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The Hydrogeology and Chemical Quality in the
Lower Paleozoic Aquifers in Southeast Kansas
and Adjoining Areas of Missouri and Oklahoma

A Report to the Kansas Department of Health and Environment

by

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ABSTRACT

The Lower Paleozoic aquifers (principally the Cambro-Ordovician) in southeast Kansas and adjoining areas are an important resource producing fresh water for municipal water supplies, industries, and agriculture in eastern sections of the region. To the west in Labette and Montgomery counties these aquifers produce oil and at one location in Montgomery County the Cambro-Ordovician is used for industrial waste disposal through well injection. The Mississippian and Cambro-Ordovician aquifers, both areally carbonate extensive units, comprise the Lower Paleozoic aquifer system. These two aquifers are generally separated by confining layers of shale and dense dolomite except in areas of southern Cherokee County, Kansas and in northern Ottawa County, Oklahoma. The undifferentiated Mississippian is unconfined where the unit is at the surface in southeast Cherokee County, Kansas and adjoining areas. Groundwater flow in both aquifers is generally to the west except in the vicinity of municipal and industrial well fields where large-scale withdrawals of groundwater have changed the prevailing direction of groundwater flow. The hydraulic properties of the Cambro-Ordovician aquifer vary widely reflecting the heterogeneity of the aquifer. Very little hydrologic data are available for the undifferentiated Mississippian aquifer.

Three groundwater regions can be defined in the Cambro-Ordovician aquifer reflecting the mixing of fresh and saline waters in the aquifer: 1) a fresh-water portion containing groundwaters with generally less than 300 mg/l total dissolved solids and calcium, magnesium, and bicarbonate as the dominant dissolved constituents; 2) a transition zone where the dominant ions in solution change from calcium, magnesium and bicarbonate to sodium and chloride and where the total dissolved solids increases rapidly in a westerly direction up to 5000 mg/l; and 3) a saline portion where the total dissolved solids content is generally above 5,000 mg/l and the water chemistry reflects more or less formation water conditions. These three zones in the Cambro-Ordovician aquifer have evolved over geologic time as fresh-water recharge entering the aquifer in the

Ozark region of Missouri has flushed formation waters from large portions of the study area. There is no evidence that groundwater development has significantly affected the position of the eastern margin of the transition zone in more recent times.

INTRODUCTION

The Cambro-Ordovician (Arbuckle) aquifer in southeast Kansas and adjoining areas of Oklahoma and Missouri is an important fresh-water resource for public water supply and industry. Large-scale pumpage of water from wells finished in this aquifer began i the late 1800's and has continued to the present. To the west of this fresh-water area the groundwater from this aquifer becomes progressively more saline and produces oil. A transition zone separating the fresh and more saline portions of the Cambro-Ordovician (Arbuckle) aquifer can be broadly defined in southeast Kansas and in the adjoining states. Within the transition zone both the chloride and total dissolved solids concentration increase rapidly. Several public water supply wells that withdraw water from the Cambro-Ordovician in southeast Kansas and adjoining states are located within the eastern half of this transitional area.

Proper management of this aquifer system may become essential in the future to protect the fresh-water portion of the aquifer from progressive degradation of groundwater chemical quality. Degradation could arise from heavy pumpage of water by the many well fields and center pivot irrigation systems in southeast Kansas, southwest Missouri, and northeast Oklahoma. However, the hydrogeologic data necessary to make these decisions for protecting groundwater chemical quality in southeast Kansas have not been available, especially for the more saline portions of the Cambro-Ordovician aquifer where there are few wells. Additional interpretation problems also arise because hydrologically the Cambro-Ordovician aquifer is heterogeneous, has a considerable thickness and is poorly understood stratigraphically. Further, no attempt has ever been made to determine the hydrologic relationship between the undifferentiated Mississippian and the Cambro-Ordovician aquifers. At several locations the undifferentiated Mississippian rests directly on the Cambro-Ordovician. Leakage of poorer quality water from the Mississippian into the Cambro-Ordovician could occur along fractures if there is a sufficient head difference to induce vertical flow.

This project was originally begun as a part of the ongoing program of the Kansas Geological Survey. During this time the research emphasis was placed on the groundwater chemical quality and hydrogeology of the Lower Paleozoic aquifers in Cherokee, Crawford, and Bourbon counties in southeast Kansas. Later additional funding was provided by the Kansas Department of Health and Environment to investigate the transition zone area to the west of the original study area. This report presents the results of both investigations in southeast Kansas.

Purpose

The purposes of this project were 1) to describe the hydrogeologic setting of the Cambro-Ordovician aquifer in southeast Kansas in both the fresh and saline portions of the aquifer and in the transition zone; 2) to map variations in groundwater chemical quality (major, minor and selected trace constituents) from the Cambro-Ordovician and Mississippian aquifers in southeast Kansas; and 3) to determine the hydrologic relationship between the Mississippian and the Cambro-Ordovician aquifers in southeast Kansas.

Area of Investigation

The area of investigation for this project was confined for the most part to nine counties in southeast Kansas: Cherokee, Crawford, Bourbon, Labette, Neosho, Allen, Montgomery, Wilson, and Woodson counties (Fig. 1). Some additional data was collected in adjoining areas of Missouri and Oklahoma for continuity. The extended study are in Missouri included portions or all of Vernon, Barton, Jasper, Newton, and McDonald counties and in Oklahoma included portions or all of Ottawa, Craig and Nowata counties.

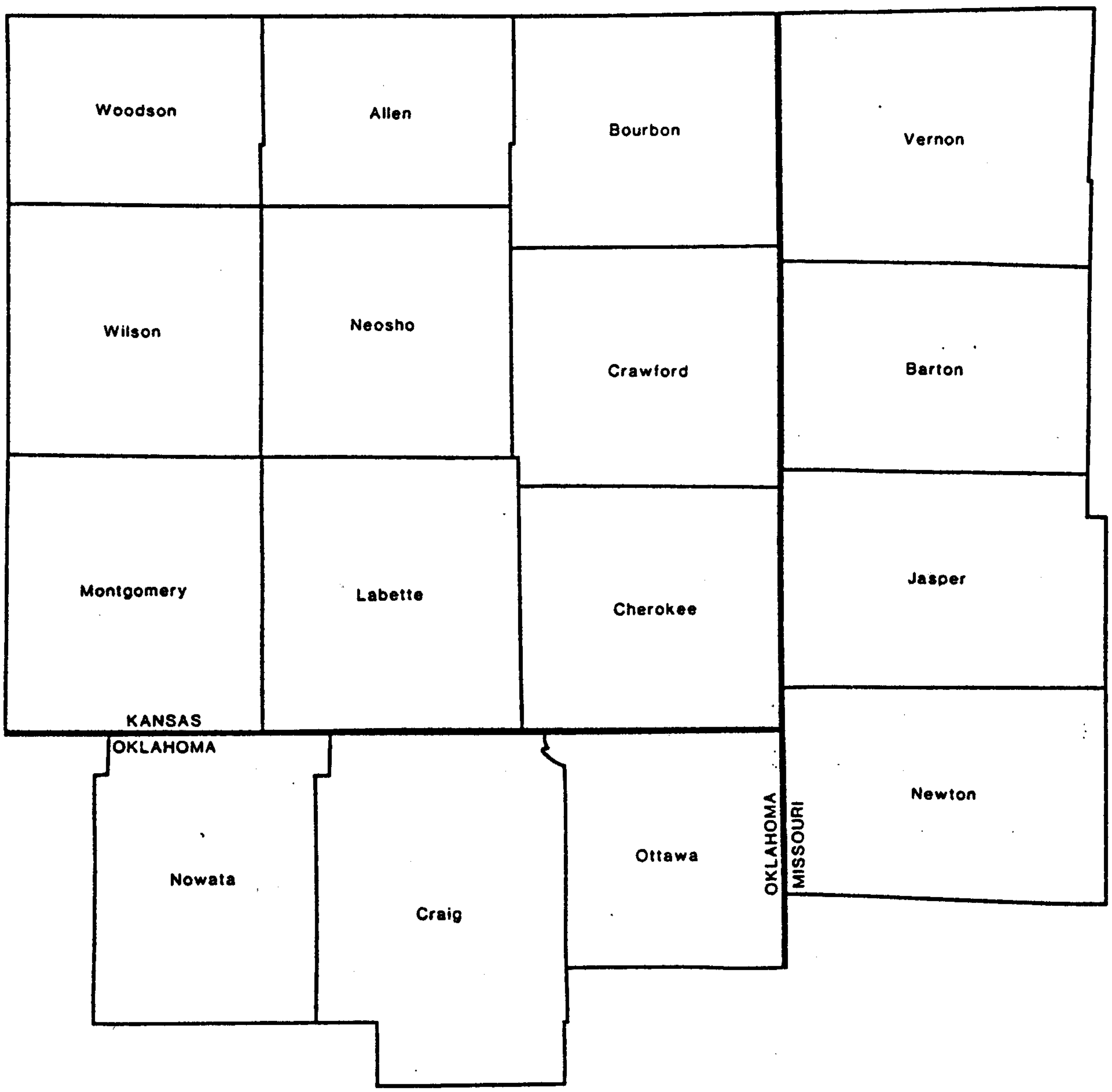


Figure 1. Location of study area.

Previous Work

Groundwater investigations pertaining to the Lower Paleozoic aquifers in southeast Kansas and in the adjoining areas of Missouri and Oklahoma have been numerous. In the early 1940s Abernathy (1941) reported on the availability of groundwater from the Cambro-Ordovician and Mississippian aquifers in Bourbon, Crawford, Cherokee, and Labette counties in Kansas. This was a reconnaissance investigation containing data from scattered wells in southwest Missouri and southeast Kansas. Abernathy recognized the great variability of groundwater chemical quality in the Cambro-Ordovician aquifer within this region. Also, he reported on the drilling and testing of a new well for the Jayhawk Ordinance Plant (now the Gulf Oil Chemical Corporation) that penetrated the Cambro-Ordovician aquifer (Abernathy, 1943). Williams (1948) wrote a report on the possible contamination of public water supply wells finished in the Cambro-Ordovician caused by leakage of waters from the overlying Pennsylvanian or Mississippian aquifers into public supply wells at McCune, Cherokee, and Arma, Kansas. Later, Stramel (1957) conducted several pumping and recovery tests on wells used for public water supply by the City of Pittsburg to determine the hydraulic properties of the Cambro-Ordovician aquifer in the well field. He noted that static water levels in wells penetrating this aquifer had declined more than 100 feet since the drilling of the first well in the early 1880s. In Oklahoma Reed et al. (1955) reported on the results of a ground-water availability study in the Mississippian and Cambro-Ordovician aquifers in Ottawa County. They showed that at Miami, Oklahoma static water level declines of approximately 400 feet have occurred in wells penetrating the deeper aquifers between 1905 and 1947. More recently, the U.S. Geological Survey and the Oklahoma Geological Survey (Marcher and Bingham, 1971) cooperatively produced from available data a hydrologic atlas of groundwater resources including those in the Lower Paleozoic for the Tulsa quadrangle in northeastern Oklahoma. Chenowith (1964a,b) produced maps of chloride concentration and the potentiometric surface for the

Arbuckle Group in Kansas, Oklahoma, and southwestern Missouri using oil company data. In Missouri, Feder et al. (1969) wrote a report on groundwater availability and chemical quality for the Mississippian and Cambro-Ordovician aquifers in the Joplin area. Farther north, using available data, Frick (1980) examined the hydrogeology of the Lower Paleozoic aquifers in portions of Bourbon, Crawford, and Cherokee counties in southeast Kansas and Jasper, Barton, and Vernon counties in Missouri. Darr (1978) wrote a report on the geochemistry of groundwater in Bates, Vernon and Barton counties in Missouri. He collected and analyzed water samples from wells completed in Pennsylvanian, Mississippian, and Cambro-Ordovician aquifers in these counties. Recently, Hathaway and Macfarlane (1980) discussed spatial and temporal variations in the chemical quality of groundwater from the Lower Paleozoic aquifers in the Tri-State region.

The U.S. Geological Survey is presently conducting two regional geohydrologic investigations that pertain to the Lower Paleozoic aquifer system in Kansas. One study is a state-wide investigation of the feasibility of waste disposal by deep-well injection into the Cambro-Ordovician. Funding from this USGS study and from our investigation was used for the drilling of an observation well at Parsons, Kansas. The second study is the Central Midwest Regional Aquifer Systems Analysis (CM RASA); its goal is to develop an overall picture of the hydrogeology and water chemistry of all bedrock aquifers in Kansas and adjoining states that contain significant amounts of groundwater (Jorgensen and Signor, 1981).

Methods of Study

This project was conducted in two stages when the emphasis of the investigation changed. The project was begun in Bourbon, Crawford and Cherokee counties in southeast Kansas and in adjoining areas of southwest Missouri and northeastern Oklahoma. Water samples were collected during spring and fall of 1979 and 1980 in an attempt to document short-term changes where groundwater from the Cambro-Ordovician aquifer is used for public water supply. Static water levels were also measured three times for the same purpose. Later the Kansas Geological Survey contracted with the Kansas Department of Health and Environment to do hydrogeology and groundwater chemical-quality work to the west in the more saline portions of the aquifer. For this second phase, each well was visited twice: once to collect a water sample and once to determine fluid levels.

A literature search was conducted to collect from federal, state, and industry files all available data on Lower Paleozoic stratigraphy, well locations, groundwater chemical quality and geologic structure in southeast Kansas and adjoining areas (Fig. 2). Several trips were made to state agencies in Kansas, Missouri, and Oklahoma for this purpose. All data were examined for accuracy and those data found to be inaccurate or questionable were discarded. The rest of the data was plotted on base maps of southeast Kansas and surrounding areas. New data developed during the study were plotted on these maps as they became available. At the end of the project, the base maps were contoured to show various features of the subsurface groundwater flow or trends in groundwater chemical quality and graphs were constructed to illustrate small-scale features or specific relationships.

Well cuttings were collected from several wells drilled during the course of this study. The cuttings were examined with a microscope and a log was prepared for the well. A portion of the cuttings was shipped to the Division of Geology and Land Survey, Missouri Department of Natural Resources, Rolla, Missouri, for stratigraphic interpretation using insoluble residues. The insoluble-residue log and the log prepared from examining the cuttings were used to interpret the characteristics of the formations penetrated by the well.

Several types of borehole geophysical logs were run on two wells drilled during the course of the investigation. At the Kansas Ord #1, a USGS-KGS monitoring well, dual-

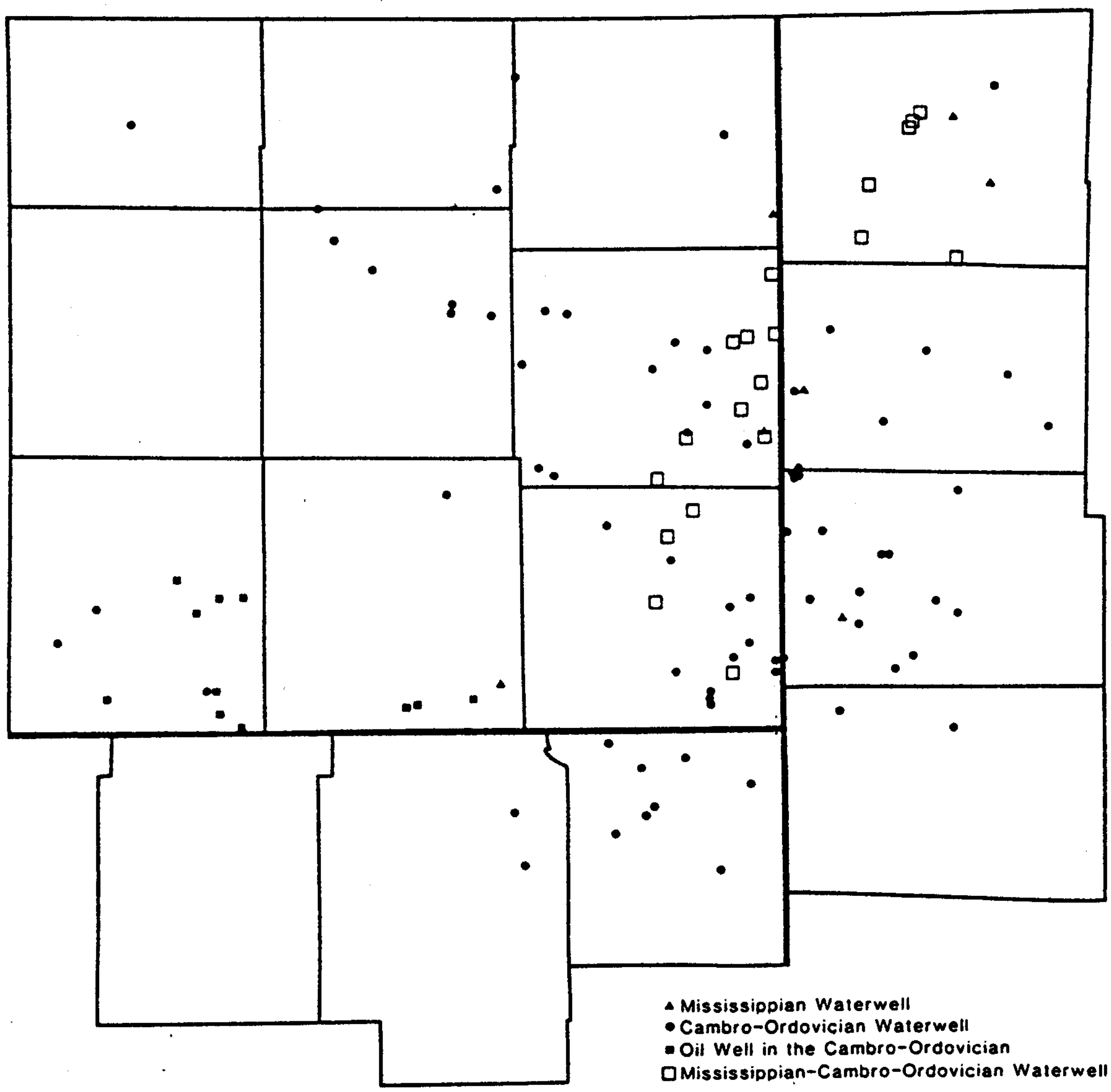


Figure 2. Locations of wells visited in southeast Kansas and adjoining areas.

induction laterologs, borehole-compensated sonic logs, and compensated neutron-formation density logs were produced by Schlumberger in hard copy and on tape. Later, temperature, spinner, and brine-injection flow logs were run by the USGS. At Crawford County Rural Water District #7, Well #2, a dual induction focused log and a compensated densilog were run by Dresser Atlas.

Water samples were collected from both water and oil wells penetrating the Lower Paleozoic aquifer in southeast Kansas and adjoining areas. Most of the fresh-water wells were sampled more than once. Each of the oil-field water-supply wells (for secondary recovery) and oil wells was sampled once. Water samples were collected only from wells that had been pumped at least 15 minutes prior to collection. Oil field waters were collected from oil wells only after the oil in the oil/water mixture to separated from the water in a five-gallon separation tank. Temperature, pH, specific conductance, and hydrogen sulfide concentration were determined at the wellhead except at oil wells. Specific conductance was determined from oil field water samples after filtration to remove the oil. At each oil well only temperature and hydrogen sulfide concentration were determined. Bicarbonate determinations were performed daily at a field laboratory on samples from fresh-water wells. These samples were kept chilled between the time of collection and analysis.

The collected water samples were analyzed for selected constituents by the Geochemistry Section, Kansas Geological Survey. These included calcium, magnesium, sodium, potassium, strontium, bicarbonate, sulfate, and chloride, fluoride, nitrate, iron, boron, lithium, barium, manganese, bromide, and iodide. All of the water chemistry data, including specific conductance, were plotted on base maps of the area and contoured to show areal distribution patterns.

Several trips were made to the field to measure static fluid levels in water and oil wells penetrating Lower Paleozoic aquifers. Static water levels were determined in the water wells with a steel tape or an Echometer. Equivalent static water levels were determined in oil wells using the Echometer only. The static water level data were then plotted on base maps and contoured to show the potentiometric surface at various levels in the Lower Paleozoic.

A SHORT HISTORY OF GROUNDWATER DEVELOPMENT IN SOUTHEAST KANSAS AND ADJOINING AREAS

The availability of groundwater from the Cambro-Ordovician (Arbuckle) aquifer system has been an important factor in the economic development of the Tri-State region of Kansas, Oklahoma, and Missouri (Abernathy, 1941; Reed _et al._, 1955; and Stramel, 1957). Since before the beginning of the 20th century deep wells have been used to supply water for milling lead-zinc ores in both the Picher Field along the Kansas-Oklahoma border southwest of Baxter Springs and the Joplin Field along the Kansas-Missouri border between Galena and Joplin, and for coal-washing operations in the Pittsburg, Kansas area. In addition, great volumes of water were also pumped out of the Mississippian to de-water mine workings in both the Picher, Oklahoma and Joplin, Missouri areas.

Since the decline of the mining industry in the Tri-State region (where Kansas, Missouri, and Oklahoma meet), the level of pumpage has continued to be high and has increased because of the demand for water by an increasing number of public water supplies, new industry, and agriculture. This is particularly true of the Joplin, Missouri, - Miami, Oklahoma and Pittsburg, Kansas areas. Most of the municipal and industrial wells produce water at a rate of 250 to 750 gallons per minute. The first rural water district facility using wells to withdraw water from the Cambro-Ordovician was built in southeast Kansas in 1964. Since then three additional water districts have been created in Cherokee County, Kansas; six in Crawford County, Kansas; one each in both Vernon and Barton counties, Missouri; and six in Ottawa County, Oklahoma. Most rural water district wells are pumped at an average rate of 100 gallons per minute (13.4 ft^3/min).

The water supplied by these districts is used for domestic, stock watering, and other miscellaneous purposes. Groundwater from the Cambro-Ordovician aquifer is also used by coal-fired electric power generating plants at Riverton, Kansas and north of Asbury, Missouri. Groundwater from the Cambro-Ordovician has been used for irrigation in southwest Missouri since the late 1960s, but not in either Kansas or Oklahoma. Current estimates of the rate of groundwater withdrawal for the region are unknown at the time of this writing; however, Reed et al. (1955) gave an estimate of four million gallons per day for Ottawa County, Oklahoma during 1948 and Stramel (1955) estimated two million gallons per day for the Pittsburg, Kansas well field during 1950.

Several attempts have been made in the past to develop water supplies at Fort Scott, Parsons, Chetopa, and Altamont in areas of the aquifer where the waters from the Cambro-Ordovician are either brackish or saline, but these have not been successful.

Several oil-field water-supply wells have been drilled into the Cambro-Ordovician in Bourbon, Allen, Neosho, Woodson, and Montgomery counties in southeast Kansas. These wells produce enough water to supply secondary oil recovery operations in Pennsylvanian reservoirs where not enough water is produced with the oil.

OIL AND GAS PRODUCTION FROM LOWER PALEOZOIC ROCKS IN SOUTHEAST KANSAS

Oil and gas production began very early in the history of the State of Kansas. Gas and oil were discovered in the Forest City Basin in 1860 and 1890 respectively and gas was discovered in the Cherokee Basin by 1883 (Oros, 1979). However, Abernathy (1940) states that gas, probably coming from the Pennsylvanian, was found in small quantities in Montgomery County as early as 1881. Since these discoveries, oil and gas production from all levels in the Paleozoic stratigraphic section has increased significantly and currently comes from all counties in the area except Cherokee County. Reservoir rocks range in age from Pennsylvanian to Ordovician with most of the production probably coming from the Pennsylvanian.

Oil and gas from reservoir rocks of Mississippian and Lower Ordovician age have been found only in the southwestern portion of the nine county study area. In Labette County Arbuckle (Cambro-Ordovician) oil is produced from the Chetopa, Lake Creek, and Edna fields. Natural gas is produced from the upper part of the Mississippian from the Coffeyville-Cherryvale field and from the Chetopa Townsite field. The oil pools are located at the top of the Arbuckle in small well-defined structural domes that reflect underlying Precambrian highs in southeast Kansas. Thickness of the pay zone at the top of the Arbuckle is typically three to five feet. Oil gravity is typically 24-26° API. Arbuckle oil is being produced from the Coffeyville-Cherryvale field (including the Alloway, Bellair, and Thompson pools), the Brewster field, the Tyro field, and the Coleman pool in Montgomery County. Some natural gas production comes from the Mississippian above these units. In Woodson County natural gas is produced from zones in the upper part of the Mississippian in the Winterscheid field and has been produced from the Mississippian in the Evans, Hoagland, Tichenor, Vernon, and Virgil North fields and from the Steele pool.

INDUSTRIAL WASTE DISPOSAL INJECTION WELLS IN SOUTHEAST KANSAS

Only one well injection field for industrial-waste-disposal is currently in operation in the study area. Located at Coffeyville in Montgomery County, the well field is owned by the Sherwin-Williams Company and comprises three wells that dispose of chemical wastes produced from plant processes. The well field has been in operation since 1980. Each well is cased into the Cambro-Ordovician and is an open bore hole below the casing point down to total depth. No injection pressures are applied to the wastes entering the well. At the time of writing, no information was available concerning the total volume injected to date, the injection rate, and the character of wastes being disposed.

STRATIGRAPHY

For the most part, the bedrock in the southeast Kansas study area consists of sedimentary rocks ranging in age from Middle Pennsylvanian to Late Cambrian resting unconformably on the Precambrian surface (Fig. 3). The total thickness of the sedimentary section ranges from less than 1,200 feet in southern Labette County to more than 2,800 feet in the northwest portion of Woodson County. Sedimentary rock types that make up the stratigraphic column include limestone, dolomite, sandstone, and shale. However, mafic (peridotite) igneous rocks are exposed at the surface in the vicinity of the Rose Dome and Silver City Dome in Woodson County (Jewett, 1954).

Subdivision of the Cambrian, Ordovician, and Mississippian systems into smaller recognizable units in the subsurface has been a difficult task because the formations are lithologically similar and there are few easily recongized stratigraphic markers. There is also a general lack of biostratigraphic data available from drill cuttings. Geologists of the Missouri Geological Survey have had considerable success correlating outcropping Mississippian and Cambro-Ordovician rocks with the subsurface section from region to region using insoluble residues in Missouri and adjoining states (McQueen, 1931; McCracken, 1955; McCracken, 1964; and Kurtz, et al., 1975). The method has also been applied specifically by Keroher and Kirby (1948) to the Kansas subsurface along selected traverses.

Precambrian System

Precambrian rock types in southeastern Kansas include granitic intrusive rocks, rhyolitic to dacitic volcanic rocks, mafic intrusive rocks, and metasedimentary rocks (Bickford, et al., 1979) (Fig. 4). The top of the Precambrian is an erosional surface of considerable relief that reflects both the effects of tectonic events and differential resistance to erosion (Cole, 1976; Chenowith, 1968) (Fig. 5).

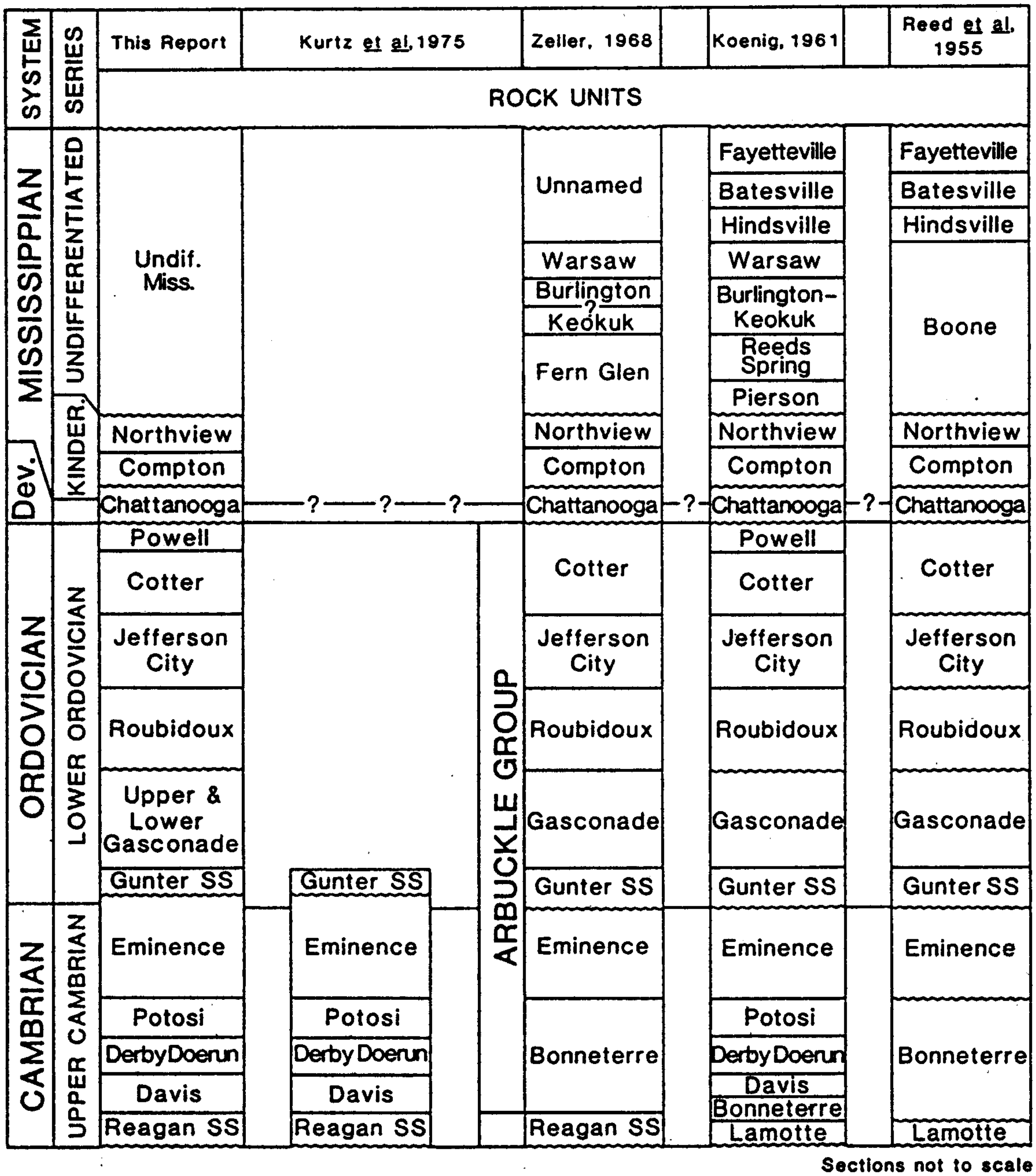


Figure 3. Subdivision and nomenclature of the Lower Paleozoic in southeast Kansas and adjoining areas.

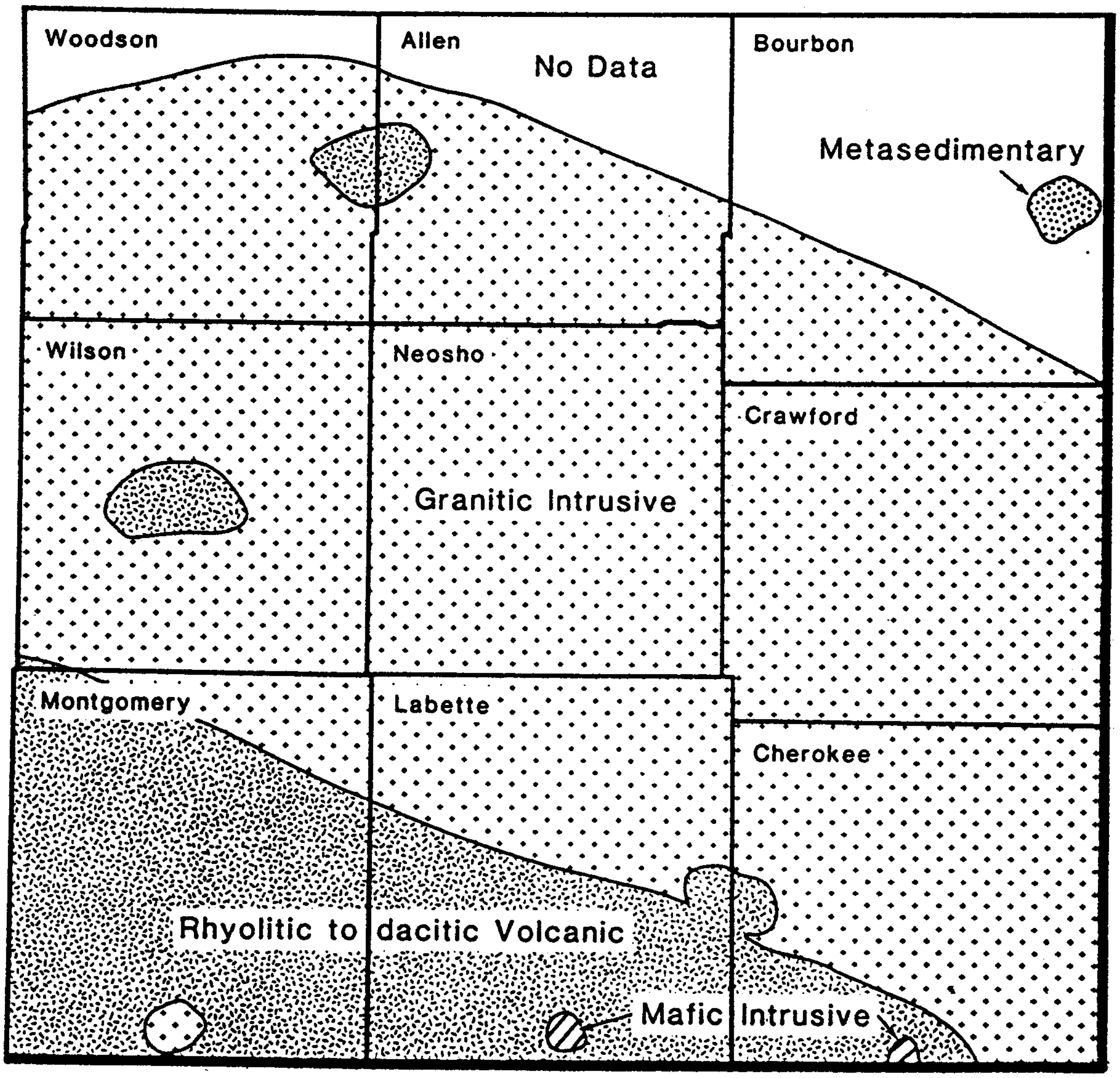
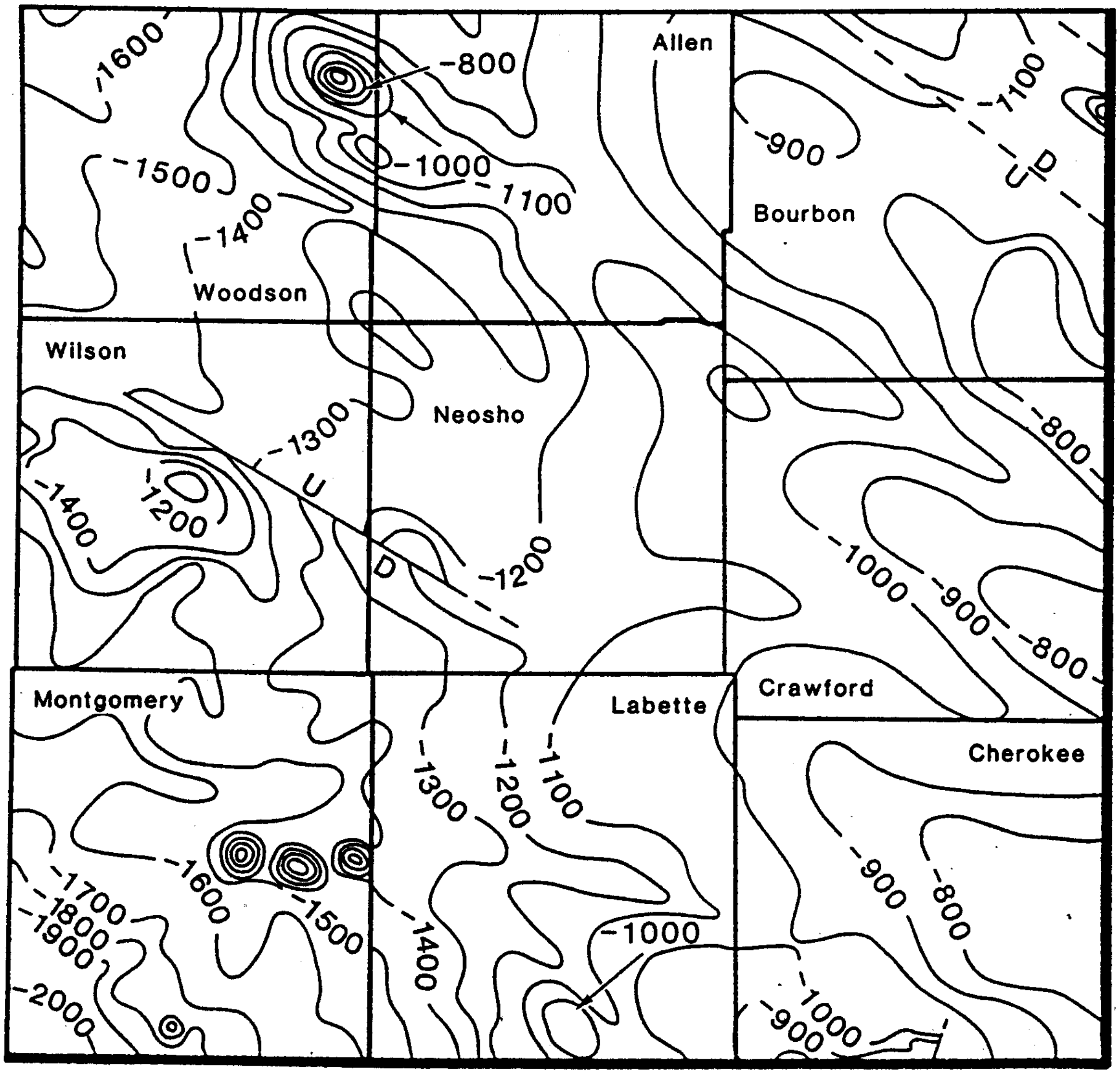


Figure 4. Preliminary geologic map of the Precambrian basement rocks, southeast Kansas.



Contour Interval=100'

from Cole (1976)
Mean Sea Level Datum

Figure 5. Configuration of the Precambrian bedrock surface, southeast Kansas.

Cambrian System

The term "Arbuckle" is used in the oil fields throughout Kansas and Oklahoma and is recognized as a formal name for undifferentiated upper Cambrian and Lower Ordovician rocks in both states. The term "Arbuckle" is not recognized in Missouri. Where possible in the remainder of this report either the term "Cambro-Ordovician" or a specific stratigraphic interval within these rocks will be used instead of "Arbuckle".

Upper Cambrian Series

Strata belonging to the Upper Cambrian Series are represented in ascending order above the Precambrian by the Reagan Sandstone, the Davis Formation, Derby-Doerun Dolomite, Potosi Dolomite, and the Eminence Formation in southeast Kansas.

The Upper Cambrian is characterized by rapid facies changes within persistent rock units in Kansas, Oklahoma, Missouri, and Arkansas (Kurtz, et al., 1975). All units of the Upper Cambrian are believed to be conformable. The Upper Cambrian is thickest in Douglas County, Missouri and thins westward into Kansas and Oklahoma (ibid; McCracken, 1964). Thicknesses of 300 to 400 feet are common in Missouri whereas in Kansas and Oklahoma thicknesses of 175 to 275 feet are more common. This section of rocks is absent over many Precambrian highs in southeast Kansas and northeast Oklahoma (Chenowith, 1968). The Upper Cambrian Series is bounded above and below by unconformities of regional extent.

Reagan Sandstone—Few wells have penetrated the Reagan Sandstone in southeast Kansas and adjoining areas. The Eagle Picher Industries, King Brand, P-1 in Cherokee County, Kansas (SW 1/4 SW 1/4 NW 1/4 Sec. 20, T28S, R25E) penetrated 90 feet of Reagan Sandstone and the LaSalle Oil Company, No. 1 Goble, in Crawford County, Kansas (SW 1/4 NW 1/4 NE 1/4 Sec. 11, T35S, R25E) penetrated 135 feet. Other wells probably penetrate this unit; however the exact thicknesses are not known. The Reagan

Sandstone in southeast Kansas is primarily coarse sandstone with some glauconitic shale and dolomite, possibly occurring near the top of the formation. The quartz grains may be frosted or angular, with some secondary quartz overgrowths. Insoluble residues generally yield nearly 100% quartz sand. In southeast Kansas, the Reagan Sandstone has been interpreted by earlier investigators to be the Lamotte Sandstone and may or may not include portions of the Bonneterre Formation (Kurtz, et al., 1975).

Davis Formation—Few wells have been interpreted as penetrating the Davis Formation, but this unit is believed to be present throughout much of southeast Kansas. This group of rocks has been misidentified as the lower part of the Bonneterre Formation (Kurtz, et al., 1975). The thickness of the Davis Formation is 60 feet in the Eagle-Picher Industries, King Brand, P-1 well in Cherokee County and 85 feet in the LaSalle Oil Company, No. 1 Goble well in Crawford County. The Davis Formation is compoased of sandy, glauconitic dolomite with or without glauconitic shale. The insoluble residues contain fine to very fine grained sand with glauconite and small fragments of mica.

Derby-Doerun Dolomite—Few wells have been interpreted as penetrating the Derby-Doerun Dolomite, because the formation has been misidentified as lower Bonneterre or Davis Formation (Kurtz, et al., 1975). Thicknesses of 90 feet and 100 feet of Derby-Doerun Dolomite are known to be present in the King Brand, P-1 in Cherokee County and in the Goble No. 1 well in Crawford County. In addition, at least 15 feet of Derby(?) is present in the bottom of the U.S.G.S. Kansas Ord No. 1 well (Center SW 1/4 Sec. 22, T31S, R20E) at Parsons, Kansas, in Labette County. The Derby-Doerun Formation is quite uniform and consists of brown, fine-grained, shaly dolomite that may be slightly sandy toward the base.

Potosi Dolomite—The Potosi Dolomite has been interpreted to be present in two wells in southeast Kansas. A thickness of 20 feet is known to be present in the Goble No. 1 well and an estimated thickness of 30 feet in the King Brand P-1 well. The Potosi is evidently not present in the Kansas Ord No. 1 well. The Potosi Formation is composed of fine-grained cherty dolomite.

Eminence Dolomite—The Eminence Dolomite has been interpreted to be present in the subsurface throughout southeast Kansas except in the vicinity of Precambrian highs. The Eminence is approximately 125 feet thick in the Kansas Ord No. 1 well and is composed of porous, fine- to medium-grained Dolomite that is cherty, sandy, and oolitic near the top and somewhat shaly in the middle. The thickness of the Eminence in the Goble No. 1 well is 145 feet and the lithology is similar to that in the Kansas Ord No. 1 well except that the middle portion of the Eminence is not shaly in the Goble No. 1 well. The thickness of the Eminence is approximately 80 feet in the King Brand, P-1 well. The top of the Eminence Dolomite is unconformable with the overlying Gunter Sandstone Member of the Gasconade Dolomite.

Ordovician System

Lower Ordovician (Canadian) Series

Strata belonging to the Lower Ordovician (Canadian) Series in southeast Kansas include in ascending order the Gasconade Dolomite, the Roubidoux Formation, the Jefferson City Formation, the Cotter Formation, the Powell Formation, and the Undifferentiated Lower Ordovician (Fig. 3). Thicknesses of the Lower Ordovician Series generally range from 685 to 800 feet except in the vicinity of Precambrian highs where the unit may be considerably diminished in thickness or not present. Lower Ordovician rocks thin considerably in northern Crawford and Bourbon counties across the Bourbon Arch where erosion has removed the Cotter and portions of the Jefferson City formations. The Lower Ordovician Series thickens to 900 feet in southwest Missouri and southeast Kansas, corresponding to an increase in the thickness of the Cotter (McCracken, 1964).

The Lower Ordovician (Canadian) Series is unconformable with the stratigraphic units both above and below. The base of the Lower Ordovician does not coincide with the base of the Gunter Sandstone Member. Rather, the Lower Ordovician Series begins near the top of the Eminence Dolomite (Kurtz, et al., 1975). A widespread unconformity at the base of the Roubidoux Formation separates the underlying Gasconade Formation from the upper units that McCracken (1964) believes are closely related in sedimentary history.

Gasconade Dolomite—The Gasconade Dolomite lies unconformably above the Eminence Dolomite and is unconformable with the overlying Roubidoux Formation. The basal portion of the Gasconade has been named the Gunter Sandstone Member and is composed of sandstone or sandy dolomite in southeast Kansas. The typical thickness of the Gunter is about 20 feet in southeast Kansas. Above the Gunter the Gasconade Dolomite is primarily a vuggy, cherty dolomite that becomes slightly sandy near the top. Glauconite and pyrite are commonly present throughout the unit. Although the Gasconade Dolomite above the Gunter Sandstone member has more recently been subdivided into an upper and lower portion by the Division of Geology and Land Survey, Missouri Department of Natural Resources, for the purposes of this report, the Gasconade Dolomite is considered a single unit.

The total thickness of the Gasconade Dolomite varies considerably across southeast Kansas, reflecting both a regional northwestward thinning from northwest Arkansas into southeast Kansas and probably the effects of post-Gasconade folding and erosion (Keroher and Kirby, 1948; McCracken, 1964). The thickness of this unit is approximately 300 feet in the Pittsburg, Kansas area and is approximately 200 feet at

Parsons, Kansas. The Gasconade Dolomite is probably not present in the vicinity of Precambrian highs in southeast Kansas.

Roubidoux Formation—The Roubidoux Formation unconformably overlies the Gasconade Dolomite but is conformable with the overlying Jefferson City Formation. In southeast Kansas the Roubidoux Formation consists of sandstone, sandy dolomite, and cherty dolomite. Usually, there is a basal sandstone unit 10 to 30 feet thick. The sandstone and sandy dolomite above the basal unit are lenticular and variable in thickness. The sandstone in the Roubidoux is white, medium-grained, friable, and may contain masses of leached chert. Sand grains may be frosted or have overgrowths of quartz. The dolomite is gray, medium-grained, and usually vuggy. Oolites are common near the top of the formation and glauconite may be present throughout.

The total thickness of the Roubidoux Formation is remarkably uniform over the four state area of Missouri, Arkansas, Kansas, and Oklahoma. Generally, its thickness ranges from 170 feet or more to less than 140 feet, but thicknesses of less than 125 feet occur in the Pittsburg and West Mineral area. The Roubidoux Formation may not be present in the vicinity of Precambrian highs.

Jefferson City Formation—The Jefferson City Formation lies conformably above the Roubidoux Formation throughout southeast Kansas and adjoining areas. The lithology of the Jefferson City is a cherty, somewhat silty dolomite with some medium-grained sandstone lenses. The dolomite is usually buff-colored, medium-grained, and silty with pyrite as an accessory mineral. Scattered oolites are common at certain horizons in the unit.

The thickness of the Jefferson City Formation varies from more than 225 feet in southern Cherokee County to less than 170 feet where erosion has removed the overlying

Cotter Formation in northern Crawford and Bourbon counties. The Jefferson City Formation is not present in the vicinity of some Precambrian highs.

<u>Cotter Formation</u>—The Cotter Formation lies conformably above the Jefferson City Formation and is unconformable with all younger formations where the Powell Formation is not present. The Cotter Formation is composed of cherty, somewhat silty dolomite with lenses of sandstone. A more or less persistent layer of sandstone ranging from five to ten feet in thickness occuring in the lower portion of the Cotter has been informally named the "Swan Creek" (McCracken, 1964). Much of the dolomite that makes up the Cotter is vuggy and fine grained. The thickness of the Cotter in southeast Kansas and in portions of southwest Missouri has been greatly affected by post-Orodvician erosion. In Bourbon and northern Crawford counties in Kansas and in Vernon and northern Barton counties in Missouri, the Cotter is not present in the subsurface (Figs. 6 and 7). The thickness of the Cotter Formation ranges from 0 to 300 feet in southeast Kansas.

<u>Powell Formation</u>—The Powell Formation rests conformably on the Cotter Formation but is unconformably overlain by formations in southeast Kansas. The Powell Formation has been identified at only one location in southeast Kansas in the Kansas Ord No. 1 well at Parsons, Kansas. The rocks penetrated by the well consist of silty dolomite near the top and sandy dolomite toward the bottom. Approximately 40 feet of this unit was penetrated by the well (Fig. 7).

<u>Undifferentiated Lower Ordovician Formation</u>—Strata assigned to the Undifferentiated Lower Ordovician lie conformably(?) above the Powell Formation and are unconformable with all units above. Included in this unit are unnamed units of sandstone and sandy dolomite of pre-Simpson and post-Cotter age, including the "Wilcox

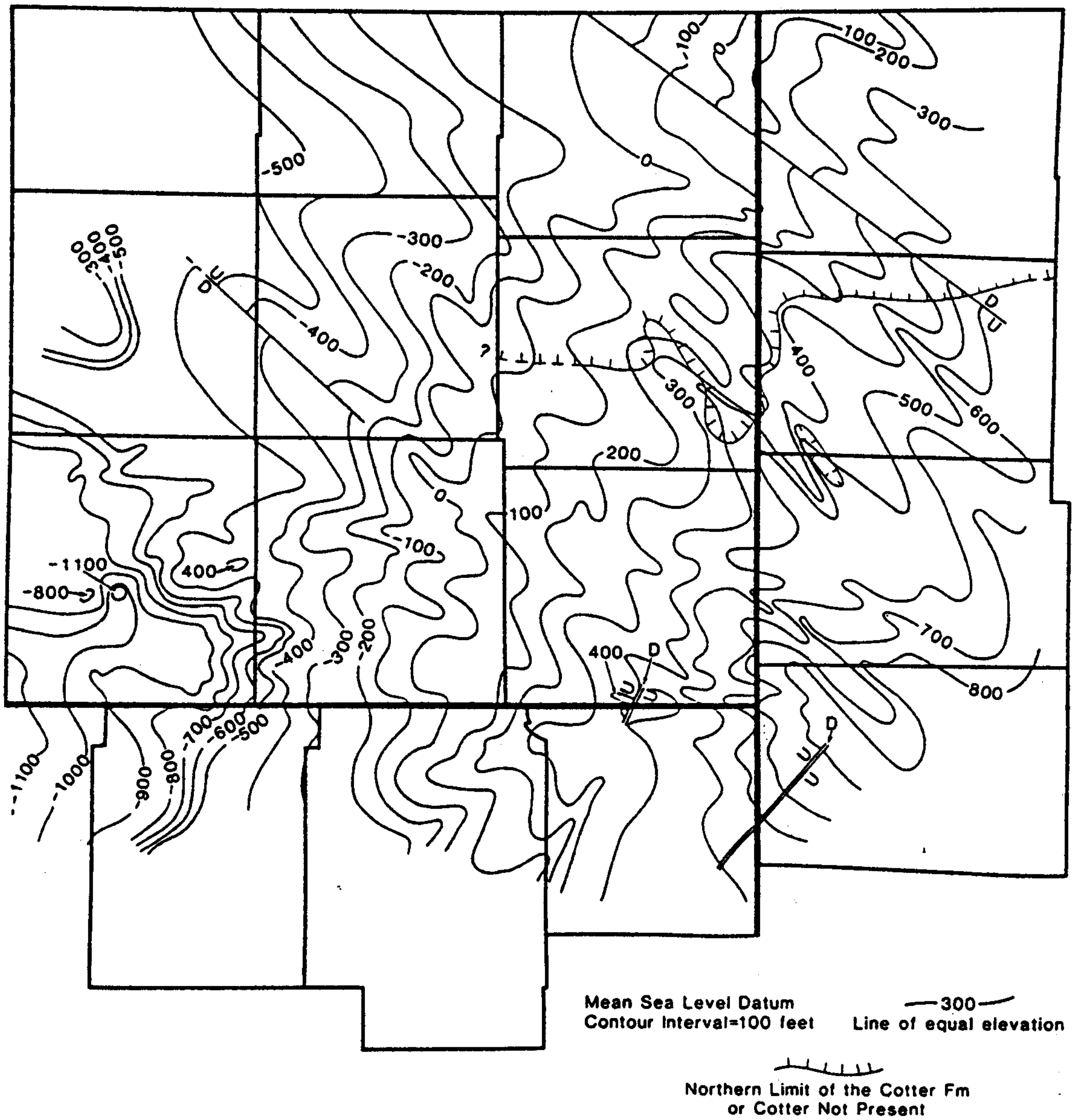


Figure 6. Configuration of the top of the Lower Ordovician System, southeast Kansas and adjoining areas.

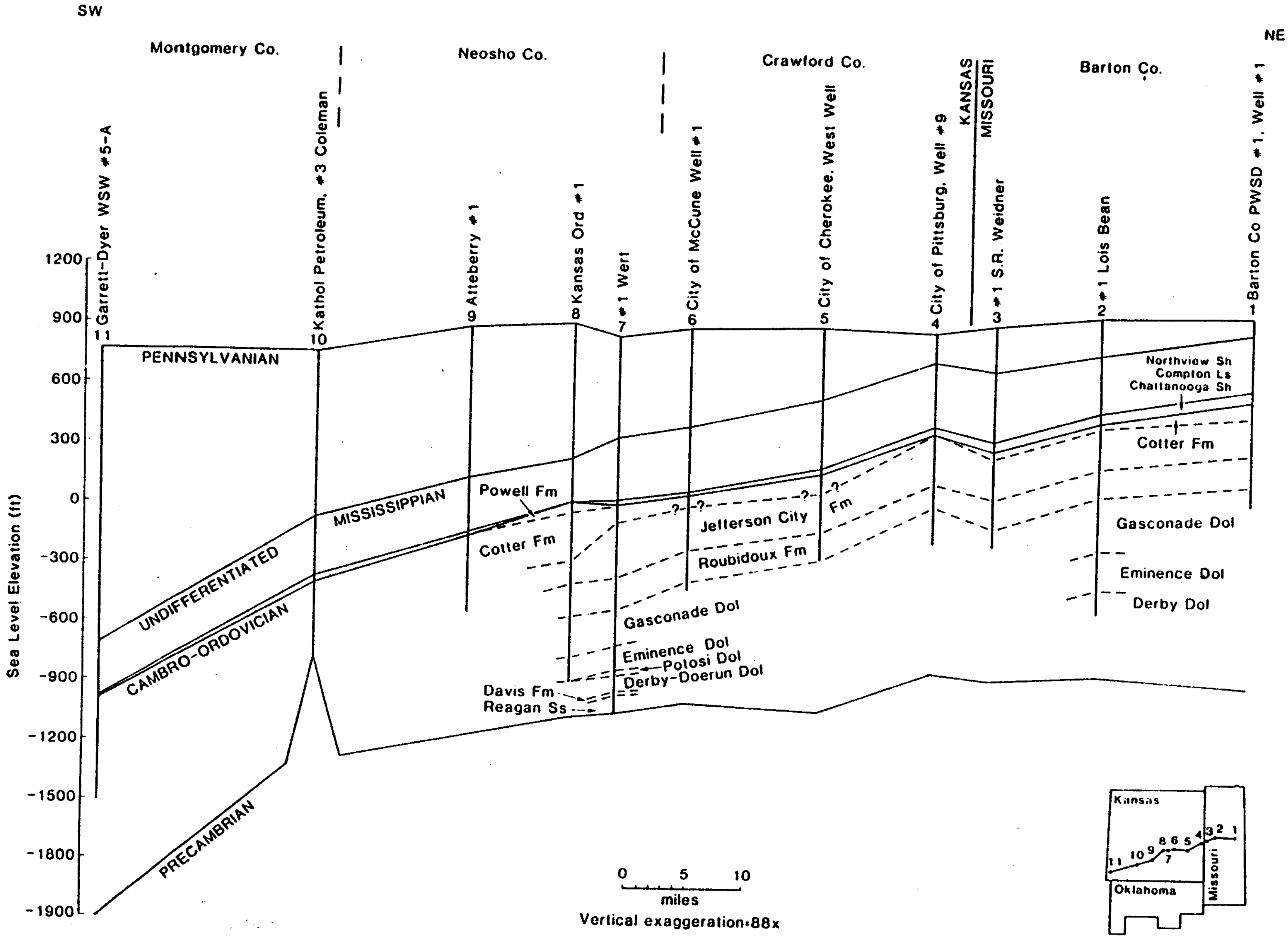


Figure 7. Subsurface cross section of the Paleozoic sedimentary rocks across southwest Missouri and southeast Kansas.

Sand" identified on drillers' logs from wells located in parts of Montgomery, Labette, Neosho, and Wilson counties and the Sylamore Formation identified in some wells farther east. The undifferentiated Ordovician may be equivalent to the Powell Formation in some areas. The term "Wilcox Sand" (Abernathy, 1940; Jewett, 1954) is an oil-field term in southeast Kansas and is easily confused with the Wilcox Sand of Oklahoma (White, 1926) or the St. Peter Sandstone of Middle Ordovician age. Typical thicknesses of this formation ranges from 5 to 20 feet.

Mississippian-Devonian System

Chattanooga Shale—The Chattanooga Shale when present lies directly above and is unconformable with the Lower Ordovician Series in southeast Kansas and adjoining areas of Oklahoma and Missouri. The rocks that comprise this unit are reported on drillers' logs to be black shale containing abundant pyrite. The Chattanooga Shale is not present in Cherokee County, in the southern half of Crawford County and in eastern Labette and Neosho counties. The thickness of the Chattanooga elsewhere in southeast Kansas ranges upward to 40 feet. This unit is unconformable with the younger Mississippian rocks above.

Mississippian System

Lower Mississippian Series

Compton Limestone—The Compton Limestone rests unconformably on the underlying Chattanooga Shale. The Compton Limestone is a finely crystalline limestone which locally may be dolomitic. This unit is not present in much of Cherokee County and Labette County. Elsewhere in southeast Kansas the thickness of this unit ranges from about 5 to 20 feet.

Northview Shale—The Northview Shale lies conformably above the Compton Limestone in southeast Kansas and is unconformable with overlying units. The Northview Shale is entirely green, pyritiferous shale in this area. The unit is absent from a large part of southern Cherokee County in Kansas. Elsewhere, the thickness of the Northview Shale ranges from feather edge to more than 40 feet. The Northview Shale is thickest in eastern Bourbon and Crawford counties and eastward into Missouri.

Undifferentiated Mississippian Series

Strata assigned to the undifferentiated Mississippian Series belong to the Lower and Upper Mississippian Series (Zeller, 1968). For the purposes of this report, the two series are considered together as undifferentiated for two reasons. The Lower and Upper Mississippian Series are not distinguished on many of the drillers' logs of wells drilled in southeast Kansas. Also, for those wells with insoluble-residue logs interpreted by geologists accustomed to Missouri stratigraphic nomenclature, the Missouri formation names and boundaries do not necessarily coincide with those in Kansas. The undifferentiated Mississippian in southeast Kansas consists primarily of limestone, dolomite, cherty limestone and cherty dolomite with layers of shale common near the base. These rocks are bounded both above and below by regional unconformities, which may have considerable relief (Fig. 8). The thickness of the undifferentiated Mississippian ranges from about 400 feet in southwest Missouri and northeast Oklahoma to 250 feet in northeast Montgomery, southwest Neosho and southern Wilson counties (Fig. 9). The average thickness of the undifferentiated Mississippian is approximately 300 feet in southeast Kansas.

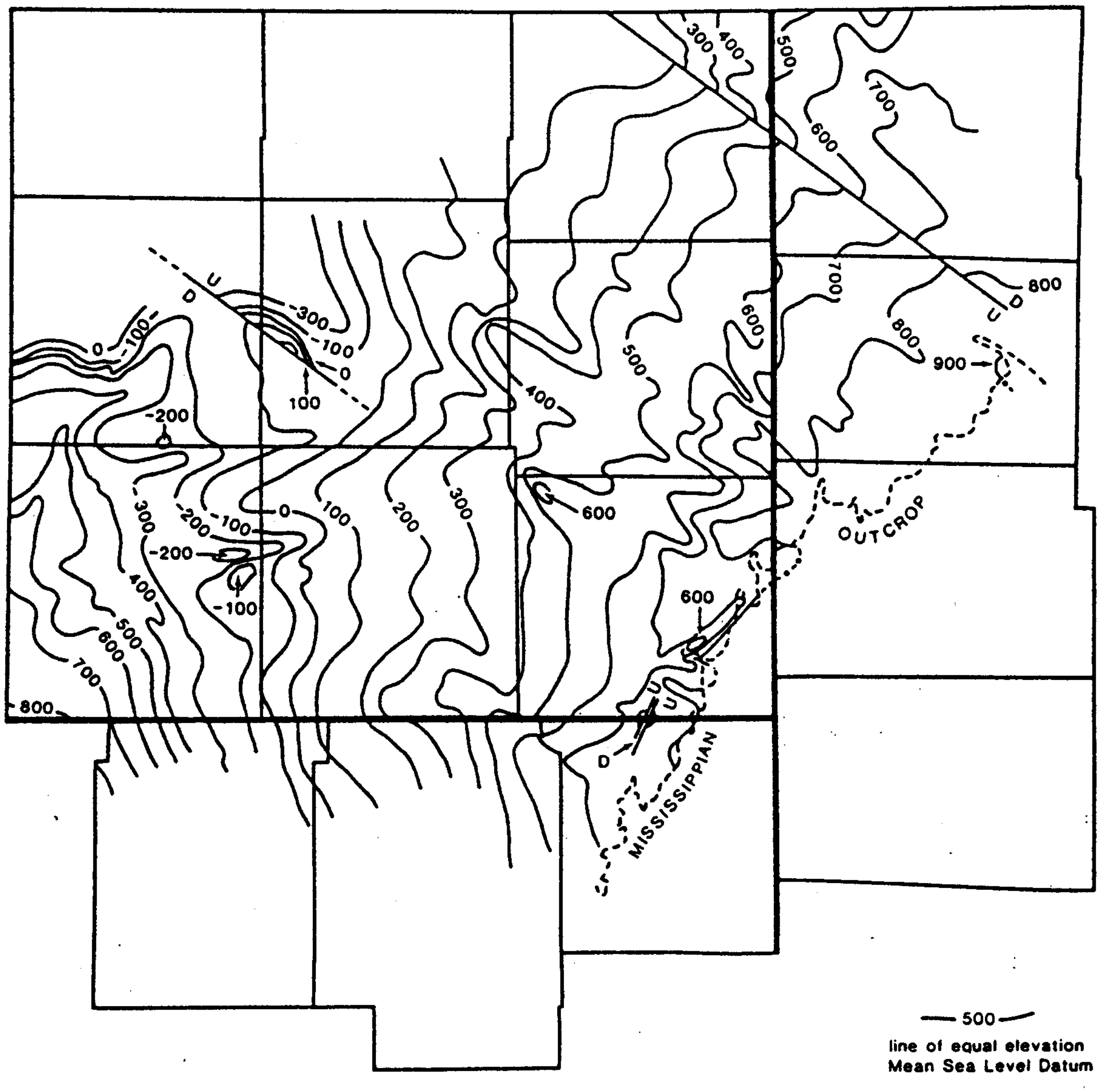


Figure 8. Configuration of the top of the undifferentiated Mississippian System, southeast Kansas and adjoining areas.

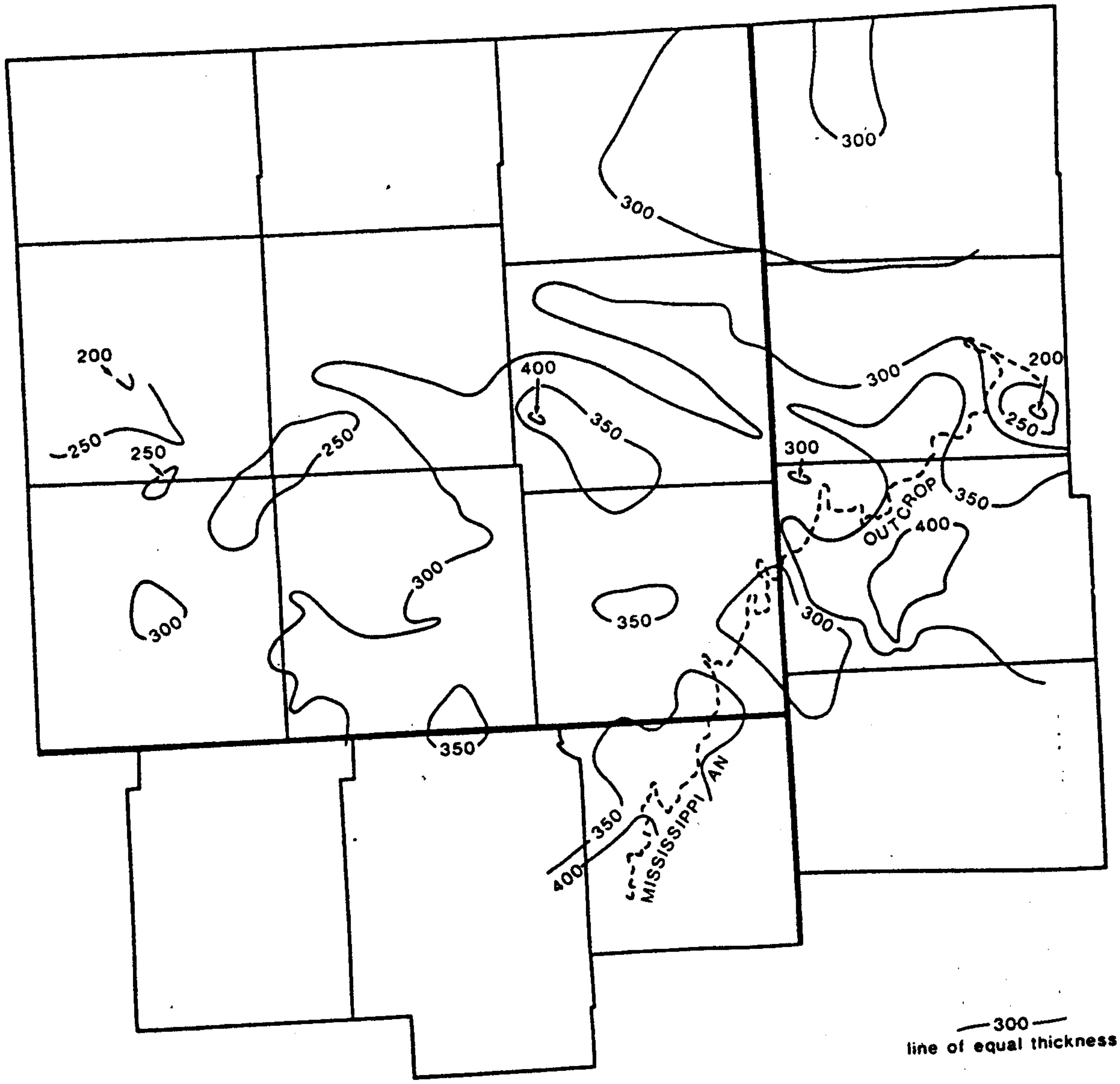


Figure 9. Isopachous map of the undifferentiated Mississippian, southeast Kansas and adjoining areas.

Pennsylvanian System

The undifferentiated Mississippian is unconformably overlain in most of southeast Kansas and adjoining areas by rocks belonging to the Cherokee Group of Middle Pennsylvanian age. Rocks that comprise the Cherokee Group are mostly shale, limestone, sandstone, and coal.

GEOLOGIC STRUCTURE

The study area, including adjoining portions of Missouri and Oklahoma, is located on the northwest flank of the Ozark Dome and covers a large portion of the Cherokee Basin and the Bourbon Arch. The regional dip is generally westward at 20 feet per mile except where geologic structures have altered the prevailing dip direction or amount (Figs. 6 and 10).

The most prominent features in the subsurface of southeast Kansas are northwest-southeast-trending folds and faults. The folds are usually of short (2-5 mile) wavelength and plunge in a northwesterly direction. Individual fold axes can often be traced in the subsurface for many miles on top-configuration and structure-contour maps. Faulting in the subsurface of southeast Kansas is probably high-angle although no drill-hole information is available to substantiate this. Some of these northwest-southeast-trending structures have been named by the geological surveys in Kansas (Jewett, 1951) and Missouri (McCracken, 1971). The Pittsburg Anticline or the Galesburg-Pittsburg Anticline in Missouri, and the Nashville-Carthage Sag are an adjacent anticline-syncline pair of two to three mile wavelength and 75 to 200 feet amplitude that extend from the Joplin, Missouri area northwestward to the Pittsburg, Kansas area. The Chesapeake Fault is an extensive northwest-southeast trending feature that begins in Christian County, Missouri, and is interpreted to end in southwest Linn County, Kansas. The fault extends across northeast Barton and southeast Vernon counties in Missouri and northeast

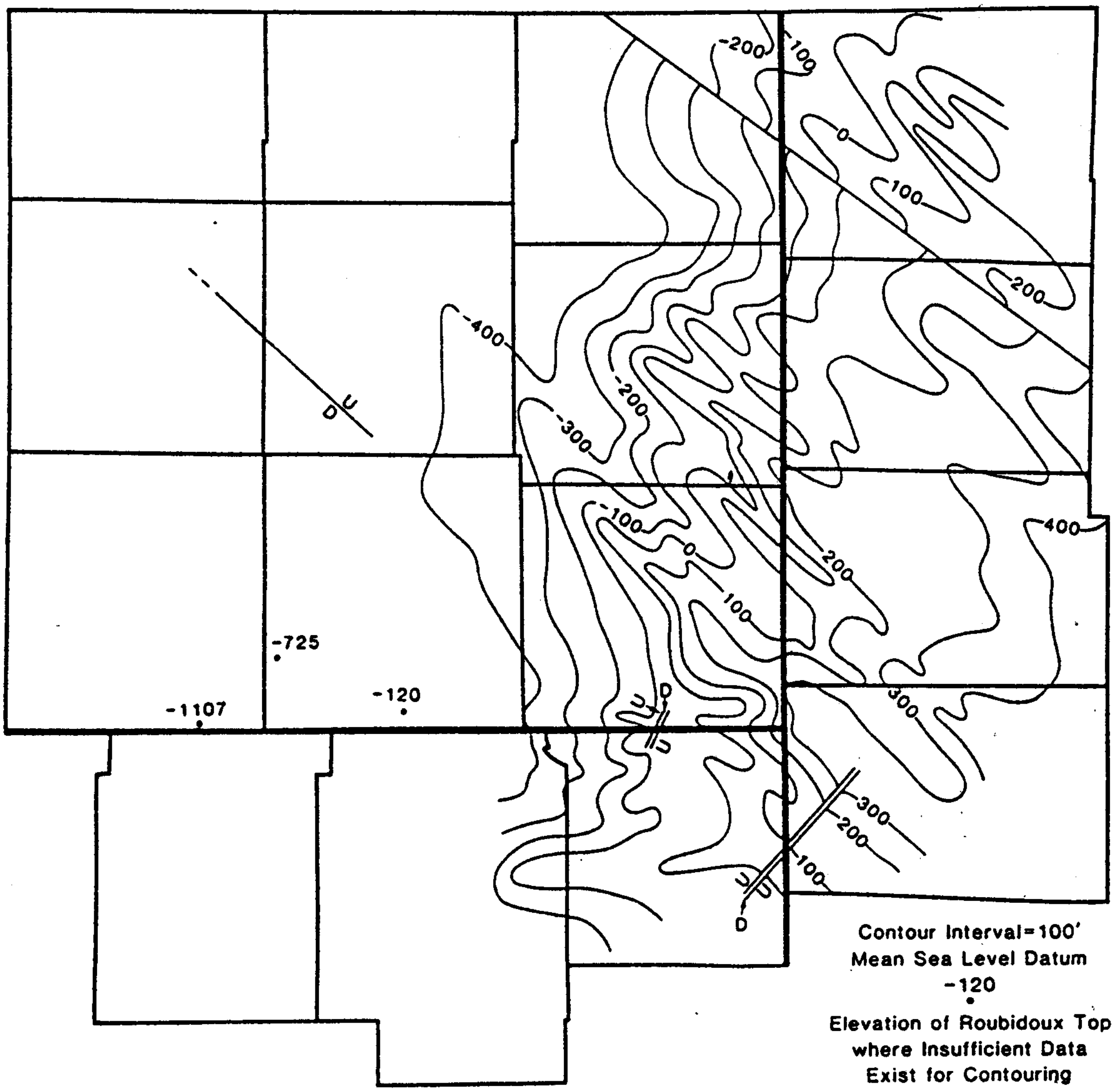


Figure 10. Structure contour map of the top of the Roubidoux Formation, Tri-State Region.

Bourbon County in Kansas. Vertical offset on the faults in Vernon county, Missouri, and Bourbon County, Kansas is estimated to be approximately 75 feet.

Two other major structures, the Miami Trough in Kansas and Oklahoma and the Seneca Fault in Oklahoma and Missouri, trend in a northeast–southwest direction. Both features are unique because they are extensive complex structures involving both faulting and folding (McKnight and Fischer, 1970). The Miami Trough is a steep–sided, narrow syncline, or at some locations a graben, that extends from southern Ottawa County, Oklahoma into Cherokee County, Kansas. Pierce and Courtier (1937) have been able to trace this feature in the subsurface as far north as Crestline, Kansas. The typical width of the Miami Trough ranges from approximately 300 to 2,000 feet. The maximum structural relief is 200 to 300 feet, but is usually only 20 to 30 feet. The Miami Trough probably formed at some time during the Pennsylvanian.

The Bourbon Arch is a broad, gentle uplift extending across all of Bourbon County, Kansas, Vernon County, Missouri, and parts of Allen and Woodson counties in Kansas (Merriam, 1963). This structure is poorly defined on the Mississippian and it is difficult to recognize structure–contour, top–configuration, and isopach maps (Figs. 6, 8, and 10). However, the southern edge of the Bourbon Arch in the study area does approximately coincide with the northern extent of the Cotter Formation in the subsurface.

Domes or dome–like structures are common features locally in the subsurface of Labette, Montgomery, Wilson, and Woodson counties. Most of these domes are roughly circular features with 20 to over 100 feet of closure in the sedimentary section, produced by draping of Paleozoic sedimentary rocks over Precambrian paleotopographic highs (Figs. 2, 6, and 8). These paleotopographic highs are abrupt features on the Precambrian surface with as much as 600 feet of vertical relief. The Cambro–Ordovician section over many of these Precambrian highs is either thin or absent. The circular nature of these features is demonstrated on several of the top configuration maps and is reflected in the overlying Pennsylvanian Section. The isolated nature of these Precambrian highs, the structural closure and thinning exhibited by younger sedimentary rocks over these Precambrian highs, and the lack of evidence to support an igneous intrusive relationship suggest that these are buried Precambrian "posts" (Frank Wilson, personal communication). However, this is not the case for the Rose Dome and Silver City Domes in Woodson County where igneous intrusion has been verified. Granitic igneous rocks are exposed at the surface and wells drilled on the flanks of Rose Dome have encountered "altered dikerock" and peridotite at depth (Jewett, 1954). These features were evidently emplaced during the Cretaceous Period (Bickford, et al., 1979).

Most of the folding and faulting in southeast Kansas and adjoining areas of Missouri and Oklahoma trends in a northwest–southeast direction, reflecting structures on the Precambrian surface (Cole, 1976). Furthermore, the northwest–southeast grain evident on McCracken's (1964) isopach maps of the Upper Cambrian section and of the Gasconade Dolomite for southwest Missouri, northeast Oklahoma, and southeast Kansas suggests that much of the post Gasconade structural activity is along reactivated zones in the Precambrian. The northwest–southeast grain is not evident on McCracken's maps of the Roubidoux Formation and Jefferson City Formation but reappears on the thickness map of post–Jefferson City, Lower Ordovician Series rocks and on the undifferentiated Mississippian isopach map presented with this report.

That major structures evident on the structure–contour map of the top of the Roubidoux Formation are still evident on the top–configuration maps indicates that the effect of erosion is relatively minor compared to the effect of structure on these horizons. This appears to be true even though post–Ordovician erosion has removed the Cotter Formation from much of the northern portion of the southeast Kansas study area. The top configuration–maps should be used only to determine broad regional structure, because paleosink holes or other local paleotopographic features might be misinterpreted as geologic structure.

HYDROGEOLOGY OF THE LOWER PALEOZOIC AQUIFERS

Groundwater occurs in the Lower Paleozoic aquifers under confined, artesian conditions except in southeast Cherokee County where the Mississippian is exposed at the surface (Fig. 8) and in the Miami, Oklahoma area where the static water level of wells penetrating the Cambro-Ordovician are below the top of the aquifer. A confined aquifer is a water-bearing, permeable, geologic unit capable of transmitting significant quantities of water under ordinary hydraulic gradients and is overlain by a geologic unit that may be saturated with water but is less permeable (Freeze and Cherry, 1979). Artesian conditions exist when the static water level of wells penetrating a confined aquifer is above the level of the top of the aquifer (ibid.).

The Lower Paleozoic sedimentary section is considered in this report to consist of two aquifer systems separated over much of the area by one or more confining layers. The upper aquifer system is comprised of Mississippian limestones, whereas the lower aquifer system is comprised of rocks of the Lower Ordovician-Upper Cambrian (Cambro-Ordovician) System. The Precambrian is considered to be a confining layer at the base of the Cambro-Ordovician aquifer.

One or more stratigraphic units act as confining layers separating the two systems throughout much of southeast Kansas and adjoining portions of Missouri and Oklahoma. These layers are composed of shale and fine-grained limestone and dolomite belonging to the Chattanooga Shale, the Compton Dolomite, and the Northview Formation (Fig. 11). No information is available locally on the vertical permeability of these confining units; however, Emmett, et al. (1979) assigned a vertical permeability of 10^{-9} ft/sec to the Northview Formation at Springfield, Missouri. Where these units are not present in the area (Fig. 11) (where Kansas, Oklahoma, and Missouri meet in the Tri-State region), the Cambro-Ordovician aquifer system probably behaves as a semi-confined system.

Groundwater is transmitted through the Mississippian and Cambro-Ordovician aquifers through pores within the rock and through fracture systems and solution

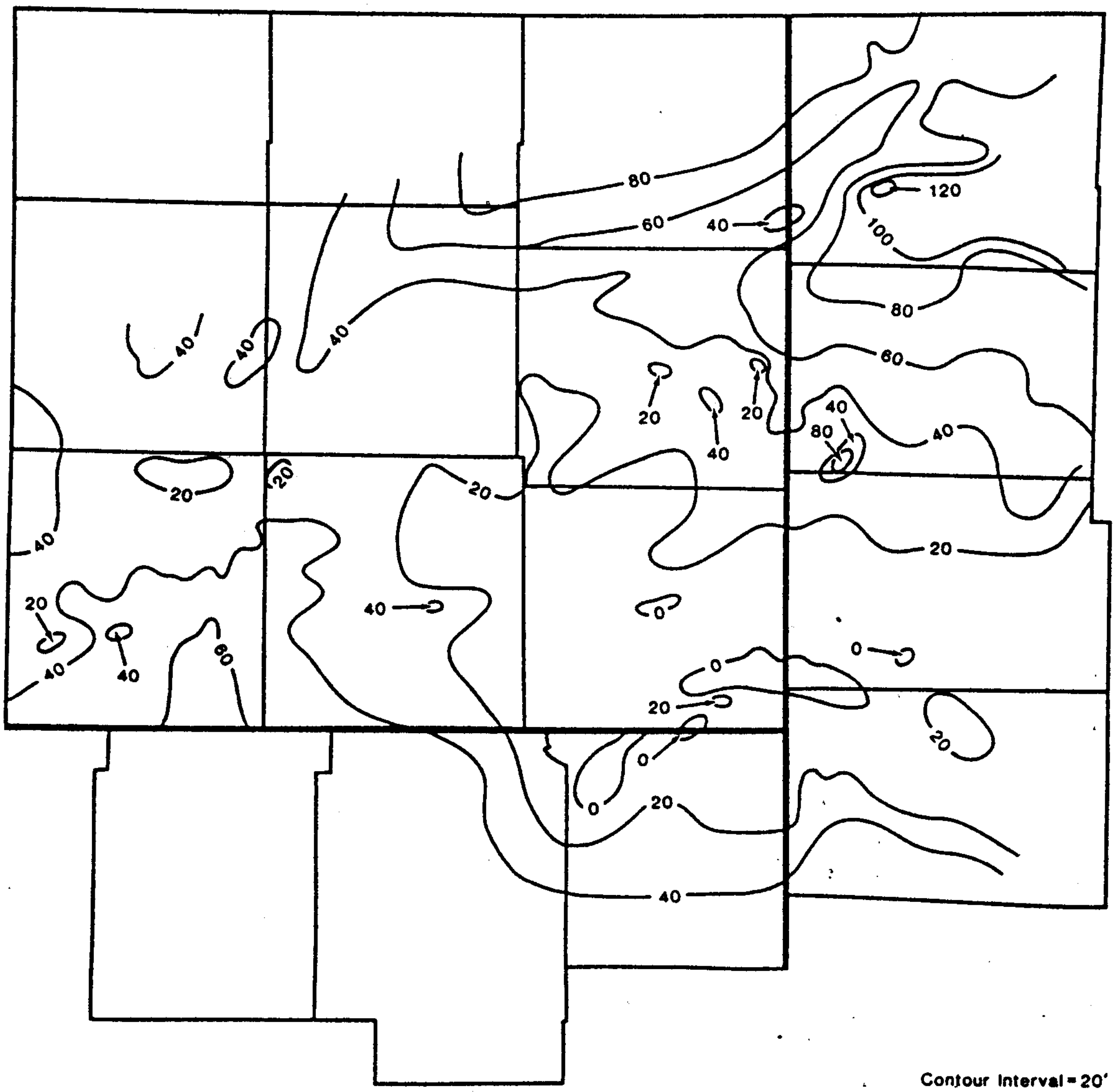


Figure 11. Isopach map of the interval between the top of the Lower Ordovician and the base of the Mississippian, southeast Kansas and adjoining areas.

channels. These fracture systems and solution channels introduce considerable heterogeneity into the aquifer system limiting the use of Darcy's Law on a local scale. This limitation can be partly ignored if the Darcian approach is used on a regional scale.

Groundwater in the fresh- (less than 500 mg/l total dissolved solids) and brackish- (500-5000 mg/l) water portions of the Lower Paleozoic aquifers flows primarily in response to hydraulic gradients, according to Darcy's Law:

$$v = Ki$$

where: v = specific discharge

K = hydraulic conductivity

i = hydraulic gradient

The direction of water flow in the aquifer is from a point of greater to lesser hydraulic head. Temperature differences probably influence the flow of groundwater slightly across the region.

The lateral direction of water flow is determined by constructing a potentiometric surface map of the aquifer in the region of interest. The configuration potentiometric surface is determined by contouring a map of measured static water levels in wells that penetrate the aquifer. The direction of water flow is perpendicular to the contours in the down gradient direction if the anisotropy of the aquifer is negligible.

Groundwater flow in aquifers containing variable-density fluids at different temperatures such as in the Lower Paleozoic aquifers is more complicated because density and temperature gradients must be considered in addition to the hydraulic gradient (Freeze and Cherry, 1979). Where the aquifer contains groundwater of variable density, the direction of flow is not necessarily in the direction of the maximum hydraulic gradient (Hubbert, 1953). Rather, coupled flow conditions involving all gradients must be considered. Coupled flow has not been considered in this report because no evidence exists to confirm the process in southeast Kansas.

The Mississippian Aquifer

Groundwater Availability

Very little hydrogeologic information that pertains to the Mississippian aquifer is available from the Kansas portion of the study area because this aquifer is not generally used for water supply except in southeast Cherokee County and for industrial purposes in a few other locations in southeast Kansas. This aquifer is used extensively in southwest Missouri for domestic supplies. Throughout most of southeast Kansas, except in southeast Cherokee County, the Mississippian does not produce adequate amounts of water for most purposes except domestic and therefore, the aquifer is used minimally.

From drillers' logs of wells in the area, water is known to occur near the top and bottom of the Mississippian, and it is likely that groundwater supplies could be developed from several horizons within the aquifer. Groundwater present in the aquifer is stored in and transmitted by fractures and solution channels, especially where pre-Pennsylvanian erosion has developed a karstic surface at the top of the aquifer or where the aquifer contains brecciated chert or collapse fractures. Where the limestone is unfractured and dense, well yields are likely to be much less. The maximum well yields can be expected to be 100 gallons per minute. More typical well yields are likely to be about 25 gallons per minute.

Groundwater Flow, Recharge, and Discharge

Not enough water wells penetrating the Mississippian were found during this study to develop a reasonably detailed potentiometric surface map for this aquifer in southeast Kansas (Fig. 12). However, from the data available, the potentiometric surface is known to slope generally westward from recharge areas where the aquifer confined in southeast Kansas, southwest Missouri, and northeast Oklahoma. Recharge to the aquifer comes from precipitation falling on the land surface where water table conditions exist. Historically the dewatering of lead-zinc mines in the Picher Field changed the direction

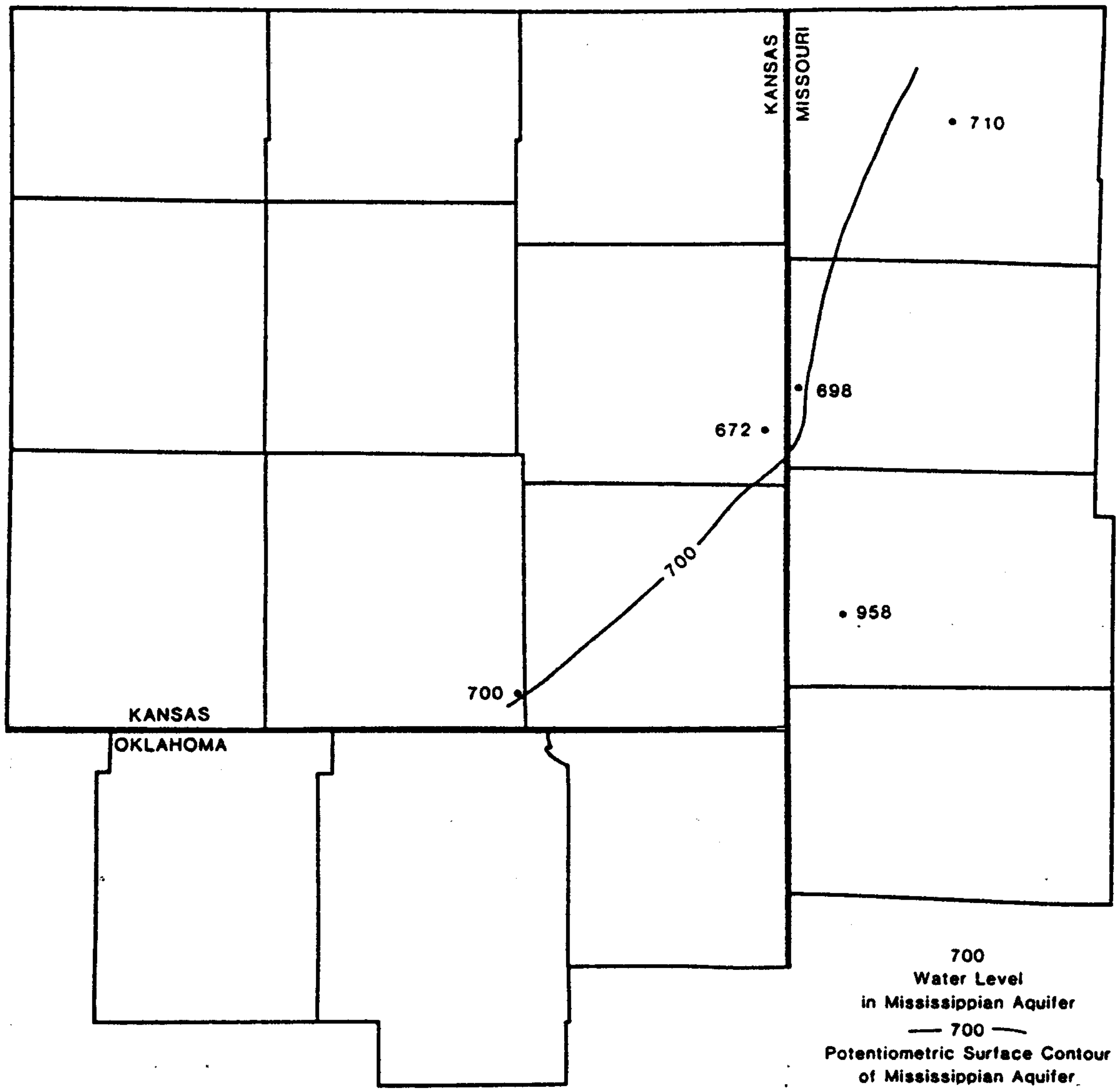


Figure 12. A comparison of static water levels in the Mississippian aquifer, southeast Kansas and adjoining areas.

of groundwater flow. Locally, the dewatering created a large cone of depression in the Mississippian aquifer (Reed, et al., 1955). With the cessation of mining, the potentiometric surface has risen in the mined area and streams in northern Ottawa County, Oklahoma are receiving some discharge from this aquifer. Small amounts of water are discharged from domestic wells in both confined and unconfined areas. Most of the regional discharge from this aquifer in the study area is to the west and south as underflow.

The Cambro-Ordovician Aquifer

Water Availability

Groundwater is known to occur throughout the Cambro-Ordovician aquifer in southeast Kansas and adjoining areas. However, water well drillers generally seek selected intervals in the Cambro-Ordovician stratigraphic section for well completion, such as the "Swan Creek" in the Cotter Formation, the "Roubidoux Sand", in the Roubidoux Formation or the "Gunter" in the Gasconade Dolomite. Typically, wells drilled into the Cambro-Ordovician are cased some distance below the top and are completed as an open bore-hole down to the total depth of the well. In the southeast Kansas region drillers have reported water in the top of the Cambro-Ordovician (Powell, Cotter, Jefferson City) where the aquifer is a dolomitic sandstone or where a paleo-karstic erosional surface has been developed at the top of the aquifer and from the Roubidoux-Upper Gasconade interval, which has both primary and secondary permeability. Most wells for public water supply are not drilled below the base of the Gasconade in eastern Cherokee and Crawford counties because the total dissolved solids content of the groundwater begins to increase appreciably in the lower part of the aquifer and because adequate water supplies can be developed above the base of the Roubidoux Formation. Water wells become progressively shallower farther west generally and are generally completed in the upper part of the aquifer because the water becomes more saline as well-depth increases. In northwestern Crawford County public water supply wells do not extend much below the top of the Cambro-Ordovician but in western Cherokee and southwestern Crawford counties some public water supply wells penetrate the base of the Roubidoux Formation.

As the relative amounts of water produced by each level in the Cambro-Ordovician aquifer for a given well is not known, it should not be concluded that certain horizons within the aquifer will always produce more water than others. Rather, the occurrence of groundwater in these carbonates is directly related to the development of both primary and secondary porosity and permeability in each of the stratigraphic units. Typical well yields of municipal and industrial wells range from 100 to 750 gallons per minute (13.4 - 100 ft^3/min). Water is generally produced at a rate of approximately 100 gallons per minute (13.4 ft^3/min) from most rural water district wells.

Groundwater Flow, Recharge, and Discharge

Groundwater flow through the Cambro-Ordovician aquifer is generally westward across southeast Kansas from recharge areas in the Ozarks of southern Missouri to discharge areas west and south of the study area (Figs. 13, 14). The main source of recharge is precipitation entering the aquifer in the Ozark region. A pre-development potentiometric surface map (Fig. 13) was drawn using static water level measurements from wells existing at about the turn of the century and from wells drilled in previously unpumped parts of the region. The contours on both the pre- and post-development potentiometric surface maps (pre-1900 and 1980) indicate steep hydraulic gradients in southwest Missouri and eastern Cherokee County, Kansas while to the west, the hydraulic gradient is flatter. The flatter gradients might indicate increased permeability in this area. Also, there appears to be a rather poorly defined groundwater divide extending from Labette County northeast into Crawford County on the post-development map,

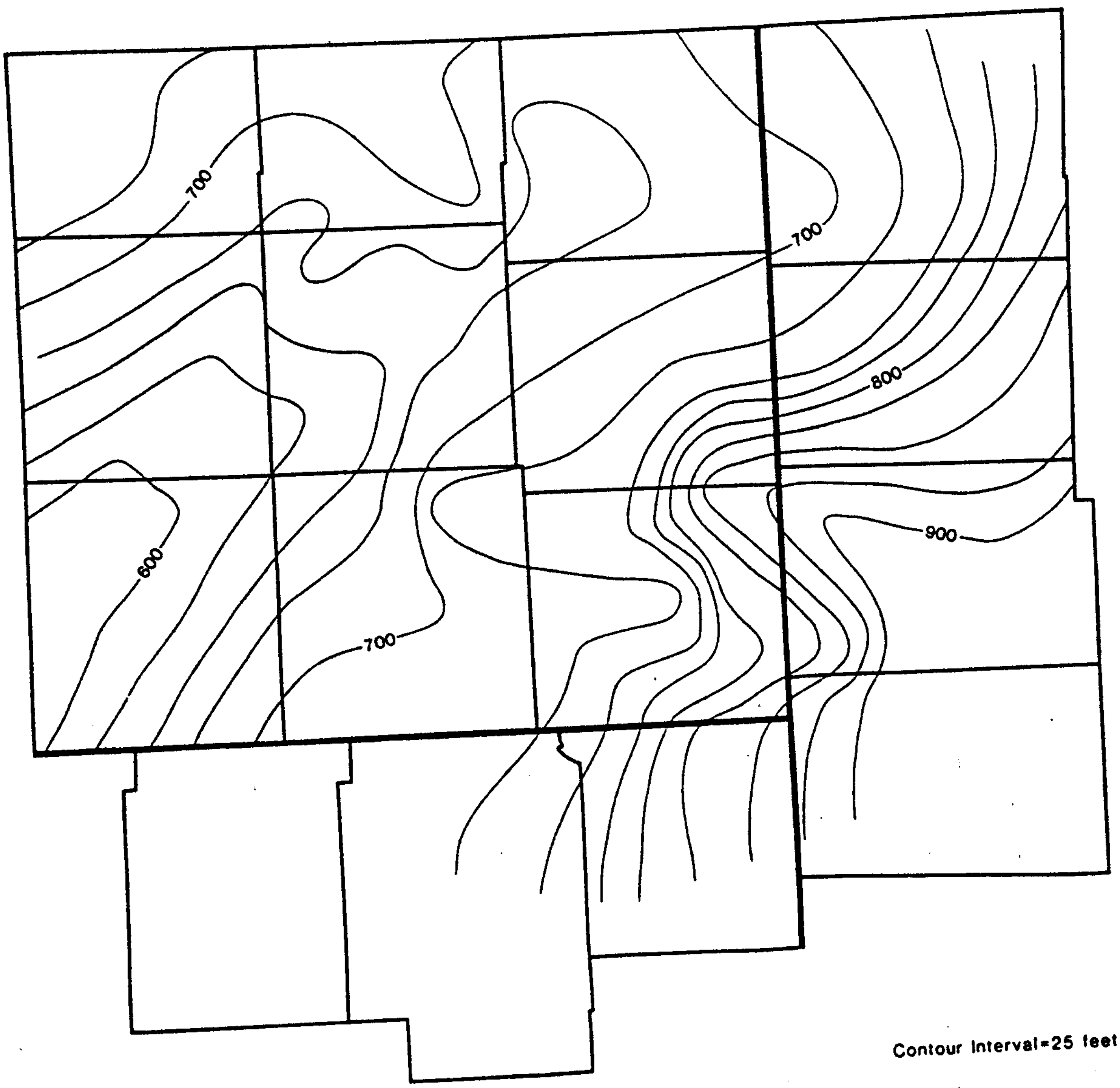


Figure 13. Pre-development potentiometric surface map of the Lower Ordovician aquifer, southeast Kansas and adjacent areas.

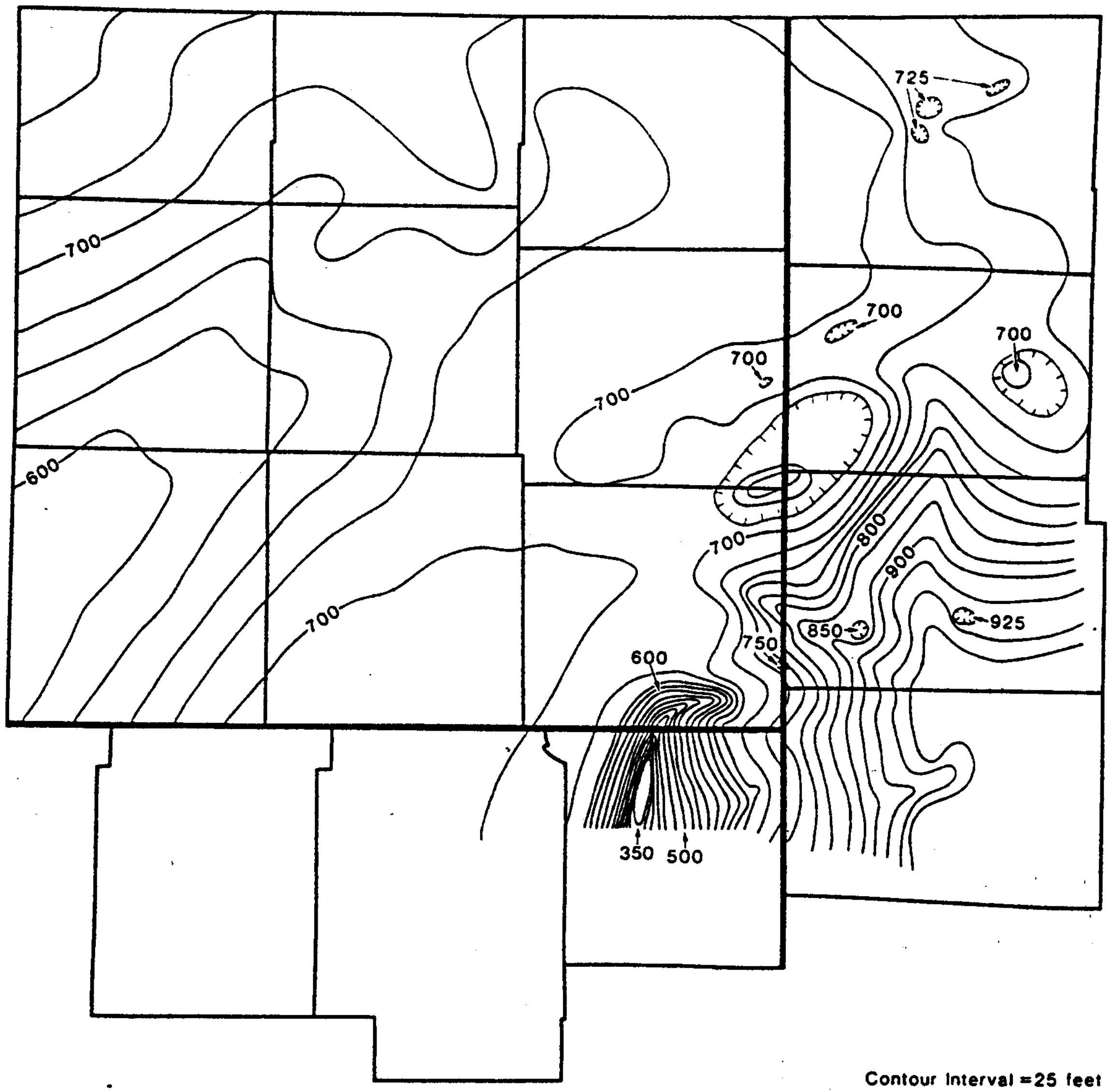


Figure 14. Potentiometric surface map of the Cambro-Ordovician aquifer, southeast Kansas and adjacent areas.

which might have been more east-west in pre-development times. In Montgomery, Woodson, and Wilson counties the groundwater flow direction in the Cambro-Ordovician is more southerly.

Groundwater is also discharged through well pumpage. Many of the municipal well fields can be readily identified by their cones of depression on the potentiometric surface map. Relatively small cones of depression are created by well fields at Carthage, Webb City, Nevada, Liberal and Barton County RWD #1 in Missouri. Larger cones of depression indicative of very large withdrawals have been created by industrial and municipal well fields southeast of Pittsburg, Kansas and in the Baxter Springs, Kansas - Miami, Oklahoma area where deep wells have been in operation since before the turn of the century. The potentiometric surface at Miami, Oklahoma has declined approximately 450 feet since 1900 (Reed, et al., 1955) and the aquifer is under water-table conditions in the vicinity of the municipal well field. At Pittsburg, Kansas water levels have declined approximately 150 feet since the late 1800s (Stramel, 1957).

Few attempts have been made to determine the vertical component of groundwater flow within the Cambro-Ordovician aquifer. The only evidence for vertical hydraulic gradients has come from the drilling of wells by cable-tool methods and from adjacent wells drilled to different depths within the aquifer (Figs. 15 and 16). The static water levels in these open boreholes provide only an indication of the vertical component because each drill hole is usually open to all aquifers above the bottom of the hole. As a result, it is not possible to compute the differences in hydraulic head between the various stratigraphic levels of the aquifer penetrated by the well. Most of the data from cable-tool drilled wells suggest that the vertical component of flow within the Cambro-Ordovician is downward when these wells were drilled. That only small changes in depth to water occur with well depth during drilling suggests that the magnitude of the vertical component of flow is small.

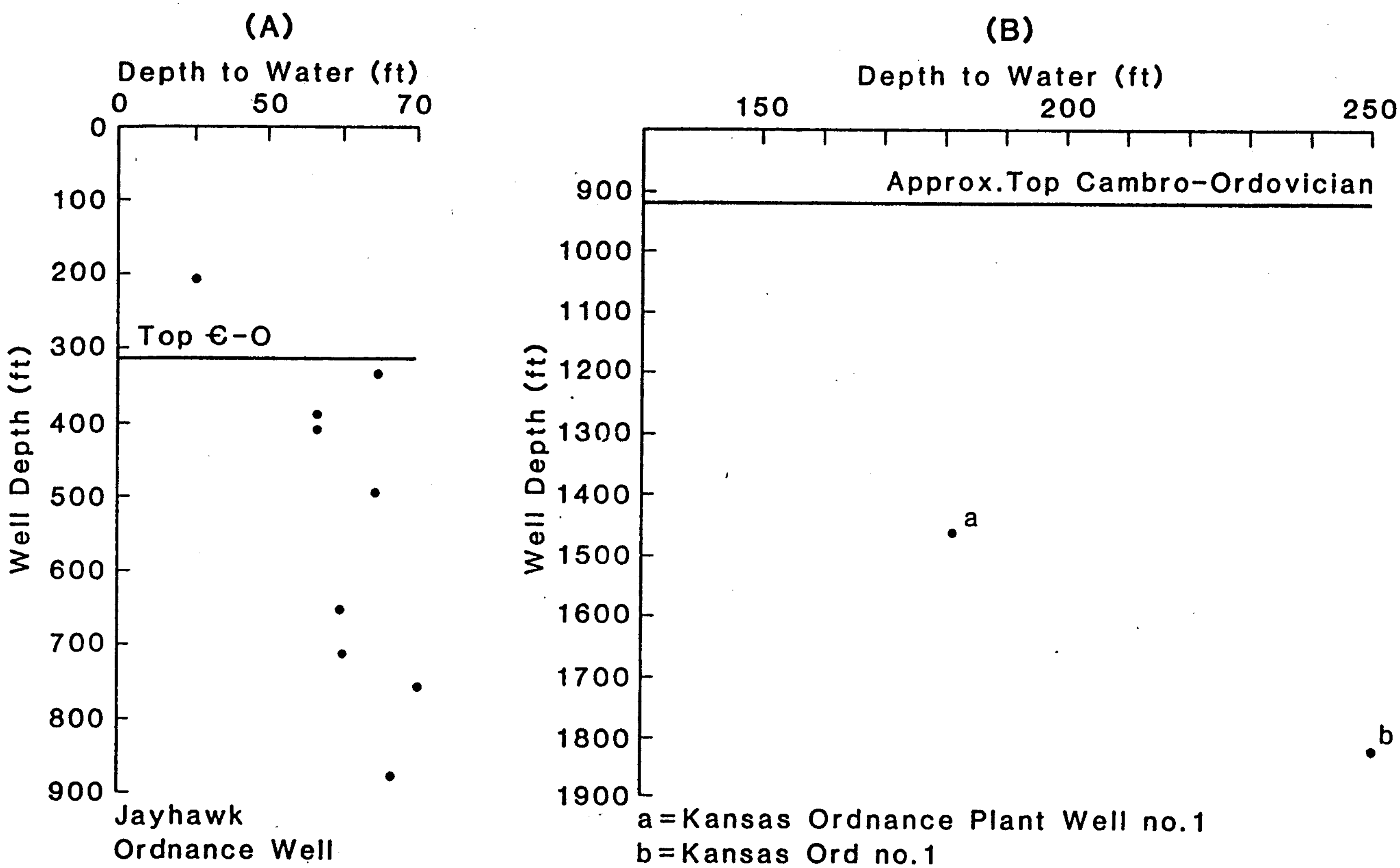


Figure 15. (A) Depth to water vs. well depth in Jayhawk Ordnance Well. (B) Water levels from two wells completed in the Cambro-Ordovician near Parsons, Kansas.

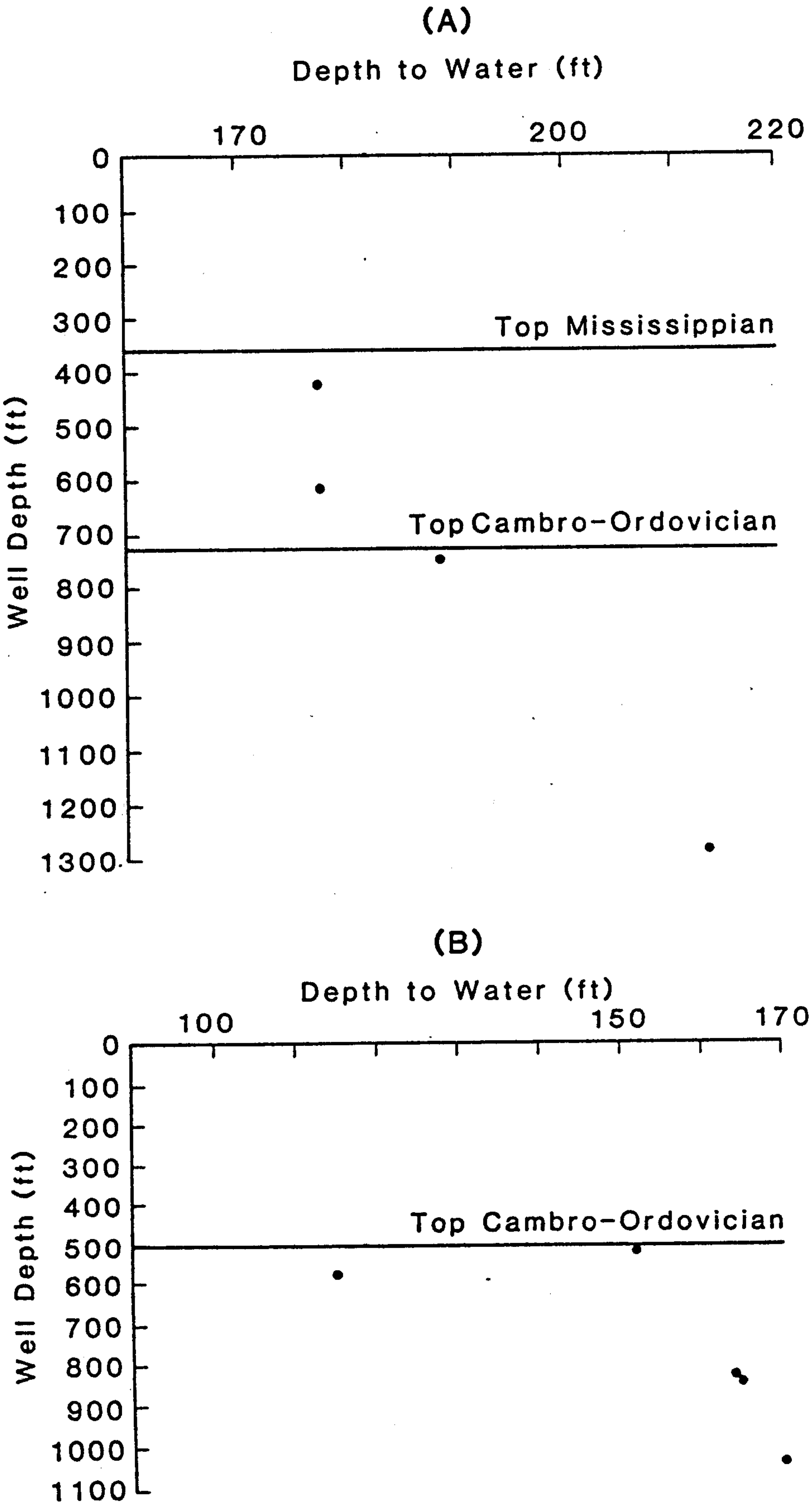


Figure 16. Depth to water vs. well depth in (A) West Mineral Municipal Well, and (B) Baxter Springs Municipal Well No. 5.

Aquifer Properties of the Cambro-Ordovician Aquifer

Transmissivity and storativity are two properties that determine the ability of a confined aquifer to transmit and store water (Freeze and Cherry, 1979). Transmissivity is defined as the product of the hydraulic conductivity and the aquifer thickness and indicates the capacity of a confined aquifer as a whole to transmit water. The storativity of a confined aquifer is defined as the volume of water an aquifer releases from or takes into storage per unit surface area of aquifer per unit decline in the component of hydraulic head normal to that surface.

Few complete pump tests have been conducted in southeast Kansas and adjoining areas to estimate transmissivity and storativity (Table 1). Most pump tests consist of determining specific capacity by measuring discharge and drawdown in the same well during a pumping period, usually of short duration. Transmissivity and storativity (storage coefficient) can be estimated from the specific-capacity data. However, the computed estimates may be unreliable if the test pumping period is not sufficiently long, if the well does not fully penetrate the aquifer, or if hydrogeologic boundaries exist nearby. These computed estimates, together with the estimates of transmissivity from pump tests, have been plotted on Figure 17 to show the areal distribution of this parameter.

Reported estimates of transmissivity and those computed from specific-capacity data range from less than 50 to over 30,000 ft^2/day across the Tri-State region of Kansas, Missouri, and Oklahoma. Storativity ranges from 6.85×10^{-5} to 1.1×10^{-3}. Variations in the estimates of these parameters are the result of variations in lithology, thickness of the aquifer, and the development of secondary porosity and permeability. The highest storativity and transmissivity values are in the Pittsburg-Girard vicinity in Crawford County. The lowest values for transmissivity are in the vicinity of Joplin, Missouri. No information on transmissivity and storativity is available for the western half of the southeast Kansas study area.

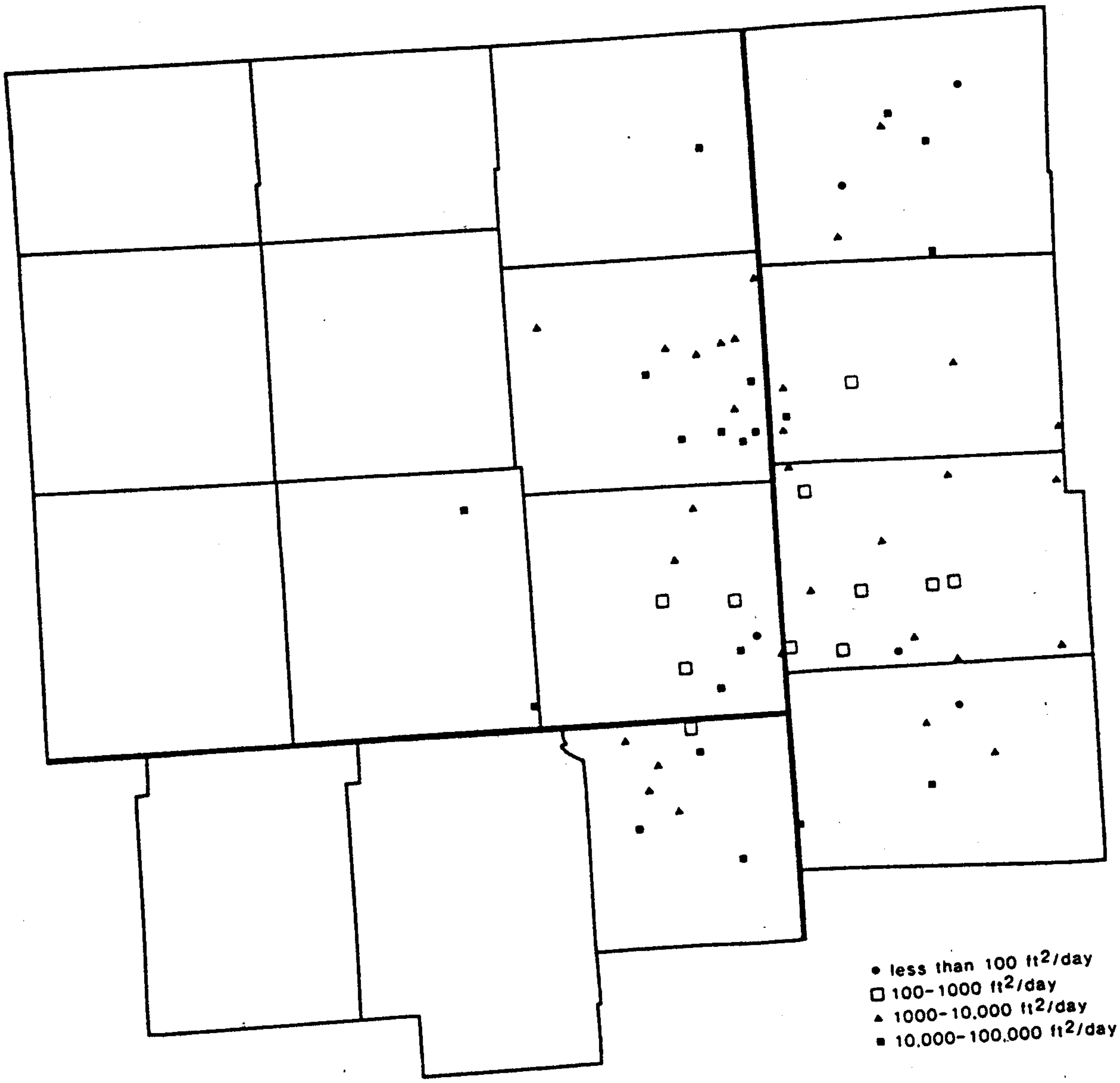


Figure 17. Distribution of transmissivity in the Cambro-Ordovician aquifer across the Tri-State Region.

TABLE 1: Transmissivity and Storativity Values Calculated from Pump Test Data, Southeast Kansas and Adjoining Areas.

Location	Year	Pump Test #	Type of Test	Transmissivity ft^2/day	Storativity	Source
Miami, Oklahoma	1944	1	Recovery	3182	---	Reed, et al (1955)
			Recovery	6371	8.43×10^{-5}	
		2	Recovery	2984	1.02×10^{-4}	
			Drawdown	4429	6.85×10^{-5}	
			Recovery	5430	6.07×10^{-5}	
			Drawdown	4328	7.87×10^{-5}	
			Recovery	4234	7.69×10^{-5}	
		3	Drawdown	4892	4.23×10^{-5}	
			Recovery	7984	6.17×10^{-5}	
			Drawdown	5538	5.77×10^{-5}	
			Recovery	5900	6.10×10^{-5}	
			Drawdown	4785	1.27×10^{-4}	
			Recovery	6559	1.41×10^{-4}	
	Overall Average			5121	8.00×10^{-5}	
Pittsburg, Kansas	1954-55	1	Recovery	34946	1.7×10^{-3}	Stramel (1957)
		2	Drawdown	32258	1.1×10^{-3}	
		3	Drawdown	33602	---	
		4	Recovery	33602	2.2×10^{-4}	
		5	Drawdown	33602	2.2×10^{-4}	
		6	Recovery	34946	1.6×10^{-4}	
		7	Drawdown	34946	5.4×10^{-4}	
		8	Recovery	33602	7.2×10^{-4}	
Webb City, Mo.	----	1	24-hour Interference	538	2×10^{-4}	Feder, et al (1969)

The Hydraulic Connection Between the Mississippian and Cambro–Ordovician Aquifers

Hydraulic connection between the Mississippian and Cambro–Ordovician aquifers in the Tri-State region has been discussed by several authors. Reed, et al. (1955) suggested that acid-mine waters from the Mississippian aquifer could leak downwards into the Cambro–Ordovician aquifer where the Chattanooga Shale is not present because of the large differences in head between these two aquifers in the area north of Miami, Oklahoma. Feder et al 1969) stated that downward leakage from the Mississippian aquifer into the Cambro–Ordivician aquifer could occur in the Joplin, Missouri area where the altitude of the potentiometric surface is higher in the Mississippian than in the deep Ordovician. The Northview Shale is not present locally in the Joplin area and where Lower Paleozoic rocks are highly fractured, leakage could occurr. Both aquifers are connected in wells where the open-bore hole portion of the well intersects both aquifers at several locations in Crawford and Cherokee counties, Kansas (Fig 2). This is quite apparent from the groundwater chemical quality data.

Leakage of groundwater from the Mississippian into the Cambro–Ordovician aquifers is likely especially where the confining layers are not present and where there is greater head in the upper than in the lower aquifer. Leakage would be particularly likely where large-scale groundwater withdrawals from the Cambro–Ordovician have occurred. The confining layers are not present in southern Cherokee County, Kansas, northern Ottawa County, Oklahoma, and in parts of Newton and Jasper counties in Missouri (Fig. 15). However, no evidence of downward leakage was found in these areas. Elsewhere, leakage could occur with small differences in head between the two aquifers if the confining layers are sufficiently fractured.

CHEMICAL QUALITY OF GROUNDWATER IN THE LOWER PALEOZOIC AQUIFERS

The Mississippian Aquifer

Very few wells that are open only to the Mississippian aquifer were available for sampling during the course of the study. Three of the sampled wells are located in southwestern Missouri in the westernmost tier of counties and three in southeast Kansas. Additional analyses of groundwater chemical quality came from Darr (1978), Feder, et al (1969) and from the files of the Kansas Department of Health and Environment.

Groundwater from the Mississippian typically has less than 500 mg/l total dissolved solids where the aquifer is unconfined (Fig. 18). The dissolved-solids content increases rapidly in a westerly direction where the aquifer is confined. The dissolved-solids iso-cons are more or less parallel to the western edge of the Mississippian outcrop. Variations in this northeast-southwest trend can possibly be attributed to effects of geologic structures in Jasper County, Missouri, and Cherokee County, Kansas, and possibly to pumpage of water from the shallow aquifer by wells open to both the Lower Paleozoic aquifers in the Nevada, Missouri - Ft. Scott, Kansas area. Groundwater temperatures range from 15°C in the unconfined portion up to 20°C in the confined portion.

The dominant ionic constitiuents also change from the unconfined to the confined portions of the aquifer. Where the aquifer is unconfined the dominant constituents in solution are calcium and bicarbonate. The dissolved-sulfate content is within the range 20-50 mg/l while concentrations of magnesium, sodium, and chloride are generally less than 10 mg/l. In the confined portion of the aquifer, where the total dissolved-solids content is above 500 mg/l, the dominant dissolved constituents are sodium and bicarbonate. The confined zone seems to be geographically associated with the transition zone waters of the deeper Cambro-Ordovician aquifer. Concentrations of calcium, magnesium, chloride, and sulfate are usually less than 50, 35, 50, and 210 mg/l

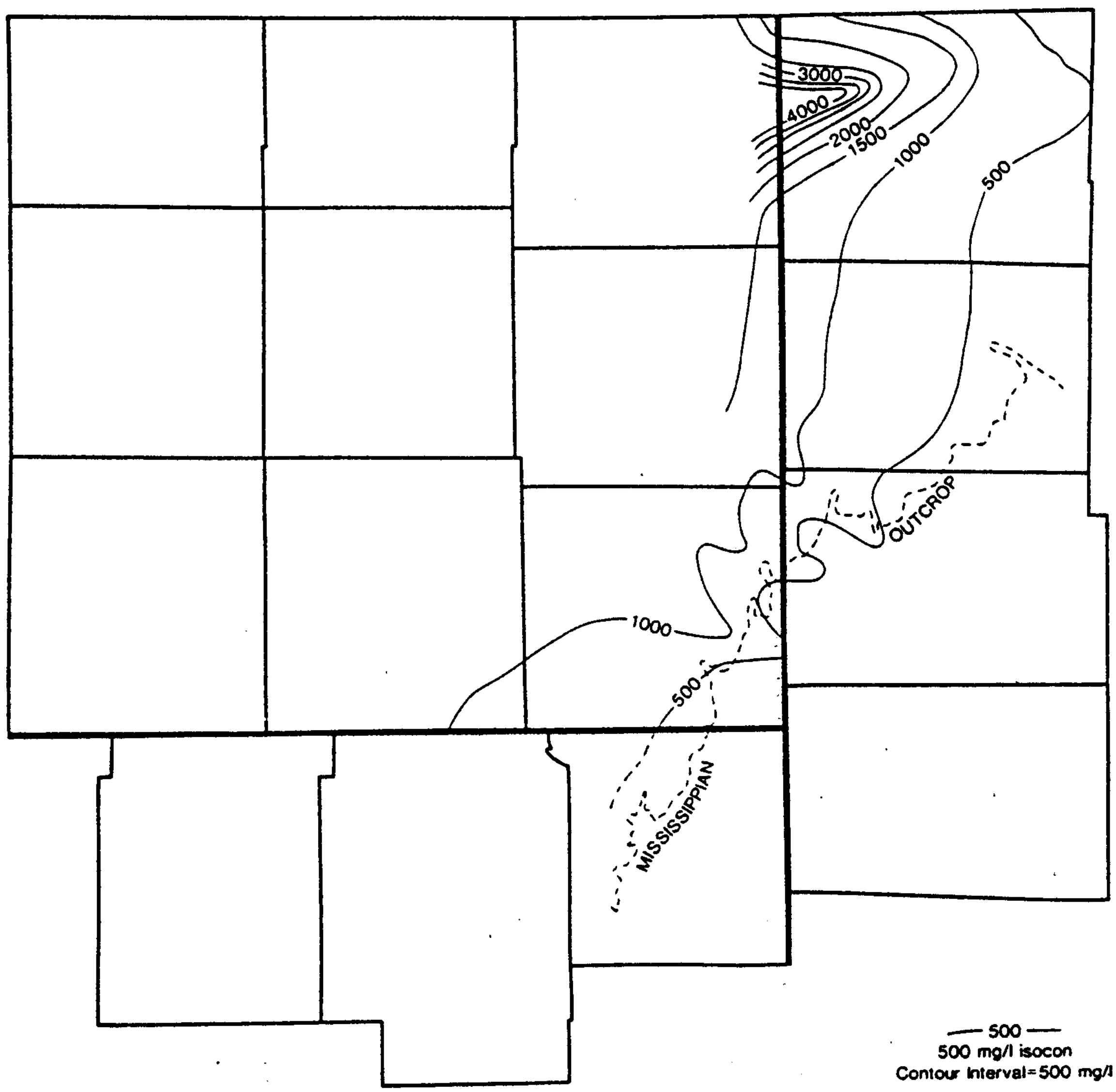


Figure 18. Total dissolved solids concentration of waters in the Mississippian aquifer in southeast Kansas and adjoining areas.

repsectively, and hydrogen sulfide is present. Dissolved sulfate present in both the unconfined and confined portions of the aquifer may be derived from the oxidation of pyrite in the strata. Farther west chloride and dissolved solids concentrations are greater than 200 and 1000 mg/l, respectively, and chloride becomes the dominant anion in solution.

The Cambro-Ordovician Aquifer

Groundwater chemical quality in the deep aquifer varies considerably from east to west across the study area (Figs. 19-22). In the southeastern portion of the area (southwestern Missouri and parts of northeastern Oklahoma) groundwaters receive fresh-water recharge moving westward from the Ozarks of southern Missouri. The waters generally contain less than 300 mg/l total dissolved solids and no hydrogen sulfide. The dominant dissolved constituents are calcium, magnesium, and bicarbonate, with ranges usually of 30-45 mg/l, 14-20 mg/l, and 150-220 mg/l, respectively. The chemistry reflects the solution of the predominantly dolomite strata of the aquifer, which buffers the pH's within the general range 7.4-7.7 units. Dissolved sulfate levels are about 14$\pm$ 5 mg/l, while concentrations of sodium and chloride are each usually less than 15 mg/l.

In the western and northwestern parts of the study area (Allen, Bourbon, Montgomery, Neosho, Wilson, and Woodson counties, Kansas) the formation waters in the Cambro-Ordovician aquifer are sodium-chloride brines. The dissolved solids concentration reache 80,000 mg/l and the chloride concentration approximately 50,000 mg/l at Coffeyville. Where dissolved chloride contents exceed 10,000 mg/l, the weight ratio of sodium/chloride falls within 0.50-0.60, and bicarbonate levels fall within 250-700 mg/l. Concentrations of calcium and magnesium range widely (300-3,500 mg/l and 150-1,100 mg/l, respectively), and generally follow the changes in total dissolved solids. Calcium, magnesium, and bicarbonate contents are probably controlled predominantly by equilibrium with dolomite, and are much higher in concentration than in the fresh waters

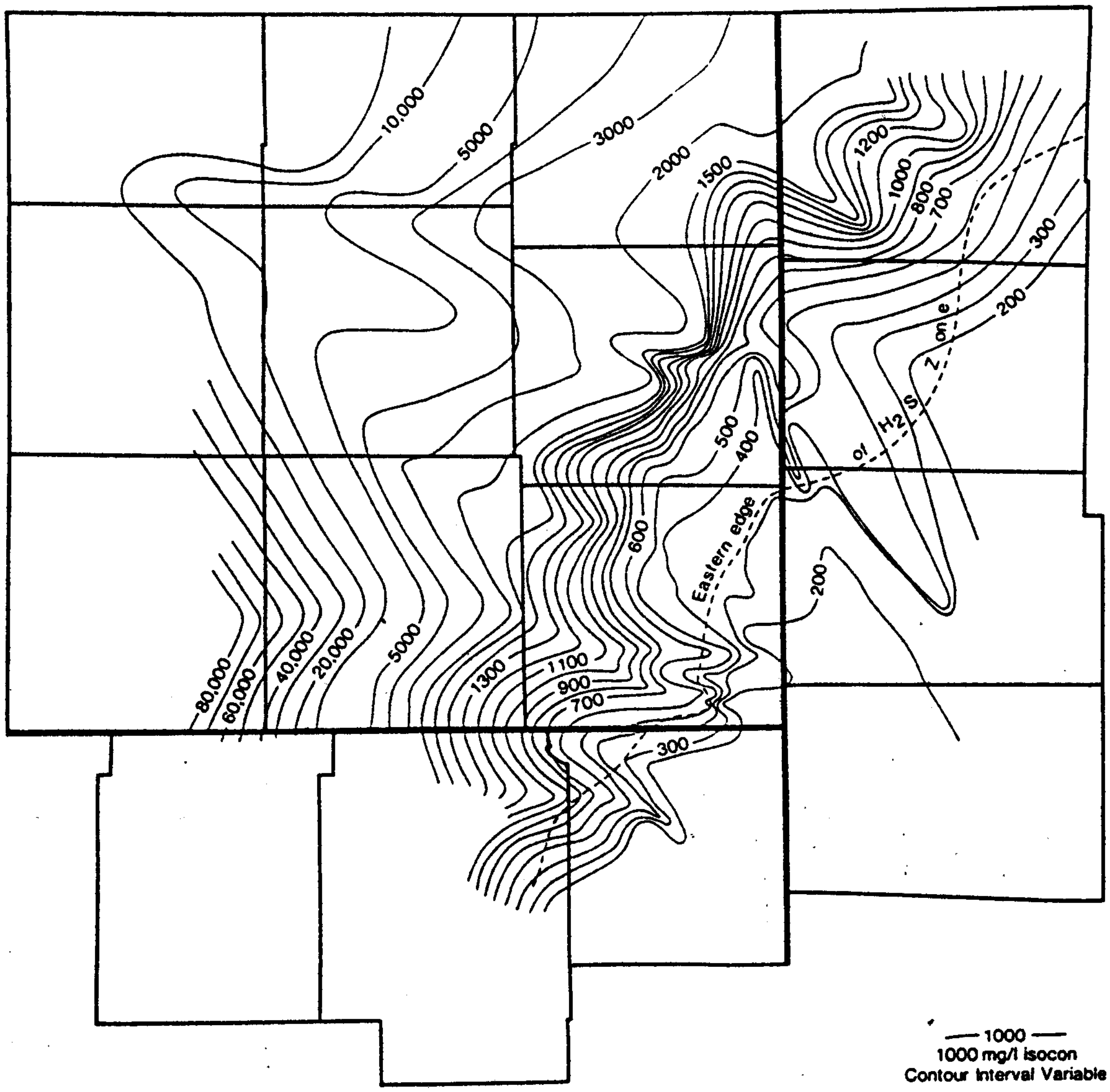


Figure 19. Total dissolved solids concentration of waters from the Lower Ordovician in southeast Kansas and adjoining areas.

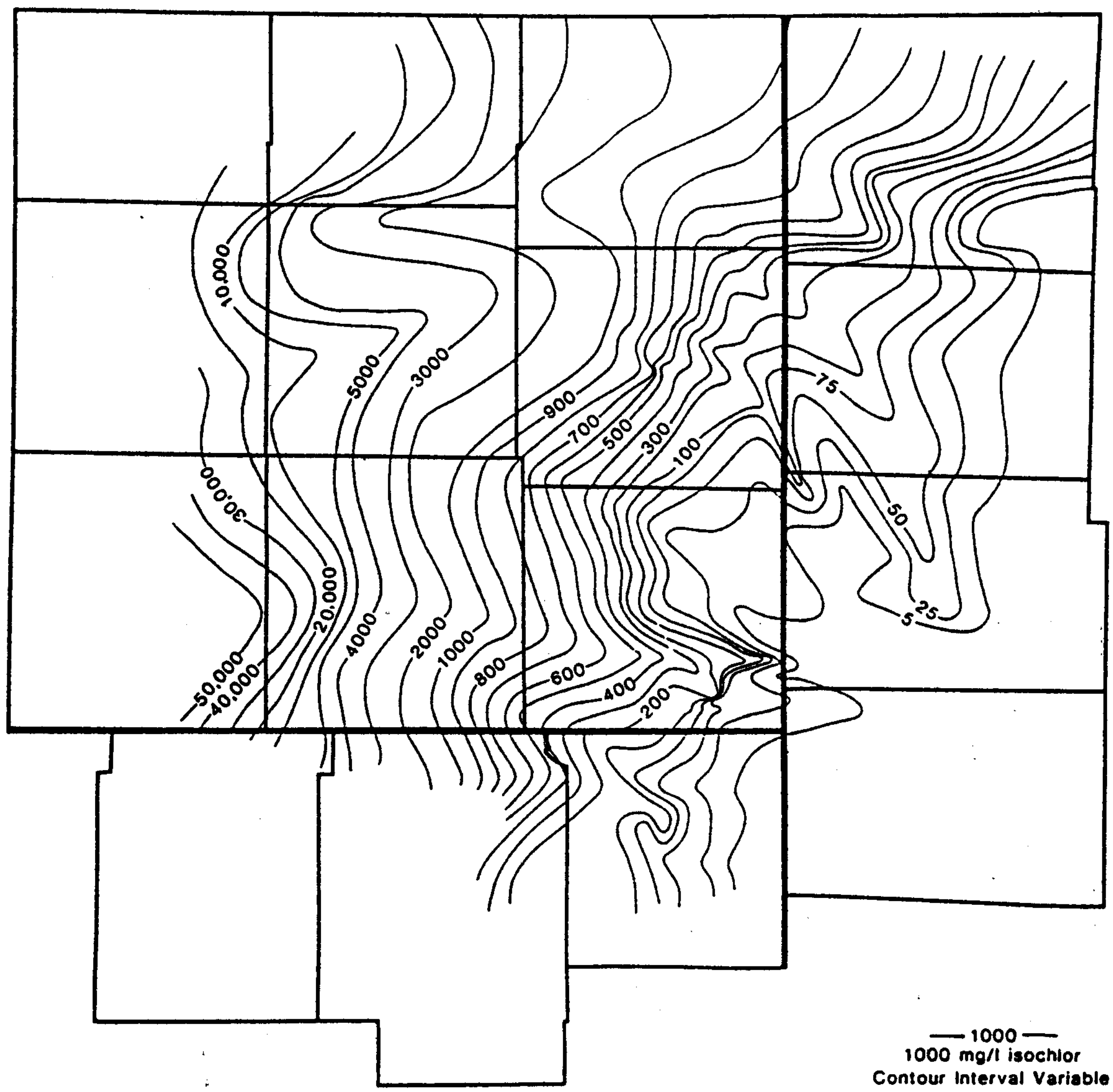


Figure 20. Chloride concentration of waters from the Lower Ordovician aquifer, southeast Kansas and adjoining areas.

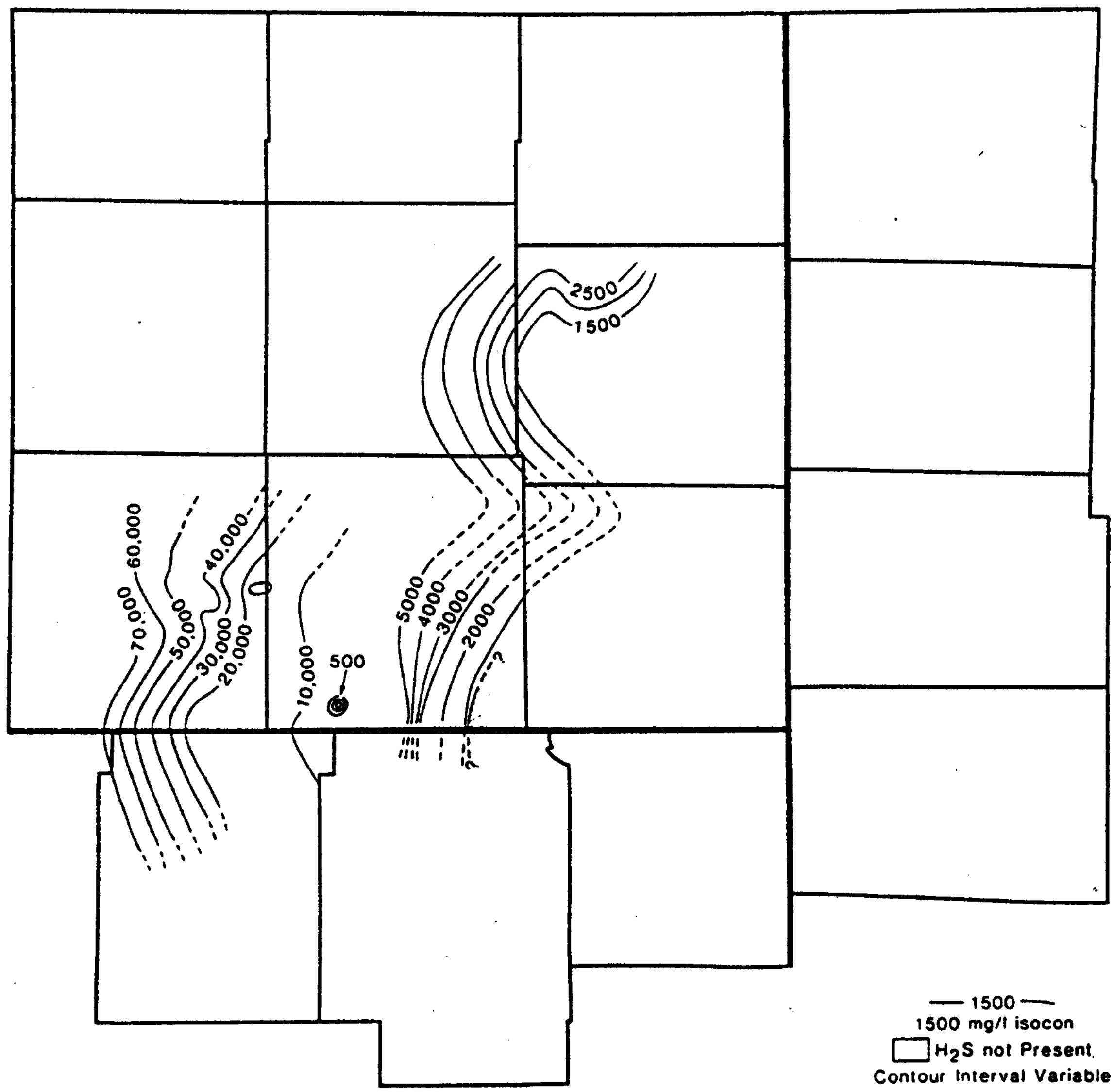


Figure 21. Total dissolved solids concentration in the uppermost Lower Ordovician in southeast Kansas and adjoining areas.

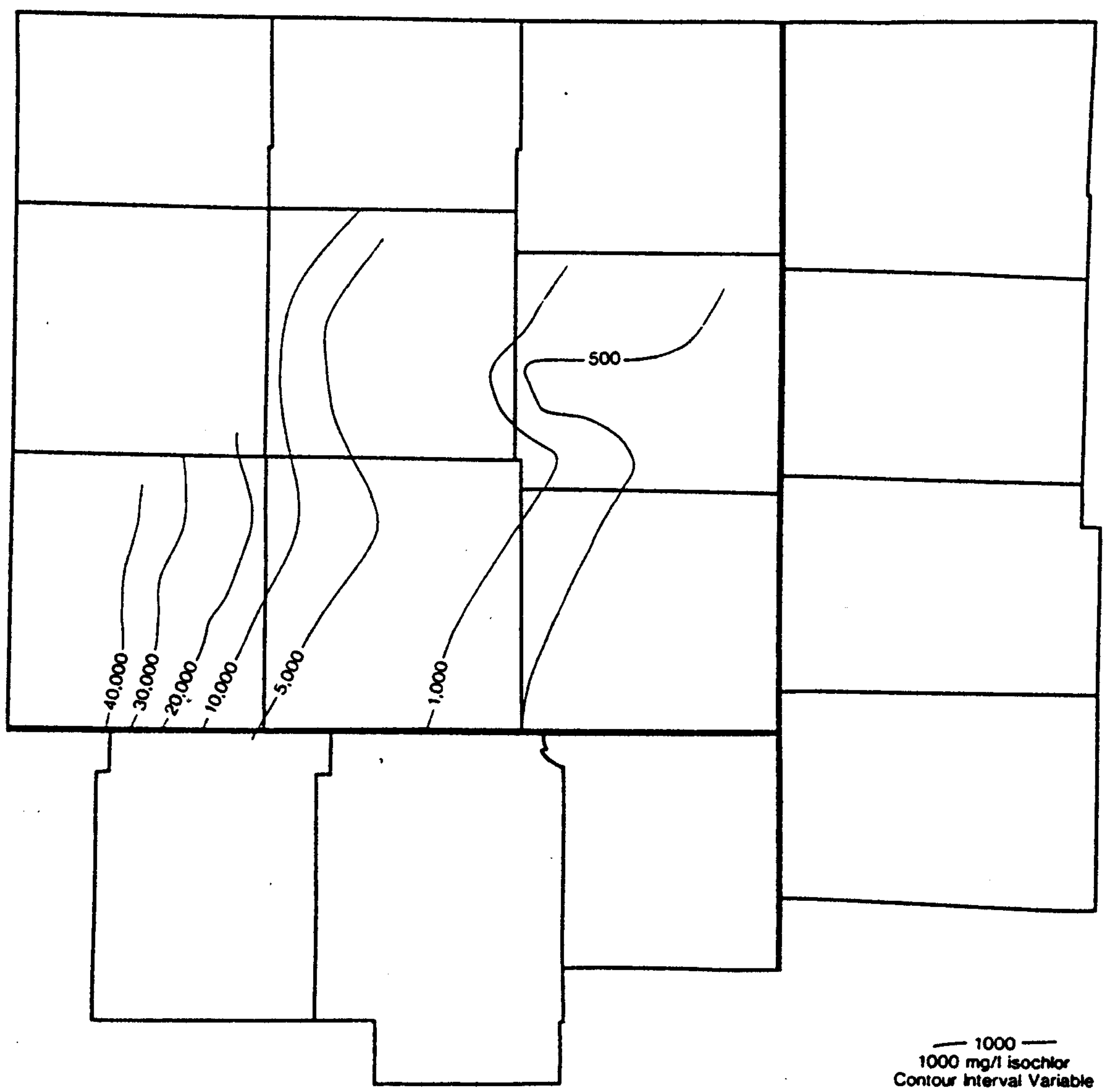


Figure 22. Chloride concentration in the uppermost Lower Ordovician in southeast Kansas and adjoining areas.

because the higher ionic strength of the brines increases mineral solubilities. Although dissolved sulfate ranges up to 1,100 mg/l, most brines contain less than 150 mg/l and often less than 10 mg/l because the sulfate has been reduced to sulfide dissolved as hydrogen sulfide and bisulfide. Total dissolved sulfide species are thus usually greater than 5 mg/l and can be as high as 100 mg/l. Where higher concentrations of sulfate are present, calcium sulfate and magnesium sulfate ion pairs become important in solution, further increasing calcium and magnesium contents through additional dolomite dissolution.

Between the formation brines in the west and the fresh groundwaters in the east, there is a transition zone with a generally south-southwest to north-northeast trend, from Nowata, Craig, and part of Ottawa County, Oklahoma, through Labette, Crawford, and parts of Neosho and Cherokee counties, Kansas, to Vernon and part of Jasper County, Missouri (Fig. 23). Mixing of the fresh waters with the brines mainly increases the sodium, chloride, and dissolved solids contents of these groundwaters. Although the absolute increases in these concentrations per lateral mile are greater approaching the brine location, the average rate of increase per mile is roughly constant. The mixing is illustrated on a modified Piper diagram (Fig. 24). The calcium, magnesium-bicarbonate waters fall in the lower right-hand part of the diagram, the sodium-chloride type waters plot in the upper left-hand portion, and a linear trend between the two water types represents the transition zone. As sodium and chloride are added, the groundwaters first become a mixed cation- (calcium, magnesium, sodium) bicarbonate type, and next a mixed cation-bicarbonate, chloride type before reaching the sodium-chloride composition.

A few waters contain a high enough bicarbonate concentration, perhaps through some cation exchange and simultaneous carbonate mineral dissolution, to be a sodium-bicarbonate, chloride type near the area where sodium and chloride predominate. This exchange process could occur in the vicinity of marine shales locally present in the

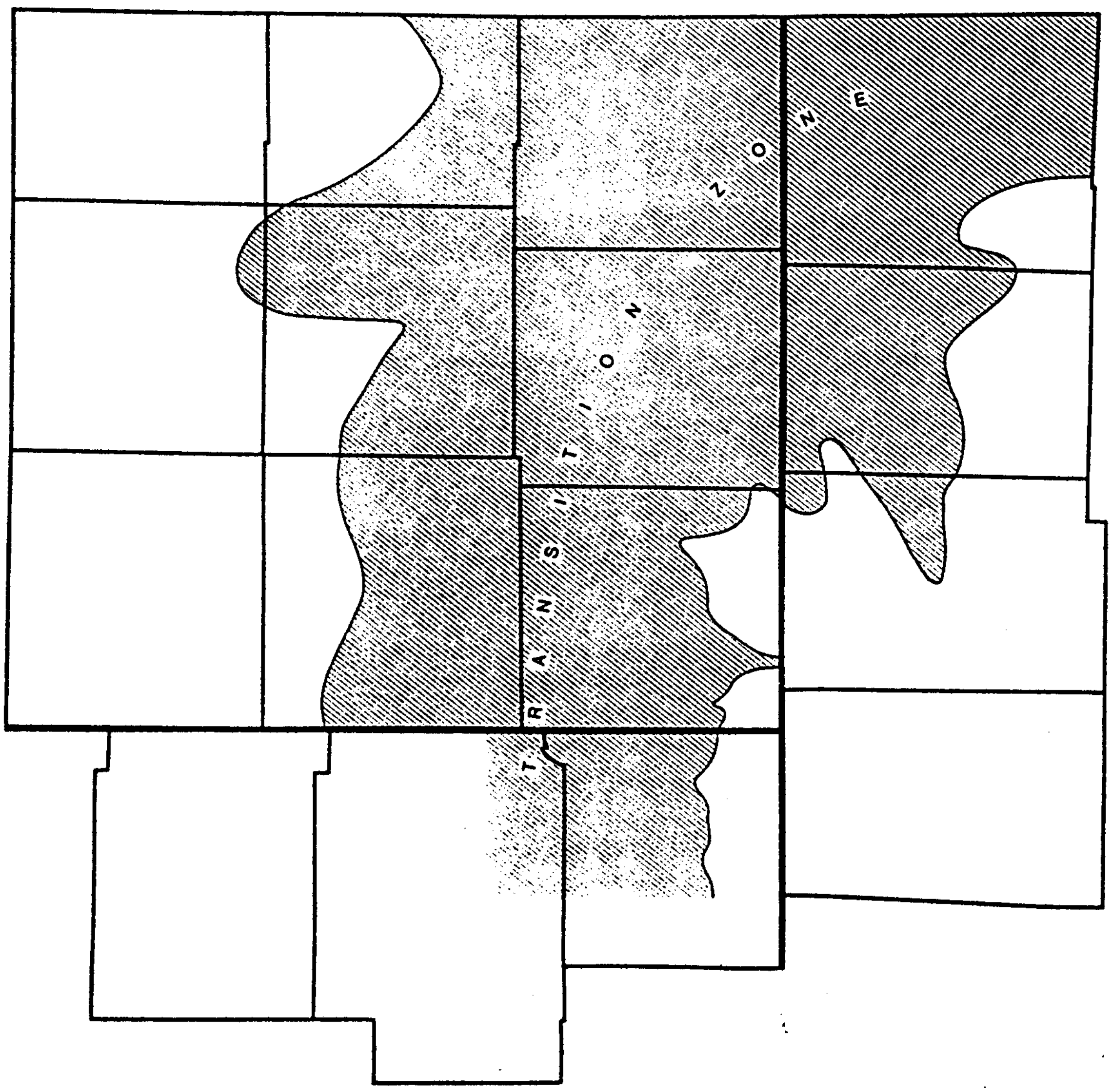
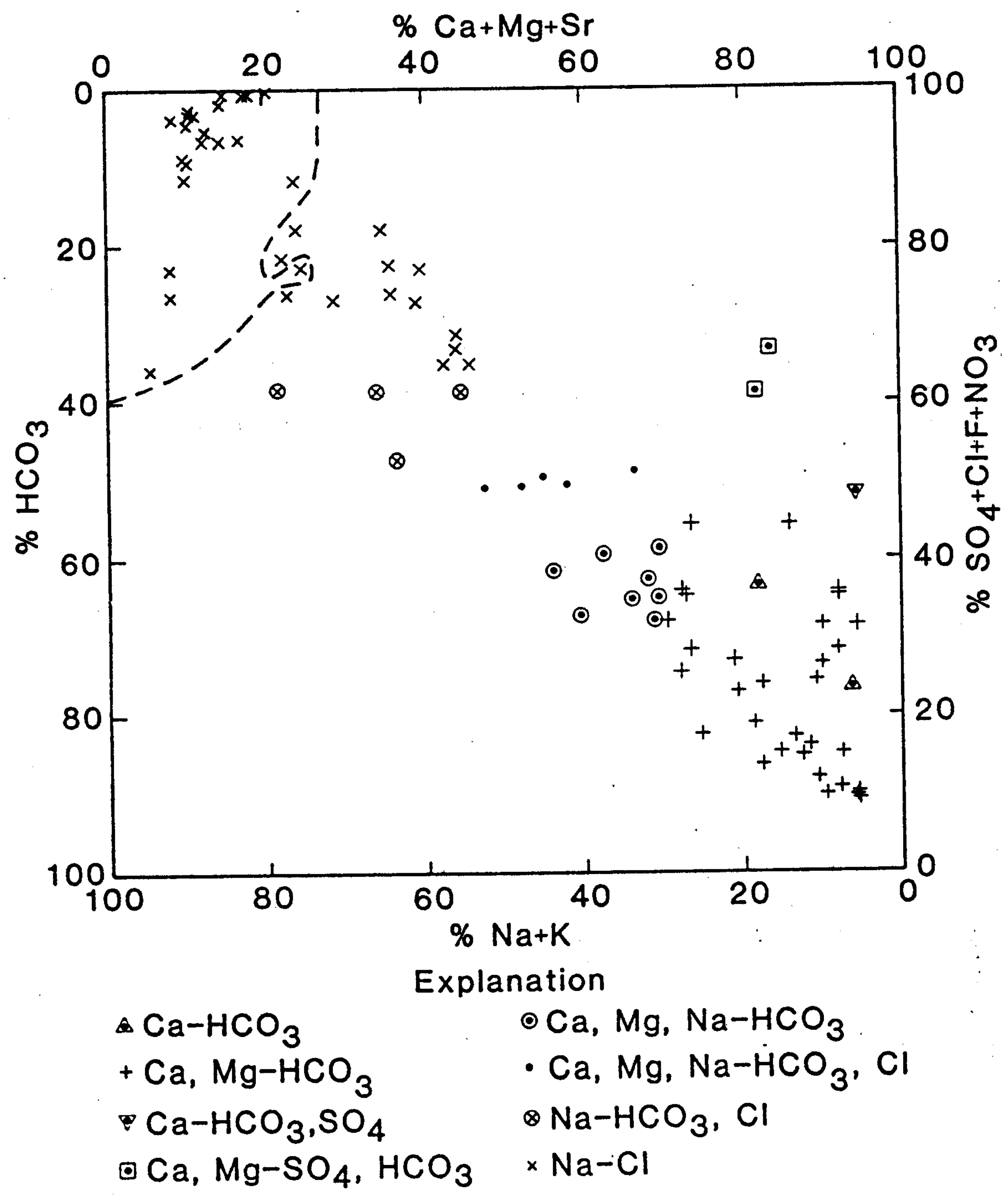


Figure 23. Areal extent of the transition zone in the Lower Ordovician aquifer, southeast Kansas and adjoining areas.

Figure 24. Modified Piper diagram of waters in the Cambro-Ordovician aquifer. Different water types are represented by symbols as listed in the explanation. Individual species are considered dominant when the meq/l percentage exceeds 40% of either cations or anions, except for the sum of calcium and magnesium, which is defined as dominant when greater than 70% where magnesium is more than 30% of the cations. Sodium-chloride waters within the dashed-line boundary in the upper left-hand corner of the diagram are oil-well or waterflood waters.



aquifer. The process of mixing the fresh waters and brines may produce waters capable of dissolving a small amount of dolomite due to a change in the activities of dissolved constituents caused by ionic strength effects. However, reduction of sulfate would decrease the concentration of sulfate ion pairs in waters of the transition zone, thereby having the opposite effect of decreasing calcium and magnesium concentrations, which could be in equilibrium with dolomite.

At the eastern margin of the transition zone between fresh and saline waters, just west of the 25 mg/l isochlor, dissolved hydrogen sulfide is present and increases with increasing chloride content from the margin westward. Just east of the eastern margin of the transition zone are many wells yielding groundwaters with higher sulfate concentrations than in groundwaters from wells further east. A plot of the analyses of these waters forms a trend of points along the right-hand side of Figure 25 from a calcium, magnesium-bicarbonate type upward to a calcium, magnesium-sulfate, bicarbonate type water. The latter water could be generated by the oxidation of pyrite and other sulfide minerals present, followed by the solution of calcite and some dolomite caused both by the acidity produced by the oxidation and the sulfate ion pair effect. The additional carbonate solution would explain the higher concentrations of calcium and magnesium in these waters in comparison with similar waters with low sulfate levels. Dissolution of gypsum is another possible source of sulfate is if gypsum is present in the strata. Concomitant incongruent solution of some dolomite could then provide the additional magnesium in solution. Wells yielding the groundwaters with higher sulfate concentrations fall within the trend of the Tri-State mining district from Quapaw, Oklahoma, through Baxter Springs and Galena, Kansas, to Joplin and Alba, Missouri. Whether the source of the waters high in sulfate is within the Cambro-Ordovician aquifer itself, or from leakage from the Mississippian strata where the ore deposits are found is unknown. The simultaneous occurrence of hydrogen sulfide levels of 10 ppm or greater and sulfate levels of 100 mg/l or greater in many waters to the west either suggests that sulfate originally in the brine and saline waters was incompletely reduced, or an additional source is supplying sulfate at a faster rate than it can be reduced to sulfide.

Plots of weight ratios of lithium/chloride and iodide/chloride versus chloride concentration suggest that the mixing from fresh water through the transition zone to the brine is predominantly simple chemically in the Cambro-Ordovician (Figs. 25 and 26). The locations of the well waters on these graphs lie along a theoretical mixing curve representing the mixing of different amounts of two end-member waters, the calcium, magnesium-bicarbonate fresh waters, and the sodium-chloride brines. The two theoretical waters representing the end-points of the curve contain 1 and 50,000 mg/l chloride, respectively. Points representing variations in the water chemistry such as the sulfate-bicarbonate type waters also fell along the mixing curve. Two of four well waters from the Mississippian strata analyzed for trace constituents gave ratios farther from the mixing line than nearly all those from the Cambro-Ordovician aquifer. This suggests that the chemical variations within the Cambro-Ordovician are probably produced mainly by interactions with minerals or redox reactions within the aquifer rather than the introduction of large amounts of different waters from the Mississippian formations.

Although the general chemistry and hydrogeology of the transition from fresh waters to brines is relatively simple on a regional scale, they are more complex on a local scale. Deflections of the isocons from a northeast-southwesterly direction generally coincide with the locations of both faults and anticlines in the region. In the Baxter Springs-Galena area east-west-trending deflections in the isocons seem to coincide with east-west tightly-folded rocks in the Cambro-Ordovician. In fact the contrasts in groundwater chemical quality between the three wells in the Baxter Springs well field are remarkable even though the wells are at the same depth and the spacing between each well is relatively small. The last date on which samples from all three wells were collected was May 13, 1980. Baxter Springs well No. 6 is the northernmost

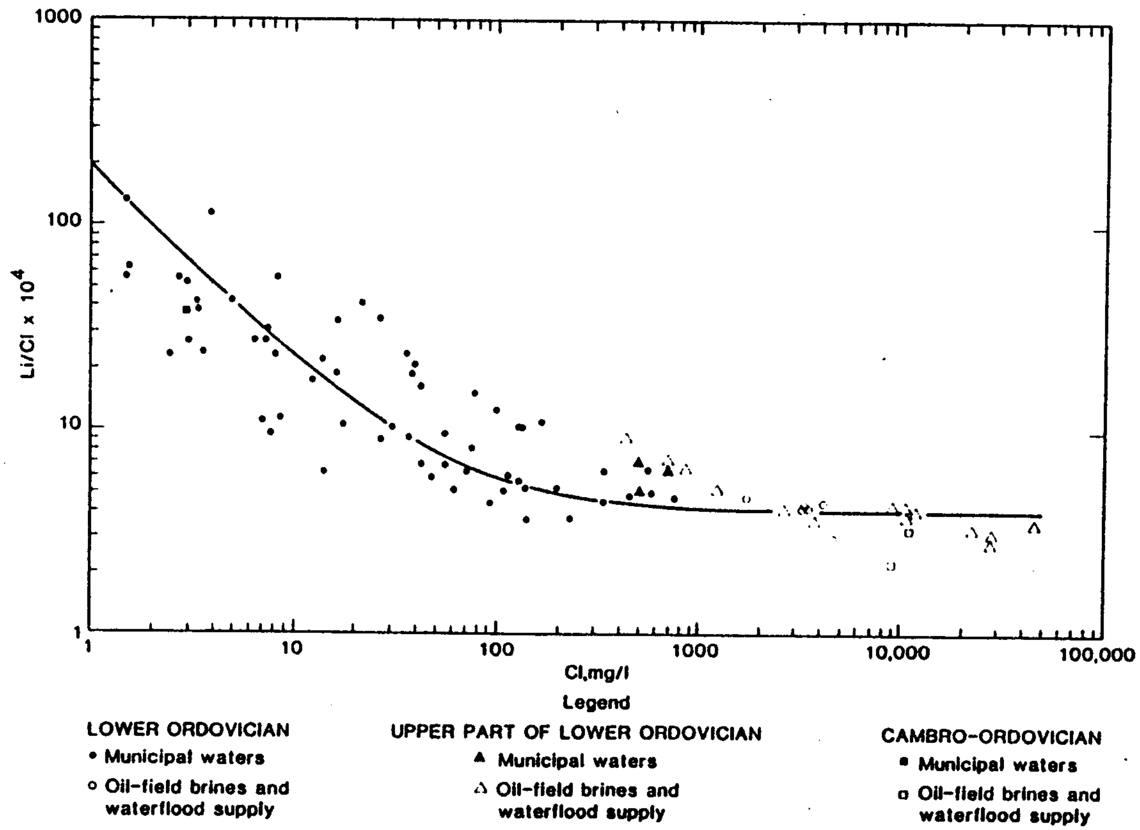


Figure 25. Variation in the weight ratio of lithium/chloride with chloride concentration. The curve is for the theoretical mixing of fresh waters and oil-field brines in the Cambro-Ordovician aquifer.

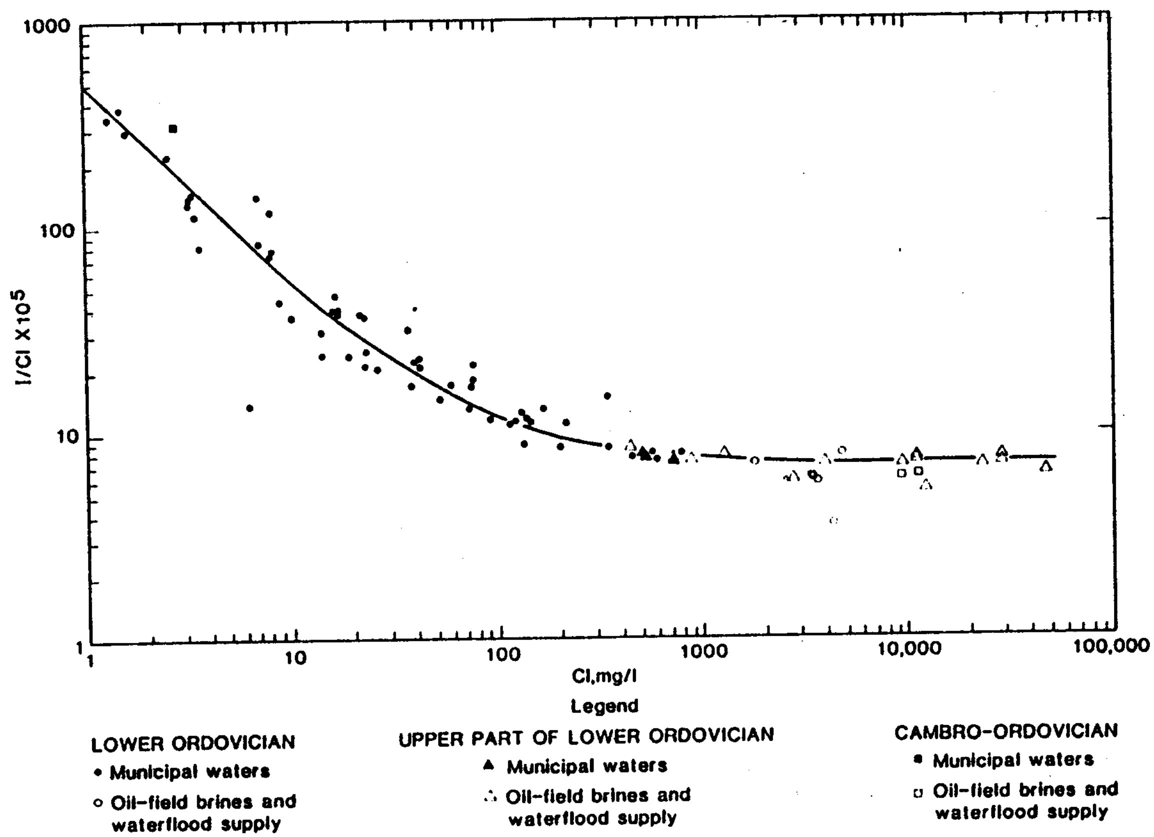


Figure 26. Variation in the weight ratio of iodide/chloride with chloride concentration. The curve is for the theoretical mixing of fresh waters and oil-field brines in the Cambro-Ordovician aquifer.

well and had total dissolved solids and chloride concentrations of 600 and 266 mg/l, respectively. The dominant ions in solution are sodium and chloride. Baxter Springs well No. 5 is located approximately 0.7 mile due south of No. 6. The total dissolved solids and chloride concentrations are 300 and 42, respectively, and calcium, magnesium, and bicarbonate were the dominant ions in solution. At Baxter Springs well No. 1, located 0.2 miles south of No. 5, the total dissolved solids and chloride concentrations are 700 and 47 mg/l respectively. Calcium and sulfate are the dominant ions in solution at this well. Calcium and sulfate concentrations fluctuate in waters from this well: the last sample taken in October 1980, had a sulfate content of 163 mg/l, about half that in May, and dissolved solids of 470 mg/l. Farther north, at Pittsburg, Kansas, northwest-southeast deflections in the total dissolved solids and chloride isocons seem to coincide with the locations of the Pittsburg Anticline and the Nashville-Carthage Sag and in southwestern Vernon County with the trace of the Chesapeake Fault. Farther to the west in southern Neosho and northern Labette counties, Kansas, northwest-southeast deflections of the iso-cons seem to be located in the vicinity of known faulting. The coincidence of deflections in the isocons and structural contours from the general northeast-southwest trend and structure can be explained as a result of poorer quality water flowing laterally from the west due to heavy well pumpage and anistropic conditions in the aquifer induced by geologic structures. In some of the areas where groundwater chemical quality changes appear to be related to geologic structures there are one or more well systems that continually pump water from the aquifer, such as in the Pittsburg and Baxter Springs, Kansas areas. Tectonic movements have undoubtedly modified the hydraulic properties considerably over geologic time. If axial fractures that developed during folding are more transmissive than those perpendicular to the fold axes, water would move preferentially along fold axes and not in the transverse directions. In the same way, water flow might be impeded across a fault plane but not along the plane. Therefore, a stagnant zone of groundwater could exist on the downgradient side of the fault.

Vertical Changes in Chemical Quality of Groundwater in the Lower Paleozoic Aquifers

Groundwater chemical quality in the Lower Paleozoic aquifers varies vertically as well as laterally. At several drilling sites chloride concentrations were determined at selected well depths during drilling (Figs. 27, 28, and 29). Although these are composite samples of groundwater from several horizons penetrated by the well, the results provide valuable information on vertical variations in groundwater chemical quality.

These measured or estimated vertical profiles of chloride concentrations show some interesting features about the Mississippian and Cambro-Ordovician aquifers. Overall chloride concentration appears to increase with depth in most of the wells except at the Clemens Coal Company well No. 1 where the chloride concentration decreases in the Lower Ordovician and in the LaSalle Oil Company No. 1 Goble where the chloride concentration does not seem to increase with depth below the Lower Ordovician (Fig. 29). The No. 1 West and No. 1 Clark wells are located within the transition zone and the increase in chlorides with depth is reasonable (Figs. 27 and 28). The Jayhawk Ordinance well is located to the east of the transition zone and shows slight increases in chloride with increasing well depth (Fig. 28).

Differences in chloride concentration between the Mississippian and Cambro-Ordovician do not appear to be consistent throughout the area. The vertical profiles of chloride concentration using measurements from the Jayhawk Ordnance well and the Clemens Coal Company No. 1 well show opposing trends in chloride concentration possibly because the Mississippian aquifer is unconfined in the vicinity of the Jayhawk Ordnance Plant. Their chloride and total-dissolved-solids concentrations also increase with depth within the Cambro-Ordovician aquifer.

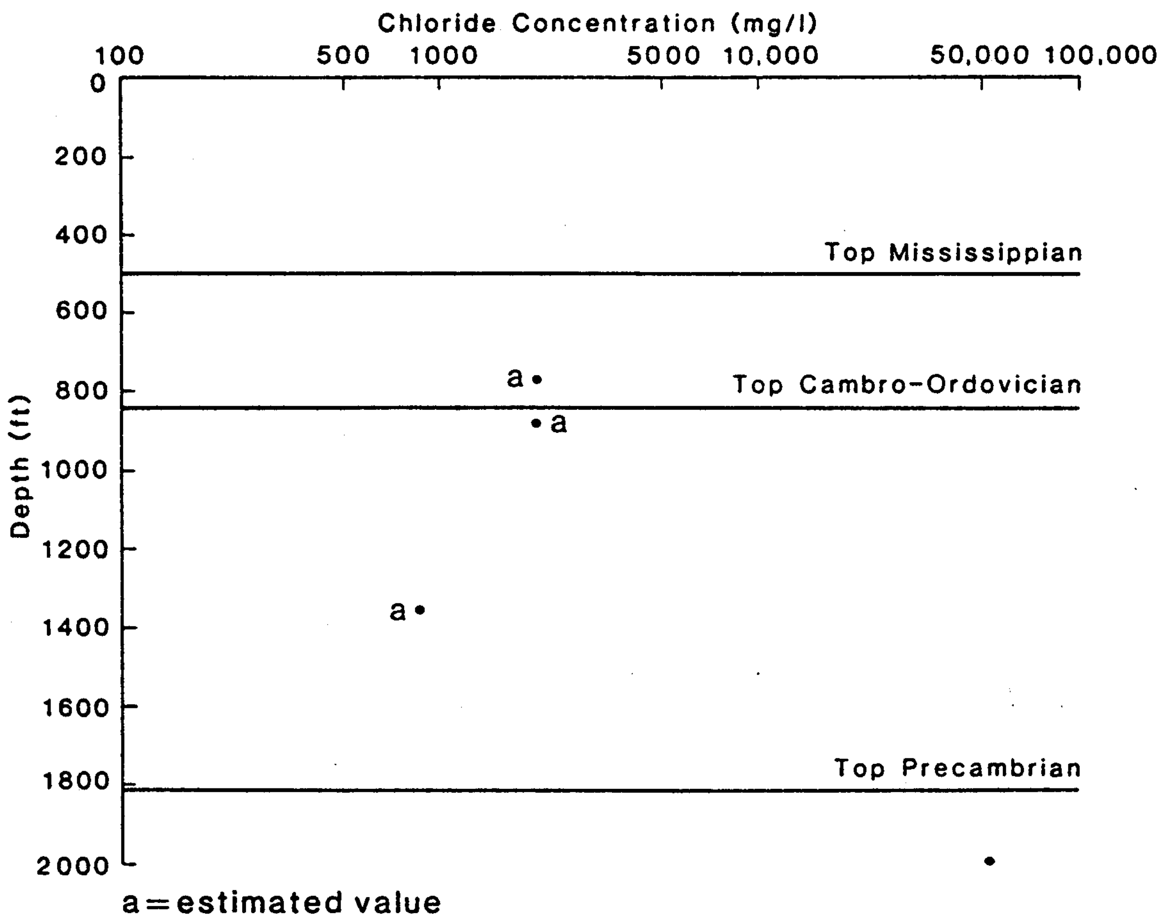


Figure 27. Chloride concentration vs. well depth in No. 1 Wert well.

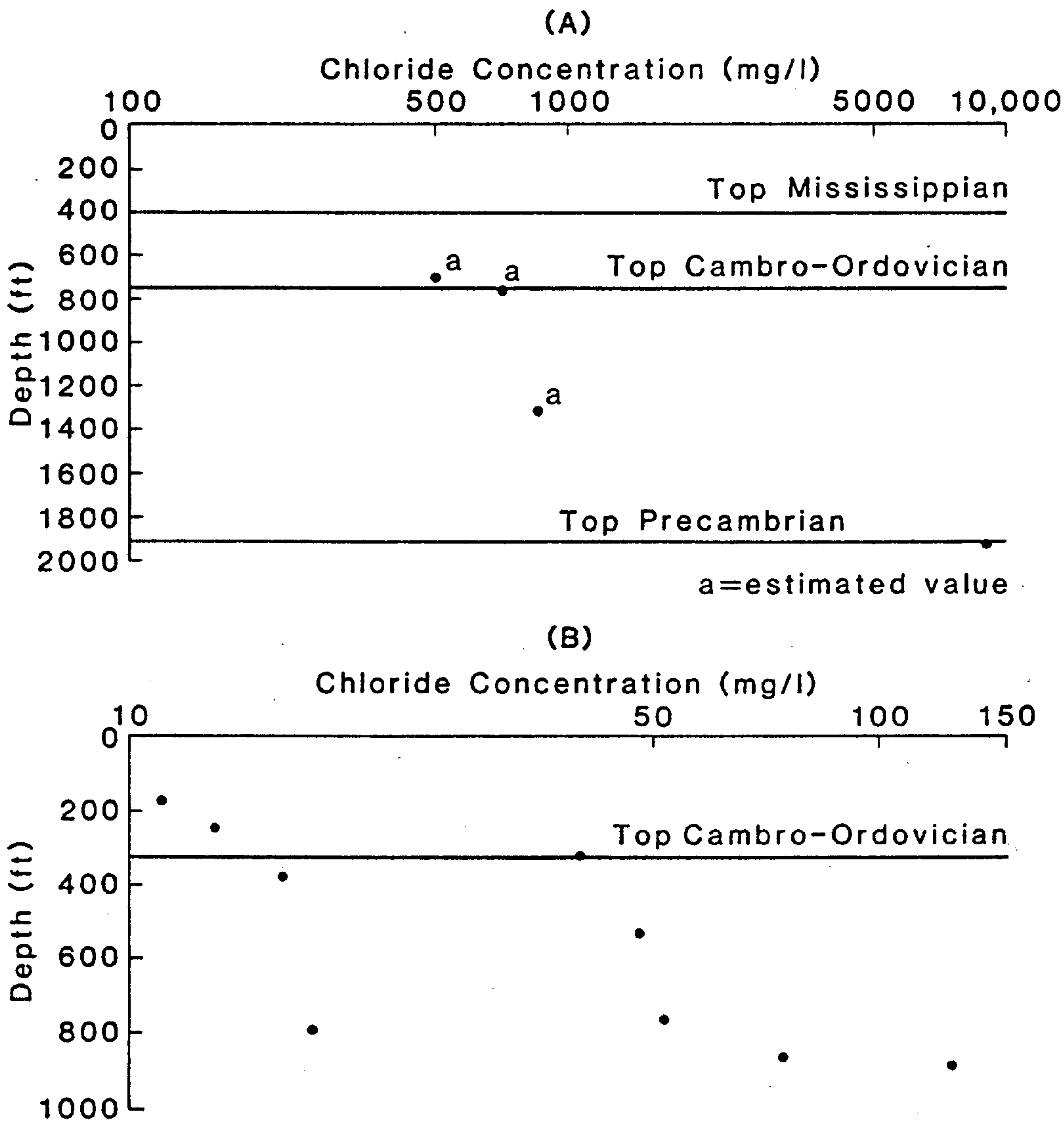


Figure 28. Chloride concentration vs. well depth in (A) Clark No. 1 well, and (B) Jayhawk Ordnance well.

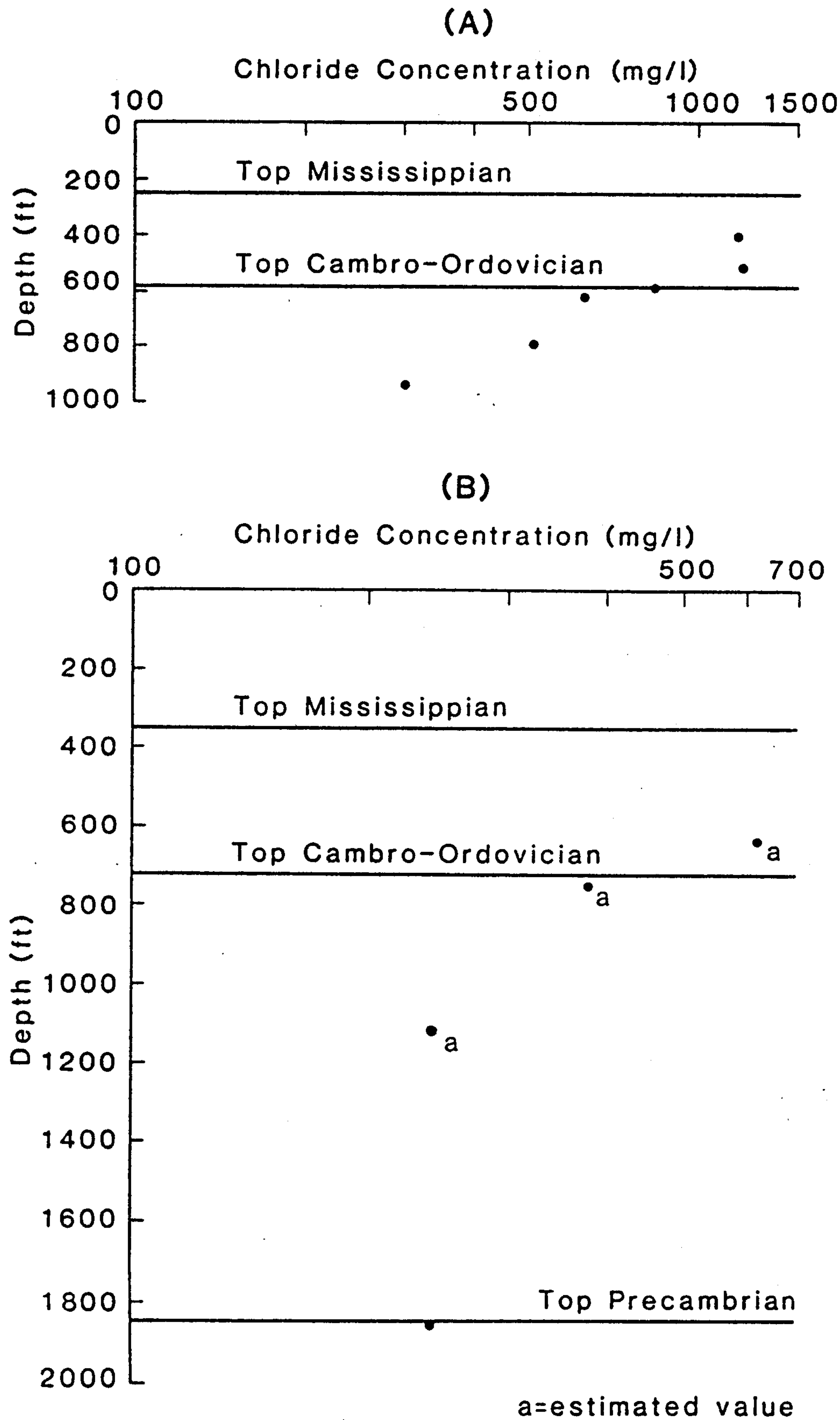


Figure 29. Chloride concentration vs. well depth in (A) Clemens Coal Co. Well No. 1, and (B) LaSalle Oil Co. No. 1 Goble.

The concentration of the constituents probably increases at a faster rate in the deeper portions of the aquifer than in shallower portions. As an example, the chloride concentration of a sample of groundwater from a well drilled into the Roubidoux Formation at the Kansas Ordnance Plant near Parsons, Kansas during 1941 was approximately 1,100 mg/l after a seven-day pump test. More recently, a USGS-KGS observation well was drilled into the underlying Derby Formation less than one mile away from the earlier site at the Ordnance Plant. The chloride concentration of a sample of groundwater taken from the Derby Formation after testing was 30,000 mg/l. The chloride and total dissolved solids concentrations of water samples also increase faster across the region in wells penetrating the middle portion of the Cambro-Ordovician aquifer than in those wells penetrating the uppermost part. This is particularly true where the aquifer is more saline. At Coffeyville, the chloride concentration of water samples from wells penetrating only the uppermost Cambro-Ordovician is 40,000 mg/l and, for wells also penetrating the Roubidoux Formation, the chloride concentration increases to 50,000 mg/l.

Changes in Groundwater Chemical Quality Over Time

Three types of fluctuations in groundwater chemical quality were investigated: (1) short-term, (2) annual, and (3) long-term. Sampling during one pump test was conducted to determine if there were short-term fluctuations. Annual or seasonal fluctuations were monitored by periodic sampling at two locations and long-term changes were determined from long-term monitoring records of wells in state and federal agency files.

A short 24-hour pumptest was conducted at Baxter Springs well No. 1 during May, 1979. Baxter Springs well No. 1 was chosen because rapid chemical quality changes are known to occur in the well field over short distances, and in the well itself, over several months time. At selected times water samples were collected and selected physical and chemical parameters were measured on water samples from the pumping well. The physical and chemical parameters measured during the test included specific conductance, pH, temperature, hydrogen sulfide concentration, and redox potential. In addition, periodic water level measurements were made in the well during pumping with the aid of a steel tape. During the test, the specific conductance of the water samples decreased from 1,065 umhos/cm to 930 umhos/cm with a simultaneous increase in the redox potential of 10 m.v. Water temperature and pH remained constant. The concentration of hydrogen sulfide reached detectable levels ($\geq$ 0.1 mg/l) only four times during the test. The results of this test show that some chemical constituents and properties fluctuate during pumping.

Results of the four complete analyses of additional samples taken from the same well during the spring and fall of 1979 and 1980 show that the dissolved constituents that vary the greatest are calcium and sulfate. As the concentrations of these constituents decrease, the total dissolved solids and the specific conductance decrease, while the chloride concentration increases. This suggests that, with prolonged pumping, increasing amounts of waters coming updip from the west or laterally from the north in the vicinity of well #6 with higher chloride content may dilute the calcium-sulfate type groundwaters.

Seasonal chemical fluctuations were investigated in two, relatively close wells to compare variations in waters from only the upper portion of the Lower Ordovician with those from both the undifferentiated Mississippian and Lower Ordovician aquifers. Temperature, pH, specific conductance, and hydrogen sulfide concentration were monitored periodically at Crawford County Rural Water District No. 7, well no. 1 and at the City well in Mindenmines, Missouri. The Crawford County Rural Water District well is an open bore hole completion only in the Cotter Formation. The City well at Mindenmines is open from the middle of the undifferentiated Mississippian to the bottom of the Roubidoux Formation. Two sections of the open-hole portion of the well are lined, casing out the lower Pierson, Northview, Compton, Chattanooga, and portions of the Jefferson City Formations. Nine sets of measurements and two water samples were collected during the one-year monitoring period. At the Crawford County Rural Water District well specific conductance and chemical quality did not vary appreciably during the year. Hydrogen sulfide concentration varied from 2.5 to 7 ppm. Temperature and pH remained relatively constant. At Mindenmines specific conductance and chemical quality varied considerably with time. Specific conductance varied from 710 umhos/cm at the beginning of the monitoring period up to 1530 umhos/cm midway through the period. Water samples collected from the well for each of these times showed that the concentrations of sodium and bicarbonate increase considerably, 82–283 mg/l and 327–744 mg/l, respectively, while chloride decreased from 53 to 39 mg/l. Water quality records from the Missouri Department of Natural Resources of the Mindenmines well from 1963–1977 show similar fluctuations. Concentrations of chloride ranged from 34 to 88 mg/l and varied inversely with sodium and bicarbonate levels of 96–378 mg/l and 327–941 mg/l, respectively, during this period. This has suggested that the well receives variable amounts of water from the undifferentiated Mississippian relative to the Cambro-Ordovician, since groundwaters from the undifferentiated Mississippian are a sodium-bicarbonate type water (Hathaway and Macfarlane, 1980).

A few other wells that are open to the lower part of the Mississippian strata, as well as the Cambro-Ordovician aquifer, yield waters with variations analogous to those at Mindenmines, although the magnitude of the concentration changes differ markedly from location to location. Chloride values for city wells at Bronaugh, Moundville, Hume, Rich Hill, and Liberal, Missouri have increased over several years, while bicarbonate concentrations have decreased (Table 2). In these locations the stress on the aquifer during pumping of the wells has resulted in a permanent increase in yield of the deeper, chloride-rich water in comparison with the sodium-bicarbonate water from the Mississippian. No similar changes have been found in Kansas.

Table 2. Chemical Changes in Waters from Wells Open to Both the Lower Part of the Mississippian and the Cambro-Ordovician Aquifer in Missouri. Concentrations are given in the time sequence in which they occurred. Data is from the Missouri Department of Natural Resources and this study. Concentrations are in mg/l.

Location	Time Period	Chloride	Bicarbonate
Bronaugh	1960 - 1980	60-495	991-318
Moundville	1966 - 1980	96-280	999-740
Hume	1954 - 1974	232-1960	1034-272
Rich Hill	1933 - 1975	749-926	316-261
Liberal	1939 - 1980	52-116	1149-240

Waters from well no. 1 of Crawford County Rural Water District No. 7 have gradually but steadily increased in sodium and chloride content. In 1973 the sodium and chloride concentrations in the well were 276 and 457 mg/l, respectively, and in 1980 were 303 and 524 mg/l, respectively. Thus, slight degradation of chemical quality has occurred in the aquifer since the well began pumping. Some fluctuations in sodium and chloride concentrations were also observed in waters from well no. 6 at Baxter Springs during the 1979–1980 sampling period. Calcium and sulfate concentrations were essentially constant in this well, in contrast with the greater changes that occurred at well no. 1 at Baxter Springs.

THE HYDROGEOLOGIC DEVELOPMENT OF THE PRESENT CONFIGURATION OF THE TRANSITION ZONE IN THE LOWER PALEOZOIC AQUIFER SYSTEM IN SOUTHEAST KANSAS

Few hydrogeologic data are available that can be used to construct a picture of the most geologically recent phase of development of the transition zone in the Cambro-Ordovician rocks of southeast Kansas. Furthermore, glimpses of how the Lower Paleozoic aquifer system developed since these rocks were deposited are obscured because these aquifers have been fresh-water near-surface aquifers at several times during the geologic past and have been flushed of their original connate waters several times. In addition, much of the Lower Paleozoic stratigraphic section has been dolomitized and subjected to rock solution and precipitation processes. However, enough information is available to support some general conclusions can be drawn about the development of this aquifer system since the early Permian.

Some time after the Pennsylvanian, erosion of the Ozark region had proceeded sufficiently that the Pennsylvanian cover was breached and the Mississippian became a water-table aquifer receiving fresh-water recharge from precipitation in the region. No evidence in the Ozark region exists to indicate whether the underlying Cambro-Ordovician rocks received any of this recharge.

During the late Permian oil and gas in the Cambro-Ordovician probably began to migrate northward from Oklahoma into central Kansas (Walters, 1958) and very likely into the Cherokee Basin in southeast Kansas and northeast Oklahoma. Migration probably continued through the Cretaceous and possibly into the Tertiary depending on when the last change in regional dip occurred in the Cherokee Basin. The migration of these hydrocarbons probably began as the head in the Cambro-Ordovician aquifer in Oklahoma increased due to loading by deposition of the Pennsylvanian-Permian overburden on top of the Lower Paleozoic rocks. Eventually these hydrocarbons became trapped in small domes and other traps in the Cambro-Ordovician in southeast Kansas and northeast Oklahoma.

Meanwhile post-Pennsylvanian erosion in the Ozark region continued removing the Mississippian and older rocks from much of the central part of the area and uncovered the Cambro-Ordovician portion of the stratigraphic section. Fresh-water recharge began entering the aquifer and eventually created fresh and saline portions of the aquifer separated by a transition zone of unknown width. As erosion has continued expanding the area of surficial Cambro-Ordovician rocks in the Ozarks region, the transition zone separating fresh and saline portions of the aquifer has moved farther out radially from the center of the Ozarks to its present position.

Flushing of the saline formation waters in the Cambro-Ordovician by fresh water recharge coming from the Ozark region has apparently progressed almost to the Labette-Montgomery County line in southeast Kansas. This is shown quite well by increases in total dissolved solids in groundwater and the halogen ratio mixing curves presented earlier (Figs. 18 and 24). In addition, the low API gravity (high density) of much of the oil in the Cambro-Ordovician in Labette and Montgomery County suggests that the oil has been water washed (Tissot and Welte, 1978). Oil shows in the Cambro-Ordovician were found in the drill cuttings of several wells farther north and east of southern Labette County. Possibly these shows may have been remnants of earlier accumulations now flushed from the area.

SUMMARY

Groundwater supplied from wells penetrating the Cambro-Ordovician has been responsible for much of the economic development in southeast Kansas and the adjoining states of Missouri and Oklahoma. Presently this aquifer system provides fresh water for public water supplies, industries, irrigated agriculture, and electric-power generation. However, since groundwater development began in the late 1800's, some areas have experienced large-scale static water level declines as shown by wells penetrating this aquifer system. Other areas have experienced groundwater chemical quality change. To the west of the fresh-water portion, groundwaters in the aquifer are more saline. The aquifer serves as a reservoir containing accumulations of oil. In very saline portions the Cambro-Ordovician aquifer is used for industrial-waste disposal through well injection. The saline and fresh water portions are separated by a transition zone that extends across the study area.

The undifferentiated Mississippian and Cambro-Ordovician aquifer make up the Lower Paleozoic aquifer system in southeast Kansas and adjoining areas. The rocks that comprise the undifferentiated Mississippian aquifer are cherty limestone, dolomite and thin discontinuous beds of shale. The rocks that comprise the deep aquifer are primarily cherty dolomite and sandstone. These aquifers are separated by confining layers of shale and dense dolomite of the Northview Shale, the Compton Limestone and the Chattanooga Shale.

Groundwater is available throughout the Lower Paleozoic stratigraphic section in varying amounts depending on the lithology of the aquifer and the development of primary and secondary porosity and permeability in the carbonate rocks. The development of secondary permeability is favored by solution of carbonate rock or by tectonic activity. The rocks that are a part of these aquifers show evidence that they have undergone these changes many times in the geologic past. Well yields are typically higher where the aquifer materials have been fractured and have interconnected solution channels. Relatively minor amounts of groundwater are available from the undifferentiated Mississippian as compared to the Cambro-Ordovician. Maximum well yields to be expected from the Mississippian is approximately 100 gpm (13.4 ft^3/min) whereas typical well yields from the Cambro-Ordovician are approximately 100-750 gpm (13.4-100 ft^3/min).

Groundwater chemical quality in the Cambro-Ordovician aquifer varies widely across southwest Missouri, southeast Kansas, and northeast Oklahoma reflecting a change from fresh to saline conditions in the aquifer. The mixing of fresh and saline waters is regionally a simple process that may be more complex locally, due to chemical interactions and the influence of geologic structure. The total dissolved solids of groundwaters in the fresh-water portion of the aquifer is generally less than 300 mg/l and the dominant dissolved constituents are calcium, magnesium and bicarbonate. Groundwaters from the saline portion of the aquifer are sodium chloride brines and contain up to 80,000 mg/l total dissolved solids in southern Montgomery County, Kansas. Sodium, chloride and the total dissolved solids increase in a westerly direction across the transition zone separating the fresh and saline waters. Chloride concentration and total dissolved solids both increase with depth in the Cambro-Ordovician aquifer. Waters from the transition zone westward have chemistries reflecting the presence of a reducing geochemical environment. The major constituents in groundwater samples from wells that are open bore hole to both the undifferentiated Mississippian and the Cambro-Ordovician aquifers are predominantly sodium and bicarbonate, reflecting contributions of these dissolved ions from the upper aquifer.

Few groundwater chemical quality changes were documented during this study in southeast Kansas. The specific conductance of water samples collected during a 24-hour pump test at Baxter Springs, Kansas did decrease during the test indicating in general a decrease in total dissolved solids and sulfate concentration. Periodic fluctuations in the level of bicarbonate in water samples collected from Mindenmines, Missouri during monitoring were also noted. Long-term monitoring of the No. 1 well at Crawford Rural Water district No. 7 facility shows long-term increases in the chloride concentration.

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