DISSOLUTION IN THE HUTCHINSON SALT MEMBER OF THE WELLINGTON FORMATION NEAR RUSSELL, KANSAS

by

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B. S., Kansas State University, 1975

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Geology

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1977

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CONTENTS

Page

Introduction 1
Purpose 1
Location 1
Acknowledgements 4

Previous Investigations 5
General Descriptions 5
Oilfield Development 6
Well Plugging and Abandonment 8
Salt Dissolution 10

Geology 14
Structure 14
Stratigraphy 17
Aquifers Above the Salt 17
Sumner Group 19
Aquifers Below the Salt 21

Methods of Investigation 22
Oil Well Information 22
Electric Log Information 22
Remote Sensing Photographs 23

Results and Interpretation of Data 23
Remote Sensing Methods 23
Interpreted Electric Log 24
Cross Section 26
Contour Map of Salt Top 29
Isopach Maps of Salt 30
Comparison of Salt Thicknesses 38

Conclusions and Recommendations for Future Study 42
Conclusions 42
Recommendations for Future Study 44
Seismic Survey 44
Borehole Reentry 45
Studies of the Salt and Overlying Rocks 46
Questionnaire 47

References 49

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APPENDICES

	Page
Appendix I. Control Points for Isopach and Contour Maps	52
II. Well Data for Cross Section	58
III. Sinkhole Descriptions	60

ILLUSTRATIONS

FIGURE 1. Thickness and Extent of Salt	2
2. Study Area	3
3. Interpreted Electric Log	15
4. North to South Cross Section of Study Area	27
5. Contour Map of Salt Top	28
6. Isopach Map of Salt with Wells Drilled 1927-1940	31
7. Isopach Map of Salt with Wells Drilled 1941-1950	32
8. Isopach Map of Salt with Wells Drilled 1951-1956	33

TABLES

TABLE 1. Comparisons of Thickness of Salt in Nearby Wells of Different Ages	40
2. Locations of Wells with Salt Missing in the Borehole	41

INTRODUCTION

Purpose

The Hutchinson Salt Member of the Wellington Formation, Sumner Group, of the Permian System underlies much of Kansas and Oklahoma (Fig. 1). The salt of the Wellington Formation in Russell County, Kansas, is being dissolved by water flowing along the boreholes of old oil or gas wells. Dissolution can cause the overlying strata to weaken, collapse and possibly form a sinkhole. The subsidence resulting from salt dissolution is a minor problem but could potentially increase in both frequency and severity.

This study was undertaken to determine the extent and detectability of areas of salt dissolution in part of Russell County using currently available information. The study also involved the possibility of predicting future subsidence by studying oil and gas well logs of the salt section and if salt thickness, well location and the date of well drilling completion are factors in salt dissolution.

Location

The area chosen (Fig. 2) consists of Townships 13 and 14 South, Ranges 14 and 15 West, an area of approximately 144 square miles (372.8 sq. km.) in southwestern Russell County, Kansas. This area includes the towns of Russell and Gorham.

The area is of interest because it includes a large number of wells drilled before 1940, contains two known sinkholes and has shallow brine aquifers.

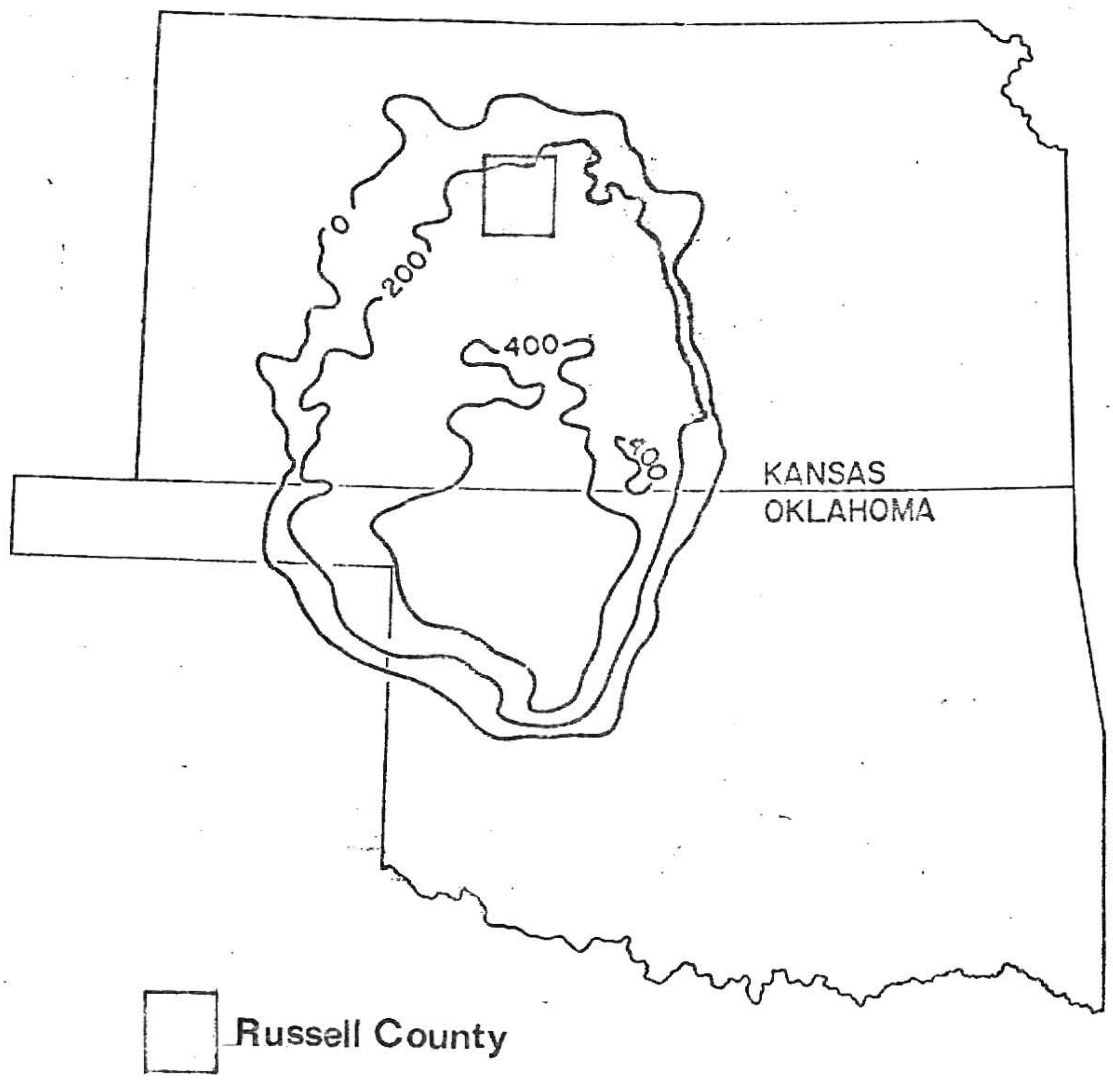


Figure 1. Thickness, in feet, and extent of the Hutchinson Salt Member of the Wellington Formation. Modified from R. Walters (1976).

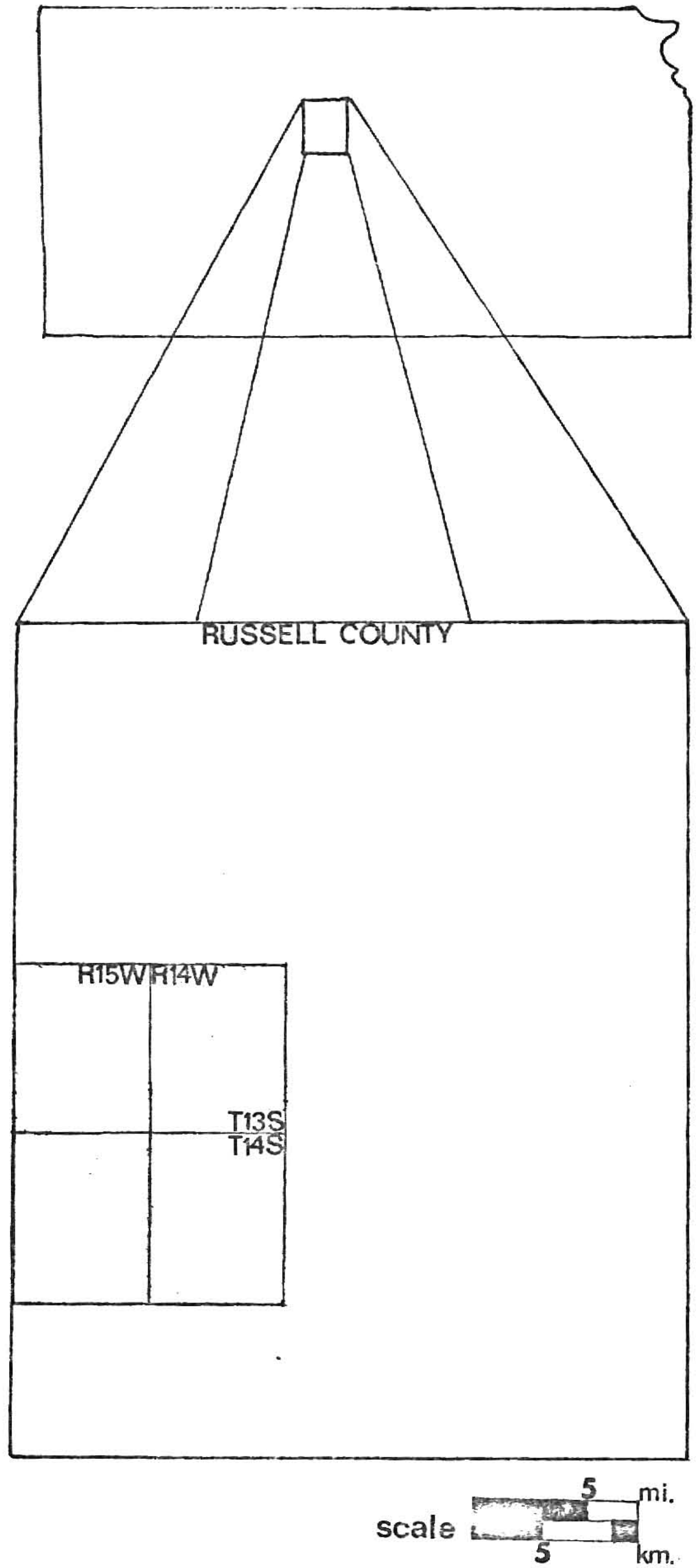


Figure 2. Study area

Acknowledgements

Thanks and appreciation are expressed to the staffs of the Kansas Geological Survey and Kansas Geological Society for their help in locating electric logs and well information of the study area; to my wife, Marsha, for typing the manuscript, and to Dr. Donald O. Whittemore and Dr. Henry V. Beck for invaluable assistance in preparing the manuscript. Finally, special thanks to Dr. Charles P. Walters for many ideas, suggestions and overall guidance on the entire project.

The manuscript has been reviewed by Professors Page C. Twiss, Charles P. Walters, Donald O. Whittemore, Department of Geology, and Professor William J. Hankley, Department of Computer Science, of Kansas State University.

PREVIOUS INVESTIGATIONS

General Descriptions

A report by Walters (1976) provides background information on the latest state of salt dissolution in Kansas. The report includes locations of all (1976) known sinkholes caused by salt dissolution in Kansas. The State Highway Commission of Kansas published a report on the Crawford and Witt sinkholes in Russell county (Taylor, 1970). This report described the efforts undertaken by the Highway Commission to determine the extent of dissolution along Interstate Highway 70. Fader (1975) reported also on salt dissolution sinkholes in Kansas.

Jones (1965) made a petrographic study of the salt at its "type locality" near Hutchinson, Kansas. Kulstead (1959) and Bass (1926b) determined the general boundaries and thickness of the salt.

Other investigations include the geology of Russell County (Rubey and Bass, 1925), and studies of the Dakota Formation (Bass, 1926a), (Hattin, 1965), and the Cheyenne Sandstone (Swineford and Williams, 1945), (Swineford, 1955), (Scott, 1970), Frye and Brazil (1943) studied the ground water and the effect of the oil industry on its quality in Russell County.

The availability and future needs of ground water in Russell, Kansas was investigated by Latta (1948). Smith (1976) studied the effects of salt dissolution in Kansas and she lists the current Kansas Statutes concerning drilling operations.

Oil Field Development

In November, 1923, an oil well was drilled in Russell County in what was later to become known as the Fairport pool. The well yielded 224 barrels (35.6 cubic meters) of high-gravity oil a day. The success of the first well stimulated other drilling along the trend of the Fairport-Natoma anticline. By January, 1942, 84,150,666 barrels (13,379,956 cubic meters) of oil had been produced in Russell County (Frye, 1943). The amount increased to 297,532,091 barrels (44,897,592 cubic meters) by 1958 (Goebel, 1959). In 1958 the yearly production was 9,005,985 barrels (1,359,003 cubic meters) and in 1959 it dropped to 8,922,064 barrels (1,346,340 cubic meters) (Goebel, 1960). The production rate has continued to decline steadily since then with 4,509,406 barrels (716,995 cubic meters) of oil being produced in 1975 (Beene, 1976). With the decrease in oil production came an increase in brine production, as formations which yield oil are brine aquifers. Some methods of disposal of large amounts of waste brine possibly have caused contamination of fresh water aquifers or salt dissolution.

During the 1920's and 1930's regulations concerning brine disposal were nonexistent. Brine was stored in unlined surface pits and eventually either seeped into the ground, was concentrated by evaporation, or was washed into streams during heavy rains. This storage method sometimes led to contamination of shallow aquifers and surface runoff. However this method of salt water disposal did not provide water for salt dissolution.

The 1935 general statutes of Kansas were not very explicit in describing procedures for salt water disposal and subsequent protection of the salt. Kansas Statute Number 55-115 concerned the casing of holes to protect oil or gas producing zones from contamination by fresh, salt or mineral water. Kansas Statute Number 55-901 stated that when the owner or operator of a gas or oil well applied for and received authority, he could return salt water or mineral water to any formation which contained or had previously produced salt water to an "appreciable degree." Rule 400 of the 1938 Kansas Corporation Commission rules and regulations concerning crude oil and natural gas, amends Statute Number 55-901 to state that the disposal formation be protected by an impervious bed and be a remote distance from its outcrop. These regulations never mentioned protection of the salt by casing or other methods and allowed the use of brine aquifers for disposal, including those above the salt that contain water capable of dissolving the salt.

Frye and Brazil (1943) studied groundwater in the oilfield areas of Ellis and Russell Counties. The study was interrupted before completion but it approved the action taken earlier by the Kansas Corporation Commission allowing the use of shallow brine aquifers as a disposal zone. The two aquifers used were the Cheyenne Sandstone and the Cedar Hills Sandstone. The Commission's actions created some problems. At several places disposal of salt water was not carefully limited to the Cheyenne or Cedar Hills Sandstones. The Dakota Formation, although not a recommended disposal zone, was often used. Because the lower Dakota Formation contains saline water, it is difficult to determine what effect the addition of waste brine had on the chemical composition of the aquifer water. However, the lenticular sandstone may have allowed the migration of brine to fresh water aquifers. The use of these sandstones for disposal also created a problem of overpressuring and lateral migration of the brine to boreholes that would permit downward movement of water.

In March 1967, regulations concerning shallow disposal wells were changed, outlawing the use of shallow brine aquifers for waste brine disposal. Most disposal wells had been abandoned before this time because problems were encountered in operating shallow wells. However, by this time water which could cause possible future dissolution of the salt was already in the brine aquifers (Walters, 1976, p. 113).

Well Plugging and Abandonment

The history of plugging abandoned oil and gas wells in Russell County closely follows the history of disposal wells. Prior to 1930 regulations concerned the salvage of removable casing and the abandonment of wells, and not the plugging of wells (Walters, 1976, p. 113).

The 1935 Kansas Statutes 55-116 and 55-128 regulated the abandonment of wells and subseqent plugging. These two statutes only required sealing off the production zone to a height of 20 feet (6.10 m.) above the zone and applied only to oil and gas discovery wells. Kansas Statute 55-128 was amended in 1953 to include seismic, core and exploratory holes penetrating salt water formations and used for exploration, discovery or production of oil or other minerals. Kansas Statute 55-116, concerning the oil zone, required wooden plugs with sand and gravel filling. This was changed by Rule 302 of the Kansas Corporation Commission requiring placement of a cement plug above the producing zone and below a penetrated fresh water aquifer. Rule 304 required plugging of exploratory wells to protect fresh water aquifers.

In the study area most exploratory wells were drilled before 1940, during the development of the oilfields, in an attempt to find oil producing horizons. The only near surface plugging requirement for these wells was that the fresh water aquifers be plugged to prevent contamination from below. The remainder of the borehole, including the salt section, was left open and often uncased. The brine aquifers, which were overpressured because of disposal practices, were not required to be plugged. Thus, the solution in the overpressured brine aquifers could migrate through the open, uncased borehole, to a zone of lower pressure resulting in a flow of water across the salt section. The flow of brine through the salt is a possible cause of dissolution in the study area.

From January 1966 to March 1967, the State Corporation Commission required a cement plug to be placed through the oil zone after the oil was depleted or the well abandoned. This restriction applied only to oil and gas test holes or wells. Starting in March 1967 all non-operational holes which penetrated a salt water formation were required to be plugged to prevent contamination of usable aquifers (Walters, 1976, p. 113).

The injection of waste brine solutions into other brine aquifers generally causes mixing of the waters. This not only makes it difficult to determine the original composition of the water in the brine aquifer but also can produce a highly corrosive solution. An example of this corrosion occurred in the State Highway Commission's test well in the Crawford sink area in Section 2, T. 14 S., R. 15 W. of Russell County. At this well a new $4\frac{1}{2}$-inch casing leaked from corrosion after 18 months (Walters, 1976, p. 120).

The Kansas Statutes or Kansas Corporation Commission rules mentioned above show that certain precautions were taken to protect the fresh water aquifers and the producing zone. However, before 1941 no personnel were hired specifically for inspecting plugging or casing of wells, only county employees were hired on a fee basis.

Thus, the plugging or abandonment of some wells was not supervised. During this time the oil potential of Russell County was rapidly being developed. With a large drilling program and a small number of supervisors it would be no surprise to find wells which had their casing pulled at least partially or wells which were not plugged as required by the law.

Approximatley 80,000 wells have been drilled through the Hutchinson Salt Member of the Wellington Formation in Kansas. If one percent of these wells were improperly plugged or abandoned, then 800 wells could possibly provide water for salt dissolution. Thus there are an undetermined, possibly small, number of locations where salt dissolution is or has occurred possibly resulting in surface subsidence or subsidence of the overlying units. Unfortunately the wells which were improperly plugged or abandoned can not be located by any easy method until after a sinkhole has started to form.

Salt Dissolution

The process of salt dissolution caused by oil and gas wells is very similar to the process of dissolution caused by the salt industry in solution mining. The similarity may help explain the behavior of the salt during dissolution and also suggests which parameters important to dissolution should be checked.

When a well for solution mining is started it is cased to the top of the salt, then salt is dissolved from the top beds downward. After the cavity in the salt becomes too large for the overlying strata to bridge, collapse occurs which may cause surface subsidence. The formation of a sinkhole does not always occur immediately around the well which caused it, but may be anywhere from several hundred feet to several thousand feet away, depending on the length of time salt has been mined from the area and how much salt has been removed.

Examples of brinefield subsidence caused by extraction of salt by solution mining are abundant. Terzaghi (1969) reported that brinefield subsidence at Windsor, Ontario, Canada caused damage to the Canadian Salt Comapny plant. Lewis (1969) briefly described salt-caused subsidence and governmental compensation for it in Europe. Walters (1976, p. 56) gave detailed descriptions of those salt solution sinkholes which are known in Kansas in the Hutchinson Salt Member of the Wellington Formation.

Solution mining for salt has shown that the roof rocks above the salt are unstable when exposed to fresh water and fail when support is removed from under them. In Kansas these overlying rocks include the shales and siltstones of the Wellington Formation.

Sinkholes formed by oil wells, gas wells, and solution mining have the same approximate size. The sinks usually range from 100 feet (30 m.) and 300 feet (90 m.) in diameter and up to 30 feet (9 m.) in depth, although, both of these parameters range considerably. The general physical appearances of the sinkholes are similar; most are circular with fairly steep sides.

Sinkholes formed by these processes seem to follow a similar pattern of development. The dissolution of the salt to the point of collapse takes place over a long period of time, usually 30 to 40 years. Once the point of collapse is reached and the overlying rocks are water saturated, sinkhole formation can occur in a matter of days, or if the overburden is unconsolidated, in a few hours (Walters, 1976, p. 2).

Presently salt dissolution caused by oil and gas wells seems to be rare in Kansas. After extensive research Walters (1976, p. 56) found only eight areas of subsidence. With over 80,000 wells penetrating the salt this is a ratio of one subsidence area of 10,000 wells. Two sinkholes, the Witt and the Crawford, are in the study area (See Appendix 5).

In order to understand why sinkhole formation caused by oil and gas well failure does not seem to be a great problem in most of Kansas it is necessary to look at the pressure relationships between the several aquifers. The assumption must be made that all wells drilled through fresh-water aquifers will not contribute water for salt dissolution because they lie above the salt and are sealed off. The other aquifers are below the salt and all contain brine. Walters (1976, p. 66-76) determined the pressure gradients of the following aquifers for a 4000 square mile study area including Russell County: Florence Limestone Member of the Chase Group, the Lecompton Limestone of the Shawnee Group, the Douglas Group, the Kansas City Group, and the Arbuckle Group. Taking into account the specific gravity of the brines and the effect this has on the piezometric surface of the brine and fresh water aquifers he concluded that pressure equalization would occur between the aquifers with no water flow in a borehole through the salt.

> 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 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 pipe, internally plugged, is cemented in place through the near surface fresh water aquifers. (Walters, 1976, p. 76)

This conclusion is valid in most of Kansas if cement plugs are in place as stated. In the areas where the stated pressure relationships and plugging requirements hold, salt dissolution can occur in several ways. An old hole which has no surface casing, for example Taylor No. 1, Pullman No. A-1, and Pullman No. 1 wells in Rice County, Kansas, and the Berscheit sinkhole in Rice County, Kansas, were caused by casing corrosion. These wells were used for salt water disposal in the Arbuckle Group. Over a period of 30 years the brine solution corroded the casing, allowing water to flow across the salt and dissolve it.

Where the Cretaceous Cheyenne Sandstone and the Permian Cedar Hills Sandstone are present, a different situation occurs. In a locality where these two aquifers are present the aquifer pressure relationships are not as simple as where these aquifers are absent. As mentioned earlier, these aquifers did not have to be cased because they contain brine. They were used as a brine disposal zone and as a result became overpressured. The increase in the hydrostatic pressure of the aquifer has enabled lateral migration of brine to a borehole allowing downward migration (Walters, 1976, p. 109). The downward flow of brine across the salt has caused dissolution.

It should be noted that the greatest amount of salt dissolution occurs after a hole is drilled. The amount of dissolution that occurs during drilling with a modern rotary rig using a non-brine mud is approximately three times the diameter of the drill bit or more than nine times the volume of the hole (Walters, 1976, p. 65). This figure is only an approximation of cavity size and can vary depending on drilling rate, mud type and other drilling factors. The approximate size of the cavity formed during drilling can be determined by at least five methods. Walters (1976, p. 58-65) listed these methods and described how they can be used to determine cavity size. The methods include caliper log study, calculation of volume of cement used in casing through the salt section, study of geophysical logs, investigation by "fishing" operations in the salt, and comparisons of recorded and calculated increases in the volume and salinity of the drilling fluid with measurements taken before the salt was encountered.

GEOLOGY

The structure and stratigraphy of Russell County have been described by Rubey and Bass (1925), Frye and Brazil (1943), Swineford and Williams (1945), Merriam (1963) and Walters (1958). The information about the aquifers, above and below the salt, is from Frye and Brazil (1943), Swineford (1955), Hattin (1965), Scott (1970), Bayne (1972), Fader (1975) and Walters (1976). Their descriptions of the formations are used in the descriptions that follow. An interpreted geophysical log (Fig. 3) shows the stratigraphic relationships and the typical depths the formations are found at in the study area.

Structure

Russell County is part of the Plains Border section of the Great Plains physiographic province (Rubey and Bass, 1925, p. 11). The county is drained by the Smoky Hill and Saline Rivers and ranges in elevation from 2050 feet (625 m.) above sea level in the northwest to 1430 feet

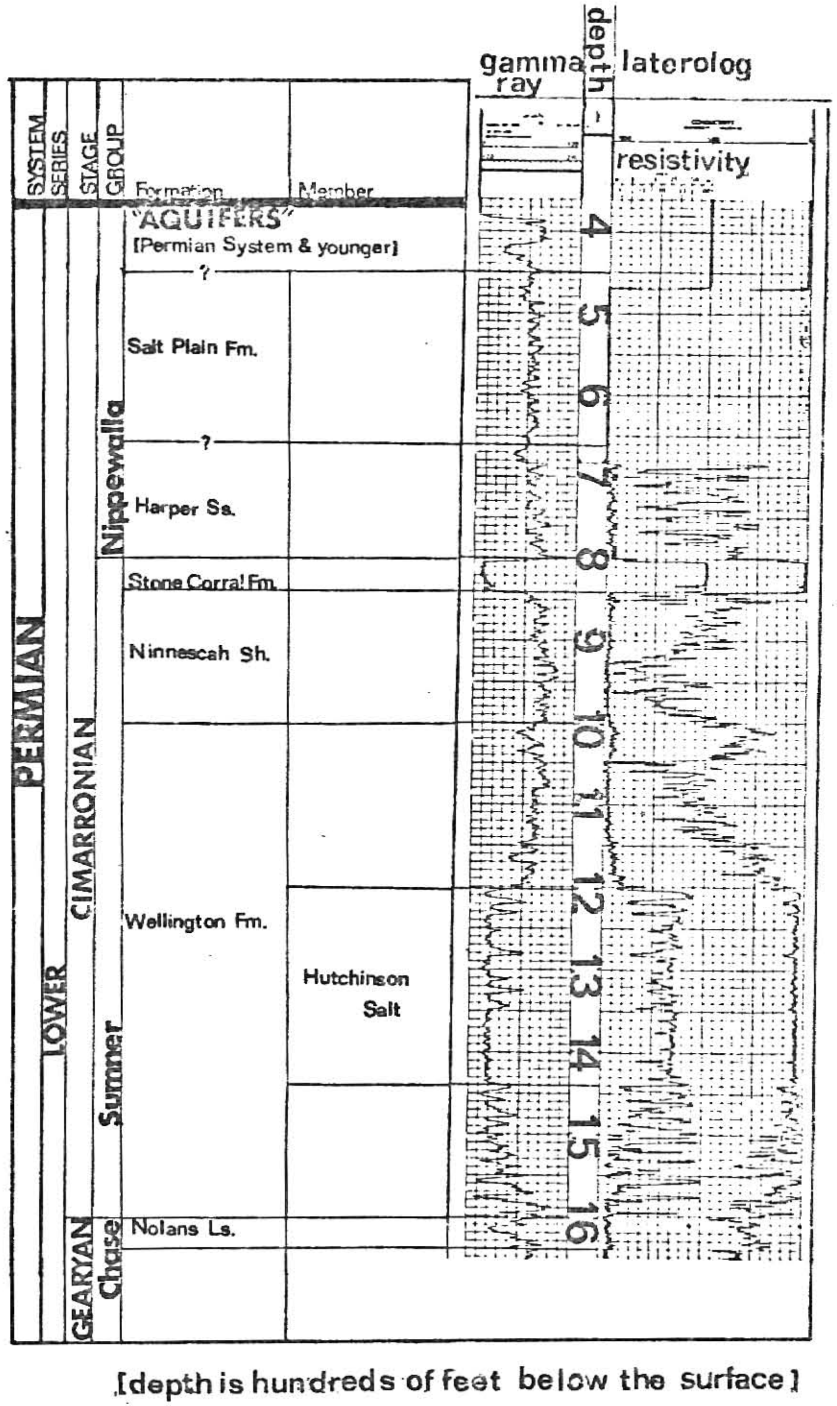


Figure 3. Interpreted electric log from study area. Modified from Kansas Geological Society 1966 type log for Russell County, Kansas.

(436 m.) above sea level along the Saline River near the middle of the eastern border. The rocks in Russell County dip slightly to the west at 9 feet per mile (Walters, 1958, p. 2155).

Russell County has been affected by the major structural events that occurred accross Kansas. During Mississippian time, until middle Permian time the Central Kansas uplift was achieving its maximum development (Lee, 1956, p. 12). By Leonardian time the region was tilting toward the Hugoton embayment of the Anadarko basin. As a result of the gentle downwarping, the Permian salt beds, including the Hutchinson Salt, were deposited to the east of the Hugoton embayment (Swineford, 1955, p. 151). Deformation in Cretaceous time tilted western Kansas northward and northwestward toward the Denver basin (Lee, 1956, p. 12).

The Permian beds have a regional north-east southwest strike and show no evidence of the buried Central Kansas uplift (Walters, 1958, p. 2154). The major Kansas structural features, including the Central Kansas uplift, show no evidence of movement during the Cenozoic Era, but minor and local movements may have occurred (Merriam, 1963, p. 221).

The Fairport-Natoma anticline is a good example of the larger folds in the Russell County area. This anticline runs for about 20 miles (32 km.) along the northern half of the western border of Russell County (Rubey and Bass, 1925, p. 67-68).

Faulting in Russell County has affected the rocks beneath the Hutshinson Salt Member of the Wellington Formation more than those above the salt. The Precambrian granite is faulted with a vertical displacement of 300 feet (91 m.) in the Gorham oilfield. The Lansing and Kansas City Groups also show evidence of faulting approximately 3000 feet (914 m.) below the surface, with a vertical displacement of of 50 feet (15 m.) (Walters, 1976, p. 101).

Stratigraphy

Aquifers above the salt. Aquifers in Russell County which overlie the salt consist of deposits of Quaternary alluvium, Cretaceous sandstones and Permian sandstones.

The Quaternary alluvium consists of gravel, sand, silt and clay about 50 feet (15 m.) thick (Bayne, 1972, p. 7). These deposits occur along the valleys and underlie some small stream valleys and their floodplains. The alluvium and surface runoff can contribute up to 300 gallons per minute (1140 litres per minute) of water to a well (Fader, 1975, p. 8). This amount is different depending upon well location but nevertheless the water from the alluvium as well as surface runoff is thought to be an important fresh water source for salt dissolution in the Witt sinkhole (Walters, 1976, p. 114).

The Cretaceous sandstones unconformably overlying the Permian deposits include the 100 to 300 foot (30 to 90 m.) thick Dakota Formation and the 60 to 150 foot (18 to 45 m.) thick Kiowa Formation. The Dakota Formation consists of varicolored clay and medium-grained, brown to yellow sandstone (Hattin, 1965). The contact between the Dakota Formation and the Kiowa Formation is difficult to determine as these units are seemingly conformable and gradational (Frye and Brazil, 1943). The Kiowa Formation consists of dark-gray fissle-weathering shale, silt and very fine-grained sand mottles common (Scott, 1970, p. 1227). Because these units are similar and difficult to separate they can be grouped as one aquifer. This aquifer was never legally used as a salt water disposal zone but surface ponding in the past has led to some contamination of it. However, because a large quantity of water was available from the aquifer, almost all wells which passed through it were cased. This includes older cable-tool drilled wells as well as more recent rotary drilled wells. The extensive use of casing through this aquifer allows little water to reach the salt. However, the aquifer does have the capability to yield up to 20 gallons (76 litres) per minute of water to a well with casing failure (Fader, 1975, p. 8).

The other Cretaceous aquifer is the Cheyenne Sandstone. The Cheyenne is a fine- to coarse-grained, light tan-gray to light red-brown sandstone (Scott, 1970, p. 1227). The Cheyenne Sandstone thins to a feather edge over topographic highs of the Cretaceous Period and thickens to about 60 feet (18 m.) in western Russell County (Swineford and Williams, 1945, p. 110). This aquifer has been used as a salt water disposal zone from the 1940's to 1961. Thus, at a shallow depth above the salt there is an aquifer with excess pressure, water unsaturated with respect to halite, and which is capable of yielding up to 20 gallons (76 litres) per minute of water to a well. This is a possible source of water for salt dissolution.

The fourth aquifer above the salt is the 900 foot (274 m.) thick. Permian Nippewalla Group. The Nippewalla Group is called the "Permian redbeds" and includes the Cedar Hills Sandstone, Salt Plains Formation, Harper Sandstone and other thin members. (Swineford, 1955, p. 90). These units are primarily red and gray sandstones, red siltstones and shales. The dominant color of this group is red and is easily distinguishable in well cuttings. The Cedar Hills Sandstone consists of red, massive, very fine-grained sandstones and sandy siltstones. Granular Gypsum "snow-balls" can be found in the top white fine-grained sandstone (Swineford, 1955, p. 60). The depositional pattern of the Cedar Hills Sandstone closely follows the erosional pattern of the Cheyenne Sandstone, thickening from a feather edge in the eastern part of the study area. The Cedar Hills Sandstone was used as a shallow disposal zone for brine during the same time as the Cheyenne Sandstone, although no specific data exists concerning its use. However, it can be assumed that the Nipewalla Group is similar to the Cheyenne Sandstone. Thus, another potential source of up to 10 gallons (37 litres) per minute of water for salt dissolution exists above the salt (Fader, 1975, p. 8).

The similarity of the Dakota Formation, Kiowa Formation, Cheyenne Sandstone and Cedar Hills Sandstone shown by electric logs allows the grouping together of these units on the interpreted log as "aquifers."

Sumner Group. The 800 foot (25 m.) thick Sumner Group of which the Hutchinson Salt is a member is an aquitard. The salt is a 400 to 500 foot (120 to 150 m.) interval underlying central Kansas and western Oklahoma. In Kansas it covers approximately 27,000 square miles (69,900 square km.) (Walters, 1976, p. 5). Figure 1 shows the thickness, in feet, and the extent of the salt. The eastern boundary is an erosional edge due to the closeness of the salt to the water table. The northeastern to the western edges are depositional boundaries first reported by Bass (1926, p. 93).

The environment and mechanics of the deposition of the salt have been investigated by Dellwig (1963). He listed features which help determine the environment of deposition. These include the layering of clear and cloudy salt, evidence of recrystallization, seasonal layering "Jahresinge" or laminations of shale and anhydrite and interbedded thick shales and anhydrite.

The salt was deposited during the Cimarronian Stage of the Permain Period in an environment of nonseasonal climatic conditions. Periodic but sporadic influx of brine is shown by laminae of clay. Mud cracks and polygons suggest shallow basins that were frequently exposed to the air (Dellwig, 1963, p. 80).

The salt has no "type locality" because there are no outcrops. However, a test hole was drilled in 1958 at the former Hutchinson Naval Air Station. This hole serves as a reference locality for the salt. The test hole is known as HNAS Core Hole No. 1 and is in the SE¼, NE¼, Sec. 29, T. 24 S., R. 5 W. Reno County, Kansas (Walters, 1976, p. 14).

A detailed lithologic and petrographic study of the salt from a depth of 423 to 734 feet (129 to 224 m.) was made by Jones (1965, p. A55-A65) and corrected with his permission by Walters (1976, p. 14). The composition of the salt was 82 percent halite, 3 percent anhydrite, 4 percent carbonate, dolomite and magnesite, and 11 percent shale and siltstone (Jones, 1965, p. A10).

The salt contains a basal transition zone that ranges up to 40 feet (12 m.) thick. This zone is generally a basal shale or siltstone that progresses upward to dolomite or magnesite, anhydrite and halite. The carbonate and anhydrite are usually only a fraction of an inch thick (Jones, 1965, p. A10). This transition zone indicates that gentle topographic highs, anticlinal areas, were present in mid-Permian time, during the deposition of the salt (Walters, 1976, p. 19). This caused thinner deposits over the high areas and thicker deposits in the low areas. The transition zone of the salt makes a precise determination of salt thickness almost impossible on geophysical logs and usually only accurate to plus or minus 10 feet (3 m.).

Anhydrite and shaly, silty, redbeds overlie the salt and have protected it from dissolution until recently, when the beds were penetrated by boreholes. The Sumner Group has not only kept water away from the salt but also has prevented upward migration of hydrocarbons.

Aquifers Below the Salt. The aquifers below the salt are Permian limestones and shales, Pennsylvanian limestones and shales, Ordovician and Cambrian dolomite and sandstones, and Precambrian "granite wash". All these formations are of interest mainly because they provide a porous zone for fluids to drain below the salt, if a borehole exists to provide hydrologic connection.

The Permian rocks below the salt include the 330 foot (100 m.) thick Chase Group that underlies the Sumner Group and consists of limestone with interbedded shale, the Council Grove Group which is approximately 315 feet (96 m.) of limestone and interbedded shale with thin limestone beds, and the Admire Group containing approximately 130 feet (40 m.) of shale with some thin limestone beds (Zeller, 1968, p. 44-48). All these units could accept water from above if it were available. The Permian Admire Group unconformably overlies the Pennsylvanian Wabaunsee Group.

The Pennsylvanian rocks which could accept water include the 500 foot (150 m.) thick Wabaunsee Group, primarily shale with thin limestones and some sandstone. The 325 foot (100 m.) thick Shawnee Group consists of four limestone and three shale formations. A distinctive type of cyclic sequence is a characteristic of the Shawnee Group (Zeller, 1968, p. 35). The 440 foot (130 m.) thick Lansing Group and Kansas City Group consist mainly of limestone and shale. They have been oil producers and have undergone secondary recovery by waterflooding. This zone would accept an unknown quantity of brine because waterflooding has possibly filled the aquifer. The Pennsylvanian rocks unconformably overlie the Ordovician and Cambrian Arbuckle Group.

The Ordovician and Cambrian aquifer is the Arbuckle Group that is dolomite and basal sandstone. As a result of weathering during the Pennsylvnaian period it has good permeability and porosity. The aquifer is an important oil producer with an unknown capacity for holding brines. The Arbuckle Formation is an aquifer likely to receive water that has caused salt dissolution, if the borehole extends to this depth.

The Precambrian "granite wash" is also am oil producer and could possibly accept some water from above, although not as much as the Arbuckle Formation could receive (Fader, 1975, p. 9).

METHODS OF INVESTIGATION

Oil Well Information

The location and completion dates of oil and gas wells in the study area were taken from the files of the Kansas Geological Survey, Lawrence, Kansas. The well location data are accurate at best to a ten acre tract. The completion dates of oil wells were taken as reported in the files. Other data such as casing size, log information, and production capability of wells were also gathered. Undoubtedly not all the wells in the study area are listed in the survey's files but no sure way exists to determine how many more wells there actually are.

Electric Log Information

Electric well logs were studied at the Kansas Geological Society offices in Wichita, Kansas, and at the Kansas Geological Survey offices in Lawrence, Kansas. These logs were interpreted and formation contacts along with well information were recorded for later use.

Drillers logs were not utilized because actual formation contacts were unreliably recorded.

Remote Sensing Photographs

LANDSAT and aerial photographs supplemented the oil well information. LANDSAT photos were borrowed from the Kansas Geological Survey and the Space Technology Center both at Lawrence, Kansas. These photos were positive transparencies of the Russell County area. Aerial photos of the study area were borrowed from the Kansas Geological Survey at Lawrence and the U.S. Department of Agriculture at Russell, Kansas.

RESULTS AND INTERPRETATION OF DATA

Remote Sensing Methods

The examination of remote sensing photographs revealed no information on salt dissolution. Both LANDSAT and aerial photos of the area were studied to attempt to find changes in the drainage patterns of streams in the study area or the formation of new sinkholes.

The LANDSAT photos used were exposed in the wavelength of light from 0.8 to 1.1 micrometers. This is the light with wavelengths longer than red light but shorter than infrared. The LANDSAT photos studied were numbers ERTS E-1347-16453-7 Ø1 taken on July 5, 1973 and ERTS-1329-16454-7 Ø1 taken on June 17, 1973. These photos represent a ground area of 185 km. (100 nautical miles) on a side. Because of the large area each photo covers, subtle details can not be distinguished. However, the wavelength chosen shows water as a dark area, in contrast to the lighter surrounding area. This contrast makes the identification of surface water fairly easy. The scale of these photos proved to be too small for the expected size of a land subsidence anomaly. Thus, no information was gained from studying the LANDSAT photos that could be used to locate a change in drainage patterns or the location of a new sinkhole.

Air photos from two different years were examined and compared for possible changes in drainage patterns. Photos taken in 1956 were compared with those taken in 1965. No detectable changes in drainage patterns were found in photos of the same area.

If the time span between the groups of photos had been greater, more information might have been obtained. However, the drainage changes that develop around an area of subsidence are usually small enough to go undetected until the sink forms.

The photos were also used to locate areas of interest after studying the isopach maps.

Interpreted Electric Log

An electric log reveals the response a certain logging method such as a gamma ray or a neutron log, records after a formation is exposed to the logging stimulus.

By interpreting the responses that are on a log information on the formation contacts can be obtained. The ideal response of a combination log, gamma ray, resistivity and focused electric log, to the formation in the study area is shown in an interpreted log (Fig. 3). This log is from an oil well at the corner of the NW$\frac{1}{4}$, NE$\frac{1}{4}$, NE$\frac{1}{4}$, Sec. 28, T. 14 S., R. 14 W. The log has been modified from the 1966 type log for Russell County, published by the Kansas Geological Society in Wichita, Kansas.

The log has been marked to show the formation contacts. By examining the contacts some of the problems which arise in log interpretation can be seen. The section marked "aquifers", including the Cedar Hills Sandstone, Cheyenne Sandstone, Kiowa Formation, Dakota Formation and Quaternary deposits, exhibits similar responses to the logging procedure. Because all the "aquifers" can contribute water for salt dissolution they can be considered as one unit making log interpretation much easier.

The indefinite contact between the Salt Plain Formation and the Harper Sandstone in the Nippewalla Group is shown by the minor fluctuations which occur throughout the lower interval of the Nippewalla Group. For this reason these two formations were considered as one interval when interpreting the logs.

The problem of determining where the lower limit of the salt occurs is not evident on this log. A rough indication of the type of record produced by a gamma ray log for the transition zone can be seen in the 20 to 30 foot (6 to 9 m.) interval beneath the salt. This zone makes the determination of the base of the salt an approximation at best.

Using the interpreted log as a guide other logs in the study area were examined. The information gathered provided data for use in the construction if a cross section, a contour map of the salt top, and an isopach map of the salt interval.

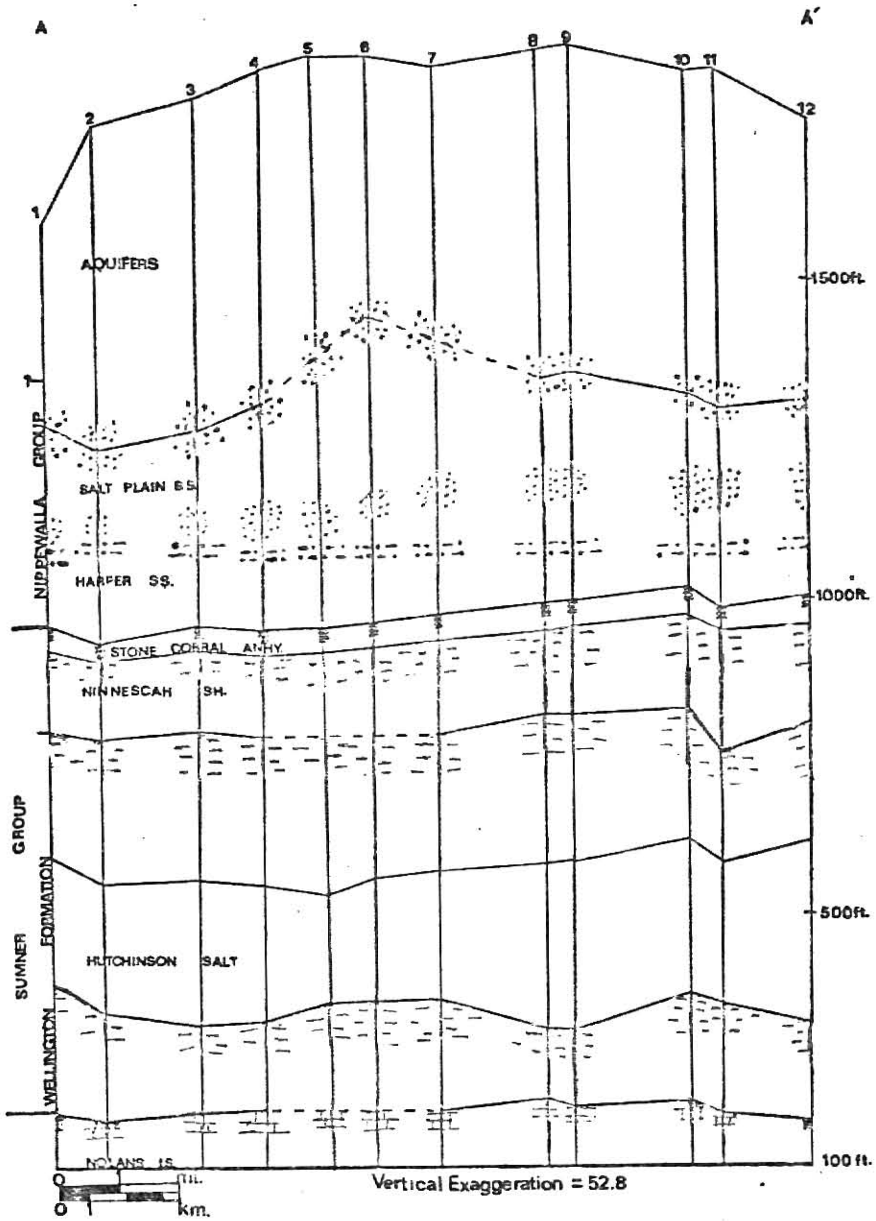
Cross Section

A north-to-south cross section was prepared using electric log information (Fig. 4). The north-to-south section was chosen because this is the only part of the study area that a fairly complete set of electric logs traverse. However, not all these logs cover the entire borehole. Many logs used did not record the upper 200 to 300 feet (61 to 91 m.) of the borehole.

A generalized graphic representation has been used to show the lithology of the units. The location of the cross section is on the contour map of the salt top (Fig. 5). A list of the wells that comprise the cross section is in Appendix 2. The elevations listed on the cross section are all above sea level.

The contact between the Salt Plain Formation and the Harper Sandstone proved difficult to determine on electric logs so these units are grouped together in the lower part of the Nippewalla Group. The location of the unit names and the lithologic change from a shale and sandstone to a siltstone is given only to show that a change does occur in the Nippewalla Group, and not to indicate where the contact between the Salt Plain Formation and the Harper Sandstone is located.

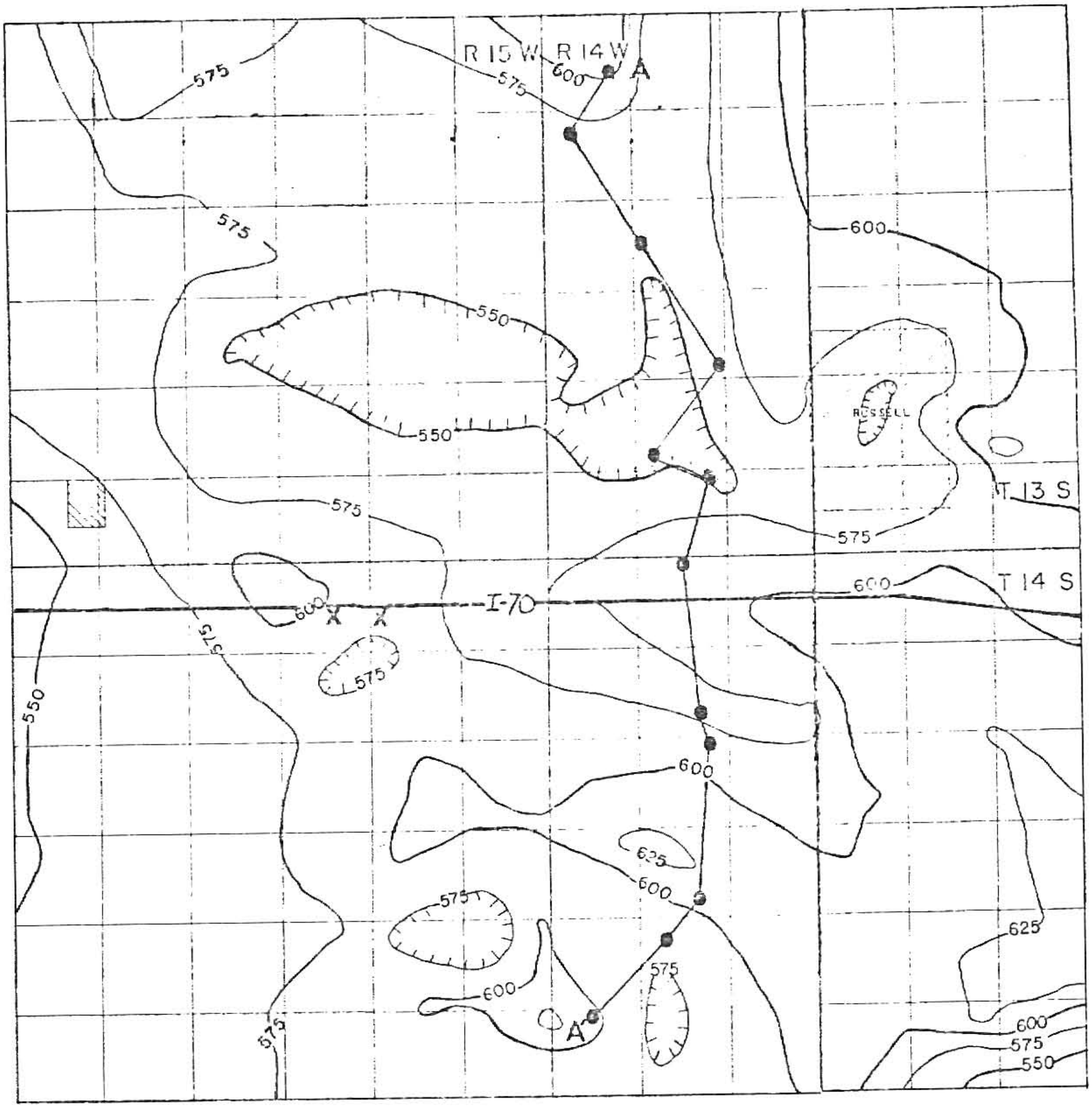
All units upward from the base of the Cedar Hills Sandstone to the surface are grouped as "aquifers". This was done because not all logs from the study area start at ground level; many do not begin until the lower part of the Cedar Hills Sandstone. This makes determining the different formation contacts a problem. Another problem is that the Cheyenne Sandstone and the Cedar Hills Sandstone have a tendency to thicken and thin unpredictably across the study area. As these two units are very similar in their response to logging, the contact between them is



(altitudes given in feet above sea level)

sandstone limestone shale
siltstone anhydrite salt

Figure 4. North to south cross section of study area.



LEGEND

CONTOUR INTERVAL = 25 FT.

— I-70 — Interstate Route 70

● - cross section well location

x - Crawford & Witt sinkholes

scale: 0 1 mi.; 0 1 km.

Figure 5. Contour map of top of the Hutchinson Salt Member of the Wellington Formation showing the location of the cross section.

difficult to determine.

The units grouped as "aquifers" are the source of unknown quantities of water available for salt dissolution. Although the exact source of the water is not known, it probably comes from the Cheyenne Sandstone or the Cedar Hills Sandstone and possibly from the Dakota Formation.

The bottom of the cross section was chosen as the Nolans Limestone in the Chase Group because it is below the Wellington Formation and also because it has a response that is easy to identify on an electric log.

Several logged intervals are incomplete at locations where an SP log had to be used. An SP log is almost impossible to use for determination of formations above the salt because after the salt has been drilled the salinity of the mud increases to a point where the log only records the largest responses, such as salt or anhydrite beds.

Examination of the cross section shows the change in thickness of the formations across the study area. Along the cross section the formations do not show much variation in thickness, even with a vertical exaggeration of 52.8. The change in the thickness of the salt at the southern edge of the cross section can be attributed to a change in the basal transition zone of the Wellington Formation.

By using the cross section as a reference when examining the thickness of the salt, the variations in the thicknesses of the remaining formations can be determined.

Contour Map of Salt Top

A contour map of the top of the salt was prepared from oil well log information to show how the surface of the salt changes over the study area (Fig. 5). The salt top is usually easy to locate on an electric log, but the base is often an estimate of where the transition zone starts and the salt stops. Therefore, the contour map provides control for the isopach maps which follow.

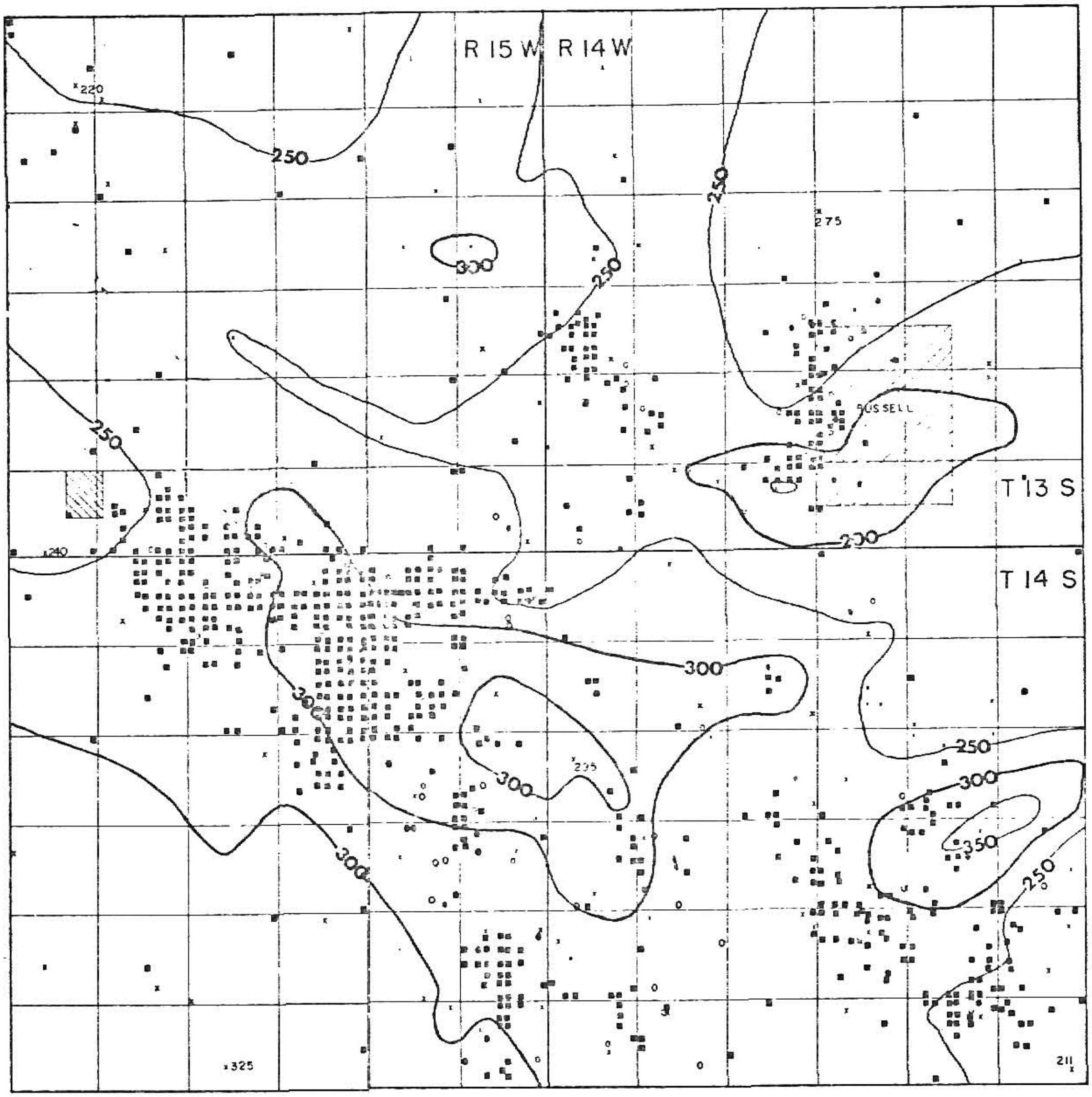
A contour interval of 25 feet (7.6 m.) was chosen for the map to show the general features of the salt. The amount of data available is too limited to justify a smaller contour interval.

The control points for this map are the same as those on the following isopach maps. The location of the wells used are in Appendix 1 and can be located using the X's on the isopach map.

The contour map shows the top of the salt as a gently rolling surface changing from a high of 600 feet (183 m.) above sea level on the northern edge to a low of under 550 feet (168 m.) above sea level near Russell, and back to a high of 625 feet (190 m.) along the southeast side. When the map is compared to the isopach maps that follow, the highest areas of the top of the salt can be roughly correlated with the thickest areas of the salt. Poor correlations are due probably to the basal transition zone causing problems in interpretation.

Isopach Maps of Salt

The relationship between the location and year of completion of oil and brine wells and the thickness of the salt is one possible factor in determining salt dissolution. Figures 6 through 8 are isopach maps of the salt with locations of oil wells and brine disposal wells. The locations of all wells are accurate to approximately a ten acre tract. All three maps contain the same isopach and brine disposal well information. The years of oil well completion varies on each map,



LEGEND

x - control point

o - shallow disposal well (< 800 ft. deep)

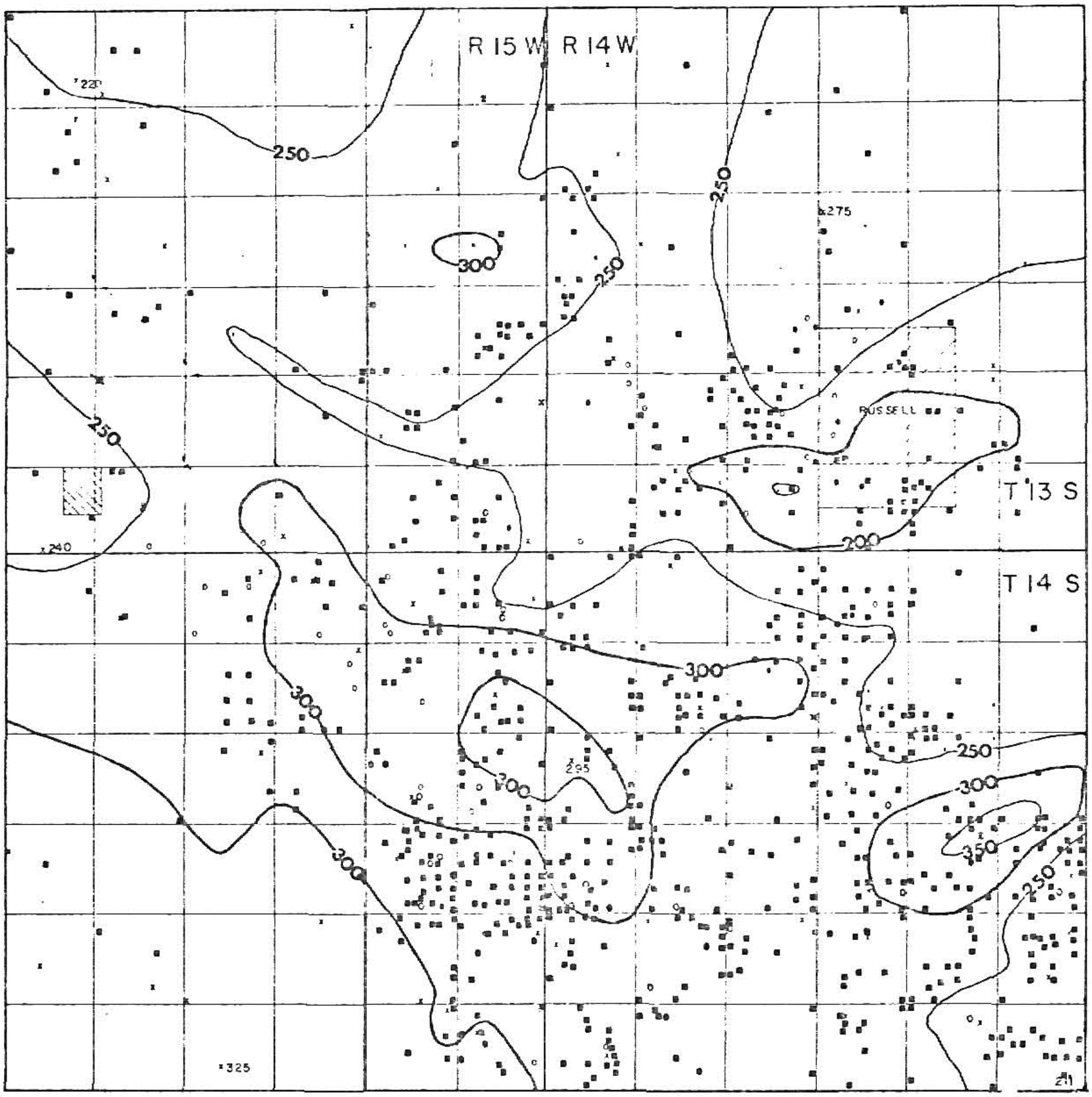
● - deep disposal well (>800 ft. deep)

▣ - borehole

contour interval = 50 ft.

scale: 0 1 mi.; 0 1 km.

Figure 6. Isopach map of the Hutchinson Salt Member of the Wellington Formation showing wells drilled from 1927 to 1940.



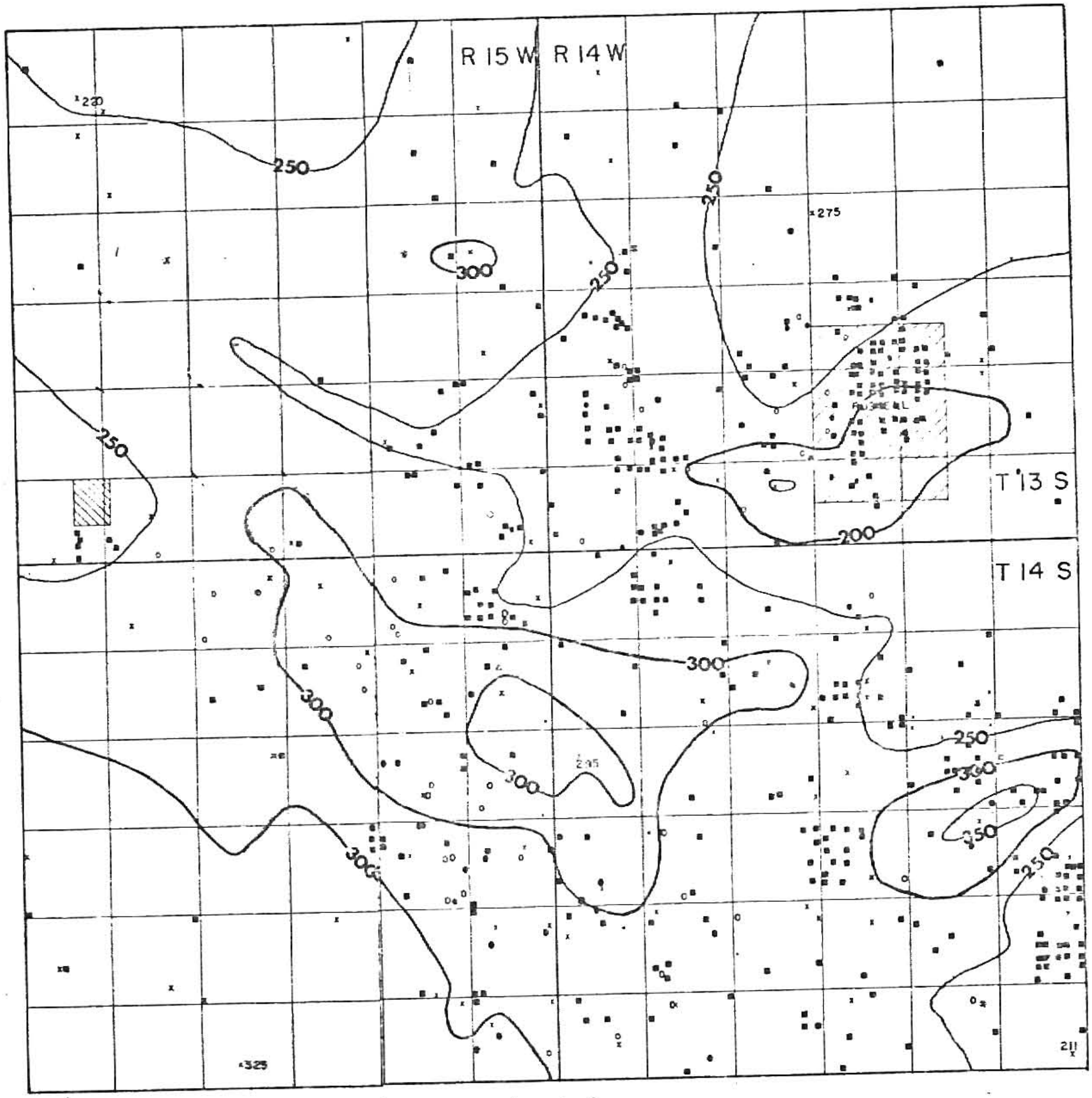
LEGEND

x - control point
o - shallow disposal well (< 800 ft. deep)
● - deep disposal well (>800 ft. deep)
▪ - borehole

contour interval = 50 ft.

scale: 0 1 mi. / 0 1 km.

Figure 7. Isopach map of the Hutchinson Salt Member of the Wellington Formation showing wells drilled from 1941 to 1950.



LEGEND

x - control point

o - shallow disposal well (< 800 ft. deep)

● - deep disposal well (>800 ft. deep)

■ - borehole

contour interval = 50 ft.

scale: 0 1 mi.
0 1 km.

Figure 8. Isopach map of the Hutchinson Salt Member of the Wellington Formation showing wells drilled from 1951 to 1956.

13 years for Figure 6, 10 years for Figure 7, 6 years for Figure 8. This was done to provide a visual guide to locating areas where salt dissolution might be occurring and also to the well density over the years.

The stopping point of 1956 for examination of wells was chosen for two reasons. First, based on observations of the known sinkholes in the area, a period of time greater than 30 years is necessary for dissolution to reach a point where collapse can occur. Any wells drilled later than 1956 are probably not old enough for dissolution to be presently detectable either at ground level or in the subsurface using currently available information. Secondly, after 1956 Kansas began to pass stricter laws concerning the grouting and sealing procedures of oil and gas wells. These regulations may have been strict enough to prevent any future dissolution from occurring.

The isopach maps were constructed from oil well log information. Gamma ray and neutron with focused logs were used whenever possible. These logs give better information on formation boundaries when run in a salty mud than does an SP log. This is because the salinity of the mud increases as the salt dissolves causing the SP log to record the potential of the salty mud rather than the potential of the formation. However, gamma ray logs are not always available so SP and resistivity logs were used if other logs were unavailable.

The isopach map is possibly in error by as much as 25 feet (7.6 m.). The error is caused by the difficulty in locating the transition zone from the log, because the zone does not respond uniformly to a recording signal. The differing responses are due to a change from an almost pure salt to a shale with differing amounts of salt and anhydrite.

A more accurate isopach map might have resulted if the interval from the top of the salt to the top of the Nolans Limestone was used. However, at the beginning of the study it was believed that the thickness of the salt was an important factor in determining dissolution and the maps were prepared using the thickness of the Hutchinson Salt.

Because of the possibility of such a large error existing in the data, a contour interval of 50 feet (15.2 m.) was chosen. This interval allows an approximate thickness of the salt to be used as a base for comparing the oil well and brine well locations.

The data used for the construction of the isopach map were first plotted on a map and then to reduce the possible error the salt thicknesses were compared to be sure that the logs had been correctly interpreted. If a difference greater than 25 feet (7.6 m.) was discovered among values less than five miles apart the logs were reexamined. This procedure provided better control over the determination of the salt.

Figure 6 shows the isopach map with the drilling dates of oil wells, both producers and dry holes, from 1927 to 1941. This time interval is important because a long period of time appears necessary for the salt to dissolve sufficiently to produce surface collapse. The time approximation is based on the approximately 35 years required for the two known sinkholes, the Witt and the Crawford, to develop and appear on the surface. (See Appendix 3 for more information.)

Other reasons that this time interval is important are that before 1940 the Kansas Corporation Commission used untrained county employees on a fee basis to supervise drilling activities and the regulations concerning well completion practices were vague.

Areas having a shallow brine disposal well surrounded by completed oil wells can be located from this map (Fig. 6). The combination of a source of undersaturated brine and boreholes to allow migration of water is possibly another important factor in determining where salt dissolution could occur.

The map also shows where the salt is the thinnest. Dissolution in a thin salt layer would result in the formation of a thinner but wider cavity than would form in thicker salt. Collapse could occur with a vertical displacement less than that associated with thicker salt but over a broader area. Because a cavity would develop, some degree of collapse could occur sooner in an area of thin salt than in an area of salt thicker than 250 feet (76 m.).

In sections 21 and 22 T. 13 S., R. 14 W. most wells drilled before 1940 were completed from 1934 to 1936. Although the disposal wells were first used in the early 1950's, the area is of interest because it is close to Russell, Kansas. However, after checking available well logs and aerial photographs no evidence of salt dissolution was found at this site.

In sections 27 and 28 T. 13 S., R. 14 W. the wells were completed from 1934 to 1937 and the disposal wells were in use by 1942. This area is a possible site to find evidence of dissolution because of the relatively thin salt, 200 to 250 feet (61 to 76 m.), the old wells (drilled approximately 40 years ago) and the shallow brine wells located nearby. Aerial photos were examined and failed to show any change in surface drainage patterns. Electric logs provided no clues about salt dissolution in the borehole. The area is next to Russell, Kansas, and so should be kept under surveillance in case dissolution is occurring, but has not yet reached a critical stage.

In section 35, T. 14 S., R. 14 W. the salt is less than 250 feet (76 m.) thick and the wells were completed from 1936 to 1940 with a brine disposal well drilled in 1944. The brine well had an initial disposal rate of 50 barrels (7.95 cubic meters) per hour at 250 pounds (1775 kiloPascals) of pressure and was drilled to a depth of 750 feet (228 m.). Aerial photos and electric well logs provided no conclusive evidence of dissolution.

The two known sinkholes, Witt and Crawford, are in sections 2 and 3, T. 14 S., R. 15 W. Near these, section 4 contains several oil wells drilled in 1929, although most wells drilled before 1940 were completed from 1934 to 1936, and the disposal wells were in use by 1942. Inspection of aerial photos and available electric well logs failed to reveal anything of interest. However, as this area so close and almost identical to the two known sinks, it should be watched as a possible salt dissolution site.

Elsewhere in T. 14 S., R. 15 W. sections 10 and 11, which are south of the known sinkholes, contain a likely area for salt dissolution to occur. Section 10 contains oil wells completed from 1935 to 1939 and brine disposal wells which were in use by 1942. Section 11 contains oil wells completed from 1936 to 1940 and a brine disposal well in use by 1942. Neither of these sections show any evidence of salt dissolution. Because of the closeness of these wells to a known area of dissolution and the similarities between the two areas, it is possible that dissolution is occurring but has not yet reached a point where surface evidence is present.

The other two isopach maps, (Fig. 7 and 8), show oil wells completed from 1941 to 1950 and 1951 to 1956 with the same brine disposal wells as the first map. No areas which indicated that salt dissolution might be occurring were found on either of these two maps. The lack of evidence is due probably to a shorter time, less than 36 years, since the wells were drilled. Other possible factors could be better casing and plugging procedures than were practiced earlier and stricter supervision by Department of Health employees during the drilling and completion of test holes and wells.

Even though no direct evidence of current salt dissolution was found, it is believed that salt dissolution is taking place in the study area. This conclusion is based on talks with state highway personnel who have stated that the water level in the borehole associated with the Crawford sink has fluctuated during various times of the year. At one point the borehole was believed to have stabilized. However, a few days later the borehole was again almost empty. Such a change could have at least two possible causes. The cavity may have become temporarily plugged, allowing water to back up and fill the hole. Alternatively the waterflooding of the Lansing-Kansas City Groups created excess pressure and forced water up the borehole. Whatever the cause, any fluctuations in the water level across the salt section could result in dissolution.

Comparison of Salt Thicknesses

Another indication of salt dissolution would be a difference in the thickness of the salt based on information gathered from two electric logs run in an area of similar salt thickness.

The time difference between compared logs was at least 5 to 10 years and sometimes 20 to 30 years. Although this time span is not as great as desired, it should show some change in thickness of the salt, if such a change exists. The greatest problem in comparing the logs comes from a lack of data over an area of equal thickness. Too often logs that are 20 to 30 years apart are from an area where a known variation in the thickness of the salt exists.

By using the isopach map of the salt and the well log location, it was usually possible to compare similar salt thicknesses over distances of less than one mile. The results of these comparisons are shown in Table 1. It is apparent that no change in salt thickness occur based solely on the time interval between two logging runs in an area of similar thickness. Any change which that was found could, upon closer inspection of the logs, be attributed to a cause other than dissolution, for example, a change in the thickness of the transition zone or the use of an SP log in determining the salt thickness.

Even though no differences in salt thicknesses were found, several logs showed that the salt is missing from the borehole. These logs are neutron logs that record a presence of hydrogen to a shallow depth of penetration. Ordinarily salt will give an indication of no hydrogen by a trace that goes to the right on the scale. In these well logs the neutron trace runs to the left side of the scale indicating a high hydrogen count or water in the borehole. The only way for water to be present throughout the salt section is for the salt to be missing along the logged interval.

Three logs were found which show no salt (Table 2). The amount of salt which has been dissolved can not be determined because of the absence of a focused electric log that would show the salt at a depth where a neutron log can not penetrate. These logs show nothing unusual about their closeness to a brine disposal well or to a particular thickness of salt.

Table 1. Comparisons of Thickness of Salt
in Nearby Wells of Different Ages

LOCATION ¼ ¼ ¼ SEC.__,	T__S,	R__W	YEAR LOGGED		SALT THICKNESS (FT.)
SW SW NW 22	13	14	1976		225
NW SE NW 22	13	14	1953		200
NE NW NW 33	13	14	1948	*	190
SW NE SW 33	13	14	1962		195
NE NW SE 31	14	14	1948	*	260
NE NW NW 31	14	14	1966	Tz	285
SW SE SE 3	14	15	1953		260
C NE 3	14	15	1964		255
SW SE NE 24	14	15	1948	*	240
SE NW NE 24	14	15	1959		260
CS2 SE SW 14	13	15	1965		240
NE NE SW 14	13	15	1951		250
NE SE NE 25	13	15	1945		270
CS2 NE NE 25	13	15	1951		270

* An SP log was used

Tz- The transition zone accounts for variation

Table 2. Locations of Wells
With Salt Missing in the Borehole

LOCATION ¼ ¼ ¼ SEC.__, T__S, R__W			COMPANY	WELL
NE SE NW 3	14	15	SOHOIO PET. CO.	FOSTER "A" NO.5
LOGGED 4-28-59				
NE NW NW 31	14	14	OKMAR OIL CO.	HUMMEL NO.4
LOGGED 3-26-66				
NE NE NE 26	13	14	JET DRILLING CO., INC.	KRUG"B" NO.1
LOGGED 11-13-72				

These logs recorded no salt along the borehole indicating that dissolution had occurred either after the well was drilled but before the log was run or between different logging runs.

The wells with the missing salt are the most likely spots for subsidence to occur. However, examination of air photos showed no surface evidence of subsidence. These wells also point out that there seems to be no positive way to determine where salt dissolution might occur. The year the well was logged ranges from 1959 to 1972. The salt thickness ranges from under 200 feet (61 m.) to over 300 feet (91 m.) and none of the wells are near a shallow brine disposal well.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

Conclusions

A connection between the location and completion date of an oil well and the thickness of the salt was sought. First, areas that seemed to have all the necessary factors for dissolution to occur, such as an old oil well, thin salt, and a shallow brine disposal well were located. Next, aerial photos were examined for signs of drainage changes. This should have revealed wells which were likely candidates for salt dissolution or where dissolution had already started to cause subsidence. These factors failed to produce positive results.

The most important factor related to salt dissolution seems to be the time since the well was completed. Unless sufficient time has elapsed since a well was drilled the salt can not have been exposed to enough water for large amounts of salt dissolution to occur. The older a well is, the more likely it is to have a corroded casing which could allow water to enter the borehole, or for the well to have deteriorated from improper sealing procedures resulting in a flow of water over the salt.

To estimate the volume of water needed to dissolve the salt certain assumptions must be made. Fader (1975, p. 5-18) made a study of the Crawford sink and determined that the following conditions influenced the dissolution process:

> 1. The volume of salt removed is equal to the volume of subsidence at the shallow limestone marker bed (4,700,000 ft^3 or 133,000 m^3).
> 2. The movement of water is downward from the Cheyenne or Cedar Hills Sandstones into the permeable formations below the salt.
> 3. The concentrations of chloride changed from 3,000 to 150,000 ppm as the fluid circulated through the salt.
> 4. The volume and mass of dissolved solids, other than sodium, is negligible.
> 5. Dissolution of salt occurred at an average rate during the 30-year period 1941-70.
> 6. All other factors, such as temperature and pressure, are considered to be constant and any errors caused by such factors are considered to be within the limits of accuracy imposed by the precision of the basic data.
>
> Using the above assumptions, 1 gal ($3.785 \times 10^{-3} m^3$) of salt solution changing from 3,000 to 150,000 ppm of chloride as it circulated through the salt, would dissolve about 0.02 ft^3 (0.0006 m^3) of salt. Therefore, about 235,000,000 gal (890,000 m^3) of solution would be needed to dissolve 4,700,000 ft^3 (133,000 m^3) of salt to equal the volume of subsidence at site 1 (Crawford sink). The average rate of flow required to discharge this volume of fluid during 30 years would be about 15 gal/min (0.95 l/s). (Fader, 1975, p. 17)

Other evidence that suggests that salt dissolution is happening in the study area is that wells drilled to the north and west of the Crawford sink have produced brine that was almost saturated with respect to halite. In addition to this, the borehole at the Crawford sink is capped and has been observed to have a partial vacuum formed before the cap is removed. This combination of a vacuum in the borehole and a report of almost saturated brine solution suggests that water is being drawn down the borehole and entering a producing horizon, dissolving salt as it goes.

The time required for dissolution is not precisely known. The only indications of how much time might be needed by wells in the study area is given by the development of the Crawford and Witt sinkholes. These two sinks needed approximately 40 years to develop to their present state. If this is an approximation that will hold for the remainder of the study area, then those wells drilled before 1940 are now entering a critical stage in the development of subsidence.

Presently the number of the wells possibly undergoing dissolution is unknown and will be difficult to determine.

Recommendations for Future Study

Certain studies are needed to determine where salt dissolution is occurring and where it might occur in the future.

Seismic Survey. A seismic survey to determine where salt dissolution is occurring could be run at least in areas where sinkhole development would present a danger to human life. A reflection seismic survey using high frequency, up to 200 Hz., sound waves has proved useful in outlining solution-mined-cavity boundaries (Cook, 1974). The isopach map of the salt (Fig. 6) showing which wells were completed prior to 1940 and the density of the old wells could be used to determine where to run such a survey. Figure 6 also shows where well drilling occurred near and around the towns of Russell and Gorham. Thus, a suitable place to run a seismic survey would be around the town of Russell or along Interstate Highway 70. Both areas have old wells drilled in locations where sinkhole formation could cause excessive damage. Although the cost of such a survey would be large, it could be justified if sinkholes begin to develop in areas of human habitation.

Borehole Reentry. Another method to determine the extent of dissolution would be to reenter boreholes that appear to be undergoing dissolution. The salt interval could then be cemented off at the top and bottom to possibly prevent further dissolution. However, determining which wells should be reentered is a problem.

Neutron logs could provide the information needed to justify the reentry of a borehole by showing no salt along the borehole, and thus, evidence of salt dissolution.

Neutron logs from the study area revealed only three wells which had evidence of borehole dissolution, including the Hummell No. 4 well, (Table 2), that was logged approximately 10 years after the well was drilled. This is not enough logs to justify the reentry of many boreholes. One possible reason that so few logs showed any salt missing is that less than fifty percent of the logs studied were neutron logs. This would mean that there are more wells with salt missing than are known.

Another problem with reentry is finding the borehole and then being able to remove any scrap iron placed into it prior to abandonment. The reentry method is expensive and could not be used until wells were located which had evidence of dissolution. If areas of dissolution can be located, possibly by a seismic survey, then borehole reentry and plugging off of the salt interval is a procedure that is recommended to stem the rate of dissolution.

Wells which are still in production but were drilled before 1940 could also be reentered and logged. These wells would be cased so logging would have to be done with a neutron log that would record the salt section through the casing.

If the salt were absent along the sides of the borehole then a thermal log could be run to determine where the water that was dissolving the salt was derived. If the salt section recorded as a low temperature the water would probably have come from the brine aquifers above the salt, a higher temperature would indicate that the source of the water was below the salt section. Once the thermal characteristics of the salt section had been determined the casing could be perforated and the salt section could be cemented off to stop further dissolution.

This method would be expensive but would be easier than reentering abandoned holes because of the unobstructed hole. Further investigation of the feasibility of this method is recommended because of the relative ease of logging the borehole once access to it is gained.

Studies of the Salt and Overlying Rocks. Exactly when the salt is dissolved to the extent where the strain on the roof rocks becomes too great is another problem needing study. The span strength of the Permian redbeds is not precisely known. The salt mining industry could provide some help in determining the strength of the rocks. However, whether or not the redbeds behave similarly in salt mining and dissolution along a borehole is unknown. During borehole dissolution it is possible the roof rocks are exposed to processes of deterioration that could weaken the rocks differently than solution mining does. The variable strength of the redbeds is another unknown. These are problems that need to be determined before predictions on where salt dissolution will occur can be made.

Another unknown problem in trying to predict dissolution is the dissolution rate of the salt. Durie and Jones (1964), Serata (1970), and von Schonfeldt (1974) have investigated cavity formation in brine solution mining. These studies all developed differential equations to simulate how salt dissolves during solution mining. The equations do not exactly apply to dissolution along a borehole for the following reasons. The waters involved in dissolution of the salt along boreholes have chloride contents that differ across the study area (Walters, 1976, p. 110-112). The salinity change in the water is a factor that contributes to the rate of dissolution, but has not been considered by the solution mining studies.

As the salinity of the water dissolving the salt increases, the solution becomes denser, sinks to the bottom of the cavity and dissolves less and less salt. This causes a funnel shaped cavity to develop as time progresses. During solution mining a more spherical shaped cavity is formed due to the constantly circulating water. The difference in cavity form is another deviation from the formulas developed for solution mining.

The rate of dissolution in a borehole is dependent upon the quantity of water flowing past the salt. The quantity of water available for dissolution from the "aquifers" is another unknown factor that needs to be determined before an estimate on the time required for dissolution can be made.

Experimental studies are needed on the processes which affect salt dissolution and ground subsidence to determine where salt dissolution could occur and to predict the possibility of future subsidence.

Questionnaire. A way of locating possible areas of dissolution that is not as expensive as the previous methods would be a survey of farmers and landowners in the study area. The survey could ask if any wet spots had been developing in fields over the past few years. These wet spots could be the first indication of the formation of a sinkhole. Another possible question would concern the location of any old oil wells on their property. This could lead to locating wells or exploratory holes which were omitted in files of the Kansas Geological Survey. Any wells located would probably have been drilled in the time prior to 1940 and so would be of interest because of their age.

Results from such a survey might be useful to locate areas of new subsidence or unrecorded wells in which salt dissolution may be occurring.

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APPENDIX I

Control Points for Isopach and Contour Maps

LOCATION						SURFACE	SALT INTERVAL	
¼	¼	¼	SEC.__,	T__S,	R__W	ELEVATION (FT.)	TOP (FT.)	BOTTOM (FT.)
SW	SE	SW	1	13	15	1780	-1235	-1510
C	NE	NE	3	13	15	1812	-1279	-1514
NE	SW	SW	5	13	15	1848	-1335	-1574
SW	NE	SE	6	13	15	1865	-1396	-1546?
CW2NE		NE	7	13	15	1908	-1320	-1608
NE	SW	SW	8	13	15	1895	-1315	-1592
SW	SE	SE	11	13	15	1837	-1278	-1547
NE	NW	SW	13	13	15	1814	-1242	-1551
NE	NE	SW	14	13	15	1836	-1275	-1545
NW	NE	SE	17	13	15	1864	-1277	-1543
NW	NW	SE	21	13	15	1801	-1343	-1592
SW	NE	SW	24	13	15	1843	-1308	-1572
NE	SE	NE	25	13	15	1876	-1328	-1557
SE	NW	SW	26	13	15	1892	-1340	-1587
SE	SE	SW	31	13	15	1889	-1342	-1528
SW	SW	NE	32	13	15	1900	-1332	-1581
CN2SW		SW	34	13	15	1913	-1322	-1643
W2	SE	SE	36	13	15	1869	-1308	-1554
NE	NW	SE	6	13	14	1601	-1110	-1330
NW	NE	SE	7	13	14	1636	-1080	-1305
NW	SE	SW	13	13	14	1822	-1215	-1465

LOCATION				SURFACE	SALT INTERVAL	
¼ ¼ ¼	SEC.__,	T__S,	R__W	ELEVATION (FT.)	TOP (FT.)	BOTTOM(FT.)
SW NW NW	15	13	14	1813	-1210	-1485
NW NW SW	17	13	14	1798	-1245	-1480
SW NW SE	18	13	14	1694	-1120	-1380
CN2S2 SE	19	13	14	1856	-1300	-1515
NE SE NW	22	13	14	1840	-1255	-1535
SE SE SE	23	13	14	1831	-1240	-1415
NW SW SW	25	13	14	* 1827	-1245	-1450
NE NE NE	26	13	14	1827	-1240	-1450
SW NE NE	27	13	14	* 1830	-1285	-1485
CW2NE NE	28	13	14	1847	-1270	-1535
NE SW SW	29	13	14	* 1860	-1326	-1510
SE NE NE	32	13	14	1862	-1318	-1515
NW SW NE	33	13	14	1865	-1295	-1440
NE SE NW	34	13	14	1845	-1290	-1455
NE NW SW	36	13	14	* 1820	-1230	-1480
SW SW SE	3	14	14	1831	-1218	-1475
NE_C NW	5	14	14	?	-1270	-1540
SE NW SE	8	14	14	1876	-1308	-1637
NE SE SE	9	14	14	1857	-1286	-1582
NW NW SE	10	14	14	1845	-1225	-1470
SW NW SE	10	14	14	1846	-1240	-1480

LOCATION						SURFACE	SALT INTERVAL	
¼	¼	¼	SEC.__,	T__S,	R__W	ELEVATION (FT.)	TOP (FT.)	BOTTOM (FT.)
SW	NW	SE	10	14	14	1846	-1240	-1480
SW	SW	SW	11	14	14	1851	-1235	-1475
SE	NE	SE	11	14	14	1852	-1237	-1482
NW	NW	NW	14	14	14	1858	-1245	-1480
SE	NE	NW	14	14	14	1837	-1205	-1450
NE	NE	NE	14	14	14	1836	-1210	-1445
NW	NE	SW	15	14	14	1858	-1262	-1524
NE	SE	SE	16	14	14	1892	-1297	-1549
NW	NE	NE	17	14	14	1879	-1288	-1573
NW	SE	NW	18	14	14	1861	-1318	-1613
NW	SW	SE	19	14	14	1831	-1260	-1604
SW	NW	NW	20	14	14	1850	-1218	-1520
W2	W2	SE	22	14	14	1841	-1238	-1535
W2	NE	NE	23	14	14	1812	-1201	-1575
NW	NE	SE	24	14	14	1755	-1120	-1360
SW	NW	SE	25	14	14	1748	-1117	-1345
SE	NE	NE	25	14	14	1750	-1120	-1350
E2	E2	NE	27	14	14	1812	-1202	-1493
SE	NE	NE	28	14	14	1816	-1188	-1440
N2	NW	NW	29	14	14	1841	-1260	-1544
N2	SW	NW	30	14	14	1819	-1228	-1480

LOCATION						SURFACE	SALT INTERVAL	
¼	¼	¼	SEC.__,	T__S,	R__W	ELEVATION (FT.)	TOP (FT.)	BOTTOM (FT.)
NE	NW	SE	31	14	14	1728	-1143	-1398
W2	NE	NW	32	14	14	1764	-1195	-1463
CW2NE		NW	34	14	14	1800	-1181	-1460
SW	NE	NE	35	14	14	1772	-1145	-1375
NW	SE	SE	36	14	14	1730	-1189	-1400
C	SW	SE	1	14	15	1872	-1315	-1622
NE	SE	NW	3	14	15	1883	-1282	-1600
S2	NE	NE	4	14	15	1893	-1283	-1577
SW	NE	SW	5	14	15	* 1874	-1312	-1583
NE	NE	NE	10	14	15	1850	-1282	-1607
NE	SE	NW	11	14	15	1865	-1272	-1612
NE	NE	SW	12	14	15	1847	-1252	-1542
SW	SE	SE	13	14	15	1850	-1249	-1550
SW	NW	SE	14	14	15	1856	-1252	-1560
CS2NE		NE	16	14	15	1855	-1284	-1566
NW	SW	NW	19	14	15	1875	-1327	-1652
CSE		NW	23	14	15	* ?	-1200	-1468
NE	SW	NE	24	14	15	1788	-1193	-1473
SE	NE	NE	25	14	15	1815	-1213	-1462
SW	NE	NW	25	14	15	1763	-1212	-1460
SE	SW	SE	26	14	15	1831	-1228	-1538

LOCATION						SURFACE	SALT INTERVAL	
¼	¼	¼	SEC.__,	T__S,	R__W	ELEVATION (FT.)	TOP (FT.)	BOTTOM (FT.)
NW	NW	NE	27	14	15	1794	-1221	-1568
SW	SW	SW	28	14	15	1875	-1312	-1610
NE	SW	SE	29	14	15	1873	-1313	-1637
NE	NE	SW	30	14	15	1810	-1253	-1581
SE	NE	SW	33	14	15	1890	-1323	-1648
NE	NE	NE	35	14	15	1796	-1208	-1489
CN2S2		NW	36	14	15	1787	-1197	-1506

* indicates that this well log is an SP-Resistivity type

? indicates that the elevation was not given or is questionable as listed

APPENDIX II

Well Data for Cross Section

CROSS SECTION WELL NUMBER	LOCATION ¼ ¼ ¼ SEC.__, T__S, R__W			
1	NE NW SE	6	13	14
2	NW SE NW	7	13	14
3	NW NW SW	17	13	14
4	SE SE SE	20	13	14
5	NE SW SW	29	13	14
6	NW NE NE	32	13	14
7	NE_c NW	5	14	14
8	SE NW SE	8	14	14
9	NW NE NE	17	14	14
10	CW2 SW SE	20	14	14
11	CN2 NW NW	29	14	14
12	NE NE NW	31	14	14

APPENDIX III

Sinkhole Descriptions

Sinkhole Name - Crawford

Location - NW¼, NW¼, SW¼, Sec. 2, T. 14 S., R. 15 W.

Date Wells Drilled - Crawford 12 1/37
Crawford 16 8/37

Casing Information -

	Diameter (inches)	Interval Cased (feet)	Date Plugged
Crawford 12	13 3/8 8 5/8	0-910 0-2,888	6/41
Crawford 16	12 1/2 6 5/8	0-916 0-3,219	1/45

Date Subsidence First Investigated - 1967 Highway Commission test hole

Maximum Subsidence - Greater than 26 feet (8 m.) in 1976

Present Status - Highway department personnel report that the sink is still active and that salt is probably still being dissolved.

Sinkhole Name - Witt

Location - center of NW¼, NW¼, SE¼, Sec. 3, T. 14 S., R. 15 W.

Date Well Drilled - Witt 1 4/36 (Deepened 7/36 and 1/45)

Casing Information -

Diameter (inches)	Interval Cased (feet)	Date Plugged
10 8 1/4 7 5 1/2	0-927 0-2,535 ------- 0-3,299	6/57

Maximum Subsidence - 17 feet (5 m.) in 1976

Present Status - Highway department personnel report that the sink is still subsiding.

This information was taken from Walters (1976) and Fader (1975).

DISSOLUTION IN THE HUTCHINSON SALT MEMBER
OF THE WELLINGTON FORMATION NEAR RUSSELL, KANSAS

by

TERRY JAY HANSEN

B. S., Kansas State University, 1975

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Geology

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1977

The Hutchinson Salt Member of the Wellington Formation of the Permian System is dissolving around the boreholes of oil and gas wells in Russell County, Kansas. The dissolution has caused two sinkholes along Interstate Highway 70 near Russell, Kansas. These sinkholes are still subsiding.

Available information was used to try to locate any additional areas of salt dissolution and resultant subsidence in Russell County.

Oil wells were grouped according to their drilling completion date, 1927 to 1940, 1941 to 1950, 1951 to 1956, and plotted on an isopach map of the Hutchinson Salt Member of the Wellington Formation. Locations of brine disposal wells were plotted and compared to the map density of the oil wells. Aerial photos of areas where a 30 to 40 year old well was located within a mile of a shallow brine disposal well, and where the salt was approximately 250 feet (76 meters) thick or less, showed no evidence of dissolution. Remote sensing photographs, LANDSAT and aerial, indicated no evidence of drainage pattern changes or new locations of land subsidence.

The date an oil or gas well was drilled may be the most important factor in determining if dissolution will occur. Older wells are more likely to have been improperly cased or sealed, allowing water to enter the boreholes. The time required for enough salt to dissolve for a sinkhole to develop is approximately 30 to 40 years, based on the formation history of the Crawford and Witt sinkholes near Russell, Kansas.

No evidence of new dissolution was found but this does not mean that dissolution is not occurring. Kansas Highway Commission personnel have recorded frequent water level fluctions in the borehole of the

Crawford sink indicating continuing salt dissolution. Other boreholes in the area are probably undergoing similar water level fluctions with salt dissolution resulting from the moving water.

Determination of salt dissolution would require an extensive search using geophysical methods such as a seismic survey or borehole reentry. Such a search is probably not economically justifiable.