GEOHYDROLOGY OF AND POTENTIAL FOR FLUID DISPOSAL IN THE ARBUCKLE AQUIFER IN KANSAS

By Jerry E. Carr, Harold E. McGovern, and Tony Gogel,

With a section on

LOG ANALYSIS OF THE ARBUCKLE AQUIFER

By John H. Doveton

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CONVERSION FACTORS

Inch-pound units of measurement used in this report may be converted to the International System of Units (SI) using the following conversion factors:

Multiply inch-pound unit	by	To obtain SI unit
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	929.0	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
barrel (bbl)	0.1590	cubic meter (m^3)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
gallon per day (gal/d)	0.06308	liter per day (L/d)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
foot per second squared (ft/s^2)	3.048×10^{-1}	meter per second squared (m/s^2)
square foot per second (ft^2/s)	929.0	square centimeter per second (cm^2/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
pound per square inch (lb/in^2)	0.07031	kilogram per square centimeter (kg/cm^2)
pound per square foot (lb/ft^2)	4.885×10^{-4}	kilogram per square centimeter (kg/cm^2)
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
degree Fahrenheit (°F)	1/	degree Celsius (°C)

[1] Degree Celsius = (degree Fahrenheit -32)/1.8.

GEOHYDROLOGY OF AND POTENTIAL FOR FLUID DISPOSAL IN THE ARBUCKLE AQUIFER IN KANSAS

By

Jerry E. Carr, Harold E. McGovern, and Tony Gogel

ABSTRACT

The Arbuckle aquifer is an extensive aquifer that contains mostly saline water and that immediately overlies Precambrian "basement" rocks throughout Kansas, except for major uplift areas where it has been removed by erosion. In the southeast part of the State, it is a major freshwater aquifer. The upper part of the Arbuckle contains significant oil and gas reservoirs in central and south-central Kansas. During the last 40 years, the Arbuckle also has become the major zone of fluid disposal in the State. Most of the fluids disposed into the Arbuckle were produced from oil and gas wells in other formations. In addition, some industrial waste is disposed of in the Arbuckle. However, in recent years, State water agencies have become increasingly concerned about injection of fluids into the subsurface and the effects of injection on the hydrologic systems involved. An investigation of the geohydrology of the Arbuckle aquifer and of the hydrologic aspects of fluid disposal into the Arbuckle was conducted by the U.S. Geological Survey, in cooperation with the Kansas Geological Survey, to evaluate these effects.

Rocks of the Arbuckle aquifer are composed almost entirely of dolomite, except for a relatively thin basal sand. The hydrologic characteristics of the dolomite have been affected by uplift, fracturing, and dissolution. Major regional karst-type cavernous zones have developed throughout the State with probably more pronounced development in the uplift areas. Thickness of the Arbuckle ranges from about 200 to 1,400 feet and increases in thickness to the south. Depths to the top of the Arbuckle range from about 500 feet in the southeast to about 7,500 feet in the southwest.

Hydraulic characteristics obtained from drill-stem tests, injection tests, and numerical modeling have indicated a range of permeability in the Arbuckle from 1 millidarcy to 30 darcys. Permeability in the basin areas probably is much smaller than in the uplift areas. Analysis of injection tests indicated that average permeability in the basin areas probably is in the 50- to 300-millidarcy range. Analyses of 76 geophysical logs indicate an average porosity of about 12 percent.

An evaluation of the geohydrology of the Arbuckle shows that it is a large regional-flow system that is in hydraulic connection with several other major aquifers. The Arbuckle is in contact with overlying rocks of different hydraulic characteristics and hydraulic heads; this results in potential for transfer of fluids between the units. Ground-water flow within the Arbuckle is principally from the west-northwest to the east-southeast, although there are areas where the flow is mainly to the east

or west. Ground-water flow in the Arbuckle enters the State from Missouri and continues to the west-northwest until it contacts a more saline ground-water flow system, where it then moves upward and to the south and north. Flow of relatively fresher ground water enters the Salina basin from the northwest and continues to the south-southeast through the Sedgwick basin. Some of this ground water flows into the Forest City and Cherokee basins. Part of this water probably is the source of fresher water in the Central Kansas uplift and Nemaha anticline areas. Ground-water flow from the Arbuckle aquifer into the Simpson Group probably occurs primarily in the Sedgwick basin area. Although the Simpson and Arbuckle generally are thought to be in hydraulic contact because much of their flow and water-quality patterns coincide, the vertical-head differences between the two units are much greater in the Sedgwick basin than in other areas.

Brine disposal in the Arbuckle has been increasing over the years. Prior to 1942, only 185.5 million barrels of brine had been injected into the Arbuckle, but by 1980 about 889 million barrels per year were being injected. Rates of injection were reported to be as great as 2,100 gallons per minute, but the average injection rate per well is reported to be about 60 gallons per minute. Maximum rates of injection are in the uplift areas. Regional effects of this injection on fluid levels in the Arbuckle are not well documented.

Model analysis, using aquifer properties similar to those expected in the basin areas and under selected conditions of well injection into the Arbuckle, indicates that, even with an injection rate of only 100 gallons per minute, pressure increases equivalent to fluid-level rises of up to 100 feet are expected as far as 500 feet away from the injection well. In general, if wells, fractures, or faults that allow communication of fluid between the injection zone and some other unit are present, the fluid-level rises, in combination with existing natural levels, would be large enough to cause movement of the injected fluid from one unit to another. The model analysis indicates that the effects of transmission of fluid through the confining layer on overlying units are minor, with the assumed values of permeability used for the confining layer. Lateral fluid movement away from the injection well after 5 years of continuous injection at a rate of 300 gallons per minute reached a maximum distance of 400 feet. The results of this study indicate that in order to contain a given fluid, the most favorable place to put it is in the lower part of the Arbuckle. Within the limits tested for density and permeability, gravity and buoyancy effects were minor, although movement of these injected fluids caused by these forces could be important over long periods of time.

The Arbuckle probably has more potential for accepting injection of fluid than any other saline aquifer in Kansas, in terms of accepting the most fluid with the least amount of injection pressure. It also has the least potential to affect overlying freshwater aquifers in most of the State. Certain areas are considered more favorable than others for confinement of fluids because of the following criteria: minimum faulting and fracturing of geologic strata, more continuous confining layers, more vertical distance between the injection zone and freshwater zones, and lesser amounts of past and present brine disposal. These areas are the Salina, Forest City, Cherokee, and Sedgwick basins, and the Hugoton embayment. The center of each basin area is considered to be more favorable than the periphery.

INTRODUCTION

Background

In recent years, Kansas has become increasingly concerned about injection of fluids into the subsurface and the effects of the injection on the hydrologic systems involved. The Arbuckle aquifer is of particular interest because of its occurrence under most of the State, because of the fluids associated with oil and gas production that have been disposed into the Arbuckle for many years, and because of the potential influence of injection to the Arbuckle on freshwater systems. The Arbuckle aquifer, as defined in this report, includes all Upper Cambrian and Lower Ordovician rocks in Kansas that underlie rocks of the Simpson Group (fig. 1). The Arbuckle also is an important freshwater aquifer in the extreme southeast part of Kansas. Most of the fluids disposed into the Arbuckle were produced from oil and gas wells in other formations. Furthermore, industrial waste has been injected into the Arbuckle in a few areas, and the State of Kansas continues to receive requests from industry for permission to dispose of liquid industrial waste into the Arbuckle. Upon injection of these fluids, the native fluids, which in this case are brines, may be displaced in order to emplace additional liquids; therefore, there could be potential effects from these activities on freshwater systems which should be evaluated. However, the effects of the injection of these fluids into the Arbuckle are not well known.

Purpose and Scope

The purpose of this report is to present the results of a study by the U.S. Geological Survey, conducted in cooperation with the Kansas Geological Survey, to evaluate the geohydrology of the Arbuckle and the hydrologic aspects of fluid disposal into the Arbuckle, primarily with existing data. The study involved describing the hydraulic characteristics of the Arbuckle and other aquifers or confining units that potentially affect the movement of fluids in the aquifer system. In addition, the report describes the distribution of injection locations and the potential effects of injection on the hydrologic system. Of particular concern are the potential effects of injection on freshwater aquifers. In general, this report summarizes the information available and discusses the conclusions that are indicated in relation to fluid movement within the geohydrologic system.

Information relevant to this investigation was available from numerous sources. Generalized descriptions of geologic units given in this report are based largely on information in publications of the Kansas Geological Survey and the U.S. Geological Survey. In addition, information was available from journals of geological societies that provided a regional perspective on geologic and hydrologic conditions. Data from tests in exploratory wells, which were obtained from numerous petroleum companies, were useful in determining the hydraulic characteristics of the aquifers and the chemical composition of associated brines.

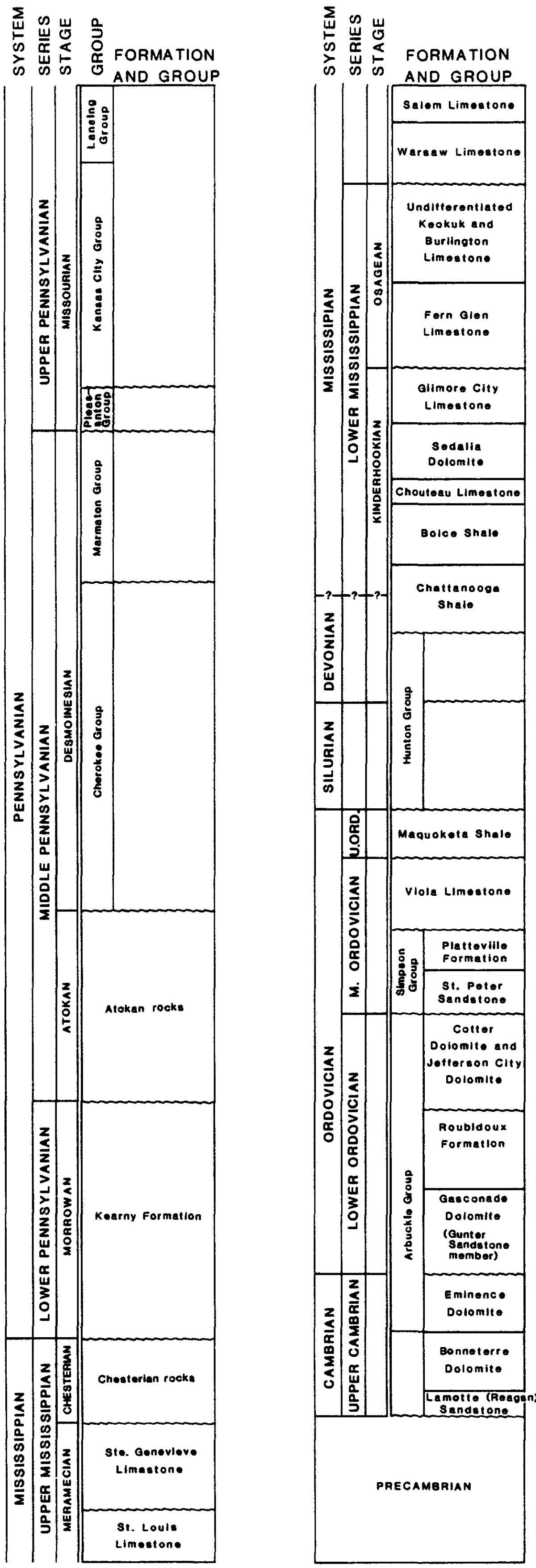


Figure 1.--Stratigraphic column. The stratigraphic nomenclature used in this report is that of the Kansas Geological Survey and may differ from that used by the U.S. Geological Survey.

In 1978, the investigation was expanded to include a cooperative program with the Kansas Department of Health and Environment and the U.S. Army Corps of Engineers for drilling test holes that would yield detailed stratigraphic and hydrologic data from the Arbuckle and related rocks at specific sites. Four test holes were drilled (fig. 2), and monitor wells were installed at sites in Douglas, Labette, Miami, and Saline Counties. Analyses of drill cuttings, cores, and geophysical logs provided information for describing the geologic framework. Drill-stem tests were used in determining formation pressure, hydraulic head, permeability, and hydraulic conductivity. Samples of formation water were used to determine the chemical composition of the fluids within the different horizons. Data obtained from the test wells drilled during this part of the cooperative program were published in U.S. Geological Survey Open-File Report 81-1112 (Gogel, 1981). Copies of the geophysical logs made during the tests are available from the Kansas Geological Survey (Lawrence, Kansas). A computer model was used to analyze injection tests from two test wells and to project fluid movement and pressure increases at different rates of injection and periods of time.

Acknowledgments

The authors would like to acknowledge the time and data contributed to this project by Jim Ebanks and Al Macfarlane of the Kansas Geological Survey.

GEOHYDROLOGIC FRAMEWORK

The Arbuckle aquifer of Late Cambrian and Early Ordovician age extends throughout Kansas with the exception of some structurally high areas on the Central Kansas uplift and the Nemaha anticline (fig. 2) where the Arbuckle has been removed by erosion. As indicated by a stratigraphic column (fig. 1) and a map of overlying rocks in contact with the top of the Arbuckle (fig. 3), rocks of different ages overlie the Arbuckle and are in contact with the Arbuckle throughout the State. Where differences in hydraulic head are present, potential for transfer of fluids exists between the units. Precambrian "basement" rocks, which consist of very dense, igneous and metamorphic rocks, underlie the Arbuckle. These basement rocks are considered to form a lower "no-flow" boundary for the Arbuckle. Younger rocks that overlie the Arbuckle vary in age (fig. 3) because some rock units were not deposited or were removed by erosion. Therefore, the rocks in contact with the Arbuckle are not uniform in lithologic or hydraulic characteristics. The youngest stratigraphic unit that is both in contact with the Arbuckle and continuous over the area is the undivided Kansas City and Lansing Groups. The contact of the Arbuckle with several rock units, variable-density fluids, diverse lithology, and existence of oil production and brine disposal result in a very complex, aquifer flow system. In order to analyze the system, it was necessary to divide the geologic column into major aquifer units based on the general bulk hydraulic characteristics of the different rock groups that may influence or control the movement of fluids in these rocks.

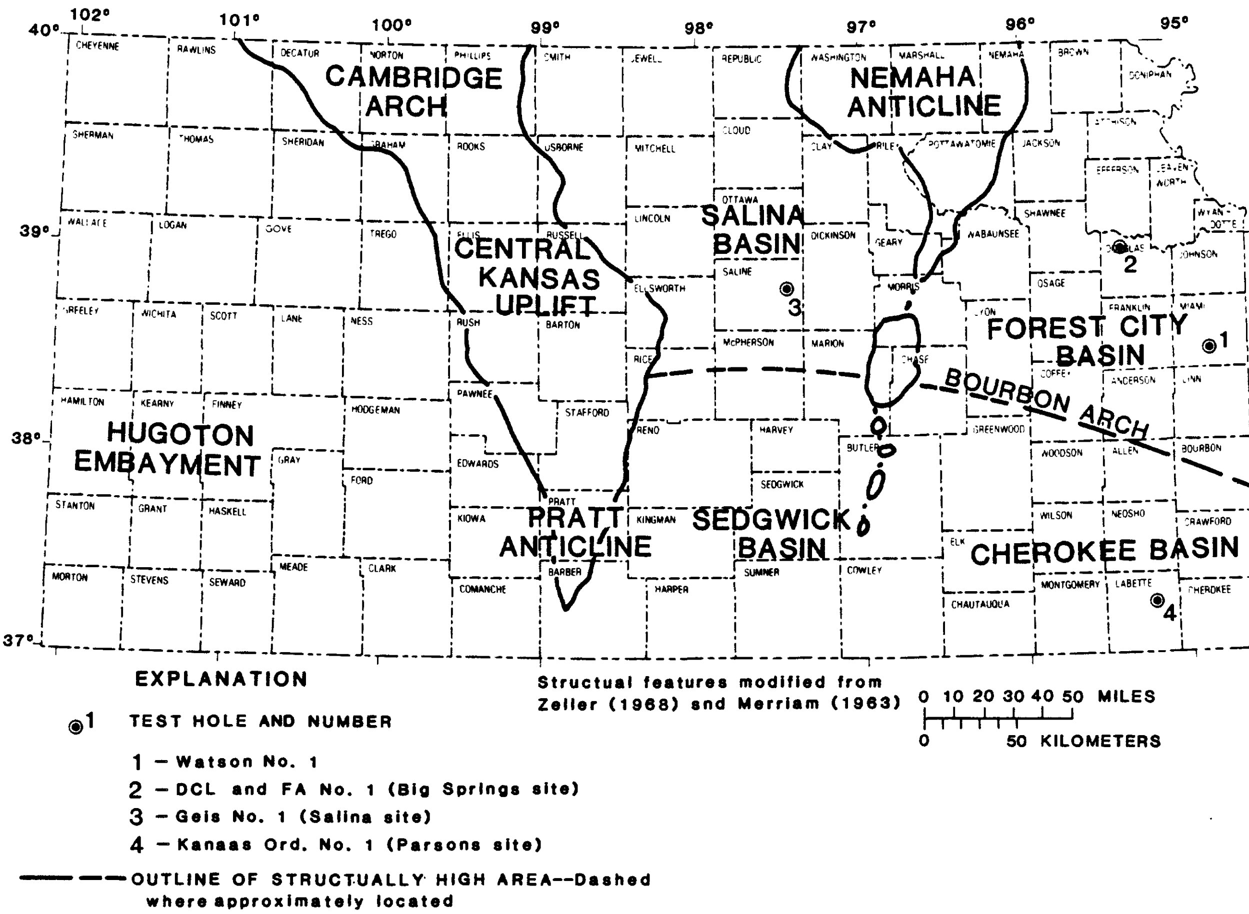


Figure 2.--Major structural features in Kansas and location of test holes drilled for this study.

The aquifers, as defined in this report, include the Arbuckle, the St. Peter Sandstone of the Simpson Group, the Viola Limestone, the Hunton Group, Mississippian rocks, and the undivided Kansas City and Lansing Groups, which are referred to in this report as the Lansing-Kansas City aquifer. These aquifers generally include stratigraphic units that have sufficient permeability in composite to transmit significant quantities of water under the existing hydrodynamic conditions. These aquifers also include some small permeability units that could restrict the flow of fluids if viewed on a more local basis. Other units that are sufficiently impermeable to restrict or confine the flow over large areas are described separately. Although the aquifers were selected because of similar lithology within each unit, this does not imply that a rigid boundary exists between the units in terms of ground-water flow because many of the aquifers may react as a combined system at some locations with fluids being transmitted between aquifers.

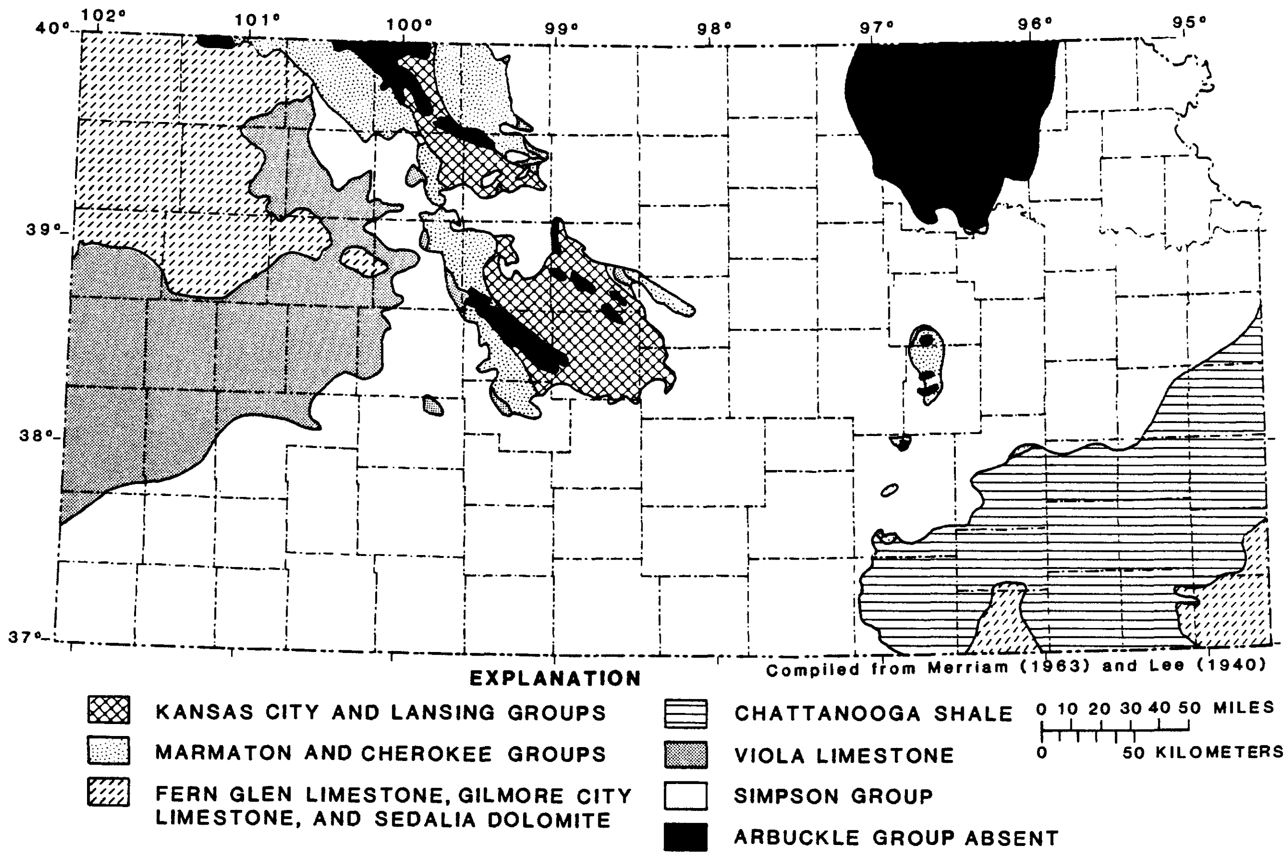


Figure 3.--Overlying rocks in contact with top of Arbuckle aquifer.

Confining units in ascending order, include the Platteville Formation of the Simpson Group, the Maquoketa Shale, the Chattanooga Shale, and Lower and Middle Pennsylvanian rocks. The Lower and Middle Pennsylvanian rocks are referred to in this report as the Pennsylvanian confining unit. The confining units within the geohydrologic sequence from the Arbuckle to the Lansing-Kansas City aquifer are effective to different degrees in restricting flow of fluids, depending on their extent, thickness, and permeability. Although only the major confining units are discussed in this section, other units, such as individual units within a given aquifer, may act as confining units in various parts of the State.

A general description of physical characteristics is given in this section for each of the principal aquifers and confining units considered. The undivided Kansas City and Lansing Groups of Pennsylvanian age comprise the uppermost aquifer defined in this study because it is the first aquifer that completely overlies the Arbuckle throughout the State. All aquifers and confining units considered to have influence on the Arbuckle are included and are defined primarily using stratigraphic boundaries. Because of the size and complexity of the overall system, along with combining many formations into one aquifer or confining unit for this study, each unit is described in terms of the various formations or groups that it includes. For the same reasons, discussions of the extent, lithology, and continuity of each of the individual formations are included, as this information has bearing on the hydrologic properties of the unit. Also, it should be noted that, although the Precambrian basement rock is considered to be a "no-flow boundary," there is some oil production from fractured Precambrian rock on the Central Kansas uplift (Walters, 1953).

Arbuckle Aquifer

The Arbuckle aquifer as used in this report includes all Upper Cambrian and Lower Ordovician rocks in Kansas that overlie the Precambrian basement rocks and underlie rocks of the Simpson Group (fig. 1). The Upper Cambrian rocks consist of the Lamotte (Reagan) Sandstone, the Bonneterre Dolomite, and the Eminence Dolomite. The Reagan Sandstone is considered to be equivalent, in part, and is included with the Lamotte Sandstone in this report. The Lower Ordovician rocks in ascending order, consist of the Gasconade Dolomite, the Roubidoux Formation, the Jefferson City Dolomite, and the Cotter Dolomite. Rocks in the Arbuckle underlie most of the State, as shown in figures 4 and 5, but are absent in a few areas along the crests of the Nemaha anticline and the Central Kansas uplift. As shown in figure 3, much of the Arbuckle is in contact with the Simpson Group (St. Peter Sandstone and Platteville Formation).

The subsurface configuration of the top of the Arbuckle is shown in figure 4. Depths to the top of the Arbuckle range from about 500 feet in the southeastern part of the State to as much as 7,500 feet in the southwestern part. The Arbuckle thickens in a southerly direction toward the Anadarko basin in Oklahoma (fig. 5). Rocks may be as much as 200 to 400 feet thick in the northern part of Kansas and as much as 1,200 to 1,400 feet thick in the southern part.

The rocks within the Arbuckle aquifer generally are dolomite, except for a relatively thin basal sand. This dolomite was susceptible to dissolution during each of the cycles of uplift and erosion, such as those represented by unconformities within the Arbuckle rocks. The diagenetic alteration from lime may have occurred over a very long time, resulting in increased porosity, because the dolomitization is complete in most areas of Kansas. Walters (1958) indicated that basement tectonics probably controlled the development of an extensive joint system in the massive Arbuckle dolomite, and that the long-continued circulation of meteoric water through sinks and fractures ultimately developed a cavernous porosity. The existence of such cavernous areas is reported to be relatively common. The great amount of porosity in the rocks has been related by Walters (1958) to both dolomitization and solution weathering.

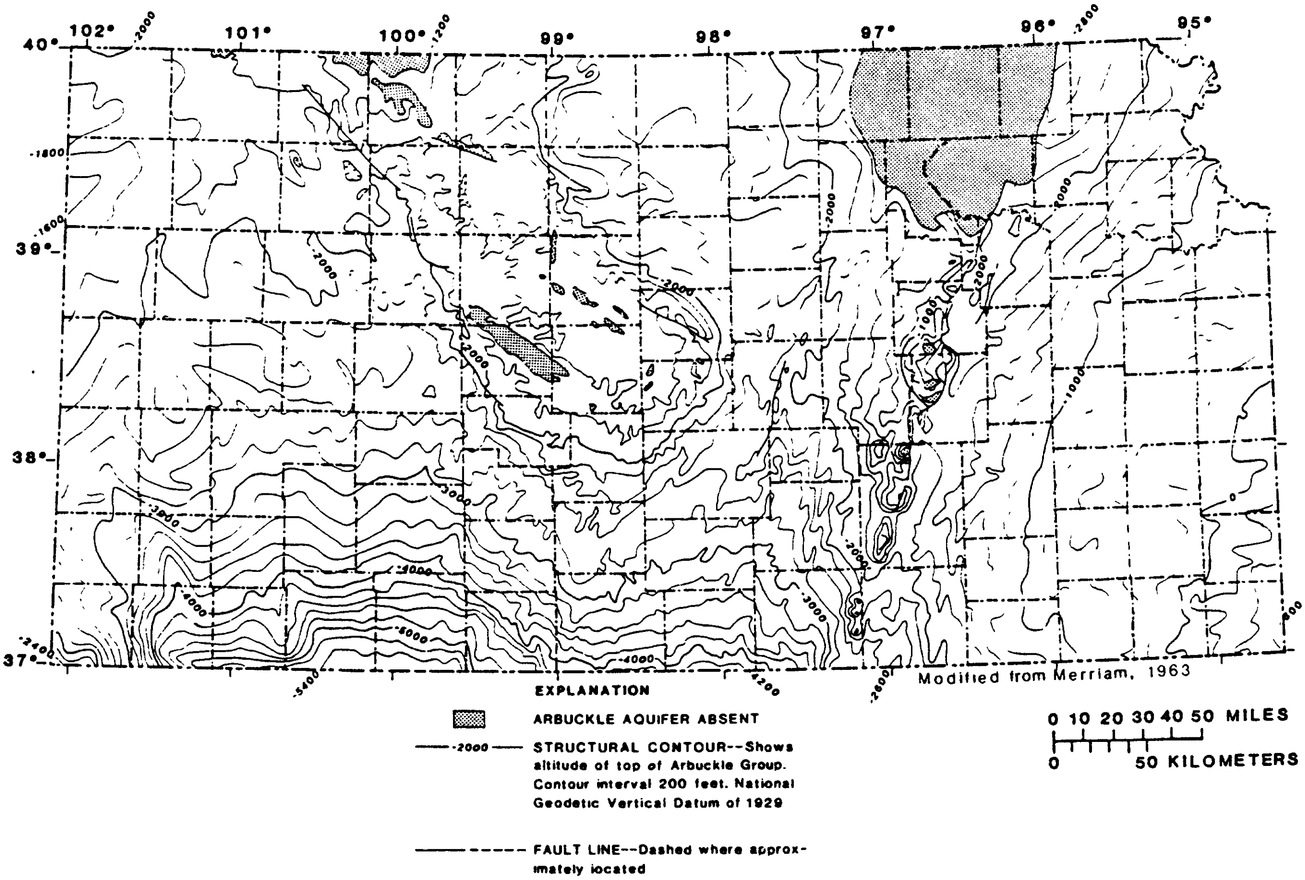


Figure 4.--Altitude of top of Arbuckle aquifer.

Much literature on the karst-type dissolution zones in the Arbuckle indicates that permeability and porosity occurs throughout the Arbuckle on a regional scale. Although the literature emphasizes the zones of unconformities where the weathering and dissolution probably would have occurred, there is no map of the extent of these features. There is some indication that the permeability may be larger in the Central Kansas uplift area, where rocks were subject to uplift, fracturing, and probably more solution than in the structural basins. Latta (1973, p. 629) states that the greatest porosity and permeability are found where the Arbuckle strata have undergone erosion on, and along the flanks of, uplift areas. However, according to Rascoe (1962) the buried "karst-like surface" of the Arbuckle is extremely erratic and its location almost impossible to predict with reasonable accuracy on the Central Kansas uplift.

St. Peter Sandstone

The St. Peter Sandstone comprises the lower part of the Simpson Group of Middle Ordovician age (fig. 1). The Simpson Group in Kansas is composed of the St. Peter Sandstone, the Platteville Formation, and unnamed beds of sandstone and shale. However, the individual thicknesses of these units are not mapped separately, so the composite thickness of the Simpson Group is shown in figure 6. The Simpson is missing from areas in the southeastern and northwestern parts of the State and on the crests of the Nemaha anticline and the Central Kansas uplift. The Simpson Group commonly ranges in thickness from 50 to 150 feet and attains a maximum thickness of about 250 feet in Harper County.

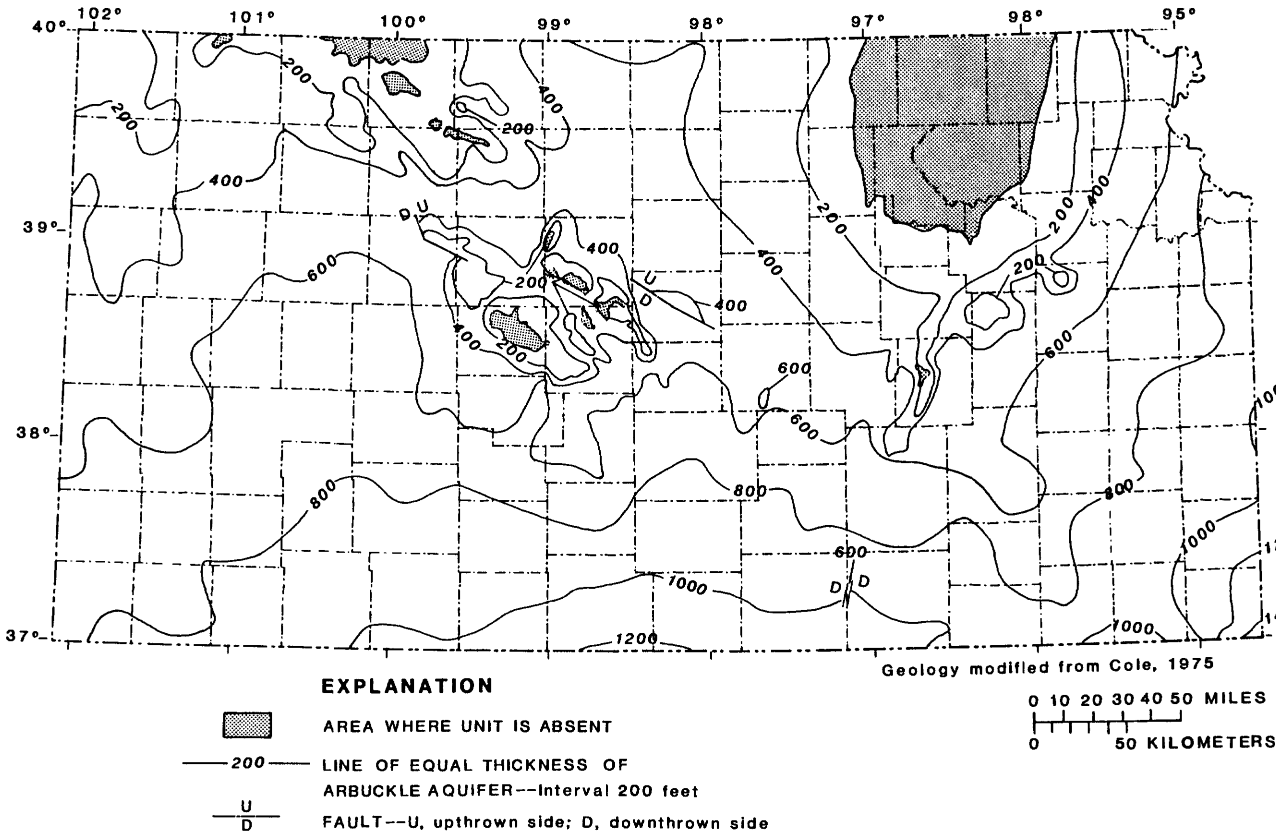


Figure 5.--Extent and thickness of Arbuckle aquifer.

The St. Peter Sandstone was deposited on an eroded karst surface of the Arbuckle aquifer that was characterized by numerous channels and sink holes. The St. Peter is composed principally of fine- to medium-grained, well-rounded quartz sand. Beds of sandstone may be loosely to well cemented with carbonate or silica. In the southern part of the State, the St. Peter Sandstone is composed of loose to well-cemented sand with a few shale layers, and this sandstone comprises from 50 to 75 percent of the Simpson rocks. By contrast, the sandstone thins and contains much more shale in areas to the southwest and northeast. In the southern part of the State, the number of sandstone beds greater than 5 feet in thickness increases to about eight towards the south, whereas in the northern part of the State the number is mostly less than two (Dapples, 1955). Thickness of the St. Peter Sandstone in eastern Kansas ranges from 10 to 84 feet but increases to about 190 feet near the Oklahoma state line.

It is assumed that porosity and permeability of the St. Peter Sandstone in the Sedgwick basin vary directly with the degree of cementation of the sand. In general, the vertical and lateral movement of fluids through the sandstone probably is affected by the amount of cementation.

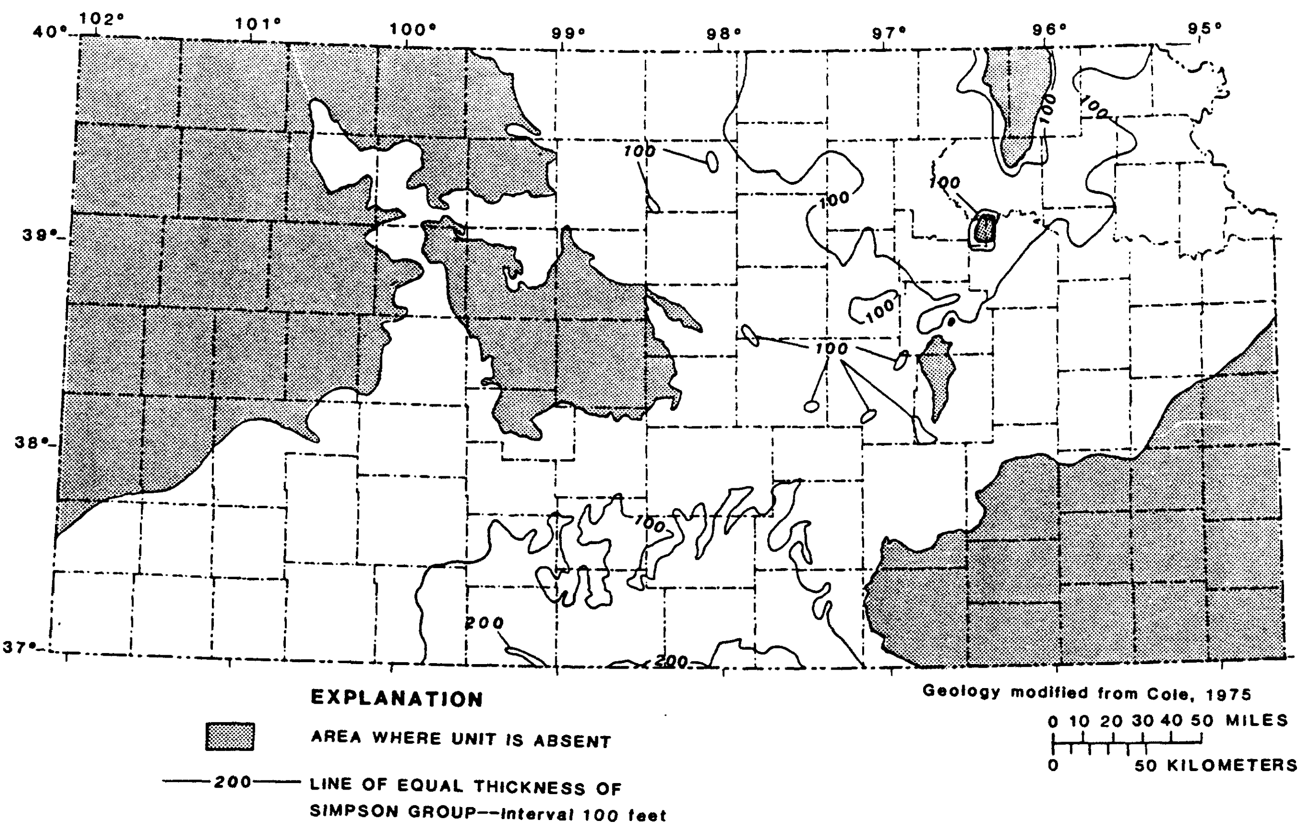


Figure 6.--Extent and thickness of Simpson Group.

Platteville Formation

The Platteville Formation comprises the upper part of the Simpson Group. The Platteville is composed of dolomite, limestone, sandstone, and shale. The basal part contains a persistent dolomite ranging in thickness from 5 to 35 feet. Some sand generally occurs in the basal dolomite and also is disseminated in the shale and dolomite of the upper part. The formation is restricted to the Salina and Forrest City basins. The Platteville acts as a confining unit over the Arbuckle aquifer, primarily in the Salina and Forest City basins. Edmund and Goebel (1968, p. 159-161) indicate that thin but persistent beds of sandstone, shale, and dolomite of the Simpson Group overlie the Arbuckle and that the shale forms an impermeable seal over the Arbuckle. Walters (1958, p. 2149) also states that the Simpson provides a seal for oil traps in the Central Kansas uplift area.

Viola Limestone

The Viola Limestone of Middle Ordovician age is composed principally of limestone and dolomite. The Viola Limestone is present in a large part of the State, as shown in figure 7, but is absent from areas in the northwestern and the southeastern parts and along the crests of the Nemaha

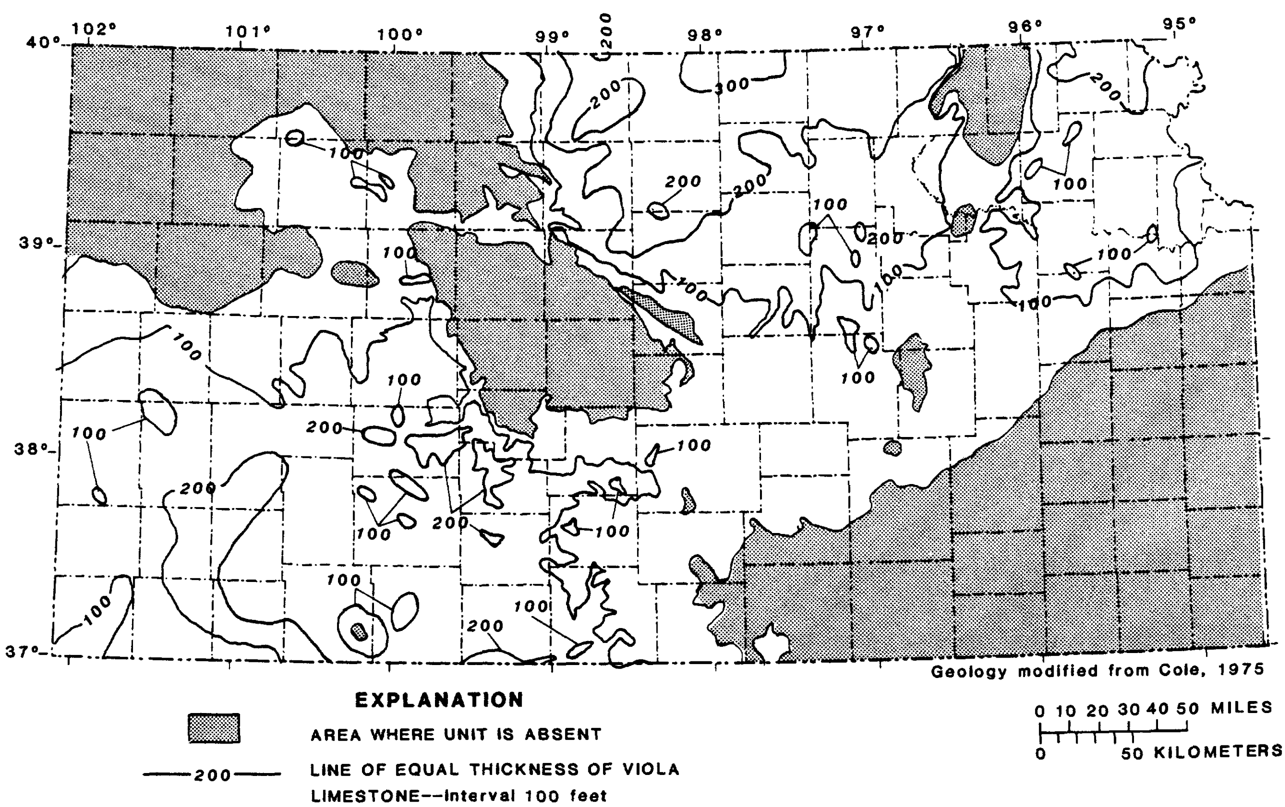


Figure 7.--Extent and thickness of Viola Limestone.

anticline and the Central Kansas uplift. The Viola thickens northward to as much as 250 feet in the Forest City basin and as much as 300 feet in the Salina basin. In the western part of the State, the unit thickens to about 200 feet in the Hugoton embayment and 250 feet along the southwestern flank of the Central Kansas uplift.

Deposits in the Viola are composed predominantly of limestone and dolomite with very few sandy or shaley zones. These carbonates generally are fine to coarsely crystalline with some zones of abundant chert. The unit is composed mostly of limestone in the eastern and northeastern part of the State, mostly of dolomite in the north-central part, interbedded limestone and dolomite in the central part, and mostly dolomite interbedded with some dolomitic shale in the southern and southwestern part.

The character of both the limestone and dolomite in the Viola has been described as quite porous locally (Chenoweth, 1966; Merriam, 1963). It is probable that some of the porosity, especially in the rocks described by Merriam (1963) as "vuggy," resulted from dolomitization of the initial deposit. Subsequent uplift and erosion, as indicated by the widespread unconformity at the top of the Viola, would have allowed the development of a significant amount of secondary porosity from solution weathering through joints and fractures. Thus, it is assumed that the permeability of the Viola Limestone would differ from one area to another in relation to the degree of dissolution along joints and fractures.

Maquoketa Shale

The Maquoketa Shale of Late Ordovician age is composed of dolomitic shale or gray pyritic shale and is interbedded with very argillaceous to cherty dolomite. Deposits of the Maquoketa, which may have been removed from a large part of the State, occur mostly in the Forest City basin, the Salina basin, and in scattered parts of the Sedgwick basin. Thickness of the unit generally ranges from a few feet to about 100 feet and is as much as 150 to 170 feet along the eastern flank of the Central Kansas uplift. Because the Maquoketa is comprised mostly of shale and silty dolomite, permeability in the unit generally is sufficiently small to restrict the vertical movement of fluids. Thus, the unit is considered to be a confining unit where it overlies the Viola Limestone in the Forest City and Salina basins and in the northern part of the Sedgwick basin.

Hunton Group

The Hunton Group is composed of rocks of Silurian and Devonian age. These rocks are considered to be correlative with the Hunton Group of Oklahoma, although they are not of the same age. A lower unit of the Hunton, which is comprised of Silurian rocks, unconformably overlies the Maquoketa Shale. The rocks are mostly fine- to medium-crystalline dolomite. Commonly these rocks are cherty and oolitic near the base, coarsely crystalline near the top, and interbedded with limestone at the margin of basins. An upper unit of the Hunton, comprised of Middle Devonian rocks, overlies the Silurian rocks and unconformably underlies the Chattanooga Shale. Rocks in the upper unit are composed of relatively pure lithographic limestone in the eastern part of the area and are mostly dense, crystalline dolomite in the western part. Sandy limestone or sandy dolomite that commonly occur near the base of the Devonian beds distinguish the zone of separation of the two units.

Silurian rocks are restricted to the Forest City and Salina basins, whereas the overlying Devonian rocks occur within these basins and extend into the northern part of the Sedgwick basin. Maximum thickness of the Devonian rocks has been reported to be 250 feet, and the thickness of both units was reported to be as much as 650 feet (Jewett and Merriam, 1959).

Silurian rocks are predominantly dolomite that have been described by Merriam (1963) and Goebel (1970) to be very porous locally. Porosity in these rocks may be related partly to dolomitization and partly to solution weathering that occurred beneath a distinctive post-Silurian erosion surface. Porosity due to solution weathering beneath the subsequent Middle Devonian surface may have been minimal because the erosion period was relatively short. Middle Devonian rocks also are composed of porous dolomite in some areas, but commonly these are interstratified with dense limestone, sandy limestone, or sandy dolomite.

Although hydrologic data for the Hunton are sparse and inconclusive, it is assumed that the permeability of the Hunton is relatively small. However, in some places, particularly just east of the Nemaha anticline, the Devonian rocks are coarsely crystalline and porous. Because of the limited areal extent of the Hunton, it is assumed that movement of fluids within this unit is not a significant factor in the hydrology of the system.

Chattanooga Shale

The Chattanooga Shale of Late Devonian and Early Mississippian age extends over most of central and eastern Kansas but is absent from the crest of the Nemaha anticline. The shale unconformably overlies most of the Hunton Group. The Chattanooga is considered to be a confining unit. The Chattanooga Shale is mostly a silty shale in the southern part of the area and grades northward to a shale locally interbedded with dolomite and silty limestone. A sandy shale commonly occurs at the base. In northeastern Kansas, an overlying silty shale with interbedded shale is reported to be the Boice Shale but is included with the Chattanooga in this report. Thickness of the Chattanooga Shale ranges from a few feet to about 200 feet. The thickness reported in northeastern Kansas probably includes the Boice Shale.

Mississippian Rocks

Mississippian rocks are subdivided into intervals that include the following stages, listed in ascending order: (1) Kinderhookian, (2) Osagean, (3) Meramecian, and (4) Chesterian. These rocks crop out in a very small area of southeastern Kansas and occur in the subsurface everywhere except along the crests of the Cambridge arch, the Central Kansas uplift, and the Nemaha anticline (fig. 8). Sediments in the lower three stages are predominantly marine, whereas those in the upper stage are both marine and nonmarine. The maximum thickness of Mississippian rocks is about 300 feet in the eastern part of the State, 300 feet in the central part, and 1,600 feet in the western part. The Kinderhookian, Osagean, and Meramecian rocks are predominantly carbonate rocks. The Chesterian rocks are composed mostly of discontinuous beds of sandstone and shale.

Rocks within the Mississippian commonly are described as locally very porous, weathered, and cherty. Some porosity in the unit probably is related to dolomitization but most is related to the tectonic processes of uplift and fracturing and the hydrologic processes of erosion and solution weathering. Several cycles of locally minor uplift and erosion are evidenced by the unconformities that mark the end of Kinderhookian and Meramecian deposition. A more significant factor in porosity development, however, was the widespread and prolonged period of uplift and erosion that occurred during Late Mississippian and Early Pennsylvanian time. Dissolution of the intensely fractured and deeply weathered carbonates also yielded great quantities of residual material found locally at the basal Pennsylvanian unconformity. It is assumed that the greatest porosity and permeability in the Mississippian rocks are related to the fractured and weathered zones beneath these erosional surfaces. Hydrologic data from numerous drill-stem tests (see table 1), however, indicate permeability values that are relatively small and suggest very limited interconnection of porous zones, except in southeastern Kansas, where locally well yields as large as 1,000 gal/min have been reported.

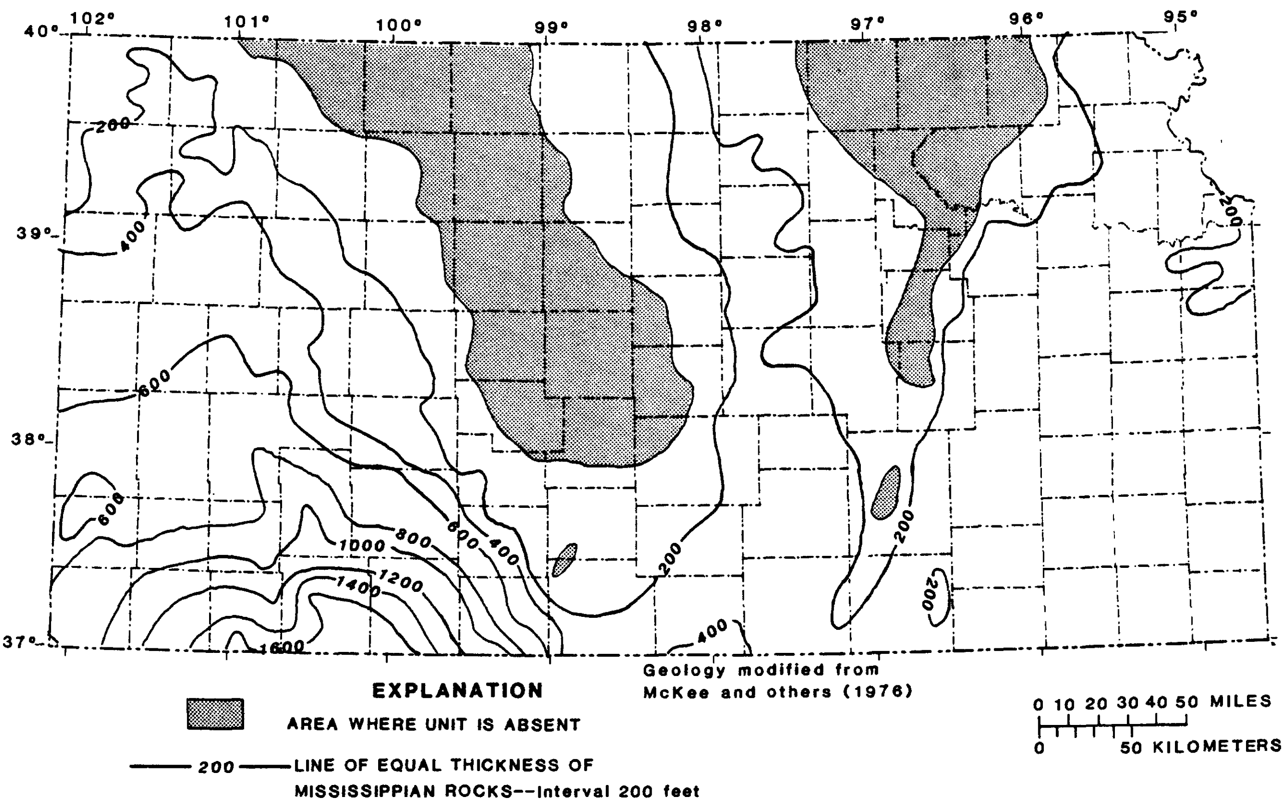


Figure 8.--Extent and thickness of Mississippian rocks.

Lower and Middle Pennsylvanian Rocks

Rocks of Early and Middle Pennsylvanian age, consisting of both marine and nonmarine sediments, comprise the Pennsylvanian confining unit. This interval includes rocks from three stages: (1) the Morrowan, (2) the Atokan, and (3) the Desmoinesian. These rocks continuously cover all of Kansas except for the Central Kansas uplift and the Nemaha anticline. Two other rock units included with this sequence, but not discussed separately, are an unnamed unit of lowermost Pennsylvanian rock and the Pleasanton Group of Early Pennsylvanian age. The unnamed unit of lowermost Pennsylvanian rock occurs throughout Kansas as a veneer of clastic residual material lying on the weathered and eroded surface of older Paleozoic rocks. The residual material is comprised of brecciated limestone, chert, clay, silt or sand reworked from the older rocks. The Pleasanton Group underlies the Kansas City Group and is composed mainly of clastic material, mostly shale. The Pleasanton ranges in thickness from about 70 to 130 feet.

In general, Lower and Middle Pennsylvanian rocks consist of an alternating marine and nonmarine sediments comprised of interbedded clayey mudstone, sandstone, and limestone with some thin layers of coal. Porosity and permeability differ greatly throughout the unit. In general, the greatest porosity occurs in parts of the basal Pennsylvanian rocks (Morrowan

Stage), where only small amounts of clay are included with the detrital deposits of chert and brecciated limestone. Porosity of the sandstone also differs greatly in relation to the degree of cementation and the amount of silt and clay included. Carbonate rocks are reported to be porous in localized areas where folding and faulting have created secondary permeability. Although some of the lenticular sandstone is very porous, most of the thick shale and interbedded dense limestone are relatively impermeable. Therefore, these rocks are considered to be an important confining unit and restrict flow between the overlying Kansas City and Lansing Groups and the underlying aquifers.

Kansas City and Lansing Groups

Kansas City and Lansing Groups of Late Pennsylvanian age crop out in eastern Kansas and occur in the subsurface throughout the area westward, as shown in figure 9. These rocks are composed mostly of limestone interbedded with shale but contain minor amounts of sandstone and a few thin beds of coal. In the southeastern part of the State, the sequence is composed mostly of shale containing thin beds of sandstone and cherty limestone. In the remainder of the State, the limestone beds thicken generally toward the west and south, contain decreasing amounts of clay and sand, and comprise an increasing percentage of the total thickness. The limestone commonly is very fine to fine grained and contains only minor amounts of chert, oolite, or dolomite. In the northern part of the State, the Kansas City and Lansing rocks range in thickness from 200 to 300 feet. In the southern part of Kansas (fig. 9), these rocks are about 700 feet thick in the southwestern and south-central parts and as much as 800 feet in the southeastern part.

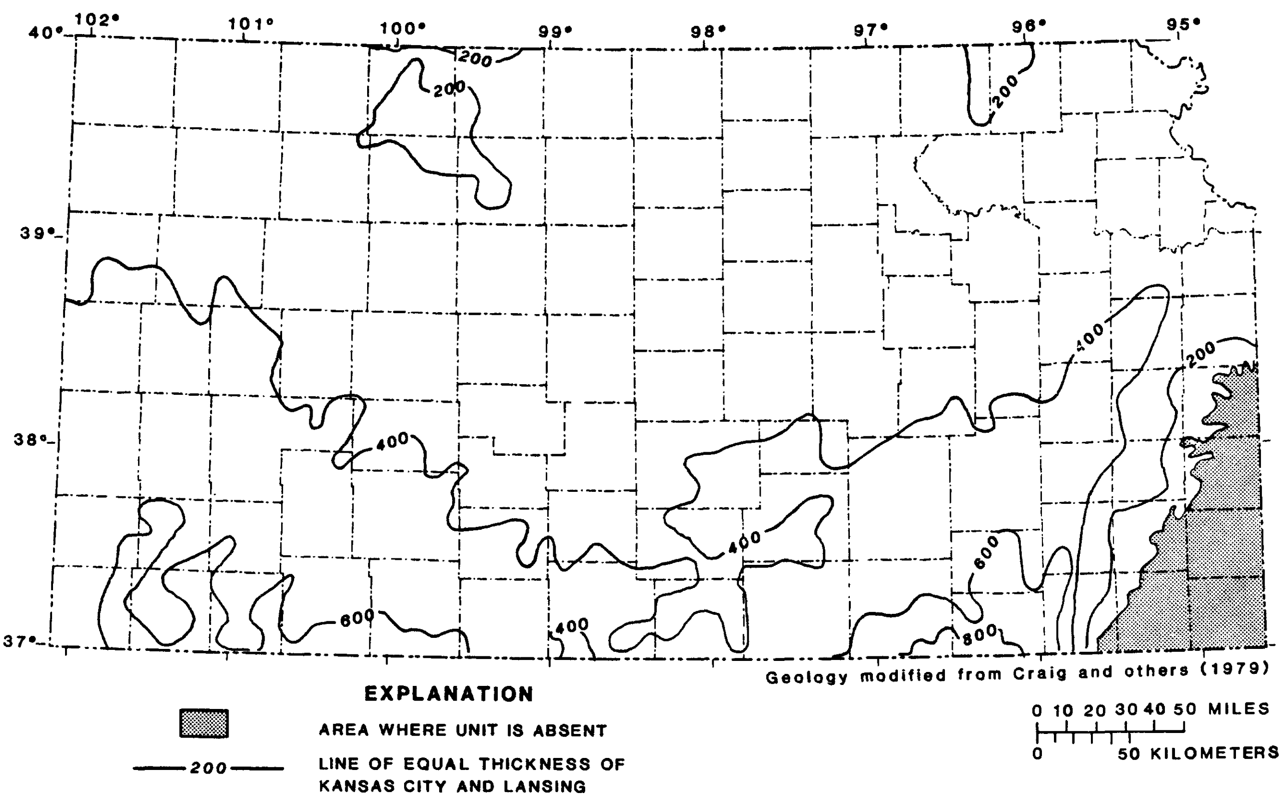


Figure 9.--Extent and thickness of Kansas City and Lansing Groups.

Intergranular porosity of the limestone beds within the Kansas City and Lansing Groups probably is relatively large, but the permeability related to intergranular porosity is relatively small. Most of the oil production from Kansas City and Lansing rocks within the State occurs in areas where some structural deformation has created a secondary permeability by fracturing. Because tectonic deformation was common throughout Kansas during Pennsylvanian time, the areas of increased permeability due to faulting and folding occur in a discontinuous pattern but have widespread distribution. Hydrologic data from numerous drill-stem tests (see table 1) indicate that permeability of the unit is relatively small and suggest limited interconnection of porous zones.

CHEMICAL QUALITY OF AQUIFER BRINES

The chemical quality of brines in the aquifers discussed in this report differ significantly from one aquifer to another, and within each aquifer. Differences in fluid density of the brines are an important factor in the determination of vertical and lateral flow within the aquifers. Also, the differences may be significant in that the changes in chemical composition of the brines may indicate the direction of existing regional flow as well as the geomorphic history of the hydrologic system.

Oil and gas production from Arbuckle rocks has been limited mostly to areas along the Central Kansas uplift and Nemaha anticline, and therefore, very few data on the chemical composition of brines in the Arbuckle are available in other areas of the State. Similarly, the availability of chemical analyses of brines from other deep aquifers are limited to relatively few areas of oil and gas production. Fortunately, chloride concentrations of brines commonly are reported with the results of exploration tests of these aquifers in many areas. Thus, a large amount of data were available from the files of the Kansas Geological Survey and the U.S. Geological Survey (Lawrence, Kansas), as well as from the records of petroleum companies.

Chloride concentrations were plotted and contoured (figs. 10-14) to define the areal differences within each of the selected aquifers, for comparison of differences between aquifers, and for obtaining the density of fluids in the aquifers. Chloride data for the St. Peter Sandstone and the Platteville Formation were not separated and are shown for this study as the Simpson Group. These maps agree closely with previously published maps by Collins (1975, p. 332). Additional discussion of these maps will be given in the section on "Regional-Flow Systems."

Most of the available data related to chemical composition of brines and concentration of chlorides normally are reported in terms of parts per million (ppm). For comparative purposes, parts per million is approximately equivalent to milligrams per liter (mg/L) until the concentration of dissolved solids exceeds about 7,000 mg/L. For greatly mineralized waters, the milligram-per-liter values would be divided by the specific gravity of the water to convert to parts per million.

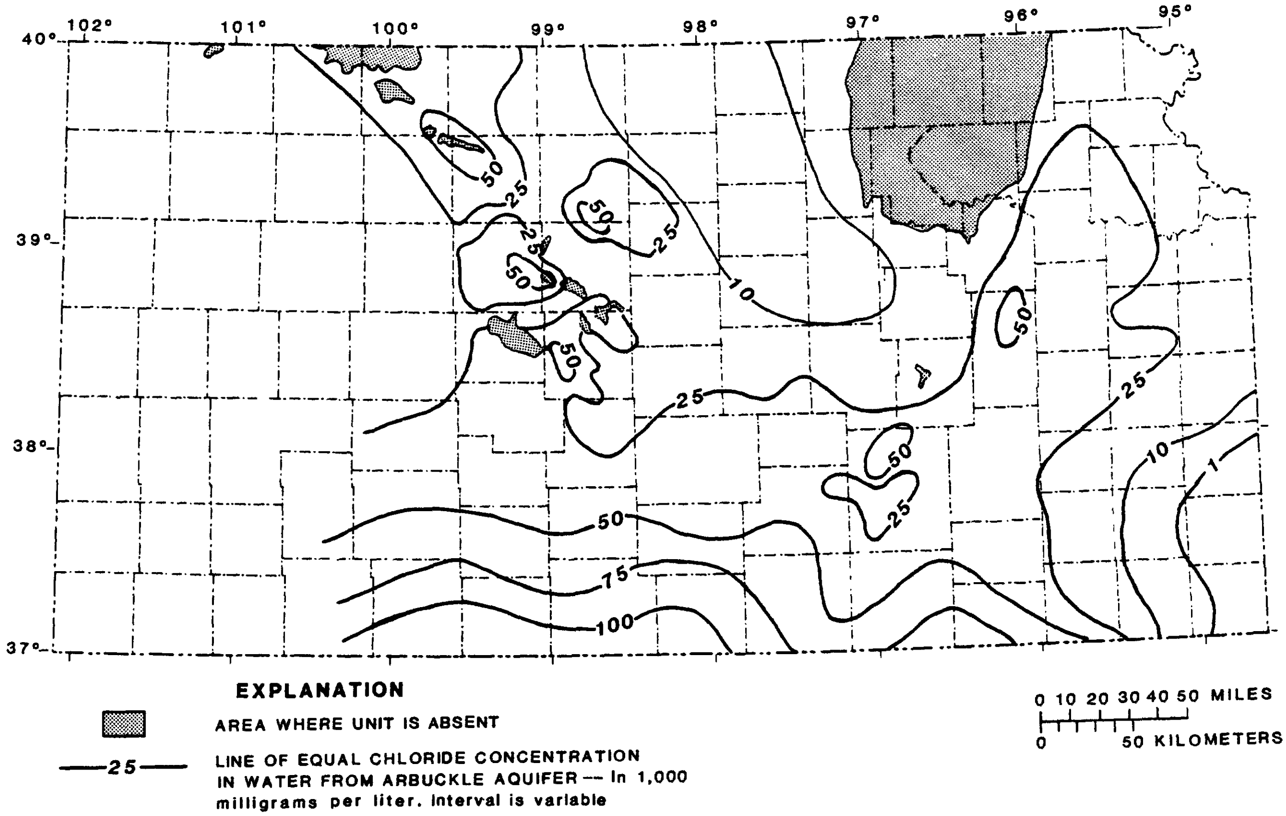


Figure 10.--Distribution of chloride concentrations in water from Arbuckle aquifer.

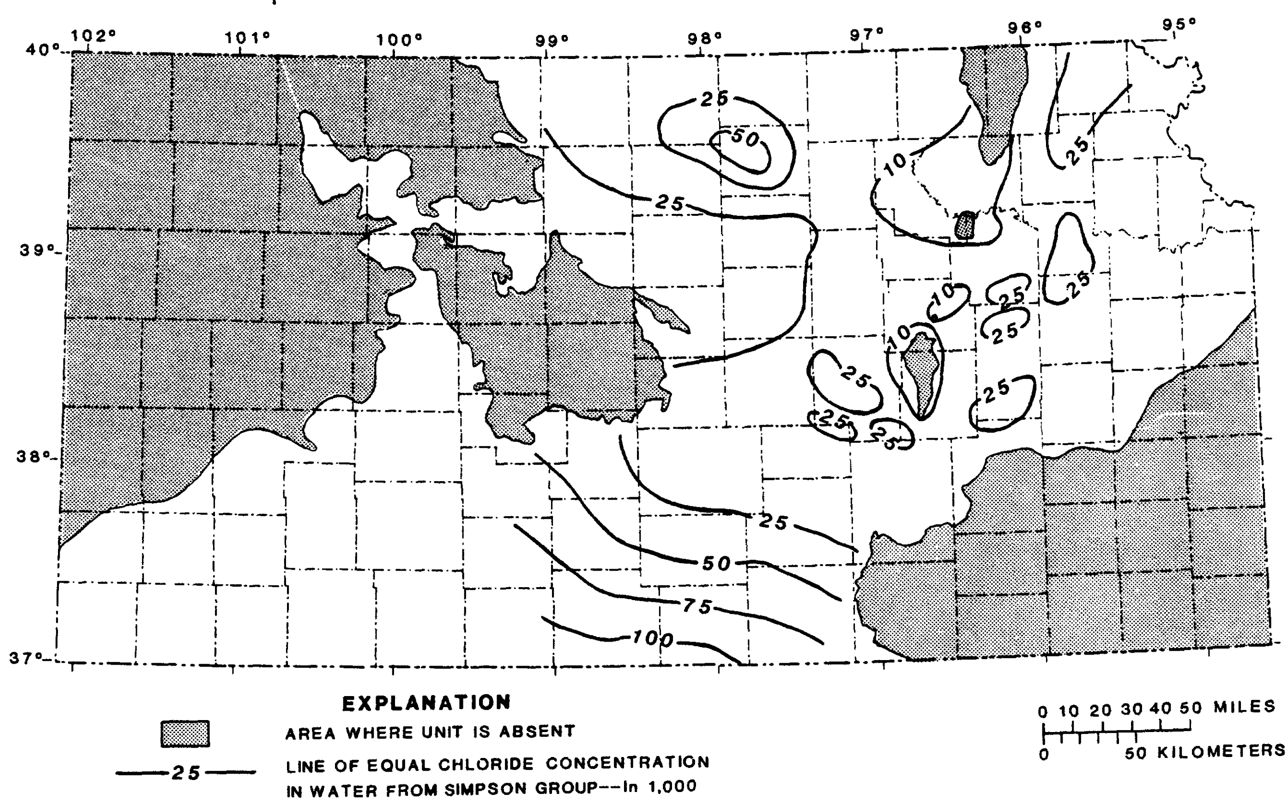


Figure 11.--Distribution of chloride concentrations in water from Simpson Group.

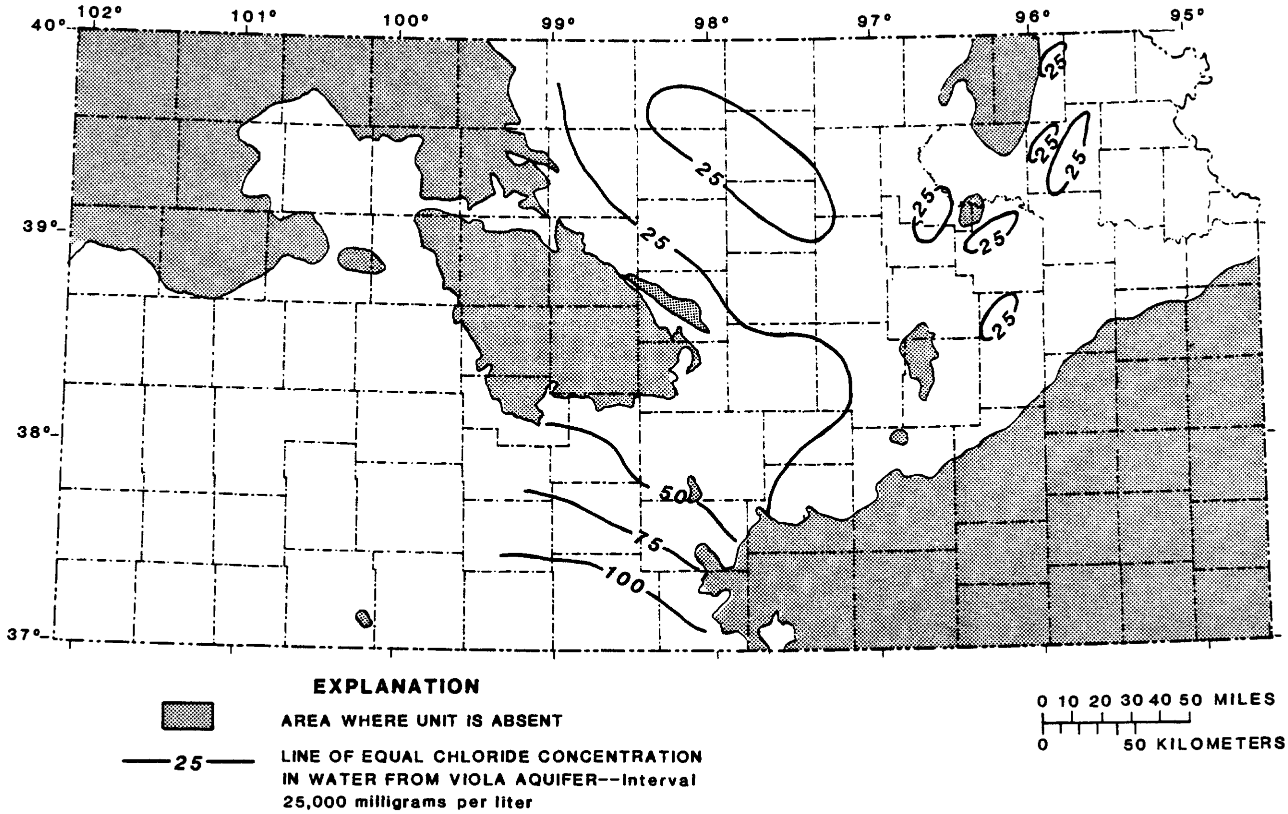


Figure 12.--Distribution of chloride concentrations in water from Viola aquifer.

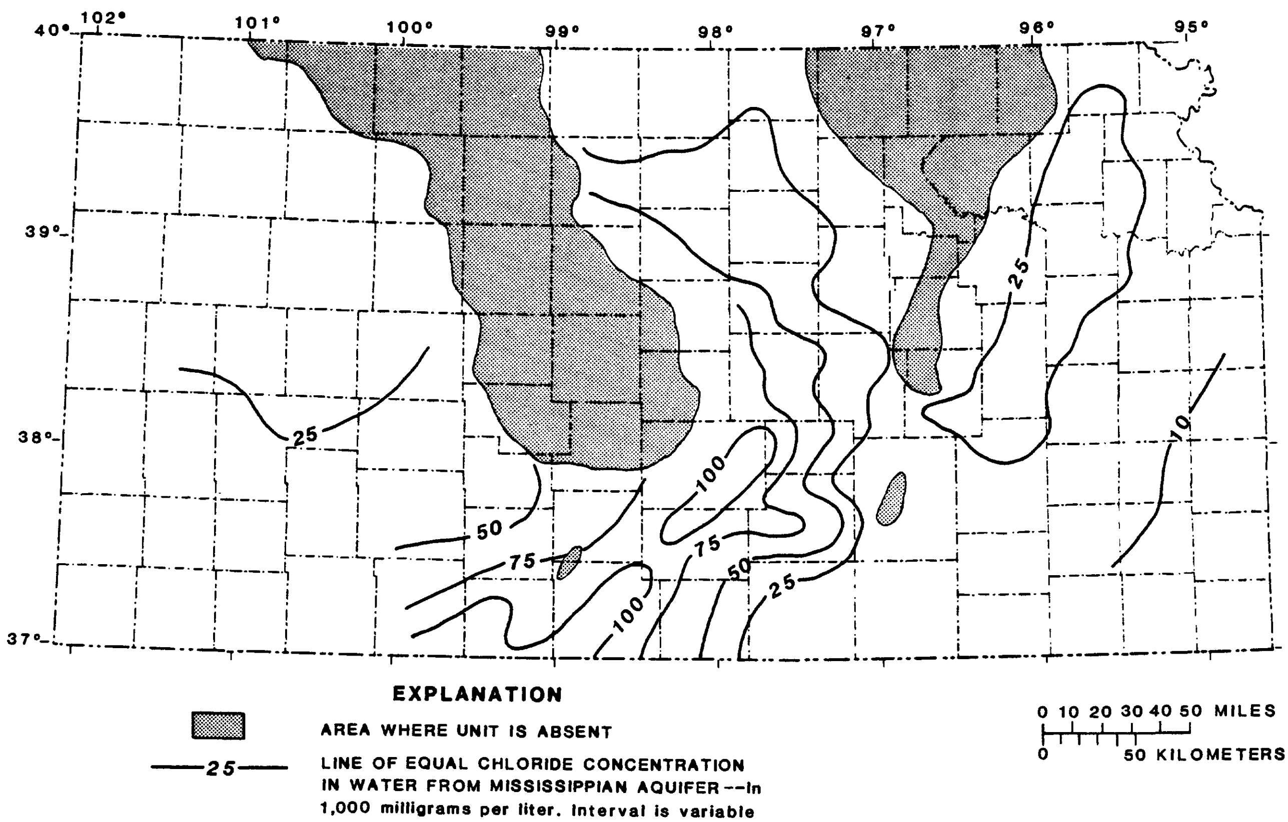


Figure 13.--Distribution of chloride concentrations in water from Mississippian aquifer.

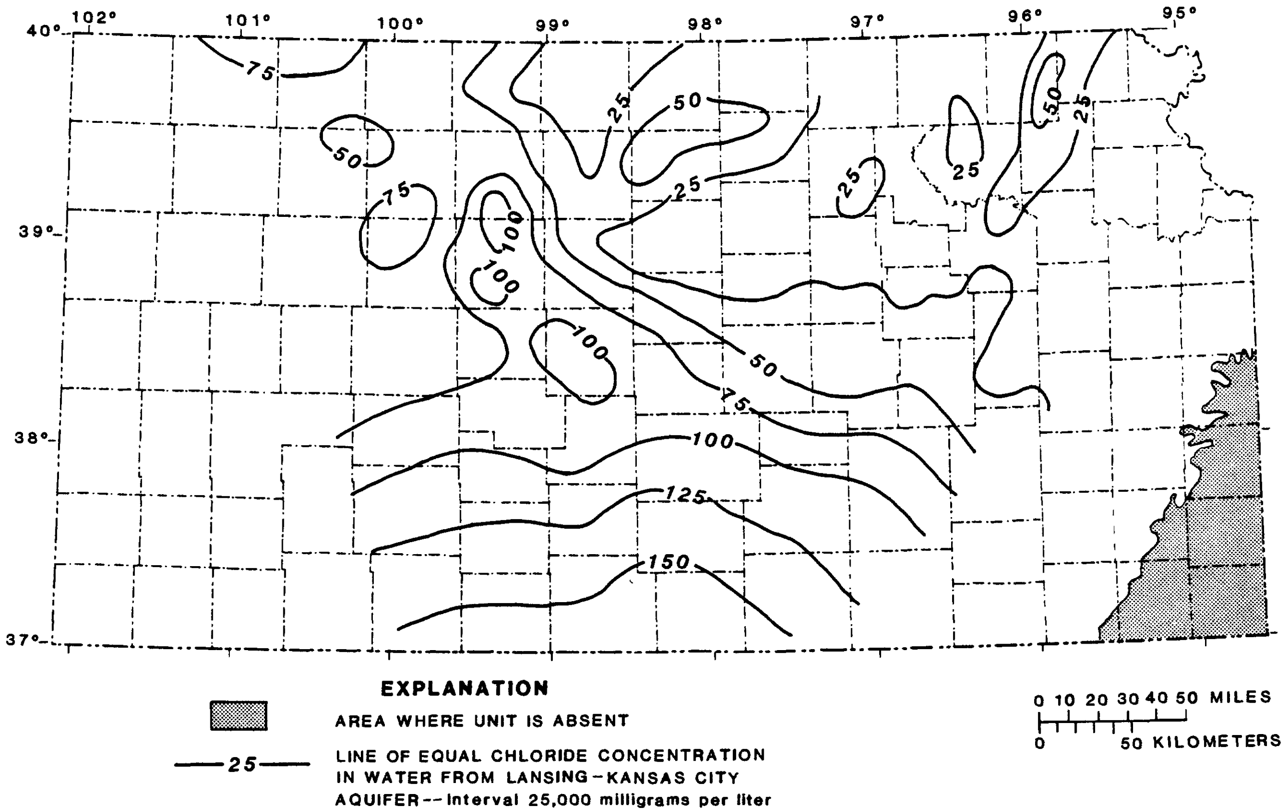


Figure 14.--Distribution of chloride concentrations in water from Lansing-Kansas City aquifer.

HYDRAULIC CHARACTERISTICS OF AQUIFERS

Hydraulic characteristics of the deep-aquifer systems, necessary to infer the rate of fluid movement and pressure responses, were estimated by utilizing oil company drill-stem tests, injection tests conducted for this study, geophysical logs, and a conceptual ground-water flow model. Estimated hydraulic characteristics included hydraulic conductivity, or intrinsic permeability, and storage coefficient.

Hydraulic Conductivity

Fluid movement in the aquifers mainly depends on permeability of the rocks associated with each aquifer, the hydraulic gradient, and the properties of fluid contained in the rocks. Permeability for freshwater aquifers usually is reported in terms of hydraulic conductivity, which incorporates the assumed constant properties of the water into the value. However, for deep-aquifer systems, the density and the viscosity of the water vary to such a degree that analysis is facilitated by using intrinsic permeability of the rocks and the density and viscosity of the fluids instead of hydraulic conductivity. Intrinsic permeability is a property of the media alone, and when determined, can be used to compute hydraulic conductivity for any given fluid condition. Analytical equations for these deep-aquifer systems utilize intrinsic permeability, and oil-company data are reported in compatible units. Therefore, both intrinsic permeability and hydraulic conductivity are given in this report for comparative purposes.

Drill-Stem Tests

Many of the available drill-stem tests were evaluated to obtain hydraulic characteristics for the selected aquifers. Results from numerous tests were rejected because the analysis of pressure buildup indicated that well-bore damage was excessive or that a boundary condition existed due to the effects of production from wells or injection to wells within the radius of influence of the test. The method used to analyze the drill-stem tests is described below, and the results of the analyses are given in table 1, which shows the maximum, minimum, and average values determined for intrinsic permeability and hydraulic conductivity in each of the principal aquifers. Related data from other sources also have been included in this section to provide a general comparison with the calculated results.

The method used in the determination of intrinsic permeability is described only for data from oil tests. Intrinsic permeability is derived by the method commonly used in the petroleum industry, as given in Johnston-Macco-Schlumberger (1976, p. 4) and Matthews and Russell (1967). Initially, bottom-hole pressures from the drill-stem test are plotted against $(T + \Delta t)/\Delta t$, where T is flow time and Δt is shut-in time. A transmissivity factor (To) of the tested interval under reservoir conditions then is calculated, in millidarcy-feet per centipoise (md-ft/cp), by the equation:

$$To = \frac{kh}{uB} = \frac{162.6 \times Q}{M}, \qquad (1)$$

where k = intrinsic permeability, in millidarcies; h = the thickness of the tested interval, in feet; u = the viscosity of the fluid at reservoir temperature and atmospheric pressure, in centipoise; B = the formation volume factor, which is assumed to be 1; Q = the rate of flow of fluid during the test, in barrels per day; and M = the rate of pressure buildup, in pounds per square inch for a log cycle of time during the "shut-in" periods.

The intrinsic permeability (k), in millidarcies, then is calculated by:

$$k = To \times (u / h). \qquad (2)$$

When the test report indicated a heavy oil, the listed American Petroleum Institute gravity and reservoir temperature were used to obtain a value for viscosity from curves published by Earlougher (1977, p. 239). When the report indicated mostly brine, the value for viscosity was obtained from curves published by Matthews and Russell (1967, p. 158) using the listed reservoir temperature.

From values given in the preceding discussion, the hydraulic conductivity (K) of water may be derived in consistent units from the following equation:

$$K = \frac{k \times (1.062 \times 10^{-14}) \times g}{v}, \qquad (3)$$

Table 1.--Summary of aquifer characteristics determined from drill-stem tests

Aquifer unit	Number of values	Intrinsic permeability (k), in millidarcies			Approximate average hydraulic conductivity, in feet per day at 20 °C
		Maximum	Minimum	Average	
Arbuckle	52	755	1	134	0.37
Simpson	39	852	1	164	.45
Viola	12	533	4	112	.31
Mississippian	72	40	1	9	.02
Lansing-Kansas City	91	78	1	12	.03

Note: A relatively small-permeability aquifer composed of unconsolidated deposits of very fine sand and silt would have an intrinsic-permeability value ranging from about 10 to 1,000 millidarcies (1 millidarcy = 2.725 x 10^{-3} feet per day at 20 °C, Freeze and Cherry, 1979, p. 29).

where K = hydraulic conductivity, in feet per second;
k = intrinsic permeability, in millidarcies;
g = acceleration of gravity, in feet per second squared; and
v = kinematic viscosity of water at the specified reservoir temperature, in square feet per second.

Values of kinematic viscosity of water were obtained from a table in "Hydraulic Models" (American Society of Civil Engineers, 1942).

Injection Tests

Injection tests were conducted at the Salina and the Parsons test-hole sites to determine permeability in the Arbuckle. The Salina site is located in northeast Saline County, and the Parsons site is located in north-central Labette County (fig. 2). Additional information about these sites were compiled by Gogel (1981). Injection causes water-level responses in the well similar to but opposite to those caused by pumping. Usually, an analytical equation for "ideal" aquifers can be used to analyze the resulting data, assuming that the aquifer meets the physical assumptions used in development of the equation. However, in the two injection tests conducted for this study, the temperature of the injection water was sufficiently different from the temperature in the aquifer to affect the results. In order to account for the density variation of the injected water with changes in temperature and in injection rates, a numerical model for calculating the effects of liquid disposal in deep saline aquifers (Intercomp, 1976) was used to evaluate the injection tests.

The model uses finite-difference techniques to simultaneously solve the equations of fluid and energy transport. The radial-coordinate version of this model was used for both sites. The model assumes that native and injected fluids are miscible and that the injected fluids are conservative. Model nodes were spaced approximately logarithmically from the well location, with the center of the first node located at a distance of about 2.6 feet. A longitudinal dispersivity of 30 feet and a transverse dispersivity of 10 feet were used in the model (Merritt, 1983; Mercer and others, 1982). These values were selected from the literature as being potentially representative of dolomite and limestone systems. No onsite values were available in the test area. Other properties required for model input, such as rock compressibility, rock-heat conductivity, fluid thermal expansion, fluid heat capacity, coefficient of thermal expansion, and fluid compressibility were selected from the literature for comparative geologic systems. Boundary conditions were simulated for each model layer as a continuous aquifer by the use of the Carter-Tracy option in the model (Intercomp, 1976).

Salina Site

A conceptual model of the aquifer system at the Salina test site is shown in figure 15. The injection well is 3,655 feet deep and is open to the borehole from 3,355 to 3,655 feet. Casing (7 5/8 inch) is set to the top of the Arbuckle. The well was developed by airlift pumping after completion. A water sample from the Arbuckle showed a chloride concentration of 3,500 mg/L. The Intercomp model was used with six layers representing the aquifers at the site. Hydraulic-conductivity values were selected either from drill-stem tests or from literature values considered to be representative of the system. Although shown as part of the model, layers one and two had little if any effect on the results of the model.

In the Salina test, two injection periods were considered. The first period was for 32 minutes at injection rates from 142 to 233 gal/min. The first period was used to determine the injection rate for the second period. The second period was conducted for 5 hours with rates varying from 142 to 156 gal/min. The injection test was ended when the water level rose to the top of the casing. A recovery period of about 2 hours occurred between the two injection periods. Water produced from the Arbuckle Group prior to the test was injected at a temperature of 17.8 °C. A transducer, set at 200 feet below land surface in the injection well, was used to record rises in water levels. Bottom-hole pressures were calculated from this water-level data by using estimated transit times of the injection fluid through the casing and an estimated average column density before the test began. Casing-friction losses were calculated with the Darcy-Weisback equation for pipe flow, using the various injection rates. These then were subtracted from the bottom-hole pressures.

Depth below land surface, in feet	System	Geologic unit	Model layer	Hydraulic conductivity, horizontal (feet per day)	Hydraulic conductivity, vertical (feet per day)	Porisity (fraction)	Chloride concentration (milligrams per liter)	Temperature (° C)
	Pennsylvanian	Cherokee Group						
2590	Mississippian	Warsaw Limestone Burlington Limestone Fern Glen Limestone	1	0.86	0.029	0.1	25,000	30.9
2820	Mississippian Silurian and Devonian Cambrian and Ordovician	Kinderhookian rocks Chattanooga Shale Hunton Group Maquoketa Shale	2	8.64×10^{-5}	4.32×10^{-5}	0.2	25,000	32.5
3170	Cambrian and Ordovician	Viola Limestone	3	0.086	0.029	0.1	25,000	34.9
	Cambrian and Ordovician	Simpson Group	4	8.64×10^{-5}	4.32×10^{-5}	0.2	25,000	35.8
3355	Cambrian and Ordovician	Arbuckle Group, Bonneterre Dolomite, and Lamotte Sandstone, undivided (open hole of injection well)	5	0.825	0.41	0.08	3,500	36.2
3655	Cambrian and Ordovician	Arbuckle Group, Bonneterre Dolomite, and Lamotte Sandstone, undivided	6	0.825	0.41	0.08	3,500	38.3
3792	Precambrian							

INJECTION WELL

Figure 15.--Conceptual aquifer system used for model analysis of Salina injection test.

The two injection periods were simulated in order to insure that the model representation of the system was as close to the actual system as possible. Matching of the observed data with the model-calculated values primarily involved adjustment of the horizontal hydraulic conductivity until a reasonable fit was found. The range of horizontal-conductivity values considered to be a possible solution was controlled partly by the fact that the water levels should rise almost to the top of the casing but not above the top of the casing during the first injection period, and the need to match the very flat curve of water-level rise during the second injection period. Because of available geophysical-log data and literature values, the model used a porosity value of 8 percent.

The result of the model analysis is shown in figure 16. A final horizontal hydraulic conductivity of 0.825 ft/d was obtained for the Arbuckle aquifer, which corresponds to about 300 millidarcies for comparison to the compilation of regional drill-stem tests (table 1). Initially, vertical hydraulic conductivity in the model was set equal to one-half of the horizontal conductivity. A comparison simulation also was made to see if the results would be about the same under these conditions if the ratio of horizontal to vertical conductivity was equal to one. The response of the system was about the same under these conditions. Boundary conditions had little or no affect on the response of the aquifer system during the relatively short time of model simulation. Although the match of model simulation and calculated water-level data is not in total agreement, additional effort was not made because of the degree of known precision of the calculated water-level data.

<u>Parsons Site</u>

The conceptual model of the aquifer system at the Parsons test site is shown in figure 17. The injection well is 1,815 feet deep and is open hole from 875 to 1,815 feet. Casing (7 5/8 inches) is set to the top of the Arbuckle at 875 feet. The chloride concentration in the Arbuckle at this site was 11,000 mg/L, as indicated by a water sample. The model was configured as four layers with the lower two representing the Arbuckle aquifer. Vertical hydraulic conductivity was set equal to one-half of the horizontal conductivity. Horizontal conductivity was established either from drill-stem tests or literature values assumed to be representative of the aquifer system.

In the Parsons test, one injection period was conducted for 147 minutes. Injection rates ranged from 210 to 292 gal/min over the test period. The model simulated these rates by using three average pumping rates. The injection-fluid temperature was 15.6 °C. A transducer was set at 261.5 feet to record water-level rises. Bottom-hole pressures were calculated as at the Salina site with pipe-friction losses subtracted. The result of the model analysis is shown in figure 18. A final hydraulic conductivity of 0.275 ft/d (about 100 millidarcies) for the Arbuckle was obtained. A porosity value of 8 percent is believed to be representative of the actual system. The model used a vertical hydraulic conductivity equal to the horizontal conductivity with little change in pressure response. Boundary conditions had little or no affect on the response of the aquifer system during the relatively short time of model simulation.

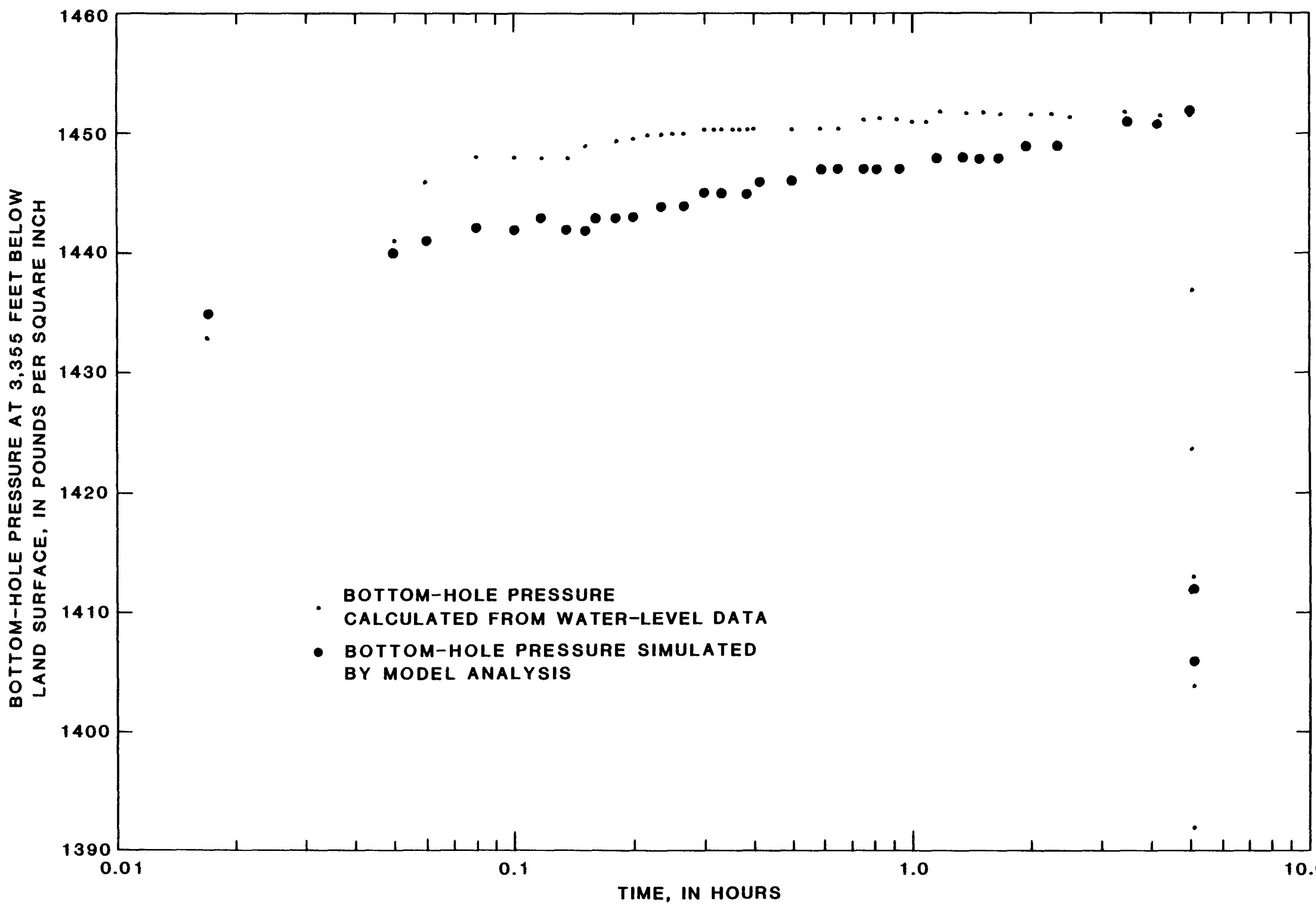


Figure 16.--Calculated and simulated injection-well pressures at Salina injection site.

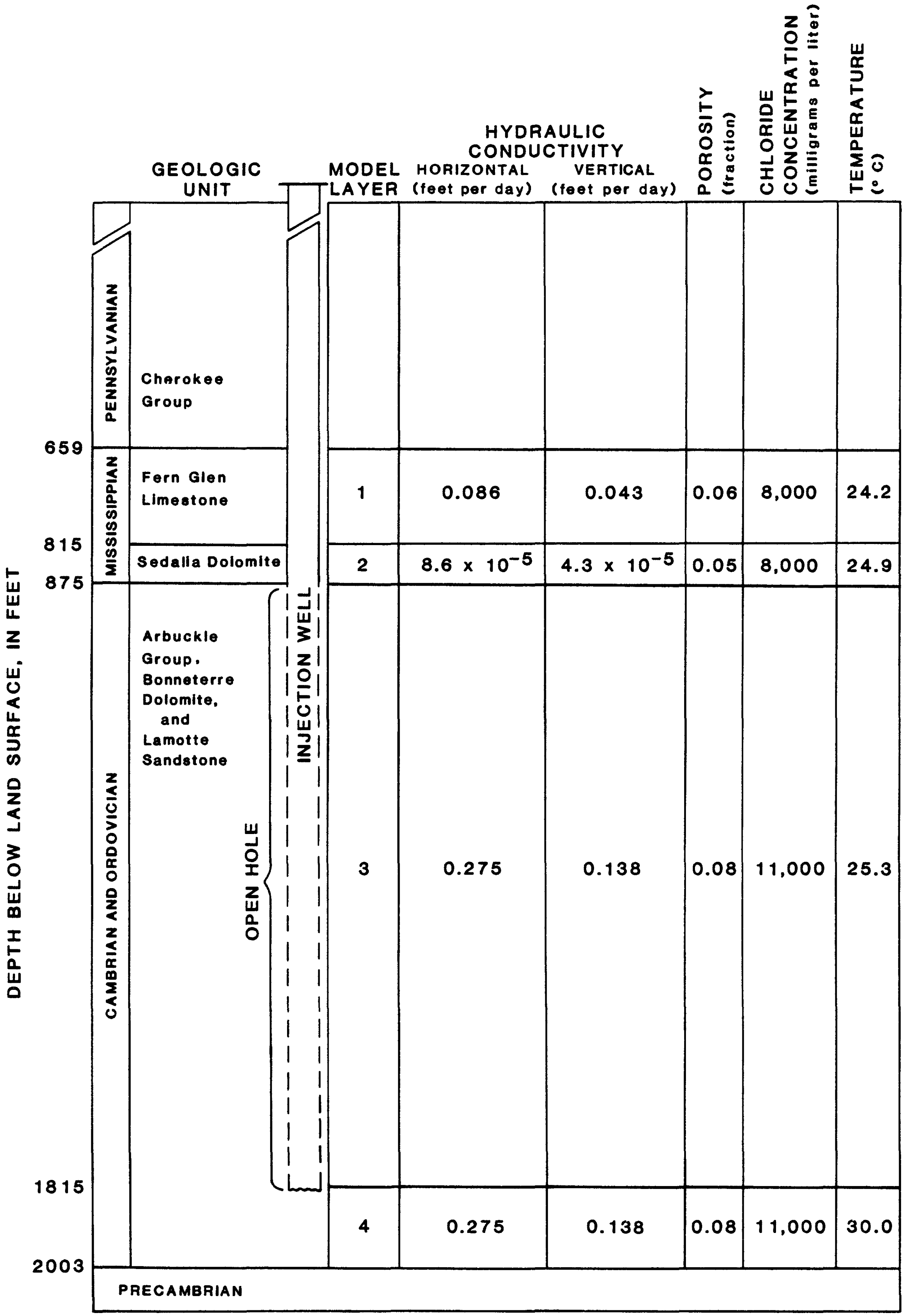


Figure 17.--Conceptual aquifer system used for model analysis of Parsons injection test.

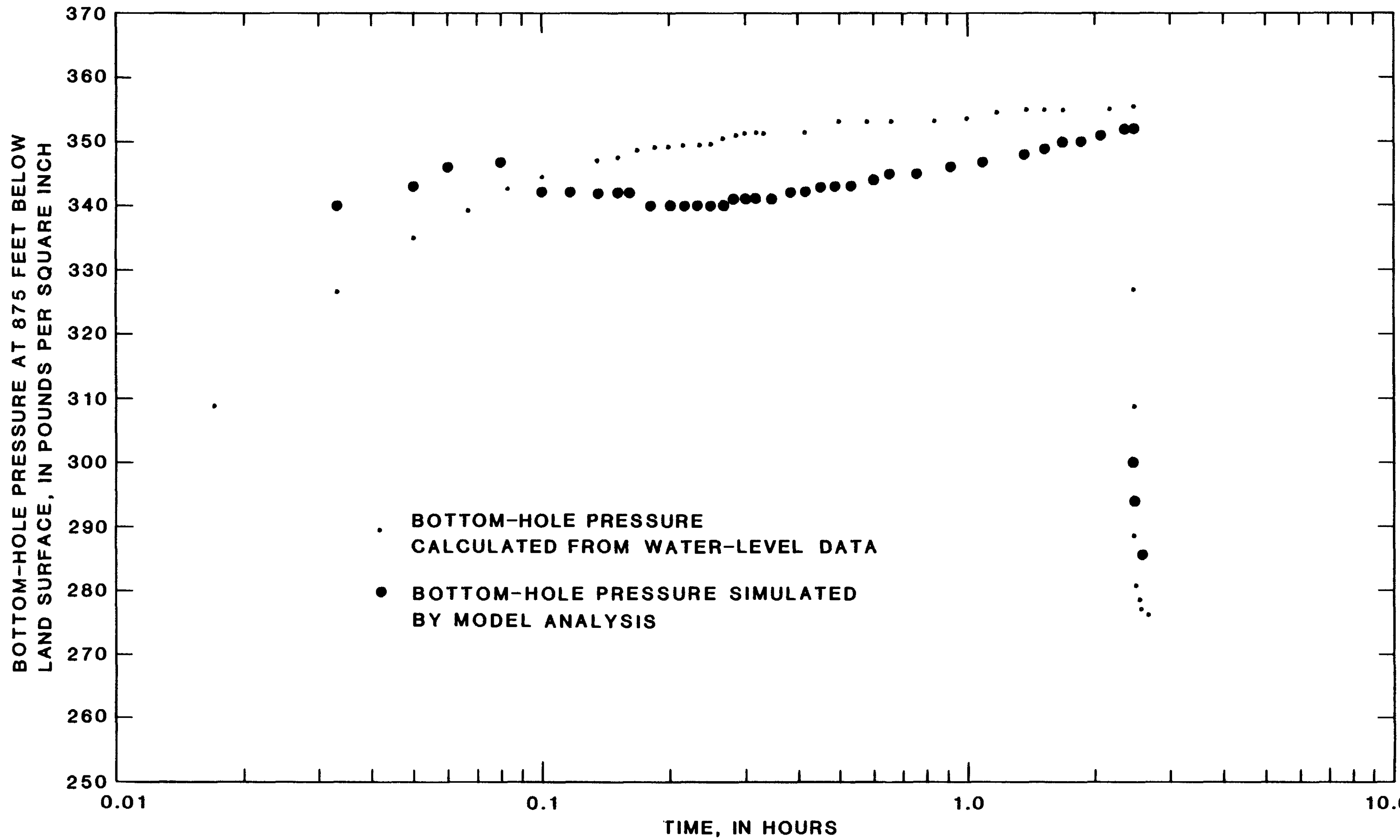


Figure 18.--Calculated and simulated injection-well pressures at Parsons injection site.

Geophysical-Log and Whole-Core Analyses

Geophysical logs of two test holes (sites 2 and 3, fig. 2) were analyzed in order to determine variations in hydraulic conductivity and to compare values obtained from this method to the values obtained from the injection tests. Geophysical logs of the two test holes consisted of gamma-ray, spontaneous-potential, caliper, neutron, density, sonic, and dual-induction laterolog resistivity logs. In addition to the geophysical logs, the test holes were cored at selected depths. Whole-core analyses for permeability at 1-foot intervals were conducted by Core Laboratories, Inc. The whole-core samples were analyzed for permeability in the maximum-permeability direction and at right angles to this orientation. In some intervals, the core was too broken to conduct whole-core analysis, and a plug of the core then was taken for analysis. Analysis of these data to estimate permeability and porosity from the geophysical logs was conducted by John Doveton of the Kansas Geological Survey (Lawrence, Kansas). The methods used are discussed by Doveton in the section on "Log analysis of the Arbuckle aquifer" at the end of this report.

According to Garb (1982), investigations of permeability distribution show that an important characteristic of permeability distribution is its skewness. Generally, it is accepted that a representative single value for permeability is usually much closer to the geometric mean of the distribution than to the arithmetic mean permeability. Therefore, the geometric mean of the permeability distribution more nearly will match a single permeability value derived from well performance, and correspondingly, the theoretical calculated performance will more nearly match actual performance of a well if the geometric mean is used in the calculations.

In comparing the log, core, and injection-test data, there is a large difference in the geometric mean permeability from the geophysical-log analysis, the whole-core data, and the permeability from the Salina injection test (site 3, fig. 2). The geometric mean permeability from the geophysical-log data for site 3 is about 0.4 millidarcy; for site 2, it is about 0.6 millidarcy; and from the whole-core data, the geometric mean permeability is about 15.5 millidarcies. In contrast, the Salina injection test indicated an average permeability of about 300 millidarcies. The differences between the geometric means resulting from the geophysical-log and whole-core analyses are explained partly because the log analysis was based on the core-plug permeability and the whole-core analysis on the maximum direction core permeability. However, the geometric mean permeability of the core data still does not compare to the value obtained from the injection test even when the maximum-direction core-permeability data are used. It is concluded, therefore, that the core samples and associated permeability values obtained from these test holes are not representative of the actual aquifer system. The problems of such representative sampling have been recognized by many investigators (such as Bennion and Griffiths, 1966), and several statistical methods of representation of results from the whole-core analysis have been developed.

Porosity, in contrast to the geometric distribution of permeability, is represented best by the arithmetic mean, which is calculated from geophysical-log data and the core data available from the test holes. The average porosity at test-hole sites 2 and 3 from geophysical-log analyses is 9 percent. The average porosity obtained from the whole-core analyses is about 8 percent. Plots of porosity data from the geophysical-log interpretations at sites 2 and 3 show a normal distribution. In comparison, other investigators have indicated an average porosity of 12 percent for the Arbuckle in Kansas (Walters, 1958, p. 2152) and 10 percent in northeastern Oklahoma (Reeder, 1971, p. 20).

Model of Central Kansas Uplift Area

As previously discussed, various investigators have described the Arbuckle aquifer in the Central Kansas uplift area as being characteristic of a karst region; for example, Ver Wiebe (1941). Erosional features may be present to a greater extent than the regional descriptions indicated by Walters (1958). In an attempt to compare values of hydraulic conductivity obtained from the "basin areas," as represented by the test-hole sites, to those in an uplift area, a very generalized numerical model of the Central Kansas uplift area was constructed for the area shown in figure 19. The model is only intended to aid in the conceptualization of the ground-water flow system and is not expected to accurately represent all of the system complexities. The area was chosen because large amounts of fluid are injected in the area, and bedrock gradients are small.

The flow system of the area was simulated using the Intercomp model with a grid representing 2,304 mi^2 (64 townships) and encompassing parts of Ellis, Graham, Osborne, Rooks, Russell, and Trego Counties. This area is one of the greatest oil-producing areas in Kansas. In the model, each township was represented by approximately one node. Four layers were included, as shown in figure 19--an upper layer representing the Lansing-Kansas City aquifer overlying the Arbuckle, a confining layer, and two lower layers representing the Arbuckle aquifer. The hydraulic conductivity of layer 1 (upper layer) was simulated at 0.1 ft/d, and the hydraulic conductivity of the confining layer (layer 2) was set at 1.0×10^{-6} ft/d. Boundary conditions were simulated for each layer as a continuous, infinite aquifer by the use of the Carter-Tracy option in the model (Intercomp, 1976). The initial fluid hydraulic head was set at sea level, which is about 2,000 feet below land surface. The density of the fluids in each aquifer was simulated at the value corresponding with the chloride value shown on the chloride maps for that unit (figs. 10-14). The injected brine was assumed to be at a density of 66.1 lb/ft^3.

Oil-production maps (figs. 27-28 of this report) were used in conjunction with the ratio of 20 barrels of brine to 1 barrel of oil to estimate the rate of fluids injected into the Arbuckle from other units (see page 48 for estimation method). The rate of oil and brine produced from the Arbuckle was subtracted from this rate to give a net injection rate for use in the model. The net injection rate for the entire model area was 782,295 barrels per day. Of the 64 nodes (townships), 46 had simulated injection, 8 nodes had simulated production, and 10 had no injection or withdrawal. The median injection rate per township was 4,200 barrels per day, or about 122 gal/min, and the maximum rate was 150,500 barrels per day, or about 4,390 gal/min.

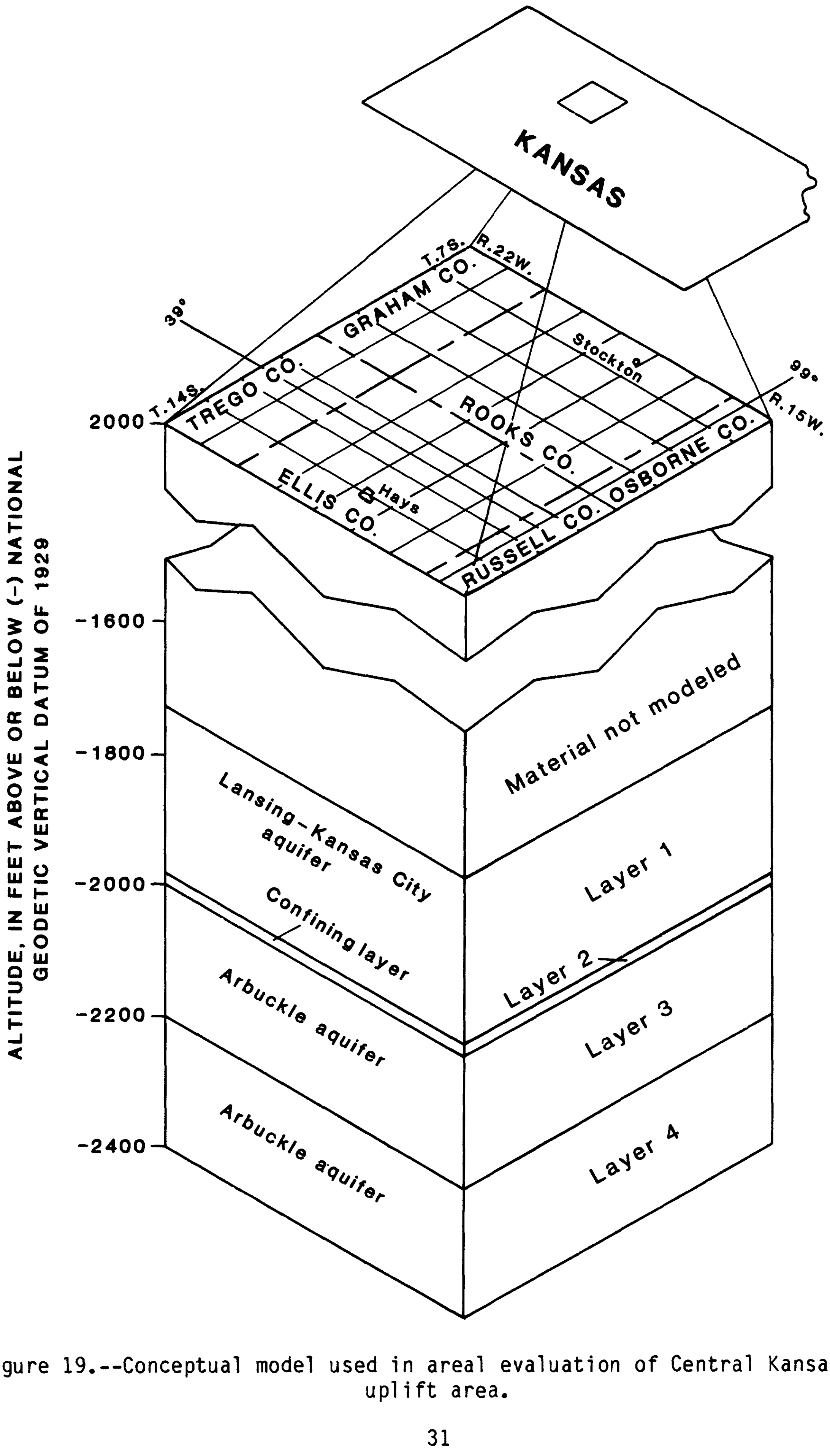


Figure 19.--Conceptual model used in areal evaluation of Central Kansas uplift area.

Few data were available to document the actual response of the aquifer system. Analysis of pressure data for determining fluid-head information has indicated a system response of 100 to 300 feet of hydraulic-head increase from about 1950 to the present. With the assumption that this is the probable range of hydraulic conditions and with the estimated injection rates, the model was used to bracket the response of the aquifer system, as described, in relation to the hydraulic conductivity needed to transmit the fluids injected into the Arbuckle mainly through the lateral boundaries of the model with little hydraulic gradient. It is recognized that some of the fluids will be transmitted upward through the confining layer, and as configured, the model took this into account. Initially, a fluid level was assigned to the upper model layer that is representative of the fluid levels in the Lansing-Kansas City aquifer. This level remained fairly constant during the simulation of the Central Kansas uplift area. However, in reality, there probably is a fluid-level decline in the Lansing-Kansas City aquifer because of the amount of fluid withdrawal from this unit. However, this discrepancy is not considered to be a major factor in the results of the Central Kansas uplift model.

The results of this model simulation must be recognized as being a first-approximation effort, and that more definitive information for the area would have to be available to bracket the hydraulic values more closely. However, the range of the fluid-level simulated responses was of such an extent that the results should be informative as to the possible hydraulic conditions present in this area. Simulated fluid-level responses from the Central Kansas uplift area for an east-west cross section are shown in figure 20.

Initially, the hydraulic conductivity was tested at the value determined at the Salina test site (0.825 ft/d). However, with the injection rate applied, the fluid levels rose locally more than 1,600 feet above land surface. Therefore, to comply with the assumption made that fluid levels had risen only by 100-300 feet, the model was used to simulate the system with several increments of greater hydraulic conductivity (fig. 20). In order to meet the stated assumptions, the hydraulic conductivity would have to be in the range of 10-30 ft/d at 20 °C (about 2,500-7,600 millidarcies). These results indicate that hydraulic conductivity in the Central Kansas uplift area is much greater than that in the basin areas.

Storage Coefficient

Storage coefficient is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head. In a confined aquifer, such as the aquifer system discussed in this report, the water added to storage by injection is accommodated by compression of the water and expansion of the aquifer skeleton. The storage coefficient (S) is a function of the elasticity of the aquifer and water and can be computed from the following

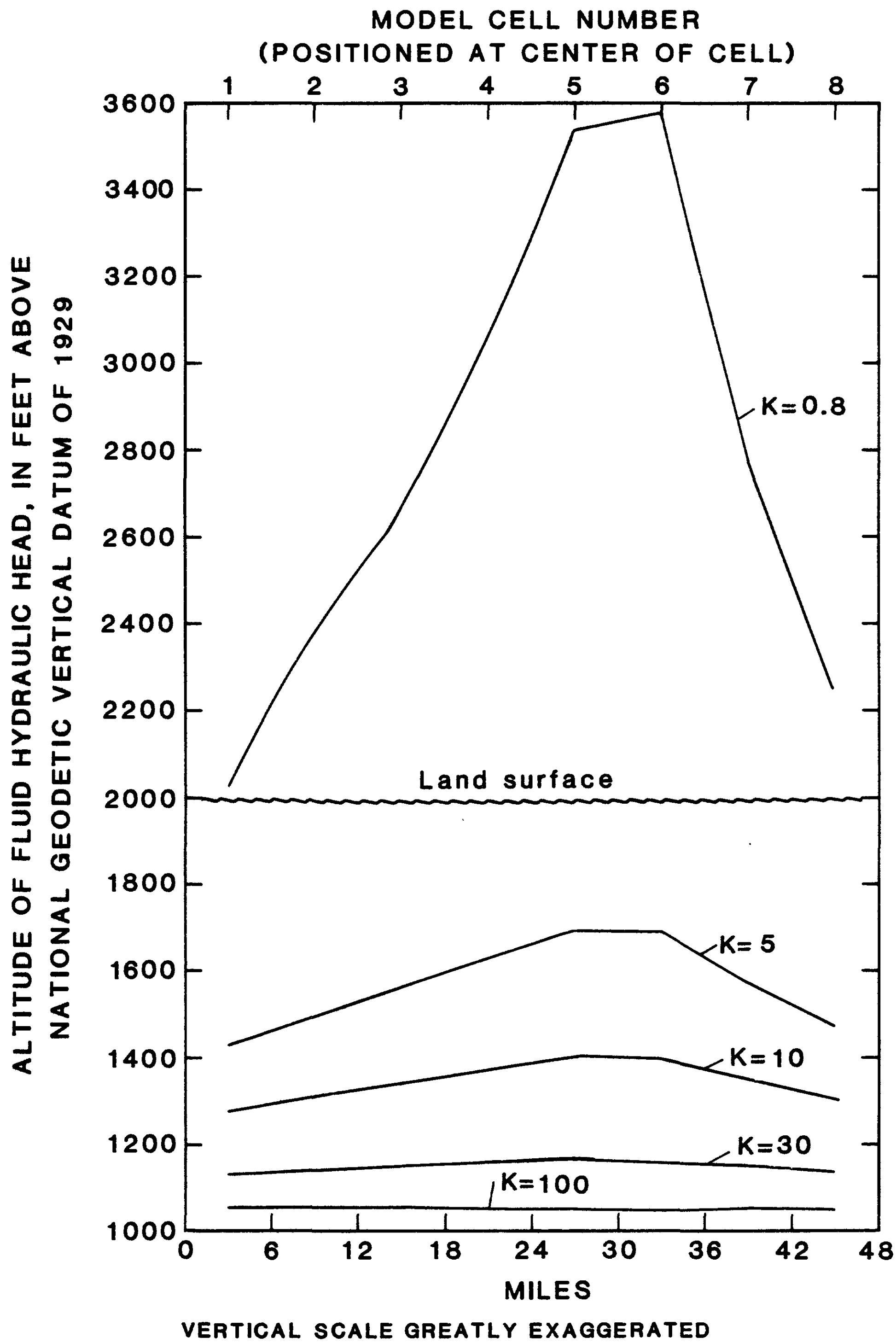


Figure 20.--Simulated fluid hydraulic-head response for selected values of hydraulic conductivity (K), in feet per day, in Central Kansas uplift area.

formula (Lohman, 1972, p. 9):

$$S = \theta\gamma b\,[(1 / E_w) + (C / \theta E_s)], \text{ dimensionless,} \qquad (4)$$

where

θ = porosity, as a decimal fraction;

γ = specific weight per unit area;

b = thickness, in feet;

E_w = bulk modulus of elasticity of water, 3×10^5 lb in^{-2};

C = a dimensionless ratio, which may be considered unity in an uncemented granular material. In a solid aquifer, as a limestone having tubular solution channels, C is apparently equal to the porosity; and

E_s = bulk modulus of elasticity of the solid skeleton of the aquifer, as confined in situ, in pounds per square inch.

An evaluation of storage coefficient, specific storage, and porosity of the Arbuckle was made using geophysical logs and equation 4. Specific storage is equal to the storage coefficient of the aquifer divided by the thickness of the aquifer. The porosity values used in equation 4 were obtained from neutron and sonic logs. Readings from the neutron logs were used with Chart Por 9a to Por 12b, (Schlumberger Limited, 1972, p. 20-25) to compute equivalent limestone porosity. Equivalent dolomite porosity then was determined using Chart Por-3 (Schlumberger Limited, 1972, p. 16). The average value of specific storage for the Arbuckle, obtained from 76 geophysical logs of wells located throughout Kansas that penetrate the entire thickness of the Arbuckle, was 3.25×10^{-6} ft^{-1}. The storage coefficient ranged from 6.8×10^{-5} to 3.2×10^{-3}.

REGIONAL-FLOW SYSTEMS

Ground-water flow in the Arbuckle aquifer is controlled by the areal extent, thickness, and hydraulic properties of the various layers within the Arbuckle and by the influence of external sources and sinks to fluids, such as injection wells or other aquifers. Because of the scale of this study, the individual layers in the Arbuckle with their associated properties are treated as one aquifer, and the assumption is made that hydraulic communication exists throughout the unit. In addition, this assumption is applied to all of the aquifers under discussion.

Additional complexities exist in the interpretation of saline-water flow systems. In aquifers that contain only freshwater, or water of constant density, the direction of water movement can be determined readily from measurements of hydraulic head. However, in ground-water systems where the density of the water varies vertically or horizontally, hydraulic-head distributions do not necessarily indicate the directions of ground-water movement. Density variations have to be taken into account in these systems to determine flow direction. In this study, maps depicting the altitude of fluid levels were constructed from drill-stem-test pressure measurements. However, as discussed later, there are restrictive qualifications to be considered in the use of the fluid-level maps.

Determination of Fluid Levels in Selected Aquifers and Qualifications for Inference of Ground-Water Flow Patterns

A large amount of data were available from exploration tests by petroleum companies for analyzing the aquifer system associated with the Arbuckle aquifer. About 3,000 drill-stem-test charts were obtained from numerous petroleum companies. However, on screening these, many tests were not used. Also, much of the data are from tests conducted in the Sedgwick basin and on the flanks of the Central Kansas uplift and Nemaha anticline. Depths and pressure data from these tests were used to determine the hydraulic head in the selected aquifers at each test site. Because the salinity of fluids differs greatly within the system, a freshwater equivalent head was computed as an indicator of horizontal-flow direction, and "point-water" heads were computed as an indicator of the potential for vertical flow. Freshwater density was used for freshwater-head calculations, and the in-situ density of the water in the aquifer was used for "point heads." "Point heads" indicate the altitude to which formation water would actually rise in a tightly cased well. The following equation was used to compute the hydraulic heads:

$$h = z + P / \rho g , \qquad (5)$$

where

h is the altitude of the water surface, in feet above sea level;

z is the altitude at the point of the drill-stem-test pressure measurement, in feet above sea level;

P is the reservoir-pressure value, in pounds per square foot;

ρ is the density of freshwater for equivalent freshwater heads or of the water in the aquifer for point heads, in pounds per cubic foot; and

g is the acceleration of gravity, in feet per second squared.

To use equation 5 for "point heads," the density of water was derived through a correlation of density and chloride concentrations in oilfield brines in Kansas by Jeffords (1948). Jeffords determined that the concentration of dissolved solids and those of the major constituents varied directly in relation to the density of the fluids. He also concluded that brines having the same densities are similar in general composition regardless of the depth or character of the producing zone. Thus, it was assumed that the relationship established by Jeffords, as shown in figure 21, could be utilized to obtain values of density of the aquifer brines through the use of the abundant data available for chloride concentrations.

Pressure data from drill-stem tests were obtained by extrapolating plotted pressure data to infinite shut-in pressures at time log $(T + \Delta t/\Delta t) = 1$. In aquifer systems that have had a history of fluid withdrawals, however, this pressure may be less than the original pressure. For point-head calculations, chloride values then were determined from the chloride-concentration maps, or from an analysis at the site, and the graph of density versus chloride concentration (fig. 21) was used to obtain a density value to compute a fluid-column height with a fluid of that density.

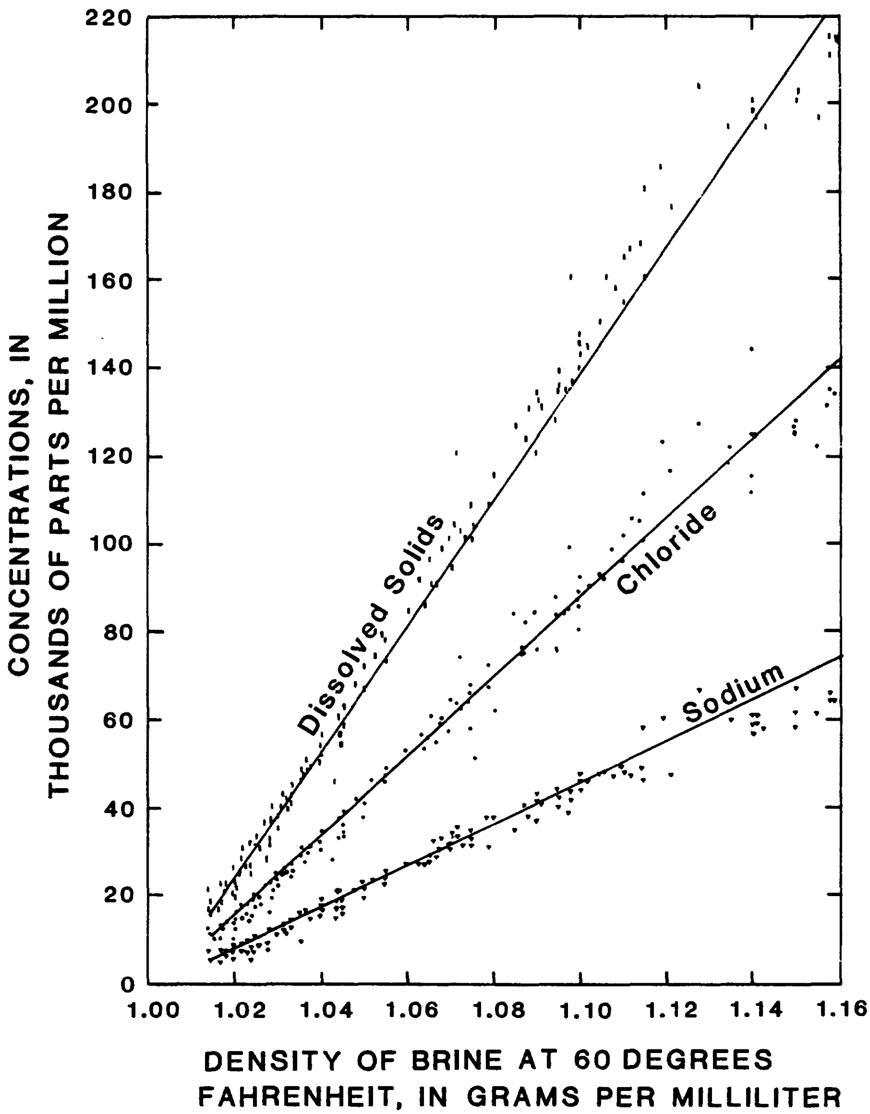


Figure 21.--Relation of concentrations of selected chemical constituents to density of brines in Kansas (from Jeffords, 1948).

In interpreting the values derived from these tests, some consideration should be given to the accuracy of the pressure values obtained from drill-stem tests. Accuracy of the recording devices used in drill-stem tests is reported to be from 0.20 to 0.25 percent of the full scale (Earlougher, 1977). Dahlberg (1982) also indicated that differences of less than 50 feet in potentiometric surfaces calculated from drill-stem tests are rarely significant for a variety of reasons.

The method applied to compute fluid levels involved a form of Hubbert's equation for potential, Φ (Hubbert, 1953, p. 1959):

$$\Phi = gz + P/\rho , \tag{6}$$

where the units are as described for equation 5. Expressing this equation in terms of hydraulic head by dividing by gravity gives equation 5 (Hubbert, 1953, p. 1973).

However, Hubbert's potential represents a combination of a pressure potential and a gravity potential, and the hydraulic-head values calculated from the hydraulic-head equation (5) still have these two potentials implied. A strict application of this equation requires that density, viscosity, and permeability remain constant, as Hubbert (1940, p. 909) states that "a velocity potential exists only for fields of flow involving a fluid of constant density and viscosity and a medium which is homogeneous and isotropic throughout." With this in mind, only generalized inferences should be made as to direction of flow within the aquifer system from the fluid-level maps presented later in this report.

Within areas of more uniform density, approximations of flow direction between points can be made from the maps by utilizing a method presented by Hubbert (1940, p. 1995) in which a row of wells (points on the map) are plotted in the direction of dip of the aquifer. This method uses a middle point as a reference-density value and computes the potential of the water at the two end points in terms of this reference-density value. The potentials at each separate point then are plotted against its distance along the profile, forming a curve. If the water in the aquifer is at rest, this curve will have a minimum point at the selected reference point. If, on the other hand, the water has a component of motion along the profile line, the curve will be tangent to a sloping line at the reference point, and the flow will be in the direction of its downward slope.

In an effort to verify that the fluid-level maps indicate a generalized direction of flow as implied by the contours, profiles were computed at selected locations on the fluid hydraulic-head maps using a method described by Jorgensen and others (1982, p. 43). This method is analogous to a U-tube configuration and checks to see if hydrostatic conditions exist by using aquifer altitude, fluid level, and density data from two points. In all cases analyzed, a component of flow did exist in the direction implied by the fluid-level map. To obtain more information of flow in variable-density systems, the reader also is referred to papers by Bond (1972) and Lusczynski (1961).

Regional Flow as Indicated by Fluid Levels and Water-Quality Information

The regional fluid-level map of the Arbuckle is based on equivalent freshwater heads and is shown in figure 22. Fluid-level difference maps maps based on point heads are shown for the other aquifer units in this study (figs. 23-25). The flow directions as indicated by the fluid-level maps are assumed to be valid, although many assumptions were made in constructing the maps.

Maps showing the relation of fluid levels in the Arbuckle aquifer to fluid levels in three other overlying aquifers (figs. 23-25) provide a probable indication of fluid flow between the Arbuckle and the other aquifers. These maps are directly comparable only in the areas where the Arbuckle and the aquifer being compared have similar densities. Also, these maps indicate the direction of potential downward fluid movement if the fluid levels and the density are greater in the overlying aquifer than the fluid levels and density in the Arbuckle in a given area. Discussion of the implications of these maps as to horizontal and vertical flow follow. In addition, discussions are presented on the inference of fluid movement

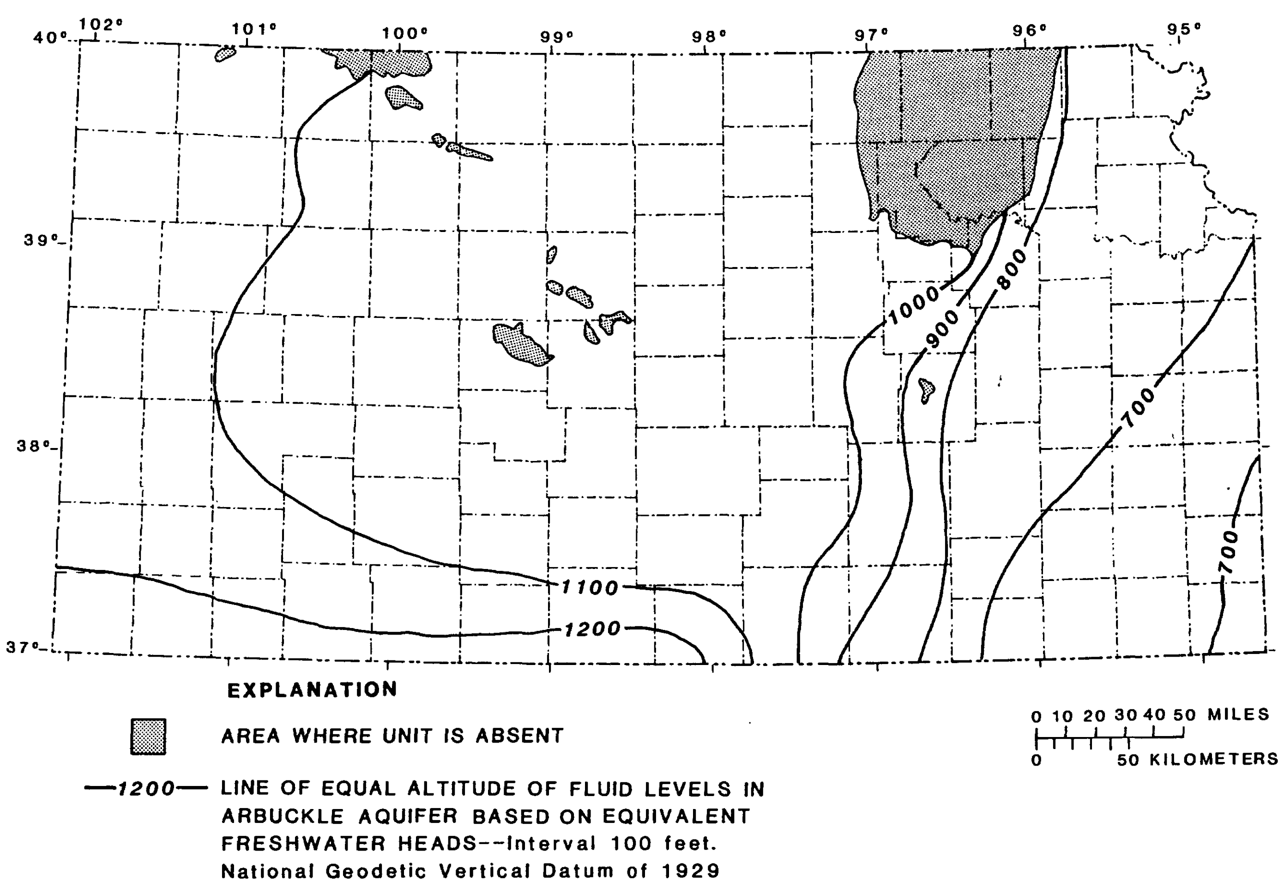


Figure 22.--Altitude of fluid levels in Arbuckle aquifer.

as indicated by water-quality data. These involve the usual assumption that the salinity of brines increases in the direction of fluid movement, and that conversely, the direction of fluid movement may be inferred from the direction of increasing chloride concentrations.

Arbuckle Aquifer

Regional flow in the Arbuckle aquifer, as indicated by fluid-level contours (fig. 22), is mainly in an east-southeasterly direction across the State. This overall trend is affected by major structural features in the State. In general, the flow directions implied by the distribution of chloride concentrations (fig. 10) agree with the flow directions indicated by the fluid-level maps.

The following discussion of flow in the Arbuckle divides the State into three parts--western, eastern, and central. The geographical dividing line of these areas is considered to be the Central Kansas uplift and the Nemaha anticline. Flow in the Arbuckle in the western part of the State is mainly from the west-northwest to the east and southeast. There is an easterly component of flow across the Central Kansas uplift area.

Flow in the eastern part of the State, which includes the Forest City and Cherokee basins (fig. 2), is primarily to the southeast through the central part of these basins. This is implied also by the distribution of chlorides. In the western part of these basins, flow is mainly to the east, away from the Nemaha anticline. Although not shown on the fluid-level map of the Arbuckle aquifer because of the contour interval, there is an indication of flow to the northeast in the northeastern part of the State. However, this flow is indicated by data points that were used to construct the map, and also by a dissolved-solids map of water in Ordovician rocks by Dott and Ginter (1930). In southeastern Kansas, a component of flow is indicated to the west-northwest into Kansas from the outcrop of the Arbuckle in the Ozark Plateau in southwestern Missouri. In this area, freshwater flows from Missouri to the west until it comes in contact with the larger regional saline-flow system where both systems then flow upward and to the south. A zone of freshwater/saline-water diffusion exists within this area, similar to that which exists in coastal areas where fresh ground-water systems come into contact with the saline ground-water system. Within this southeastern area, the chloride distribution generally agrees with this concept of flow.

Flow in the central part of the State, which includes the Salina and Sedgwick basins, is primarily from the west-northwest to the south-southeast. An increase in chloride concentrations from less than 10,000 mg/L in the Salina basin to more than 100,000 mg/L in the Sedgwick basin (fig. 10) indicates a direction of flow from the north-northwest to the south-southeast. A north-to-south direction of flow also is discussed by Edmund and Goebel (1968) and Larson (1971). Recent work by the U.S. Geological Survey, Central Midwest Regional Aquifer Systems Analysis group (Lawrence, Kansas) also has indicated that the reason for fresher water in the Salina basin is because of a regional-flow system from the northwest to the south-southeast transmitting fresher water into the basin (Jorgensen and others, 1986).

Fluid level and chloride-concentration distributions generally agree with each other as to the implied direction of flow. However, there are some water-quality relationships between the Arbuckle and the overlying aquifers that are opposite to the expected relationships of such a flow system. Two relationships stand out in particular: (1) Larger and smaller chloride concentrations than regional background concentrations in some areas on the Central Kansas uplift than in adjacent areas, and (2) fresher waters in the Arbuckle, mainly in the Salina basin and along the Nemaha anticline, than in overlying aquifers. The present view of regional flow in the Arbuckle should account for some of these differences.

As mentioned previously, there are several anomalies of fresher and poorer-quality water in the Arbuckle than would normally be expected. For example, the test hole at the Salina site only had 3,500 mg/L of chloride in the Arbuckle aquifer as compared to 25,000 mg/L of chloride in the overlying Simpson Group (St. Peter Sandstone). In the case of fresher water in the Arbuckle on the Central Kansas uplift or the Nemaha anticline than in the overlying aquifers, the water-quality differences in the Arbuckle aquifer are considered as anomalies because, in the studies of brine in deep aquifers, it has been noted that there is a tendency within a basin for the concentration of dissolved solids to increase with depth (Parker, 1967; White, 1965).

However, an appraisal by Dingman and Angino (1969) of more than 1,800 selected samples of water from Kansas brines in a four-county area of central Kansas indicated that the more concentrated brines were found in Permian rocks (overlying the Lansing-Kansas City aquifer) and that salinity decreased below the Permian until the Arbuckle was reached, at which point the salinity again increased until the Precambrian basement rocks were reached.

In part of the Central Kansas uplift area, data on the chemical quality of brines in the different aquifers do not indicate that depth is significantly related to concentrations of dissolved solids, as shown in table 2. Table 2 is a summary of about 600 chemical analyses compiled by Rall and Wright (1953) and does provide a general comparison of the brines in the principal aquifers. These data are representative mostly of the major oil-producing areas along the Central Kansas uplift and Nemaha anticline, although it is believed that the relative percentages of each constituent are similar to those occurring in the basin areas. On a more regional scale, chloride and, therefore, dissolved solids do increase with depth as can be seen in figures 10 to 14 where depths to the aquifers increase to the south along with the chloride concentrations.

Various theories have been proposed to explain the occurrences of reduced salinity at depth. These theories include recharge on the uplift areas from flow by membrane filtration through clay layers, or from downward flow through fractures. In the area along the Central Kansas uplift, the vertical hydraulic gradients based on pressure differences (see fig. 26) imply that recharge to the Arbuckle from the overlying Lansing-Kansas City aquifer possibly could occur. However, water in Lansing-Kansas City is of much poorer quality than in the Arbuckle, thus indicating that this would result only in a poorer-quality water in

Table 2.--Summary of chemical and dissolved-solids concentrations in aquifer brines

[All values are given in parts per million. Data from Rall and Wright, 1953]

Aquifer		Calcium	Magnesium	Sodium	Bicarbonate	Sulfate	Chloride	Dissolved solids
Arbuckle	Maximum	8,200	4,500	31,000	910	7,600	90,000	113,000
	Mean	2,100	630	12,140	400	1,720	23,230	37,000
	Minimum	70	160	4,200	30	10	8,800	15,300
Simpson Group (St. Peter Sandstone and Platteville Formation)	Maximum	6,700	1,720	34,000	460	1,130	66,000	109,000
	Mean	4,500	1,150	22,100	210	470	44,660	73,000
	Minimum	850	290	4,600	30	0	12,100	7,700
Viola	Maximum	10,000	2,700	52,000	540	1,600	110,000	171,000
	Mean	3,780	990	20,000	200	510	40,300	65,980
	Minimum	170	60	2,640	40	0	3,840	7,700
Hunton	Maximum	5,200	1,500	34,000	980	1,200	66,000	107,000
	Mean	2,080	550	8,240	310	600	28,640	40,400
	Minimum	230	90	3,600	80	160	5,300	10,500
Mississippian	Maximum	12,900	2,660	59,300	820	3,540	122,000	196,890
	Mean	5,000	1,290	28,630	280	880	55,910	91,990
	Minimum	560	210	9,100	30	0	15,300	25,870
Morrowan-Desmoinesian	Maximum	19,000	1,910	45,000	850	3,010	87,000	142,000
	Mean	3,400	810	18,400	270	920	35,870	59,020
	Minimum	420	180	6,510	20	0	11,300	20,810
Lansing-Kansas City	Maximum	19,000	6,200	76,100	820	4,080	142,000	231,300
	Mean	8,010	2,570	41,770	90	410	86,040	141,700
	Minimum	1,290	440	13,000	0	0	10,000	46,000

the Arbuckle. In fact, flow through fractures in the Lansing-Kansas City may be a reason for the larger concentrations of chloride in the Arbuckle in some places on the Central Kansas uplift.

The possibility that semipermeable clay, such as that present at the base of the Lansing-Kansas City aquifer, could function as a filtering membrane in decreasing the concentration of dissolved salts in the fluids moving through them is discussed in the literature. Filtration by shale may work primarily through two mechanisms--osmotic pressure or ultrafiltration. Osmotic pressure involves fresher water moving across a membrane to a more saline water, which is just the opposite of the physical setting on the Central Kansas uplift. Ultrafiltration requires a large enough hydraulic pressure to overcome the osmotic pressures present and force water through the shale in the direction opposite to the force generated by the osmotic pressures. However, as indicated by Neglia (1979, p. 575), if an electrolyte is forced to pass through shale, theoretically, a greater salinity gradient should immediately develop between the solutions on both sides of the membrane. Consequently, greater hydraulic pressure is needed to overcome the osmotic pressure. Natural shale apparently does not support this additional pressure (up to thousands of pounds per square inch), and consequently it will break up into small segments to establish a salinity equilibrium between the upper and lower solutions.

The available differential hydraulic-head drive within the Central Kansas uplift area is not considered enough to cause ultrafiltration, and as Neglia (1979) has indicated, natural shale would allow the poorer quality water to pass through very small fractures if the required differential head was present without filtration when the shale broke up. Other investigators have evaluated the difficulties of explaining the occurrence of brines in natural geologic environments and have concluded that the pressure requirements for appreciable salt filtration are not satisfied by any known situations (Manheim and Horn, 1968). Therefore, it is concluded that fresher water in the Arbuckle on the Central Kansas uplift is not a result of ultrafiltration.

In addition, the possibility exists that downward flow of the fluids through fractures could occur to account for relatively greater salinities in localized areas in the Central Kansas uplift. Uplift of the central Kansas area has been described as a gentle post-Ordovician, post-Pennsylvanian, and post-Cretaceous arching movement that affected the entire Central Kansas uplift (Walters, 1946). Other writers have indicated that there is faulting that may have affected fluid movement. Edmund and Goebel (1968, p. 156) stated that there is faulting of the southwestern and southern flanks of the Salina basin. In addition, Larson (1962) in his discussion of the Ackman field in Nebraska, which is located about 40 miles into Nebraska along the Cambridge arch, stated that the Cambridge arch was upfolded in post-Cretaceous time. He also stated that core data indicate that fracturing has taken place in the Lansing-Kansas City aquifer in this area. Therefore, a more likely mechanism available to cause relatively greater salinities in the Arbuckle aquifer on the Central Kansas uplift is for saline water to move downward along fractures or faults from the Lansing-Kansas City to the Arbuckle. However, the possibility that the injection of poorer quality water from the Pennsylvanian rocks into the Arbuckle in this area has affected the distribution of chlorides in the Arbuckle to this extent also would have to be considered.

As considered, flow in the Arbuckle aquifer can account for most of the water-quality distributions as presently inferred in this study.

Relatively fresher water enters the Salina basin from the north-northwest and moves through the Salina basin into the Sedgwick basin. As discussed in the section on "Hydraulic Conductivity," the basin areas are believed to have smaller values of hydraulic conductivity than uplift areas. Therefore, ground water moving through the basins will have a tendency to follow the path of greater conductivity which, in this case, is the periphery of the basins. This would enable fresher waters to move southward along the east side of the Central Kansas uplift and on the west side of the Nemaha anticline. Relatively fresher water also would flow through the center part of the Salina basin but at a slower rate. Flow into the Salina basin, from the western flow system across the Central Kansas uplift or at a lower structural point such as the saddle between the Cambridge arch and the Central Kansas uplift, will bring in saline water with larger concentations of chloride. Fresher water along the east side of the Central Kansas uplift probably would mix with the more saline water flowing across the Central Kansas uplift area.

Larger concentrations of chloride in other areas of the Central Kansas uplift could have originated partly from the large amount of brine disposal in the area or by very slow leakage from the Lansing-Kansas City aquifer placing poorer quality waters in these locations. Martin (1968) also showed that there is water with larger chloride concentrations near the location of the basement Precambrian hills, some of which extend through the entire thickness of the Arbuckle aquifer. He also showed that the water in the Arbuckle aquifer and in the Lansing-Kansas City aquifer is similar on a profile along the Central Kansas uplift from the northwest to the southeast, implying mixing of these waters.

Relatively fresher water in the Nemaha anticline area could occur because of the flow to the east from the Salina basin. This relatively fresher water would seem to indicate recharge areas, when in fact they are not in the classical context of recharge coming from a source overlying the aquifer. The overall flow in the Salina basin is to the east-southeast. Water from the Salina basin does cross into the Forest City and Cherokee basins flowing to the east.

The pattern of movement of water in some of the other overlying units, such as the Simpson and the Viola, would be similar to the pattern of movement in the Arbuckle in some areas of the State because of their interconnection with the Arbuckle and the relative magnitude of their permeability. Movement of water in the Mississippian and the Lansing-Kansas City aquifers would be much slower, as suggested by comparison of permeability values (table 1) and by the many references to the requirement of having to inject under pressure to dispose of fluids in these units, for example as noted by Grandone and Schmidt (1943).

Simpson Group

Flow from the eastern margin toward the middle of the Salina basin is indicated by the distribution of chloride concentrations in the Simpson Group (mainly St. Peter Sandstone), which has a moderately significant increase in salinity in this direction (fig. 11). Relatively small changes in salinity are indicated in the Forest City basin. The most significant change occurs in the Sedgwick basin where chloride concentrations increase southward from less than 25,000 mg/L to more than 100,000 mg/L. The direction of fluid movement implied by the increase in chloride in this aquifer is similar to that in the underlying Arbuckle aquifer.

The relation of fluid levels in the Simpson to those in the underlying Arbuckle aquifer is shown in figure 23. The data show that the altitude of fluid levels in the overlying Simpson ranges from 0 to 100 feet below the fluid levels in the Arbuckle in the Sedgwick basin. This relation implies that there may be some upward flow. Fluid levels in the Simpson are indicated to be above fluid levels in the Arbuckle along part of the Nemaha anticline, which implies that there could be some downward leakage in this area. The close agreement of the maps of chloride concentrations also indicates that the Arbuckle and Simpson may be in hydraulic connection.

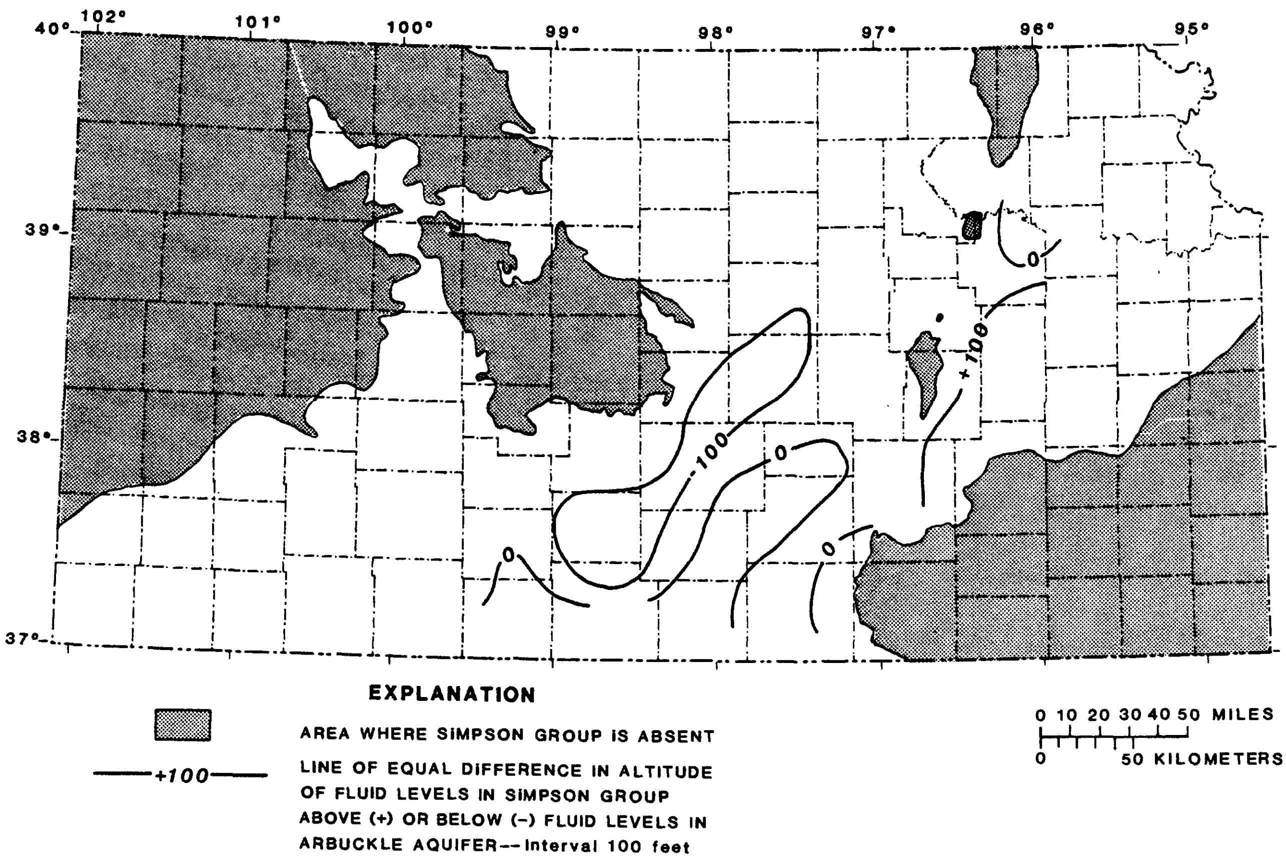


Figure 23.--Relation of fluid levels in Arbuckle aquifer to fluid levels in Simpson Group.

Viola Aquifer

The distribution of chloride concentrations in the Viola aquifer is noteworthy in that relatively small changes in salinity are indicated in most of the area (fig. 12). Only the increase in chloride concentrations from less than 50,000 mg/L to more than 100,000 mg/L in the southern part of the Sedgwick basin suggests a direction of flow. The pattern of chloride in this unit is similar to the underlying Simpson.

The relation of fluid levels in the Viola aquifer to those in the Arbuckle aquifer is shown in figure 24. The data show that the altitude of fluid levels in the Viola ranges from 100 feet below to 100 feet above fluid levels in the Arbuckle. This relation implies that there may be upward flow in some areas and downward flow in other areas. The map of chloride concentrations (fig. 12) suggests that the formations may be in hydraulic connection. Because data are relatively sparse in the Sedgwick basin, the general relationship is unclear.

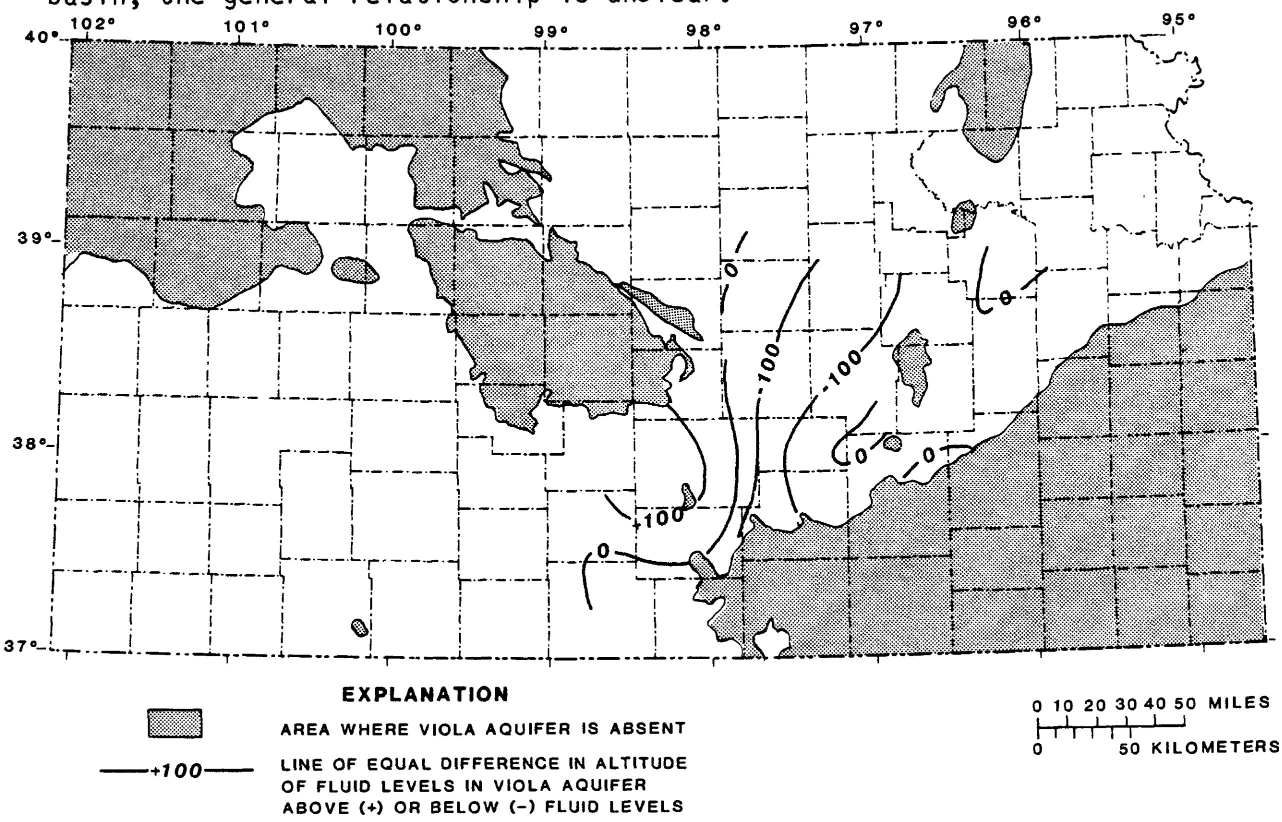


Figure 24.--Relation of fluid levels in Arbuckle aquifer to fluid levels in Viola aquifer.

Mississippian Aquifer

Chloride concentrations in the Mississippian aquifer (fig. 13) are more varied than those in underlying aquifers. The most significant increases in chloride concentrations occur in a band along the eastern and southern flanks of the Central Kansas uplift. In the Salina basin, increases in a southwesterly direction toward the Central Kansas uplift may suggest flow from the north-northeast. An increase in chloride concentrations from less than 25,000 mg/L to more than 100,000 mg/L in the Sedgwick basin suggests a westward direction of fluid movement within the aquifer.

The relation of fluid levels in the Mississippian aquifer to those in the Arbuckle aquifer is shown in figure 25. The data show that the altitude of fluid levels in the Mississippian ranges from about 300 feet below to as much as 100 feet above the fluid levels in the Arbuckle. The relation implies that there is a great potential for upward movement of fluids in the central part of the Sedgwick basin. However, because the Maquoketa and Chattanooga Shales are relatively thick in the Sedgwick basin, they could form a tight confining layer and, therefore, restrict upward flow.

Lansing-Kansas City Aquifer

The areal distribution of chloride concentrations in the Lansing-Kansas City aquifer, as shown in figure 14, indicates a general increase southward across the State. Concentrations indicate a moderate increase from margins toward the middle of the Salina basin but a rapid increase from less than 50,000 mg/L to more than 150,000 mg/L in a southerly direction through the Sedgwick basin. The rapid increase in concentrations in the Sedgwick basin suggests fluid movement toward the south. Also, it is evident that a marked increase to more than 100,000 mg/L occurs along the crest of the Central Kansas uplift. This increase in concentrations in the Lansing-Kansas City aquifer may be related to the downward movement of fluids from the overlying Permian beds along the crest of the uplift via various fracture or fault planes.

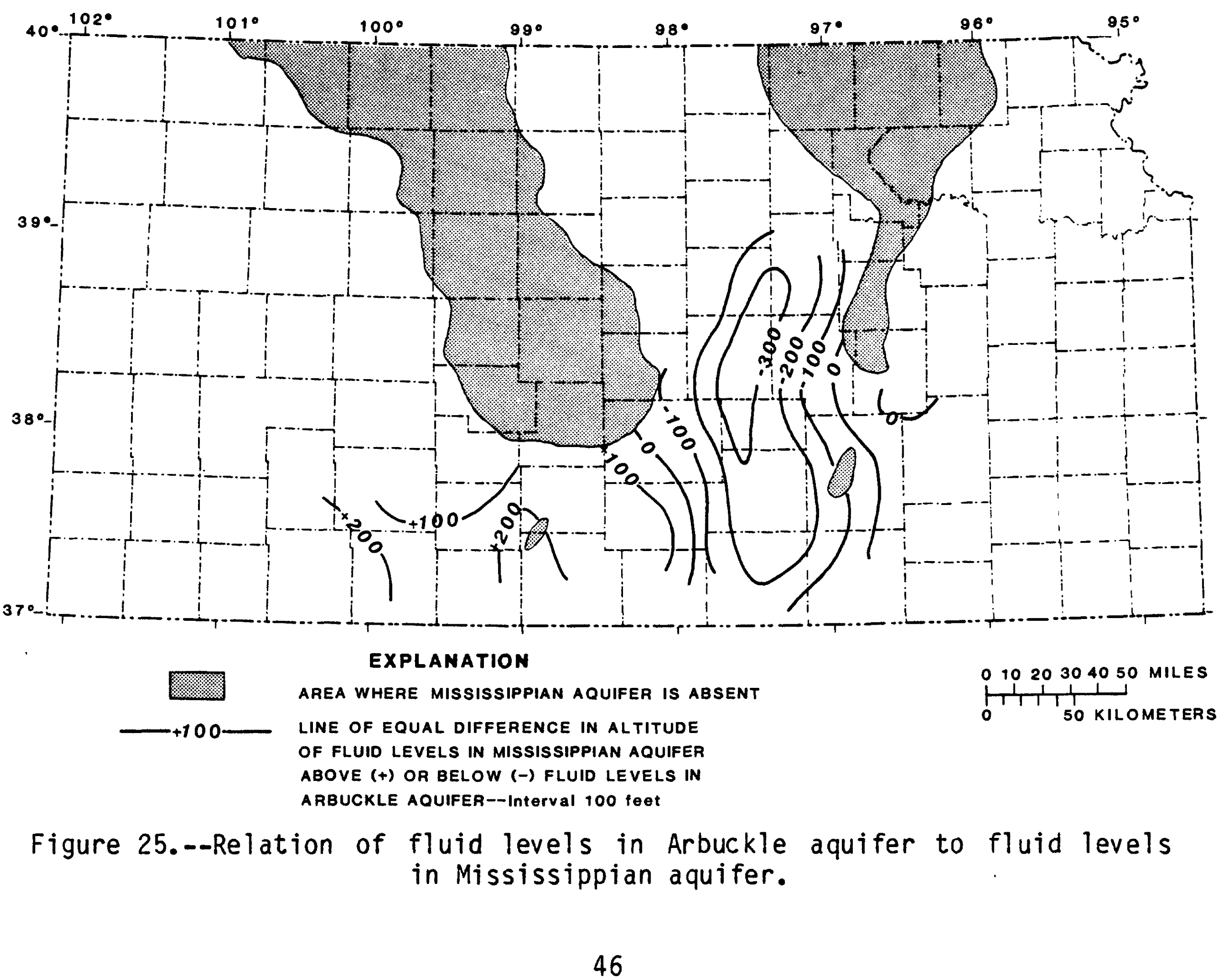


Figure 25.--Relation of fluid levels in Arbuckle aquifer to fluid levels in Mississippian aquifer.

The relation of fluid levels in the Lansing-Kansas City aquifer to those in the Arbuckle aquifer is shown in figure 26. Data show that the altitude of fluid levels in the Lansing-Kansas City generally is higher than the altitude in all of the underlying aquifers. In the Sedgwick basin, fluid levels are as much as 500 feet above fluid levels in the Arbuckle. All data related to fluid levels suggest a potential for downward flow from the Lansing-Kansas City.

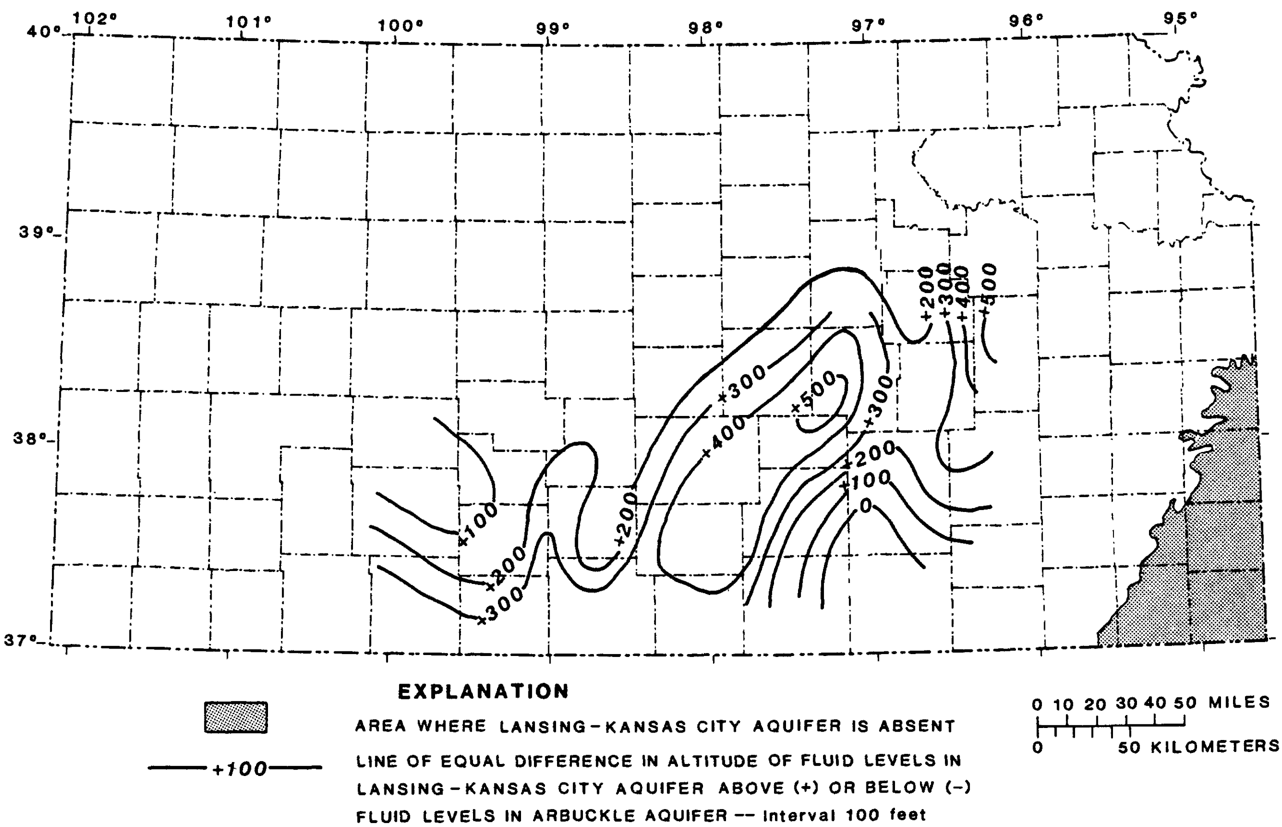


Figure 26.--Relation of fluid levels in Arbuckle aquifer to fluid levels in Lansing-Kansas City aquifer.

OIL PRODUCTION AND BRINE DISPOSAL

Data on oil and gas production and the disposal of the associated brines were analyzed to provide some perspective on the existing conditions regarding the injection of fluids. The injection to or withdrawal of fluids from the aquifer system has the potential to significantly modify hydraulic heads and fluid flow. Some areas are less desirable for injecting particular kinds of fluids because of the possibility of noncontainment of injected fluids in the unit in which they are injected.

Quantity and Distribution of Oil Production

Records from the Kansas Geological Survey for 1980 (Paul and Bahnmaier, 1981) showed that 39,871 wells produced a total of 58.5 million barrels of crude oil and that 10,541 wells produced a total of 694,406 million cubic feet of natural gas. It was estimated that 10 million barrels of the oil produced were obtained by water flooding or other methods of enhanced recovery. Water flooding was done by using an additional 6,481 wells to inject 321 million barrels of fluid, mostly brine, into producing zones of the various fields to increase oil production.

The areal distribution and volume of oil produced during 1980 were determined for different geologic sources. Because the volumes listed for a field commonly included sources from more than one stratigraphic unit and several wells, the total was divided equally between each of the stratigraphic units and assigned at the location of the initial site. Quantities from each stratigraphic unit were totaled by township (generally 36 square miles) to indicate the distribution by volume.

Production of oil from the Arbuckle during 1980, as shown in figure 27, was calculated to be 7.6 million barrels or about 13 percent of the Kansas total. Rates of production during 1980 for each township where oil was produced ranged from about 100 to 350,000 barrels, but averaged 38,000 barrels. Also, 6.7 million barrels or 88 percent of production in the Arbuckle was derived from the Central Kansas uplift area. This area of about 7,000 square miles will be used in subsequent comparisons.

Records of oil production during 1980 from all formations except the Arbuckle, as shown in figure 28, were calculated to be 50.9 million barrels or about 87 percent of the Kansas total. Rates of production during 1980 for each township where oil was produced ranged from about 100 to 1,350,000 barrels, but averaged 57,000 barrels. The records also indicate that 17.0 million barrels or 33 percent of the total production excluding the Arbuckle was derived from wells in the Central Kansas uplift area.

Quantity and Distribution of Brine Disposal

In order to provide a basis for computations, several assumptions were made in relation to the production and disposal of brines. It was assumed that all of the oil wells pumped an average of 20 barrels of brine for each barrel of crude oil produced. Because the production ratio of brine to gas differs greatly from field to field and with time, no estimates of the quantities derived from gas wells were included in the comparison. Also, it was assumed for these comparisons that all of the brine derived within a township was disposed into one or more horizons within the same township.

Using these assumptions and the values previously given, a total of 1,170 million barrels of brine were produced in association with crude oil during 1980. Similarly, 152 million barrels (13 percent) were derived from the Arbuckle, as shown in table 3, and 1,018 million barrels (87 percent) were derived from other formations. The total volume of brine produced in the Central Kansas uplift area during 1980 was calculated to be 474 million barrels, of which 134 million barrels (28 percent) were from the Arbuckle and 340 million (72 percent) were from all other formations.

Data related to the disposal of oilfield brine within the State were obtained from the files of the Kansas Department of Health and Environment (Topeka, Kansas). The records, as of January 1984, indicated that a total of 3,871 wells had an adjudicated right for the permanent disposal of brine in the subsurface. Those records include location of the well, stratigraphic unit and depth of the disposal zone, amount of pressure required for injection, and maximum daily rate at which fluids may be disposed.

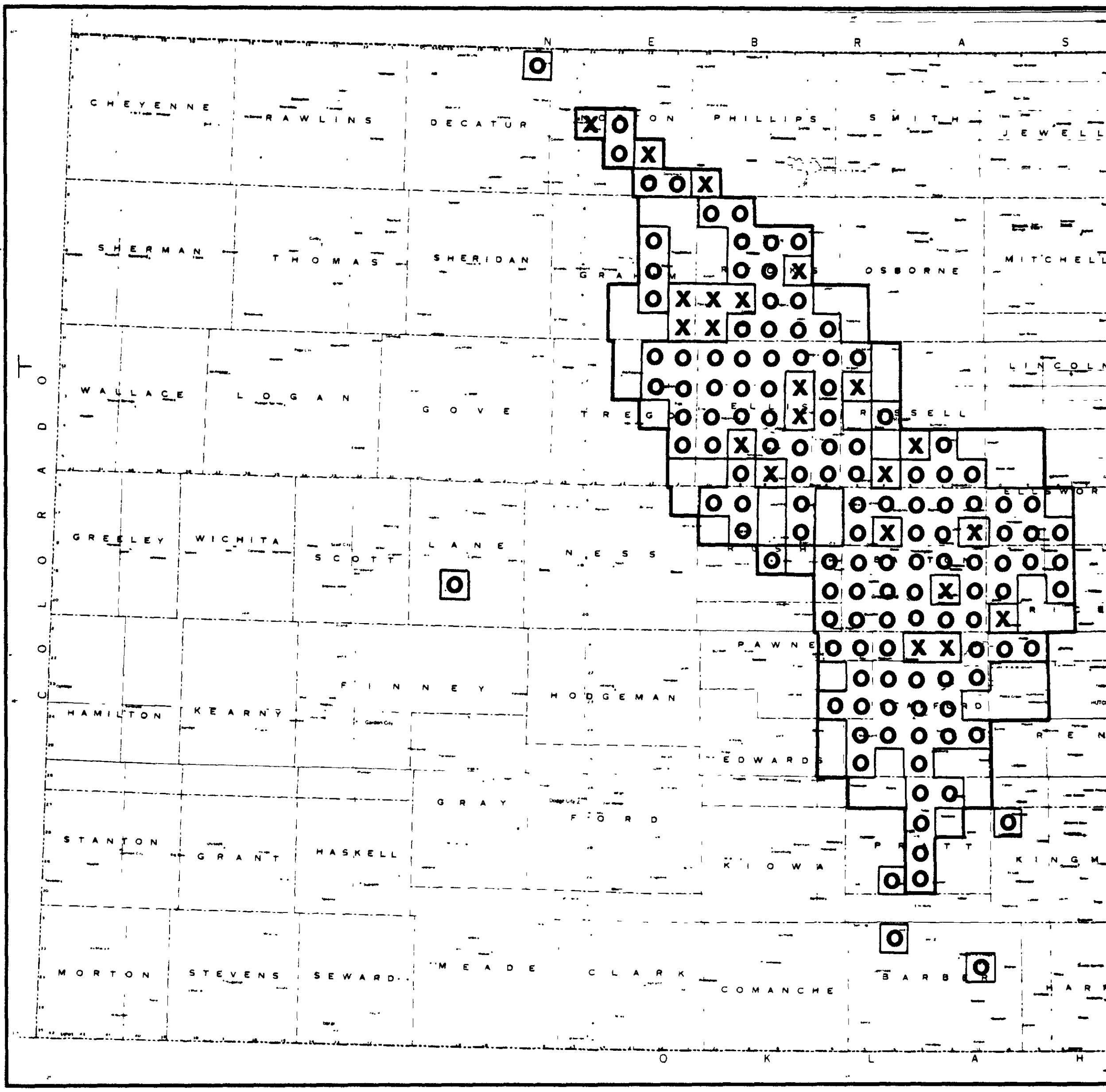
Table 3.--Annual production and disposal of oilfield brine in Kansas

Brine production[1] (Based on 1980 oil-production data)			Calculated brine disposal[2] (Based on 1984 rates for disposal wells)		
Area	Rate, in million barrels per year	Percentage	Area	Rate, in million barrels per year	Percentage
Statewide					
Arbuckle	152	13	Arbuckle	889	76
All other formations	1,018	87	All other formations	281	24
Total	1,170	100	Total	1,170	100
Central Kansas Uplift Area					
Arbuckle	134	28	Arbuckle	427	90
All other formations	340	72	All other formations	47	10
Total for area[3]	474	100	Total for area[3]	474	100

1 From records of the Kansas Geological Survey, Lawrence, Kansas. (Estimates based on an assumed 20 barrels brine per barrel of oil.)

2 From records of Kansas Department of Health and Environment, Topeka, Kansas.

3 Area of about 7,000 square miles overlying the Central Kansas uplift.



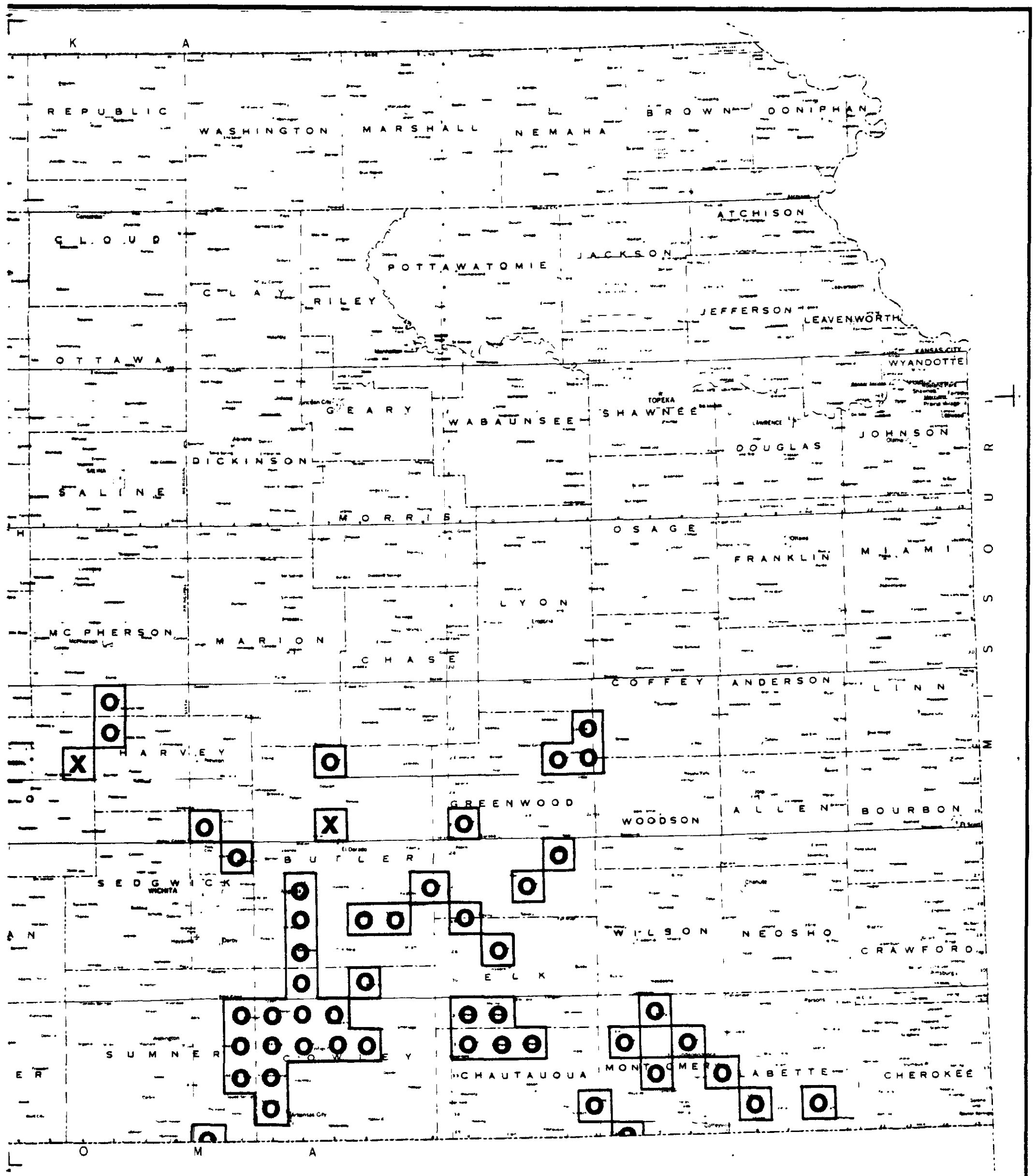
EXPLANATION

1980 OIL PRODUCTION PER TOWNSHIP, IN THOUSANDS OF BARRELS

O 1-100

X 101-500

——— APPROXIMATE BOUNDARY OF CENTRAL KANSAS UPLIFT AREA

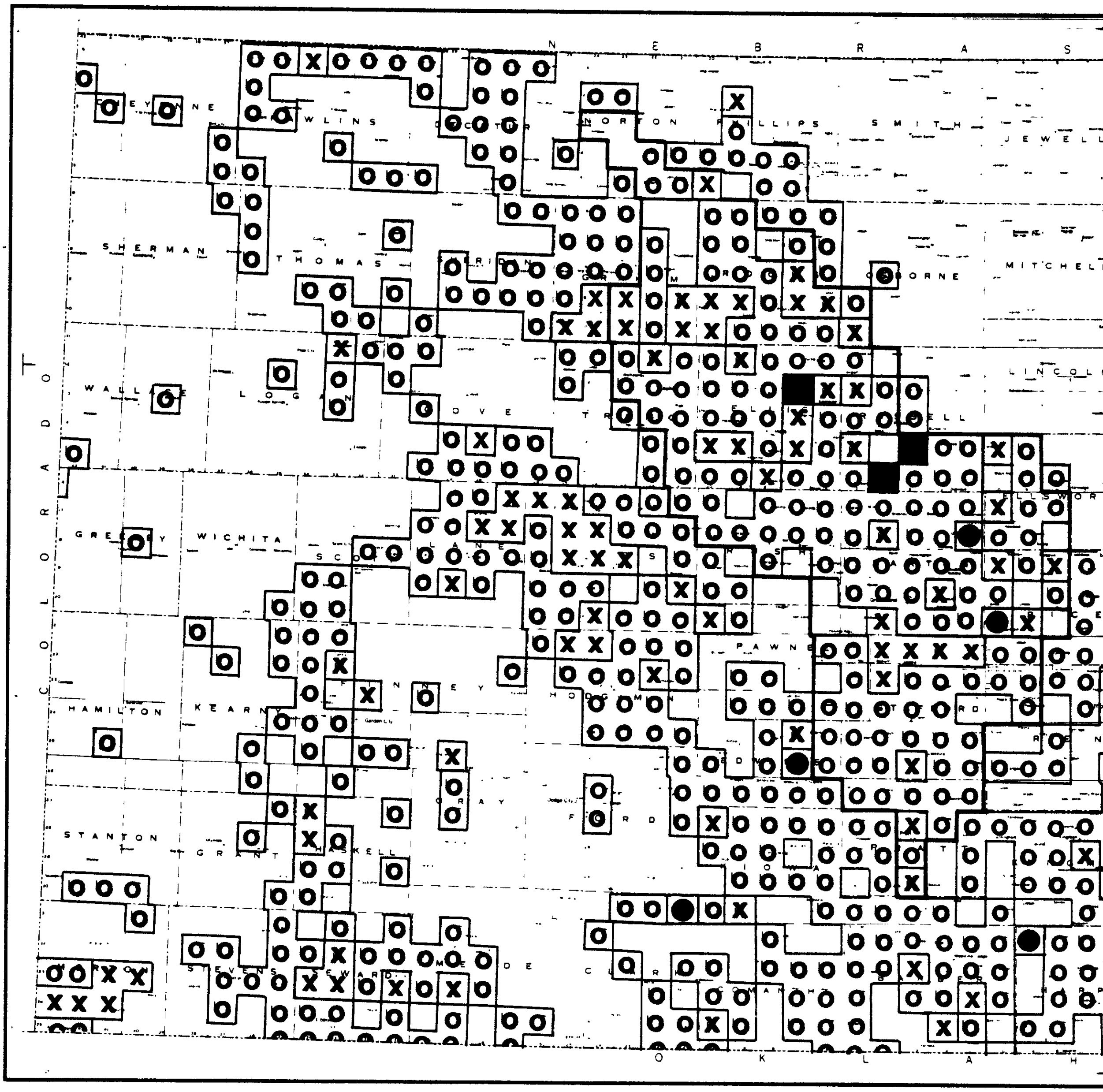


Data from Paul and Bahnmaier, 1981

0 10 20 30 40 MILES

0 10 20 30 40 KILOMETERS

Figure 27.--Oil production from Arbuckle aquifer, 1980.



EXPLANATION

1980 OIL PRODUCTION PER TOWNSHIP, IN THOUSANDS OF BARRELS

- 1-100
- 101-500
- 501-1000
- Greater than 1000
- APPROXIMATE BOUNDARY OF CENTRAL KANSAS UPLIFT AREA

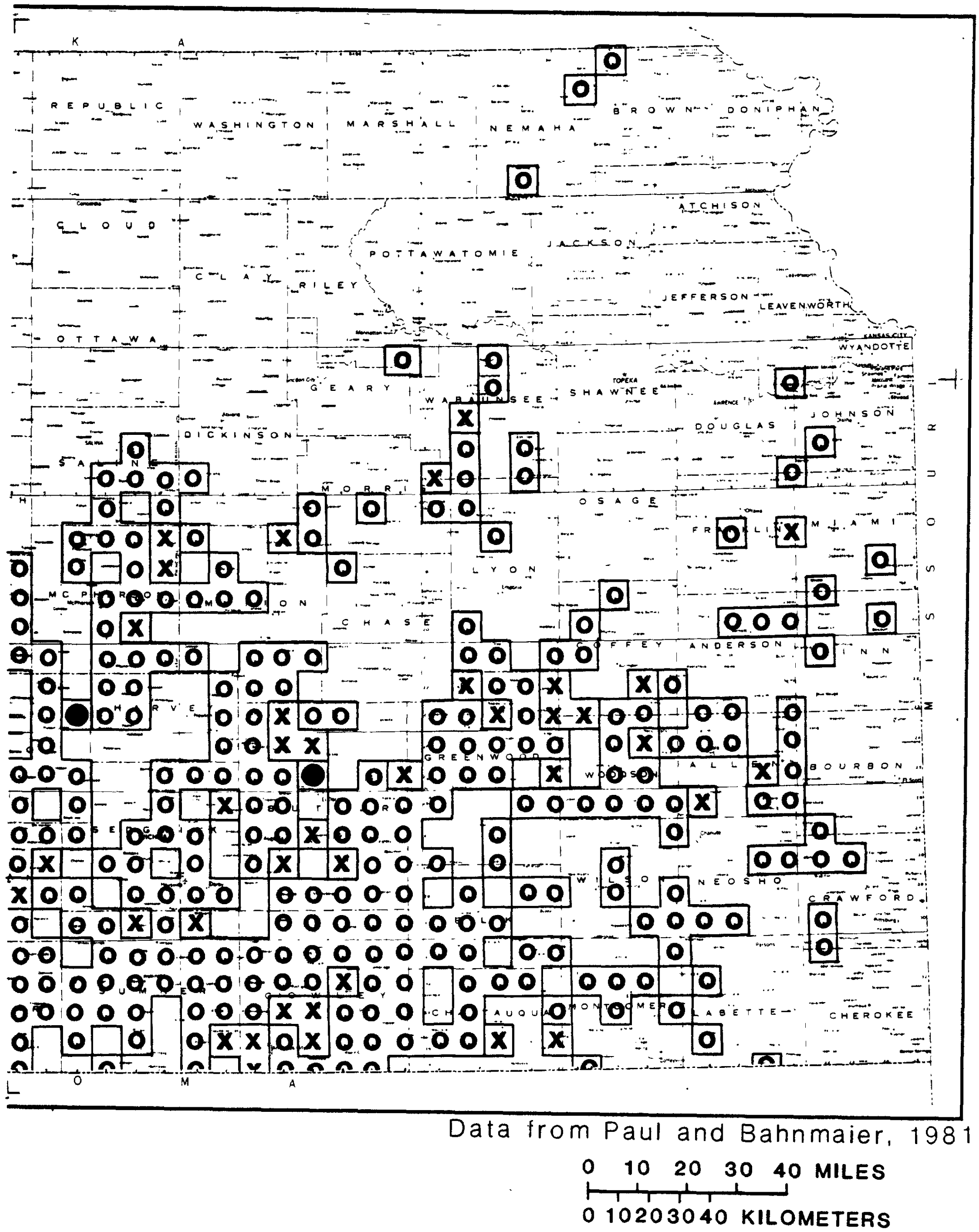


Figure 28.--Oil production from all formations except Arbuckle aquifer, 1980.

Although the well records do not indicate a duration of operating time for determining volumes, the assumption was made that the rates on record are continuous rates. With this assumption, the average disposal rate for 1,794 wells screened in all formations other than the Arbuckle was determined to be 224,475 barrels per year. In contrast, the average disposal rate for 2,077 wells screened in the Arbuckle was determined to be 591,300 barrels per year.

In order to evaluate the existing conditions related to brine disposal, the data were analyzed by using the adjudicated rates as of January 1984 for the different stratigraphic units. The rates for each unit were totaled by township where disposal occurred in a manner similar to those for brine production. Values determined in this manner are used in this report to depict the areal distribution of brine disposal for the different units.

The rates per township where brine was disposed into the Arbuckle during 1984, as shown in figure 29, ranged from about 100 to as much as 150,000 barrels per day (3 to 4,375 gal/min). The disposal rates for these townships averaged 7,400 barrels per day (216 gal/min) statewide and 13,400 barrels per day (391 gal/min) within the Central Kansas uplift area. Rates per township where brine was disposed into all formations except the Arbuckle during 1984, as shown in figure 30, ranged from about 100 to 23,000 barrels per day. Rates per day for these townships averaged 1,460 barrels statewide and 1,950 barrels within the Central Kansas uplift area.

Several assumptions were made so that the disposal rates could be compared with the volume of brine produced. As previously stated, it was assumed that all of the brine derived within a given area was disposed of within the same area. Also, it was assumed that the total volume of brine was disposed into the different stratigraphic units at rates proportional to the respective adjudicated rights.

The annual volume of brine disposed in the different areas was calculated on the basis of the above assumptions. The adjudicated rates per day for all wells disposing into the Arbuckle during 1984 totaled 3.4 million barrels and for all wells disposing into other formations totaled 1.1 million barrels. Using the ratio of these values to the total brine produced, as shown in table 3, it was calculated that 889 million barrels (76 percent) were disposed into the Arbuckle during 1984 and that 281 million barrels (24 percent) were disposed into other formations. In the Central Kansas uplift area, the adjudicated rates per day for wells disposing into the Arbuckle totaled 2.3 million barrels and for wells disposing into other formations totaled 0.3 million barrels. Using the ratio of values in the Central Kansas uplift area, disposal into the Arbuckle was calculated to be 427 million barrels (90 percent), and disposal into other formations was 47 million barrels (10 percent).

A summary of information based on 1980 oil-production data provided a general perspective of existing conditions. It has been shown that about 72 percent (737 million barrels) of the oilfield brine derived from other formations in Kansas was injected into the Arbuckle. About 86 percent (293 million barrels) of that brine was injected into the Arbuckle in the

Central Kansas uplift area. The quantity of brine generally produced in association with gas, which was not included in the calculations, was assumed to be of minor significance in this comparison. An examination of data related to secondary recovery also indicates that during 1980 secondary-recovery projects probably had little effect on the aquifer. These data show that the quantity of brine withdrawn from the Arbuckle for injection into other horizons was less than 2 percent of the quantity added by disposal. A comparison of the disposal rates showed that those in the Arbuckle may be as much as 10 times greater than those in other formations.

The accumulative volume of this brine added to the aquifer over many years could cause notable changes in pressure and chemical composition of the fluids. Unfortunately, data have not been available for determining the effects of the changes in detail. Because oil production, water flooding, and brine disposal have modified greatly the hydrology of uplift areas, it may not be possible to accurately determine initial hydraulic conditions within these areas. It is evident from the annual records, however, that oil production from the Arbuckle has decreased, and the injection from brine disposal has increased progressively.

FLUID DISPOSAL

General Principles

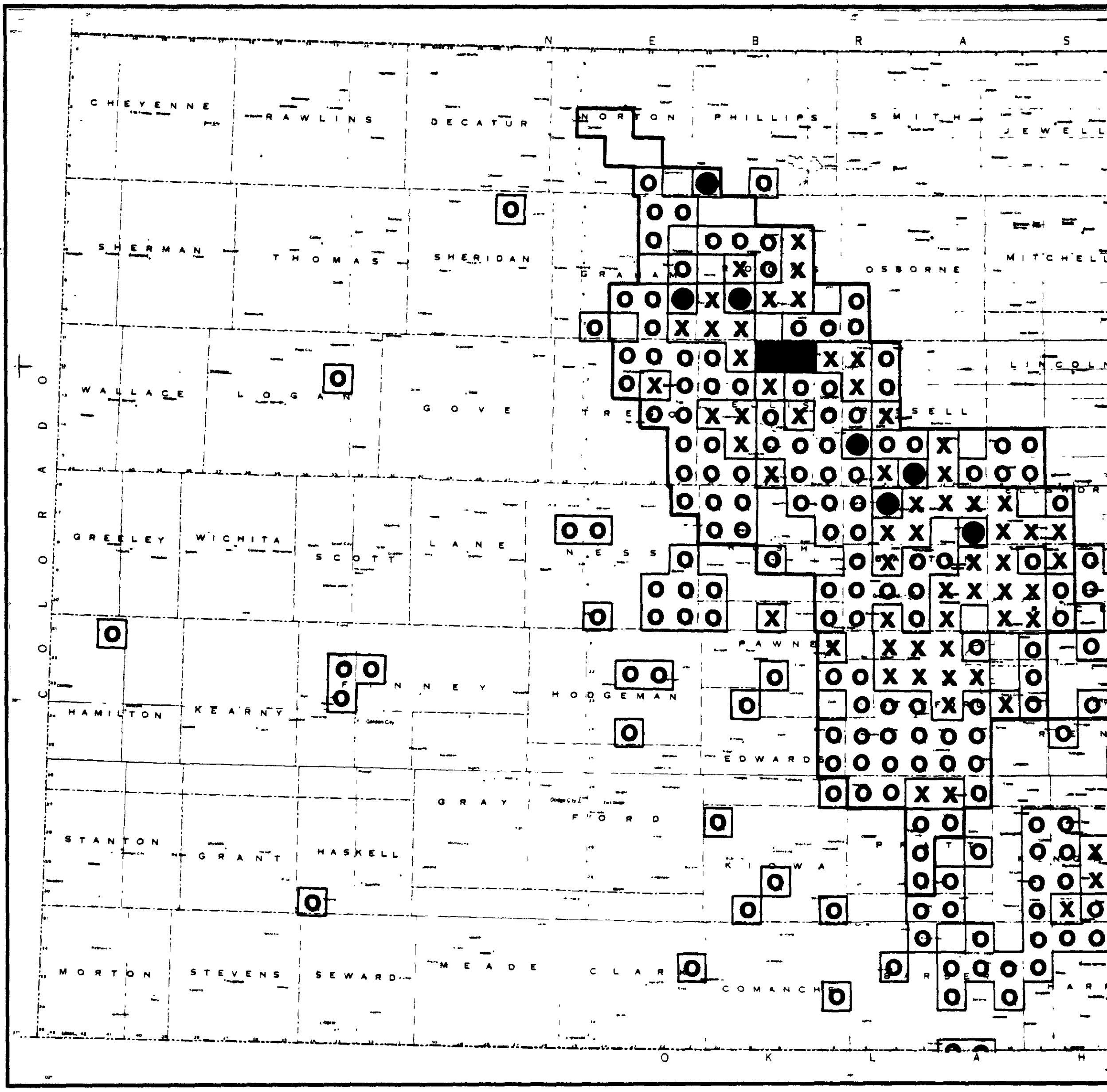
Disposal of fluids to the subsurface requires an injection well constructed of material resistant to corrosion and capable of withstanding the pressures applied during injection. In addition, knowledge of the geology and hydrologic characteristics of the subsurface environment at the injection-well site and in the surrounding region is fundamental to the evaluation of the suitability of a site for fluid injection. The type and character of the rocks and the native fluid of the disposal zone determine fluid transmission, pressure buildup, and chemical-reaction characteristics within the receiving zone. All of these factors are involved in ensuring the delivery to and containment of the fluids in the injection zone and in ensuring that freshwater zones are not affected by the injected fluids.

Some desirable characteristics desired for an acceptable disposal zone are (modified from Collins, 1975):

(1) The rocks used for disposal should have large porosity, permeability, and thickness so that a significantly large volume is available for fluid injection at relatively fast rates and at reasonably small pressures.

(2) The disposal reservoir should be of large areal extent suitable for injection of large quantities of fluid.

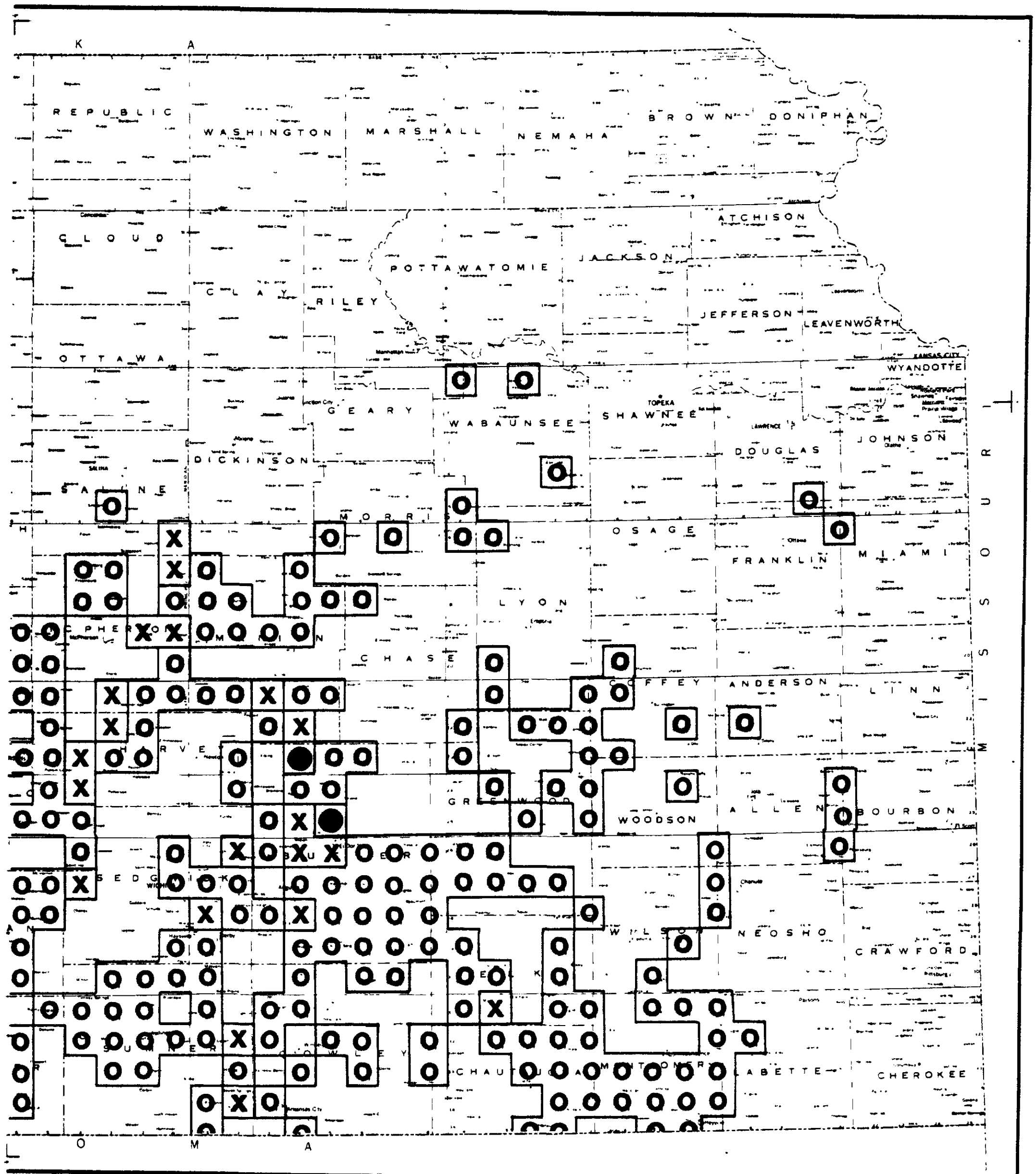
(3) The reservoir rocks should be uniform and not too heterogeneous to allow calculations concerning the behavior of injection fluids, injection pressures, and possible fluid-rock reactions.



EXPLANATION

1984 ADJUDICATED RATE OF BRINE DISPOSAL PER TOWNSHIP, IN THOUSANDS OF BARRELS PER DAY

- O — 1-10
- X — 11-50
- ● — 51-100
- ■ — 101-200
- —— APPROXIMATE BOUNDARY OF CENTRAL KANSAS UPLIFT AREA

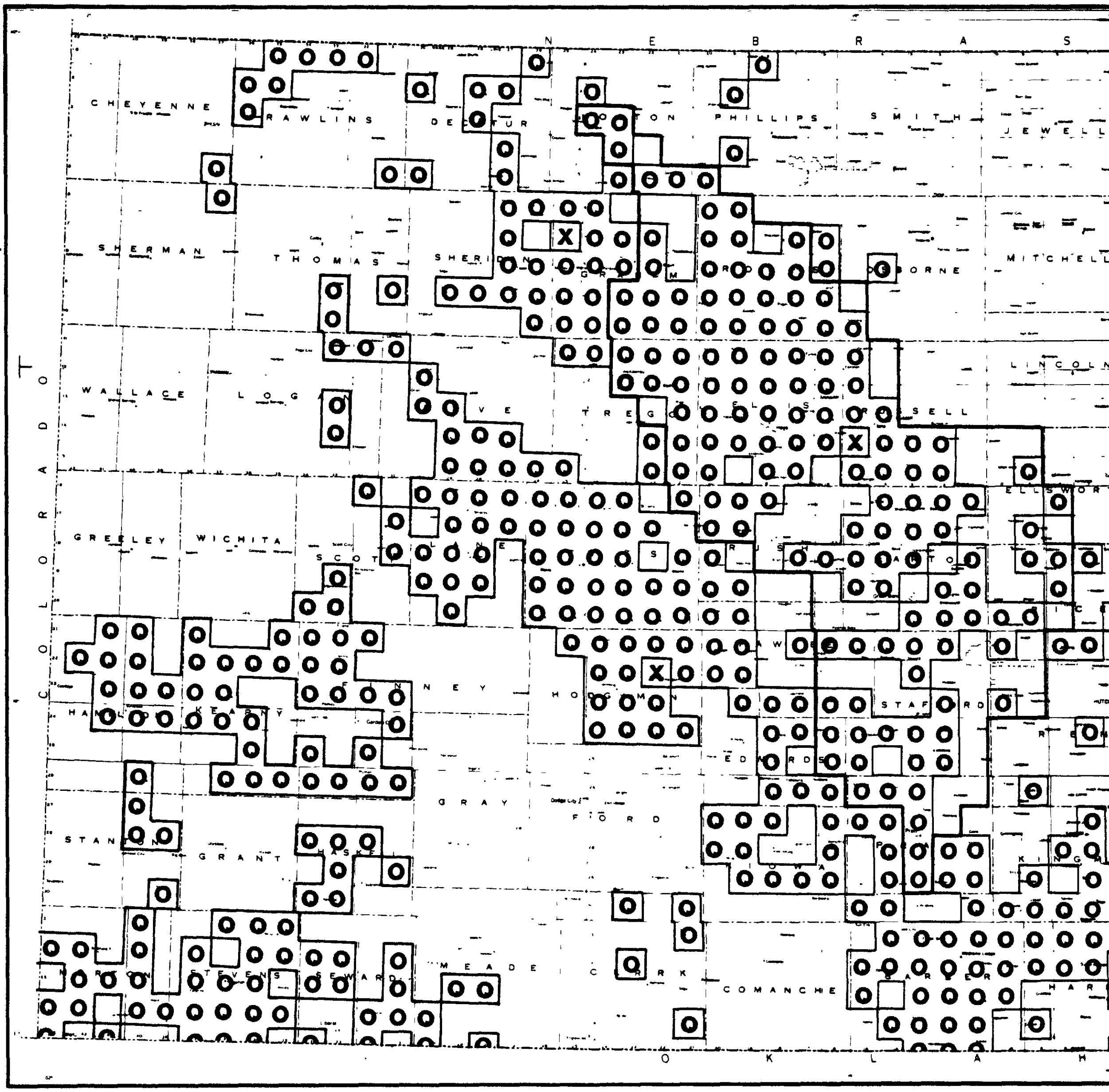


Data from records of the Kansas Department of Health and Environment, 1984

0 10 20 30 40 MILES

0 10 20 30 40 KILOMETERS

Figure 29.--Adjudicated rate of brine disposed into Arbuckle aquifer, 1984.



EXPLANATION

1984 ADJUDICATED RATE OF BRINE DISPOSAL PER TOWNSHIP, IN THOUSANDS OF BARRELS PER DAY

O 1-10

X 11-50

——— APPROXIMATE BOUNDARY OF CENTRAL KANSAS UPLIFT AREA

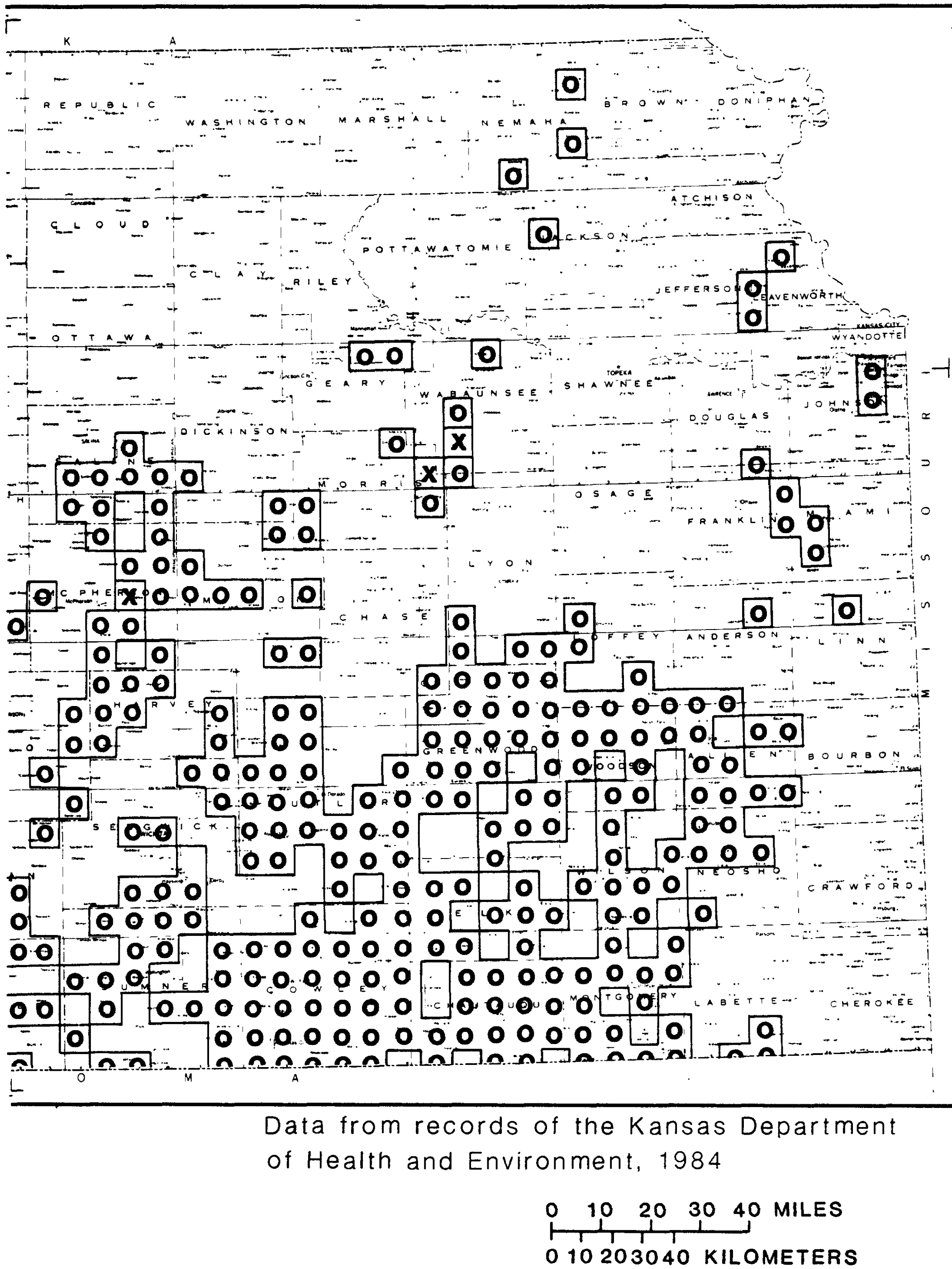


Figure 30.--Adjudicated rate of brine disposed into all other formations, 1984.

(4) The injection zone should contain brackish or salty water. Water containing more than 1,000 mg/L of dissolved solids is used for domestic, irrigation, and industrial water in some areas.

(5) The proposed injection zone must be separated from freshwater zones both laterally and vertically. Such an injection zone should be vertically below the level of freshwater circulation and confined vertically by strata that have slight permeability.

(6) There should be no unplugged or improperly plugged wells penetrating the proposed zone in the vicinity of the disposal well.

(7) The fluids to be injected should be compatible with the rocks in the injection strata and with the fluids in the strata.

(8) The injection zone should have a small internal hydraulic pressure to allow a sufficient margin for injection of fluids without causing hydraulic fracturing of the surrounding strata and to assure a long operating life of the disposal well.

(9) The proposed injection zone should be surrounded above, below, and laterally by strata with slight permeability. Many potential zones are surrounded above and below by such strata, and the lateral movement can be monitored in the injection zone. Good seals to minimize fluid movement are provided by anhydrite, clay, gypsum, marl, salt, slate, and unfractured shale.

(10) The hydrodynamic gradient, if any, for the proposed injection zone should be determined so that the path of fluid movement can be calculated.

As previously described, the Arbuckle aquifer has many of these characteristics. However, some areas of the Arbuckle would be less desirable for fluid injection than others, depending on the type of fluid under consideration. Several of the characteristics listed indicate that it may be difficult to contain fluid within the Arbuckle in some areas. Mainly, these areas are where large numbers of wells are drilled in the State, and the areas where geological uplift and fracturing have occurred. These areas would tend to have greater potential for vertical movement of fluids. Although the criteria that the injected fluids should be compatible with the rocks and native fluids is a very important part of waste disposal, its investigation was beyond the scope of this report. Therefore, this subject will not be covered, except to indicate that continued injection of acidic-type fluids could have a pronounced effect on the structural integrity of the Arbuckle. An example of this situation is discussed by Kaufman and others (1973).

Injection Wells

Present State law allows for the disposal of oilfield brines as a solution to the environmental problem of what to do with the fluids that are produced along with oil and gas production. In 1934, the State of Kansas enacted laws permitting the return of oilfield brines to any subsurface formation that already contained greatly mineralized water and also allowing the oil operators to use their produced brine for repressuring oil zones (Latta, 1973, p. 624). These brines are injected into aquifers containing other brines of a similar nature and, assuming containment in the saline-injection zone, normally do not pose problems. However, this injection can result in greater hydraulic potential for brines to move into adjacent aquifers than under natural flow conditions and can, therefore, cause greater dispersion of other more hazardous fluids if they were injected near these kinds of activities.

Although the State has regulations on the plugging of wells, some of the older oil wells in the State may not be plugged. In some cases, the location of the older wells may not even be known. The location, as of January 1984, of 2,077 active brine-disposal injection wells in the Arbuckle is shown in figure 31. Most of these injection wells are located on the Central Kansas uplift, the Nemaha anticline, or in the Sedgwick basin. The location of the active injection wells in the Arbuckle also was plotted by source of fluid, as listed in records of the Kansas Department of Health and Environment (Topeka, Kansas), and is shown in figures 32 and 33.

Although the source of fluid by geologic unit, as given by the records, was used to produce figures 32 and 33, it should be noted that the injected fluids are, in some cases, a composite of fluids from several different horizons. However, these maps still tend to demonstrate areas where large

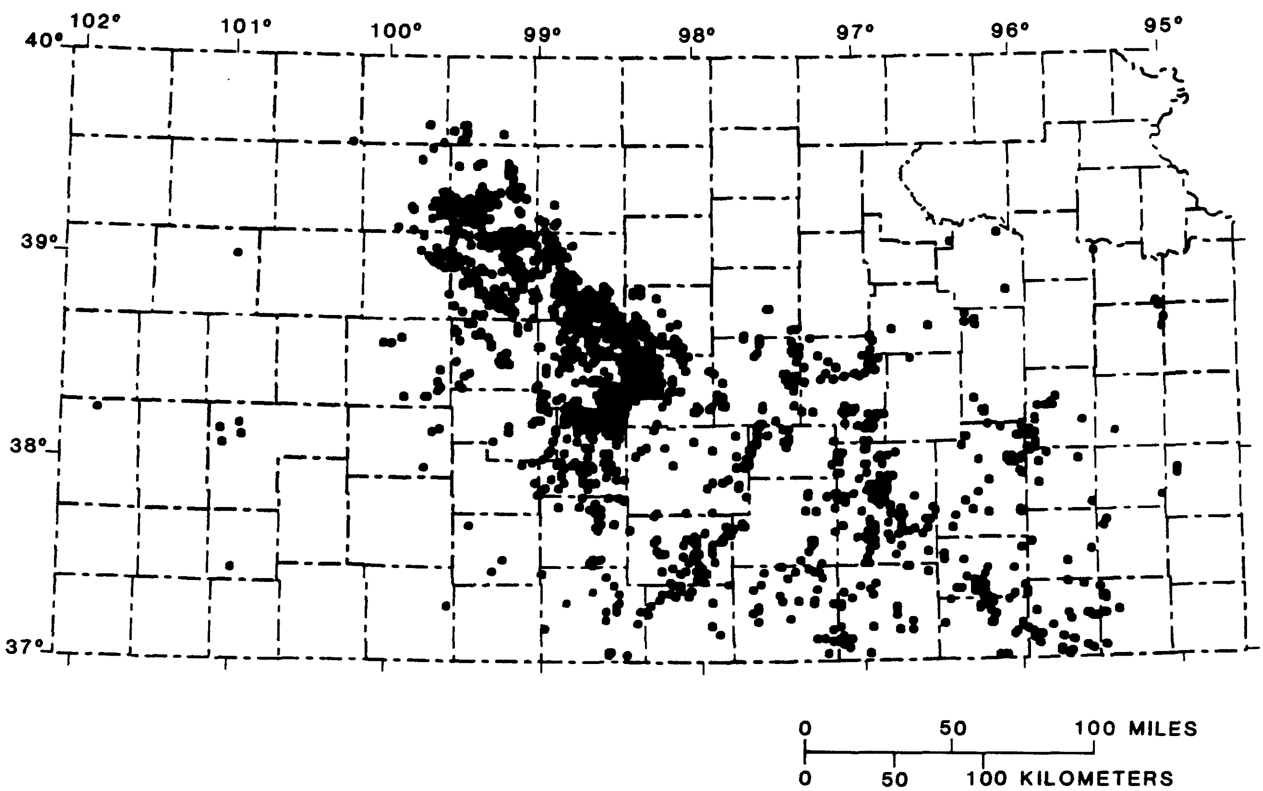


Figure 31.--Location of wells active in injection to Arbuckle aquifer, 1984.

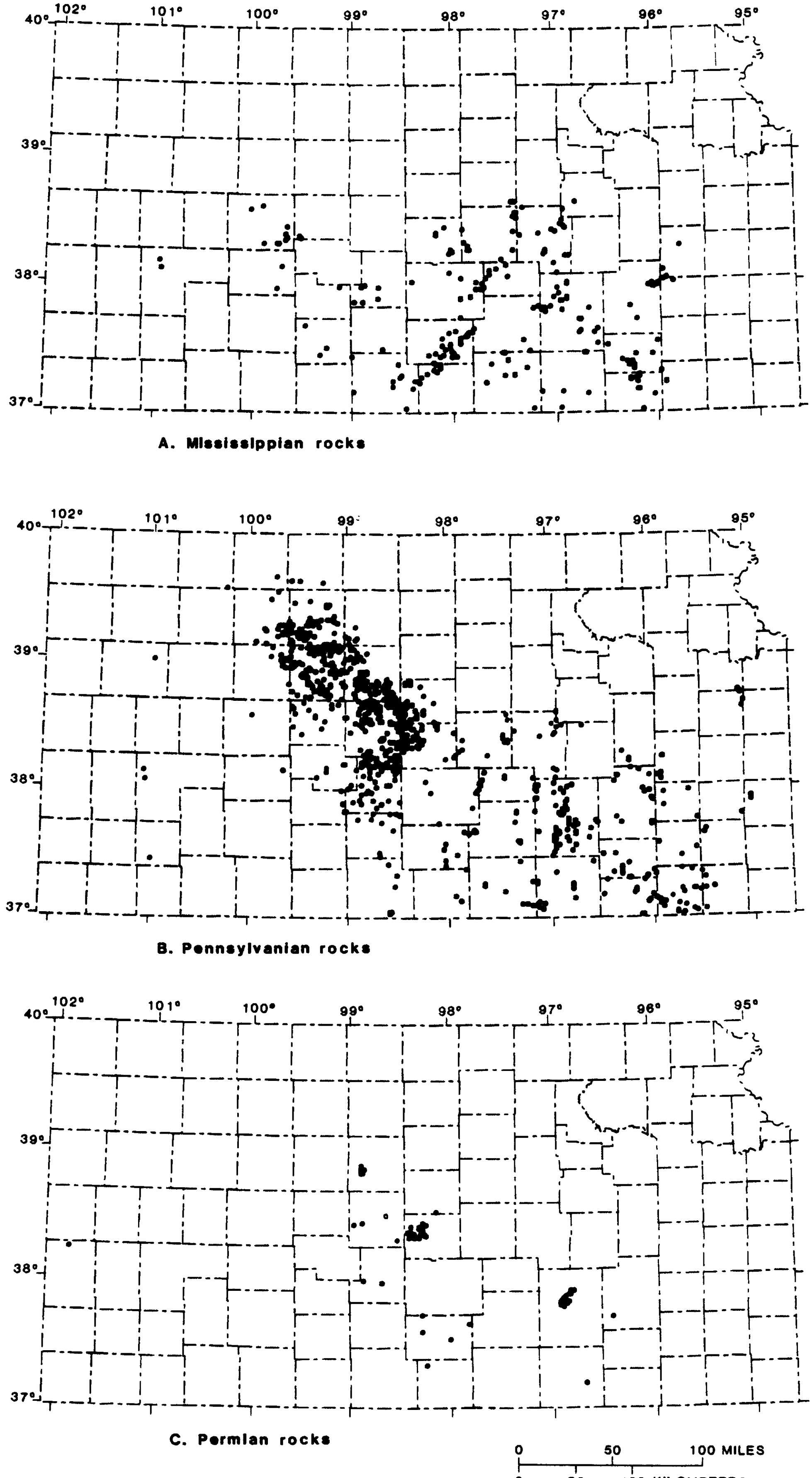


Figure 32.--Location of wells active in injection to Arbuckle aquifer with source of fluids from (A) Mississippian, (B) Pennsylvanian, and (C) Permian rocks, 1984.

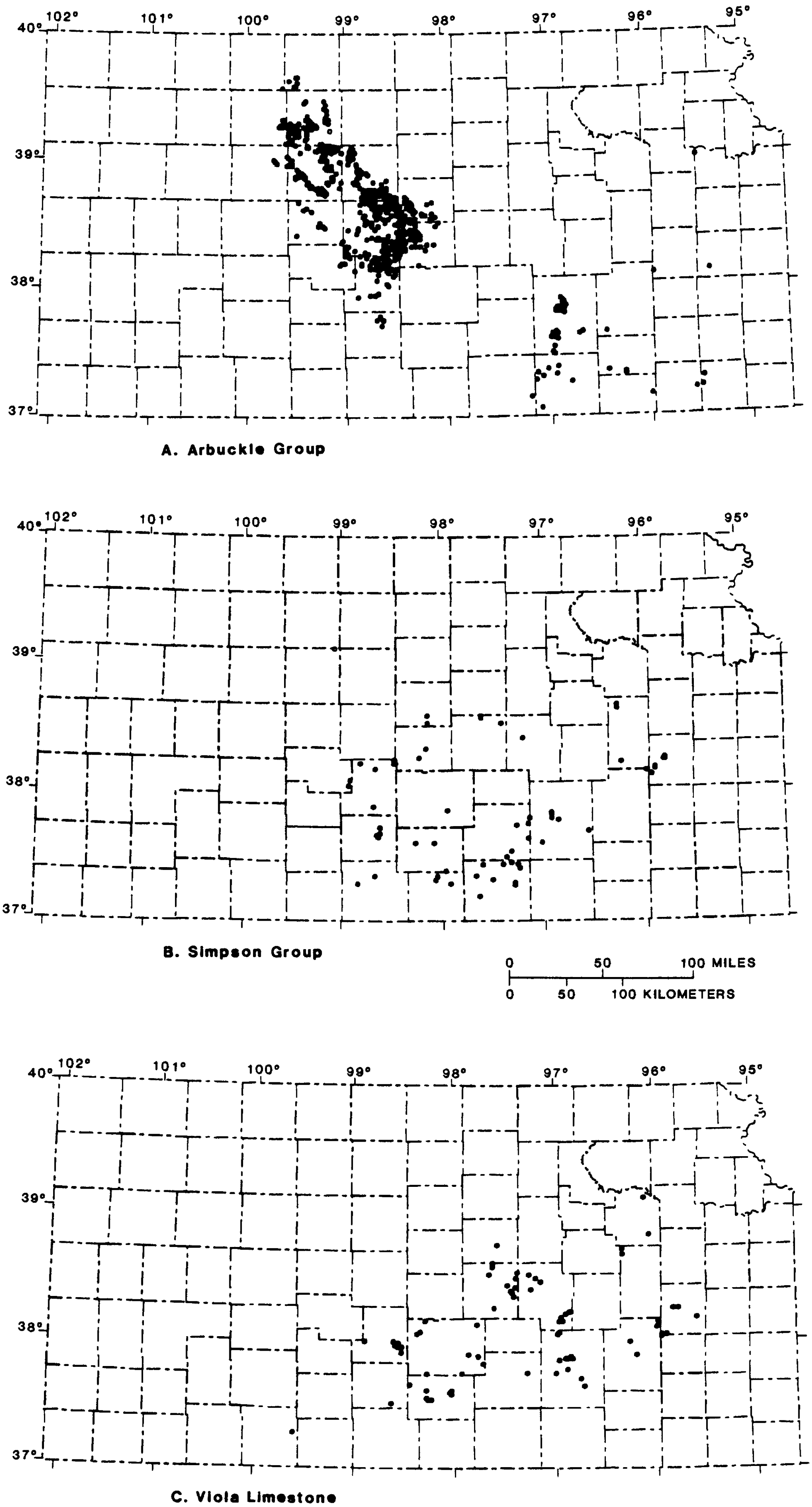


Figure 33.--Location of wells active in injection to Arbuckle aquifer with source of fluids from Cambrian and Ordovician rocks, 1984.

amounts of fluids are withdrawn from a particular geologic unit. Therefore, these fluids, with their corresponding water-quality characteristics in the area of withdrawal, could be imposed on the Arbuckle.

Historically, the records indicate that about 3,418 permits have been applied for disposal of brine into the Arbuckle. Of these, about 61 percent are active; 25 percent, plugged; 7 percent, never completed; 5 percent, abandoned; and 2 percent, inactive. About 80 percent of the plugged wells were plugged during 1942-67. About 50 percent of the active wells were permitted after 1970. In addition to the brine-disposal wells, there are about 60 waste-disposal wells in the State, but only 6 wells, located in the Sedgwick basin, were active as of 1982. During 1973, there were 30 industrial waste-disposal wells located in the Arbuckle, but only 25 were disposing of waste.

For brine-disposal wells, conductor casing is set and cemented in the lower 200-500 feet, or cemented from the bottom to the top of the hole. Tubing and packers are run, with the packing set just above the disposal zone. A noncorrosive fluid is place in the annulus between the tubing and the conductor casing. Industrial waste-disposal wells are constructed in a similar manner to protect freshwater zones. Surface casing is set and cemented through all freshwater zones. Most of these wells operate under gravity pressures.

Dependence of Pressure Response and Fluid Movement on Geohydrologic and Management Factors

The pressure response of an aquifer into which fluid is being injected partly determines the potential for fluid injection to affect other aquifers. The disposal-zone response is proportional to the permeabilty of the disposal zone and confining units, the viscosity of the native and the injected fluids, injection rates, and the accumulative time of injection. Leakage out of the injection zone may be composed of either native fluid, injection fluid, or both, depending on the emplacement position of the injected fluids in the aquifer. The rate of leakage will depend on the permeability of the confining units and on the accumulative time of injection. If the permeability of the injection zone is great enough, small pressures or even gravity flow may convey the required quantity of fluids and, therefore, lessen the possibility of potentially adverse effects on another aquifer. Greater injection pressures would have more potential to cause the injected fluids to rise in abandoned wells, if present, to cause more leakage vertically through the confining unit into other aquifers, to transmit more of the injected fluid vertically in the same aquifer, or to cause vertical fracturing near the well bore.

Although the Arbuckle is not uniform in permeability, depth, temperature, and thickness, a typical well site was assumed and analyzed using a conceptual model so that pressure responses and movement of injected fluid could be illustrated in this report. The purpose of the model was to illustrate a range of responses expected under different conditions of permeability, injected-water density, and time of injection. The response of the conceptual model under the assumed hydrologic conditions demonstrated that pressure buildup in the Arbuckle could cause abandoned wells to flow or fluids to leak upward into other aquifers. Also, the model results quantified the amount of injected-fluid that moved from the well under the assumed aquifer conditions.

The Intercomp model (Intercomp, 1976) was used to simulate an 11-layer, conceptualized aquifer system in radial cross section under varying conditions. Model nodes were spaced radially outward at approximately logarithmic intervals from the well site, with the center of the first node located at a distance of about 2.6 feet. The uppermost model layer (layer 1) represents an aquifer overlying the Arbuckle aquifer. An intervening confining unit is represented by layer 2. The Arbuckle aquifer is represented by layers 3 to 11 (9 layers) so that the effects of gravity and buoyancy could be observed. All layers were assigned a thickness of 60 feet. The top of layer 1 was assumed to be at a depth of 3,380 feet below land surface. The temperature at the top of the Arbuckle (layer 3) was assumed to be 40 °C. The permeability of the Arbuckle initially was simulated at a conservative uniform value of 100 millidarcies (0.2 ft/d) for each layer. Porosity of the Arbuckle was assumed to be 8 percent. The permeability of layer 1 was held constant at 100 millidarcies for all simulations. The horizontal permeability of the confining unit (layer 2) was set at 0.02 millidarcy (about 8.6×10^{-5} ft/d), and the vertical permeability was 0.01 millidarcy (about 4.3×10^{-5} ft/d). The logitudinal dispersivity was assigned a value of 30 feet. Although fluid density in the Arbuckle varies from about 62.3 to 70.8 lb/ft^3, a value of about 63.5 lb/ft^3 or about 25,000 mg/L of chloride was assumed to be typical for much of the State. The injected water was assumed to have a density of 65.1 lb/ft^3 or about 50,000 mg/L of chloride. It was assumed that the injected water did not react with the rocks or native fluid in the aquifer.

Permeability

Permeability in the Arbuckle aquifer, as previously discussed, is not uniform but varies both horizontally and vertically. Fractures and joint systems provide secondary permeability in some zones, and some of the zones have increased permeability resulting from vuggy porosity. As listed in table 1, permeability of the Arbuckle from drill-stem tests ranges from 1 to 755 millidarcies. Investigators have indicated that zones of relatively greater permeability might be expected to represent about 20 percent of the entire section of the Arbuckle. The estimate is based primarily on information obtained from geophysical logs. Geophysical-log interpretation at test holes 2 and 3 (fig. 2) also indicate intervals with much greater permeability than others.

Although zones of differing permeability occur in the Arbuckle, it can be shown that the pressure response of the system to injection is about the same for layered systems as it is for nonlayered systems, as long as the two systems are of equal transmissivity. Therefore, the pressure response can be approximated by analytical equations that make the assumption of uniform permeability. However, in a layered aquifer system, the movement of an injected fluid in a given layer is a function of the permeability, porosity, and thickness of that layer. If a well is open to various layers with different permeability, the fluid will travel more rapidly away from the well in the layer of greatest permeability. Therefore, the injected fluid will be transmitted outward in an irregular pattern from the well in this situation. Also, although considered as a constant in this model analysis, the hydraulic dispersivity of the media will affect the eventual distribution of the injected fluid. Because of the lack of better data on the Arbuckle, the analysis was limited to making gross simplifications of the system and indicating the system's response in terms of pressure changes under assumed ranges of values that approximately represent the Arbuckle aquifer.

The simulated pressure response of the Arbuckle, with the assumed hydraulic constants and with an injection rate of 11,551 ft^3/d (60 gal/min), is shown in figure 34. The distribution of pressure around the well after 1 day, 1 year, and 5 years of continuous injection illustrates that the rate of pressure increase is relatively rapid at first but decreases with time. The equivalent fluid-level rise that would occur in an observation well open to the top of the aquifer at any given distance on the graph also is shown in the figure. This is calculated using the density of the native water, although it is realized that the density will change as the injected water mixes with the native water. The 80-percent concentration point in the aquifer moves outward from the well with time. This point represents the location in the aquifer where 80 percent of the water in the aquifer is injected water and 20 percent is native water. Locations closer to the well will have larger concentrations of injected water. After 5 years of continuous injection, the 80-percent point of concentration of injected fluid has moved out to a point about 190 feet from the well. That is, within this radius all void space in the entire thickness of the Arbuckle would be filled with 80 percent or more of injected water. Again, it should be stated that these results assume uniform permeability and porosity throughout the aquifer.

In order to compare the results of a uniform aquifer system with those of a layered aquifer system, the model was setup so that the first Arbuckle layer (layer 3) had a permeability of 176 millidarcies and the second layer (layer 4) had a value of 5 millidarcies. This pattern was repeated for the remainder of the Arbuckle layers, resulting in alternating layers of larger and smaller permeability. The selected values result in a lateral transmissivity for the aquifer equivalent to that of the previous example. The vertical permeability was assumed to be one-half of the horizontal permeability. The results of this simulation are shown in figure 35. A comparison of the pressure distributions indicate very similar results to the uniform permeability simulated earlier. As previously discussed, the movement of the injected fluid is dependent on the permeability and porosity of the various layers. This is shown in figure 35 by the difference in the distance of the 80-percent concentration point with time between the two layers. The 80-percent concentration point of layer 3, with a permeability of 176 millidarcies, after 1 year of continuous injection has moved out to about 92 feet and after 5 years of continuous injection has moved out to about 230 feet. Whereas, the 80-percent concentration point in layer 4, with a permeability of 5 millidarcies, is located near the well after 1 year and has moved out from the well only

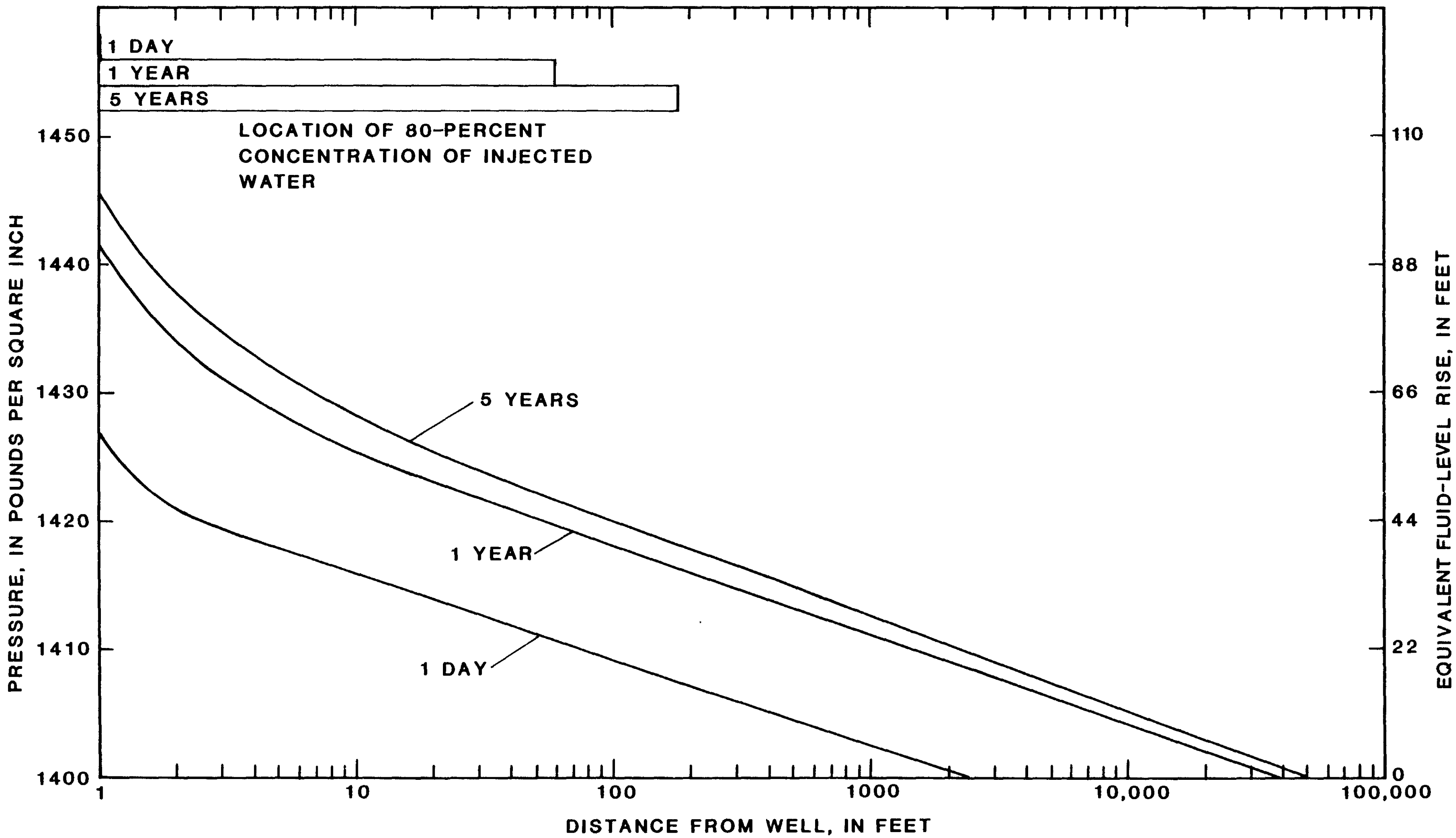


Figure 34.--Model-computed pressure and solute movement in top of Arbuckle aquifer after 1 day, 1 year, and 5 years of continuous injection in a homogeneous, anisotropic aquifer.

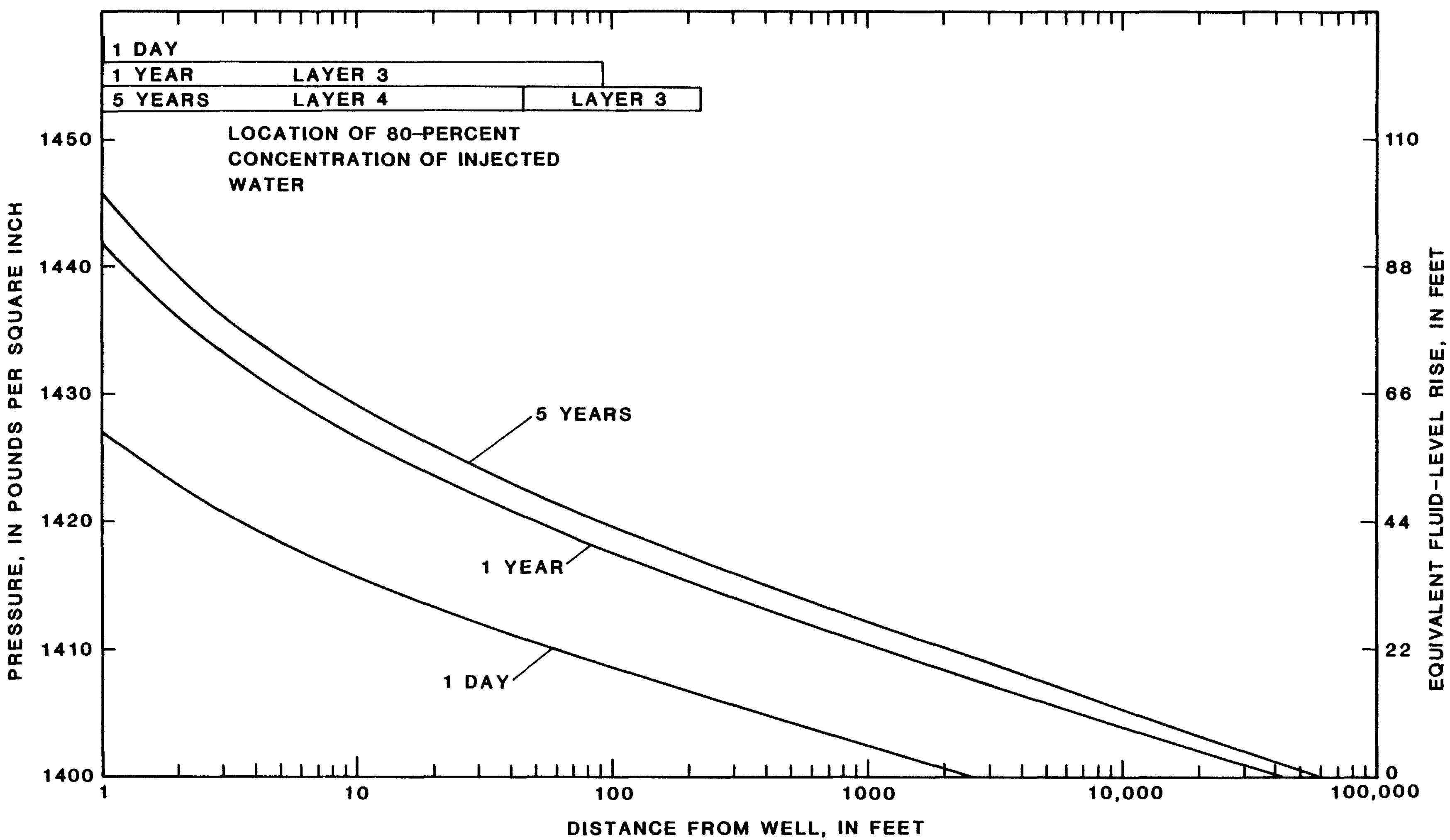


Figure 35.--Model-computed pressure in top of Arbuckle aquifer (layer 3) and solute movement in layers 3 and 4 after 1 day, 1 year, and 5 years of continuous injection in a heterogeneous, anisotropic aquifer.

about 45 feet after 5 years. With the assumed conditions of the model, the layers with the larger permeability acted as a source of injected fluids to the adjacent layers, transmitting the injected fluid vertically after sufficient time has passed.

The pressure response of the aquifer system can change dramatically depending on the transmissivity at the site of injection. The two previous simulations were of uniform and layered permeability but were of equal net lateral transmissivity. Pressure responses of the aquifer, assuming uniform permeability of different magnitudes are shown in figure 36. The permeability values used in the simulations were 100 millidarcies (about 0.2 ft/d at 20 °C), 200 millidarcies (about 0.4 ft/d), and 400 millidarcies (about 0.8 ft/d). Although permeability was changed in the simulations, the difference in the location of the 80-percent concentration point was minimal. The range of the 80-percent concentration point was from about 180 feet to 197 feet from the well after 5 years of continuous injection.

Changes in the vertical permeability of the confining layer were not tested in the model. Only the ratios of 0.5 and 1.0 of the vertical-to-horizontal permeability in the Arbuckle were compared, although in long-term operations a leaky confining layer can be of major importance. The pressure response in the overlying aquifer to 60 gal/min of injection fluid, the least-stressed simulation, was an increase of about 6 lb/in^2 near the well. Also, the injected fluid did move into the confining layer. If the simulation period was long enough, the injected fluid would have entered the overlying aquifer but at a very slow rate.

In areas where the Arbuckle is overlain by a confining unit, such as the Platteville Formation in the Salina and Forest City basins, or the shale within the St. Peter Sandstone in the Sedgwick basin, the injected fluid would tend to spread out over large distances before any substantial leakage would occur. The longer the path of movement in the Arbuckle, the more time there is for dilution of the injected fluid to take place.

Fluid Viscosity and Density

As shown in figure 36, the pressure response to injection is partly a function of the hydraulic conductivity or intrinsic permeability. Hydraulic conductivity, as described in the section on hydraulics, is partly dependent on the viscosity of the fluids, which is, in turn, a function of the temperature and solute concentration. The native fluid has a viscosity dependent on the temperature and concentration of dissolved solids in the fluid under aquifer conditions. The injected fluid may have a different viscosity and concentration of dissolved solids, which, on entering the aquifer, would result in a different hydraulic conductivity than that associated with the native fluid. Therefore, the aquifer will have one hydraulic conductivity with the native fluid, another with the properties of the injected fluid, and a range of hydraulic conductivity as the injected fluid mixes with the native fluid and equilibrates with temperatures in the aquifer. The Intercomp model takes all of these factors into account in the calculation of the pressure response to injection.

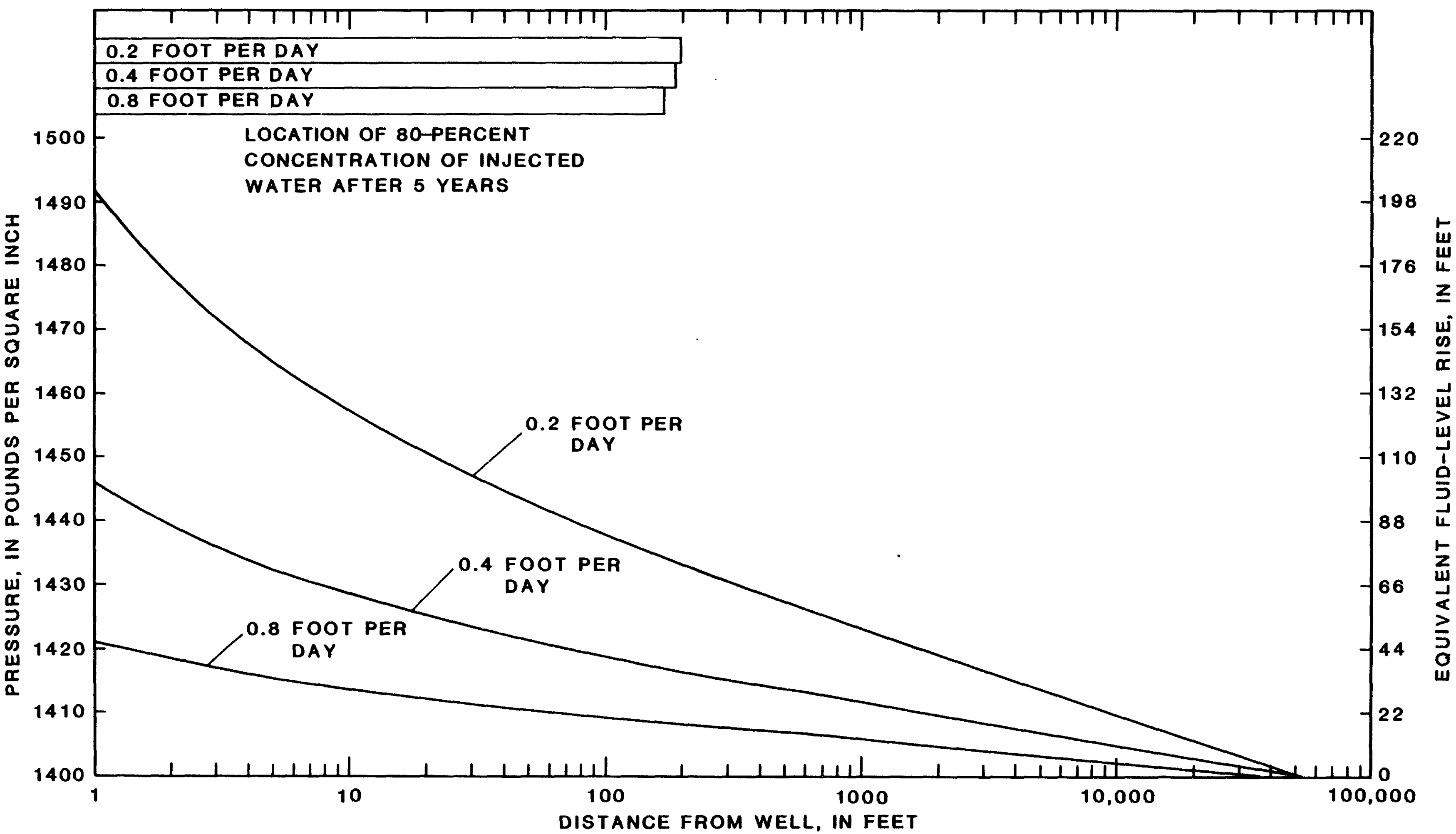


Figure 36.--Model-computed pressure and solute movement in top of Arbuckle aquifer (layer 3) with selected permeability values after 5 years of continuous injection in a homogeneous, anisotropic aquifer.

Three model simulations were made under conditions of different solute concentrations, and therefore viscosity, to demonstrate the range of expected pressure responses and injected-fluid movement. Also, these simulations were conducted to observe effects of buoyancy and gravity as related to different densities of injected fluid. These factors were observed under three different aquifer-permeability distributions. The first distribution consisted of a uniform permeability of 100 millidarcies assigned to each layer modeled. The second simulation alternated the permeability of each Arbuckle layer with values of 140 and 50 millidarcies. The third simulation used alternating-layer permeability values of 176 and 5 millidarcies. The results of these simulations are shown in figures 37-39. As shown by these figures, the pressure response was similar in all cases. In practical terms, the movement of the injected fluid was about the same for all cases, with the maximum distance of the 80-percent concentration point at about 260 feet after 5 years of continuous injection.

Under the conditions simulated, the effects of gravity and buoyancy due to the density differences were minor. Vertical differences in the solute concentrations were observed in the modeled layers, but these differences were small. The gravitational and buoyancy driving forces are a function of the relative difference between the density of the native- and injected-fluid density. However, with the gradients generated, only minor fluid movement occurred with the vertical hydraulic conductivity assigned to the model within the time span of the model simulation. The relative differences in the density values of the two simulated fluids covered the approximate range that exist in the aquifers throughout the State. The vertical hydraulic conductivity assigned to the model layers was within the range believed to be present in the basin areas of the Arbuckle. Therefore, the results indicated that vertical movement of fluids occurs when density differences are present but that the movement is slow. Simulations also were made to determine if a change in the ratio of the vertical to horizontal permeability (by a factor of two) would change the results substantially. These simulations indicated only small differences with the permeability values simulated.

Rate of Injection

The pressure response and injected-fluid movement for various rates of injection are shown in figure 40. The rates simulated were 19,251 ft^3/d (100 gal/min), 38,503 ft^3/d (200 gal/min), and 57,754 ft^3/d (300 gal/min). The density of the injection fluid was 66.0 lb/ft^3. The average rate of injection in the Arbuckle aquifer for brine-disposal wells is about 50 gal/min; however, many wells may inject as much as 300 gal/min. Hatfield and Hicks (1949) indicated that some wells may inject up to 15,000 barrels per day (438 gal/min) under gravity conditions into the Arbuckle. Latta (1973) indicated that brines were injected into a well in the Arbuckle at a rate of 3,000 barrels per hour (2,100 gal/min) under gravity conditions. The 80-percent concentration point for the simulated rates of injection ranged from about 230 to 410 feet from the well after 5 years of continuous injection.

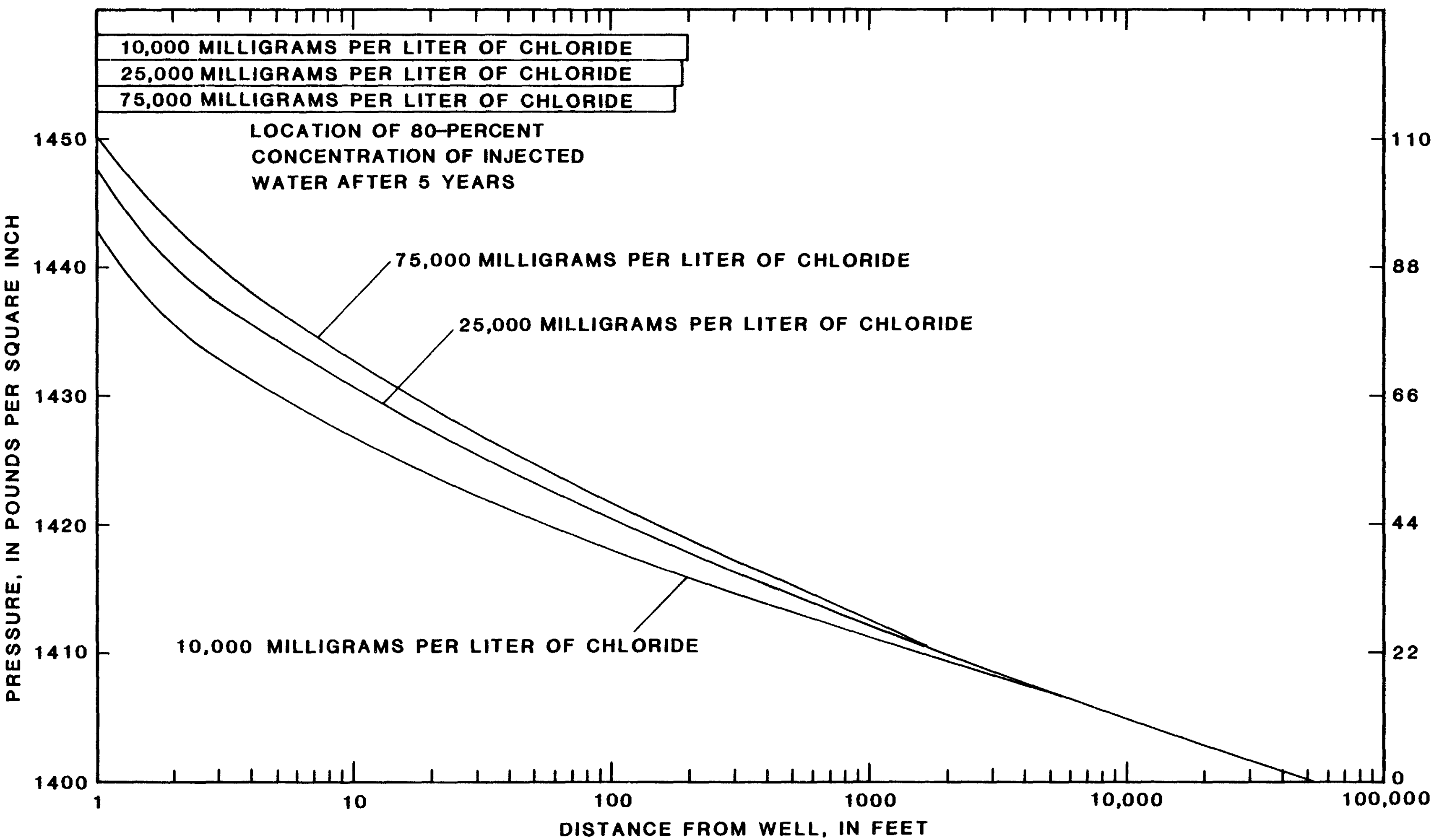


Figure 37.--Model-computed pressure and solute movement in top of Arbuckle aquifer (layer 3) with selected values of injection-fluid density after 5 years in a homogeneous, anisotropic aquifer.

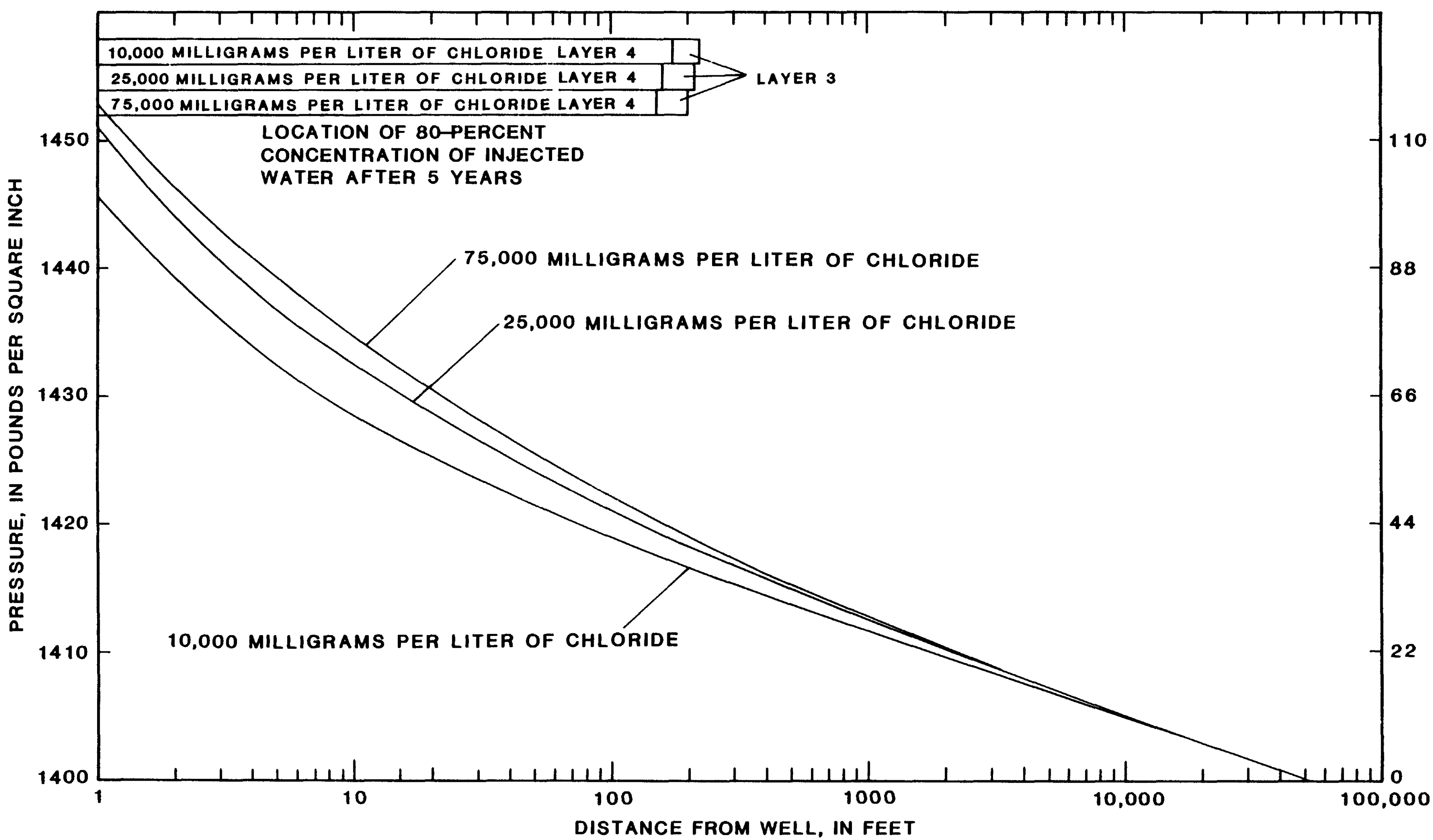


Figure 38.--Model-computed pressure in top of Arbuckle aquifer (layer 3) and solute movement in layers 3 and 4 with selected values of injection-fluid density after 5 years of continuous injection in a heterogeneous, anisotropic aquifer ($\frac{K3}{K4} = 2.8$).

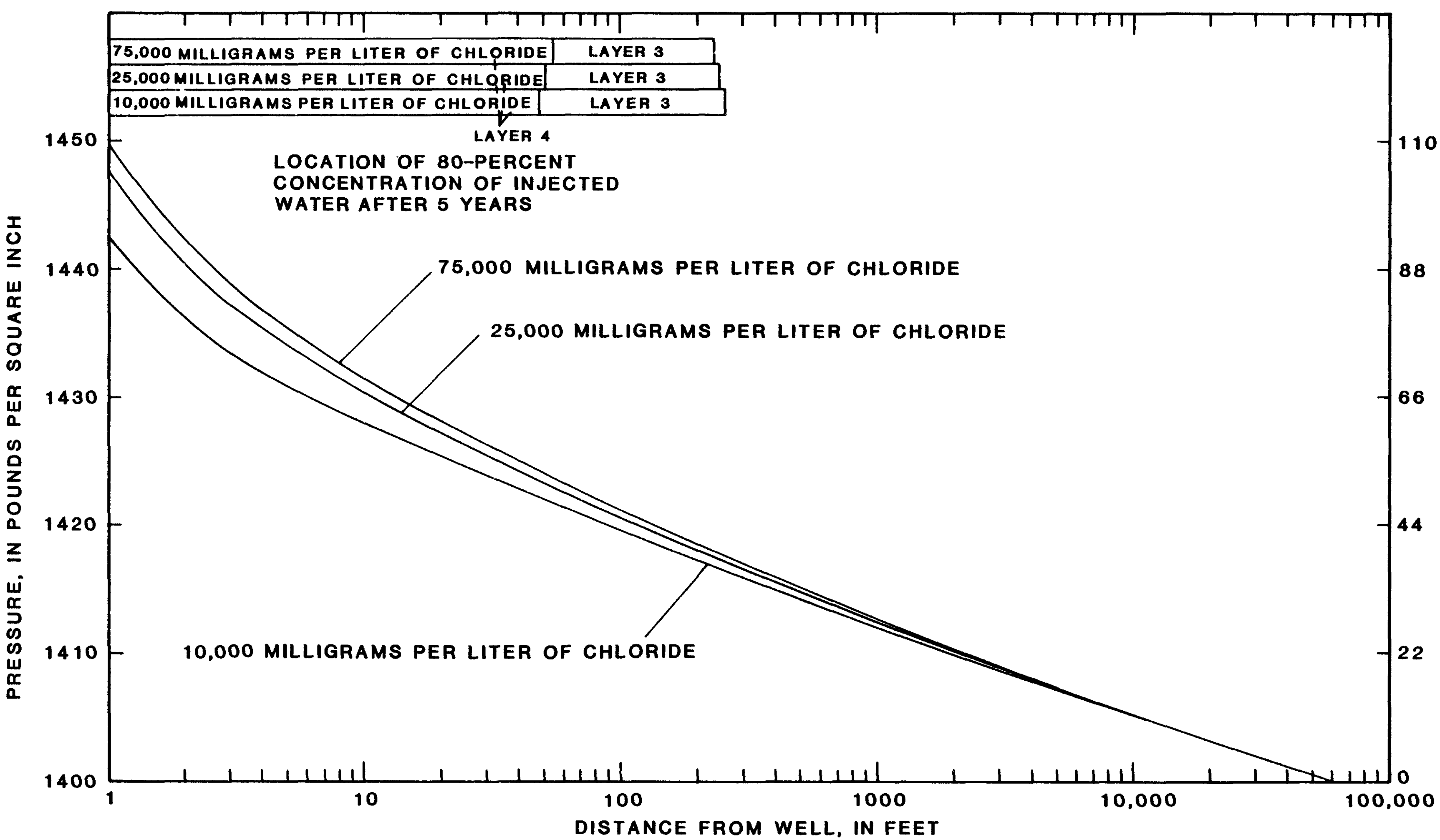


Figure 39.--Model-computed pressure in top of Arbuckle aquifer (layer 3) and solute movement in layers 3 and 4 with selected values of injection-fluid density after 5 years of continuous injection in a heterogeneous, anisotropic aquifer ($\frac{K3}{K4}$ = 35.2).

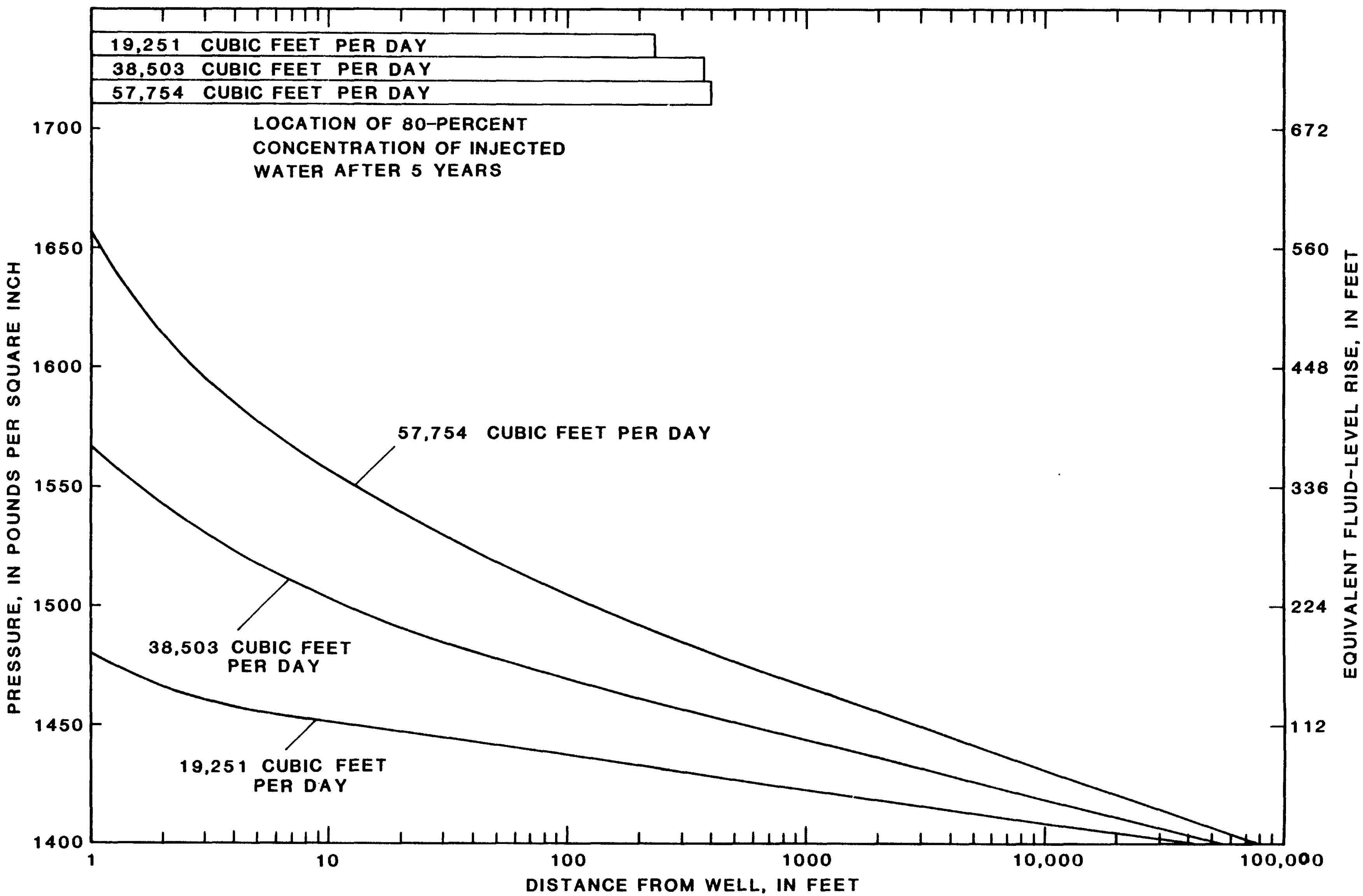


Figure 40.--Model-computed pressure and solute movement in top of Arbuckle aquifer (layer 3) with selected injection rates after 5 years of continuous injection in a homogeneous, anisotropic aquifer.

Partial Well Penetration

As discussed, the Arbuckle aquifer and the other aquifers are a composite of layers, and each layer has different permeability. If an injected fluid is present in the top of an aquifer and in contact with a confining layer, then that fluid can be driven upward by either natural gradients or gradients resulting from fluid injection. However, increases in pressure will be dissipated, and associated vertical fluid movement will be contained in an aquifer because energy is lost in driving the fluid through the confining layer or through aquifer materials overlying the point of injection. Therefore, if it is desired to contain a given fluid, then a logicial position for the placement of that fluid would be in the lower part of the aquifer, assuming a "no-flow" boundary below as in the case of the Arbuckle. This also assumes that there are no wells, faults, or fractures present that might transmit the fluids upward with relatively little resistance. The fluid then must traverse the overlying aquifer material and their associated resistance to flow before coming into contact with the confining layer or an overlying aquifer.

A model simulation with a uniform-layer permeability of 100 millidarcies was used to demonstrate the decrease in pressure in the upper layer of the Arbuckle aquifer if the well is open only to the lower layers. The well was open to layers 9-11 in the model. The results of this simulation are shown in figure 41. The injected fluid is first displaced outward in the layers open to the well, and a slow increase of pressure occurs in layers above these. The pressure in layer 3 (top of the Arbuckle) is now very small relative to the pressure in layer 9. The effects as shown will depend, of course, on the vertical and horizontal permeability of the aquifer. However, the Arbuckle has zones of greater and lesser permeability and, therefore, in general would be expected to react in a similar fashion. This mode of operation probably would be of particular interest in basin areas where the layering may be more continuous and areally extensive.

Natural Regional-Flow Velocities

When fluid is injected into an aquifer, the flow distribution resulting from the well is superimposed onto the regional-flow field. The existing background fluid velocities and potentials in the aquifer will alter the flow distribution around the well, distorting the symmetrical pattern that would occur if the background field were stationary. The degree of distortion will be a function of the velocities in the regional-flow system and could substantially alter the direction of movement of injected waste. However, the regional rate of movement of natural flow in the Arbuckle aquifer is believed to be very slow, possibly less than 1 ft/yr. Therefore, the influence of this background fluid velocity on the distribution of fluid moving away from an injection well would be minimal, and the flow pattern would be fairly symmetrical. That is, the injected fluid would move out from the well at almost equal rates in all directions from the well.

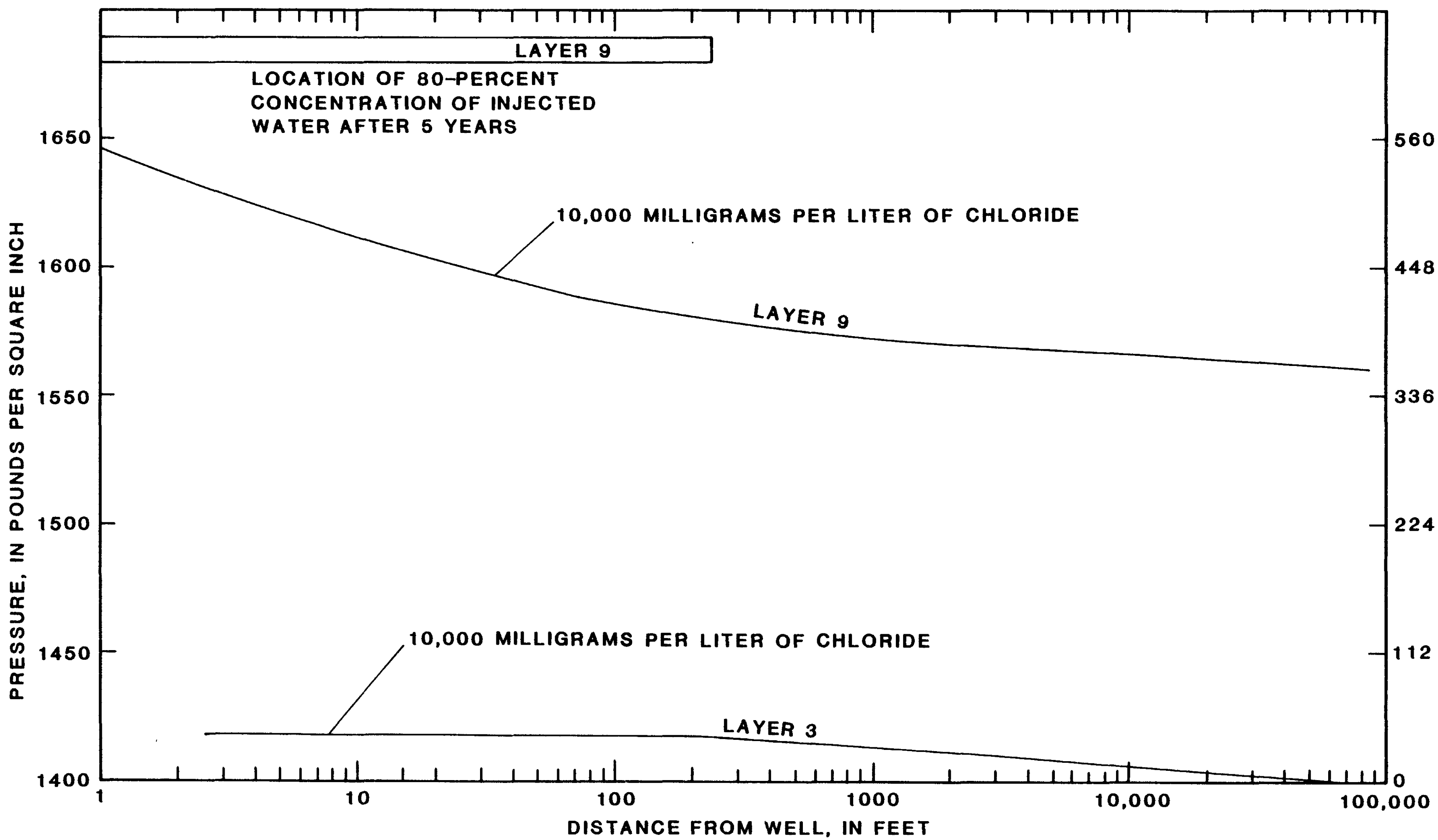


Figure 41.--Model-computed pressure in top of Arbuckle aquifer (layer 3) and layer 9 and solute movement in layer 9 after 5 years of continuous injection with well open to lower part of a homogeneous, isotropic aquifer (layers 9-11).

Evaluation of Injection Potential

The Arbuckle aquifer probably has more potential for accepting injection of fluids than any other saline aquifer in the State, in terms of accepting, under proper conditions of disposal, the most water with the least injection pressure and the least potential of affecting freshwater resources. Grandone and Schmidt (1943) indicated that 185.5 million barrels of brine had been injected into the Arbuckle up to 1942. By 1980, some 889 million barrels of brine per year were being disposed of in the Arbuckle. Injection rates have been reported as great as 2,100 gal/min for a well in the Central Kansas uplift area. Total disposal for 1980 (table 3) in the Central Kansas uplift area was about 474 million barrels per year (54.5 million gal/d). Yet fluid-level data indicate minimal fluid-level rise in this area. This information indicates that the Arbuckle can accept a large amount of fluid with little pressure increase in some areas, thereby decreasing the potential for contamination of other aquifers or freshwater zones.

However, as indicated by the simulations for individual wells with hydraulic properties similar to those assumed to be in the basin areas, there is more potential for an increase in pressure in the basin areas. This could present problems of containment if there are wells open to both the injection zone and to overlying strata or if the unit that confines the aquifer is relatively permeable. However, within these basin areas there probably is a greater potential to contain injected fluids because of more continuous confining units, relatively less disruption of the geologic strata, and less disruption of the natural flow system due to large amounts of brine injection. With these criteria, the more favorable areas of containment of fluids probably would be the central areas of the various structural basins, including the Salina, Forest City, Cherokee, and Sedgwick basins, and the Hugoton embayment.

CONCLUSIONS

The Arbuckle aquifer extends throughout Kansas, except for the major uplift areas where it has been removed by erosion. Rocks of different ages and different hydraulic characteristics are in contact with the Arbuckle. Where hydraulic-head differentials are present, a potential for transfer of fluids between these units results. The Arbuckle is comprised almost entirely of dolomite, except for the relatively thin basal sand. The dolomite has been affected by uplift, fracturing, and dissolution. Major regional zones of large permeability have developed throughout the State and probably are more well-developed on the uplift areas than elsewhere in the State. The thickness of the Arbuckle ranges from about 200 to 1,400 feet, generally increasing in thickness to the south. Depths to the top of the Arbuckle range from about 500 feet in the southeast part of the State to about 7,500 feet in the southwest. Ground water in the Arbuckle is saline everywhere except for the extreme southeastern part of the State.

Analysis of data obtained from drill-stem tests, injection tests, and modeling indicate that the permeability of the Arbuckle ranges from 1 millidarcy to about 30 darcies. Permeability in the basin areas is indicated to be smaller than in the uplift areas. Analysis of injection tests indicate the average permeability in the basin areas probably is in the range of 50 to 300 millidarcies. Analyses of 76 geophysical logs indicate an average porosity within the Arbuckle of about 12 percent. Specific-storage values calculated with data from geophysical logs indicate that the average specific storage for the Arbuckle is about 3.25×10^{-6} ft^{-1}.

The Arbuckle aquifer is part of a large regional ground-water flow system that is in direct hydraulic connection with several other major aquifers. Flow within the Arbuckle is principally from the west-northwest to the east-southeast, although there are areas where the flow is mainly to the east or west. Ground water in the Arbuckle enters the State from stratigraphically equivalent rocks in Missouri and moves to the west-northwest until it contacts a more saline ground-water flow system that moves upward to the south and east. Ground water of relatively freshwater enters the Salina basin from the north and moves to the south-southeast through the Sedgwick basin. Some of the ground water flows into the Forest City and Cherokee basins. Part of this water probably is the source of freshwater in the Central Kansas uplift and Nemaha anticline. Ground-water flow from the Arbuckle into the overlying Simpson Group (St. Peter Sandstone) probably occurs, primarily in the Sedgwick basin. The Simpson Group and Arbuckle aquifer generally are thought to be in hydraulic contact over much of Kansas because much of their flow and water-quality patterns coincide, and pressure gradients between the two units are much greater in the Sedgwick basin than elsewhere in the State.

Brine disposal in the Arbuckle has been increasing over the years. Prior 1942, only a total of 185.5 million barrels of brine had been injected into the Arbuckle, but by 1980 about 889 million barrels per year were being injected. Rates of injection were reported to be as great as 2,100 gal/min, but the average injection rate per well was about 60 gal/min. The greatest rates of injection are in the uplift areas. Regional effects of this injection on fluid levels in the Arbuckle are not well documented. However, reported fluid levels in the Central Kansas uplift area have not increased notably.

Model analysis, using aquifer properties similar to those expected in the basin areas and under selected conditions of well injection into the Arbuckle, indicates that, even with an injection rate of only 100 gal/min, pressure increases equivalent to fluid-level rises of up to 100 feet are expected as far as 500 feet away from the injection well. In general, if wells, fractures, or faults are present that allow avenues of transmission of fluid between the injection zone and some other unit, the fluid-level rises would be large enough to cause movement of the injected fluid from one unit to another. The model analysis indicates that the effects of transmission of fluid though the confining layer to overlying units are minor, with the assumed values of permeability used for the confining layer. Lateral fluid movement away from the injection well after 5 years of continuous injection at a rate of 300 gal/min reached a maximum of 400 feet. The model results indicate that the most favorable place to confine a given fluid is in the lower part of the Arbuckle. Within the limits tested for density and permeability, gravity and buoyancy effects were minor. However, movement of injected fluids caused by these forces could be important over long periods of time.

The Arbuckle probably has more potential for accepting injection of fluids than any other saline aquifer in the State, in terms of accepting the most fluid with the least amount of injection pressure. It also has the least potential to affect overlying freshwater aquifers. Certain areas are considered more favorable than others for containment of fluids because of the following criteria: minimum faulting and fracturing of geologic strata, more continuous confining units, more vertical distance between the injection zone and freshwater zones, and lesser amounts of brine disposal. These areas are the Salina, Forest City, Cherokee, and Sedgwick basins and the Hugoton embayment. The center of each basin area is considered to be more favorable than the periphery.

Additional information about the hydraulic characteristics of the Arbuckle aquifer and about the regional response of the Arbuckle to injection of fluids is needed to more fully evaluate the effects of injection on a regional scale. In particular, data on fluid-level changes due to previously injected fluids are sparse. Most available data provide information only for one point in space and time. Continuous-record observation sites need to be established to facilitate a more accurate appraisal of the regional characteristics of the Arbuckle. More complete records on injected fluids need to be recorded and so that better projections of regional response of fluid levels to injection in the Arbuckle can be made.

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LOG ANALYSIS OF ARBUCKLE AQUIFER

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Introduction

Modern geophysical logs provide the most cost-effective means of obtaining detailed and continuous information on rock and fluid properties in thick units such as the Arbuckle aquifer. The logging program conducted in the test wells of the Arbuckle aquifer for this investigation consisted of gamma-ray, spontaneous-potential, caliper, neutron, density, sonic, and dual-induction laterolog resistivity logs. The choice was dictated by the recognition of the Arbuckle rocks as "complex carbonate rocks" and by the aim of the investigation to elucidate mineralogical and porosity variation, as well as estimation of permeability.

Rocks in the Arbuckle aquifer are composed primarily of dolomite, chert, quartz sand, and shale. Porosity types are variable but are dominantly intercrystalline, intergranular, "vuggy," and fracture. Analysis of log data from the Arbuckle can determine mineral compositions of dolomite, silica, and shale as proportional estimates graphed as a function of depth. Chert and quartz sand are not determined separately by this logging analysis but are combined in a "silica" component. The log-analysis estimate of porosity includes a "primary-porosity" volume (broadly equivalent to intercrystalline and intergranular grades) and a "secondary-porosity" volume (vugs and fractures), on the basis of neutron-density and sonic-log relationships. Separate but somewhat inaccurate estimates of fracture and vuggy porosity can be made by analysis of the resistivity logs.

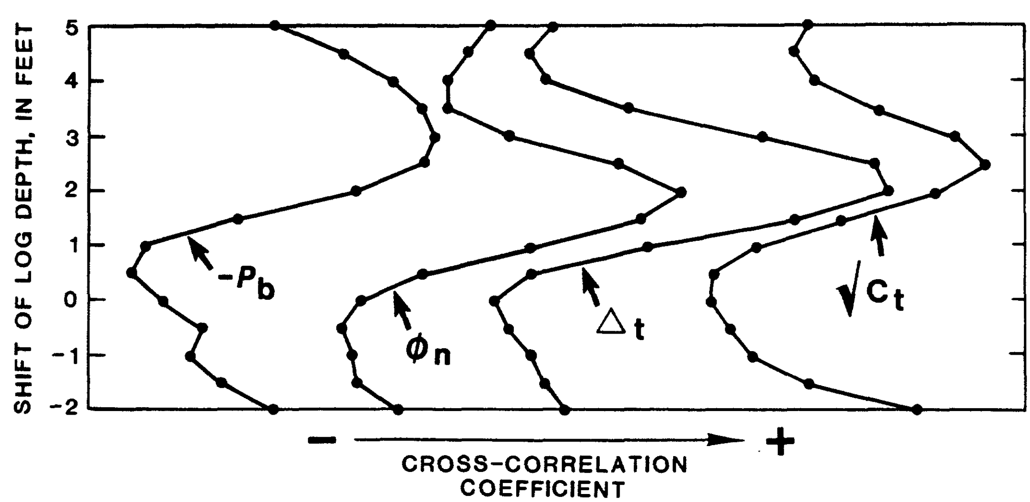
Estimates of geological properties can be made from combinations of logs using standard procedures of log analysis. However, many of these techniques are based on generalized relationships drawn either from theory or from empirical observations that are representative of "average" formation characteristics. Core-analysis data from short intervals of the Arbuckle are invaluable as a "ground-truth" reference for "remotely sensed" log data. Core data may be used for purposes of depth correction, log calibration (normalization), validation of log interpretations, and the development of predictive relationships that are specific to the Arbuckle. In the following sections, a detailed analysis of the Arbuckle formations is described for the section penetrated by test hole 2 in Douglas County (fig. 2), based on both log and core data.

Log-Depth Registration and Normalization

The stratigraphic sequence that overlies the Precambrian in the Douglas County test hole (site 2, fig. 2) consists of (in ascending order) the Lamotte Sandstone, Bonneterre Dolomite, Eminence Dolomite, Gunter Sandstone Member of the Gasconade Dolomite, Gasconade Dolomite, Roubidoux Formation, and the Jefferson City Dolomite. The sequence was logged with gamma-ray, spontaneous-potential, caliper, neutron, density, sonic, and dual-induction laterolog resistivity logs. Magnetic tapes were obtained for digitized log data recorded at a frequency of two readings per foot.

Continuous core was taken from a 24-foot interval in the Jefferson City Dolomite. Neutron, density, sonic, and laterolog resistivity logs were cross correlated with the core sequences of porosity to determine "best-depth" position match. Plots of cross correlation with depth lag are shown in figure 42. The optimal depth-match positions dictated the required vertical shifts of the logs to converge on a common value of depth. This step is a necessary prerequisite to the process of log normalization based on core data. In the remainder of the uncored section, local depth adjustments were made between logs based on recognition of specific features to accommodate depth discrepancies introduced by the variable stretch of the logging tool cables.

Once a common value of depth was determined for all logs, the core and log intervals were positioned for normalization. If grain density and porosity of a core are measured, the average bulk density of the cored interval is the appropriate criterion to normalize the density log. Transit times can be measured in core samples, and their average is suitable to calibrate the sonic log. However, this information is not commonly avail-



EXPLANATION

POROSITY VALUES FROM:

$-P_b$ Density log

ϕ_n Neutron log

Δ_t Sonic log

$\sqrt{C_t}$ Laterolog resistivity

Figure 42.--Cross correlation of log core data with lag shift for determination of depth registration.

able on routine core-analysis reports. Instead, apparent transit times may be estimated if the lithology is simple, based on mineralogical compositions deduced from the grain density. Following similar logic, neutron porosity can be estimated from core measurements of grain density and porosity. The averages of these estimates of transit time and neutron porosity over the interval are useful (if not precise) standards to compare with corresponding sonic- and neutron-log averages. The comparative figures from core and logs of the Douglas County test hole were:

	Core	Log
Average bulk density, in grams per cubic centimeter	2.64	2.64
Estimated average transit time, in microseconds per foot	60.3	57.0
Estimated average neutron porosity, in percent	14.1	14.3

Since these data show extremely close agreement between core and log estimates of average bulk density and neutron porosity, there is no need to make any corrections. The small discrepancy between the respective transit times can be explained easily. Vugs were reported in several of the core samples and could cause slower transit times in the computation of apparent transit time based on total porosity. The conclusion from this specific example is that log quality in this well was extremely good. If large deviations exist between core and log data, then the logs must be normalized using the core values as the standard.

Quantitative Mineral and Porosity Estimation from Logs

The basic composition of the Arbuckle is a five-component system of dolomite, silica (either chert and/or sand), shale, "primary porosity" (intercrystalline and intergranular), and "secondary porosity" (fractures and vugs). The grouping of quartz sand with chert is the consequence of the sensitivity of the logs to silica, but insensitivity of the logs to separate silica mineral species. However, primary and secondary porosity can be distinguished because of the preferential response of the sonic tool to small pore spaces as contrasted with the neutron and density logs, which are a measure of total porosity.

Unique solutions to give values to these five components require four logs for their resolution since the component proportions sum collectively to a closed system (Doveton, 1986). It is possible to write an equation set that links the unknown component proportions with the log responses measured at any depth:

Neutron:	$N_pP + N_sS + N_dD + N_qQ + N_{sh}Sh = N;$
Density:	$R_pP + R_sS + R_dD + R_qQ + R_{sh}Sh = R;$
Sonic:	$T_pP + T_sS + T_dD + T_qQ + T_{sh}Sh = T;$
Gamma ray:	$G_pP + G_sS + G_dD + G_qQ + G_{sh}Sh = G;$ and
Unity:	$P + S + D + Q + Sh = 1;$

where P, S, D, Q, Sh are the proportions of primary and secondary porosity, dolomite, silica, and shale, respectively; N, R, T, G are the neutron, density, transit time, and gamma-radiation log responses, respectively; and N_x, R_x, T_x, G_x, are the logging physical properties of component x, where x is assigned p, s, d, g or sh, matched with the components defined above.

The equation set can be simplified considerably when written in matrix algebra as:

$$CV=L,$$

where C is a matrix of the component log properties; V is a vector of the component proportions; and L is a vector of the log readings for a given zone. The solution of the unknown component proportions then is given by:

$$V=C^{-1}L,$$

where C^{-1} is the inverse of the component log properties matrix. By means of this relationship, the proportional composition of any zone in the Arbuckle sequence can be found immediately by premultiplying a column vector of the zone-log readings by the inverse of the component coefficient matrix. The elements of matrix algebra and their application to this method are described more fully by Doveton (1986, p. 154-159).

The algorithm is easily coded as a computer program and is the basis for the PETRA module of the KOALA system (described by Doveton and Cable, 1980). The digitized neutron, density, sonic, and gamma-ray logs were processed for numerical solutions of composition throughout the entire Arbuckle Group. The results of this long record were averaged over 10-foot intervals for ease of comparison with the sample-log description from cuttings, as shown in figure 43. In the presentation, the computed results are drawn on the left, while the formation designations from the sample log and the sample-log graph are transcribed on the right, together with statigraphic boundaries and unconformities. Overall, there is a striking concordance between these two independent sources of data, while the log analysis amplifies the compositional variation of the Arbuckle.

The subdivision of the Arbuckle into stratigraphic units has been based primarily on systematic changes in the character of insoluble residues at unit boundaries (Keroher and Kirby, 1948). These insoluble elements are the residues that remain following the dissolution of carbonate drill cuttings

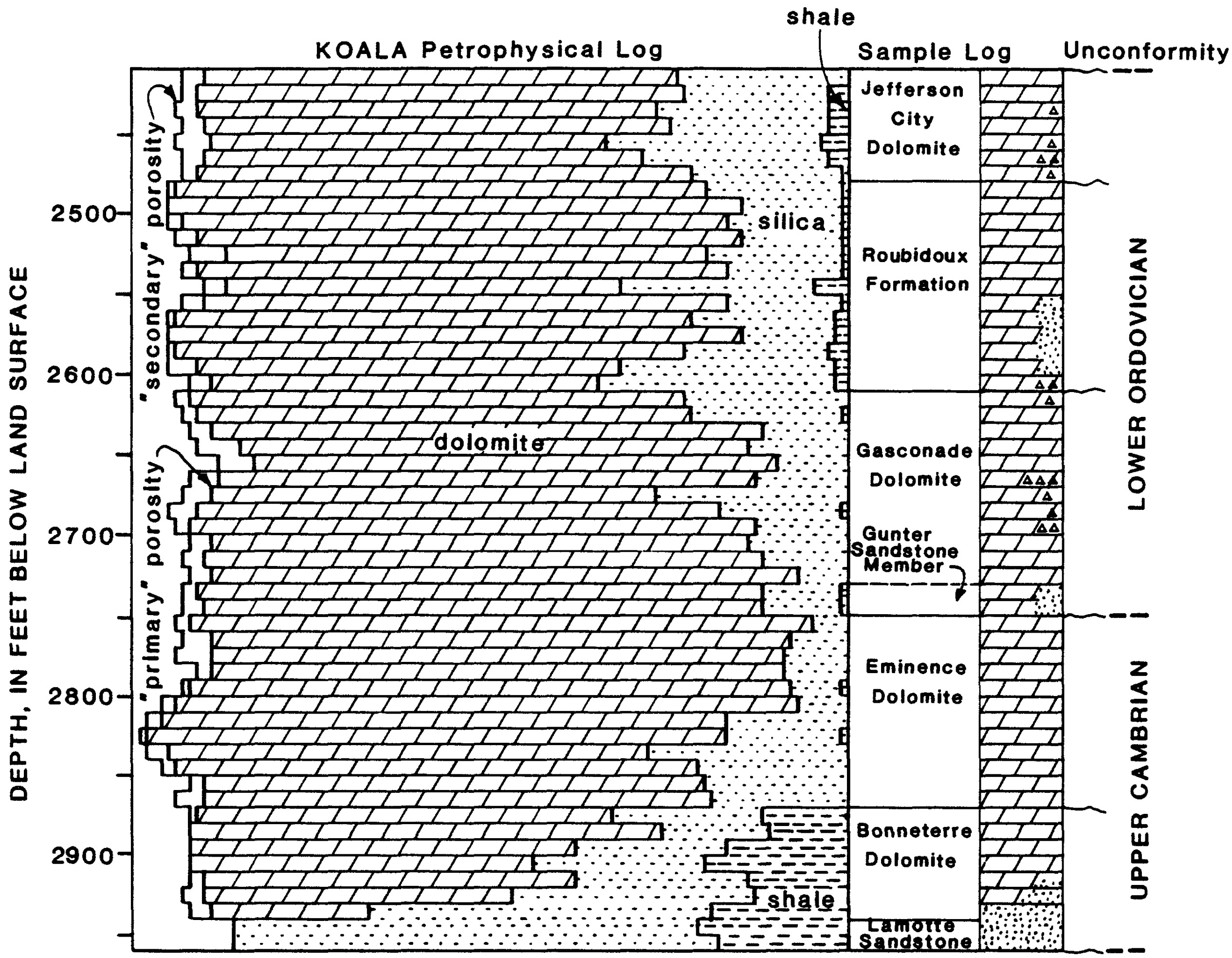


Figure 43.--Compositional profile of Arbuckle aquifer in test hole 2 in Douglas County derived from logs and matched with sample log.

in hydrochloric acid. Early work in stratigraphic correlation found that fossils were of limited value for formation definition, mainly because of their sporadic occurrence. The problem was compounded further in correlations based on drill cuttings, whose small size resulted in only limited amounts of fragmentary fossil material. Conventional lithostratigraphic methods were hampered by both the minor occurrence of distinctive shale and sandstone beds and their lack of persistence when traced laterally. The use of insoluble residues has proved successful in tracing equivalents of the Arbuckle units from their outcrop in the Ozark region of Missouri into the subsurface of both Kansas and Oklahoma (Ireland, 1944).

The procedure to determine insoluble residue is time consuming and not entirely accurate. Detailed analysis of drill cuttings requires the elimination of caving materials, solution of the hand-picked fraction in hydrochloric acid, and careful volumetric measurement. Even with these safeguards, the quantitative estimate of residue is too large owing to the loss of part of the dolomite host as rock flour in the drilling operation.

By contrast, the computer analysis of combinations of logs in the estimation of silica content (either sand or chert) has the merits of both speed and in-place measurement of the formation. The silica content can be equated with the volume of insoluble residues and applied to stratigraphic-correlation problems in the Arbuckle. The major drawback of logs is their failure to distinguish chert from sand so that their use must focus on patterns of volumetric change in silica as a function of depth.

The log-analysis solution of silica content for test hole 2 is shown in figure 44 in comparison with insoluble-residue estimates for Stanley No. 1, a test hole at a distance of 25 miles to the east of test hole 2. Most of the features of the two traces can be correlated when allowance is made both for the overestimate of residue and sampling problems associated with drill-cutting analysis and variations attributed to lateral facies changes over a distance of 25 miles. In practice, the application of data from computer-processed logs to solving problems of zonation and correlation could be coordinated with study of drill cuttings in much the same way that unprocessed logs are used to aid geologists in the preparation of detailed sample logs. In the specific case of work with the Arbuckle sections, data from analysis of the drill cuttings could be an essential key to allocate computed silica between components of chert and sand.

Porosity Variation in Arbuckle Aquifer

In addition to framework mineral composition, the computer-processed log provides estimates of "primary" and "secondary" porosity at a frequency of two readings per foot. The vertical resolution of the neutron-density, sonic-log combination dictates the scale of derived porosity variation at a dimension of approximately 2 vertical feet.

Histograms of total porosity (the sum of "primary" and "secondary" porosity) are shown in figure 45 for the separate units in the Arbuckle stratigraphic sequence. The histograms demonstrate that porosity distributions are markedly different between units. Stratigraphically defined divisions appear to be characterized by distinctive porosity distributions that are probably the cumulative result of differences in original depositional facies and diagenetic histories. Correlation coefficients computed between volumes of "primary" and "secondary" porosity are listed in table 4. Correlations of the Jefferson City Dolomite, Gunter Sandstone Member of the Gasconade Dolomite, and Bonneterre Dolomite show systematic negative coefficients. The implied inverse relationship between volumes of primary and secondary porosity may account for the relatively constricted range of porosity in these formations. By contrast, correlations in the Roubidoux Formation, Gasconade Dolomite, and Eminence Dolomite are uniformly small and are matched with a wider dispersion of porosity values. Regardless of the genetic explanation of these observations, it is clear that hydraulic studies of the Arbuckle should take interformational differences into account rather than consider the Arbuckle aquifer to be relatively homogeneous.

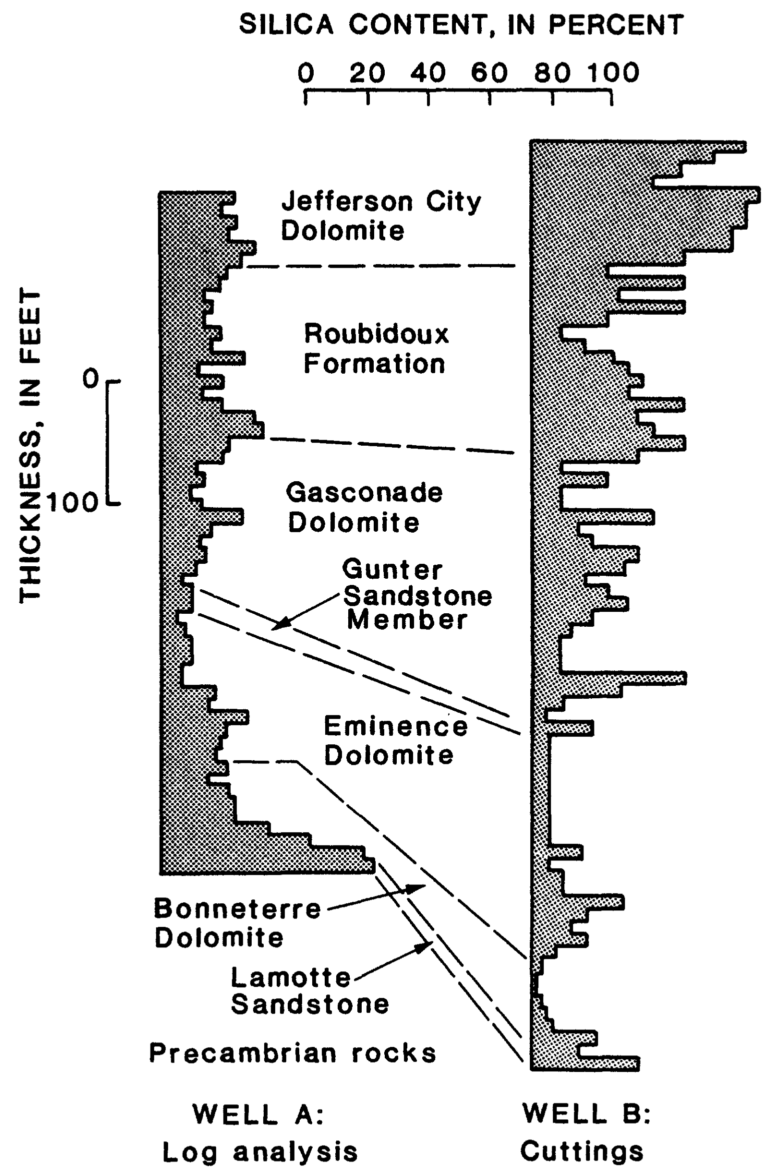


Figure 44.--Comparison of log analysis of silica content in Arbuckle aquifer of test hole 2 (well A) with drill cuttings in Stanley No. 1 (well B). Well B data from Keroher and Kirby (1948).

Resistivity-Porosity Relationships

Archie (1942) defined the formation factor as the ratio of the resistivity of a water-saturated rock to the resistivity of its pore water. From laboratory measurements of sandstone, he concluded that there was an approximately linear relationship between the formation factor and porosity when both are plotted on logarithmic scales. The numerical form of this relationship is:

$$F = 1/\phi^{m} ,$$

where F is formation factor; $\emptyset$ is fractional porosity; and m is a constant generally known as the "cementation factor." Subsequent workers have generalized this "Archie equation" to:

$$F = a/\emptyset^m ,$$

where "a" can take a value other than unity. Archie (1952) found t at the same relationship was an adequate description for limestone although there tended to be a greater scatter about the line, presumably reflecting the wider range of limestone pore structures. The most widely used form of the Archie equation for both limestone and dolomite is:

$$F = 1/\emptyset^2.$$

The apparent simplicity of this equation represents an average relationship that best typifies carbonate with intergranular and intercrystalline porosity.

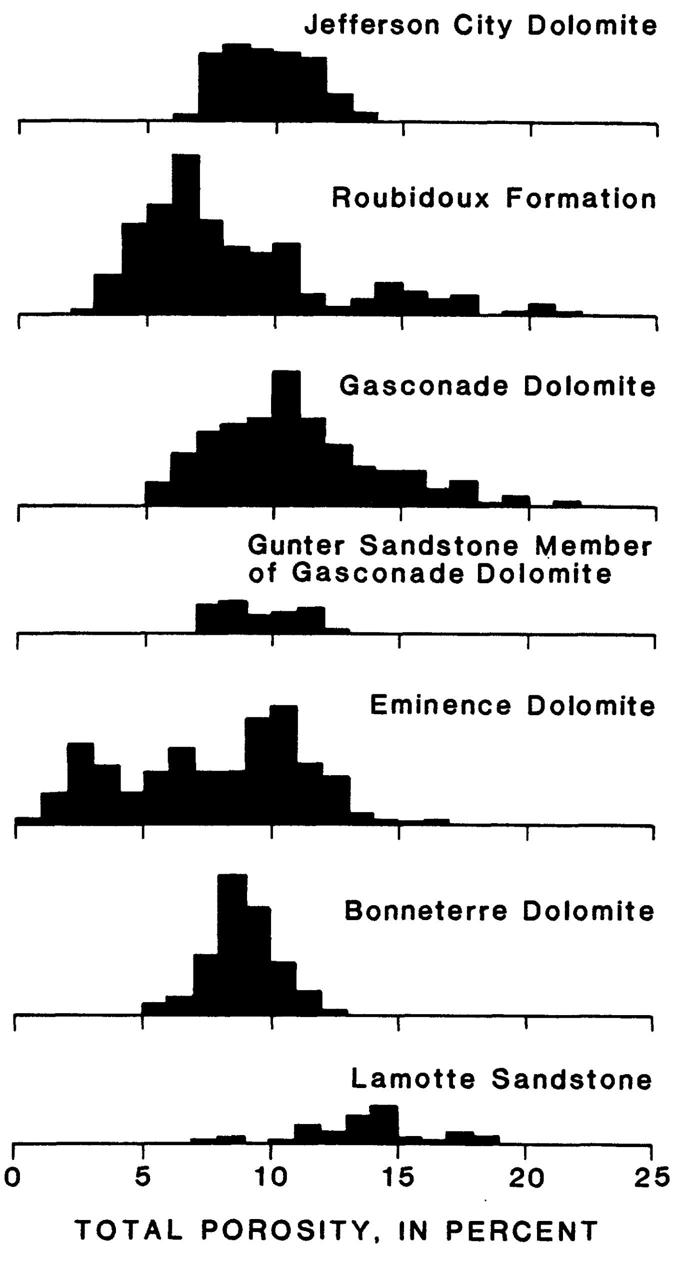


Figure 45.--Total porosity variation in units of Arbuckle aquifer in test hole 2.

Table 4.--Correlation coefficients between "primary" and "secondary" porosity in Arbuckle aquifer

Stratigraphic unit	Correlation coefficient
Jefferson City Dolomite	-0.77
Roubidoux Formation	.18
Gasconade Dolomite	- .01
Gunter Sandstone Member of Gasconade Dolomite	- .34
Eminence Dolomite	- .04
Bonneterre Dolomite	- .66

Cementation factors derived from carbonate core samples are generally associated with textural character. Chombart (1960) reported that cementation factors are generally between 1.8 and 2.0 for crystalline and granular carbonate, 1.7 to 1.9 for chalky limestone, and 2.1 to 2.6 for carbonate with vugs. The presence of fractures causes a reduction in the cementation factor to values in the neighborhood of 1.4 (Suau and Gartner, 1980). These numbers reflect the relative tortuosity of the aggregate pore network in each case. As such, they can be used as indicators of pore morphology, but any genetic implications are a matter for geological interpretation.

Core data from test hole 2 (Douglas County), test hole 3 (Saline County), and test hole 4 (Labette County) were combined to derive the relation between formation factor and porosity measured from the core. Plots of formation factor and porosity (fig. 46) were fitted with a function whose cementation factor is 1.94, which is close to an "average" carbonate cementation factor. However, computation of cementation factors for individual cores suggested that smaller cementation-factor values are associated with smaller porosity values. The degree of correlation between cementation-factor values and porosity was assessed in the calculation of a Spearman correlation coefficient of 0.49, which is statistically significant. The Spearman statistic is a ranked measure of similarity, which was used in preference to the more commonly used Pearson product-moment coefficient since it reveals distinctive monotonic trends but is not restricted to linear functions. This observation probably indicates the marked influence of fractures on the cementation factor in the small-porosity range. The effect would be compounded by the tendency of vugs to increase the cementation factor at larger porosity levels.

The same phenomenon also is suggested when a comparison is made between cementation factors computed from resistivity logs and corresponding zone porosity values in wells in the Arbuckle aquifer. A typical "cementation-factor log" is shown for a short section of the Roubidoux Formation from Douglas County test hole 2 (fig. 47). The cementation factor generally is close to the expected value of 2 but shows minor oscillations to larger values (possible vugs) and smaller values (possible fractures).

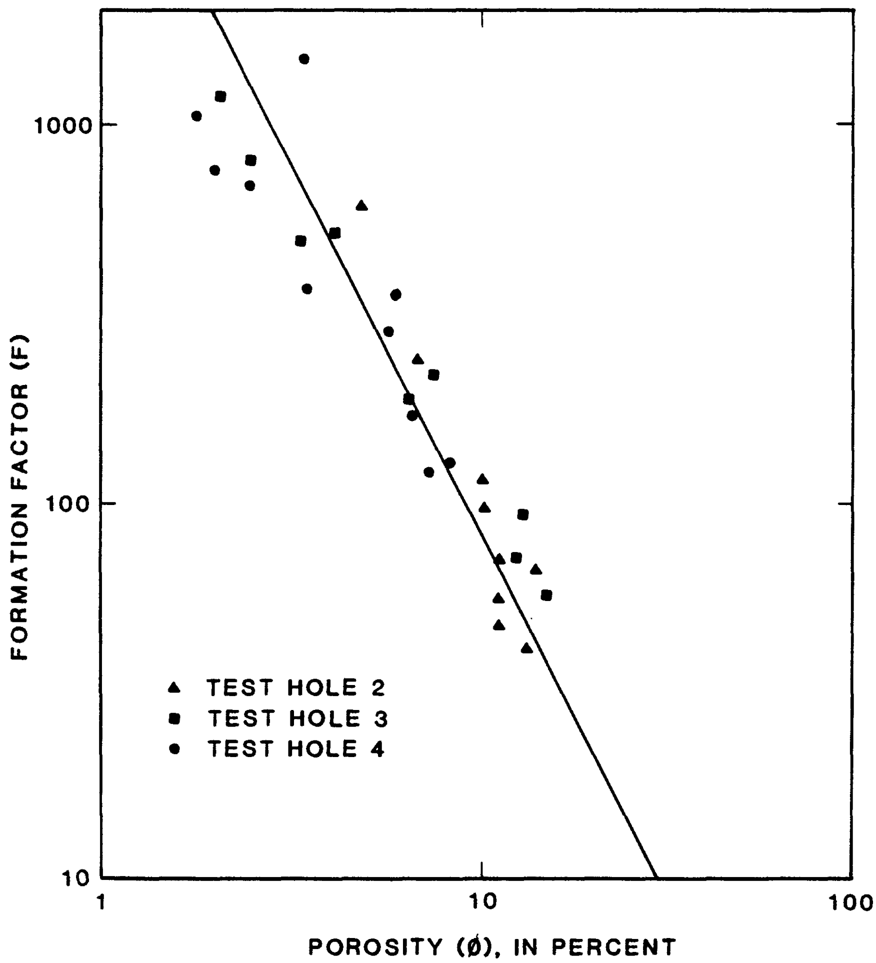


Figure 46.--Formation factor as a function of porosity from core data of Arbuckle aquifer.

As a method to characterize pore geometry, the use of the cementation factor is at best a qualitative technique. This limitation is due partly to the poorly understood relationships between electrical conductivity and the geometry of carbonate pore networks. However, a major complication is the fact that most carbonate zones exhibit several porosity types. Consequently, a cementation factor will reflect an aggregate average that may not be useful unless the porosity is dominated by a specific type. Finally, the primary interest in this type of method usually is in its potential to aid in the recognition of fractures. Unfortunately, the influence of fractures on resistivity logs is variable and affected by factors such as shape and orientation of fractures, and their fluid content.

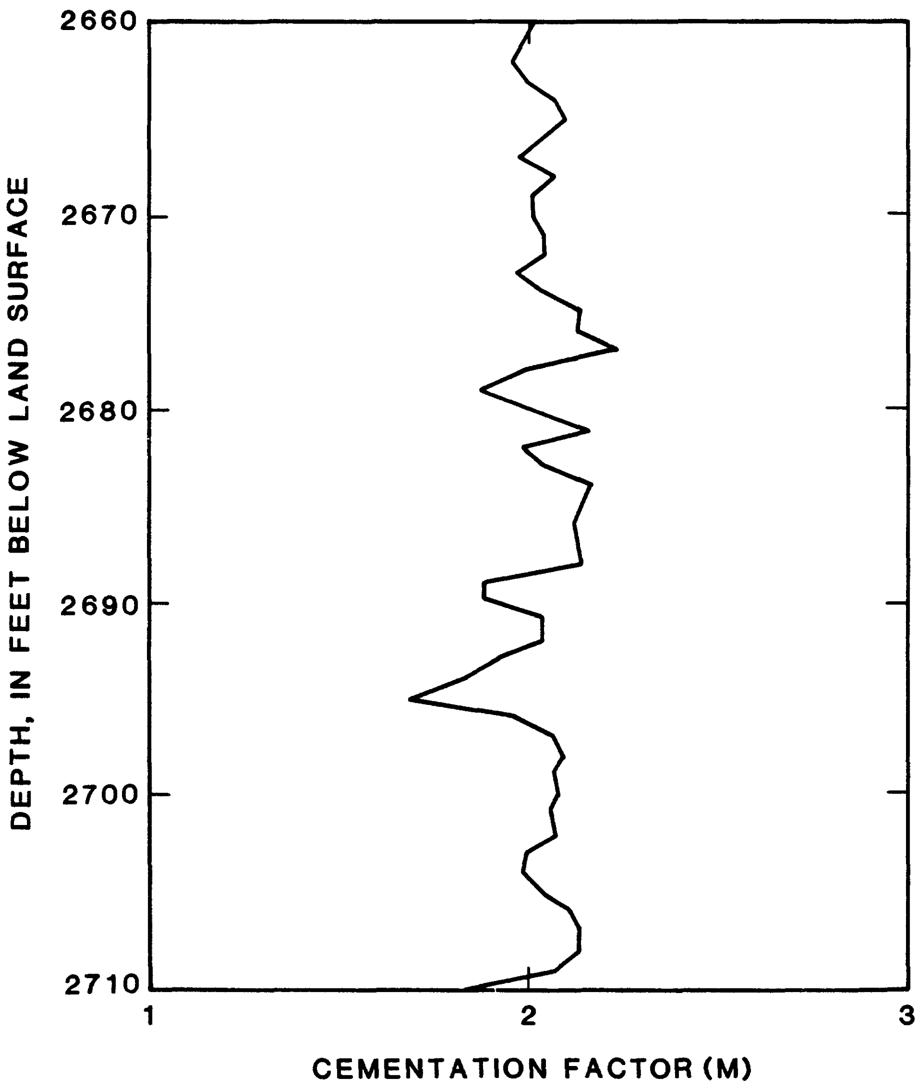


Figure 47.--Cementation factor for a short section of Roubidoux Formation from test hole 2.

Permeability Estimates from Logs

No log gives a direct measure of permeability. Consequently, estimates of permeability from logs must be based on relationships established between permeability and other formation properties. Core analysis provides the necessary data both to determine relations and to assess the degree of confidence that can be associated with estimates of permeability. In this Arbuckle study, no satisfactory relations could be developed to estimate permeability from logs because of the large difference between measurements of permeability from cores and permeability assessed from hydraulic tests of wells in the Arbuckle aquifer.

Core-plug measurements of porosity and permeability from the wells in the Arbuckle aquifer were combined and plotted in figure 48. The degree of confidence associated with estimates of permeability from this line is indicated by the correlation coefficient of 0.84 between the measurements of porosity and permeability. As an alternative predictor, a function was developed between permeability and formation factor measured in core plugs. The function is shown in figure 49, but the correlation coefficient of 0.82

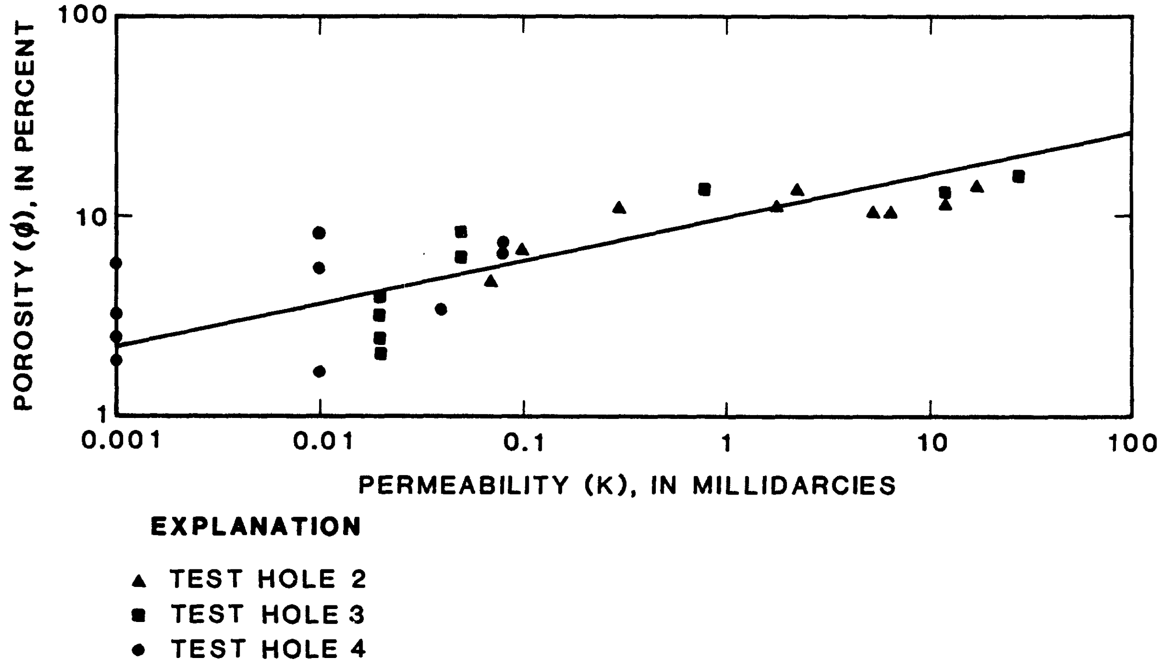


Figure 48.--Total porosity as a function of permeability from core data in Arbuckle aquifer.

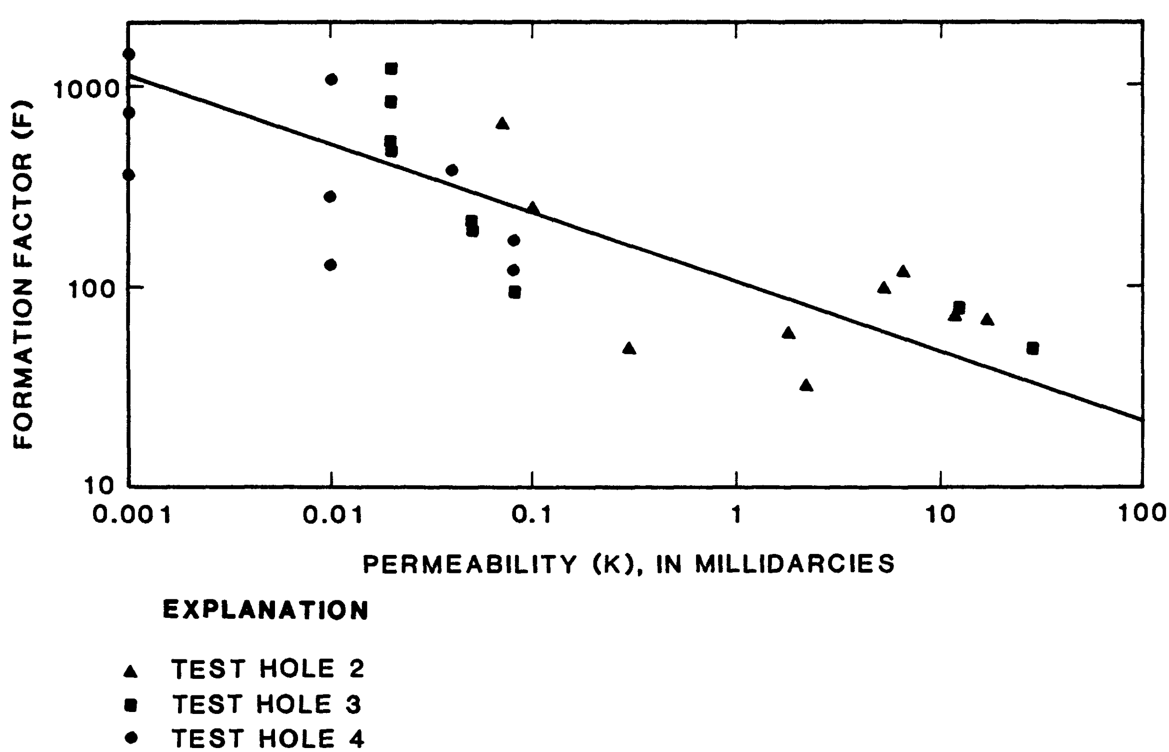


Figure 49.--Formation factor as a function of permeability from core data in Arbuckle aquifer.

between the permeability and the formation factor indicates that there is no improvement in predictive capability over a relationship based on porosity alone.

The geometric mean permeability of the core plugs is 0.1 millidarcy, which is about three orders of magnitude less than the permeability of 50 to 300 millidarcies estimated from hydraulic tests of wells. This difference suggests a sample-size problem, in which the pore structure of core plugs, is a grossly inadequate representation of the ranges of porosity types that occur in an extensive section of the Arbuckle aquifer. Analysis of measurements from a whole core did not resolve this problem. The correlation coefficient of 0.21 linking maximum permeability with porosity measured from the whole core is not large enough to develop a usable predictive relationship. While the geometric mean maximum permeability of 15.5 millidarcies is significantly larger than the mean value from plugs, this figure is still substantially smaller than the assessment of permeability from well tests.

Collectively, these observations suggest that porosity development in the Arbuckle is a phenomenon that is scale dependent. At the scale of core plugs, the predominance of intercrystalline and intergranular porosity results in a strong relationship between porosity and permeability but yields small values of permeability. At the level of a 1-foot whole core, the increasing importance of vugs and fractures results in increased permeability but causes more complex relationships between porosity and permeability. Finally, the markedly larger permeability of 50 to 300 millidarcies estimated for sections of the Arbuckle suggests the occurrence of major fracture systems and possible solution openings that are not sampled by cores or core plugs.

Conclusions

Data from geophysical logs of test wells in the Arbuckle aquifer were evaluated for their ability to estimate hydraulic properties of the Arbuckle. Logs have the advantage of providing long, detailed, and continuous records that may be used to make estimates of mineral composition, porosity type and volume, and, possibly permeability.

Computer-processed log data were used to generate a description of the composition of the Arbuckle penetrated in test hole 2 (Douglas County), expressed in terms of percentages of dolomite, quartz, shale, and "primary" and "secondary" porosity. The results matched well with the geological description based on drill cuttings, while providing a quantitative result with greater vertical resolution.

Comparison of the porosity distributions of separate formations within the Arbuckle indicated differences in distribution type. This suggests that detailed hydrologic modeling should not consider the Arbuckle as a homogeneous unit but should take into account the distinctive porosity of each of the Arbuckle formations. The variability of the porosity distributions is a clear indication of the range of porosity types within the Arbuckle. So, for example, the more constricted distributions of the Jefferson City Dolomite, Gunter Sandstone Member of the Gasconade Dolomite, and Bonneterre Dolomite are explained partially by strong inverse relations between "primary" porosity (small pore spaces) and "secondary" porosity (large pore spaces). In contrast, the more widespread distributions in the Roubidoux Formation, Gasconade Dolomite, and Eminence Dolomite corresponded with no significant association between these two porosity types. Other differences were evident in the shapes of the distributions, with the porosity of the Roubidoux Formation and the Gasconade Dolomite exhibiting positive skew, as compared with a negative skew for the Eminence Dolomite.

Attempts to estimate permeability based on logs were not successful. Since logs do not measure permeability directly, predictive relationships must be based on core measurements. Analysis of core-plug data from all test holes revealed a moderately strong positive association between permeability and porosity, but this relation was rejected as unrepresentative because the geometric average plug permeability of 0.1 millidarcy was much less than the 50-300 millidarcy values derived from well tests. Analysis of porosity-maximum permeability relationships using data from a 1-foot whole core did not resolve the situation because maximum permeability was not strongly correlated with porosity. Furthermore, although the geometric mean permeability value from whole-core measurements was 15.5 millidarcies, this estimate still was substantially smaller than the permeability calculated on the basis of well tests.

When considered together, these results indicate scale dependence of permeability of the Arbuckle. At the level of core plugs, permeability is small but correlated with porosity. At the scale of a 1-foot whole core, porosity probably is a mixture of types and has a weaker correlation with permeability, which has larger values. At still greater scales, it is probable that large-scale fracture systems and solution openings may account for the permeability measured in hydraulic tests of wells.

Collectively, these results suggest that the most effective application of geophysical logs in this study is the subdivision of the Arbuckle into zones that are characterized by distinctive porosity distributions. The zones appear to coincide with formations whose stratigraphy is defined conventionally by their insoluble residue content. In any detailed regional aquifer model, the porosity measurements of each formation should be coupled with permeability estimated from hydraulic tests of wells, such as drill-stem tests or injection or production tests, to take into account the lateral and vertical stratigraphic variability of the Arbuckle aquifer.