

EFFECTS OF PERMIAN EVAPORITE DISSOLUTION
IN KANSAS

by

BARBARA J. (STOUT) SMITH

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Approved by:


Major Professor

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INTRODUCTION

Purpose and Method

Evaporites underlie a large part of Kansas. Many publications report the type of ground or surface contamination resulting from dissolved evaporites. Surface collapse features, some having occurred in historic time, demonstrate that appreciable dissolution has taken place. This investigation demonstrates that widespread deterioration caused by solution of evaporites and subsequent effects on overlying strata and potential deterioration exist, outlines probable mechanisms responsible for deterioration, and proposes coordinated study and evaluation that will lead to control or management of the deteriorating areas. The study area includes the area of Kansas underlain by evaporites of Permian Age. The boundaries lack clear definition because exact locations of evaporites have not been established (see Fig. 3, 5-8). The methods used include searches of the geological and appropriate non-geological literature and the construction of a map showing density of petroleum drilling operations in or near the study area.

Previous Studies

Earlier studies of the evaporites in Kansas are numerous. Cragin (1896,1897) described the Permian rocks of western Kansas. Grimesly (1897) made an early study of gypsum occurrences. Descriptions of the Permian redbeds were published by Norton (1939) and a petrographic study was made by Swineford (1955). Salt occurrences were described by Bass (1926) and gypsum by Kulstad et al (1956). A masters thesis on the Permian evaporites was written by Schumaker (1966). Bayne (1972) discussed rock salt occurring in thick beds.

Probably the most studied evaporite sequences occur in the Wellington Formation, Sumner Group. Studies of the Hutchinson Salt or the Wellington Formation were made by VerWiebe (1937b), Darton (1921), Kulstad (1959), Dellwig (1963), Jones (1965), Vincent (1965), and Goebel (1971).

Evaporites between the Stone Corral Formation, Sumner Group and the Blaine Formation, Nippewalla Group were discussed by Campbell (1963). Blaine Formation was studied by Fay (1961), and Malone (1962). Evaporite-bearing rocks of Kansas correlated with those of adjoining states were described in Maher (1953), Jordan and Vosburg (1963), Green (1937) and Muir (1934).

Evaporite-bearing Rocks

Rocks of the Permian System occur under nearly three quarters of Kansas. The lowermost beds of predominantly marine limestones and shales crop out in an escarpment belt, known as the Flint Hills, north-south across the state. Permian marine and non-marine strata occur in the two-thirds of the state lying west of the Flint Hills. Except for the Flint Hills, the Red Hills from Harper County to Meade County, and the Wellington Lowland west of the Flint Hills, Permian units usually do not crop out but are unconformably overlain by Jurassic, Cretaceous, Tertiary and Quaternary rocks and sediments. Dip is to the west or northwest (Fig. 1 and 2).

The majority of evaporite beds consist of halite, gypsum, dolomite, and anhydrite and are included in the Lower Permian Series, Cimarronian Stage. Some beds occur in the Upper Permian Series, Custerian Stage and also in the Lower Permian Series, Gearyan Stage (below the Cimarronian). In ascending order, from the earliest recognized evaporite bed, the evaporite-bearing units are listed below. (See Fig. 3 for map.)

Lower Permian Series

Gearyan Stage

Council Grove Group

Easley Creek Shale

Cimarronian Stage

Sumner Group

Wellington Formation

Ninnescah Shale

Stone Corral Formation

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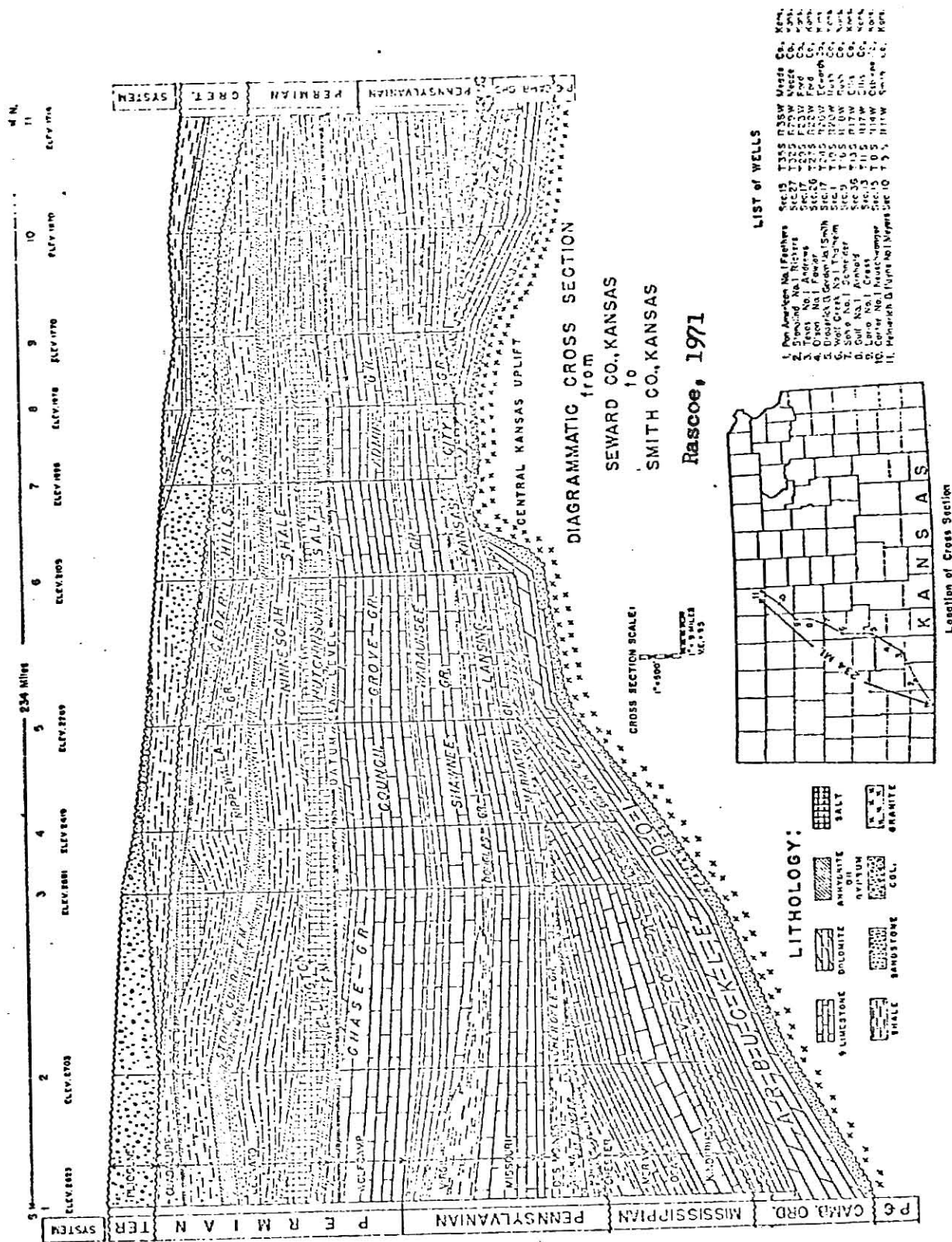
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Fig. 1-Generalized geologic map of Kansas showing distribution of major outcropping rocks (from Schoewe, 1949).



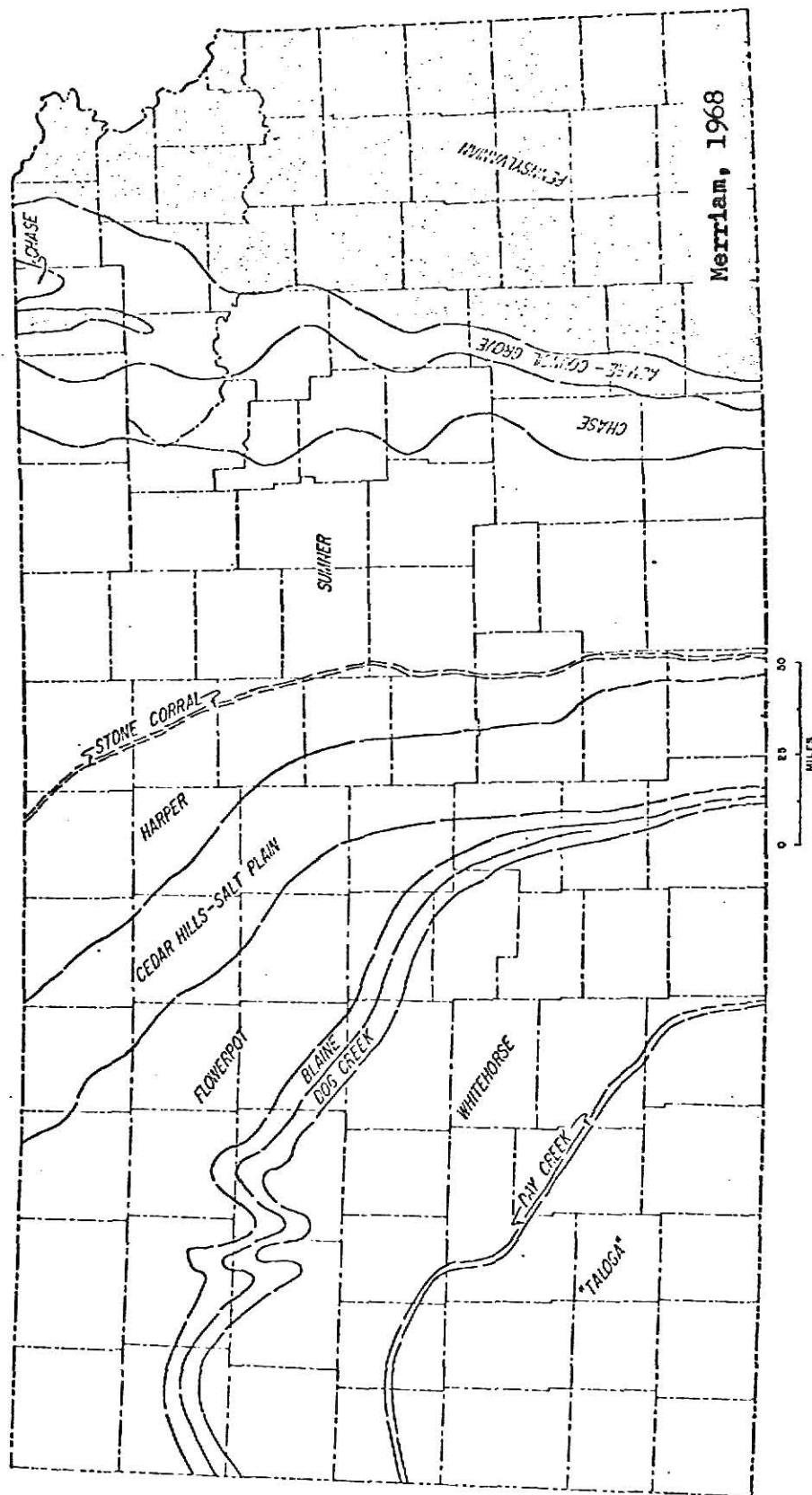


Fig. 3--Map showing Permian rocks under Mesozoic beds or inferred position in pre-Mesozoic time (Merrill, 1968).

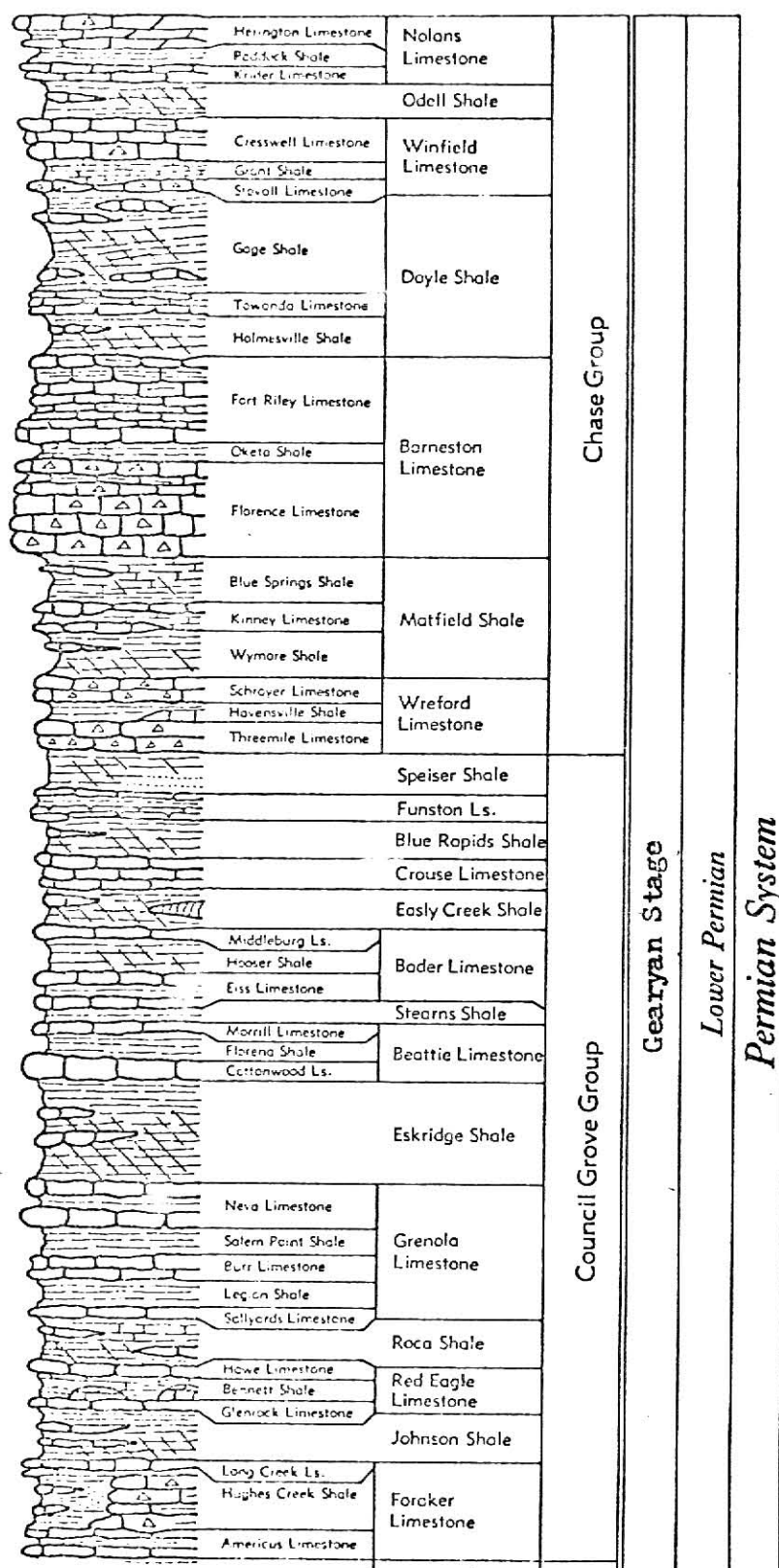


Fig. 4-Generalized stratigraphic section of Permian evaporites in Kansas (after Jewett, 1959 and Zeller, 1968). Approximate vertical scale, 1 inch=75 feet.

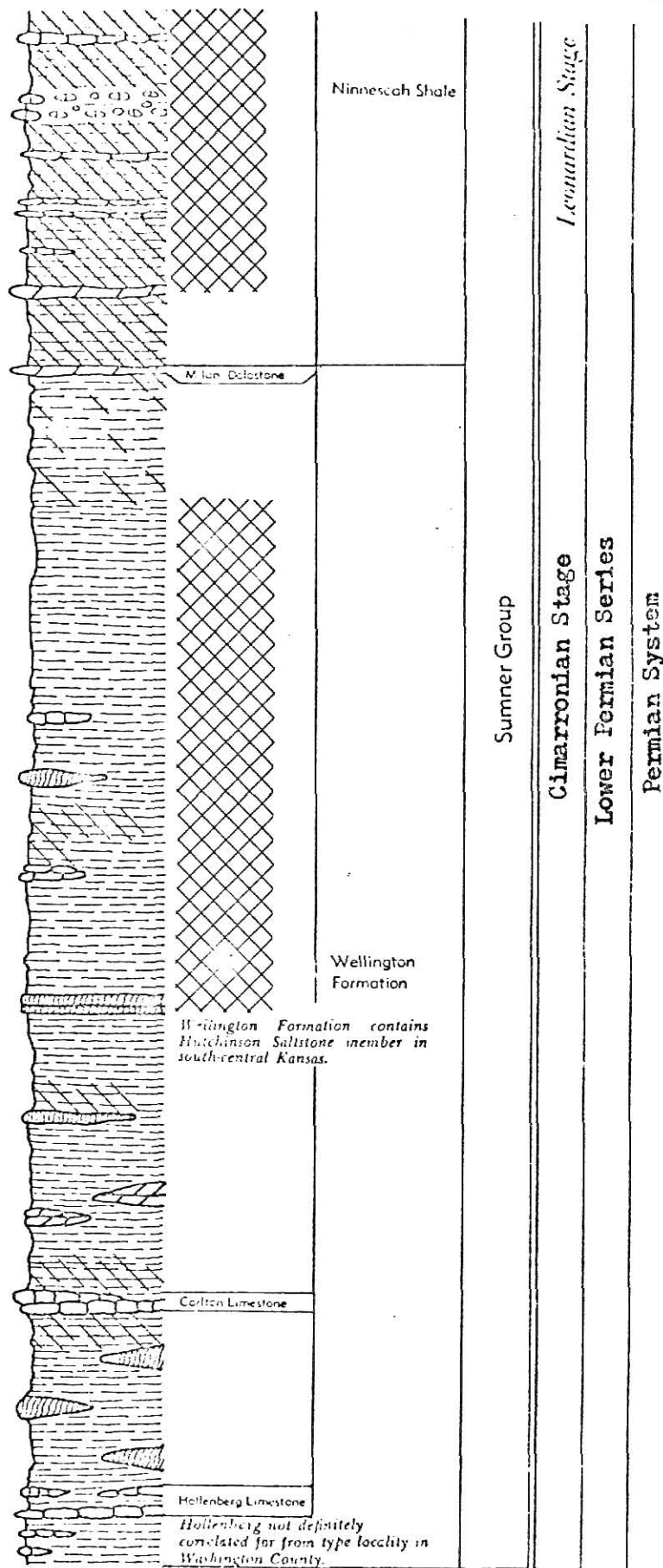


Fig. 4-Continued

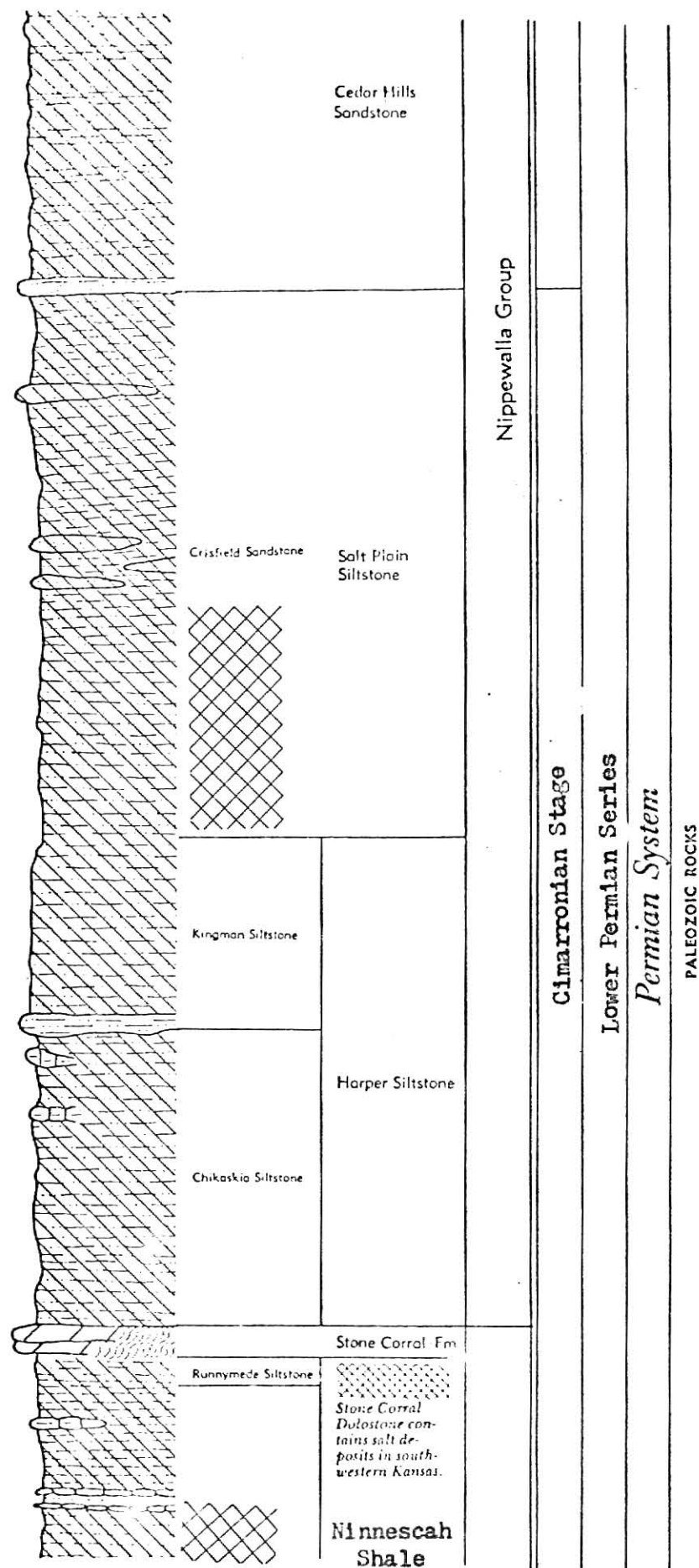


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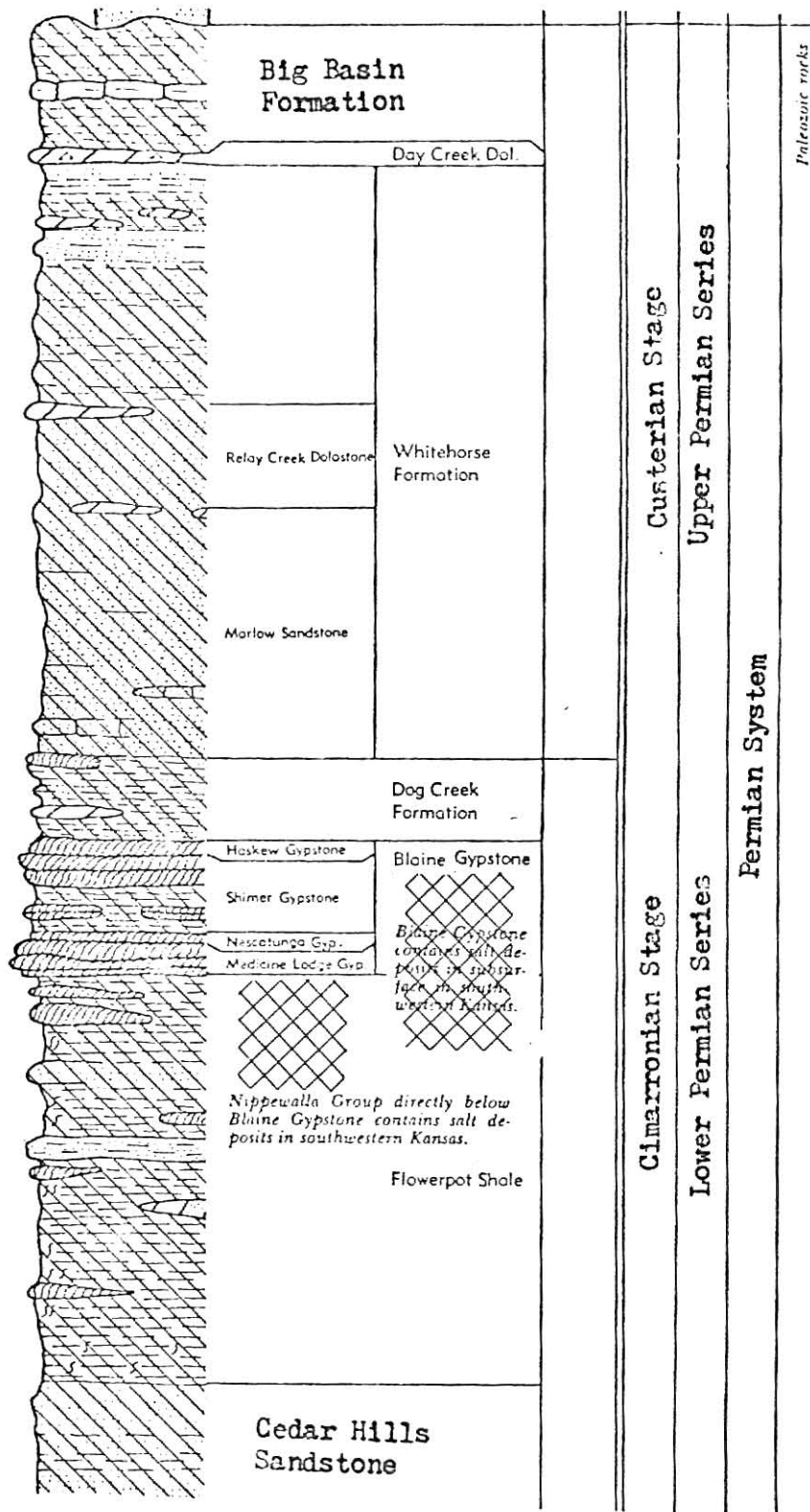


Fig. 4-Continued

Cimarronian Stage

Nippewalla Group

Salt Plain Formation

Flower-pot Shale

Blaine Formation

Dog Creek Formation

Upper Permian Series

Custerian Stage

Whitehorse Formation

Day Creek Dolomite

Big Basin Formation

A part of a generalized stratigraphic section of Permian rocks in Kansas is in Fig. 4.

Units above the Wellington Formation are referred to as the "redbeds" because the shales, siltstones, and sandstones are predominantly red. The redbeds contain few limestones. Below the Wellington Formation are alternating shales and limestones. The descriptions of the evaporite-bearing units are given below, and are from Zeller (1968) and Merriam (1963) except where otherwise stated.

The Easley Creek Shale has eight feet of gypsum in the lower part of the red, green, and gray shale unit which is being mined in Marshall County. The extent and thickness of gypsum in this formation is not known.

The Wellington Formation is gray, red and purple shale with anhydrite in the lower third of the unit and rock salt in the upper part. Thickness maps of the rock salt (Hutchinson Salt Member) are available (Kulstad 1959; Schumaker, 1966, pl. 4). The average thickness is 200 feet and ranges from 0 to 700 feet. The eastern edge is a solution front as shown by surface features indicating

solution and collapse (discussed in later sections) and by well log data (Dellwig, 1963, p. 72). (Fig. 5).

The Ninnescah Shale is red, gray, and maroon. Norton (1939, p. 1773) described veins of gypsum and hopper salt crystal casts that he correlated with the "Cimarron Salt" in parts of this formation. The "Cimarron Salt" or "Lower Cimarron Salt" ranges from 0 to 250 feet thick. Schumaker (1966, p. 28) pointed out that this salt could be incorrectly logged as Stone Corral Formation. (Fig. 6).

The Stone Corral Formation is dolomite, anhydrite, shale, halite, and gypsum. Merriam (1963, p. 86-93) summarized the studies of this formation and also described the formation differences from one subsurface anhydrite bed to two beds with intervening shale. This subsurface anhydrite is also called the "Cimarron anhydrite".

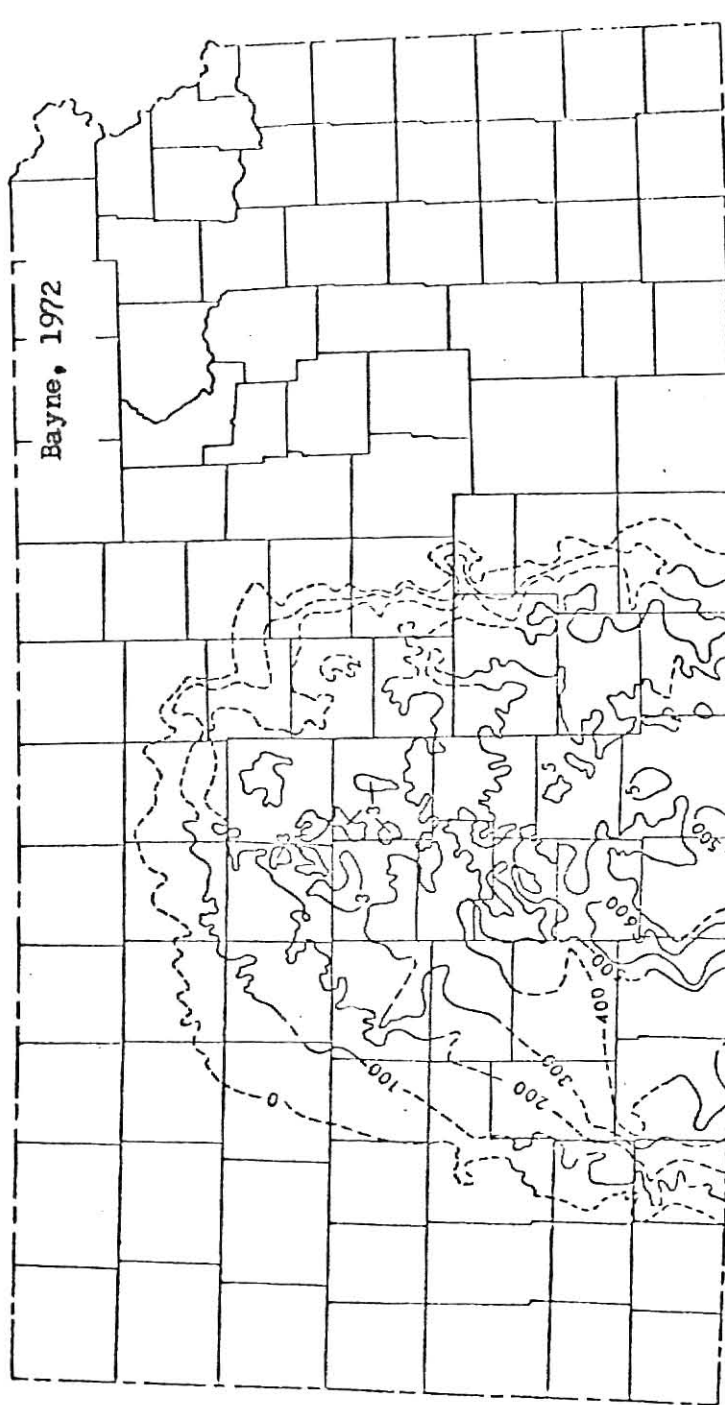
Fig. 7 shows the distribution of the lithologic types in Stone Corral.

Salt Plain Formation contains salt in the lower portion in Kearny and Scott counties. (Maher, 1946, 1947).

Cedar Hills Sandstone is red sandstone with white sandstone at the base and top. The top contains white gypsum "snowballs" (Norton, 1939, p. 1789).

Flower-pot Shale contains soft gypsiferous red shales with localized areas of gypsum or gypsiferous sandstone near the top. Saline springs and rock salt in this section have been noted (Norton, 1939, p. 1792). The "Blaine Salt" in the Flower-pot Shale is bedded rock salt 0 to 600 feet thick. Thickness and limits of the Blaine salt are in Fig. 8.

The Blaine Formation contains beds of gypsum separated by shale and dolomite. The Medicine Lodge Gypsum Member averages 20 feet of gypsum, anhydrite, and dolomite. The Nescatunga Gypsum Member has



EXPLANATION

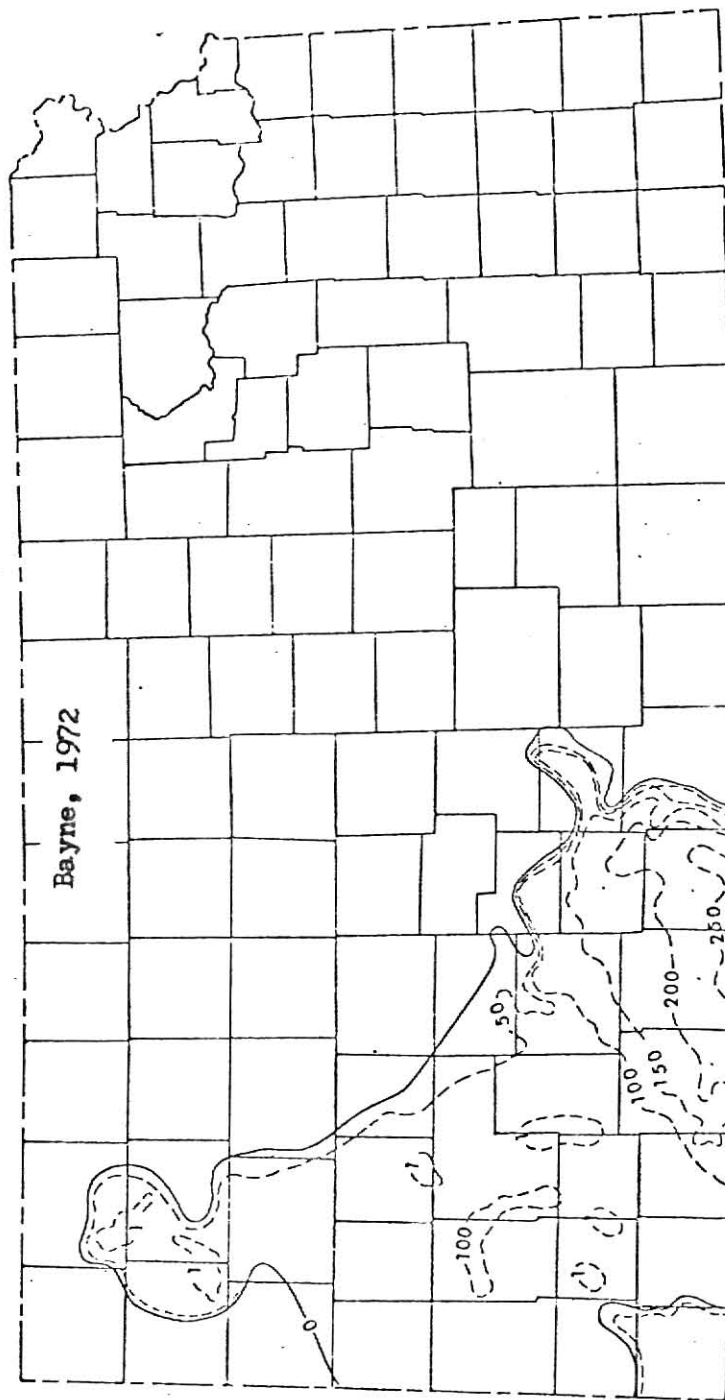
- Information based on cable tool logs, drillers' logs, or logs showing presence of salt, but thickness data unreliable
- Information based on electric logs

Contour interval = 100'

0 50 100

Scale in miles

Fig. 5-Thickness and limits of the Hutchinson Salt (contoured by Robert O. Kulstad) (from Bayne, 1972).



EXPLANATION

50 Contours indicate thickness of Cimarron salt

0 50 100
Scale in miles

Fig. 6-Thickness and limits of the Cimarron salt (contoured by Robert O. Kulstad) (from Bayne, 1972).

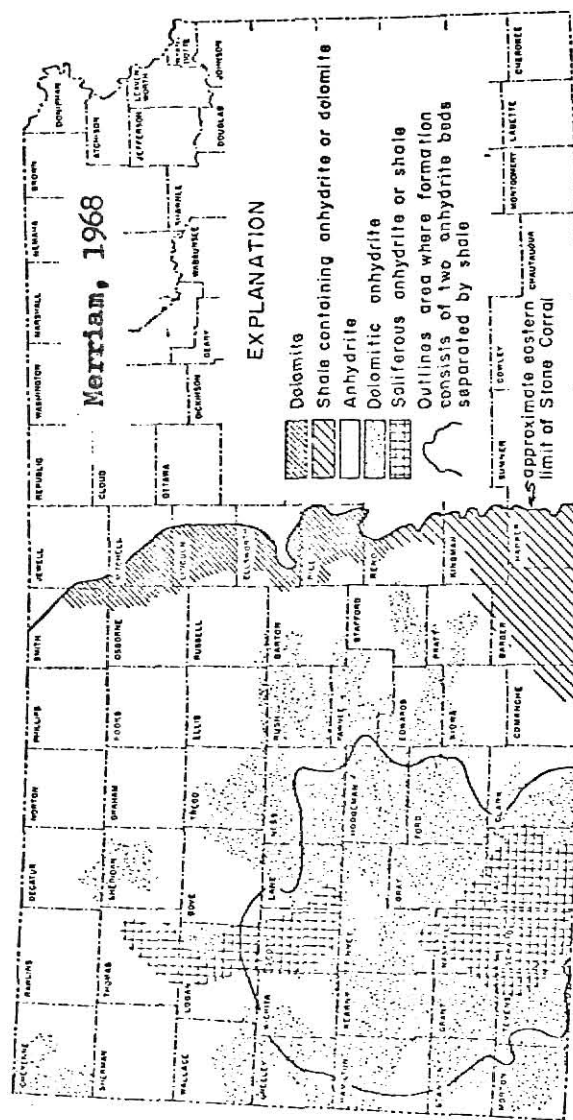


Fig. 7-Generalized surface and subsurface distribution of lithologic types in Stone Corral Formation (from Merriam, 1968).

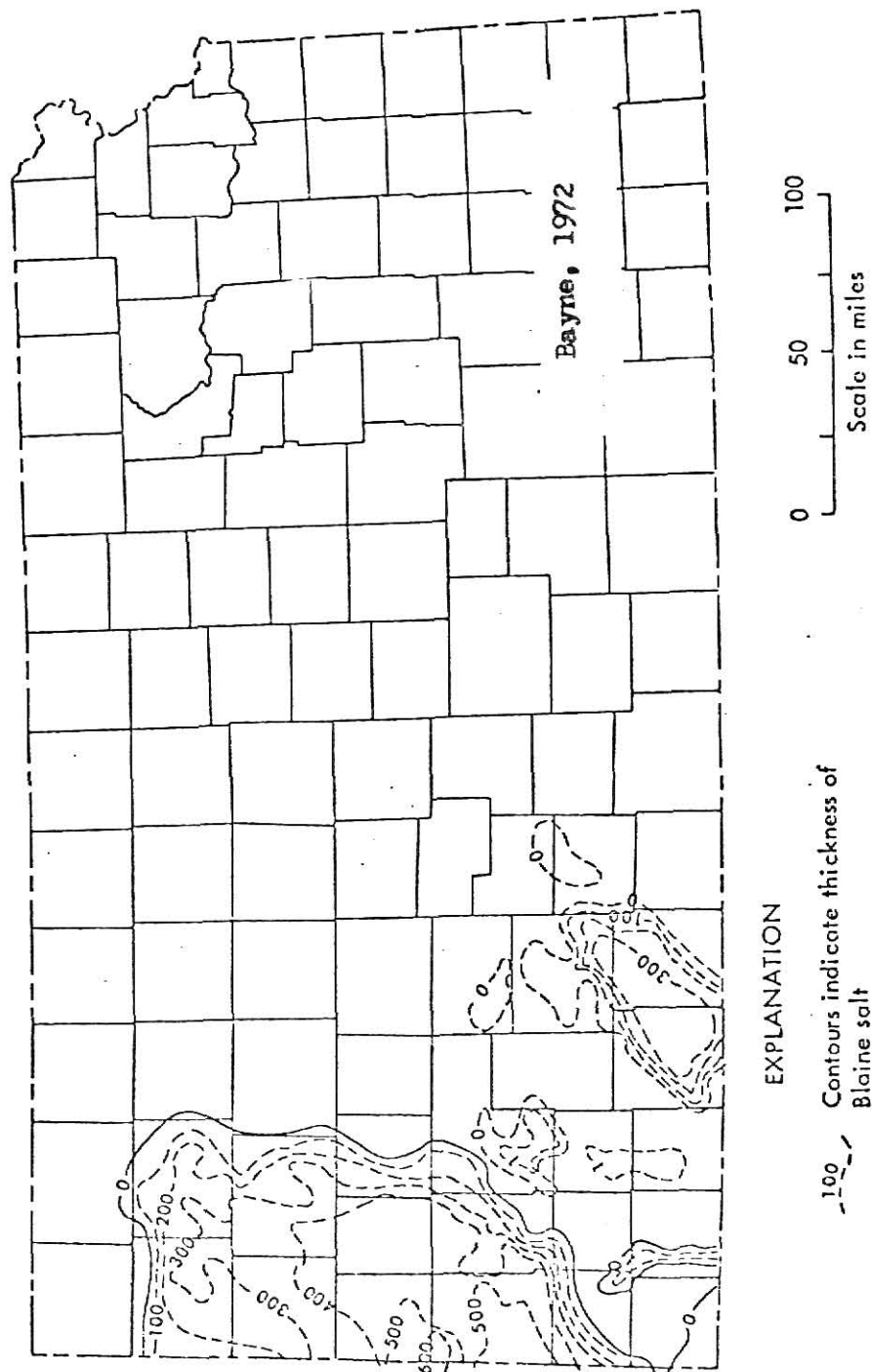


Fig. 8-Thickness and limits of the Blaine salt (contoured by Robert O. Kulstad) (from Bayne, 1972).

two to eight feet of gypsum whereas the Shimer Gypsum Member is 13 to 23 feet of gypsum and one half-to one and a half-feet of dolomite at the base. Haskew Gypsum Member has one foot of gypsum where this has not been removed by solution.

Dog Creek Formation has dolomite, dolomitic sandstone, gypsum and anhydrite with one foot of gypsum at the top. Hollweg (1963, p. 15) noted that halite casts occur in a few localities.

Sandstones, siltstones and shales comprise the Whitehorse Formation. Thin evaporitic beds of dolomite grade to anhydrite in the west and gypsiferous shale is in the eastern portions. Merriam (1963, p. 86) showed salt in Logan county.

Day Creek Dolomite crops out as fine-grained dolomite and is massive anhydrite in the subsurface. Pockets of gypsum and a few halite casts are found. The dolomite is two feet thick at the surface and thickens to the southwest merging into anhydrite and anhydritic shale so actual thickness is difficult to determine (Hollweg, 1963, p. 18).

Big Basin Formation ("Taloga") is silty shale, sandstone, and very fine-grained sandstone with a few thin lenses of anhydrite and gypsum (Hollweg, 1963, p. 20).

Fig. 9 illustrates total thickness of evaporite deposits in the Permian sequence. The correlation of these Kansas units to those in New Mexico, Oklahoma and Texas is shown in Fig. 10 and 11.

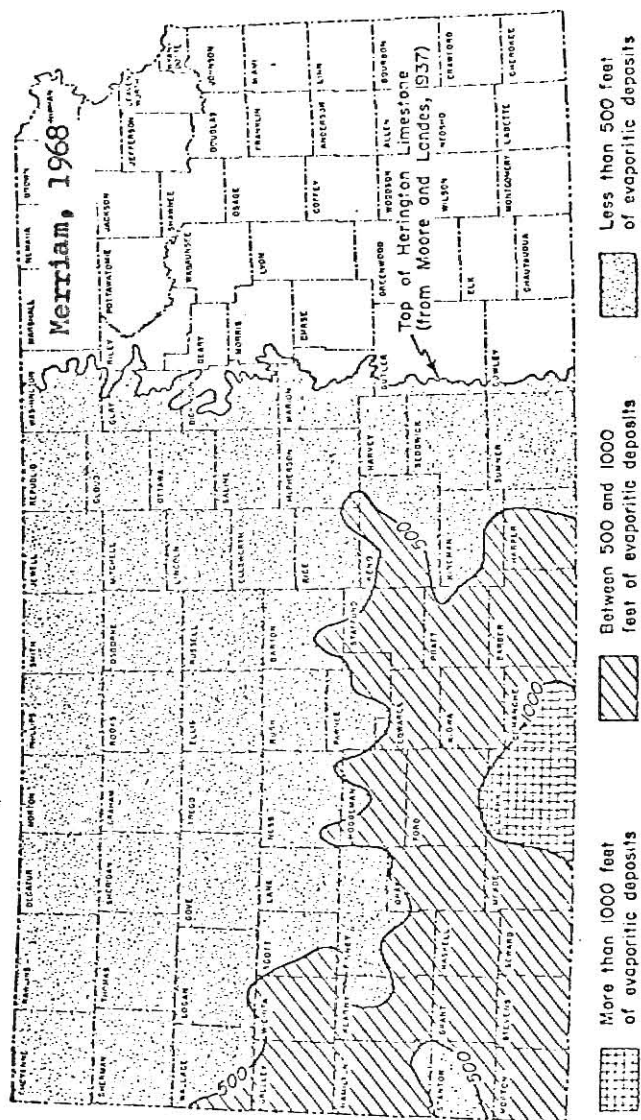


Fig. 9-Thickness of Permian evaporites in Kansas (Merriam, 1968).

Irwin and Morton, 1969

AGE	NORTHEASTERN NEW MEXICO	TEXAS PANHANDLE	OKLAHOMA PANHANDLE	KANSAS
TERTIARY QUATERNARY	OGALLALA FORMATION AND YOUNGER ROCKS	OGALLALA FORMATION AND YOUNGER ROCKS	OGALLALA FORMATION AND YOUNGER ROCKS	OGALLALA FORMATION AND YOUNGER ROCKS
	PIERRE SHALE		ABSENT	PIERRE SHALE
	NICORARA FORMATION	ABSENT		NICORARA FORMATION
	CARLILE SHALE			CARLILE SHALE
	GREENHORN LIMESTONE			GREENHORN LIMESTONE
CRETACEOUS	GRANEROS SHALE			GRANEROS SHALE
	DAKOTA SANDSTONE			DAKOTA SANDSTONE
	ABSENT	ABSENT		KIOWA SHALE
	PURGATORIO FORMATION			CHEYENNE SANDSTONE
	ABSENT			ABSENT
JURASSIC	MORRISON FORMATION	MORRISON FORMATION	MORRISON FORMATION	
	EXETER (INTRACAL) SANDSTONE	EXETER (INTRACAL) SANDSTONE	EXETER (INTRACAL) SANDSTONE	
	CHINLE FORMATION			
	SANTA ROSA SANDSTONE	SANTA ROSA SANDSTONE ?	SANTA ROSA SANDSTONE ?	
	TECOVAS FORMATION			
TRIASSIC	ABSENT	QUARTER - MASTER FORMATION	QUARTER - MASTER FORMATION	
	ABSENT	ELK CITY MEMBER	ELK CITY MEMBER	
	ABSENT	DOXEY MEMBER	DOXEY MEMBER	
	ABSENT	ALLIANCE MEMBER	ALLIANCE MEMBER	
	ABSENT	CLOUD CHIEF FORMATION	CLOUD CHIEF FORMATION	
PERMIAN	ABSENT	RUSH SPRINGS SANDSTONE	RUSH SPRINGS SANDSTONE	
	ABSENT	MARLOW FORMATION	MARLOW FORMATION	
	ABSENT	DOG CREEK SHALE	DOG CREEK SHALE	
	SAN ANDRES LIMESTONE	BLAINE GYPSUM	BLAINE GYPSUM	
	GLORIETA SANDSTONE	FLOWERPOT SHALE	FLOWERPOT SHALE	
PERMIAN	YESO FORMATION	GLORIETA SANDSTONE	GLORIETA SANDSTONE	
	DE CRISTO FORMATION	"CIMARRON" ANHYDRITE	HENNESSEE "CIMARRON" ANHYDRITE	
		TUBB SAND	SHALE	
		RED CAVE	"CIMARRON" SAND	
		"PANHANDLE LIME"	WELLINGTON FORMATION	
PERMIAN		HERINGTON LIMESTONE	CHASE GROUP	CHASE GROUP

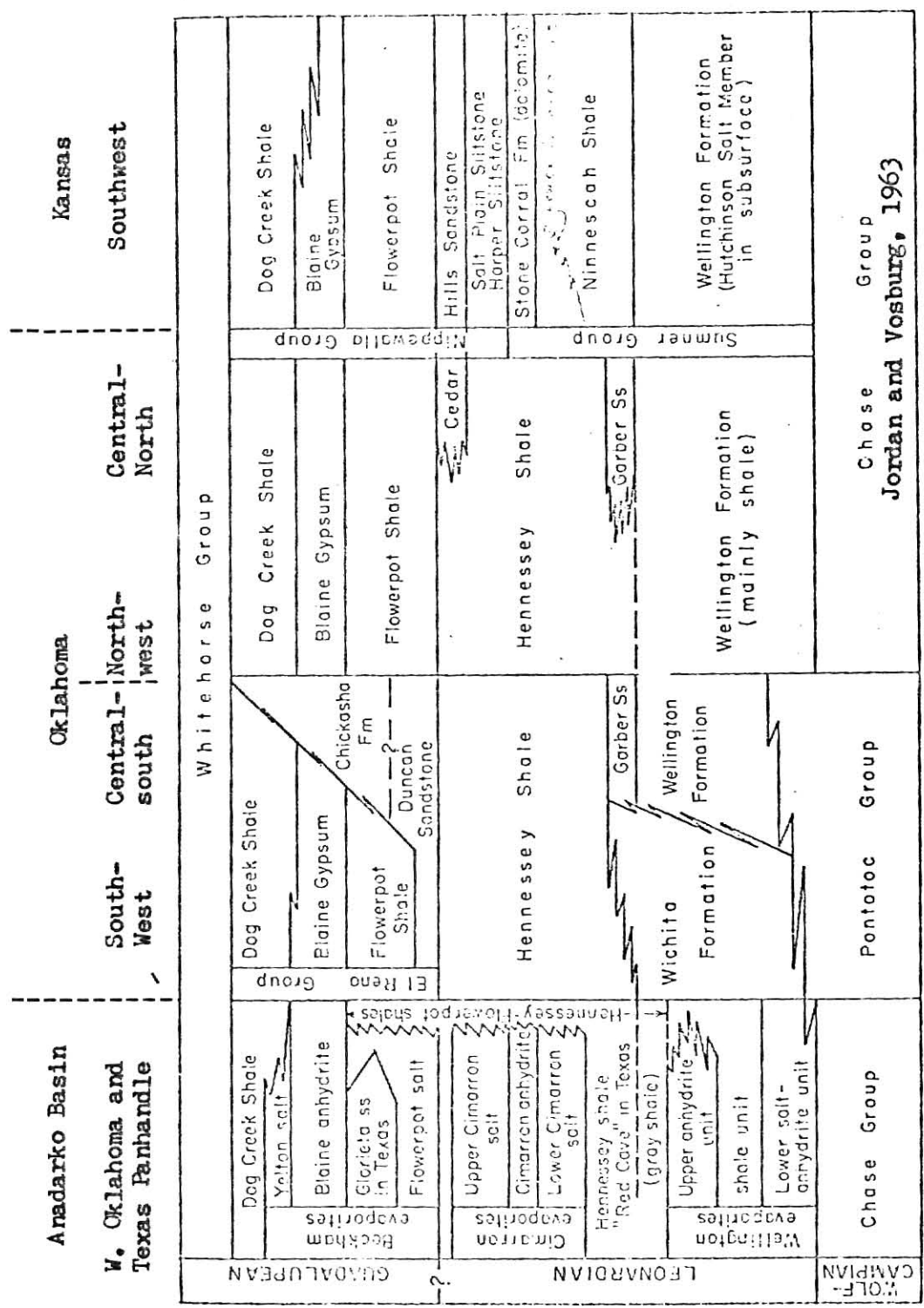


Fig. 11-Correlation of Permian Formations in Oklahoma, Texas, and Kansas (Jordan and Vosburg, 1963).

Structure

Structural features present during the deposition of evaporites are in Fig. 12. The Ouachita Basin received thick deposits during the Pennsylvanian and Early Permian which are thicker in the southeast. By Leonardian time (Cimarronian Stage) the Central Kansas Uplift stabilized. Later as the region was tilted toward the Anadarko Basin, Hugoton Embayment, the Wellington Formation was deposited. The deposits are thicker toward the south than toward the southwest. Before Cretaceous sediments were deposited, the Permian redbeds were tilted to the northeast and eroded. (Lee, 1953; Lee, 1956, p. 142) A cross section from Seward County, Kansas, to Smith County, Kansas, is in Fig. 2.

Surface Water

The study area is in two major drainage basins. The Kansas River basin includes the Solomon, Saline, Smoky Hill and Kansas Rivers which drain the northern half of the area. The southern half is in the Arkansas River basin area and includes the Arkansas River, its tributaries and the Cimarron River. General discussions of Kansas rivers are found in Schoewe (1951). Water quality stations have been established and are maintained by the United States Geological Survey. Studies of water quality and relation of quality to stream flow are listed in appendix A.

Ground Water

Ground water or phreatic water is subsurface water in the zone of saturation. An aquifer is a subsurface formation containing and transmitting ground water. Several types of ground water are defined by the amount and kind of dissolved solids contained. Definitions based on sodium chloride content and used by the petroleum industry

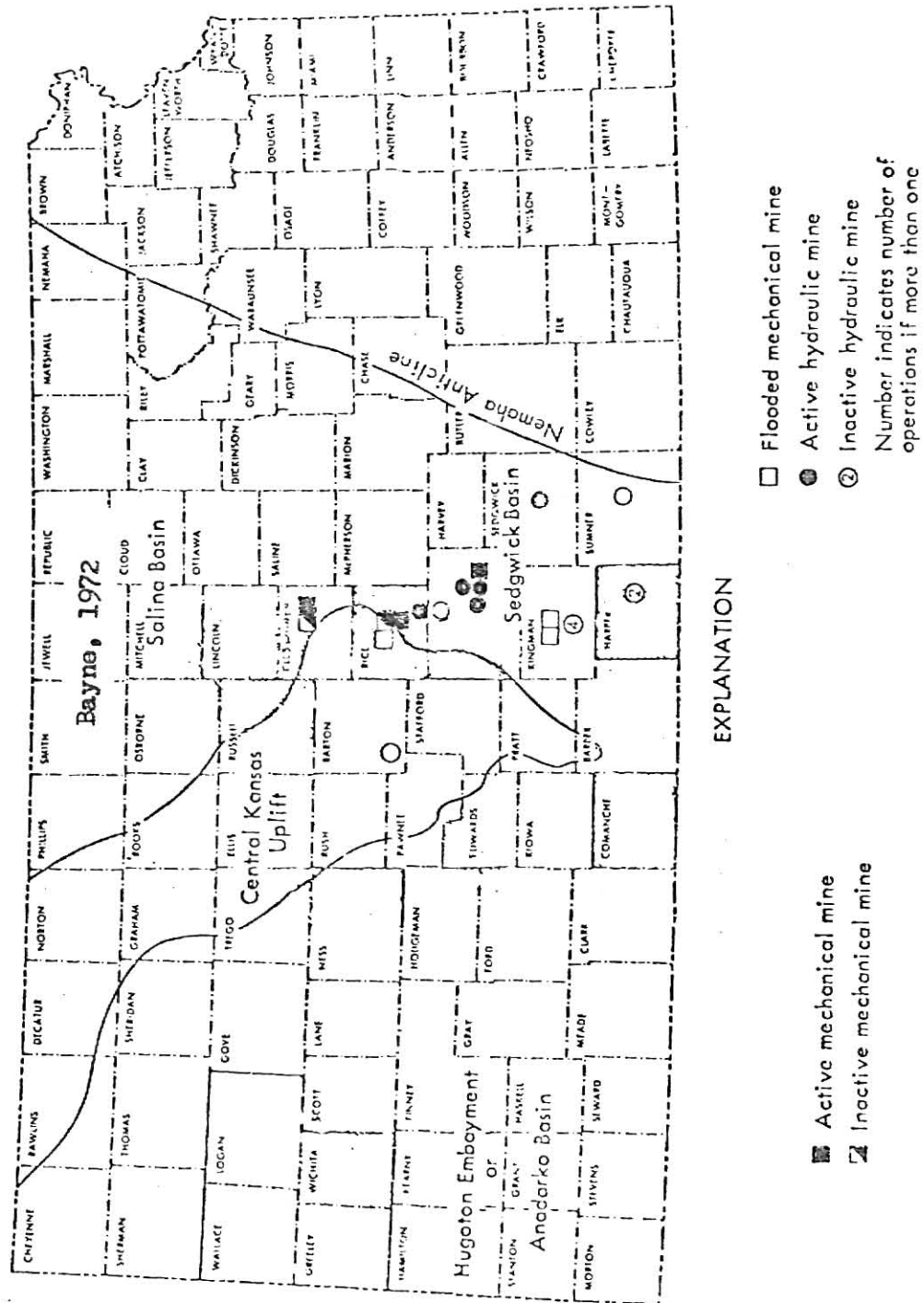


Fig. 12-Map showing structural features and salt mines (Bayne, 1972)

are summarized by Gorell (1958, p. 2513). Geohydrological definitions are based on amount of total dissolved solids (TDS) (Table I)(Pfannkuch, 1969). Fresh water is also defined for legal purposes. Public health services list 250 milligrams per liter (mg/l) Cl and 500 mg/l TDS as the upper limits recommended for most uses (U.S. Public Health Service, 1962).

Ground water for household, irrigation, industrial and agricultural purposes is obtained from several formations: Carlile Shale, Kiowa Shale, and Dakota Formation, and also from consolidated and unconsolidated deposits of Pliocene, Pleistocene, Holocene and Recent Series in many areas. Some water occurs in Permian rocks but is commonly highly mineralized. Bulletins of the State Geological Survey of Kansas (appendix B) provide hydrogeological information for specific formations of particular counties.

Knowledge of the depths and compositions of mineralized groundwaters helps ground water management. A map by Feth and others (1965) (Fig. 13) shows the uppermost ground waters, excluding oil field brines, that contain 1000 mg/l total dissolved solids (TDS). The ground waters of one third to one half of the study area contain 1000 to 3000 mg/l TDS at depths less than 500 feet below land surface. Isolated areas having 3000 to 35,000 mg/l TDS are also less than 500 feet deep. These areas occur in Saline, McPherson, Harvey, Sedgwick, Sumner, Stafford, Rice, Reno, Kiowa, Meade, Barber and Harper Counties in the central and southern parts of the state. In north central Kansas these areas include Russell, Ellis, Rooks, Osborne, Mitchell, Smith, Jewell, Republic and Cloud Counties. The ground waters of one fourth of the study area contain 1,000 to 10,000 mg/l TDS at depths of 500 to 1000 feet. Another fourth of the area

TABLE I
Definitions of Water Quality

(as defined by industry, health,
and legal standards)

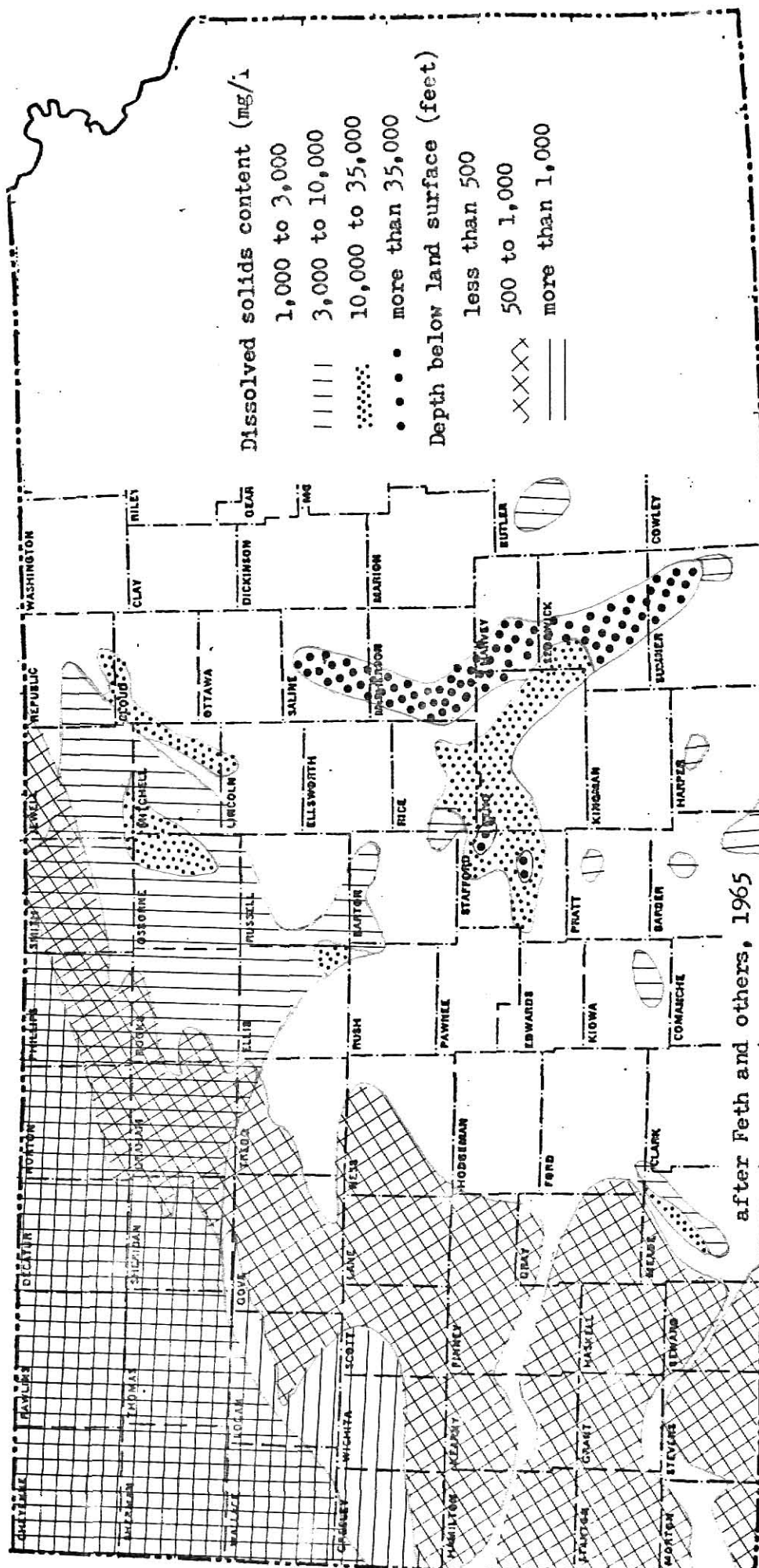
Descriptive term	Content expressed in Total Dissolved Solids	Content expressed in Chloride concentrations
Fresh water	0-1,000 mg/l ¹	0-1,000 mg/l ² 0-500 mg/l ³
Brackish water	1,000-10,000 mg/l ¹	1,000-10,000 mg/l ²
Salty water	10,000-100,000 mg/l ¹	10,000-100,000 mg/l ²
Brine	over 100,000 mg/l ¹	over 100,000 mg/l ²
Usable water		500-5,000 mg/l ³
Usable for most purposes	0-500 mg/l ⁴	0-150 mg/l ⁴
Usable for municipale supply	0-500 mg/l ⁴	0-250 mg/l ⁴
Usable for irrigation and most industrial purposes		0-350 mg/l ⁴

1) Pfannkuch, 1969.

2) Gorell, 1958, p. 2513.

3) Kansas Statutes Annotated.

4) U.S. Public Health Service, 1962.



shows 3000 to 10,000 mg/l TDS more than 1000 feet deep. These deeper waters are in the northern and western areas. The major constituents of the waters are sodium and chloride, although some central western Kansas samples also contain significant amounts of bicarbonate.

Harper County contains mainly calcium and magnesium sulfate waters.

Springs and marshes form where ground water occurs at or near the surface. Kansas has salt marshes and mineral springs, of which many having been economic resources in the history of the state. Analyses or locations of many are given by Schoewe (1953), Bailey (1902) and Peale (1886). Ward and Leonard (1961) described the origin of salt springs, seeps and plains in southern Kansas.

Many data have been collected on concentrations and types of waters produced from formation brines which have been encountered in many oil and gas bearing formations of Kansas. Some studies of subsurface waters and oil field brines are listed in appendix C.

ORIGINS OF SURFACE AND GROUND WATERS IN KANSAS

The waters of the state probably originate as meteoric or connate water. Meteoric water is water that has been derived from the atmosphere. Connate water is the water trapped in sedimentary rocks at the time of deposition (Pfannkuch, 1969) or water that has been out of the atmosphere for long periods of time (Davis and DeWiest, 1966, p. 124).

Meteoric water can be studied most easily by measurements of precipitation. The average precipitation is 16 and 30 inches per year in southwestern and central Kansas, respectively, but varies from year to year (Kansas Water Resource Fact-Finding and Research Committee, 1955, p. 15). The inorganic quality of the water that

becomes recharge or stream flow is, in part, controlled by the amount of precipitation, the type of rocks and soils encountered in overland flow, interflow, and ground water flow, and evaporation-crystallization processes (Durum, 1953; Feth, 1971; Gibbs, 1970; Gorham, 1961; Whittemore, 1976).

Connate water can range from fresh water to brine. In Kansas the dominant dissolved constituents are Cl, Na, Ca, Mg; minor constituents Br, I, Al, Fe, and K are also present (Schoewe, 1943, p. 48). Iso-concentration maps of some subsurface waters of Kansas were given by Case (1934). Analyses of oil field brines and other subsurface waters were given by White, Hem and Waring (1963), McClure (1973), and Rall and Wright (1953).

Many waters in Kansas have higher concentrations of dissolved constituents than sea water. The formations yielding the waters were formed as marine sediments. DeSitter (1947) listed two stages for changing the concentrations and compositions of marine water to that of connate water: (1) absorption of cations on clays during the compaction of sediments, and (2) salt filtration by clays acting as a semi-permeable membrane. Chave (1960) stated that shales in Kansas were not effective as semi-permeable membranes and could not account for the composition changes in Kansas waters. He suggested that the waters were concentrated elsewhere and migrated to their present locations. Other mechanisms for changing concentrations of dissolved constituents include dissolution of evaporites, inclusion of altered bitterns left over from evaporite formation and dilution by fresher waters (Rittenhouse, 1967). Other relevant studies are

listed in appendix D. Knowing the probable mechanisms responsible for the mineral concentrations of waters can aid in evaluating analyses of migrating waters.

Water can be held in hydrated minerals or in filled inclusions in the crystals. Clay and micaceous minerals, gypsum, amorphous ferric oxyhydroxides, goethite, polyhalite, gibbsite and brucite can yield water upon dehydration and are common in marine limestone, shale and sandstone sequences. Neutron-logging devices can indicate hydrogen-bearing fluids in the subsurface (Schlumberger Well Logging Corp., 1958, p. 92-93). Brine or water inclusions are in evaporites. Mined samples of halite from the Hutchinson Salt Member contained 0.5 percent water by volume (Bradshaw and Sanchez, 1968, p. 35) but studies showed that there was more water as inclusions than was expected (Holdaway, 1974, p. 304).

GROUND WATERS INDUCED BY THE ACTIVITIES OF MAN

Agricultural Activities

Agricultural and industrial activities induce water into formations. Agricultural activities, such as irrigation of crop lands, and artificial recharge of fresh water aquifers add water to some formations. Water with sodium-adsorption ratio (SAR) values between 8 and 18 may be harmful to soil permeability and SAR values above four can be harmful to sodium-sensitive crops. Water with TDS of less than 500 mg/l (milligrams per liter) is recommended for irrigation although water with up to 2000 mg/l TDS can be used if managed properly (U.S. Dept. of Interior, 1968, p. 115-117). The use of water with high TDS concentrations results in the build up of

mineral salts in soils when irrigating. Consequently recharge by irrigation water must be prevented so that deterioration of existing ground water supplies does not occur (Carlson, 1968; Kansas Water Resources Board, 1967, p. 16).

When the rate of water withdrawal from an aquifer is faster than the rate of natural recharge, artificial recharge may be useful in maintaining the water level of the aquifer. Generally good quality water should be used in order to maintain the water quality of the recharged aquifer and also to keep the suspended solids and precipitation minerals from clogging pore space. Some artificial recharge is being done in Kansas (Gillespie and Slagle, 1972). This practice is not common at present (Beck, 1976, personal communication).

Industrial Activities

Activities of the petroleum industry induce water on a large scale by oil brine reinjection. In 1960 nearly 274 thousand barrels per day of oil were produced in Kansas. When oil is produced, brine is also produced. Total brine production was 2.54 million barrels per day with an estimated chloride load of 36,700 tons per day. Of this produced brine, 99.7 percent was reinjected into the subsurface (U.S. Dept. of Health, Education and Welfare, 1964, p. 13). In 1973 3,200 oil-field disposal wells received about 3.5 million barrels of brine per day. There are 2,550 repressuring systems with one or more injection wells (Latta, 1973, p. 626). Other sources of water induced by man are water-base drilling muds and brine pits (Collins, 1971, p. 2385; Jones, 1950, p. 9). Plugging failures and defects and corroded casings of abandoned or dry holes allow water to be induced

from the surface or from other formations (U.S. Environmental Protection Agency, 1973a, p. 95; Jones, 1950, p. 60-66).

Deep underground waste disposal is used by many industries including chemical and fertilizer manufacturing and the salt mining industry. In 1973 there were 30 wells excluding oil or gas field wells. These are presented in table II a & b (Latta, 1973, p. 627, 632). These wells are in the central, southern or southwestern areas of the state (Latta, 1973, p. 629). Discussions of state controls and drilling completion and operation of wells are presented in Latta (1973) and Donaldson (1964). Rima, Chase and Meyers (1971) present an up to date bibliography.

Brine wells used by the salt industry also induce water into the subsurface. This industry is discussed in a later section. Induced water of organic origin is not considered in this paper although it is certainly important. Water induced by man's activities into a formation often has a different source than water in the formation, for example oil field brine reinjected from one production zone into a different formation. Thus the possibility of induced waters can be important in determining the origins of migrating waters.

INDUSTRIAL OPERATIONS AFFECTING EVAPORITES

Many industrial operations use evaporite beds or bore through them. Locations of 22 active and inactive mechanical and hydraulic extraction mines in rock salt are shown by Bayne (1972, p. 40) (Fig. 12). Taft (1946) and Kaufman (1960) described typical brine extraction operations which are discussed later. Cavities in the salt resulting from mining operations are used for storage (Donaldson, 1964). Schul

TABLE II a

Disposal Wells by Type of Industry in Kansas (3,4)

Type of Industry	Number of Wells	Character of Waste
LP Gas Underground Storage (10) ¹	17	Mostly sodium solution ²
Natural Gas Compressor Station (4)	4	Sodium brine solution
Natural Gasoline Plant (2)	3	Sodium brine solution and cooling tower blow-down fluid
Chemical Manufacturing (1)	3	Liquid chemical wash
Salt Mining (Hydraulic)(2)	2	Sodium brine solution
Ammonia Fertilizer Manufacturing (1)	1	Nitrate-Ammonia process fluid and cooling tower blowdown fluid
Petroleum Production	29 ⁴	Sodium brine solution

1) Number of industries using disposal wells.

2) From solutioning of salt formation to develop gas storage "wells".

3) Latta, 1973, p. 632.

4) Irwin and Morton, 1969, p. 13.

TABLE II b
Industrial-waste Disposal Wells and
Disposal Zones in Kansas (1,2)

Number of Wells	Disposal Zone	Depths in feet
25 ⁽¹⁾	Arbuckle	3,300 to 6,300
2 ⁽¹⁾	Pennsylvanian Limestone	3,900 to 4,400
1 ^(1,3)	Upper Permian Glorieta Sandstone	1,065 to 1,100
2 ⁽¹⁾	Lost circulation zone of Wellington Formation	220 to 420
29 ^(2,4)	Upper Permian Glorieta Sandstone	not given

1) Latta, 1973, p. 627.

2) Irwin and Morton, 1969, p. 13.

3) does not include petroleum bore waste wells.

4) includes petroleum brine waste wells.

(1963) described storage facilities for business records in rock salt near Hutchinson, Kansas. Liquified petroleum gases are also stored in the Hutchinson Salt Member (Crow, 1963). Solid and liquid waste disposal in the Hutchinson Salt was suggested by Edmund and Goebel (1968, p. 162). Project Salt Vault was conducted to test a site near Lyons, Kansas, for disposal of radioactive wastes. That project is inactive now (Empson, Bradshaw, McClain and Houser, 1970, p. 455-462).

The petroleum and gas industries and deep waste disposal operations bore through the evaporites. Fig. 14 shows density of gas and petroleum drilling operations in the area underlain by evaporites. Besides drilling for producing oil and gas wells there are non-producing wells used for repressuring and wells used for deep waste disposal (Latta, 1973).

DISSOLUTION OF EVAPORITES AND ACCESS OF WATER TO EVAPORITES

Evidence of Dissolution

Landes (1963) listed the effects of the solution of bedrock salt as brine springs, streams and lakes, salt caves and surface collapse. Salt springs of historic or economic interest have already been discussed (Schoewe, 1953; Bailey, 1902; Peale, 1886), but springs of lesser public interest should be mentioned. Ward and Leonard (1961, p. 424-428) listed the chloride content of salt springs in Kansas and Oklahoma as ranging from about 20,000 to 190,000 mg/l and total salt loads to the Arkansas and Red Rivers of about 15,000 tons per day. Shallow halite deposits are the sources for much of the salt dissolved in the springs. Many studies of chloride-contaminated surface and ground waters concluded that

the contamination was from natural sources, if not caused by oil field brines. Natural sources were given in these studies: Walters (1969, p. 49,59), Nolan (1963, p. 40), Williams (1946, p. 194-195), Noland (1964, p. 39), Fent (1950, p. 52), Lane and Miller (1965, p. 22-25, 50), Frye (1942, p. 64-65), Layton and Berrr (1973, p. 24), Landes (1963, p. 377). Brine lakes and marshes are described by Latta (1950, p. 40, 45-47, 83-84, 134-135) and also Williams and Lohman (1949, p. 87). Landes (1963, p. 69) provided a map locating a band of lakes and depressions resulting from solution of the Hutchinson Salt Member.

Evidence for surface collapse is the slumped strata above beds once having evaporites, and the sinks and basins. Merriam (1963, p. 189) mentioned locations of better known sinkholes. A recently formed sinkhole was reported in Hutchinson (Kansas City Times, Oct. 23, 1974, p. 4). Descriptions of sinks and basins are in Merriam (1963, p. 187-192), Smith (1940, p. 131-140, 168-171), Frye (1950), Prescott (1951), McLaughlin (1943) and Bell (1969). Norton (1939) described minor slump structures above dissolved evaporites and listed areas of cave structure in gypsum and anhydrite as did Kulstad et al (1956) and Swineford (1955). Salt casts and solution breccia are discussed in Norton (1939) and Swineford (1955). Subsurface logging and seismic reflections techniques provide evidence of truncated beds of soluble minerals. Such truncations, accompanied by slump structures, are on the eastern edge of Hutchinson Salt Member (VerWeibe, 1937b, p. 16), in the Blaine Formation (Malone, 1962) and in Flowerpot Shale (Irwin and Morton, 1969).

Access of Water to Evaporites

Natural Means.--Water that will dissolve evaporites can gain access by natural means such as along faulting planes and fractures following fold axes. Faults are associated with many solution and collapse structures in Kansas (Merriam, 1963), (Frye, 1950), (VerWeibe, 1937a), (Elias, 1930), (Bass, 1931), (Landes, 1931), (Frye and Schoff, 1942) and (Smith, 1940). Bayne, Franks, and Ives (1971) discussed faults in the area of monoclinal folds and haphazard dips and strikes of rocks in Ellsworth County but did not determine the relationships of solution and collapse to faulting. Fractures developed along the axes of folds form conduits along which water can travel (Jacoby, 1966, p. 311).

Petroleum and gas bore holes.--Man's activities also allows access of water to evaporites. According to McClain (1974, p. 341) drilling operations for oil and gas and salt-solution mining are two reasons for the abandonment of the Lyons, Kansas, site as a repository for radioactive waste. Because the brine in most petroleum operations is corrosive the average life of casings is as short as twelve years (Leonard, 1972, p. 22). Corroded casings, improper plugs, or incomplete cement grouting provide a vertical conduit for water (Jones, 1950).

"In four known instances, the situation has developed where fresh water has gotten into a well from surface aquifers, circulated past the salt section dissolving it, and been discharged into lower, higher permeable zones" (McClain, 1974, p. 341).

Salt-Solution mining.--Salt-solution mining allows water access to evaporites. The recent formation of a sinkhole in Hutchinson,

Kansas, was attributed to an old salt brine well (Kansas City Times, Oct. 23, 1974, p. 4). The techniques and materials used in the construction and maintenance of salt-solution mines are similar to those for oil wells except the wells are in rock salt (Ludwig, 1951; Eaton, 1974; Boughton and Spangle, 1970; Boughton, 1966; Baker and Smith, 1966; Henderson, 1963; Bays, 1963). Brine-mining operations at Sterling and Hutchinson in the 1940's were described by Taft (1946, p. 244-247). An eight-inch diameter casing was placed and cemented to 160 feet depth. Five and five-eighths-inch diameter pipe was inserted and cemented to rock 60 feet deeper. A two and one-half-inch pipe was inserted to the salt beds. Water was pumped down the smallest pipe and brine forced up the five and five-eighths-inch pipe. Usually brine was 99 percent saturated, but if it dropped as low as 90 percent and could not be increased the well was plugged. Well life could average as much as 14 years before cave-ins or too large a cavity caused too low brine saturation. Wells as far apart as 1000 feet could be used by pumping water down one and producing brine from the other well once the cavities connected. Natural coalescence of two or more wells has several disadvantages including overworked wells (Henderson, 1974, p. 211). Connecting wells by fracturing is the least expensive but can be the most complex way to connect two wells as is shown by the case histories given in Henderson (1974, p. 212-217) and Haimson (1974, p. 204-210). Both coalescence and fracturing share the problem of water being pumped in and out without knowing where the growing cavity is located until it connects with another instrumented well.

Deep waste disposal.--Deep disposal of liquid wastes below salt beds in western Kansas is questioned because of possible solution of salt in the Flowerpot Shale. In Kansas 29 waste-disposal well locations are in the Glorieta (Cedar Hills) Sandstone just below the Flowerpot Shale (Irwin and Morton, 1969, p. 13). These wells are in the Hugoton gas field and are used for brine disposal (Irwin and Morton, 1969, plate 4). As of April 26, 1971, injection into the Glorieta was still allowed in Haskell, Morton, Stevens, Finney, Seward and part of Meade counties. Injection 50 feet below the salt in the Glorieta is authorized in Stanton, Grant, Kearney and Gray counties. Other areas of the state where disposal could be questioned are in parts of Saline and McPherson counties where brine can be injected into the lost-circulation zones in the Hutchinson Salt Member. For most other counties in the study area minimum depths for disposal range from 500 feet to 1000 feet or below the top of the Red beds (State Corporation Commission, Table II, April 26, 1971)(appendix F). Latta (1973, p. 623) indicated that 60 percent of oil and gas field disposal wells inject brine into limestones or dolostones, 25 percent into sandstones and the other 15 percent injected into sandy or gypsiferous shale, salt, anhydrite, conglomerate, and "granite wash". Of the 30 industrial-waste disposal wells Latta mentioned, one discharged into the Glorieta Sandstone and two into the lost-circulation zones of the Hutchinson Salt Member (Latta, 1973, p. 627).

Deep waste disposal places fluids directly into a given formation but the liquids may migrate to other formations. Brine may escape through corroded casings and faulty plugs or cementation.

Brine may also migrate through induced fractures in formations if the bottom hole pressure, which should not exceed one psi/ft (pound per square inch per foot) (0.23 kg/sg-cm/m (kilogram per square centimeter per meter)) of overburden, is too great (Collins, 1971, p. 2390). Caswell (1970, p. 646) stated that for disposal wells hydraulic fracturing was commonly used and allowed the well to operate at vacuum or gravity flow for a year or two. Most disposal wells in the Glorieta were reported to be injected by gravity flow (Irwin and Morton, 1969, p. 13).

Radioactive waste disposal.--Disposal of radioactive wastes in salt has been considered for Kansas. The heat generated by this type of waste would produce a heat gradient in the salt bed. Brine inclusions in the salt (estimated at 0.5 percent by volume) would migrate up the gradient to the source of the heat. Jenks (1972, p. 86) estimated that water accumulated around a waste container for 10 years could be around 24 liters or about 53 liters after 50 years. Migration of water from brine inclusions and lost from hydrated minerals at temperatures of $102 \pm 3^{\circ} \text{C}$ ranged from about 0.5 percent in relatively pure halite to 19 percent in shallow gypsum beds (Kopp and Fallis, 1973, p. 410). Although this is not strictly a means of access of water to the salt it is a means of accumulation of water already present. Once water has accumulated in one area it could damage the storage area or waste containers.

Dissolution of Evaporites

After water gains access to evaporite deposits dissolution takes place unless the water is already saturated. The salinity of the water introduced into a bedded-salt deposit controls rate of dissolution so that fresher water dissolves salt faster than more saline water. The flow rate influences the shape of the growing cavity; slower flow rates form wider cavities in the upper region than faster rates.

The water in contact with the salt will increase in density and move down the salt surface by natural convection forming a flowing boundary layer between the salt face and the bulk of fluid (Durie and Jessen, 1964a, p. 184-185). The velocity of the boundary layer flow is a function of density difference between the boundary layer and the main body of water and the viscous shear forces tending to retard downward flow. Surface irregularities, such as those caused by invasion of fluid between crystals, increase the dissolution rate in the laboratory more than that calculated by mathematical analysis. The measured rate of salt removal was two to three times the calculated rate (Durie and Jessen, 1964a, p. 188). Studies of the layer flow for inclined salt surfaces (Durie and Jessen, 1964b, p. 277) indicated that dissolution is greater where the salt surface is inverted above the water and there are surface irregularities due to insoluble layers or fluid invasion between crystals. Where the salt layer is inverted the dissolution takes place with both boundary layer flow and cellular flow. The studies were done under laminar free-convection flow rather than laminar forced-convection

flow. If flow is turbulent the boundary layer is disturbed and rate of salt removal is increased several times (Durie and Jessen, 1964a, p. 190).

Studies of cavity formation along both horizontal and vertical fractures have also led to models which predict cavity formation and shape (Jessen, 1970a, and Jessen, 1970b). Temperature also influences cavity shape and formation because the salt-fluid interface with the higher temperature will have more active dissolution (Bradshaw and Sanchez, 1969). Temperature gradients during heating of salt caused migration of fluid inclusions towards the source of heat (Holdaway, 1974, p. 303; Anthony and Cline, 1972, p. 254). Pegler (1970, p. 216) also suggested that the thermal conductivity from induced heat sources is not isotropic in the rock, but that little research has been done on the question.

Studies of the structural stability of cavities show that behavior of a cavity is not the same as conventional mine behavior (Serata, 1970, p. 249-279). Failures of mined evaporites have been studied since the 1940's but the results of these studies have been contradictory (Baar, 1970, p. 280). Prerequisites for studies of both mines and cavities, as stated by Serata (1970, p. 250), are to obtain equations for the materials based on tensor testing of samples, to calibrate using an adequate model-testing technique, with the equations, and to determine the underground stress field for adoption to a finite element computation program. Ordinary testing methods do not apply to underground structures because of three-dimensional compression; therefore strength and structural behavior will differ from those of two-

dimensional testing. Because the behavior is time dependent, time should be included in the equations used for these studies. Also plastic and viscous behavior is pronounced in triaxial compression as opposed to a two-dimensional model (Serata and Gloyna, 1960, p. 2979). Baar (1970, p. 280) recommended in situ testing of rock because laboratory testing is misleading. In the laboratory, samples are being loaded and in the mine salt is being unloaded in at least one direction of stress.

According to Serata (1970, p. 250) brittle fracture, yielded, plastic, and elastic zones develop around an underground cavity regardless of its shape. He tested ten tensor coefficients to describe the behavior of the cavity. The predication of cavity behavior becomes more complex when more cavities are created in the formation. Cavity closure, in the case of multiple cavities, is determined partly by the behavior of the granular rock salt, the difference between overburden pressure and cavity pressure, the distance separating the cavities, and the number of cavities in the system (Chao, 1974, p. 120). These factors interact and affect cavity closure nonlinearly and closure continues over long periods of time even when stress equilibrium of the system has been established (Chao, 1974, p. 119,124). Studies using different temperatures and pressures in rock salt cavities indicate that higher temperatures or pressures increase flow rates (Lomenick, 1968). A computer program to predict closure was given by Nair, Chang, Singh, and Abdullah (1974). Creep deformation may lead to creep rupture or failure. Nair and Singh (1974, p. 41-49) summarized several mathematical models for predicting failure of

rock salt. The conditions for rupture are those that cause surface spalling. Solution collapse breccia in the Saline Group of Michigan shows that cavity rubble can fill a growing cavity and impede destructive subsidence (Jaron, 1970, p. 427).

Although the surface responds to any underground excavation, direct earth pressure generally prevents underground cavities from collapsing (Abel, 1970, p. 199; Serata and Glo, 1960, p. 2979). Panek (1970, p. 322) described subsidence over excavations in two ways, either gradual down-warping of the surface or large blocks slumping in a stair-step fashion. Terzaghi (1970, p. 289-307) gave one of the few published and documented histories of a subsidence area. The mechanism for subsidence in this case was the deformation of rock strata above a group of cavities with gradual thinning of the strata as the rocks dropped into the cavities. The surface sinkhole that formed rapidly after a gradual subsidence could be attributed to failure of the remaining strata. This mode of sudden failure is commonly called stoping. In the published description the larger shallower and slower subsiding area was underlain by cavities filled or "bulked" with broken rubble whereas under the region of deeper sinkholes the cavities were more open. The salt beds being solution mined at depths of 1000 feet were 300 feet thick with several intercalated nonevaporite strata. In Kansas, both gradual down-warping and sudden subsidence have occurred. Gradual subsidence of about one foot a year has occurred in Russell County and is attributed to solution of salt and sagging of overlying strata into the forming cavity (Bayne and Ward, 1971, p. 61).

Studies to describe and model what happens to cause surface subsidence over cavities have been summarized by Abel (1970). Panek (1970), Abel (1970), and Chang and Nair (1974) discussed the prediction of subsidence if the cavity geometry and formation mechanics are known. Emery (1966) monitored redistribution of surface strains caused by a growing brine cavity. Experiments in Europe have resulted in the monitoring and controlling of subsidence to minimize surface deformation (Panek, 1970, p. 324). Because the shape of the cavity is important in storage of liquified petroleum gas and in cavity stability, studies to predetermine the shape of the growing cavity have been made (Remson, Dommers, and Jessen, 1966; Snow and Nielsen, 1970; von Schonfeldt, 1974).

EFFECTS OF WATER IN EVAPORITES

Effects on Industries

Water in evaporite beds, the solution of the evaporites, and the formation and migration of brines can affect the residents and industries of the involved areas in several ways. In mechanical or dry-salt mining brine channels or solution cavities near the mine are hazardous because the intersection of a dry mine and a brine cavity would flood the mine (Cock, 1974, p. 27; Scharon, 1963, p. 379; Lomenick, 1968, p. 40-42). Brine is corrosive to metal casings used by the petroleum industry (Leonard, 1972, p. 22). Containers for radioactive wastes have to be corrosion resistant over long periods of time when placed in salt beds containing appreciable brine (Bradshaw and McClain, 1971; Empson, Bradshaw, McClain and Houser, 1970, p. 455-462).

Effects on Water Quality and Quantity

Deterioration of quality and reduction of the quantity of water can affect everyone in the areas involved. Loss of water occurs when fresh water leaks into the evaporites (McClain, 1974, p. 341; Bayne and Ward, 1971, p. 61). The formation of dense brine has been discussed. Although the water in the Permian strata is too highly mineralized to use, the brine formed by the dissolution of bedded evaporites is usually denser (Collins, 1971, p. 2388; Levorsen, 1958, p. 663). The displacement of waters contained in the Permian rock and the mixing and migration of the invading brines with these waters results in saline springs and seeps on the surface and into streams (Landes, 1963, p. 64; U.S. Dept. of Health, Education and Welfare, 1964; Ward and Leonard, 1961, p. 424-428; Frye and Schoff, 1942, p. 36; Durum, 1953; Williams, 1946, p. 194, 195). The water in Permian rock, much of which is already under artesian pressure, may develop higher pressures because of brine invasion, making upward migration of water more likely (Latta, 1950, p. 91; Fent, 1950, p. 47; Fishel, 1952, p. 69-70; Bayne and Ward, 1974, p. 13-15). Any movement of waters into fresh water aquifers is likely to result in contamination (Walters, 1961, p. 59; Bayne, Franks, and Ives, 1971, p. 44). The equivalent of one barrel of brine having 100,000 mg/l chloride would require more than 400 barrels of fresh water to dilute it to drinking water standards (Collins, 1971, p. 2388). This would mean a reduction of the quality of fresh water supply. Not all chloride contamination of water is attributable to dissolution of evaporites in the Permian strata. Some waters in strata above

the Permian have high chloride contents (Berry and Durum, 1952, p. 50, 59, 61-62). Seasonal local contamination may come from the use of road salt (Terry, 1973). Examples of pollution caused by improper disposal of oil field brines can be found in geological bulletins for Kansas counties.

Because "polluted ground water can emerge at the surface far from the source of pollution" (Leonard, 1972, p. 23) and because hydrodynamic pressures cause changes that extend laterally for some distance, the initial area involved gradually extends its influence to neighboring areas. Irwin and Morton (1969, p. 13-15) summarized several ways vertical and horizontal movement of water can occur when the potentiometric surface of a lower aquifer is above that of a higher fresh water aquifer. A map of a potentiometric surface of a confined aquifer shows the level water would rise if vertical conduits were provided. Changes in water density would cause the water to rise higher if the density became lower or to be depressed if the density were raised. Vertical movement of fluids can occur through natural or artificial conduits including joints, faults, solution channels or wellbores. If the sufficient confining pressure and the conduit are present, foreign water can be admitted to fresh water zones. Lateral downgradient movement of denser, foreign water would result and the movement downgradient would continue even if the source were found and corrected. The significance of the invasion of foreign water would depend on factors such as degree of dispersion and dilution, and quality of the foreign water.

Other factors to be considered here are water withdrawal and the

drawdown characteristics of pumped well fields. The Ghyben-Herzberg theory explains how pumping of fresh water over denser water decreases the pressure and causes an upward coning of the denser water (Brown, 1925, p. 16, 34-37; Deutsch, 1963). Saline water encroachment into fresh water zones resulting from artesian well withdrawals has been studied in New Mexico (Hood, 1963). Thus the downward leakage from an aquifer to a dissolution zone could supply the drive for water movement to higher formations. Given vertical conduits, enough hydraulic pressure and/or withdrawal of fresh water, the leaking aquifer could cause the contamination of an otherwise unrelated area. Mineralized water from Permian strata occurs as seeps, springs, leakage from older oil wells, and ground water influent to streams (Nolan, 1963, p. A40; Nolan, 1964, p. A39; Jordan, Jones and Petri, 1964, p. 40; Pecora, 1970, p. A186). The contaminated water reaching a surface drainage basin then affects chemistry of waters entering the basin downstream (Pinder and Jones, 1969, p. 438-445; Gibbs, 1970, p. 1088-1090; Whittemore, 1976).

Effects on the Land Surface

Physical changes in land surfaces or changes in the physical properties of underlying rock also affect residents and industries. Landes (1963) mentioned salt caves and surface collapse as some major effects of salt dissolution. Caves and surface collapse in Kansas attributed to solution of evaporites have been noted by McGregor (1952, p. 1277-1278), Bell (1969, p. 555-560), Irwin and Morton (1969) and Frye (1950, p. 1-20). Changes in physical properties of the rock surface include changes in the strain pattern

(Emery, 1966, p. 103) and in the accoustical properties of brine receiving formations (Baar, 1973) which are associated with fluctuations in formation density. Seismic study in western Kansas is difficult because dissolution zones and missing evaporites cause erroneous velocities (Widess, 1952).

Formation of Brine after Dissolution

Chemical changes.--Water that has dissolved bedded evaporites is highly mineralized. The constituents in solution depend upon the evaporites dissolved, the reaction of the water with other formations, and the initial composition of the water before dissolution. An example can be seen on the maps by Feth and others (1965)(Fig. 13). Ground water having more than 35,000 mg/l TDS occurs in a narrow band from S. Line County to Sumner County. The water is high in sodium chloride and is less than 500 feet below the surface. This band corresponds to the solution front of the Hutchinson Salt Member of the Wellington Formation (Fig. 5). Although anhydrite and gypsum are associated with bedded halite they are less soluble and do not contribute the same percent of dissolved solids to the water. These minerals are more soluble where associated with dissolved sodium and chloride than in pure water (Tanzi and Doneen, 1966; Blount and Dickson, 1969). Kaufmann (1960, p. 24) reported that the impurities in commercial Kansas halite are 94.5 percent anhydrite and 2.4 percent dolomite. The remainder is insoluble. Composition of brine inclusions would also influence composition of water dissolving the bedded salt. The Mg/Cl, Ca/Cl, SO_4/Cl , and Br/Cl ratios of inclusions in Permian

rocks of Kansas are given by Holser (1963). The initial composition of the water before dissolution would in part be dependent on the source or sources of the water. The reaction of the water in formations it contacts would depend on the dissolved constituents as well as the compositions of the formations and their included fluids (Collins, 1975). References have been given for surface and ground waters and their origins (see sections on water and appendices A,B,C,D).

Hydrodynamic pressure changes.--As water dissolves halite and brine is produced, the density of the brine increases, some brines obtain a density 20 percent higher than fresh water. The brine will sink to the base of the dissolving cavity (Kaufman, 1960, p. 160). If the brine is not pumped out, (as in solution mining), but reaches lower formations, the brine invades the formations. The denser brine from cavity solution pushes out or displaces the less dense formation waters. The displaced waters move in the direction of lower pressure or the direction of least resistance (Levorsen, 1958, p. 397). This produces a new hydrodynamic system having elevated pressure zones expanding outward from the area of invasion. The invading brine and the invaded formations act as would injected fluid and receiving formations in deep well disposal operations (Van Everdingen, 1968).

Discharging higher hydrodynamic pressures into zones of lower pressures can occur in several ways. Leakage may be upward through semiconfining formations (De Wiest, 1965, p. 271; Layton and Berry, 1973, p. 24).

"...by way of abandoned and improperly constructed wells and along minor faults and fractures produced by the irregular settling...in response to solution of underlying salt beds. It is probable that recent geophysical exploration for oil has added to the leaks in the upper confining beds" (Frye, 1942, p. 64).

Leakage may also be downward into more permeable formations or into former oil production zones (Bayne and Ward, 1971, p. 61; McClain, 1974, p. 341; Jewett, 1948, p. 142). Because hydrodynamic pressure is exerted laterally along the bedding planes water may be displaced eventually at the outcrop of the invaded formations (Levorsen, 1958, p. 380, 397; Nolan, 1963, p. A40; Lane and Miller, 1965, p. 22, 50). Some factors that influence the amount of dense brine accepted by the formation are permeability and porosity of the formations, density and viscosity of the invading and displaced fluids, the temperatures and pressures of the formations (Levorsen, 1958, p. 397), the volume of fluid already accepted as well as the rate of emplacement in the formations, and the presence of similar invaded zones in the same formations (Van Everdingen, 1968).

DETECTION OF DETERIORATION IN EVAPORITES

Direct Methods

Direct detection of evaporite deterioration can be made by observing surface subsidence features, salt seeps, springs, and marshes (see previous sections for references to these in Kansas). Cracking and tilting in architectural structures can be observed before obvious subsidence (Terzaghi, 1970, p. 298; Panek, 1970, p. 323). Change in vegetation from fresh-water-dependent to salt-water-tolerant or lack of vegetation can be observed around some areas having contaminated surface or ground waters (Davis and DeWiest,

1966; Jones, 1950; U.S. Dept. of Interior, 1968, p. 148, 195).

Another observation is the change in taste occurring in water having 500 mg/l chloride content (Johnson Division, 1966, p. 74).

Indirect Methods

Aquifer tests.--Indirect detection of deterioration can be done by various tools, instruments and accumulated geologic and hydrologic records. Changes in ground water quantity, movement, and pressure can be detected by several aquifer tests. Pumping tests to describe aquifer characteristics, such as head, drawdown, leakage, boundaries and special problems, were given by Ferris, Knowles, Brown and Stallman (1962), Bental (1963), Fader (1967), Pinder (1970), Rorabaugh (1953), and Walton (1962). Economic cost of impairment caused by lowered water level was discussed by Nuzman (1966). A bibliography of methods was given by Johnson (1964). Methods for measuring water levels in deep wells were given by Garber and Koopman (1968). Water level studies, such as those by Winslow, McGovern, and Mackey (1968), Fischel (1956), Meinzer and Wenzel (1937) give information about particular aquifers and can be used to find changes not accounted for by industrial or agricultural uses of the wells. Ground water temperature studies can give information about lateral movement of pollutants in the fresh water aquifer, vertical movement of saline ground water into aquifers and downward leakage of fresh waters from aquifers (Stevens, Ficker and Smoot, 1975, p. 2-3). Geothermal techniques and applications to groundwater study were given by Birman (1966), Schneider (1962), Cartwright (1968), Bredehoeft and Papadopoulos (1965), Halepaska and Hartman (1971), Stevens, Ficke, and

Smoot (1975). Several geophysical techniques for ground water study were given by Kelley (1962), Patten and Bennett (1963), Keys and MacCary (1971), Zohdy, Eaton and Mabey (1974), and Keys and Brown (1973).

Water analyses.--Chemical changes can be studied by water sampling and testing as given by Brown, Skougstad, and Fishman (1970). Transport equations for fresh-saline water interface were given by Bredehoeft and Piner (1972). Applications to saline contaminated areas were described by Fryeberger (1975 and 1972) and Leonard (1964 and 1972). The origin of contaminating water is important in deciding if evaporite dissolution is involved. Bromide content of saline water seems to be one indicatio of origin (Rittenhouse, 1967; McClure, 1973). Analytical procedures for determining small bromide concentrations are necessary because much smaller concentrations are derived from the solution of rock salt than oil field brines. Procedures for determining small bromide concentrations are given by Brown, Skougstad and Fishman (1970). Studies of streams during low flow indicate relationships of dissolved minerals contributed by ground water to dissolved minerals in surface runoff (Durum, 1953; U.S. Environmental Protection Agency, 1973b; Hardison, Marshalle and Gilroy, 1972).

Mechanical aids for evaluation.--Evaluations of field and laboratory testing is made easier with statistics and computers. Riggs (1968) described statistical methods applicable to hydrologic data interpretation. Lowell, Morgan, and McNellis (1970), Leonard and Morgan (1970), Ropes, Morgan, and McNellis (1969), McNellis and

Morgan (1969), Morgan and McNellis (1969) discussed programs and types of data available in Kansas. Other studies and applications using computer simulation and evaluation include those by Molz (1974), Walton and Prickett (1963), Skibitzke (1961), and Remson, Hornberger and Molz (1971).

Geophysical tests.--Cavities in bedded evaporites are detected by several geophysical methods. Often cavities are recognized by changes in drilling time encountered in drilling a susceptible formation (Terzaghi, 1970, p. 300; Schlumberger Well Surveying Corp., 1958). Electrical well logs run after drilling can detect cavities behind cement, indicate cavity dimensions and kinds of evaporites affected (Hicks, 1974; Caldwell and Strabala, 1970; Alger and Crain, 1966; Zohdy, 1970). Stereo photography can be used in cavities to determine size and shape (Boger, 1966). Gravity and magnetic surveys can detect cavities although gravity anomalies from large cavities less than 2000 feet deep are the most useful (Lange, 1965; Moorhouse and Millet, 1973; Speed, 1970). Analysis of data from seismic reflection techniques can help to locate and measure shallow cavities up to 1500 feet deep (Watkins, Godson, and Watson, 1967; Whitcomb, 1969; Moorhouse and Millet, 1973; Myers, 1963; Cook, 1966 and 1974b). Changes related to deterioration caused by solution and collapse of bedded evaporites can be recognized using seismic methods (Widess, 1952; Barr, 1973). In dry or mechanical salt mines, water in the formation occurring in channels or cavities can be detected by radar, laser radar and resistivity studies (Cook, 1974a; Unterberger, 1974a and 1974b; Scharon, 1963). Information

about rock composition, properties, and deformation in deteriorating formations can be obtained using several methods including three dimensional velocity logs in borehole and rock mechanics instrumentation (Christensen, 1966; Myung and Helander, 1974; Sellers, 1970; Abel, 1970). Theory, applications, and additional studies using geophysical methods are included in appendix E.

Remote sensing.--Remote sensing, detection of electromagnetic waves coming from the earth's surface with air-borne instruments and cameras, can detect cavities and potential collapse sites (Johnston, 1973; Oberste-Lehn, 1966; Pecora, 1969, p. A196-197; Pecora, 1970, p. A208). Remote sensors can detect ground and surface waters, vegetation and rock types (Wilson, 1969; Sabins, 1973). Air-borne photographic studies have been used to trace features of fracture traces and jointing (Lattman, 1958; Nickelsen and Hough, 1967). Publications giving capabilities and methods for using different types of remote sensors are in appendix E.

SUGGESTIONS FOR FURTHER STUDY

Introduction

Further study of Kansas evaporites is needed. Not much is known about the formation of natural cavities, migration of brines, or the physical changes that occur during and after cavity formation. Management and control of dissolution of evaporites requires additional engineering studies and application of new technologies. Planning requires proposals for zoning ordinances and land and water use regulations that reflect good planning for the future.

Locating and Studying Potential Subsidence

Subsidence of the land could have sudden disastrous and potentially tragic results. Assessments of the study area to designate potential subsidence can be undertaken. This assessment might include remote sensing studies, geophysical testing, and comparison of early and recent aerial photograph stereo pairs. Once potential or suspected subsidence areas are identified, more thorough study of each restricted area can include geophysical and electrical logging tests, comparisons of earlier and later results for changes, and some evaluation of each area for immediacy of additional observation. Observation and testing would serve to find ways to control or manage the developing deterioration, to define the causative factors, and to guide changes in land and water uses, planning, and development. If further testing does or does not seem to be immediately called for, periodic monitoring of the site can help in evaluating any changes occurring after the initial studies, or signal need for renewed study. An appropriate state agency for supervision, coordination and funding of these studies would be the State Geological Survey through Kansas statute 76-322 (See appendix F for summaries of this law and other laws, rules and regulations that are relevant or mentioned later).

From the initial studies research could reveal new understanding of natural cavity development and factors influencing preferential cavity development in one area versus another, methods of monitoring and controlling cavity growth in situ, changes in formations adjacent to growing cavities, information on structural differences and

changes in bedded evaporites, and refinement of thickness and purity maps of the existing evaporite deposits to help in interpreting geophysical tests.

Monitoring and Studying Water Quality and Quantity

Water records.--Because water is important, monitoring stations have been established throughout the state to monitor water quality, surface water discharge, and ground water table levels. The United States Geological Survey works with the State Geological Survey of Kansas, the Kansas Water Resources Board and the Kansas Department of Health and Environment to provide the water records from the monitoring stations. Other officers and agencies of the counties and state involved in collecting data or filing records of water quantity, quality, use, or disposal since 1963 include the following (with authorization, see appen ix F): registrar of deeds (K.S.A. 42-330), artesian well supervisor (K.S.A. 42-411, 42-414, 42-417, 42-418, 42-419), State Corporation Commission (K.S.A. 55-1003, 55-1006, regulations 82-2-400 and 82-2-500), State Board of Health (K.S.A. 65-171), Chief Engineer of the State Board of Health (K.S.A. 65-170, regulation 28-13-2), Ground Water Management Districts (K.S.A. 82a-1001 to 82a-1009), Division of Water Resources (K.S.A. 74-506), Chief Engineer of the Division of Water Resources (K.S.A. 82a-706), State Irrigation Commission (K.S.A. 74-509), State Water Resources Board (K.S.A. 74-2608), Department of Health and Environment (Executive Reorganization Order No. 3).

Water resources planning.--The State Water Resources Board through K.S.A. 74-2608 is required to collect information about

water use and availability, to work out a state water plan, to recommend legislation or policy changes concerning water use and development. The State Water Plan (K.S.A. 82a-901 to 82a-904, 82a-907, 82a-927 and 82a-928) has as some of its goals the prevention of water pollution, maintenance of water quality, development of irrigation water with SAR values not exceeding 15, plugging of abandoned wells, control of mineralized water seepage areas and proper disposal of brines. To achieve its goals the cooperation of these agencies and officers is required (K.S.A. 74-2610), The Division of Water Resources and the Chief Engineer of the State Board of Agriculture, the State Geological Survey of Kansas, the Director of Agriculture Experiment Stations, the Chief Engineer of the State Board of Health and any other state and local agencies. Because of the existing functions, goals and powers of this board, the logical state agency for coordinating water studies, supervising research, and funding would be the State Water Resources Board.

Proposed investigations.--Knowing the goals of the state water plan and the implications of evaporite dissolution in decreasing water quality, several problems for study can be suggested. Changes in water quality in wells and surface waters can be investigated to find whether increased mineral content is from connate waters, solution of evaporites, or a combination of both. Computer programs are available for this. Pressure changes and water level changes not explained by normal recharge and discharge can help explain the entry of foreign water into fresh water supplies. Testing and monitoring a well field showing increased mineral content in waters or unexplained

pressure and water level changes may indicate which of several mechanisms is responsible. The changes in water level or pressure may result from loss of water to formations having lower pressures, such as leakage around defective wells or plugs, excessive pumping causing upward coning of denser water already present in the formation or in hydraulically connected formations, or depressions in fresh water levels caused by dense water present below the depressed water. The changes in water quality result from invasion of inferior water to the producing zone. When exit points of fresh water or entrance points of invading waters are found, appropriate action such as decreased pumping, plugging of abandoned holes, or repair of defective wells could be taken. Continued monitoring might be advised. Preparation and revision of hydrodynamic pressure models using results of tests and gathered monitoring data can be most helpful in future management and development. Because Kansas waterways eventually become part of the interstate waterways, funds for programs might be sought from federal sources.

Investigations of Industrial Practices

Industrial records.--A seemingly unrelated clue pointing toward migration of water into other formations would come from oil and gas well records. Gradual repressuring of a producing formation when artificial water flooding is not being done indicates that natural water flooding may be operating. This would indicate faulty plugging of exploratory or production boreholes or natural hydraulic connection. Records of gas well pressure are made by the gas inspector and kept in the office of the registrar of deeds (K.S.A. 55-305). Records of

oil well pressures are not kept, but shut off tests may be conducted (K.S.A. 82-2-122). Salt water can be returned to producing strata (K.S.A. 55-901, regulations 82-2-400 to 82-2-404), but no records are required. Especially if a return well is accepting saltwater of more than one producing well, records may help explain changes in the production formation. Water-flooding records are kept for three years by the owner of the injection well (regulation 82-2-504).

Boreholes.--To safeguard against migration of fluids, abandoned holes must be properly plugged whether drilled for exploration, gas, or oil production, or water wells (K.S.A. 19-2504, 55-128, 55-136 to 55-140, regulations 82-2-122, 82-2-302 to 82-2-304, 82-2-306, section 13 of House Bill no. 1372). After abandonment, the site is left suitable for the use it had before drilling (K.S.A. 55-132), which results in difficulty in relocating an abandoned well if replugging is necessary. A great number of unrecorded and/or unplugged holes were abandoned before laws required recording of locations or plugging of holes. Even where plugging has been done, regulation 82-2-123 section 5 permits the prior removal of surface casing when the hole is less than 2,500 feet deep or was drilled with cable tools. Thus relocating the hole cannot be done by magnetic means. The goals of locating and plugging holes that allow migration of fluids requires methods for relocating the lost holes. The areas likely to need hole relocation are those having the older drilling operations for exploration and production or those having corrosive concentrations of brines in contact with the casings long enough to cause them to leak. Also those areas having denser drilling activity will have correspondingly

higher probability of defects in plugging or casing. Investigation of public records, geologic files and reports, and area newspapers can give some information about the number and locations of old boreholes that are not recorded through present agencies. Methods for reducing fluid migration without harming aquifer capacity and the transmissivity are needed where open borehole migration is indicated, but exact relocation is impossible.

Drilling operations.--Industrial drilling practices are related to both cavity formation and fluid migration in evaporites, especially bedded salt. State oil and gas regulation 82-2-121 states in part that persons drilling any hole

"that penetrates formation containing oil, gas, fresh water, mineralized water, or valuable minerals, shall case or seal off such formations as may be necessary to effectively prevent migration of oil, gas, or water from or into strata that would be damaged by such migration".

Also oil and gas regulation 82-2-307 (D) states "should circulation be lost in the drilling of any exploratory hole, an approved plug shall be placed immediately above the cavernous condition". Can the first quoted regulation be interpreted to require casing of bedded salt where it occurs in thin beds interstratified with shale and/or anhydrite? The second regulation clearly does not protect the zone of lost circulation from water in lower formations having enough artesian pressure to reach the zone. If the zone is in evaporites, indicating that solution has already taken place, then more water means more solution is likely. These are the only two instances where casing or plugging are mentioned with regards to minerals or lost circulation zones. Filing intents to drill is required (K.S.A.

55-128). Informed citizenry, honest operators and diligent, responsible state agents can help prevent the practice of unreported drilling or improper plugging of boreholes.

Salt industry.--Salt brine wells are not mentioned in the laws and regulations. Although advances in developing new cements and casings for the special problems faced by the brine extraction wells have been made (Boughton, 1966; Boughton and Spangle, 1970; Baker and Smith, 1966), there is still need for better application and testing. When and how to abandon wells is a problem because inadequate data exist. Monitoring could be useful in adding to existing data and helping decision making (Bays, 1963a).

Legal Implications of Water Injection

A problem that can occur in salt wells, water disposal wells and water flooding operations is the legal liability of the operator if he loses control of the fluid and the fluid subsequently damages subsurface or surface properties. The actual locations of salt brine cavities is often uncertain or unknown. Water flooding in Texas (Garland, 1962) caused channeling of water into fissures and zones of high permeability. Also Lenahan (1973) pointed out that hydraulic fracturing can occur in grouting operations. Both channeling and hydraulic fracturing imply the undesired movement of fluids. A well-planned monitoring system could help with management of an injection system and explanation of injection fluid effects on the upper and lower formations of a given system. This could lead to better decisions when approval of additional disposal or water-flooding systems is considered.

Radioactive Waste Disposal

A radioactive waste disposal site, if ever an actuality in Kansas, would require location in undrilled salt to be very safe. Selection of a site should follow careful consideration of the water availability and probability of access of water to the site. Another question is the adequacy of knowledge concerning heat transfer in bedded salt. Halepaska (1971a, 1971b) and Halepaska and Hartman (1971) made recommendations for further study of the heat transfer question.

State Wide Coordination and Communication

Even if most of the suggestions for study and monitoring of evaporites are implemented, the benefits will not be maximum without coordination of the studies and education of the citizens in the stakes involved. Land and well owners need to be aware of changes in water quality and quantity that should be reported. They need to know the agencies interested in the changes. Land owners need to be aware of the drilling and plugging laws and regulations which protect the water supply. The easiest way for information of these kinds to be distributed and used is to make it available to people whom land and water users are already likely to contact. Agricultural and 4-H club extension county agents presently provide information on agricultural practices, agricultural land use and planning and some geological topics (K.S.A. 2-608). Their work brings them into daily contact with present and future land and water users. Suggestions of coordination of studies have already been given but it should be emphasized that the studies concerning evaporite deterioration will require the communication and cooperation of all involved agencies.

SUMMARY

Bedded rock salt, gypsum and anhydrite dissolve when in contact with water undersaturated with respect to them. Water availability and access to bedded evaporites is demonstrated by solution features such as slump structures, sinkholes and salt seeps, springs and marshes. Water contacts evaporites by transmission through natural paths provided by faults, fractures, joints and pore spaces in formations. Petroleum and water drilling operations and salt solution extraction can accelerate normal deterioration. The denser water that forms from dissolving evaporites behaves hydrodynamically, migrating to zones having lower pressures. Over pumpage, defectively plugged boreholes and natural hydraulic connections are some factors accounting for mineralized water contamination. Analyses to determine sources, and monitoring of well fields for information for better management and planning decisions are programs that can be coordinated by the Water Resources Board. County extension agents can produce a better informed citizenry by working with future and present land and water users. The Geological Survey can coordinate programs to detect dissolving evaporites, potential subsidence areas, and propose changes in policy, regulation and land use practices to control and manage evaporite deterioration.

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SELECTED REFERENCES

- Abel, J.F., 1970, Rock mechanics-can it pay its way?, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 2, p. 197-207.
- Alger, R.P., and Crain, E.R., 1966, Defining evaporite deposits with electrical well logs, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 2, p. 1673-1681.
- Anthony, T.R., and Cline, H.E., 1972, The thermomigration of biphasic vapor-liquid droplets in solids: *Acta Metall.*, v. 20, p. 247-255.
- Baar, C.A., 1970, Correct interpretation of data for better understanding of salt pillar behavior in mines, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 2, p. 280-289.
- Bailey, E.H.S., 1902, Special report on mineral waters: University Geol. Survey of Kansas, v. VII, 243 p.
- Baker, Weldon, and Smith, D.K., 1966, Cementing practices for salt wells, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 2, p. 344-358.
- Barr, F.J., 1973, Feasibility study of a seismic reflection monitoring system for underground waste-material injection sites, in Braunstein, Jules, ed., Underground waste management and artificial recharge: Am. Assoc. Petroleum Geologists, U.S. Geol. Survey, International Assoc. Hydrological Sci., v. 1, p. 207-218.
- Bass, N.W., 1926, Geologic investigation in western Kansas with special reference to oil and gas possibilities: Kansas Geol. Survey Bull., no. 11, 96 p.
- _____, 1931, Recent subsidence in Hamilton County, Kansas: Am. Assoc. Petroleum Geologist, v. 15, no. 2, p. 201-205.
- Bayne, C.K., compiler, 1972, Supplemental areas for storage of radioactive wastes in Kansas: Kansas Geol. Survey, Spec. Dist. Pub. no. 60, 20 p.
- Bayne, C.K., Franks, P.C., and Ives, W., Jr., 1971, Geology and groundwater resources of Ellsworth County, Kansas: Kansas Geol. Survey Bull., no. 201.
- Bayne, C.K., and Ward, J.R., 1971, Surface geology and groundwater hydrology in Angino, E.E., and Hambleton, W.W., compilers, Final report, geology and hydrology of the proposed Lyons, Kansas, radioactive waste repository site: Kansas Geol. Survey, University of Kansas Center for Research, Inc. for the U.S.A.E.C. and Union Carbide Corp. under A.E.C./U.C. Subcontract no. 3484, 190 p.

- Bayne, C.K., and Ward, J.R., 1974, Geology and hydrology of Rice County, Kansas: Kansas Geol. Survey Bull., no. 206, pt. 3, 17 p.
- Bays, C.A., 1963a, Significant uncertainties in current salt solution extractions operations, in Northern Ohio Geol. Soc., Symposium on Salt, p. 467-481.
- _____, 1963b, Use of salt solution cavities for underground storage, in Northern Ohio Geol. Soc., Symposium on Salt, p. 564-578.
- Beck, H.V., 1976, Personal Communication.
- Bell, E.L., 1969, A soil-topography relationship in the two size groups of depressions in Logan County, Kansas: Kansas Acad. of Sci. Trans., v. 72, no. 4, p. 555-560.
- Bental, Ray, compiler, 1963, Shortcuts and special problems in aquifer tests: U.S. Geol. Survey Water-Supply Paper 1545C, 117 p.
- Berry, D.W., and Durum, W.H., 1952, Geology and groundwater resources of Lincoln County, Kansas: Kansas Geol. Survey Bull., no. 95, 96 p.
- Birman, J.H., 1966, Detection of seepage by geothermal techniques, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 2, p. 212.
- Blount, C.W., and Dickson, F.W., 1969, The solubility of anhydrite (CaSO_4) in $\text{NaCl-H}_2\text{O}$ from 100° to 450°C . and 1 to 1000 bars: Geochim. et Cosmochim. Acta v. 33, p. 227-245.
- Boger, W.H., 1966, Stereo photography in brine wells, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 2, p. 359-362.
- Boughton, L.D., 1966, Techniques and materials for sealing large diameter pipe in rock salt, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 1, p. 369-378.
- Boughton, L.D., and Spangle, L.B., 1970, Materials for better hydraulic and shear bonds in solution mining, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 1, p. 417-421.
- Bradshaw, R.L., and McClain, W.C., 1971, Project Salt Vault: A demonstration of high activity waste in underground salt mines: Oak Ridge National Lab., Unpub., ORNL-4555, 355 p.
- Bradshaw, R.L., and Sanchez, F., 1968, Brine migration studies, in Annual Progress Report, Health Physics Division, Oak Ridge National Laboratory, Unpub., ORNL-4316, p. 32-35.
- _____, 1969, Migration of brine cavities in rock salt: Journal Geophysical Research, v. 74, no. 17, p. 4209-4212.

- Bredehoeft, J.D., and Papadopoulos, I.S., 1965, Rates of vertical groundwater movement estimated from the earth's thermal profile: *Water Resources Research*, v. 1, no. 2, p. 325-328.
- Bredehoeft, J.D., and Pinder, G.F., 1972, Application of transport equations to ground water systems: *Am Assoc. Petroleum Geologists Mem. no. 18, Underground Waste Management and Environmental Implications*, p. 191-201.
- Brown, Eugene, Skougstad, M.W., and Fishman, M.J., 1970, Methods for collection and analysis of water samples for dissolved minerals and gases, *Techniques of water-resources investigations of the U.S.G.S.: U.S. Geol. Survey, Book 5, Laboratory Analysis, Chap. A1*, p. 160.
- Brown, J.S., 1925, A study of coastal ground water with special reference to Connecticut: *U.S. Geol. Survey Water-Supply Paper 537*, 101 p.
- Caldwell, J.W., and Strabala, J.M., 1970, Applications of Modern well logging methods to salt solution cavities, *in Northern Ohio Geol. Soc., Third Symposium on Salt*, v. 2, p. 341-352.
- Campbell, C.L., 1963, Upper Permian evaporites of western Kansas between the Blaine Formation and the Stone Corral Formation: *Unpub. M.S. Thesis, Kansas University, Dept. of Geology*, 73 p.
- Carlson, E.J., 1968, Removal of saline water from aquifers: *U.S. Govt. Printing Office, Washington, D.C., Water Resources Tech. Pub. Research Report no. 13*, 43 p.
- Cartwright, K., 1968, Thermal prospecting for groundwater: *Water Resources Research*, v. 4, no. 2, p. 395-401.
- Case, L.C., 1934, Subsurface water characteristics in Oklahoma and Kansas, *Wrather, W.E., and Lahee, F.H., eds., Problems of Petroleum Geology: Am. Assoc. Petroleum Geologists*, p. 855-868.
- Caswell, C.A., 1970, Underground waste disposal; concepts and misconceptions: *Envir. Sci. Technol.*, v. 4, no. 8, p. 642-647.
- Chang, C-Y., and Nair, Keshavan, 1974, Analytical methods for predicting subsidence above solution-mined cavities, *in Northern Ohio Geol. Soc., Fourth Symposium on Salt*, v. 2, p. 101-117.
- Chao, Robert, 1974, Long term creep closure of solution cavity system, *in Northern Ohio Geol. Soc., Fourth Symposium on Salt*, v. 2, p. 119-127.
- Chave, K.E., 1960, Evidence on history of sea water from chemistry of deeper subsurface waters of ancient basins: *Am. Assoc. Petroleum Geologists Bull.*, v. 44, no. 3, p. 357-370.

- Christensen, D.M., 1966, The determination of the in-situ elastic properties of rock salt with a 3-dimensional velocity log, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 2, p. 104-115.
- Collins, A.G., 1971, Oil and gas wells-potential polluters of the environment?: Washington D.C., Water Pollution Control Federation Jour., v. 43, no. 12, p. 2383-2393.
- _____, 1974, Saline groundwaters produced with oil and gas: U.S. Environmental Protection Agency, Office of Research and Development, Project 16060 EQQ Program Element 1BA024, p. 39-40.
- _____, 1975, Geochemistry of oil field waters: New York, Elsevier Scientific Publishing Co., Developments in Petroleum Science, 1, 496 p.
- Cook, J.C., 1966, Seismic delineation of solution cavities, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 2, p. 131-139.
- _____, 1974a, How to locate water hazards in salt mines, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 27-31.
- _____, 1974b, Yes, we can locate solution cavity boundaries, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 33-40.
- Cragin, F.W., 1886, Further notes on the Dakota gypsum of Kansas: Washburn College Lab. Natural History, v. 1, no. 1, p. 166-168.
- _____, 1896, The Permian System in Kansas: Colorado College Studies, v. 6, 48 p.
- _____, 1897, Observations on the Cimarron Series: American Geologist, v. 19, p. 351-363.
- Cram, I.H., ed., 1971, Future Petroleum Provinces of the United States-Their geology and potential: Am. Assoc. Petroleum Geologists, Mem. 15, 2 v.
- Crow, R.D., 1963, Salt cavern storage of LPG at Lowell, Michigan and Hutchinson, Kansas, in Northern Ohio Geol. Soc., Symposium on Salt, p. 616-620.
- Darton, N.H., 1921, Permian salt deposits of the south-central United States: U.S. Geol. Survey Bull., no. 715-M, p. 205-230.
- Davis, S.N., and DeWiest, R.J.M., 1966, Hydrogeology: New York, John Wiley and Sons, Inc., 463 p.
- Dellwig, L.F., 1956, The Barber County earthquake of January 6, 1956: Kansas Geol. Survey Bull. 119, pt. 5, p. 175-185.
- _____, 1963, Environment and mechanics of deposition of the Permian Hutchinson Salt Member of the Wellington Shale, in Northern Ohio Geol. Soc., Symposium on Salt, p. 74-85.

- DeSitter, L.U., 1947, Diagenesis of oil-field brines: Am. Assoc. Petroleum Geologists Bull., v. 31, no. 11, p. 2030-2040.
- Deutsch, Morris, 1963, Ground water contamination and legal controls in Michigan: U.S. Geol. Survey Water-Supply Paper 1691, 79p.
- De Wiest, R.J.M., 1965, Geohydrology: New York, John Wiley and Sons, Inc., 366 p.
- Dommers, O.B., and Jessen, F.W., 1961, Feasibility of creating spherical cavities in underground salt domes: University of Texas, Dept. of Petroleum Engg. Report of the U.S. Atomic Energy Commission, January, 1961.
- Donaldson, E.C., 1964, Subsurface disposal of industrial waste in the United States: U.S. Bur. Mines Inf. Circ. 8212, 34 p.
- Durie, R.W., Jr., and Jessen, F.W., 1964a, Mechanism of the dissolution of salt in the formation of underground salt cavities: Soc. Petroleum Engineers Journal, June, 1964, p. 183-190.
- _____, 1964b, The influence of surface features in the salt dissolution process: Soc. Petroleum Engineers Journal, v. 4, no. 3, p. 275-281.
- Durum, W.H., 1953, Relationship of the mineral constituents in solution to streamflow, Saline River near Russell, Kansas: Am. Geophy. Union Trans., v. 34, p. 435-442.
- Eaton, B.A., 1974, Fracture gradient prediction and application, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 153-175.
- Edmund, R.W., and Goebel, E.D., 1968, Subsurface waste-disposal potential in Saline Basin of Kansas, in Galley, J.E., ed., Subsurface disposal in geologic basins- a study in reservoir strata: Am Assoc. Petroleum Geologists Mem. 10, p. 154-164.
- Elias, M.K., 1930, Origin of cave-ins in Wallace County, Kansas: Am. Assoc. Petroleum Geologists Bull., v. 14, p. 316-320.
- Emery, C.L., 1966, An experiment to define the strain redistribution at surface caused by a growing cavity at depth (abs.), in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 2, p. 103.
- Empson, F.M., Bradshaw, W.C., McClain, W.C., and Houser, B.L., 1970, Results of the operation of Project Salt Vault: A demonstration of disposal of high level radioactive solids in salt, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 1, p. 455-462.
- Fader, S.W., 1967, Notes on the shape of the truncated cone of depression in the vicinity of an infinite well field: Kansas Geol. Survey, Special Distrib. Pub. 33.

- Fay, R.O., 1961, The Blaine and related formations of northwestern Oklahoma and Kansas: Unpub. Doctorial disseration, University of Kansas, 474 p.
- Fent, O.S., 1950, Geology and groundwater resources of Rice County, Kansas: Kansas Geol. Survey Bull., no. 85, 142 p.
- Ferris, J.G., Knowles, D.B., Brown, R.H., and Stallman, R.W., 1962, Theory of aquifer tests: U.S. Geol. Survey Water-Supply Paper 1536-E, 174 p.
- Feth, J.H., 1971, Mechanisms controlling world water chemistry: Evaporation-crystallization process: Science, v. 172, p. 870.
- Feth, J.H., and others, 1965, Preliminary map of the conterminous United States showing depth to and quality of shallowest ground water containing more than 1,000 parts per million dissolved solids: U.S. Geol. Survey, Hydrologic Inv. Atlas, HA-199.
- Fishel, V.C., 1952, Groundwater resources of Pawnee Valley, Kansas: Kansas Geol. Survey Bull., no. 94, 144 p.
- _____, 1956, Long-term trends of ground water levels in the United States: Am. Geophysical Union Transactions, v. 37, p. 429-435.
- Fryberger, J.S., 1972, Rehabilitation of a brine-polluted aquifer: U.S. Env. Protection Agency, Project 14020 DLN, EPA-R2-72-014, Dec. 1972
- _____, 1975, Investigation and rehabilitation of a brine-contaminated aquifer, in Groundwater, v. 13, no. 2, p. 155-160.
- Frye, J.C., 1942, Geology and groundwater resources of Meade County, Kansas: Kansas Geol. Survey Bull., no. 45, 152 p.
- _____, 1950, Origin of Kansas great plains depressions: Kansas Geol. Survey Bull., no. 86, 20 p.
- Frye, J.C., and Schoff, S.L., 1942, Deep-seated solution in the Meade Basin and vicinity, Kansas and Oklahoma, in Symposium on relations of geology and the groundwater problems of the Southwest: Am. Geophys. Union Trans., 23rd Annual Mtg., pt. 1, p. 35-39.
- Garber, M.S., and Koopman, F.G., 1968, Methods of measuring water levels in deep wells, Techniques of water resources investigations of the U.S.G.S.: U.S. Geol. Survey, Book 8, Instrumentation, Chapter A1, 23 p.
- Garland, T.M., 1962, Performance of water floods in Wichita County, Texas: U.S. Bur. of Mines Rept. Inv. 6072, 135 p.
- Gibbs, R.J., 1970, Mechanisms controlling world water chemistry: Science, v. 170, p. 1088-1090.

- Gillespie, J.B., and Slagle, S.P., 1972, Natural and artificial groundwater recharge Wet Walnut Creek, Central Kansas: Kansas Water Resources Board Bull. no. 17, 94 p.
- Goebel, E.D., 1971, Subsurface geology at the proposed site of the National radioactive waste repository at Lyons, Kansas (abs.): Geol. Soc. America Abs. with Programs, v. 3, no. 3, p. 237.
- Gorell, H.A., 1958, Classification of formation waters based on sodium chloride content: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 2513.
- Gorham, Eville, 1961, Factors influencing supply of major ions to inland waters, with special reference to the atmosphere: Geol. Soc. America Bull., v. 72, p. 795-840.
- Green, D.A., 1937, Major divisions of Permian in Oklahoma and Southern Kansas: Am. Assoc. Petroleum Geologists Bull., v. 21, p. 1515-1533.
- Grimsley, G.P., 1897, Gypsum deposits of Kansas: Geol. Soc. America Bull., v. 8, p. 227-240.
- Haimson, B.C., 1974, Well communication in salt formation, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 203-210.
- Halepaska, J.C., 1971a, Heat transfer in Angino, E.E., and Hambleton, W.W., compilers, Final Report, Geology and Hydrology of the proposed Lyons, Kansas radioactive waste repository site: Kansas Geol. Survey, University of Kansas Center for Research, Inc. for the U.S. Atomic Energy Commission and Union Carbide Corp. under A.E.C./U.C. Subcontract no. 3484, 190 p.
- _____, 1971b, Problems of heat transfer at the Lyons, Kansas site (abs.): Geol. Soc. America Abstracts with programs, v. 3, no. 3, p. 237-238.
- Halepaska, J.C., and Hartman, F.W., 1971, Numerical solution of the 3-dimensional heat flow equation: Kansas Geol. Survey Bull., no. 204, p. 11-15.
- Hardison, C.H., Marshall, E.M., and Gilroy, E.J., 1972, Accuracy of low-flow characteristics estimated by correlation of base-flow measurements: Manual of Hydrology; Pt. 2, Low-flow techniques, U.S. Geol. Survey Water-Supply Paper 1542-B, 55 p.
- Henderson, J.K., 1963, Well construction; Possible causes of failure and remedial measures, in Northern Ohio Geol. Soc., Symposium on Salt, p. 555-562.
- Henderson, Keller, 1974, Methods of joining two or more wells for brine production, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 211-218.

- Hicks, Bill, 1974, Special logging techniques of underground storage and solution mining wells, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 227-230.
- Holdaway, K.A., 1974, Behavior of fluid inclusions in salt during heating and irradiation, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 1, p. 303-312.
- Hollweg, W.A., 1963, Permian evaporites overlying the Blaine Formation of Western, Kansas: Unpub. M.S. Thesis, University of Kansas, 76 p.
- Holser, W.T., 1963, Chemistry of brine inclusions in Permian salt from Hutchinson, Kansas, in Northern Ohio Geol. Soc., Symposium on Salt, p. 86-95.
- Holser, W.T., Kaplan, I.R., and Silverman, S.R., 1963, Isotope geochemistry of salt rocks (abs.): Geol. Soc. America Spec. Paper 76, p. 82.
- Hood, J.W., 1963, Saline groundwater in the Roswell Basin, Chaves and Eddy Counties, New Mexico, 1958-1959: U.S. Geol. Survey Water-Supply Paper 1539-M.
- Irwin, J.H., and Morton, R.B., 1969, Hydrogeologic information on the Glorieta Sandstone and the Ogallala Formation in the Oklahoma Panhandle and adjoining areas as related to underground waste disposal: U.S. Geol. Survey Circ. 630.
- Jacoby, C.H., 1966, Effect of geology on the hydraulic fracturing of salt, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 2, p. 311-320.
- Jaron, M.G., 1970, Investigation of solution collapse Breccia in mature salt cavities, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 1, p. 422-428.
- Jenks, G.H., 1972, Radiolysis and hydrolysis in salt mine brines: Oak Ridge National Laboratory, Unpub. Report TM-3717, 99 p.
- Jessen, F.W., 1970a, Solution of salt in a horizontal fracture system between wells, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 1, p. 393-411.
- _____, 1970b, Solution mining operations in the presence of vertical fracture systems, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 1, p. 383-392.
- Jewett, J.M., 1948, Sub-surface aspects in Kansas water-flooding: World Oil, v. 128, pt. 8, p. 142-152.
- Johnson, A.I., 1964, Selected bibliography on laboratory and field methods in ground-water hydrology: U.S. Geol. Survey Water-Supply Paper 1779-A, 21 p.

- Johnson Division, Universal Oil Products Co., 1966, Ground water and wells; A reference book for the water-well industry: St. Paul, Minnesota, Johnson Division, Universal Oil Products Co., 440 p.
- Johnston, J.E., 1973, ERTS and remote sensing's niche in geoscience (abs.): Am. Assoc. Petroleum Geologists Bull., v. 57, no. 4, 786 p.
- Jones, C.L., 1965, Petrography of evaporites from the Wellington Formation near Hutchinson, Kansas: U.S. Geol. Survey Bull., no. 1201-A, 70 p.
- Jones, O.S., 1950, Fresh water protection from pollution arising in the oil fields: Lawrence, Kansas, University of Kansas Press, 132 p.
- Jordan, Louise, and Vosburg, David, 1963, Permian salt in the Anadarko Basin of the Western Oklahoma-Texas Panhandle region: Oklahoma Geol. Survey, Bull. 102, 76 p.
- Jordan, P.R., Jones, B.F., and Petri, L.R., 1964, Chemical quality of surface waters and sedimentation in the Saline River Basin, Kansas: U.S. Geol. Survey Water-Supply Paper 1651, 90 p.
- Kansas Water Resource Fact-Finding and Research Committee, 1955, Water in Kansas: Topeka, Kansas, 216 p.
- Kansas Water Research Board, 1967, Irrigation in Kansas, Planning for development: Kansas Water Resource Board, '701' Project No. Kans. P-43, Report no. 16(e), 22 p.
- Kansas City Times, Oct. 23, 1974, Ground drops away near salt plant in Kansas: Kansas City Times, p. 4.
- Kaufmann, D.W., 1960, Sodium chloride: Am. Chem. Soc. Mon. Series no. 145, New York, Reinhold Pub. Corp., 743 p.
- Kelly, S.F., 1962, Geophysical exploration for water by electrical resistivity: Jour. New England Water Works Assoc., v. 76, no. 2.
- Keys, W.S., and Brown, R.F., 1973, Role of bore hole geophysics in underground waste storage and artificial recharge, in Braunstein, Jules, ed., Underground waste management and artificial recharge: Am. Assoc. Petroleum Geologists, U.S. Geol. Survey, International Assoc. Hydrological Sci., v. 1, p. 147-191.
- Keys, W.S., and MacCary, L.M., 1971, Application of borehole geophysics to water-resources investigations of the U.S.G.S.: U.S. Geol. Survey, Book 2, Collection of Environmental Data, Chapt. E1, 126 p.

- Kopp, O.C., and Fallis, S.M., 1973, Mineral sources of water in evaporite sequences (abs.): Geol. Soc. America Abs. with Programs, v. 5, no. 5, p. 410.
- Kulstad, R.O., 1959, Thickness and salt percentage of the Hutchinson salt: Kansas Geol. Survey Bull. 137, p. 241-247.
- Kulstad, R.O., et al., 1956, Gypsum in Kansas: Kansas Geol. Survey Bull. 113, 110 p.
- Landes, K.K., 1931, Discussion, recent subsidence, Hamilton County, Kansas: Am. Assoc. Petroleum Geologists Bull., v. 15, no. 6, p. 708.
- _____, 1963, Effects of solution of bedrock salt in the Earth's crust, in Northern Ohio Geol. Soc., Symposium on Salt, p. 64-73.
- Lane, C.W., and Miller, D.E., 1965, Geohydrology of Sedgewick County, Kansas: Kansas Geol. Survey Bull. 176, 100 p.
- Lange, A.L., 1965, Cave detection by magnetic surveys: Cave Notes, v. 7, no. 6, p. 41-56.
- Latta, B.F., 1950, Geology and groundwater resources of Barton and Stafford counties, Kansas: Kansas Geol. Survey Bull. 88.
- _____, 1973, Subsurface disposal of waste in Kansas, in Braunstein, Jules, ed., Underground waste management and artificial recharge: Am. Assoc. Petroleum Geologists, U.S. Geol. Survey, International Assoc. Hydrological Sciences, v. 1, p. 622-633.
- Lattman, L.H., 1958, Technique of mapping geologic fracture traces and lineaments on aerial photography: Photogrammetric Engineering, v. 24, no. 4, p. 568-576.
- Layton, D.W., and Berry, D.W., 1973, Geology and groundwater resources of Pratt County, South-central Kansas: Kansas Geol. Survey Bull. 205, 33 p.
- Lee, Wallace, 1953, Subsurface geologic cross section from Meade County, Kansas to Smith County, Kansas: Kansas Geol. Survey, Oil and Gas Invest. no. 9, 23 p.
- _____, 1956, Stratigraphy and structural development of the Salina Basin area: Kansas Geol. Survey Bull. 121, 167 p.
- Lenahan, Tom, 1973, Discussion, suspension grouts and their injection: Bull. Assoc. Eng. Geologists, v. 10, no. 4, p. 324.
- Leonard, R.B., 1964, A method for evaluating oil field brine pollution of the Walnut River in Kansas: U.S. Geol. Survey Prof. Paper 501B, p. B173-B176.

- Leonard, R.B., 1972, Chemical quality of water in the Walnut River Basin, South-central Kansas: U.S. Geol. Survey Water-Supply Paper no. 1982, 113 p.
- Leonard, R.B., and Morgan, C.O., 1970, Application of computer techniques to seepage-salinity surveys in Kansas: Kansas Geol. Survey, Spec. Dist. Pub. 47, 44 p.
- Levorsen, A.I., 1958, Geology of petroleum: San Francisco, W.H. Freeman and Co., 703 p.
- Lomenick, T.F., 1968, Accelerated deformation of rock salt at elevated temperatures and pressure and its implication for high level radioactive waste disposal: PhD. Dissert., University of Tennessee.
- Lowell, B.H., Morgan, C.O., and McNellis, J.M., 1970, Brief descriptions of and examples of output from computer programs developed for use in the water data in Kansas: Kansas Geol. Survey Special Dist. Pub. 48, 54 p.
- Ludwig, N.C., 1951, Effects of sodium chloride on setting properties of oil well cements: Oil and Gas Jour., v. 50, no. 3, p. 125.
- Maher, J.C., 1946, Subsurface geologic cross section from Ness County, Kansas to Lincoln County, Colorado: Kansas Geol. Survey, Oil and Gas Invest. no. 2, 12 p.
- _____, 1947, Subsurface cross section from Scott County, Kansas to Otero County, Colorado: Kansas Geol. Survey, Oil and Gas Invest. no. 4, 11 p.
- _____, 1953, Permian and Pennsylvanian rocks of southeastern Colorado: Am. Assoc. Petroleum Geologists Bull., v. 37, no. 5, p. 913-939.
- Malone, D.J., 1962, Stratigraphic relations and structural significance of the Blaine Formation in the subsurface of Southwestern Kansas: Unpub. M.S. Thesis, University of Wichita, 72 p.
- McClain, W.C., 1974, Status of Atomic Energy Commission Project to establish a salt mine radioactive waste repository, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 337-342.
- McClure, J.W., Jr., 1973, Base metal content of oil field brines in eastern Kansas (abs.): Geol. Soc. America Abstracts with Program, v. 5, no. 4, p. 336.
- McGregor, D.J., 1952, Geology of the gypsum deposits near Sun City, Barber County, Kansas (abs.): Geol. Soc. America Bull., v. 63, p. 1277-1278.
- McLaughlin, T.G., 1943, Geology and groundwater resources of Hamilton and Kearny Counties, Kansas: Kansas Geol. Survey Bull. 49, 220 p.

- McNellis, J.M., and Morgan, C.O., 1969, Modified Piper diagrams by the digital computer: Kansas Geol. Survey Spec. Dist. Pub. 45, 36 p.
- Meinzer, O.E., and Wenzel, L.K., 1937, Water levels and artesian pressures in observation wells in the United States in 1936: U.S. Geol. Survey Water-Supply Paper 817, 511 p.
- Merriam, D.F., 1963, The geologic history of Kansas: Kansas Geol. Survey Bull. 162, 317 p.
- Molz, F.J., 1971, Practical simulation models of the subsurface hydrologic system with example applications: Auburn, Alabama, Water Resources Research Inst., Bull., no. 19, 46 p.
- Moorhouse, D.C., and Millet, R.A., 1973, The use of geophysical methods to explore solution susceptible bedrock; Davis-Besse Nuclear Power Station (abs.): Geophysics, v. 38, no. 1, p. 185.
- Morgan, C.O., and McNellis, J.W., 1969, Stiff Diagrams of water-quality data programed for the digital computer: Kansas Geol. Survey Spec. Dist. Pub. 43.
- Muir, J.L., 1934, Anhydrite-Gypsum problem of Blaine Formation, Oklahoma: Am. Assoc. Petroleum Geologists Bull., v. 18, p. 1297-1312.
- Myers, A.J., 1963, Sonar measurements of brine cavity shapes, in Northern Ohio Geol. Soc., Symposium on Salt, p. 546-554.
- Myung, J.I., and Helander, D.P., 1974, Borehole investigations of rock quality and deformation using the 3-D velocity log, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 141-152.
- Nair, Keshavan, Chang, C-Y, Singh, R.D., and Abdullah, A.M., 1974, Time dependent analysis to predict closure in salt cavities, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 129-139.
- Nair, Keshavan, and Singh, R.D., 1974, Creep rupture criteria for salt, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 41-49.
- Nickelsen, R.P., and Hough, V.N.D., 1967, Jointing in the Appalachia Plateau of Pennsylvania: Geol. Soc. America Bull., v. 78, no. 5, p. 609-630.
- Nolan, T.B., 1963, Summary of investigation; Geological Survey Research: U.S. Geol. Survey Prof. Paper 475, pt. A, 300 p.
- _____, 1964, Geological survey research 1964: U.S. Geol. Survey Prof. Paper 501.

- Norton, G.H., 1939, Permian redbeds of Kansas: Am. Assoc. Petroleum Geologists Bull., v. 23, no. 12, p. 1751-1815.
- Nuzman, C.E., 1966, Engineering economics of groundwater pumpage for conditions of multiple well interference: Lawrence, Kansas, University of Kansas M.S. Thesis, 27 p.
- Oberste-Lehn, 1966, Remote sensors for detecting underground cavities: Rand Corp., ARPA Contract SD-79, DDC No. AD 373 709 (Confidential).
- Panek, L.A., 1970, Methods and equipment for measuring subsidence, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 2, p. 321-338.
- Patten, E.P., Jr., and Bennett, G.D., 1963, Application of electrical and radioactive well logging to ground-water hydrology: U.S. Geol. Survey Water-Supply Paper 1544-D, 60 p.
- Peale, A.C., 1886 Lists and analyses of the mineral springs of the United States (A preliminary study): U.S. Geol. Survey Bull., no. 32, 235 p.
- Pecora, W.T., 1969, Summary of investigation; Geological Survey Research: U.S. Geol. Survey Prof. Paper 650, pt. A, p. A196-A197.
- _____, 1970, Summary of investigation; Geological Survey Research: U.S. Geol. Survey Prof. Paper 700, pt. A, p. A208.
- Pegler, A.V., 1970, The anisotropy of thermal conductivity in rock, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 2, p. 216-255.
- Pfannhuck, Hans-Olaf, 1969, Elsevier's dictionary of hydrogeology: New York, Elsevier Publishing Co., 168 p.
- Pinder, G.F., 1970, A digital model for aquifer evaluation, techniques of water-resources investigations of the U.S.G.S.: U.S. Geol. Survey, Book 7, Automated Data Processing and computations, Chapter C1, 39 p.
- Pinder, G.F., and Jones, J.F., 1969, Determination of the ground water component of peak discharge from the chemistry of total runoff: Water Resources Research, v. 5, no. 2, p. 438-445.
- Prescott, G.C., Jr., 1951, Geology and groundwater resources of Lane County, Kansas: Kansas Geol. Survey Bull. 93, 126 p.
- Rall, C.G., and Wright, Jack, 1953, Analysis of formation brines in Kansas: U.S. Bur. Mines Rept. Inv. 4974.
- Rascoe, Bailey, Jr., 1971, Western Kansas and western Nebraska, in Am. Assoc. Petroleum Geologists Mem. 15, p. 1046-1054.

- Remson, D.R., 1963, Model studies of techniques for dissolving spherical cavities in massive salt: University of Texas, Dept. of Petroleum Engg., Unpub. M.S. Thesis.
- Remson, D.R., Dommers, O.B., and Jessen, F.W., 1966, Techniques for developing predetermined shaped cavities in solution mining, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 2, p. 297-310.
- Remson, Irwin, Hornberger, G.M., and Molz, F.J., 1971, Numerical methods in the subsurface hydrology with an introduction to the finite element method: New York, Wiley-Interscience, 389 p.
- Riggs, H.C., 1968, Some statistical tools in hydrology, techniques of water-resources investigations of the U.S.G.S.: U.S. Geol. Survey, Book 4, Hydrologic analysis and interpretation, Chapt. A1, 39 p.
- Rima, D.R., Chase, E.B., and Meyers, B.M., 1971, Subsurface waste disposal by means of wells-a selective annotated bibliography: U.S. Geol. Survey Water-Supply Paper 2020, 305 p.
- Rittenhouse, Gordon, 1967, Bromide in oil-field waters and its use in determining possibilities of origin of these waters: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 2430-2440.
- Ropes, L.H., Morgan, C.O., and McNellis, J.M., 1969, Fortran IV program for synthesis and plotting of water-quality data: Kansas Geol. Survey Spec. Dist. Pub. 39.
- Rorabaugh, M.I., 1953, Graphical and theoretical analysis of step-drawdown test of artesian well: Am. Soc. Civil Engineers Proc., v. 79, no. 12, 23 p.
- Sabins, F.F., Jr., 1973, Geologic interpretation of radar and space imagery of California (abs.): Am. Assoc. Petroleum Geologists Bull., v. 57, no. 4, p. 802.
- Scharon, LeRoy, 1963, Electrical resistivity surveys in salt mines, in Northern Ohio Geol. Soc., Symposium on Salt, p. 379-389.
- Schlumberger Well Surveying Corp., 1958, Introduction to Schlumberger Well Logging: Schlumberger Doc. no. 8, 176 p.
- Schneider, Robert, 1962, An application of thermometry to the study of ground water: U.S. Geol. Survey Water-Supply Paper 1544-B, 16 p.
- Schoewe, W.H., 1943, Kansas oil field brines and their magnesium content: Kansas Geol. Survey Bull. 47, pt. 2, p. 37-70.
- _____, 1949, Geography of Kansas, Part II, Physical Geography, Geology: Kansas Academy of Science Trans., v. 52, no. 3, p. 261-333.

- Schoewe, W.H., 1951, The geography of Kansas, Part III, Hydrogeography: Kansas Academy of Science, v. 54, p. 263-329.
- _____, 1953, The geography of Kansas, Part III concluded, Hydrogeography: Kansas Academy of Science, v. 56, p. 131-190.
- Schul, J.H., 1963, Storage operations in a salt mine, in Northern Ohio Geol. Soc., Symposium on Salt, p. 413-416.
- Schumaker, R.D., 1966, Regional study of Kansas Permian evaporite formations: Unpub. M.S. Thesis, Dept. of Geology, Wichita State University, 87 p.
- Sellers, J.B., 1970, Rock mechanics instrumentation for salt mining, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 2, p. 236-248.
- Serata, Shosei, 1970, Prerequisites for application of finite element method to solution cavities and conventional mines, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 2, p. 249-279.
- Serata, Shosei, and Gloyne, E.F., 1960, Principles of structural stability of underground salt cavities: Jour. Geophysical Research, v. 65, no. 9, p. 2979-2987.
- Skibitzke, H.E., 1961, Electric computers as an aid to the analysis of hydrologic problems: Rome, International Assoc. of Sci. Hydrology, Pub. no. 52, p. 347-358.
- Smith, H.T.U., 1940, Geologic studies in southwestern Kansas: Kansas Geol. Survey Bull. 34, 212 p.
- Snow, R.H., and Nielsen, H.J., 1970, IITRI-SMRI Solution Mining Studies, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 1, p. 341-359.
- Speed, R.C., 1970, Gravity anomalies from cavities in salt beds. 1. the surface field, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 2, p. 367-385.
- State Corporation Commission, 1971, Table II, April 26, 1971, (See Appendix F), Topeka, Kansas.
- _____, 1973, General Rules and Regulations for the conservation of crude oil and natural gas, Topeka, Kansas, 114 p.
- Stevens, H.H., Flicke, J.F., Jr., and Smoot, G.F., 1975, Water temperature-influential factors, field measurement, and data presentation, techniques of water-resources investigation of the U.S.G.S.: U.S. Geol. Survey, Book 1, Collection of water data by direct measurement, Chapter D1, 65 p.

- Swineford, Ada, 1955, Petrography of upper Permian rocks in southcentral Kansas: Kansas Geol. Survey Bull. 111, 179 p.
- Taft, R., 1946, Kansas and the nations salt: Kansas Acad. Sci. Trans., v. 49, p. 223-272.
- Tanji, K.K., and Doneen, L.D., 1966, Predictions on the solubility of gypsum in aqueous salt solutions: Water Resources Research, v. 2, p. 543-548.
- Terry, R.C., Jr., 1973, Road salt, drinking water, and safety; Improving public policy and practice: Cambridge, Mass., Ballinger Pub. Co., 161 p.
- Terzaghi, R.D., 1970, Brine field subsidence at Windsor, Ontario, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 2, p. 298-307.
- Unterberger, R.R., 1974a, A laser radar for probing salt, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 3-9.
- _____, 1974b, Electromagnetic wave propagation in salt-probing into salt with radar, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 11-26.
- U.S. Dept. of Health, Education, and Welfare, 1964, Arkansas-Red River basins water quality conservation: Report on a basic study of water quality, sources of natural and manmade salt pollution, and suggested corrective measures: U.S. Div. of Water Supply and Pollution control, 3 v.
- U.S. Dept. Interior, 1968, Water Quality Criteria, Report of the National Technical Advisory Committee to the Secretary of Interior; Washington, D.C., U.S. Dept. Interior, Federal Water Pollution Control Adm., 234 p.
- U.S. Environmental Protection Agency, 1972, Kansas Water Quality Standards Summary: Kansas State Board of Health, Kansas State Dept, Health, 33 p.
- _____, 1973a, Groundwater pollution from subsurface excavation: U.S. Environmental Protection Agency, Office of air and water Programs, EPA-430/9-73-012.
- _____, 1973b, Methods for identifying and evaluating the nature and extent of non-point sources of pollutants: U.S. Environmental Protection Agency, EPA-430/9-73-014.
- U.S. Public Health Service, 1962, Drinking water standards: U.S. Public Health Service Pub. 956, 61 p.
- Van Everdingen, R.O., 1968, Mobility of main ion species in reverse osmosis and the modification of subsurface brines: Canadian Jour. Earth Sci., no. 5, p. 1253-1260.

- Ver Wiebe, W.A., 1937a, Cretaceous deformation in Kansas: Am. Assoc. Petroleum Geologists Bull., v. 21, no. 7, p. 954-958.
- _____, 1937b, The Wellington Formation of central Kansas: Wichita Municipal University Studies, Bull. 2, 18 p.
- Vincent, D.A., 1965, Evaporites and associated clastics within the Sumner Group (Lower Permian) of central and western Kansas: Unpub. M.S. Thesis, University of Kansas, 63 p.
- von Schonfeldt, Hilmer, 1974, Model studies in solution mining, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 181-188.
- Walters, C.P., 1975, Personal Communications.
- Walters, K.L., 1961, Geology and groundwater resources of Sumner County, Kansas: Kansas Geol. Survey Bull. 151, 198 p.
- Walters, R.F., 1976, Salt dissolution in oil and gas test holes in central Kansas (abs.): Am. Assoc. Petroleum Geologists Bull. 60, p. 323.
- Walton, W.C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois Water-Supply Bull. 49, 81 p.
- Walton, W.C., and Prickett, T.W., 1963, Hydrogeologic electric analog computers: Am. Soc. Civil Eng. Proc., v. 89.
- Ward, P.E., and Leonard, A.R., 1961, Geology and groundwater features of salt springs, seeps and plains in the Arkansas and Red River Basins of western Oklahoma and adjacent parts of Kansas and Texas: U.S. Geol. Survey Prof. Paper 424-428, p. D150-D151.
- Watkins, J.S., Godson, R.H., and Watson, K., 1967, Seismic detection of near-surface cavities: U.S. Geol. Survey Prof. Paper 599-A, 12 p.
- Whitcomb, J.H., 1969, Detection of SH-Type seismic shear waves by means of angular accelerometers: U.S. Geol. Survey Prof. Paper 599-D.
- White, D.E., Hem, J.D., and Waring, G.A., 1963, Chemical composition of subsurface waters: U.S. Geol. Survey Prof. Paper 440-F, 67 p.
- Whittemore, D.O., 1976, Mechanisms controlling world water chemistry: Overland flow-groundwater inflow (abs.): Geol. Soc. America Abstracts with Programs, v. 8, p. 71-72.
- Widess, M.B., 1952, Salt solution, a seismic velocity problem in western Anadarko Basin, Kansas-Oklahoma-Texas: Geophysics, v. 17, p. 481-504.

- Williams, C.C., 1946, Groundwater conditions in Arkansas River Valley in the vicinity of Hutchinson, Kansas: Kansas Geol. Survey Bull. 64, p. 5, p. 145-216.
- Williams, C.C., and Lohman, S.W., 1949, Geology and groundwater resources of a part of south-central Kansas with special reference to the Wichita municipal water supply: Kansas Geol. Survey Bull. 79, 455p.
- Wilson, J.E., 1969, Sensor detection capabilities study: U.S. Geol. Survey Circ. 616, Interagency Report NASA-143, contract W-125701, Task no. 160-75-01-31-10.
- Winslow, J.D., McGovern, H.E., and Mackey, H.L., 1968, Water-level changes in Grant and Stanton Counties, Kansas, 1939-1964: Kansas Geol. Survey Spec. Dist. Pub. 37, 17 p.
- Zeller, D.E., 1968, The stratigraphic succession in Kansas: Kansas Geol. Survey Bull. 189, 81 p.
- Zohdy, A.A.R., 1970, Variable azimuth Schlumberger resistivity sounding and profiling near a vertical contact: New techniques in direct current resistivity exploration: U.S. Geol. Survey Bull. 1313-A, 22 p.
- Zohdy, A.A.R., Eaton, G.P., and Mabey, D.R., 1974, Applications of surface geophysics to ground water investigations, Techniques of water resources investigations of the U.S.G.S.: U.S. Geol. Survey, Book 2, Collection of Environmental Data, Chapter D1, 116 p.

APPENDIX A

Surface Water Quality

- Feth, J.H., 1971, Mechanisms controlling world water chemistry; Evaporation-crystallization process: Science, v. 172, p. 870.
- Gibbs, R.J., 1970, Mechanisms controlling world water chemistry: Science, v. 170, p. 1088-1090.
- Gorham, Eville, 1961, Factors influencing supply of major ions to inland waters, with special reference to the atmosphere: Geol. Soc. America Bull., v. 72, p. 795-840.
- Hem, J.D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 363 p.
- Jordan, P.R., Jones, B.F., and Petri, L.R., 1964, Chemical quality of surface waters and sedimentation in the Saline River Basin, Kansas: U.S. Geol. Survey Water-Supply Paper 1651, 90 p.
- Kansas Center for Regional Progress, 1973, Fact book, Near southwest Kansas Region 06: Planning Div. Kansas Dept. Economic Dev. Report 41, 211 p.
- _____, 1973b, Fact book, far southwest Kansas Region 07: Planning Div. Kansas Dept. Economic Dev. Report 42, 226 p.
- _____, 1973c, Fact book, north central Kansas Region 10: Planning Div. Kansas Dept. Economic Dev. Report 43, 234 p.
- Kansas Water Resources Board, 1958, Preliminary appraisal of Kansas water problems, sect. 2, Cimarron Unit: Kansas Water Resources Board, State Water Plan Studies, pt. A, 124 p.
- _____, 1960, Preliminary appraisal of Kansas water problems, Sect. 4, Lower Arkansas Unit: Kansas Water Resources Board, State Water Plan Studies, pt. A, 177 p.
- _____, 1961, Preliminary appraisal of Kansas water problems, Sect. 8, Solomon-Saline Unit: Kansas Water Resources Board, State Water Plan Studies, pt. A, 154 p.
- _____, 1962a, Preliminary appraisal of Kansas water problems, Sect. 11, Upper Arkansas Unit: Kansas Water Resources Board, State Water Plan Studies, pt. A, 121 p.
- _____, 1962b, Preliminary appraisal of Kansas water problems, Sect. 12, Smoky Hill Unit: Kansas Water Resources Board, State Water Plan Studies, pt. a, 125 p.

- Latta, B.F., 1946, Cretaceous stratigraphy of the Belvidere Area, Kiowa County, Kansas: Kansas Geol. Survey Bull. 64, p. 216-260.
- Leonard, R.B., 1972, Chemical quality of water in the Walnut river basin, south-central Kansas: U.S. Geol. Survey Water-Supply Paper no. 1982, 113 p.
- Parker, H.N., 1911, Quality of the water supplies of Kansas: U.S. Geol. Survey Water-Supply Paper 273, 375 p.
- Pinder, G.F., and Jones, J.F., 1969, Determination of the ground water component of peak discharge from the chemistry of total runoff: Water Resources Research, v. 5, no. 2, p. 438-445.
- Tanji, K.K., and Doneen, L.D., 1966, Predictions on the solubility of gypsum in aqueous salt solutions: Water Resources Research, v. 2, p. 543-548.
- U.S. Dept. of Agriculture, 1972, Arkansas River Basin, Kansas: U.S. Dept. of Agriculture, Soil Conservation Service, Economic Research Service, 306 p.
- U.S. Dept. of Health, Education and Welfare, 1964, Arkansas-Red River Basins water quality conservation: Report on a basic study of water quality, sources of natural and manmade salt pollution, and suggested corrective measures: U.S. Dept. of Health, Education and Welfare, U.S. Public Health Service, U.S. Div. of Water Supply and Pollution Control, 3 v.
- U.S. Environmental Protection Agency, 1971, Water quality criteria data book vol. 2, Inorganic chemical pollution of fresh water: U.S. Environmental Protection Agency, Project 18010 DPU, contract no. 14-12-538, 234 p.
- U.S. Geol. Survey, 1969, Surface water supply of the United States 1961-1965, pt. 7, Lower Mississippi River Basin, v. 2, Arkansas River Basin: U.S. Geol. Survey Water-Supply Paper 1921, 878 p.
- _____, 1972, Water resources data for Kansas, pt. 2: U.S. Geol. Survey, Kansas Water Resources Board, State Highway Commission of Kansas, State Geol. Survey of Kansas, City of Wichita, U.S. Army Corps of Engineers and Bureau of Reclamation, 10 p.
- Wells, J.V.B., 1955, Compilation of records of surface waters of the United States through Sept. 1950, pt. 7, Lower Mississippi River Basin: U.S. Geol. Survey Water-Supply Paper 1311, 606 p.

APPENDIX B

Bulletins of the Kansas Geological Survey and
other publications about Kansas aquifers

- Bayne, C.K., 1956, Geology and groundwater resources of Reno County, Kansas: Kansas Geol. Survey Bull. 120, 130 p.
- _____, 1960, Geology and groundwater resources of Harper county, Kansas: Kansas Geol. Survey Bull. 143, 184 p.
- Bayne, C.K., Franks, P.C., and Ives, W., Jr., 1971, Geology and groundwater resources of Ellsworth County, Kansas: Kansas Geol. Survey Bull. 201, 84 p.
- Bayne, C.K., and Ward, J.R., 1974, Geology and hydrology of Rice County, Kansas: Kansas Geol. Survey Bull. 206, pt. 3, 17 p.
- Berry, D.W., and Durum, W.H., 1955, Geology and groundwater resources of Lincoln County, Kansas: Kansas Geol. Survey Bull. 95, 96 p.
- Bradley, Edward, and Johnson, C.R., 1957, Geology and groundwater resources of the Ladder Creek Area in Kansas: Kansas Geol. Survey Bull. 126, 194 p.
- Byrne, F.E., and McLaughlin, T.G., 1948, Geology and groundwater resources of Seward County, Kansas: Kansas Geol. Survey Bull. 69, 140 p.
- Fader, S.W., Gutentag, E.D., Lobmeyer, D.H., and Meyer, W.R., 1964, Geohydrology of Grant and Stanton Counties, Kansas: Kansas Geol. Survey Bull. 168, 147 p.
- Fent, O.S., 1950, Geology and groundwater resources of Rice County, Kansas: Kansas Geol. Survey Bull. 85, 142 p.
- Fishel, V.C., 1952, Groundwater resources of Pawnee Valley, Kansas: Kansas Geol. Survey Bull. 94, 144 p.
- Frye, J.C., 1942, Geology and groundwater resources of Meade County, Kansas: Kansas Geol. Survey Bull. 45, 152 p.
- Frye, J.C., and Brazil, J.J., 1943, Groundwater in the oil-field areas of Ellis and Russell County, Kansas: Kansas Geol. Survey Bull. 50, 104 p.
- Gutentag, E.D., Lobmeyer, D.H., and McGovern, H.E., 1972, Groundwater in Kearney County, Kansas: U.S. Geol. Survey Hydrol. Inv. Atlas HA 416.
- Gutentag, E.D., Lobmeyer, D.H., McGovern, H.E., and Long, W.A., 1972, Groundwater in Finney County, Southwestern Kansas: U.S. Geol. Survey Hydrol. Inv. Atlas HA 442.

- Hodson, W.G., 1963, Geology and groundwater resources of Wallace County, Kansas: Kansas Geol. Survey Bull. 161, 108 p.
- _____, 1965, Geology and groundwater resources of Trego County, Kansas: Kansas Geol. Survey Bull. 174, 80 p.
- Johnson, C.R., 1958, Geology and groundwater resources of Logan County, Kansas: Kansas Geol. Survey Bull. 129, 175 p.
- Kansas Center for Regional Progress, 1973, Fact book, near southwest Kansas Region 06: Planning Div., Kansas Dept. Economic Dev. Report 41, 211 p.
- _____, 1973b, Fact book, far southwest Kansas Region 07: Planning Dev., Kansas Dept. Economic Dev. Report 42, 266 p.
- _____, 1973c, Fact book, north central Kansas, Region 10: Planning Dev., Kansas Dept. Economic Dev. Report 43, 234 p.
- Kansas Water Resources Board, 1960, Preliminary appraisal of Kansas water problems, sect. 4, Lower Arkansas Unit, State Water Plan Studies, pt. A: Kansas Water Resources Board, 177 p.
- _____, 1961, Preliminary appraisal of Kansas water problems, sect. 8, Solomon-Saline Unit, State Water Plan Studies, pt. A: Kansas Water Resources Board, 154 p.
- _____, 1962a, Preliminary appraisal of Kansas water problems, sect. 11, Upper Arkansas Unit, State water plan studies pt. A: Kansas Water Resources Board, 125 p.
- _____, 1962b, Preliminary appraisal of Kansas water problems, sect. 12, Smoky Hill Unit, State Water Plan Studies, pt. A: Kansas Water Resources Board, 125 p.
- _____, 1967, Irrigation in Kansas, planning for development: Kansas Water Resources Board, '701' Project No. Kans. P-43, Report no. 16(e), 22 p.
- Lane, C.W., 1960, Geology and groundwater resources of Kingman County, Kansas: Kansas Geol. Survey Bull. 144, 174 p.
- Lane, C.W., and Miller, D.E., 1965, Geohydrology of Sedgwick County, Kansas: Kansas Geol. Survey Bull. 176, 100 p.
- Latta, B.F., 1941, Geology and groundwater resources of Stanton County, Kansas: Kansas Geol. Survey Bull. 37, 119 p.
- _____, 1944, Geology and groundwater resources of Finney and Gray Counties, Kansas: Kansas Geol. Survey Bull. 55, 272 p.
- _____, 1946, Cretaceous stratigraphy of the Belvedere Area, Kiowa County, Kansas: Kansas Geol. Survey Bull. 64, p. 216-260.

- Latta, B.F., 1947, Geology and groundwater resources of Kiowa County, Kansas: Kansas Geol. Survey Bull. 65, 151 p.
- _____, 1950, Geology and groundwater resources of Barton and Stafford Counties, Kansas: Kansas Geol. Survey Bull. 88, 228 p.
- Layton, D.W., and Berry, D.W., 1973, Geology and groundwater resources of Pratt County, South-central Kansas: Kansas Geol. Survey bull. 205, 33 p.
- Leonard, A.R., and Berry, D.W., 1961, Geology and groundwater resources of Southern Ellis County and parts of Trego and Rush Counties, Kansas: Kansas Geol. Survey bull. 149, 156 p.
- McLaughlin, T.G., 1942, Geology and groundwater resources of Morton County, Kansas: Kansas Geol. Survey Bull. 49, 220 p.
- _____, 1943, Geology and groundwater resources of Hamilton and Kearny Counties, Kansas: Kansas Geol. Survey Bull. 49, 220 p.
- _____, 1946, Geology and groundwater resources of Grant, Haskell, and Stevens Counties, Kansas: Kansas Geol. Survey Bull. 61, 221 p.
- _____, 1949, Geology and groundwater resources of Pawnee and Edwards Counties, Kansas: Kansas Geol. Survey Bull. 80, 189 p.
- McNellis, J.M., 1973, Geology and groundwaters of Rush County, Kansas: Kansas Geol. Survey Bull. 207, 45 p.
- Meyer, W.R., Gutentag, E.D., and Lobmeyer, D.H., 1969, Finney County basic data: U.S. Geol. Survey Water-Supply Paper 1891, 117 p.
- Prescott, G.C., Jr., 1951, Geology and groundwater resources of Lane County, Kansas: Kansas Geol. Survey Bull. 93, 126 p.
- Prescott, G.C., Jr., Branch, J.R., and Wilson, W.W., 1954, Geology and groundwater resources of Wichita and Greeley Counties, Kansas: Kansas Geol. Survey Bull. 108, 134 p.
- State of Kansas, 1975, Kansas 2000: State of Kansas, Div. of State Planning and Research, Dept. of Adm., 96 p.
- Stramel, G.J., 1956, Progress report on the groundwater hydrology of the Equus Beds Area, Kansas: Kansas Geol. Survey Bull. 119, pt. 1, 59 p.
- Stramel, G.J., Lane, C.W., and Hodson, W.G., 1958, Geology and groundwater hydrology of the Ingalls area, Kansas: Kansas Geol. Survey Bull. 132, 154 p.
- U.S. Dept. of Agriculture, 1972, Arkansas River Basin, Kansas: U.S. Dept. of Agriculture, Soil Conservation Service, Economic Research Service, 306 p.

- Waite, H.A., 1942, Geology and groundwater resources of Ford County, Kansas: Kansas Geol. Survey Bull. 43, 250 p.
- Walters, K.L., 1961, Geology and groundwater resources of Sumner County, Kansas: Kansas Geol. Survey Bull. 151, 198 p.
- Water Research Association, 1971, Artificial groundwater recharge: Proceeding of a conference held at the University of Reading England, 21-24 Sept., 1970, 2 v.
- Williams, C.C., 1946, Groundwater conditions in Arkansas River Valley in the vicinity of Hutchinson, Kansas: Kansas Geol. Survey Bull. 64, p. 5, p. 145-215.
- Williams, C.C., and Bayne, C.K., 1946, Groundwater conditions in Elm Creek Valley, Barber County, Kansas: Kansas Geol. Survey Bull. 64, pt. 3, p. 77-124.
- Williams, C.C., and Lohman, S.W., 1949, Geology and groundwater resources of a part of south-central Kansas with special reference to the Wichita municipal water supply: Kansas Geol. Survey Bull. 79, 455 p.
- Winslow, J.D., McGovern, H.E., and Mackey, H.L., 1968, Water-level changes in Grant and Stanton Counties, Kansas, 1939-1968: Kansas Geol. Survey Spec. Distrib. Pub. no. 37, 17 p.

APPENDIX C

Subsurface Waters

- Anderson, R.J., Graf, D.L., and Jones, B.F., 1966, Calcium and Bromide contents of natural waters: *Science*, v. 153, p. 1637-1638.
- Back, W., and Hanshaw, B., 1965, Chemical geohydrology, in Chow, V.T., ed., *Advances in hydrosience*: New York, Academic Press, Inc., v. 2, p. 49-109.
- Banin, A., 1972, Transfer properties and friction coefficients for salt and water flow through clays, in *Fundamentals of Transport Phenomena in porous media*: Amsterdam, Elsevier Publishing Co., p. 212-220.
- Berry, F., and Hanshaw, B., 1960, Geologic evidence suggesting membrane properties of shales: *Proc. International Geol. Cong. 21st.*, Copenhagen, Abstract v. 1960.
- Bredehoeft, J.D., Blyth, C.R., White, W.A., and Maxey, G.B., 1963, Possible mechanism for concentration of brines in subsurface formations: *Am. Assoc. Petroleum Geologists Bull.*, v. 47, no. 2, p. 257-269, 8 figs.
- Bredehoeft, J.D., and Hanshaw, B.B., 1968, On the maintenance of anomalous fluid pressures; I. Thick sedimentary sequences: *Geol. Soc. America Bull.*, v. 79, p. 1097-1106.
- Bredehoeft, J.D., and Pinder, G.F., 1972, Application of transport equations to groundwater systems: *Am. Assoc. Petroleum Geologists Mem. no. 18, Underground Waste Management and Environmental Implications*, p. 191-201.
- Bredehoeft, J.D., White, W.A., and Maxey, G.B., 1964, Reply: Possible Mechanism for concentration of brines in subsurface formations: *Am. Assoc. Petroleum Geologists Bull.*, v. 48, no. 2, p. 236-238.
- Chave, K.E., 1960, Evidence on history of sea water from chemistry of deeper subsurface waters of ancient basins: *Am. Assoc. Petroleum Geologists Bull.*, v. 44, no. 3, p. 357-370.
- Choi, K.W., and Bennion, D.N., 1973, Membrane potential and transport of alkali and alkaline earth metal chlorides across modified cellulose acetate membranes: U.C.L.A., School of Engg. and Applied Sci., Water Resources Center Desalination Rpt. no. 55, UCLA-ENG-7370.
- Collins, A.G., 1975, *Geochemistry of oil-field waters*: New York, Elsevier Scientific Publishing Co., 496 p.
- DeSitter, L.U., 1947, Diagenesis of oil-field brines: *Am. Assoc. Petroleum Geologists Bull.*, v. 31, no. 11, p. 2030-2040.

- Dickey, P.A., Collins, A.G., and Fajardo, M.I., 1972, Chemical composition of deep formation waters in southwestern Louisiana: Am. Assoc. Petroleum Geologists Bull., v. 56, no. 8, p. 1530-1533.
- Engelhardt, W.V., and Gaida, K.H., 1963, Concentration changes of pore solutions during the compaction of clay sediments: Jour. Sed. Petrology, v. 33, p. 919-930.
- Erikson, Erik, 1960, The yearly circulation of chloride and sulfur in nature: meteorological, geochemical, and pedological implications: Tellus, v. 11, p. 375-403.
- Graf, D.L., Friedman, I., and Meents, W.F., 1965, The origin of saline formation waters, II. Isotopic fractionation by shale micropore systems: Illinois State Geol. Survey Circular 393, 32 p.
- Hanshaw, B.B., 1962, Membrane properties of compacted clays: Unpub. PhD. Thesis, Harvard University, 113 p.
- Hartman, R.J., 1947, Colloid chemistry, 2nd ed.: Boston, Mass., Houghton Mifflin Co., 572 p.
- Helferich, Frederick, 1962, Ion exchange: New York, McGraw-Hill Book Co., 624 p.
- Hem, J.D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 363 p.
- Hiroi, K., 1974, Behavior of some trace elements during the concentration of sea water by electrodialysis with ion-exchange membranes, in Northern Ohio Geol. Soc., Fourth Symposium on Salt, v. 2, p. 461-466.
- Holser, W.T., 1966, Bromide geochemistry of salt rocks, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 1, p. 248-275.
- Holser, W.T., Kaplan, I.R., and Silverman, S.R., 1963, Isotope geochemistry of salt rocks (abs.): Geol. Soc. America Spec. Paper 76, p. 82.
- Kemper, W.D., 1960, Water and ion movement in thin films as influenced by the electrostatic charge and diffuse layers of cations associated with clay minerals surfaces: Soil Soc. Am. Proc. V. 24, p. 10-16.
- Lang, W.B., 1954, Relations of potassium bromine and iodine in marine sedimentation: Geol. Soc. America Bull., v. 65, p. 1276.
- Lonsdale, H.K., and Podall, H.E., ed., 1972, Reverse osmosis membrane research, based on the symposium on "Polymers for Desalination" held at the 162nd. National Meeting of the Am. Chem. Soc. in Washington, D.C., Sept. 1971: New York, Plenum Press, 503 p.

- Magara, Kinji, 1974, Compaction, Ion filtration and osmosis in shale and their significance in primary migration: Am. Assoc. Petroleum Geologists Bull., v. 58, no. 2, p. 283-290.
- Manheim, F.T., and Bischoff, J.F., 1969, Geochemistry of pore waters from Shell Oil Co. drill holes on the continental slope of the northern Gulf of Mexico: Chemical Geology, v. 4, p. 63-8.
- McKelvey, J.G., Jr., and Milne, I.H., 1962, The flow of salt solutions through compacted clay, in Swineford, Ada, ed., Clays and Clay minerals: National conference on clays and clay minerals, 9th., Lafayette, Ind., Proc., p. 248-259.
- McKelvey, J.G., Jr., Spiegler, K.S., and Wylie, M.J.R., 1957, Salt filtering by ion-exchange grains and membranes: Jour. Physical Chem., v. 61, p. 174-178.
- _____, 1959, Ultra filtration of salt solution thru ion exchange membranes: Chem. Engg. Progress Symposium Series 25, v. 44, p. 199-208.
- Merten, Ulrich, ed 1966, Desalination by reverse osmosis: Cambridge, Mass., The Massachusetts Institute of Technology Press, 289 p.
- Milne, I.H., McKelvey, J.G., Jr., and Trump, R.P., 1962, Permeability and salt filtering properties of compacted clay: 11th Clay Minerals Conf., Ottawa, Canada, p. 250-251.
- _____, 1964, Semi-permeability of Bentonite membranes to brines: Am. Assoc. Petroleum Geologists Bull., v. 48, no. 1, p. 103-105.
- Overstreet, Roy, 1945, Ionic reactions in soils and clay suspensions: the significance of soil filtrates: Soil Science, v. 59, no. 4, p. 265-270.
- Overton, H.L., and Timko, D.J., 1969, The salinity principle: a tectonic stress indication in marine sands: Oil and Gas Jour., v. 67, no. 40, p. 115-124.
- Pandey, G.N., Tek, M.R., and Katz, D.L., 1974, Diffusion of fluids through porous media with implications in petroleum geology: Am. Assoc. Petroleum Geologists Bull., v. 58, no. 2, p. 301-303.
- Powers, M.C., 1967, Fluid release mechanisms in compacting marine mudrocks and their importance in oil exploration: Am. Assoc. Petroleum Geologists Bull., V. 51, no. 7, p. 1240-1254.
- Rittenhouse, Gordon, 1964, Discussion on possible mechanism for concentration of brines in subsurface formations: am. Assoc. Petroleum Geologists Bull., v. 48, no. 2, p. 234-238.

- Rittenhouse, Gordon, 1967, Bromide in oil-field waters and its use in determining possibilities of origin of these waters: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 2430-2440.
- Russell, W.L., 1933, Surface concentration of chloride brines: Am. Assoc. Petroleum Geologists Bull., v. 17, no. 10, p. 1213-1228.
- Schmidt, G.W., 1973, Interstitial water composition and geochemistry of deep Gulf Coast shales and sandstones: Am. Assoc. Petroleum Geologists Bull., v. 57, no. 2, p. 321-337.
- Schwerdtner, W., 1963, Analysis of small amounts of Bromide in presence of large amounts of Chloride, in Northern Ohio Geol. Soc., Symposium on Salt, p. 247-248.
- Schwerdtner, W., and Wardlaw, N.C., 1963, Geochemistry of Bromide in some salt rocks of the Prairie Evaporite Formation of Saskatchewan, in Northern Ohio Geol. Soc., Symposium on Salt, p. 240-246.
- Spiegler, K.S., 1966, Principles of desalination: New York, Academic Press, 566 p.
- Tuwiner, S.B., 1962, Diffusion and membrane technology: New York, Reinhold Publishing Corp., Am. Chem. Soc. Mon. Ser., 421 p.
- UCLA Sch. of Engg. and Appl. Sci., 1973, Saline water research, Water Resource Center Desalination Report No. 53: UCLA-ENG-7301, UCLA Sch. of Engg. and Appl. Sci., 67 p.
- Valiashko, M.G., 1956, The geochemistry of bromide in halogenesis processes and the use of bromide content as a genetic and prospecting criterion: Geochemistry, no. 6, p. 33-48.
- Van Everdingen, R.O., 1968, Mobility of main ion species in reverse osmosis and the modification of subsurface brines: Canadian Jour. Earth Sci., no. 5, p. 1253-1260.
- Van Olphen, H., 1963, An introduction to clay colloid chemistry for clay technologists, geologists, and soil scientists: New York, Interscience Pub., Div. John Wiley and Sons, 301 p.
- White, D.E., 1965, Saline waters of sedimentary rocks in Young, Addison, and Galley, J.F., eds., A Symposium: Fluids in Subsurface Environments: Am. Assoc. Petroleum Geologists Memoir 4, p. 342-366.

APPENDIX D

Mechanisms responsible for water quality

- Anderson, R.J., Graf, D.L., and Jones, B.F., 1966, Calcium and bromide contents of natural waters: *Science*, v. 153, p. 1637-1638.
- Bradshaw, R.L., 1968, Major conclusions from studies on disposal in natural salt formations, in *Annual Progress Report, Health Physics Division, Oak Ridge National Lab*, Unpub. ORNL-4316, p. 42-46.
- Bredehoeft, J.D., Blyth, C.R., White, W.A., and Maxey, G.B., 1963, Possible mechanism for concentration of brines in subsurface formations: *Am. Assoc. Petroleum Geologists Bull.*, v. 47, p. 257-269.
- Bredehoeft, J.D., and Pinder, G.F., 1972, Application of transport equations to groundwater systems: *Am. Assoc. Petroleum Geologists Mem. no. 18, Underground Waste Management and Environmental Implications*, p. 191-201.
- Carlson, E.J., 1968, Removal of saline water from aquifers: Washington, D.C., U.S. Gov. Printing Office, Water Resources Tech. Pub. Research Report no. 13, 43 p.
- Case, L.C., 1934, Subsurface water characteristics in Oklahoma and Kansas in *Wrather, W.E., and Lahee, F.H., eds., Problems of Petroleum geology*: *Am. Assoc. Petroleum Geologists*, p. 855-868.
- Collins, A.G., 1974, Saline groundwaters produced with oil and gas: U.S. Environmental Protection Agency, Office of Research and Development, Project 16060, EQQ Program Element 1BA024, p. 39-40.
- Darton, N.H., 1905, Preliminary report on the geology and underground water of the central Great Plains: U.S. Geol. Survey Prof. Paper no. 32, 433 p.
- Dingman, R.J., and Angino, E.E., 1969, Chemical composition of selected Kansas brines as an aid to interpreting change in water chemistry with depth: *Chemical Geology*, v. 4, p. 325-339.
- Engelhardt, W.V., and Gaido, K.H., 1963, Concentration changes of pore solutions during the compaction of clay sediments: *Jour. Sed. Petrology*, v. 33, p. 919-930.
- Feth, J.H., and others, 1965, Preliminary map of the conterminous United States showing depth to and quality of shallowest ground water containing more than 1,000 parts per million dissolved solids: U.S. Geol. Survey, Hydrologic Inv. Atlas, HA-199.
- Fishel, V.C., 1956, Long-term trends of ground water levels in the United States: *American Geophysical Union Trans.*, v. 37, p. 429-435.

- Fleischer, Michael, tech. ed., 1963, Data of geochemistry, 6th ed., Chapter F, Chemical composition of subsurface waters, in White, D.E., Hem, J.D., and Waring, G.A., U.S. Geol. Survey Prof. Paper 440-F, 67 p.
- Gould, C.N., 1901, The Dakota Cretaceous of Kansas and Nebraska: Kansas Academy of Science Transactions, v. 17, p. 122-178.
- Graf, D.L., Friedman, I., and Meents, W.F., 1965, The origin of saline formation waters, II. Isotopic fractionation by shale micropore systems: Illinois State Geol. Survey, Circular 393.
- Gutentag, E.D., Lobmeyer, D.H., and McGovern, H.E., 1972, Ground water in Kearney County, Kansas: U.S. Geol. Survey Hydrol. Inv. Atlas HA-416.
- Gutentag, E.D., Lobmeyer, D.H., McGovern, H.E., and Long, W.A., 1972, Groundwater in Finney County, Southwestern Kansas: U.S. Geol. Survey Hydrol. Inv. Atlas HA-442.
- Gutentag, E.D., and Stulken, L.E., 1974, Ground water in Haskell County, Southwestern Kansas: U.S. Geol. Survey Hydrol. Inv. Atlas HA-515.
- Hanshaw, B.B., 1962, Membrane properties of compacted clays: Unpub. PhD. Thesis, Harvard University, 113 p.
- Haworth, Erasmus, 1897, Underground waters of Southwestern Kansas: U.S. Geol. Survey Water-Supply Paper no. 6, p. 65.
- Leonard, R.B., 1964, A method for evaluating oil field brine pollution of the Walnut River in Kansas: U.S. Geol. Survey Prof. Paper 501B, p. B173-B176.
- Lobmeyer, D.H., and Sauer, C.G., 1974, Water resources of Hamilton County, Southwestern Kansas: U.S. Geol. Survey Hydrol. Inv. Atlas HA-516.
- McClain, T.J., Jenkins, E.D., Keene, K.M., and Pabst, M.E., 1975, Water resources of Grove, Logan, and Wallace Counties, West-central Kansas: U.S. Geol. Survey Hydrol. Inv. Atlas HA-521.
- McClure, J.W., Jr., 1973, Base metal content of oil field brines in Eastern Kansas (abs.): Geol. Soc. America Abstracts with Programs, v. 5, no. 4, p. 336.
- McGovern, H.E., and Long, W.A., 1974, Groundwater in Gray County, Southwestern Kansas: U.S. Geol. Survey Hydrol. Inv. Atlas HA-517.
- McGuinness, C.L., 1963, The role of ground water in the National water situation: U.S. Geol. Survey Water-Supply Paper 1800, 1120 p.

- McKelvey, J.G., and Milne, I.L., 1962, The flow of salt solutions through compacted clay: Clays and Clay Minerals, 9th Conf., Pergamon, New York, p. 248-259.
- Manheim, F.T., and Bischoff, J.L., 1969, Geochemistry of pore waters from Shell Oil Co. drill holes on the continental slope of the northern Gulf of Mexico: Chemical Geology, v. 4, p. 63-82.
- Meinzer, O.E., 1918, Bibliography and Index of the publications of the U.S. Geol. Survey relating to groundwater: U.S. Geol. Survey Water-Supply Paper 427, 169 p.
- Meinzer, O.E., and Wenzel, L.K., 1937, Water levels and artesian pressure in observation wells in the United States in 1936: U.S. Geol. Survey Water-Supply Paper 817, 511 p.
- Rall, C.G., and Wright, Jack, 1953, Analysis of formation brines in Kansas: U.S. Bur. Mines Rept. Inv. 4974, 40 p.
- Randolph, J.R., Baker, N.M., and Deike, R.G., compilers, 1964, Bibliography of hydrology of United States and Canada: U.S. Geol. Survey Water Supply Paper no. 1864, 232 p.
- Randolph, J.R., and Deike, R.G., compilers, 1966, Bibliography of hydrology of the United States, 1963: U.S. Geol. Survey Water-Supply Paper no. 1864, 232 p.
- Rapp, J.R., Doyel, W.W., and Chase, E.B., 1969, Catalog of information on water data, Index to groundwater stations: U.S. Geol. Survey, 650 p.
- Roberts, R.S., and Hodson, W.G., 1966, Groundwater in Kansas, Bibliography and subject index: Kansas Geol. Survey Bull. 182, 41 p.
- Schneider, Robert, 1962, An application of thermometry to the study of groundwater: U.S. Geol. Survey Water-Supply Paper 1544-B, 16 p.
- Schoewe, W.H., 1943, Kansas oil field brines and their magnesium content: Kansas Geol. Survey Bull. 47, pt. 2, p. 37-76.
- Smith, H.T.U., 1940, Geological studies in southwestern Kansas: Kansas Geol. Survey Bull. 34, 212 p.
- Stumm, Werner, and Morgan, J.J., 1970, Aquatic chemistry: An introduction emphasizing chemical equilibria in natural waters: New York, Wiley-Interscience, Division John Wiley and Sons, Inc., 583 p.
- U.S. Environmental Protection Agency, 1971, Water quality criteria data book vol. 2, Inorganic chemical pollution of fresh water: U.S. Environmental Protection Agency, Project 18010, Contract no. 14-12-538.

Van der Leeden, Frits, 1974, Groundwater: A selected bibliography: Port Washington, New Jersey, Water Information Center, Inc., 146 p.

White, D.E., Hem, J.D., and Waring, G.A., 1963, Chemical composition of subsurface waters: U.S. Geol. Survey Prof. Paper 440-F, 67 p.

APPENDIX E

Geophysical and electrical geological testing

- Biot, M.S., 1952, Propagation of Elastic waves in cylindrical bore containing a fluid: Jour. of Applied Physics, v. 23, p. 997-1005.
- Birch, Francis, Schairer, J.F., and Spicer, H.C., 1942, Handbook of Physical Constants: Geol. Soc. America Special Papers no. 36, Baltimore, Wavery Press, 325 p.
- Bird, J.M., 1966, Well log application and interpretation in a brine field, in Northern Ohio Geol. Soc., Second Symposium on Salt, v. 2, p. 57-69.
- Cook, J.C., 1965, Seismic mapping of underground cavities using reflection amplitudes: Geophysics, Society of Exploration Geophysicists, v. 30, Aug. 1965.
- Dutta, N.P., et al, 1970, Detection of solution channels in limestone by electrical resistivity method: Geophysical Prospecting, v. 18, p. 405-414.
- Gaskell, T.F., and Threadgold, P., 1960, Borehole surveying, in Runcorn, S.K., ed., Methods and techniques in geophysics: New York, Interscience Publishers, Inc., v. 1, p. 62-103.
- Grant, F.S., and West, G.F., 1965, Interpretation theory in applied geophysics: New York, McGraw-Hill Book Co., 583 p.
- Griffiths, D.H., and King, R.F., 1965, Applied geophysics for engineers and geologists: Oxford, Pergamon Press, 223 p.
- Habberjam, G.M., 1969, The location of spherical cavities using a tri-potential resistivity technique: Geophysics, v. 34, no. 5, p. 780-784.
- Jakosky, V.J., 1938, Continuous electric profiling: Geophysics, v. 3, p. 130-153.
- Keller, G.V., and Frischknecht, F.C., 1967, Electrical methods in Geophysical prospecting: New York, Pergamon Press, 527 p.
- Keys, W.S., and Brown, R.F., 1973, Role of borehole geophysics in underground waste storage and artificial recharge, in Braunstein, Jules, ed., Underground Waste Management and Artificial Recharge: Am. Assoc. Petroleum Geologists, U.S. Geol. Survey, International Assoc. Hydrological Sci., v. 1, p. 147-191.
- Lattman, L.H., 1958, Technique of mapping geologic fracture traces and lineaments on aerial photography: Photogrammetric Engineering, v. 24, no. 4, p. 568-576.

- Lattman, L.H., and Nickelsen, R.P., 1958, Photogeologic fracture trace mapping in Appalachian Plateau: Am. Assoc. Petroleum Geologists Bull., v. 42, p. 2238-2245.
- McCanley, J.R., 1976, Kansas geology as seen by ERTS-1: Am. Assoc. Petroleum Geologists Bull. 60, p. 320-321.
- Mattox, R.B., ed., 1962, Saline deposits: a symposium based on papers from the International conference on Saline Deposits, Houston, Texas: Geol. Soc. America Special Paper no. 88, 701 p.
- Morgan, C.O., and McNellis, 1969, Fortran IV Program, KANS, for the conversion of General Lands Office locations to Latitude and Longitude Coordinates: Kansas Geol. Survey Spec. Dist. Pub. 42.
- Nettleton, L.L., 1971, Elementary gravity and magnetics for geologists and seismologists: Tulsa, Ok., Soc. of Exploration Geophysicists, Monograph no. 1, 121 p.
- Palmer, L.S., 1954, Location of subterranean cavities by geoelectrical methods: Mining Mag. (London), v. 91, no. 3, p. 137-141.
- _____, 1958, Examples of geoelectric surveys: Institute of Electrical Engineering Paper no. 2791M, p. 231-243.
- Ray, R.G., 1960, Aerial photographs in geologic interpretation and mapping: U.S. Geol. Survey Professional Paper 373, 230 p.
- _____, 1964, Photogeologic procedures in geologic interpretation and mapping: U.S. Geol. Survey Bull. 1043-A, 21 p.
- Rechtien, R.D., 1970, A high frequency wave generator for application to cavity delineation, in Northern Ohio Geol. Soc., Third Symposium on Salt, v. 2, p. 357-366.
- Schlumberger Well Surveying Corp., 1958, Introduction to Schlumberger well logging: Schlumberger Document no. 8, 176 p.
- Stingelin, R.W., 1969, Operation airborne thermal imaging surveys: Geophysics v. 34, no. 5, p. 769-771.
- Trainer, F.W., and Ellison, R.L., 1967, Fracture traces in the Shenandoah Valley, Virginia: Photogrammetric Engineering, v. 33, no. 2, p. 190-199.
- U.S. Environmental Protection Agency, 1971, Detection of abandoned underground coal mines by geophysical methods: H.R.B. Singer, Inc. for U.S. Environmental Protection Agency and Pennsylvania Dept. of Environmental Resources, Project 14010-EHN, April 1971, Water Pollution Control Research Series.

- U.S. Geol. Survey, 1969, Bibliography of Remote Sensing of Earth Resources for hydrological applications 1960-1967: U.S. Geol. Survey Interagency Report NASA-134.
- Wait, J.R., ed., 1971, Electromagnetic probing in geophysics: Boulder, Colo., The Golem Press, 391 p.
- Wilson, J.E., 1969, Sensor detection capabilities study: U.S. Geol. Survey Circ. 616, Interagency Report NASA-143.

APPENDIX F

Kansas Legislation and Regulations Governing Drilling Operations,
Record Keeping, and Authorization for State Agencies

- K.S.A. 2-608 County extension agents provide instructions in agriculture, home economics and in 4-H club work.
- K.S.A. 19-2504 Unused or abandoned wells and other excavations are to be enclosed or filled in by the owner.
- K.S.A. 42-330 Records of artesian well construction are to be filled with the registrar of deeds of the county. Records should include strata passed through, water occurrence, height of water rise in well, rate of flow, casing record, and other information.
- K.S.A. 42-401 An artesian well is an artificial well over 400 feet deep from which water is raised to the surface but does not include mineral shafts.
- K.S.A. 42-402 to 42-407 These define waste of water, nuisance wells, and proper uses of water from artesian wells.
- K.S.A. 42-408 to 42-410 These define requirements and inspection for drilling, casing, and construction of artesian wells.
- K.S.A. 42-411 Records are kept by drilling contractor to be filled with artesian well supervisor.
- K.S.A. 42-413 The county artesian well board is elected from owners of wells in the county and they appoint an artesian well supervisor who serves at the board's pleasure.
- K.S.A. 42-414 Duties of supervisor are to inspect wells, keep a record of inspection, make complaints against any person violating provisions of the act.
- K.S.A. 42-417 to 42-418 Permits for construction or repair of wells and statements of such are to be filed with the well supervisor and the county clerk.
- K.S.A. 42-419 The well supervisor takes pressure readings twice yearly and keeps the records in his office.
- K.S.A. 55-118 Oil or gas wells going through salt water must be cased or plugged to exclude salt water from upper or lower strata having water suitable for domestic purposes.

- K.S.A. 55-128 Drilling for exploration, discovery or production of oil, gas, or minerals is preceded by application to the state corporation commission and the commission determines amount of pipe necessary to protect usable water. Usable water contains no more than 5,000 ppm chlorides. All pipe set must be approved by the state corporation commission and any hole abandoned must be plugged according to the rules and regulations of the corporation commission. A report is filed with the corporation commission after completion of work done on the hole. Before abandoning the well, notice must be given to the corporation commission of intention to plug the well.
- K.S.A. 55-128a Any person engaged in drilling for geological information or in plugging holes shall be licensed.
- K.S.A. 55-132a Within six months of abandonment the operator of a well must remove all equipment and any obstacles to the use of the land and grade the land to its previous contour.
- K.S.A. 55-133 Application is required to inject fluid under pressure into a well producing oil or gas. Injection is done under rules and regulations of the corporation commission.
- K.S.A. 55-136 to 55-140 When a well is drilled there should be surface or drive pipe cemented below the lowest fresh water strata and additional pipe may be required to protect usable water. Abandoned wells found to be the cause of pollution by the state board of health or the state corporation commission shall be plugged.
- K.S.A. 55-301 The board of County Commissioners appoints a "gas inspector" for the county.
- K.S.A. 55-303 Gas wells are to be reported to the gas inspector within two days of completion.
- K.S.A. 55-304 The inspector is to see that all provisions of the law regarding drilling for gas and regulating of gas wells are carried out.
- K.S.A. 55-305 The inspector is to measure and record the initial rock pressure and volume of gas for each well once every six months. The records are kept in the office of registrar of deeds.
- K.S.A. 55-901 Application to and approval from state corporation commission allows salt water produced from oil and gas wells to be returned to the producing strata or any horizon which contains salt waters when the return is done in compliance with corporation commission rules.

- K.S.A. 55-1003 Disposal of brines may be done provided plans for disposal works are submitted to the corporation commission and the state board of health for approval.
- K.S.A. 55-1004 to 55-1006 Plans for disposal wells for brines are submitted to the corporation commission and the state board of health for approval. The minimum depth of disposal is set by the corporation commission and the maximum pressure allowed is set by the state board of health. The corporation commission inspects the wells for compliance.
- K.S.A. 65-170 The engineer of the state board of health is to investigate and report on pollution of the waters of the state and to make recommendations as necessary.
- K.S.A. 65-171 The definition of pollution is such contamination, or other alteration of the physical, chemical, or biological properties of any waters of the state as will or is likely to create a nuisance or render such waters harmful, detrimental, or injurious to public health, safety, or welfare, or to the plant, animal, or aquatic life of the state, or to other legitimate beneficial uses. Storage of salt water at the surface is prohibited except by approval from the state board of health. If any oil, gas, salt water injection well, or underground storage reservoir or surface storage facility for salt water is causing or is likely to cause pollution an order from the state board of health can be issued to prohibit the use of the facility.
- K.S.A. 74-506a The division of water resources is created within the state board of agriculture to consolidate the water commission and division of irrigation.
- K.S.A. 74-506d A chief engineer of the state board of agriculture is to be employed to carry out provisions of the law.
- K.S.A. 74-509 The state irrigation commissioner is to gather and publish data from irrigation works in the state and to advise about the feasibility of installing additional irrigation works in the state.
- K.S.A. 74-2608 Duties of the state water resources board are to collect and compile information relating to water use and availability; work out a state plan of water resources development; review that plan; to study laws relating to water and water use and development; to make recommendation to other agencies involved in water use and development and to the Kansas Legislature concerning legislation necessary.

- K.S.A. 74-2610 Cooperation of these agencies is required, the division of water resources of the State Board of Agriculture and the chief engineer, the State Geological Survey, the director of Agriculture Experiment Stations, the chief engineer of Kansas State Board of Health and any other state and local agencies being requested to make available information.
- K.S.A. 76-322 The State Geological Survey is to make a complete survey of the state with special attention to natural products of economic importance.
- K.S.A. 76-326 These natural products include gypsum, salt, and underground water.
- K.S.A. 82a-701 Definitions of appropriations right, water right, vested right, pertaining to appropriation of water are given.
- K.S.A. 82a-706 and 706a The chief engineer of the division of water resources shall enforce the laws of the state and also adopt reasonable rules and regulations concerning water usage.
- K.S.A. 82a-706c and 706e The chief engineer may require the water user to make checks and report findings of water quality and water waste. He may appoint a water commissioner for each field office, to be his agent.
- K.S.A. 82a-901 to 904 The state water plan is to protect the water of the state and the water users of the state. It is a comprehensive use plan for the development of water use by long range goals of control and conservation, development, and utilization.
- K.S.A. 82a-907 The water plan shall include consideration for public health and the interrelationship of surface and ground-water supplies among other things.
- K.S.A. 82a-927 and 928 Some of the goals are protection of water quality, prevention of water waste, prevention of water pollution, coordination of development of water with other natural resources of the state. These are to be accomplished in part by achievement of the drinking water standards for public water supply, maintenance of quality so that neither chlorides nor sulfates exceeds 250 mg/l, developing irrigation water so that SAR does not exceed 15, plugging abandoned wells and control of seepage areas of mineralized waters, disposing of brines so they do not pollute water supplies.

K.S.A. 82a-941 Agencies of the state having responsibility for water resources shall carry on data collection, research and analysis of water quantity and quality.

K.S.A. 82a-1001 to 1009 Groundwater management districts are to be organized for management of groundwater and prevention of economic deterioration. The board of directors of the district shall collect and disseminate information, research, and data on groundwater conversation and recommend to the chief engineer or the division of water resources any rules and regulations it sees necessary.

Frank Corrick, compiler and editor, 1964, Kansas Statutes Annotated, Topeka, Kansas.

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Rules and Regulations of the State Corporation Commission

- 82-2-118 to 121 Fresh water and minerals are to be protected by proper cementing, casing of oil wells, and sealing off of formations containing fluids or valuable minerals.
- 82-2-122 Shut off testing may be required to determine if fluids are migrating from the well. The owners of an abandoned well found to be allowing migration of fluid shall plug the well.
- 82-2-123 Rules and definitions for cementing-in surface or drive pipe are given (Table I).
- 82-2-125 Samples and information to be sent to Kansas Geological Survey, Wichita, include formation samples, and copies of logs run by operators. There are ways to request permission not to send in the samples and information.
- 82-2-301 Fluid bearing formations are to be protected from migrating fluids from abandoned oil or gas wells.
- 82-2-302 to 304 Notice of intent to abandon a well must be given to the conservation division and a representative of that division is to be present to supervise the plugging. Procedures for plugging are to protect the fresh water supply.
- 82-2-305 Notice of intent to drill must be filed when drilling will penetrate salt water formations. That notice will include information about fresh water formations and fresh water wells in the vicinity of the proposed well.
- 82-2-306 All exploratory holes drilled must be properly plugged.

82-2-307 Methods for plugging exploratory holes are given to prevent migration of fluids into fresh or usable waters.

82-2-310 and 82-2-311 Drillers and well pluggers shall be licensed by the corporation commission.

82-2-312 The license may be revoked if the licensee is found to have failed to plug any holes required, failed to file the proper forms, or made false statements on the forms, or willfully violated the rules and regulations.

82-2-400 to 82-2-404 Salt water may be disposed of in approved strata in properly constructed and tested wells. Notice of commencement and discontinuance of disposal shall be made to the corporation commission.

82-2-500 to 82-2-504 Water-flooding may be performed in properly constructed wells. Notice of commencement and discontinuance must be given to the corporation commission. Records must be taken and preserved for three years. Recorded are amount of fluid injected and other information as may be required.

State Corporation Commission, 1973, General Rules and Regulations for the conservation of Crude Oil and Natural Gas, Topeka, Kansas, 114 p.

Table I Established depths above which usable and fresh water should be protected by recommended methods (Revised March 1, 1967). Minimum surface casing requirements are given by county. (Surface pipe requirements as specified in Rule 82-2-123).

Table II Established minimum depths for disposal wells (Revised April 26, 1971). Absolute minimum depths permitted are given by county. (As specified in Rule 82-2-400).

State Corporation Commission, Conservation Division (Oil, Gas, and Water), unnumbered.

House Bill No. 1372 Known as the "Kansas Groundwater exploration and protection act".

Sect. 2 provides for licensing and regulation of water well contractors and protection of water by requiring descriptions of location, drilling and construction, and abandonment of wells, and providing data on water supplies.

Sect. 5 provides for the act to be administered and enforced by the state department of health. The state department of health shall recommend to the state board of health rules and regulations for standards of water well construction, treatment, and plugging. The department may inspect wells being drilled or already drilled, and may examine well contractors requesting license.

Sect. 7 provides that a candidate for license examination shall know state ground water laws, have some knowledge of underground geology and show proof of financial responsibility.

Sect. 10 provides for revocation or suspension of license if the licensee has violated the laws, rules and regulations, or has been negligent or incompetent.

Sect. 12 provides for a record of the well being drilled be kept by the contractor to include location, description of formations passed through, depth of water encounter, static water level in completed well, pumping tests if any, construction details of well and a water sample.

Sect. 13 provides that all holes not used be properly plugged by the contractor according to the rules of the board.

(This bill will be known as K.S.A. 82a-1201 to 1215). State of Kansas, 1973, 1973 Session Laws of Kansas, Topeka, Kansas, 1388 p.

Executive Reorganization Order No. 3

Sect. 1 provides for the creation of a department of health and environment whose head is the secretary of health and environment. The department shall consist of the division of health and the division of environment.

Sect. 2 provides for the transfer of the duties, powers, and records of the state board of health, the state department of health to the new department.

Sect. 3 provides that the new secretary shall have the powers and functions of the state board of health, state department of health and the director of health and that whenever those agencies or agent are designated the reference shall now apply to the secretary of health and environment.

Sect. 5 provides for the creation of the division of environment whose head is the director of the division of environment.

Sect. 6 provides for the duties and functions of the division of environmental health, the director of environmental health and the engineer of the state board of health be transferred to the secretary of health and environment.

Senate Bill No. 652 amends existing laws by abolishing appropriate agencies and transfers their powers, functions, and records to the new department of health and environment and its head.

State of Kansas, 1974, 1974 Session Laws of Kansas, Topeka, Kansas, 1615 p.

House Bill No. 2607 modifies and approves administrative regulations as adopted by the secretary of health and environment.

Sect. 2 to 4 define terms to be used in enforcement of K.S.A. 82a-1201 to 82a-1215 and gives table of minimum wall thickness for water wells.

Sect. 5 gives regulations for proper abandonment of water wells.

State of Kansas, 1975, 1975 Session Laws of Kansas, Topeka, Kansas, 1818 p.

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Kansas State Board of Health Revised Rules and Regulations adopted April 1, 1966.

Article 8. Oil field waste disposal

28-8-1 Definitions are given of terms used in the rules.

28-8-2 Permits for storage or disposal of salt water are obtained by application to Director of the oil field section, Environmental Health Services, Kansas State Department of Health.

28-8-4 Surface pond construction regulations state that the pond must not cause deterioration of water supply.

28-8-8 Disposal wells shall have a fitting and valve for injection pressure measurement.

Kansas State Board of Health Regulations approved May 4, 1966.

Article 13. Underground Storage, Disposal wells and Surface ponds.

28-13-1 This article regulates the construction and use of wells, ponds, and underground reservoirs for disposal of industrial wastes not including oil field brines.

28-13-2 to 28-13-11 Definitions for underground storage reservoir, surface pond and disposal well are given. Plans for underground reservoirs are submitted to the chief engineer of the state board of health. Permanent records of type and quantity of products stored and injection pressures are kept and reported to the chief engineer. Application to and approval of the state department of health are required for disposal wells and surface pond construction and use.

EFFECTS OF PERMIAN EVAPORITE DISSOLUTION
IN KANSAS

by

BARBARA J. (STOUT) SMITH

B. S., Kansas State University, 1969

B. S., Kansas State University, 1975

AN ABSTRACT OF A MASTER'S THESIS

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requirements for the degree

MASTER OF SCIENCE

Department of Geology

KANSAS STATE UNIVERSITY
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Abstract

Evaporites underlie the western two-thirds of Kansas with accumulated thickness of gypsum, anhydrite, and halite over one thousand feet in the southwest. Evidence of dissolution includes sinkholes, salty springs, salt marshes, and subsurface truncations of evaporite beds. Water, from naturally occurring and induced sources, comes in contact with evaporites by natural and artificial means including faults, joints, and boreholes. Overpumpage of fresh water, defective borehole plugs, and natural hydraulic connections account for mineralized water return to ground and surface waters. Comparison of maps of evaporite occurrences and a map of petroleum drilling operations demonstrate the coincidence of drilling and shallow evaporite occurrences. Proposed studies to detect and monitor potential subsidence areas could be coordinated through the State Geological Survey of Kansas. The Kansas Water Resources Board could coordinate studies to detect contaminated water supplies and monitor well fields. Better informed citizens and state agencies can adopt policy and land use changes reflecting good land and water use and conservation.