious anhydrites and interbedded red clay shales with a thickness of about 150 feet. The Hutchinson Salt Member has survived for 200 million years since mid-Permian time because it was so securely wrapped in a protective envelope of these aquitard redbeds. Only with the breaching of this protective cover in the past 50 years in the Gorham Oilfield by the 1600 oil and gas test holes (average density, 36 holes per square mile, with 10 holes in the least drilled square mile) has water been able to intrude into this impermeable aquitard to dissolve salt.

It is noteworthy that all of the aquifers below the Sumner Group, from the Chase Group, next below, to and including cracks in the Precambrian granite, depth near 3350 feet, are in some area of the Gorham Oilfield an oil or gas reservoir, indicating general saturation of the anticline with hydrocarbons and upward leakage probably through fracture systems such as that known in the Topeka Limestone, Shawnee Group. None of the aquifers above the Chase Group have any hydrocarbon "shows" testifying again to the imperviousness of the Sumner Group redbeds and salt as an aquitard, serving as a seal inhibiting fluid movement, either up or down, of hydrocarbons, or water.

Aquifers below the Sumner Group relate to the Hutchinson Salt principally by their presence as porous zones into which fluids from aquifers above the salt might drain by gravity flow if interconnected. Several of these aquifers are similar as indicated in Figure 35 and Table 4. They include: **Chase, Council Grove-Admire, Wabaunsee, and Shawnee Groups.** Note the inferred common pressures (Fig. 35) and similar chemical analyses, Table 4, with about 100,000 ppm chlorides.

In Aquifer 9, the **Lansing-Kansas City Group**, the brines have about twice the salinity of the underlying Arbuckle-Basal Sandstone Group, and about one-half the salinity of the more shallow Pennsylvanian and Permian aquifers. It is interesting and probably significant that in spite of the differences in chlorides, total solids, and specific gravity, the brines in the Lansing-Kansas City in their original reservoir condition appear to have been in pressure equilibrium with the shallower brines. This is illustrated in Figure 35, where Aquifers 5, 6, 7, and 8 are shown as having the same static fluid level as Aquifer 9-A, all about 700 feet below the surface of the ground. Column 9-A pertains to the original condition of the Lansing-Kansas City aquifer. During the 50 years that oil has been produced from these limestones, fluid conditions have varied widely. During the 1940s in many portions of the oilfield, and specifically in the older area near the town of Gorham, bottom hole pressures were depleted to near-zero condition as indicated by column 9-B of Figure 35. During the 1960s and 1970s, secondary recovery by waterflood employed water from a Cheyenne sandstone supply well which was injected into the producing Lansing-Kansas City zones at 600 psi wellhead pressure. This is a bottom hole pressure of over 1900 psi as is suggested diagrammatically in column 9-C, Figure 35. The example shown by columns 9-A, 9-B, and 9-C emphasizes that the static fluid level of an aquifer or reservoir varies, and cannot be adequately described without a qualification as to time of measurement.

Aquifer 10, the **Arbuckle Dolomite**, is an aquifer of enormous capacity. The author considers the entire area of the Arbuckle Dolomite and Basal Sandstone within the Gorham Oilfield to be a single reservoir (aquifer) with an original oil-water contact near subsea −1450 feet. This broad picture fits with the concept of long distance migration of oil and gas and differential entrapment (Walters, 1958).

The truncated beds of the Ordovician and Cambrian Arbuckle Dolomite and Basal Sandstone are bounded on the lower side by the Precambrian basement rocks, and on the upper side by the sub-Pennsylvanian unconformity, a former land surface. Porosity and permeability were greatly enhanced by subaerial weathering in Pennsylvanian time with accompanying increase in carbonate porosity by partial dissolution. Inherited from the long exposure on a karst peneplain are the present dilute brines of this great common aquifer. The brines averaging 26,100 ppm chlorides are far less saline than those in shallower aquifers (Table 4) presumably because of dilution by and mixing with ancient rainwater. Pennsylvanian clays and limestones unconformably overlying the truncated Arbuckle beds acted as aquitards confining highly mobile hydrocarbons within the Arbuckle for about 250 million years since mid-Permian time.

The capacity of the Arbuckle Dolomite reservoir to either yield or receive fluid is so great as to often be limited by mechanical constraints such as size of casing, tubing, or pump. Three wells (January 1, 1975) with 3-inch tubing were each pumping 900 barrels of fluid per day and one well was regularly pumping 2000 barrels of fluid per day with a bottom hole Reda pump, or 58 gallons per minute from a depth of 3300 feet. The brine from these and other wells flows into an Arbuckle disposal well which has disposed up to 10,000 barrels of water per day, or about 300 gallons per minute, by gravity flow day and night for more than ten years without trouble or repairs. The principal role of this aquifer as regards salt dissolution within the Gorham Oilfield is that it served, and still serves, as an outlet or "sewer" of almost limitless capacity for receiving brines moved downward by gravity whether controlled within the casing of salt water disposal wells or uncontrolled through boreholes left unplugged below surface casing.

SURFACE SUBSIDENCE AREAS—GORHAM OILFIELD

History of investigation. In July 1970, Wallace K. Taylor, Regional Geologist, and Virgil A. Burgat, Chief Geologist, State Highway Commission of Kansas (renamed Kansas Department of Transportation, August 15, 1975), submitted an intradepartmental report, "Sinking Ground Along Interstate Highway 70 West of Russell, Kansas." An abstract of their report was published by Burgat and Taylor (1972). S. W. Fader (1975) published in redrafted and simplified form two maps and two cross sections from the Taylor and Burgat report. Using their data, he made theoretical calculations as to the amount and rate of salt dissolution at the two localities, and concluded that a flow rate of three to four gallons per minute across the salt face for 30 years would suffice to cause the measured subsidence.

Burgat and Taylor named the eastern area of sinking ground the "Crawford Sink," and the western location the "Witt Sink," using names originally given to the abandoned oil wells in the sink areas. The Crawford Sink surrounds abandoned twin oil wells 50 feet apart, Crawford No. 16 and Crawford No. 12, in the center of the NW/4 NW/4 SW/4 of Section 2, Township 14 South, Range 15 West. The wells are 175 feet and 165 feet south of the hub of the highway. In August 1967, they supervised the drilling of the Highway Commission's test hole (location indicated by an open circle in Figures 33 and 34), 155 feet south of the highway hub, between these abandoned wells. Maximum subsidence occurs at the wells and totals more than 26 feet in 1976, affecting approximately 1000 feet of the highway lanes. The Witt Sink developed around the Witt No. 1 oil well, abandoned and plugged in 1957, located one-half mile west in the center of the NW/4 NW/4 SE/4 of Section 3, Township 14 South, Range 15 West, 180 feet south of the hub of the highway. Maximum subsidence is at the well site and totaled about 17 feet in 1976. Subsidence affects about 750 feet of the highway lanes. Sinking is thought to have commenced shortly after the well was abandoned in 1957, and is still continuing.

A chronology of events concerning Interstate Highway 70 and these twin subsidence areas includes:

1938 Aerial photograph. Crawford lease, 15 oil wells. Witt lease, 15 oil wells. Many brine ponds, but no evidence of subsidence.

1951 Aerial photograph. Witt No. 1 producing oil. Crawford Sink wells abandoned (plugged in 1941 and 1945). No indication of subsidence.

1957 Aerial photograph. Pond 400 feet by 200 feet at Crawford location, indicating subsidence. Witt No. 1 oil well visible, but no evidence of subsidence.

1965-1966 Highway constructed. "Neither the existence of these wells nor the sinking ground was discovered until the highway was near completion" (Burgat, personal communication, October 1, 1975).

1967 Highway Commission test hole (Crawford) drilled in August, as part of geological investigation of sinking ground.

1970 Taylor and Burgat report submitted in July.

1971 Highway rebuilt in summer months at a cost of about $250,000 after subsiding 4.0 feet (Witt area), and 3.50 feet (Crawford area).

1976 To January 15, 1976, the subsidence of the rebuilt highway totals 3.35 feet (Witt), and 2.85 feet (Crawford). Bridge No. 3.99 (Crawford) undergoing differential settlement. Subsidence continuing at rate of one-half foot per year at points on the highway closest to the abandoned oil wells.

No other subsidence areas are known in the Gorham Oilfield. It is recognized that in this agricultural region other areas of subsidence of one or two feet, if not affecting a carefully surveyed highway, might go unnoticed unless water standing in a low spot interferred with farming.

Direct evidence of dissolution of salt. The Crawford Sink is unique in that several observations provide direct evidence of dissolution of the salt section, depth from 1293 to 1533 feet in the Highway Commission's observation well. The most conclusive data consists of measurements not included in the Taylor and Burgat reports, but preserved in their photographs, well logs, and files, all of which they considerately made available to the author. Figure 36 is a sketch from their photograph of the wellhead of the State Highway Commission of Kansas' test well at the Crawford Sink. When photographed in June 1969, the downward subsidence of the 8⅝-inch casing relative to the 4½-inch casing was 7.43 inches in 461 days, or a subsidence rate of about one-half foot per year. Most important is the fact that the subsidence is bracketed as occurring within and above the salt section. This is because the 4½-inch casing was set at 1638 feet and cemented to 1372 feet, hence securely anchored to the rocks below and within the lower salt section. The 4½-inch casing, completely free above the top of the cement, was under compression due to gravity. The 8⅝-inch surface casing was set at 447 feet with cement circulated to the surface, hence was securely bonded to the near-surface rocks above the salt section. Because of evident strain, the 4½-inch casing formerly welded to the 8⅝-inch casing was cut loose on March 26, 1968, at which time it jumped up one-half inch. The 4½-inch casing protruded further above the 8⅝-inch casing with the passage of time. Measurements were made every few months, and recorded for over a year during which time the casing continued to protrude at a rate measured at about one-half of an inch per month. On May 5, 1970, it was found that the 4½-inch casing was broken near 990 feet with the fluid level inside the casing at 291 feet, the static level of the Permian Cedar Hills aquifer. On July 22, 1970, the 4½-inch casing could be probed only to 947 feet. It had dropped and was hanging in the hole supported by the clamp. The 4½-inch casing was again welded to the 8⅝-inch casing. On July 14, 1971, the 4½-inch casing could be probed only to 470 feet, indicating another break, and the fluid level both inside and outside the

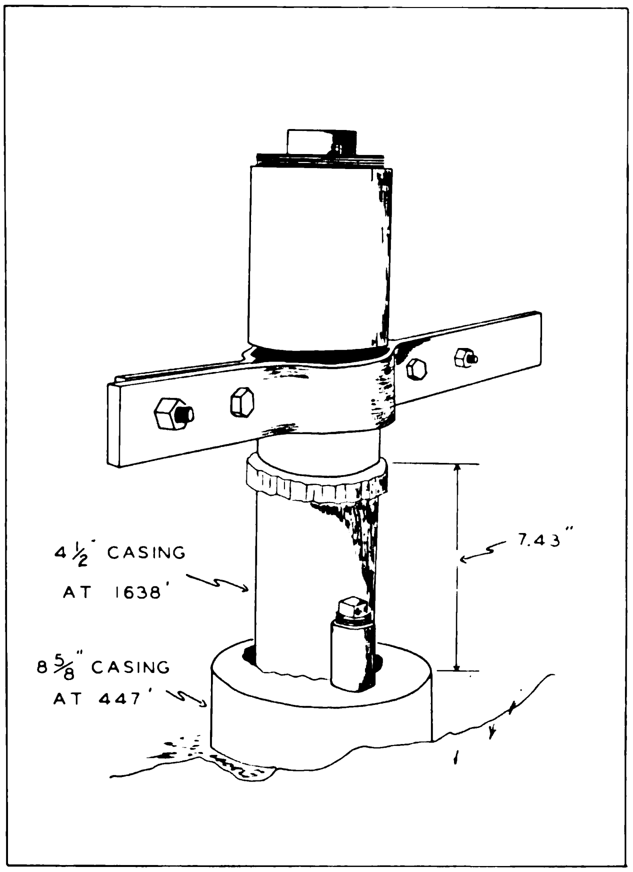


FIGURE 36.—Wellhead equipment, State Highway Commission of Kansas test hole, Crawford Sink. Sketch made from their photograph taken in June 1969.

casing was at 233 feet, the static level of the Cretaceous Cheyenne Sandstone brine aquifer.

The 4½-inch casing, originally dry, first leaked March 6, 1969 due to corrosion and/or settling after only one and one-half years of service. Static fluid level inside the casing was then at 296 feet. The first actual casing break near 950 feet, or stratigraphically opposite the Stone Corral Anhydrite, is thought to be due to slumping of a huge block of the massive anhydrite, shearing the casing. The last break near 470 feet opposite the Cheyenne Sandstone is thought to be due to corrosion from mixed waters formerly injected into that reservoir plus gravity adjustment in a salt dissolution subsidence area.

This direct evidence from the Highway Commission's observation test hole of subsidence specifically due to salt dissolution is confirmed by several other observations made by Taylor and Burgat including:

1. The sudden drop of the bit for seven feet upon entering the void or cavern at 930-foot depth just above the top of the Stone Corral Anhydrite during the drilling of the Highway Commission's test hole.
2. The lowering of the Stone Corral Anhydrite by removal of supporting material below the Stone Corral, as shown by comparative well logs.
3. Lost circulation, or the complete and irrecoverable loss of fluid returns during drilling with rotary tools from the depth of 540 feet to 1670 feet total depth.
4. Cementing of casing—when 4½-inch casing was cemented near 1670 feet, it was desired to fill the hole with cement to the surface; calculations of double the volume of the drilled hole were used in ordering cement, yet the top of the cement reached only to 1372 feet, or stratigraphically within the salt section, coinciding with the base of a fast drilling zone from 1320 to 1380 feet.

In 1967, when the Highway Commission's test well was drilled, the near-surface Fence Post Limestone (slumped depth 46 feet) had subsided 19 feet. From the gamma-neutron log recorded August 30, 1967 (0.5 feet above the casinghead; elevation 1861.55 feet on September 8, 1967) as compared with the drillers' logs of the Crawford No. 12, drilled December 1936, and the Crawford No. 16 twin well, drilled in June 1937, it may be determined that there was then 28 feet of subsidence on the top of the Permian redbeds, Nippewalla Group, depth 538 feet; 38 feet of subsidence on the Permian Stone Corral Anhydrite, depth 938 feet (marks the top of the Sumner Group, Cross Section I-J, Fig. 34); and about the same amount on the top of the salt encountered near 1300 feet. The twin Crawford wells are 50 feet apart, with the Highway Commission test hole between them. This increase in amount of subsidence is additional evidence for salt dissolution as the cause of subsidence.

Evidence for solution of salt by other than surface water. The earliest sign of localized subsidence of the Crawford Sink was the "ponding" of an intermittent stream recorded in vertical aerial photographs taken in 1957. The area of the pond was about three acres on April 2, 1963. The highway was constructed in 1965-1966. The very presence of ponded fresh water infers lack of downward connection with the salt section.

During exploratory drilling for shallow mapping of the structure of the subsidence area, it was found that a test hole 150 feet from the proposed location of the Highway Commission's deep test hole had flowing fresh water in the upper Dakota Sandstones at a depth of approximately 200 feet. A water well was completed and used for the rotary drilling of the Highway Commission's test hole to a depth of 550 feet, or stratigraphically to just below the Cheyenne Sandstone, at which depth circulation was suddenly lost, never to be regained during drilling operations, indicating a connection with the void area (presumably salt section void) below. At that time, the water well suddenly went dry. In the test hole itself, water could be heard falling. To complete the drilling of the Highway Commission's test hole, it was necessary to drill "blind" which is without return circulation. All available water trucks, fifteen, were utilized in hauling water for drilling fluid. They hauled 14,685 barrels (616,770 gallons) of fresh water. The history of these two holes provides evidence, therefore, that the surface water pond at the Crawford Sink and the fresh water in the Dakota Sandstone water well, near 200-foot depth, are part of a perched water table separated from the salt section by shale beds from 225 feet to 296 feet in depth. It is concluded that very little, if any, of the extensive salt solution resulting in collapse and development of the surface sink area and highway subsidence is due to surface water.

Source of water dissolving salt. The Cretaceous Cheyenne Sandstone, depth 496 to 568 feet, in the Highway Commission's test hole is a source for water undersaturated as to sodium chloride capable of dissolving large quantities of salt and corroding casing. Likewise, the Permian Cedar Hills Sandstone, Nippewalla Group, encountered within the interval from 568 to 938 feet, is an excellent aquifer. Both zones were utilized for salt water disposal in the closest shallow disposal well, shown in Figures 33 and 34 as 1500 feet southeast of the Crawford Sink. This shallow disposal well, total depth 665 feet with 8-inch casing set at 443 feet, was in use for many years after its completion in September 1936. Another shallow disposal well is known to have been present 1500 feet northeast of the Crawford Sink, and a third shallow salt water disposal well is located in the S/2 of Section 3, 3000 feet southwest of the Crawford Sink, and 1300 feet south of the Witt Sink, as mapped in Figure 33 by the symbol for "SWD." One such shallow disposal well in Section 1, about 8000 feet east of the Crawford Sink, was still in use January 1, 1975. Large quantities of salt water were introduced into both the Cheyenne and Cedar Hills formations under more than static pressure, so that the sandstones were thoroughly charged with a mixture of their native water and brine from Kansas City limestones and/or from the Basal Sandstone. Such mixed waters are commonly corrosive and may themselves have been the cause of casing corrosion leading to leakage in the Crawford No. 12, Crawford No. 16, Witt No. 1, and in the Highway Commission's test hole.

It is concluded that the principal source of the water which dissolved salt under the Crawford and Witt Sinks was oilfield brine disposed in shallow disposal wells in the vicinity. With the abandonment of the shallow salt water disposal wells and with the passage of time, excess pressure on the Cheyenne and Cedar Hills sandstones appears to have been relieved by downward drainage through such holes as the Crawford and Witt holes under discussion. Evidence of this is provided by the fluid levels measured in the Highway Commission's test hole in 1967 at which time the static level of the Cheyenne aquifer was near 200 feet, and the static level of the Cedar Hills Sandstone aquifer was near 300 feet. Subsidence is continuing, but at a declining rate.

Present status, Crawford Sink. The Crawford Sink area is a "prairie pothole" pond about five acres in size, with marshy conditions, cattail vegetation, and (Spring 1974) a pair of nesting Canvasback ducks. Most of the oil wells are abandoned, as mapped in Figure 33 which shows well status on January 1, 1975. The SW/4 of Section 2, on which the sink is located, has been returned to agriculture, and there is no surface evidence other than the subsidence area and pond to show for nearly 50 years of oil activity. The bridge on the section line road between Sections 2 and 3 over Interstate Highway 70 has settled differentially two feet on the nearest (southeast) abutment, and is under torque stress. The wellhead equipment for the Highway Commission's test hole, illustrated in Figure 36, is under water. Subsidence affecting both lanes of Interstate Highway 70 and the section line bridge is continuing, but at a diminishing rate. Table 5 shows the maximum highway subsidence in feet for the period from highway construction in 1966 to the time of rebuilding the highway in the summer of 1971, and compares the pre-1971 subsidence with that occurring after rebuilding the highway. Subsidence affecting the eastbound lane at both sinks since the highway was rebuilt is shown graphically in Figure 37.

Present status, Witt Sink. The Witt Sink, one-half mile west of the Crawford Sink, is smaller, less conspicuous, and not as thoroughly studied. A closed sinkhole depression (Fig. 33) has developed around the Witt No. 1 abandoned oil well located a few feet south of the highway fence. A steep gully leads from the highway directly to the sunken well bore of the abandoned well. Subsidence has caused rainwater to run directly from the highway into the well bore which acts as a storm sewer. It is reported that during heavy rains, a temporary pond forms. This unplanned method of draining a small area of Interstate Highway 70 is a factor affecting the rate of subsidence in this sink. The maximum measured rate of about one foot per year for the eastbound lane occurred in 1973. Subsidence since has diminished to about one-half foot per year, as listed in Table 5 and illustrated on Figure 37.

It is thought that the principal cause of salt dissolution was the former use of shallow disposal wells within 1500 feet of the Witt Sink. Surface water intake directly into the abandoned well bore is considered a secondary contributing factor. It is not understood exactly why and how the well bore takes fluid, as the official well plugging report filed with the

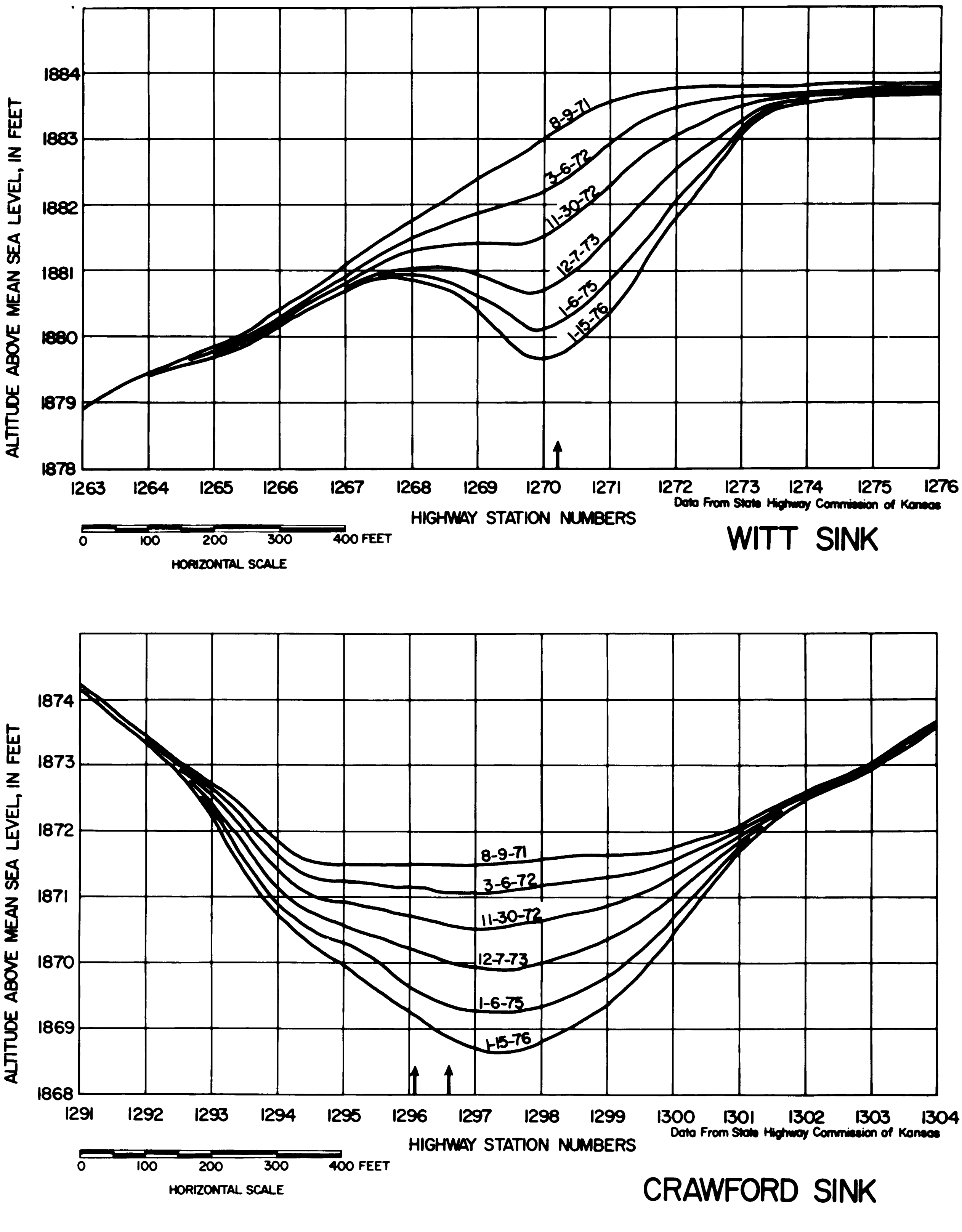


FIGURE 37.—Subsidence in feet of eastbound lane of Interstate Highway 70, 1971-1976. Arrows indicate positions of abandoned oil wells about 150 feet south of highway.

TABLE 5.—Subsidence: U.S. Interstate Highway 70, Russell County, Kansas.

Maximum Subsidence in Feet	Time in Days	Ending Date	Rate of Subsidence in Feet Per Year
CRAWFORD-WESTBOUND LANE			
1.85	......	1-26-70	....
0.75	476	5-17-71	0.575
2.60			
1.20	863	12-20-73	0.507
0.85	756	1-15-76	0.410
2.05			
CRAWFORD—EASTBOUND LANE			
2.40	......	1-26-70	....
1.10	476	5-17-71	0.844
3.50			
1.60	850	12-7-73	0.687
1.25	769	1-15-76	0.593
2.85			
WITT—WESTBOUND LANE			
3.15	1670	5-17-71	0.688
3.15			
2.00	850	12-7-73	0.859
0.80	769	1-15-76	0.380
2.80			
WITT—EASTBOUND LANE			
4.00	1670	5-17-71	0.874
4.00			
2.30	850	12-7-73	0.988
1.05	769	1-15-76	0.498
3.35			

Notes: Highway constructed in 1965-1966.
Highway rebuilt through sink areas, summer 1971.

Kansas Corporation Commission shows both 7-inch and 5½-inch casing left in the hole, with a total of 200 sacks of cement used in plugging both the hole and the annular space between the two casing strings.

The present status of the Witt Sink is that it is a problem area for the Department of Transportation. Continuing subsidence enlarges the sinkhole area, and increases the internal storm water drainage down the well bore of the abandoned Witt No. 1.

CONCLUSIONS

This report summarizes results of an extensive search for examples of land subsidence in central Kansas associated with rock salt dissolution caused by man's activities in exploring for and producing natural resources—oil, gas, water, salt—for nearly a century from the 1880s to 1976. As documented within the report, only 13 such areas are known, leading to the conclusion that such depressions are unusual and that the formation of a noticeable surface subsidence area is a rare event. There are only eight known subsidence areas associated with oil exploration or production, although an estimated 80,000 boreholes penetrated the Hutchinson Salt in Kansas. This is a ratio of one subsidence area for each 10,000 holes drilled through the salt. Only five documented surface subsidence areas are associated with the continuous production of salt in Kansas, largely by solution mining since 1888, or an average of one subsidence area for each 17 years of salt production.

Evidence is presented that solution of salt during modern rotary drilling using fresh water results in borehole enlargement within the salt section to about three times the diameter of the drilled hole, an amount too small to cause surface subsidence.

Evidence is also presented that solution of salt during early rotary drilling in the 1930s using fresh water resulted in borehole enlargement to five feet or more in diameter (bit size commonly nine inches) through the salt section. Gamma-neutron cased hole logs recorded years later are interpreted as indicating, opposite the lower, cleanest portion of the salt, the packing of former void space behind the casing with shale cavings. It is concluded that salt dissolution tends to be self-limiting due to caving shale in such early rotary holes. This conclusion also applies to case histories of two documented holes completed before 1935 which have no surface casing at all, and no plugging except in the cellars 10 to 17 feet below the land surface.

Ordinarily, no salt dissolution occurs after drilling ceases. This important principle is valid if shallow aquifers above the salt are adequately isolated by surface casing and/or by proper hole plugging as required by regulations of the Kansas Corporation Commission. This is the normal situation in the broad ten-county study area. The subject was investigated by a study of the ten principal aquifers, depths to 4000 feet, within the 4,000 square mile area of Russell, Lincoln, Barton, Ellsworth, and Rice Counties. These aquifers are oil reservoirs where hydrocarbon trapping conditions exist. In boreholes with properly isolated shallow aquifers above the salt, the deeper aquifers below the salt—although possessing static fillup levels higher than the top of the salt—will equalize pressure by flowing up or down the borehole from one aquifer into another without flow across the salt face, hence without dissolving the salt. This is true for all such oil and gas test holes regardless of how else the borehole is plugged, if at all. This principle accounts for the scarcity of surface subsidence areas in central Kansas due to salt dissolution.

It is further concluded that where aquifers above the salt are not isolated by casing or hole plugging, flow from them by gravity downward across the salt causes salt dissolution. This situation prevails in the

Witt and Crawford Sinks in the Gorham Oilfield. After 20 years of sinking, these two areas are still subsiding, causing damage to Interstate Highway 70.

It is also concluded that subsidence areas around former salt water disposal wells (Panning, Berscheit, Hilton) were caused by casing failure which permitted disposed brine, unsaturated as to chlorides, to circulate across the salt. In such a system, the disposed brine falls down the borehole, across the salt face, and downward into a lower permeable zone by gravity flow, accelerated by increase in brine density as salt is dissolved, but the basic energy source is provided by oil well pumping units which lift oil and brine upward. With the abandonment of the oil wells, the energy input is terminated, brine flow ends, subsidence other than that due to compaction ceases, and the areas become stable.

It is an important observation of this investigation that all surface subsidence areas in Kansas related to salt removal have a common history of slow development in a time frame of months and years, but where near-surface materials consist of water-saturated unconsolidated sands and gravels, and the underlying bedrock is breached, a surface sinkhole formed in a few hours or days.

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WILLIAMS, CHARLES C., and STANLEY W. LOHMAN, 1949, Geology and ground-water resources of a part of south-central Kansas with special reference to the Wichita municipal water supply: State Geol. Survey of Kansas, Bull. 79, 451 p.

YOUNG, C. M., 1926, Subsidence around a salt well: Am. Institute of Mining Engineers, transactions, v. 74, p. 810-817.

APPENDIX A
LIST OF LOCALITIES MAPPED IN FIGURE 3

A. Subsidence Areas Related to Mining of Salt

Morton Salt Company .... Page 16
Southwest of Hutchinson
Sec. 23, T.23S, R.6W
Reno County, Kansas

Carey Salt Company .... Page 16
Downtown Hutchinson
Sec. 13, T.23S, R.6W
Reno County, Kansas

Barton Salt Company .... Page 17
Southeastern Hutchinson
NW/4 Sec. 19, T.23S, R.5W (north of plant)
Reno County, Kansas

Cargill, Inc. .... Pages 17-25
Southeastern Hutchinson
NW/4 Sec. 19, T.23S, R.5W (south of plant)
Reno County, Kansas

Crystal Salt Mine Shaft .... Pages 27-29
Kanopolis (east edge)
Sec. 25, T.15S, R.8W
Ellsworth County, Kansas

B. Subsidence Areas Related to Oil and Gas Operations (See Table 1, p. 33)

Crawford .... Pages 68-72
Sec. 2, T. 14S, R.15W
Gorham Oilfield
Russell County, Kansas

Witt .... Pages 68, 71-73
Sec. 3, T.14S, R.15W
Gorham Oilfield
Russell County, Kansas

Hodge .... Page 33
Sec. 25, T.20S, R.6W
Welch-Bornholdt Oilfield
Rice County, Kansas

Hilton .... Pages 59-60
Sec. 6, T.20S, R.9W
Chase-Silica Oilfield
Rice County, Kansas

Berscheit Heirs .... Pages 57-59
Sec. 6, T.20S, R.10W
Chase-Silica Oilfield
Rice County, Kansas

Panning .... Pages 52-57
Sec. 2, T.20S, R.11W
Chase-Silica Oilfield
Rice County, Kansas

Pierce .... Page 32
Sec. 33, T.23S, R.4W
Burrton Oilfield
Reno County, Kansas

Lovett .... Page 32
Sec. 14, T.20S, R.4W
Groveland South Oilfield
McPherson County, Kansas

C. Salt Test Holes, Cored

	Permanent Storage of Cores	Text
The Geotechnical Corporation .... HNAS Core Hole No. 1, Sec. 29, T24S, R.5W, Reno County, Kansas, Total Depth: 734 feet (May 1958)	A,B,C,D	Pages 7, 8, 12
U.S. Atomic Energy Commission (AEC) Test Hole No. 1—Lyons, Kansas, Sec. 26, T.19S, R.8W, Rice County, Kansas, Total Depth: 1300 feet (Aug.-Oct. 1970)	B	Pages 9-12
U.S. Atomic Energy Commission (AEC) Test Hole No. 2—Lyons, Kansas, Sec. 35, T.19S, R.8W, Rice County, Kansas, Total Depth: 1215.6 feet (October 1970)	B	Page 9
Union Carbide Corporation .... AEC Test Hole No. 3, Sec. 22, T.13S, R.8W, Lincoln County, Kansas, Total Depth: 1100 feet (May-June 1972)	A	
Union Carbide Corporation .... AEC Test Hole No. 4, Sec. 9, T.11S, R.10W, Lincoln County, Kansas, Total Depth: 1275 feet (May-June 1972)	A	
Cargill Salt Company .... Brine Field Well No. H-1, Sec. 19, T.23S, R.9W, Reno County, Kansas, Total Depth: 791 feet (August 1975)	E	Page 25

Code: Repositories for permanent storage of cores:

A. Union Carbide Corporation—Nuclear Division
Oak Ridge National Laboratory
Building 9104-3
Post Office Box Y
Oak Ridge, Tennessee 37830
c/o Dr. William C. McClain

B. Kansas Geological Survey
1930 Avenue "A"—Campus West
The University of Kansas
Lawrence, Kansas 66044
c/o Dr. William W. Hambleton

C. The Geotechnical Corporation
Dallas, Texas

D. United States Geological Survey
Reston, Virginia

E. Cargill, Inc.
Post Office Box 1403
Hutchinson, Kansas 67501
c/o Donald S. Robinson, Plant Manager

D. Underground (Dry) Salt Mines

Independent Salt Company
Operating Salt Mine
Sec. 29, T.15S, R.8W
Ellsworth County, Kansas

Crystal Mine .... Pages 27-30
Abandoned Salt Mine
Sec. 30, T.15S, R.7W
Ellsworth County, Kansas (shaft cratered 1972)

Royal Mine
Abandoned (connected with Crystal Mine)
Sec. 25, T.15S, R.8W
Ellsworth County, Kansas

Little River Salt Mine .... Pages 29-30
Sec. 18, T.19S, R.6W
Abandoned Salt Mine (converted to LPG storage)
Rice County, Kansas

Carey Salt Company (Lyons) .... Page 6
Inactive; standby status
Sec. 34, T.19S, R.8W
Rice County, Kansas

American Salt Company
Operating Salt Mine
Sec. 10, T.20S, R.8W
Rice County, Kansas

Carey Salt Company .... Page 7
Operating Salt Mine
Sec. 16, T.23S, R.5W
Reno County, Kansas

Kingman Mine
Closed 1911-1912
E/2 SE/4 Sec. 19, T.27S, R.7W
Kingman County, Kansas

E. Solution Well Fields

American Salt Company
Sec. 15, T.20S, R.8W
Rice County, Kansas

Morton Salt Company .... Page 16
Sec. 22, T.23S, R.6W
Reno County, Kansas

Carey Salt Company
Sec. 17, T.23S, R.6W
Reno County, Kansas

Cargill, Inc. .... Pages 13-27
Sec. 19, T.23S, R.6W
Reno County, Kansas

Vulcan Materials Company
Sec. 20, T.29S, R.2W
Sedgwick County, Kansas

F. Liquefied Petroleum Gas (LPG) Stored in Salt Cavities

List supplied by N. W. Biegler and Ralph E. O'Connor, District Geologists, Oilfield and Environmental Geology Section, State of Kansas Department of Health and Environment, January 1976.

County and Operator	Sec-Twp-Rge Location	Storage Cavities In Use	Storage Cavities Under Construction
Ellsworth County			
Northern Natural Gas Company	30-17S-9W	101	....
Kingman County			
Phillips Petroleum Company	15-30S-7W	8	....
McPherson County			
Home Petroleum Corporation	28-19S-4W	92	....
Mid-West Underground, Inc.	29-19S-4W	29	....
National Cooperative Refinery Assoc.	29-19S-4W	80	....
Skelly Underground Storage	30-19S-4W	28	....
Mid-America Pipeline	24-19S-5W	55	....
Reno County			
Consolidated Storage, Inc.	30-22S-6W	12	21
Cities Service Oil Co.	22-23S-6W	64	....
Hillsdale Underground Storage, Inc.	28-23S-6W	13	7
Amoco Oil Company	14-24S-6W	18	....
Atlantic Richfield Company	14-24S-6W	7	....
Empire Underground Storage	14-24S-6W	0	13
Rice County			
Mid-America Pipeline	27-19S-7W	6	....
		507	41
Rice County Sentry Underground Storage Co. North Jefferson Street Kearney, Mo. 64060	18-19S-6W	1*	....

* Capacity 2,000,000 barrels. The abandoned Little River Salt Mine (pp. 29-30), depth 785 to 796 feet, area 25 acres, was converted in 1975 for propane storage.

G. Volume of Liquefied Petroleum Gas (LPG) Stored in Salt Cavities

Year	Kansas	U.S.A.
1975	52,522,000	306,332,000
1973	42,366,000	234,732,000
1971	32,979,000	167,381,000

The above figures, furnished by the Gas Processors Association, Tulsa, Oklahoma, and quoted by The Oil and Gas Journal, September 8, 1975, indicate that about 17 percent of the light hydrocarbons stored in underground leached or mined cavities in the U.S.A. is stored in central Kansas. Kansas storage capacity has increased by about 12.5 percent per year, and the U.S. capacity by about 15 percent per year. Figures in barrels (42 gals. or 5.61 cubic feet each).

APPENDIX B

LIST OF BORINGS

Oil test holes, salt test holes, and water wells used in the construction of CROSS SECTION A-B, FIGURE 2

(For map showing locations, see Figure 3)

Number	Name	Description
1	Three G Oil, Incorporated Dumler "B" #2 Elevation: 1846 KB	Section 5-13S-15W NE/4 SW/4 NW/4 Russell County, Kansas
2	Sunray DX Oil Company Polcyn #D-7 Elevation: 1850 KB	Section 14-14S-15W SE/4 NE/4 NW/4 Russell County, Kansas
3	K&P Oil Company Driscoll "A" #2 Elevation: 1768 KB	Section 4-15S-14W SE/4 NW/4 NW/4 Russell County, Kansas
4	Gulf Oil Corporation L. Hoffman #4 Elevation: 1839 KB	Section 31-15S-13W NW/4 NE/4 SW/4 Russell County, Kansas
5	Petroleum, Inc. Hitschmann "B" #1 Elevation: 1904 KB	Section 28-16S-12W SW/4 SW/4 SE/4 Barton County, Kansas
6	Alpine Oil & Royalty Co. Schlessiger #1 Elevation: 1811 KB	Section 28-17S-11W NE/4 SW/4 SE/4 Barton County, Kansas
7	Clinton Oil Company Musenberg #V-1 Elevation: 1771 KB	Section 10-19S-11W NE/4 SE/4 SE/4 Barton County, Kansas
8	Stanolind Oil & Gas Co. Panning #A-6 Elevation: 1763	Section 2-20S-11W NE/4 SE/4 SE/4 Barton County, Kansas
9	Mapco Incorporated Bernstorf #1 Elevation: 1751 KB	Section 27-19S-10W 50′ East of Center NE/4 Rice County, Kansas
10	Samson Resources Proffitt #4 Elevation: 1727 KB	Section 20-19S-9W C N/2 N/2 NW/4 Rice County, Kansas
11	Atomic Energy Commission Hole No. 1 Elevation: 1745	Section 26-19S-8W NE/4 NE/4 NW/4 Rice County, Kansas
12	Raymond Oil Company Miller No. 1 Elevation: 1689 KB	Section 7-20S-7W SE/4 SE/4 SW/4 Rice County, Kansas

Number	Name	Description
13	Cherry Drilling Co. Rose No. 1 Elevation: 1578 KB	Section 9-20S-6W NE/4 NE/4 SE/4 Rice County, Kansas
14	Cities Service Petroleum Co. Hamilton #2 LPG Storage Elevation: 1553 KB	Section 22-23S-6W 1502′ North & 970′ East of SW Corner (SE NW SW) Reno County, Kansas
15	Cargill Salt Company Well #H-1 Elevation: 1522±	Section 19-23S-5W 1000′ North of South Line, 200′ West of East Line } SW¼ App. C E/2 E/2 E/2 SW/4 Reno County, Kansas
16	Westpan Hydrocarbon Swanson #1 Elevation: 1513	Section 22-23S-5W SE/4 SE/4 NW/4 Reno County, Kansas
17	Hinkle Oil Company Van Buren #1 Elevation: 1474	Section 28-23S-4W SE/4 NE/4 SE/4 Reno County, Kansas
18	Se Ro Bee Drilling Company Evans #5-W SWD Elevation: 1461 KB	Section 36-23S-4W C W/2 NE/4 Reno County, Kansas
19	Wofford Oil Company Base #A-1 Elevation: 1456 KB	Section 31-23S-3W NW/4 NE/4 SW/4 Harvey County, Kansas
20	State Geological Survey Water Test Well #186 Elevation: 1450 (Williams & Lohman, 1949)	Section 11-23S-3W SE Corner Harvey County, Kansas
21	State Geological Survey Water Test Well #162 Elevation: 1403	Section 16-23S-2W NW Corner Harvey County, Kansas
22	Anderson Pritchard Dyck #1 Elevation: 1429	Section 10-23S-2W NE/4 NE/4 NW/4 Harvey County, Kansas
23	State Geological Survey Water Test Well #142 Elevation: 1442	Section 11-23S-1W SW Corner Harvey County, Kansas
24	Bay Sauder #1 Elevation: 1466	Section 3-23S-1E SE/4 SW/4 SW/4 Harvey County, Kansas
25	Hummon Oil Company Dey #1-A Elevation: 1470 KB	Section 16-23S-2E SW/4 SW/4 NW/4 Harvey County, Kansas

APPENDIX C

WELLS AND SHAFTS

CROSS SECTION C-D, FIGURE 4
(All in Township 19 South, Range 8 West, Rice County, Kansas)

1. Lyons Natural Gas, Oil, and Mineral Co. No. 1 Prospect (or #1 Lyons Gas Well) Cable tools—drilled 1887 Total depth 1230 feet	Section 34, C E/2 SW/4 SW/4 (South end of Block 18, Diamond Addition) Elevation: 1693 Derrick Floor Produced natural gas at a rock pressure of 67 lbs. for a short while from Herrington Limestone, Chase Group. The first producing well in the west ranges of Kansas. Discovery well for salt in this area.
2. AEC Entry Shaft Carey Salt Mine Rotary drilled shaft, 1964 Total depth 1060 feet	Section 34, C NE/4 SW/4 Elevation: 1699 Kelly Bushing Shown on log as well X-15-40, Carey Salt Company. Set 26″ surface casing at 309′. Drilled 9⅞″ diameter, and logged. Reamed hole: large diameter casing set and cemented prior to developing AEC mine rooms. Entry shaft for simulated radioactive waste containers, Project Salt Vault. Mine floor at 1000′. Ceiling 15′.
3. Carey Salt Mine Main Shaft Hand dug 7′ × 16′ in 1889-1890 Total depth 1083.5 feet	Section 34, few feet NW of Center of Section. Elevation of Shaft Collar: 1702 Salt 806′ to 1068′ Mine ceiling 9′; older areas 12′ Floor of mine 1024′
4. Woodman & Iannitti Drilling Co. No. 2 Stockham Rotary drilled, Nov. 1970 Total depth 3466 feet in Simpson	Section 34, NE/4 NW/4 NE/4 Dry Hole
5. Western Petroleum Company No. 1 Stockham Rotary drilled, Nov. 1964 Total depth 3493 feet in Arbuckle	Section 34, C NE/4 NE/4 Elevation: 1721 Kelly Bushing Oil Well: Two producing zones Kinderhook 3344′-3348′ Simpson 3398′-3418′ 41 BOPD + 15% water—gravity 33°
6. Barnett Oil Company No. 1 Wright Rotary drilled, 1971 Total depth 3585 feet in Simpson (Est. Arbuckle 3604′-1910′)	Section 35, Approx. C S/2 NW/4 810′ from south line; 1150′ from west line Elevation: 1694 Kelly Bushing Four aquifers (indicated by "W" on cross section) were cored, then drill stem tested for water information. Dry hole, 1971.
7. USAEC Test Hole No. 2 Rotary drilled, 1970 (6¾″ diameter) Total depth 1215.6 feet in Chase Group	Section 35, 30′ North of Center N/2 Elevation: 1704 Ground Level Stratigraphic test hole Cored 739.9′ to 1099.6′, 4-inch cores. Salt section 755.0′ to 1002.5′. U.S. Corps of Engineers' rotary rig.
8. Atlantic Refining Co. No. 1 Pulliam "A" Drilled 1936 Cable tools 0′ to 3305′ Rotary tools 3305′ to 4085′ total depth in Arbuckle (Est. Precambrian 4121 or −2390)	Section 35, C S/2 N/2 NE/4 Elevation: 1731 Derrick Floor Gas Well: 1936 to 1945 41 million cubic feet of gas per day. Plugged and abandoned in 1945. Reentered and replugged in 1974.
9. Kansas Petroleum Inc. No. 1 Pulliam Rotary drilled, 1962 Total depth 3541 feet in Arbuckle Re-entered 1974; set 5½″ casing Gas Storage: input-withdrawal well Northern Natural Gas Company	Section 35, Center NE/4 Elevation: 1729 Kelly Bushing Dry hole. Drilled 17 years after abandonment of the Pulliam "A"-1. Penetrated the Arbuckle 300′. Three drill stem tests in the Arbuckle recovered water. Simpson-Arbuckle drill stem test, 7 million cubic feet per day of "sour" (H_2S) gas and salt water.

APPENDIX D

FIELD INVESTIGATIONS AT CARGILL SINKHOLE IN 1977

Introduction. In April and May 1977, a drilling program financed by the Solution Mining Research Institute (SMRI) investigated the geometry of the roof failure in the rock strata beneath and surrounding the sinkhole developed in October 1974 on the property of Cargill, Inc., Hutchinson, Kansas. Four vertical and two inclined (30° from vertical) exploratory boreholes were drilled in the vicinity of the sinkhole by Nebraska Testing Laboratories, using a tractor-mounted Mobile-50 drilling rig. Casing with 4-inch inside diameter was set in shale bedrock near elevation 70 feet to prevent cave-ins from the shallow water sand. A tricone bit attached to 2⅜-inch drilling rods was used in all holes except V-3, in which continuous 1⅞-inch diameter NX core was taken. The investigation was conducted by Alfred J. Hendron, Jr., Ronald E. Heuer, and Gabriel Fernandez-Delgado, who submitted a preliminary report entitled "Field Investigations at Cargill Sinkhole, Kansas" to SMRI June 13, 1977. Information from their report, abstracted by the author, is here included with the permission of SMRI. Dr. Fernandez was resident engineer at the site during drilling and coring operations.

Drilling Program. The six test holes drilled in 1977 at the Cargill sinkhole, in the NW/4 of Section 19, Township 23 South, Range 5 West, near the city of Hutchinson, Reno County, Kansas, are briefly characterized in Table 6. Borehole locations are mapped in Figure 38.

Vertical borehole V-3, on the northwest bank of the sinkhole, is discussed first because it was cored with excellent recovery, permitting numerical analysis of RQD (Rock Quality Designation; Deere, 1963), and a gamma-neutron log was recorded. The upper 70 feet which were drilled, not cored, are clean loose sand; the grain size increases downward with pea gravel, ⅜-inch diameter, in the lower two feet. Underlying this Pleistocene sand is a layer ten feet thick of very soft, Permian, red shale which, under small vertical stresses and in contact with the water-bearing strata above, has undergone swelling. The attendant increase in water content has resulted in reduced strength of the shale and in more loss of core. From depths of 80 feet to 190 feet, core samples consist of hard red shale with an average RQD of 55 percent. This hard red shale is horizontally interbedded with thin (¼" to 1") gypsum layers in the lower 40 feet.

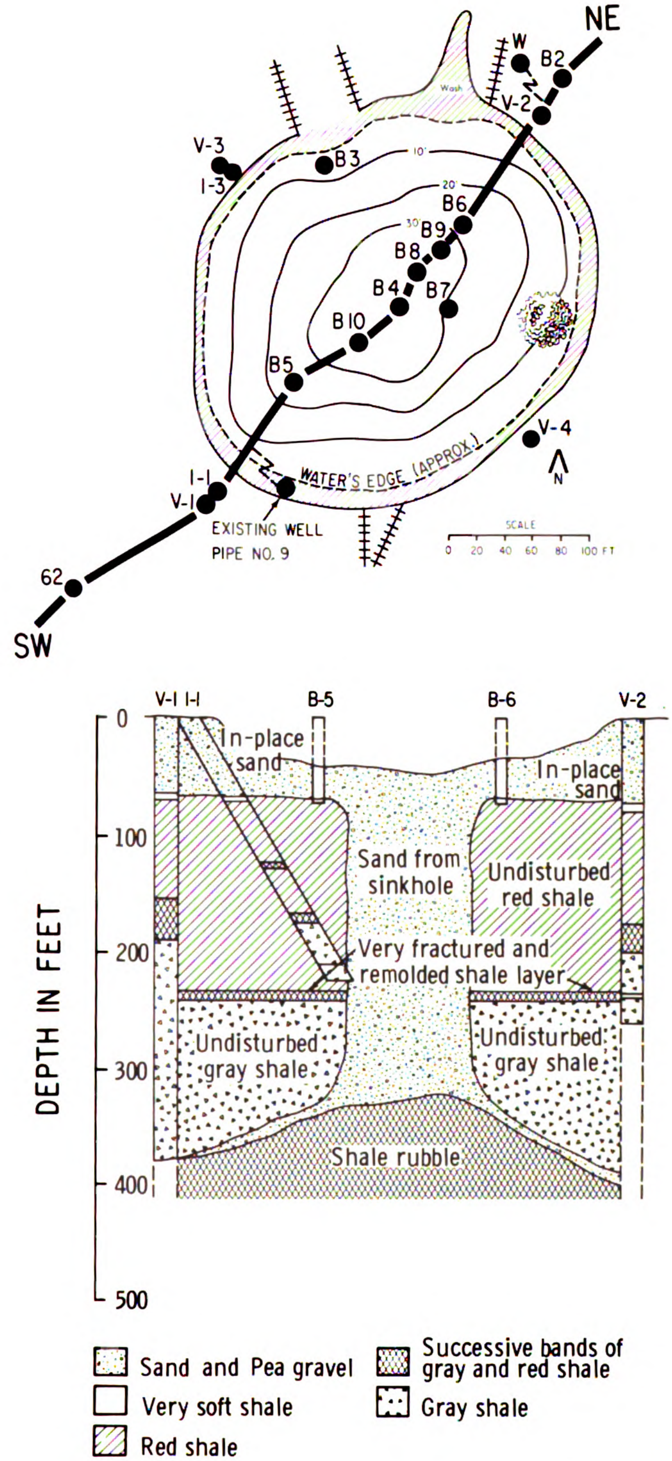

FIGURE 38.—Index map, Cargill sinkhole and conceptual sketch showing underground conditions along a southwest-to-northwest cross section. Prepared for the Solution Mining Research Institute by Hendron, Heuer, and Fernandez-Delgado, June 13, 1977.

A transition zone of alternating layers of red and gray shale, between depths of 190 and 205 feet, has horizontal bedding and an average RQD value of 60 percent. From 205 to 242 feet, gray, horizontally laminated, competent shale was cored, with RQD values averaging 66 percent. A zone five feet thick of fractured and deteriorated material (RQD = 7%) occurs between depths 242 and 247 feet. Very competent gray shale from 247 to 420 feet has an average RQD value of 95 percent. Thin (¼″ to 1″) gypsum layers and 8-inch anhydrite layers were found in this gray shale. Most of the bed partings found in the gray shale were located along the contacts between the shale and the interbedded thin horizontal gypsum layers. Joints and bedding cracks (up to ¼″ thick) in the lowest portion of the gray shale, overlying the uppermost salt layers, are filled with red halite. The Permian Hutchinson Salt was penetrated at 420 feet. Thin (½″ to 1″) layers of very "porous" salt with RQD values of zero were encountered from 420 to 480 feet. The salt has a considerable volume of holes or pores, apparently indicating the beginning of a dissolution process. Throughout the entire salt section penetrated from a depth of 420 feet to the bottom of the boring at 527 feet, salt layers are interbedded with gray shale layers which have an average RQD of 55 percent. A void 2½-feet deep was found below a depth of 480 feet. Circulation of the drilling water was completely lost. The gamma-neutron log could not be recorded below 482 feet. The salt from 482 to 490 feet was porous with fractures at 483 feet and 485 feet and with a 6-inch void at 489 feet. Salt beds from 490 to 512 feet are again solid, with RQD values averaging 60 percent. From 512 to 527 feet, total depth of the hole, one-half inch to one inch layers of alternating white and dark salt are found which have RQD values less than 20 percent.

The adjacent 30-degree inclined hole, I-3, was drilled, not cored, through the upper sand, into the soft and hard red shales. It then continued through the transition zone of alternating red and gray shale, and penetrated 35 feet into gray shale. At that depth the boring encountered granular materials which squeezed against the drilling rods and caved the hole. Further advance of the hole was not possible without the use of casing. This deepest point penetrated is 230 feet below the ground surface and 110 feet southeast of the northwest edge of the sinkhole. The complete loss of water circulation at a depth of 220 feet, 10 feet before the hole started to squeeze and cave, indicates the presence of continuous voids or fractures in the formation at this location.

In vertical borehole V-4, drilled on the opposite or southeast bank of the sinkhole, cuttings samples which were recovered, as well as rate of drill bit penetration, indicate a stratigraphic sequence similar to that which was cored in borehole V-3. The circulation of drilling water was partially lost at a depth of 410 feet, was completely lost at the top of the salt, depth 420 feet, then was regained, only to be completely lost again after the bit penetrated 25 feet into the uppermost salt layers. Water circulation was never recovered from 445 feet to 535 feet (total depth). From the variability in drilling penetration rate, it is thought that gray shale layers are interbedded with the salt.

In the vertical borehole V-1, on the southwest bank of the sinkhole, normal rock sequence was drilled to a depth of 388 feet. At elevations 208 and 210 feet excessive rig vibration indicated the presence of thin (4″ to 6″) fractured layers in the shale. Between depths 240 and 250 feet the presence of a very fractured zone was also indicated by excessive vibration of the drilling rig. At 388 feet water circulation was completely lost, indicating the presence of a heavily fractured zone. The material below 388 feet started to squeeze against the drilling rods and the walls started to cave. Further continuous penetration below a depth of 400 feet was not possible without the use of casing. Immediately after drilling in V-1 was stopped, a split-spoon sample was taken from 400 to 405 feet total depth. The material in the sample consisted of contorted gray shale mixed with fine sand, the amount of sand decreasing downward.

The 30-degree inclined borehole, I-1, which is adjacent to V-1 on the southwest bank, drilled a normal section of rocks to a depth of 190 feet, where circulation was lost completely. At depth 217 feet (slant depth 250 feet) squeezing of the drill rods occurred. This point is about 105 feet northeast of the southwest edge of the sinkhole. An additional 15 feet of drilling to total depth of 230 feet (slant depth 265 feet) was accomplished with heavy squeezing of the surrounding granular material on the drill rods. When the drilling rods were pulled out and the length of the open hole measured, a complete cave-in of the bottom 17 feet of hole was detected. From drilling characteristics it is deduced that material in the lower part of this hole is similar to that encountered in the previously drilled and cored inclined hole I-3, and that both inclined holes encountered a sand-filled chimney beneath the central sinkhole area.

Vertical borehole V-2, on the northeast bank of the sinkhole, was drilled with a tricone bit to a depth of 245 feet. A void three feet deep was found between depths of 242 and 245 feet, and water circulation was completely lost in this interval. The walls repeatedly caved into the hole. No further progress could be made because of excessive vibration of the

TABLE 6.—Boreholes, Cargill Sinkhole, 1977, SMRI.

Location	Test Hole	Angle	Total Depth	Drilled or Cored	Remarks
SW Bank	V-1	Vertical	405 ft	Drilled	Rough drilling 245-250′. At 388′ drilled "remolded shale and fine sand."
	I-1	Inclined 30 degrees	230 ft	Drilled	Sand-filled chimney 105′ NE of bank at elevation 217′.
NE Bank	V-2	Vertical	265 ft	Drilled 245′ Cored 265′	Void 242′-245′ due to "large block movement."
	I-2		....	Not drilled	....
NW Bank	V-3	Vertical	527 ft	Cored NX	Salt at 420′.
	I-3	Inclined 30 degrees	230 ft	Drilled	Sand-filled chimney 110′ SE of bank at elevation 230′.
SE Bank	V-4	Vertical	525 ft	Drilled	Salt at 420′.
	I-4		....	Not drilled	....

drilling rig due to squeezing of material around the drilling rods. After a waiting period of several days, NS core samples of 1⅞-inch diameter consisting of gray shale were recovered in the next 20 feet. Heavily fractured, soft, altered gray shale with an RQD value of 23.75 percent was present from 249 to 254 feet. The quality of the shale improved with depth to a value of 68 percent in competent, horizontally laminated, dark gray shale with tight joints cored from 259 to 264 feet (total depth).

Interpretation of Borehole Results. Boreholes V-3 and V-4 at the northwestern and southeastern edges of the sinkhole encountered salt at a depth of 420 feet, and both holes penetrated about 100 feet into the salt. Cores of the formations and progress of the drilling provide evidence of dissolution of rock in the subsurface, but no indication of a gallery-size cavity or of sand which might have come from the sinkhole was noted. These boreholes are 300 feet apart; hence the cavity-roof span is less than 300 feet in this direction.

Boreholes V-1 and V-2 on the southwestern and northeastern edges of the sinkhole both found evidence of voids and disturbance in the gray shale at depths of 240 to 245 feet, or about 180 feet above the salt. Borehole V-1 was continued to a depth of 388 feet, about 30 feet above the estimated former (pre-dissolution) position of the salt, where a large void containing sand was encountered. All of this information suggests that major dissolution activity among nearby brine wells has developed a cavity elongated in the southwest-northeast direction under the sinkhole. About 30 feet of roof shale has collapsed into the void beneath at the location of borehole V-1, and movement of large blocks has affected 180 feet of shale above the elongated cavity. The length of span of the gallery-roof in a southwest-to-northeast direction is unknown, but it may be more than 1300 feet (Figure 8, page 18).

The location at which sand was encountered under the sinkhole in the inclined borings I-1 and I-3 confirms the presence of a sand-filled chimney which is approximately 100 feet in diameter, and which is located below the center of the sinkhole, extending vertically from a depth of 70 feet to about 370 feet. The volume of a cylindrical plug of that general dimension is approximately 90,000 cubic yards, or approximately the same volume as the sinkhole. Both the surface sinkhole and the underlying plug, or sand-filled chimney, appear to be slightly elongated in the south-northeast direction, reflecting the influence of the underlying cavity elongated along the line of brine wells in the Airlift Field gallery southwest of the sinkhole.

The conceptual sketch showing underground conditions along a southwest to northeast cross section, Figure 38, is reproduced from the report by Hendron, Heuer, and Fernandez (1977). Information from their sketch, from their report, from records of early brine wells, and from all other available sources is combined in the natural scale cross section by the author, Figure 39. For a discussion of brine well 9, projected 23 feet into the cross section, and brine well 62 connected hydraulically to the sinkhole at the time of subsidence, see text pages 19 and 20. The lithology of the Hutchinson Salt, depth 420 to 750 feet, was projected from boreholes V-3 and V-4 and from the logs of brine well H-3 about 2000 feet southeast of the line of section.

The amount of salt dissolution and the resulting cavity shape are hypothetical. Significant features beneath the surface sinkhole are the presence of (1) a vertical, sand-filled, roof-fall chimney, (2) bedding plane dilation cracks in the Permian shales due to slight downward movement of large blocks of shale, (3) open solution voids as large as 2½ feet in vertical dimension in the upper salt beds, and (4) an extensive former solution cavity which is now plugged with roof-fall rubble debris. Not indicated on the cross section is the former position of the main line tracks of the Missouri-Pacific Railroad directly above the central sand-filled chimney. The tracks were left suspended by rapid surface subsidence forming the Cargill sinkhole on October 22, 1974, Figures 10, 11 and Cover.

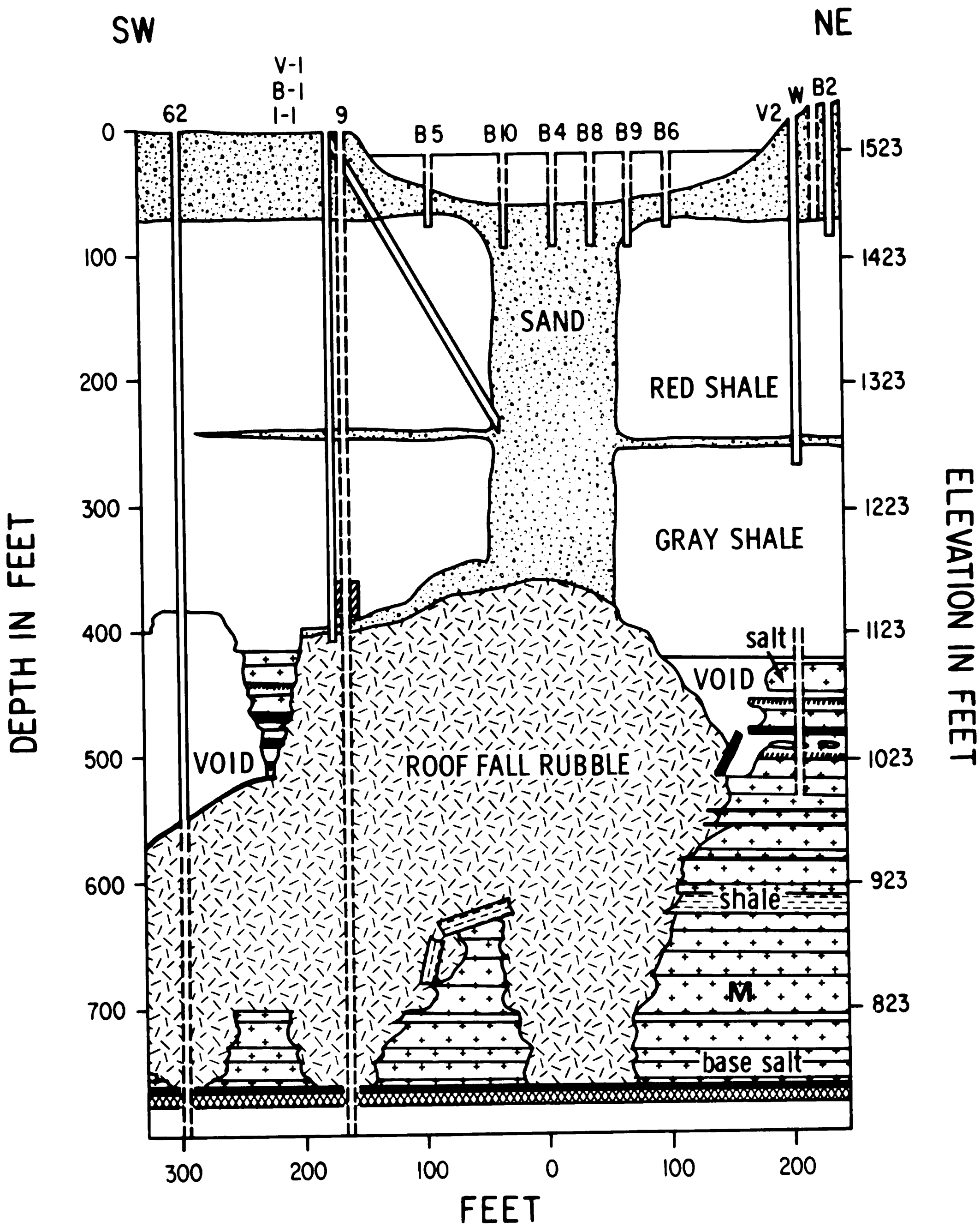

FIGURE 39.—Natural scale cross section through the Cargill sinkhole by the author. The amount of salt dissolution and the resulting cavity (gallery) shape are hypothetical: "M"—Salt bed mined in underground dry mines; "Shale"—Nonsoluble beds utilized as roof-rock in LPG installations; "W"—Fresh water supply well. Not shown are the Missouri-Pacific Railroad tracks formerly located directly above the surface sinkhole (see Cover).