

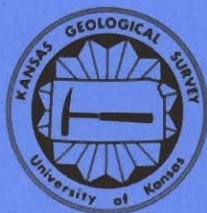
Ground-water Series 9
1987

The hydrogeology and chemical quality of ground waters

from the lower Paleozoic aquifers in the Tri-State region
of Kansas, Missouri, and Oklahoma



by P. Allen Macfarlane and Lawrence R. Hathaway



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The University of Kansas
Lawrence, Kansas

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1

Executive summary

The lower Paleozoic aquifer system is an important natural resource in southeast Kansas, southwest Missouri, and northeast Oklahoma (the Tri-State region). This system consists of aquifers in the limestones and dolomites of Mississippian and Cambrian–Ordovician age. Three ground-water regions can be broadly defined in the Cambrian–Ordovician aquifer reflecting the mixing of low total-solids recharge waters from the Ozark region and high total-solids sodium chloride brines in Kansas and Oklahoma. To the west of the freshwater portion of the aquifer is a reservoir containing scattered accumulations of oil. This study was undertaken to define the regional hydrogeology and variations in ground-water chemical quality of this aquifer system in the Tri-State region.

Abundant supplies of freshwater suitable for most uses can be obtained from aquifers in the Cambrian–Ordovician rocks in Crawford and Cherokee counties in Kansas, in southwest Missouri, and in northeast Oklahoma. This is the major aquifer system in the study area. Aquifers in Mississippian rocks supply most domestic needs in parts of the study area but are not widely used.

Ground waters in the lower Paleozoic aquifer system generally move westward across the study area from recharge areas in the Ozarks of Missouri. Static water-level declines since wells began pumping have been generally less than 50 ft (15 m) over most of the area except where large cones of depression have been created. Static water-level declines in excess of 450 ft (135 m) have occurred in the Miami, Oklahoma, area and in excess of 150 ft (45 m) in northwestern Jasper County, Missouri. Both the Mississippian and Cambrian–Ordovician aquifers seem to be interconnected in portions of the Tri-State region. The spatial variations in ground-water chemistry in the Cambrian–Ordovician aquifer are largely consistent with this mixing phenomenon. A similar zonation probably occurs in the Mississippian aquifer, but not enough data were collected during the study to fully describe the mixing of fresh and saline waters in this aquifer.

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Contents

EXECUTIVE SUMMARY	ii
ABSTRACT	1
INTRODUCTION	2
PURPOSE	2
LOCATION AND EXTENT OF AREA	2
PREVIOUS WORK	2
GEOLOGIC FRAMEWORK	3
STRATIGRAPHY	3
PRECAMBRIAN SYSTEM	4
CAMBRIAN SYSTEM	4
ORDOVICIAN SYSTEM	4
MISSISSIPPIAN-DEVONIAN SYSTEM	4
MISSISSIPPIAN SYSTEM	5
PENNSYLVANIAN SYSTEM	5
GEOLOGIC STRUCTURE	5
HYDROGEOLOGY	7
AQUIFERS IN MISSISSIPPIAN ROCKS	8
AQUIFERS IN CAMBRIAN-ORDOVICIAN ROCKS	8
CHEMICAL QUALITY OF GROUND WATERS FROM LOWER PALEOZOIC AQUIFERS	11
SAMPLING SITES	11
GROUND-WATER QUALITY	11
DISTRIBUTION OF SELECTED MEMBERS OF URANIUM-238 AND THORIUM-232 DECAY CHAINS IN WATERS OF THE LOWER PALEOZOIC AQUIFERS OF TRI-STATE AREA	18
SUMMARY AND CONCLUSIONS	22
REFERENCES	23

Figures

1—Location of study area showing Mississippian-Pennsylvanian outcrop boundary	3
2—Regional geologic structures in vicinity	5
3—Configuration of top of Lower Ordovician surface in Tri-State region	6
4—Isopach map of stratigraphic interval that includes Northview Shale, Compton Limestone, and Chattanooga Shale	7
5—Composite potentiometric surface map of lower Paleozoic aquifers	9
6—Specific-capacity variation reported for wells completed in lower Paleozoic aquifers	10
7—Aquifer units contributing ground waters to wells sampled in study area	11
8—Modified Piper diagram for water samples collected from wells in lower Paleozoic aquifers	12
9—Generalized representation of transition zone in Cambrian-Ordovician aquifer	13
10—Classification of ground waters from lower Paleozoic aquifers based on dominant cation and anion present	14
11—Calculated total dissolved solids (ppm) of ground-water samples from lower Paleozoic aquifers	14
12—Sulfide concentrations in ground waters from lower Paleozoic aquifers	15
13—Boron concentrations in ground waters from lower Paleozoic aquifers	15
14—Geographic location of well sites and Picher mining field	16
15—Partial radioactive decay chains for thorium-232 and uranium-238	19
16—Radium-226 distribution in ground waters from lower Paleozoic aquifers	20
17—Location of wells along two traverse lines sampled for selected radionuclides	21
18—Radium-226 activity, uranium concentration, uranium-234/uranium-238 activity ratio, total dissolved solids, and sulfide concentration variations along two traverses across Tri-State region	22

Tables

1—Bedrock stratigraphic units in southeast Kansas, southwest Missouri, and northeast Oklahoma	4
2—Short-term chemical-quality changes associated with two multiaquifer wells from study area	17
3—Sulfate concentrations for selected wells at Quapaw and Commerce, Oklahoma, April 1979–May 1980	18

Appendices

1—Listing of stratigraphic data points	25
2—Listing of static water levels and specific-capacity data points for wells visited during study	31
3—Listing of ground-water chemical-quality data	33

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Abstract

The lower Paleozoic aquifers (principally the Cambrian–Ordovician) are an important resource producing freshwater for municipal water supplies, industry, and agriculture in southeast Kansas, southwest Missouri, and northeast Oklahoma (the Tri-State region). These aquifers produce oil in Labette and Montgomery counties in Kansas. Aquifers in undifferentiated Mississippian and Cambrian–Ordovician carbonate rocks comprise the lower Paleozoic aquifer system. The Mississippian and Cambrian–Ordovician aquifers are generally separated by confining layers of shale and dense dolomite except in areas of southern Cherokee County, Kansas; northern Ottawa County, Oklahoma; and Jasper and Newton counties, Missouri. Both aquifer systems seem to be interconnected in these areas on the basis of the hydrogeochemistry and the hydraulic-head differences between the aquifers. The undifferentiated Mississippian is unconfined where the unit is at the surface in the southeastern part of the study area. Along the Kansas–Missouri state line, ground-water flow in both aquifers is generally westward except in the vicinity of municipal and industrial well fields where large-scale withdrawals of ground water may have changed the prevailing direction of ground-water flow. Very little hydrologic data are available for the Mississippian aquifer. Three ground-water regions can be broadly defined in the Cambrian–Ordovician aquifer reflecting the mixing of fresh and saline waters. From east to west, one encounters: 1) a freshwater portion containing CaHCO_3 -type ground waters; 2) a transition zone where the total dissolved solids and the contribution from NaCl -type waters increase rapidly in a westerly direction; and 3) a saline portion containing sodium chloride brines. The Mississippian outcrop is the approximate boundary of the freshwater transition zone. The 2,500 mg/L isochlor is taken as the boundary of the saline transition zone. Sulfide concentrations >0.2 mg/L are associated with ground waters west of the Mississippian outcrop. These three zones in the Cambrian–Ordovician aquifer evolved over geologic time as freshwater recharge entering the aquifer in the Ozark region of Missouri flushed saline waters from large portions of the study area. The distribution of radium-226, uranium, and uranium-234/uranium-238 activity ratios in waters from the Cambrian–Ordovician aquifer is consistent with a freshwater transition zone and saline hydrogeochemical partitioning of the aquifer. The manner in which these parameters change from the freshwater to transitional environments suggests that the source of radium-226 in the eastern part of the transition zone is largely from the radioactive decay of uranium precipitated on surfaces in the carbonate aquifer in the comparatively recent geologic past. The relative enrichment of radium-226 in waters from the saline portion of the aquifer system is problematic.

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Introduction

The availability of ground water from the carbonate aquifers in lower Paleozoic rocks has been an important factor in the economic development of the Tri-State region of Kansas, Oklahoma, and Missouri (Abernathy, 1941; Reed and others, 1955; Stramel, 1957). Aquifers in the Mississippian and Cambrian-Ordovician rocks make up the lower Paleozoic aquifer system in the Tri-State region. Before the beginning of the 20th century, deep wells were used to supply water for milling lead-zinc ores in both the Picher field along the Kansas-Oklahoma state border southwest of Baxter Springs and the Joplin field along the Kansas-Missouri state border between Galena and Joplin. These wells also supplied water for coal-washing operations in the Pittsburg, Kansas, area and for public water supply.

Since the decline of mining industry in the Tri-State region in the 1930's, the level of pumpage from deep wells continues to be high because the demand for water has increased for public water supplies, industry, and agriculture. This is particularly true in the Joplin, Missouri; Miami, Oklahoma; and Pittsburg, Kansas, areas. Many new deep wells have been drilled to increase the capacity of the public water-supply systems of these population centers. Approximately 5,544 million gallons (Mgal; 17,015 acre-ft) of water was pumped from deep wells in the Tri-State during 1982 (unpublished data from the Kansas Board of Agriculture, Missouri Department of Natural Resources, and U.S. Geological Survey). The first rural-water-district facility in southeast Kansas using deep wells was built in 1964 in Cherokee County. Since then, additional rural water districts that produce ground water from aquifers in lower Paleozoic rocks have been created: three in Cherokee County; six in Crawford County; one each in Vernon and Barton counties, Missouri; and six in Ottawa County, Oklahoma. The water supplied by these districts is used for domestic, stock watering, and other purposes. Deep wells also supply ground water to the coal-fired electric-power generating plants at Riverton, Kansas, and Asbury, Missouri, and to irrigators in southwest Missouri.

Proper management of these aquifers may become essential in the future to protect the freshwater resources from progressive degradation of ground-water chemical quality. Degradation could be induced by large withdrawals of ground water by the many public and industrial water-supply-well fields and center-pivot irrigation systems in the area. Already some areas have experienced large-scale static water-level declines and ground-water chemical-quality changes. However, the hydrogeologic data necessary to make decisions for protecting ground-water chemical quality are not available. Additional problems arise

because the aquifer framework, composed of thick, heterogeneous carbonates, is poorly understood both stratigraphically and hydrologically across the region.

Purpose

The purpose of this study is to define the regional hydrogeology and variations in ground-water chemical quality of the lower Paleozoic aquifers in the Tri-State region of Kansas, Oklahoma, and Missouri. The information contained herein will be useful to all groups in the public and private sectors interested in developing new water supplies or expanding the capacity of existing systems in the study area.

Location and extent of area

The area of investigation covered by this report is the Tri-State region which includes portions of southeast Kansas, southwest Missouri, and northeast Oklahoma (fig. 1). This includes portions or all of Cherokee, Crawford, Allen, Bourbon, Neosho, Montgomery, and Labette counties in Kansas; Vernon, Barton, Jasper, and Newton counties in Missouri; and Ottawa and Craig counties in Oklahoma.

Previous work

Ground-water investigations pertaining to the lower Paleozoic aquifers in southeast Kansas and in the adjoining areas of Missouri and Oklahoma are numerous. Abernathy (1941) reported on the availability of ground water from the Cambrian-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 ground-water chemical quality in the Cambrian-Ordovician aquifer within this region. He also reported on the drilling and testing of a new well for the Jayhawk Ordnance Plant (now the Gulf Oil Chemical Corporation) that penetrated the Mississippian and Cambrian-Ordovician aquifers (Abernathy, 1943). Williams (1948) wrote a report on the possible contamination of public water-supply wells completed in the Cambrian-Ordovician by leakage of waters through holes in the well casing from 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 deep wells used for public water supply by the city of Pittsburg, Kansas, to determine the hydraulic properties of

the lower Paleozoic carbonate aquifers in the well-field area. He noted that static (nonpumping) water levels in wells penetrating these aquifers had declined more than 100 ft (30 m) in the Pittsburg area since the drilling of the first well in the early 1880's. Reed and others (1955) reported on ground-water availability in the Mississippian and Cambrian-Ordovician aquifers in Ottawa County, Oklahoma. They showed that at Miami, Oklahoma, static water-level declines of approximately 400 ft (120 m) occurred between 1905 and 1947 in wells penetrating the deeper Cambrian-Ordovician aquifers. Marcher and Bingham

(1971) produced a hydrologic atlas of ground-water resources including those in the lower Paleozoic for the Tulsa quadrangle from available data in northeastern Oklahoma. Feder and others (1969) reported on ground-water availability and chemical quality for the Mississippian and Cambrian-Ordovician aquifers in the Joplin area in Missouri. Recently, Hathaway and Macfarlane (1980) and Macfarlane and others (1981) discussed the regional hydrogeology and the spatial and temporal variations in chemical quality of ground water from the lower Paleozoic aquifers in the Tri-State region and adjoining areas.

Geologic framework

Stratigraphy

The lower Paleozoic stratigraphic section in the Tri-State region consists of Mississippian, Lower Ordovician, and Upper Cambrian rocks bounded above by the Pennsylvanian and below by the Precambrian systems (table 1). The thickness of the section ranges from 1,735 ft (520 m) in the Joplin, Missouri, area to 1,390 ft (417 m) near Parsons, Kansas, except in the vicinity of Precambrian topographic highs where the thickness of the lower Paleozoic may be considerably less. Lower Paleozoic rocks that make up the stratigraphic column in the study area consist of limestone, dolomite, chert, sandstone, and shale.

Subdivision of the major stratigraphic units in the lower Paleozoic into smaller recognizable units in the

subsurface has been a difficult task because the formations are lithologically similar, few easily recognizable stratigraphic markers are present, and biostratigraphic data are unavailable. Geologists of the Missouri Geological Survey have had considerable success correlating outcrops of lower Paleozoic rocks in the subsurface from region to region using insoluble residues of drill cuttings in Missouri and adjoining states (McQueen, 1931; McCracken, 1955, 1964; Koenig, 1961). Insoluble residues have been used to show regional stratigraphic changes in the Lower Ordovician-Upper Cambrian rocks in the subsurface of Kansas and Missouri along selected traverses (Keroher and Kirby, 1948; Kurtz and others, 1975). The stratigraphic subdivisions of the lower Paleozoic section that have resulted from

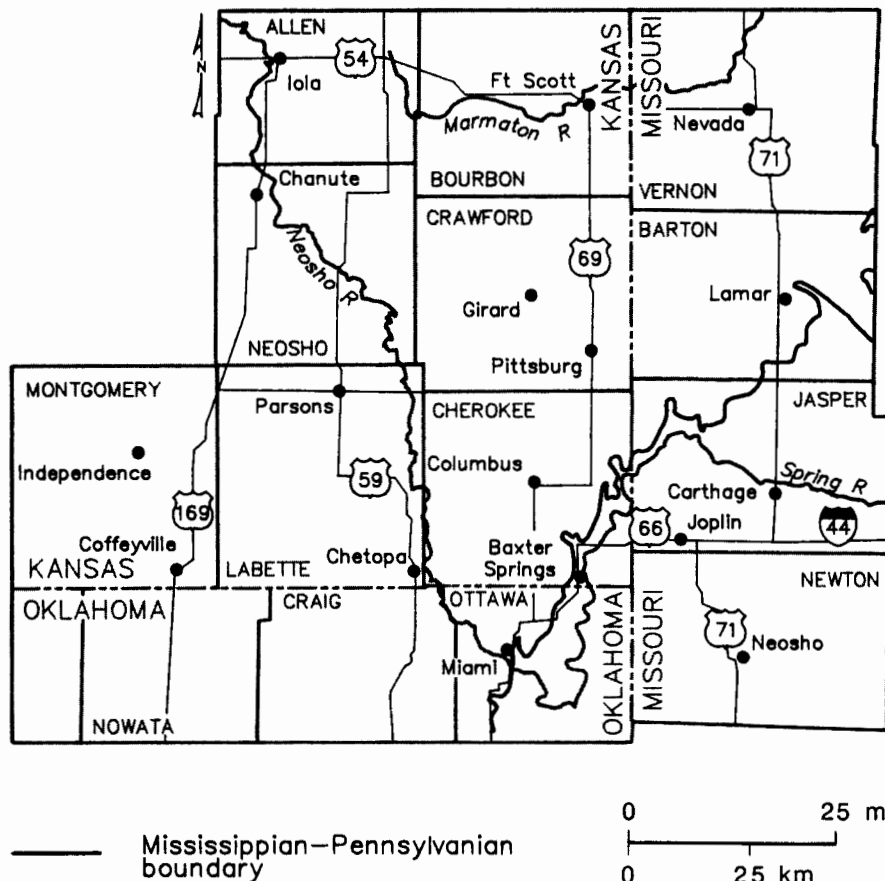


FIGURE 1—LOCATION OF STUDY AREA SHOWING MISSISSIPPIAN-PENNSYLVANIAN OUTCROP BOUNDARY, TRI-STATE REGION.

the application of the insoluble-residue method are used in this report where appropriate.

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 (Zeller, 1968); however, the term Arbuckle is not recognized in Missouri. The term Roubidoux also is used as a synonym for these rocks in parts of southwest Missouri and southeast Kansas. Where possible in the remainder of this report either the term Cambrian-Ordovician or a specific stratigraphic interval within these rocks will be used instead of Arbuckle or Roubidoux.

Precambrian System

Precambrian rocks in the Tri-State region include igneous and metasedimentary rock types (Bickford and others, 1979; Kisvarsanyi, 1975; Denison, 1968). The top of the Precambrian is an erosional surface of considerable relief in some places and reflects both the effects of tectonic events and differential resistance to erosion (Cole, 1976; Chenoweth, 1968).

Cambrian System

Upper Cambrian Series

The Upper Cambrian Series is bounded above and below by unconformities of regional extent. Strata belonging to this series are represented in ascending order above the Precambrian by the Reagan Sandstone, Davis Formation, Derby-Doe Run Dolomite, Potosi Dolomite, and the Eminence Dolomite in the Tri-State region. Upper Cambrian rocks are absent over isolated Precambrian highs in southeast Kansas and northeast Oklahoma (Chenoweth, 1968). The rocks that comprise the Upper Cambrian Series consist of dolomite, sandstone, and shale.

Ordovician System

Lower Ordovician (Canadian) Series

Strata belonging to the Lower Ordovician (Canadian) Series in the Tri-State region include in ascending order the Gasconade Dolomite, the Roubidoux Formation, the Jefferson City Formation, the Cotter Formation, and the Powell Formation. The Powell Formation was identified at only one location in the Kansas Ord #1 well at Parsons, Kansas, in northeast Labette County. Lower Ordovician rocks thin considerably in the northern part of the Tri-State region where erosion along the Bourbon arch has removed the upper portion of the Jefferson City and all of the Cotter formations. At one location in northwestern Ottawa County (Oklahoma), Mississippian carbonates rest on top of a Precambrian high. The Lower Ordovician Series is unconformable with stratigraphic units above and below and consists of dolomite, sandy dolomite, sandstone and chert.

Mississippian-Devonian System

Chattanooga Shale

The Chattanooga Shale where present lies unconformably upon the Lower Ordovician Series in the Tri-State region and is composed of black shale containing abundant pyrite. The Chattanooga is not present in Cherokee County and portions of Crawford, Bourbon, Labette, and Neosho counties in Kansas; in most of southwest Missouri; and in northern Ottawa County in Oklahoma. Elsewhere, the thickness of the Chattanooga Shale ranges upward to 40 ft (12 m) and is unconformable with the overlying Mississippian rocks above.

TABLE 1—BEDROCK STRATIGRAPHIC UNITS IN SOUTHEAST KANSAS, SOUTHWEST MISSOURI, AND NORTHEAST OKLAHOMA (AFTER KEROHER AND KIRBY, 1948; KURTZ AND OTHERS, 1975).

System	Series	Rock units	Thickness (ft)	Lithology	
Pennsylvanian Mississippian	M. Pennsylvanian	Cherokee Group	0-500	shale, limestone, sandstone	
	Undifferentiated	—	250-400	limestone, cherty limestone, dolomite, cherty dolomite, and shale near base	
Mississippian- Devonian	—	Lower	Northview Fm.	0-40	green shale
		Compton Ls.	0-20	finely crystalline limestone or dolomitic limestone	
		Chattanooga Sh.	0-40	black shale	
Ordovician	L. Ordovician	Powell Dolomite	40	dolomite, occasionally sandy, vuggy	
		Cotter Dolomite	0-250	dolomite, sandy near base	
		Jefferson City Fm.	170-250	dolomite, occasionally sandy	
		Roubidoux Fm.	125-170	dolomite, sandy dolomite, sandstone	
		Gasconade Dolomite	150-300	dolomite, sandy dolomite, sandstone near base, vuggy	
Cambrian	U. Cambrian	Eminence Dolomite	0(?) - 195	dolomite, fine- to medium-grained, cherty, vuggy	
		Potosi Dolomite	0-30	dolomite, fine-grained, cherty	
		Derby-Doe Run Dolomite	0-100	dolomite	
		Davis Fm.	0(?) - 95	dolomite, sandy, glauconitic	
		Reagan Sandstone	0(?) - 135	medium- to coarse-grained sandstone grading upwards to glauconitic shale and dolomite	
Precambrian	—	—	—	igneous and metasedimentary rocks	

Mississippian System

Lower Mississippian Series

Strata belonging to the Lower Mississippian Series are represented in ascending order above the Chattanooga Shale by the Compton Limestone and the Northview Shale. The Lower Mississippian Series is unconformable with stratigraphic units above and below and ranges in thickness from 0 ft (m) in southern Cherokee County, Kansas, to over 50 ft (15 m) in northern Crawford, Bourbon, and Neosho counties in Kansas and northern Barton and southern Vernon counties in Missouri. The Compton Limestone consists of finely crystalline limestone which may be dolomitic locally. The Compton Limestone thicknesses range from 0 to 20 ft (6 m) in the Tri-State region. The Northview Shale consists of green shale containing abundant pyrite, and it ranges in thickness from 0 to more than 40 ft (12 m) through the area. It is thickest in eastern Bourbon and Crawford counties in Kansas and in Vernon and Barton counties in 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, both series are considered together as undifferentiated for two reasons. The Lower and Upper Mississippian are not distinguished on many well logs in southeast Kansas. Additionally, for

those wells with insoluble-residue logs interpreted by geologists accustomed to Missouri stratigraphic nomenclature, the Missouri formation names and stratigraphic boundaries do not necessarily coincide with those used in Kansas or Oklahoma. The undifferentiated Mississippian in the Tri-State region consists primarily of limestone, dolomite, and chert, and it exhibits extensive sulfide mineralization in the Picher and Joplin mining fields (fig. 13). Thin gray or green shaly zones are common near the base. The undifferentiated Mississippian is bounded above and below by unconformities of regional extent, which may have considerable relief. The thickness of this unit ranges from approximately 400 ft (120 m) in southwest Missouri and northeast Oklahoma to 250 ft (75 m) in southwest Neosho County in Kansas. The undifferentiated Mississippian crops out and is the surficial bedrock in much of Jasper and Newton counties in Missouri, the extreme southeast corner of Cherokee County in Kansas, and in eastern Ottawa County in Oklahoma (fig. 1).

Pennsylvanian System

The undifferentiated Mississippian is unconformably overlain in most of the Tri-State region by rocks belonging to the Cherokee Group of Middle Pennsylvanian age (Zeller, 1968). Rocks that comprise the Cherokee Group are mostly shale, limestone, sandstone, and minor amounts of coal. The near-surface bedrock is composed of Pennsylvanian-age rocks over much of the area (fig. 1).

Geologic structure

The study area is located on the northwestern flank of the Ozark dome and covers a portion of the Cherokee basin and the Bourbon arch in Kansas, Missouri, and Oklahoma (fig. 2). The regional dip is generally westward at 20 ft/mi except where geologic structures have altered the prevailing dip direction or amount. Fig. 3 is a map of the configuration of the top of the Lower Ordovician surface. This map should be used only to interpret broad regional structures because paleokarstic or other paleotopographic features that have resulted from erosion might be misinterpreted as geologic structure.

The most prominent features in the subsurface are northwest-southeast trending folds and faults (fig. 3). The folds are usually of short wavelength (2–5 mi [3–8 m]) and plunge in a northwesterly direction. Individual fold axes often can be traced in the subsurface for many miles. Faulting in the subsurface of southeast Kansas is probably high-angle, although no drill-hole information is available to substantiate this. However, 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.

The Bourbon arch is a broad, gentle uplift extending across all of Vernon County, Missouri, and across Bourbon and part of Allen counties in Kansas (fig. 2; Merriam, 1963). The southern edge of the Bourbon arch coincides approximately with the northern extent of the Cotter Formation in the subsurface (fig. 3).

Domes or domelike structures are common features locally in the subsurface of Montgomery and Labette

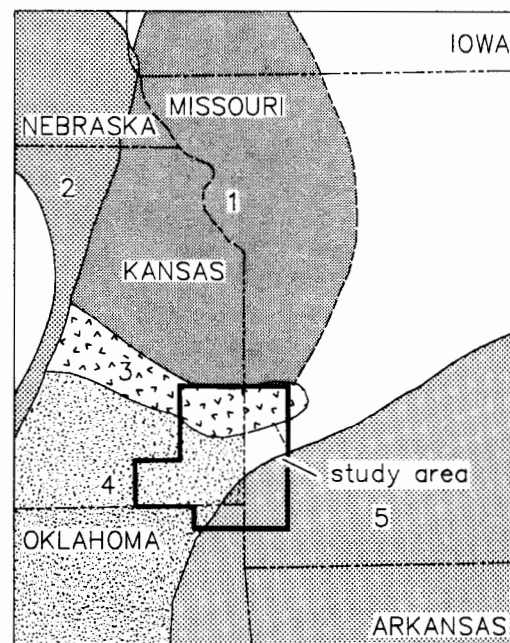


FIGURE 2—REGIONAL GEOLOGIC STRUCTURES IN VICINITY OF TRI-STATE REGION ARE FOREST CITY BASIN (1), NEMAHA RIDGE (2), BOURBON ARCH (3), CHEROKEE BASIN (4), AND OZARK UPLIFT (5).

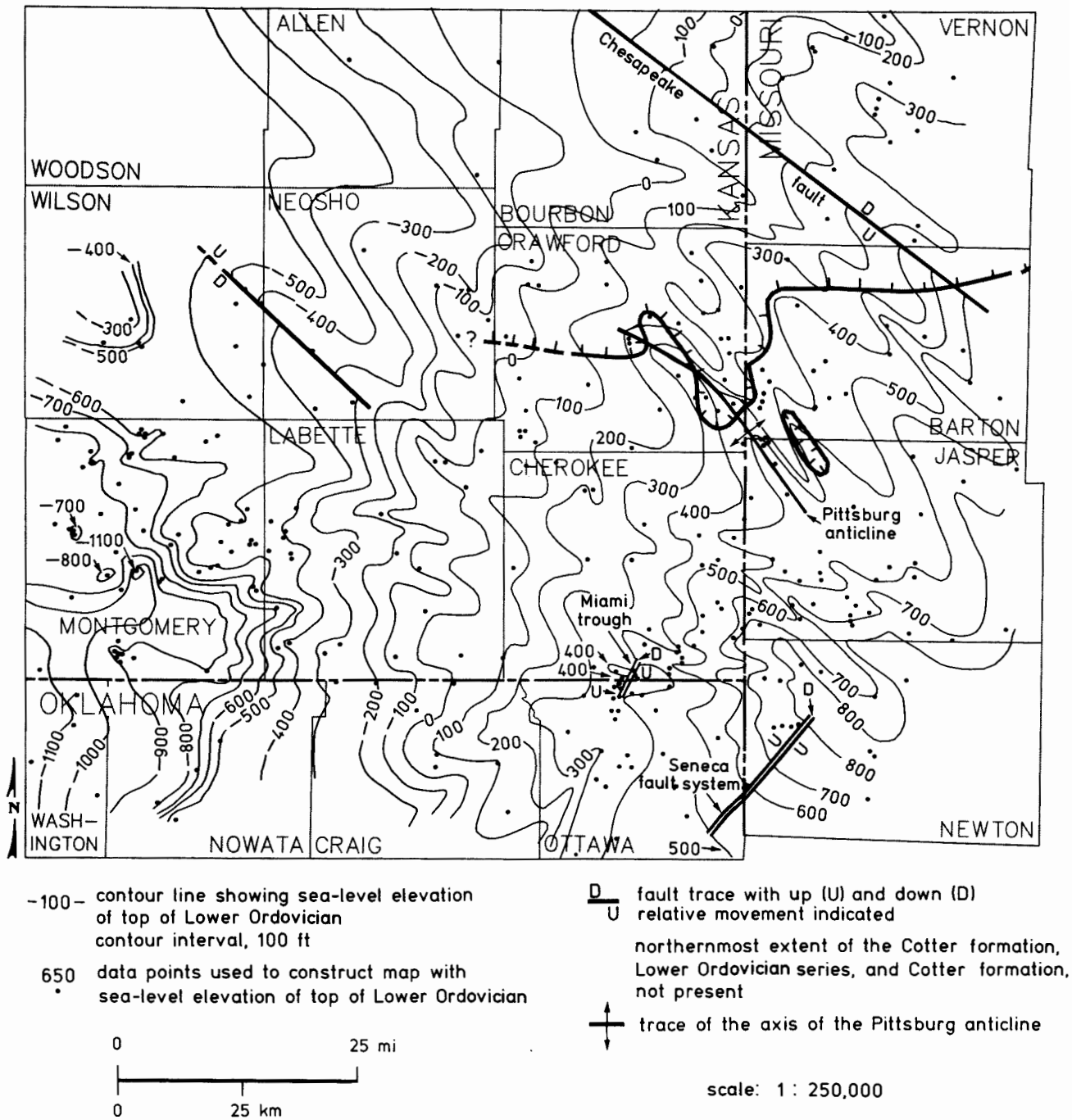


FIGURE 3—CONFIGURATION OF TOP OF LOWER ORDOVICIAN SURFACE IN TRI-STATE REGION OF KANSAS, MISSOURI, AND OKLAHOMA.

counties, Kansas, and in northeast Oklahoma. Most of these domes are roughly circular features with 20 ft (6 m) to over 100 ft (30 m) of closure in the sedimentary section. They are produced by the draping of Paleozoic sedimentary rocks over Precambrian paleotopographic highs. These

highs are abrupt postlike features on the Precambrian surface with as much as 600 ft (180 m) of vertical relief. The Cambrian–Ordovician section over many of these Precambrian highs is either thin or absent.

Hydrogeology

The lower Paleozoic aquifer system is considered in this report to consist of two carbonate aquifers separated over much of the area by a confining layer. The upper aquifer is composed of undifferentiated Mississippian carbonates, whereas the lower aquifer consists of rocks of the Cambrian–Ordovician System. Rocks of the Precambrian and Pennsylvanian systems are considered to be confining layers. However, in some parts of the study area shallow wells do obtain ground water from low-yielding sandstone and limestone aquifers in the Pennsylvanian. The U.S. Geological Survey has, for the Central Midwest Regional Aquifer Systems–Analysis Study, subdivided the lower Paleozoic rocks into geohydrologic units that differ from the designations used in this study (Bob Leonard, personal communication, 1984). Ground water occurs in these lower Paleozoic aquifers under confined artesian conditions except where the Mississippian is exposed at the surface.

A confined aquifer is a water-bearing, permeable geologic unit capable of transmitting significant quantities of water under ordinary hydraulic gradients, which 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 top level of the aquifer.

One or more stratigraphic units act as confining layers separating the Mississippian and Cambrian–Ordovician

aquifers over most of the study area. These layers are composed of shale and fine-grained, dense limestone and dolomite belonging to the Chattanooga Shale, the Compton Dolomite, and the Northview Formation. Fig. 4 shows the variation in thickness of the confining layer across the study area. No field estimates of vertical permeability are available for the confining unit to assess leakage; however, Emmett and others (1979) assigned a vertical permeability of 10^{-9} ft/sec to the Northview Formation in the Springfield, Missouri, area. Where the confining layers are not present, the two aquifers might behave as one system although little data are available to confirm this hypothesis.

Ground-water flow in most of the study area is in response to hydraulic gradients according to Darcy's Law. The 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. The direction of water flow in the freshwater portion of the aquifer is from points of greater to lesser hydraulic head. Temperature, density, and hydraulic-head gradients influence the flow of ground water in the more saline portions of the aquifer. The lateral direction of water flow in the less saline portions of the aquifer can be found by constructing a potentiometric surface map in the region of interest. The configuration of the potentiometric surface is determined by contouring a map of measured, static water

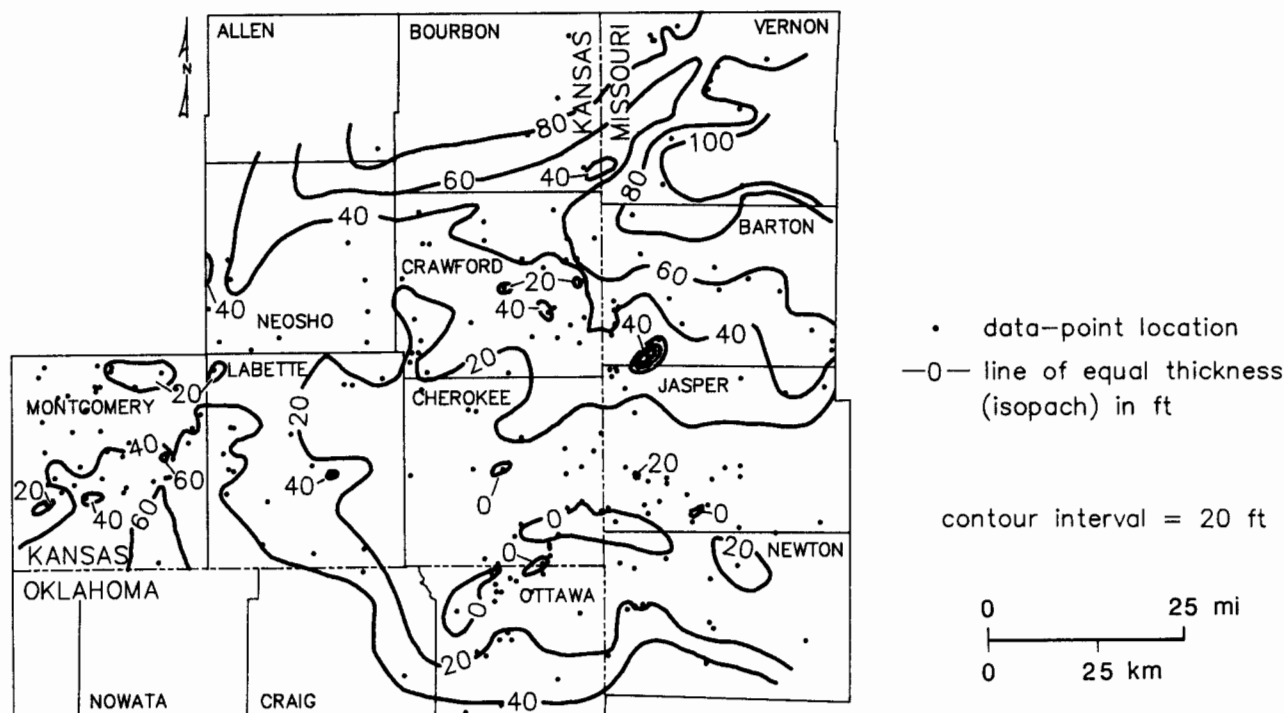


FIGURE 4—ISOPACH MAP OF STRATIGRAPHIC INTERVAL THAT INCLUDES NORTHVIEW SHALE, COMPTON LIMESTONE, AND CHATTANOOGA SHALE IN TRI-STATE REGION.

levels in wells that are open to the aquifer. The direction of water flow is then perpendicular to contours in the down-gradient direction. The authors have assumed that the aquifers are mostly isotropic since no data indicate the orientation of principal directions of anisotropy.

Aquifers in Mississippian rocks

Ground-water availability

The aquifer in Mississippian rock is used extensively for domestic supplies where the depth to the top of the aquifer is shallow and water quality is acceptable in southwest Missouri and northeast Oklahoma. The aquifer does not produce adequate amounts of water for most other purposes. Farther west in southeast Kansas and parts of northeast Oklahoma, ground-water chemical-quality changes make this aquifer unsuitable for domestic use.

Driller's logs of wells in the area indicate several water-bearing zones in the Mississippian. Ground water is stored in and transmitted by fractures and solution channels in the carbonate rock, especially where pre-Pennsylvanian erosion has developed a karstic surface in the rock at the top of the aquifer or where the aquifer contains brecciated chert or collapse features. Where the carbonate rocks are unfractured and dense, well yields are likely to be low. The maximum well yields can be expected to be 100 gal/min or more where the aquifer is more open. Typical well yields are likely to be approximately 25 gal/min.

Ground-water flow, recharge, and discharge

An insufficient number of water wells penetrating the Mississippian were studied to develop a reasonably detailed potentiometric surface map for the Mississippian aquifer in the study area. However, from the data available, the potentiometric surface is believed to slope generally westward from recharge areas where the aquifer is unconfined. Most of the recharge to the aquifer comes from precipitation falling on the land surface and entering solution-enlarged fractures and bedding-plane openings where the Mississippian is exposed at the surface (Feder, 1969). The aquifer also is recharged by surface water entering unplugged drill holes and mine shafts in the Tri-State mining area. Feder (1969) presents some hydrographs of water levels in abandoned mines in the Joplin, Missouri, area which show that water levels in the mines respond rapidly to precipitation events. Historically, the dewatering of lead-zinc mines in the Picher field along the Kansas-Oklahoma border created a large cone of depression in the Mississippian aquifer and changed the local direction of ground-water flow in Ottawa County, Oklahoma (Reed and others, 1955).

With the cessation of mining, the potentiometric surface is recovering in the Picher field. Streams in northern Ottawa County, Oklahoma, are receiving discharge from the aquifer and mines (Spruill, 1984). Outside the mining areas, ground water from the unconfined Mississippian aquifer normally supplies the base flow to many of the streams. Feder (1969) estimated that the undifferentiated Mississippian aquifer discharges an average of approximately 300 ft³/sec (135,000 gal/min) to streams in the

Joplin area. Reed and others (1955) estimated that the total annual ground-water discharge from the aquifer in Ottawa County, Oklahoma, was 10,220 Mgal/yr (43 ft³/sec). Most of the regional discharge from the Mississippian aquifer in the study area is to the west into the deeper parts of the Cherokee basin.

Aquifers in Cambrian-Ordovician rocks

Well construction and water availability

Public water supply and industrial water wells in the Tri-State region are usually constructed in one of two ways. In most wells the casing extends from ground surface through the Mississippian and into the Cambrian-Ordovician; below the casing the well is an uncased bore hole to the total depth of the well. In the other method, portions of the Mississippian are not cased out. Thirty-two wells with this latter type of construction were inventoried during this study. In one well at Capaldo, Kansas, the open bore-hole portion intercepts aquifers in the Pennsylvanian, Mississippian, and Cambrian-Ordovician rocks. Typically, well depths range between 900 and 1,500 ft (270-450 m) for both types of wells and depend upon desired yield and changes in ground-water chemical quality noted with increasing depth in the aquifer.

The occurrence of ground water is directly related to the development of secondary porosity and permeability in the rocks. Secondary porosity and permeability are enhanced where there are solution-enlarged interconnected fractures and cavities. As a result, the relative amount of water produced by each zone in the Cambrian-Ordovician for a given well is difficult to predict. It should not be concluded that certain horizons within this aquifer will always produce more water than others. Porous zones can be readily identified on the sonic neutron-formation density and caliper logs and in well cuttings of several wells. Typical well yields of municipal and industrial wells range from 250 to 750 gal/min (33-100 ft³/min). Water is generally produced at a rate of approximately 100 gal/min (13.4 ft³/min) from most rural water-district wells. In areas where well yields are relatively low, the yield often can be increased somewhat by acid treatment of the well.

Ground-water flow, recharge, and discharge

Ground-water flow in these aquifers is generally westward across the region from recharge areas in the Ozarks of southern Missouri to discharge areas west and south in Kansas and Oklahoma (fig. 5). The main source of recharge is precipitation entering the rocks where they are exposed at the surface in the Ozark region of southern Missouri. The potentiometric-surface map was drawn using 1980 static water-level measurements and other relatively recent static water-level data from other sources. Additionally, static water levels from wells open to the Mississippian and the Cambrian-Ordovician were included to supplement the data because head differences between the units seem to be small where these measurements were used. The contours on the potentiometric-surface map were closely spaced in

southwest Missouri and eastern Cherokee County, Kansas, indicating relatively steep hydraulic gradients in the Cambrian–Ordovician, whereas to the west, the gradient decreases. The smaller gradients indicate increased permeability and relatively stagnant flow conditions in the aquifer in the chemical-quality transition zone. Also, a rather well-defined ground-water divide extends from Jasper County, Missouri, into Cherokee County, Kansas, between two pumpage centers in the Miami, Oklahoma, and Pittsburg, Kansas, areas. Large cones of depression have been created in these areas where wells have been pumping ground water from the deep aquifer since before 1900.

Properties of Cambrian–Ordovician aquifer

Transmissivity and storativity are two properties that determine the ability of a confined aquifer to transmit and to 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 the Tri-State region to estimate transmissivity and storativity. Several drawdown and recovery pump tests were conducted in the 1940's at Miami, Oklahoma, on water-supply wells owned by B. F. Goodrich Rubber Company. The average transmissivity and storativity values determined from these tests were 38,100 gpd/ft (5,100 ft²/day) and 8.00×10^{-5} respectively (Reed and others, 1955). Pump tests also were

conducted on the city wells at Pittsburg, Kansas (Stramel, 1957). These wells were open to aquifers in both Mississippian and Cambrian–Ordovician rocks. The average transmissivity and storativity values computed from these tests were 252,000 gpd/ft (33,800 ft²/day) and 7.8×10^{-4} , respectively. Feder and others (1969) reported that values computed from a 24-hr interference test at Webb City, Missouri, were 4,000 gpd/ft (540 ft²/day) for transmissivity and storativity, 2×10^{-4} .

Some estimate of an aquifer's ability to transmit water can be developed from production tests on wells. During these tests both drawdown and discharge are measured in the pumping well. The test results are usually reported as the specific capacity (gpm/ft of drawdown). These tests, usually of short duration, may yield unreliable estimates of transmissivity if the test-pumping period is not sufficiently long, the well does not fully penetrate the aquifer, or if hydrogeologic boundaries exist nearby. In general, however, the specific capacity is directly related to transmissivity (Walton, 1970).

Fig. 6 shows the distribution of well specific capacities across the region. Specific capacities are generally less than 10 gpm/ft in Cherokee County, Kansas, and in Jasper and Newton counties, Missouri. To the north the specific capacities of wells are much higher and range from 10 to greater than 100 gpm/ft. The lower values of specific capacity (less than 10 gpm/ft) in Cherokee County, Kansas, and Jasper County, Missouri, coincide with steeper hydraulic gradients in the aquifer. These findings indicate that aquifers in Cambrian–Ordovician rocks are less permeable in this part of the study area than in other parts. The highest specific capacities in the area found near Pittsburg, Kansas, correspond to the highest values of transmissivity in the region.

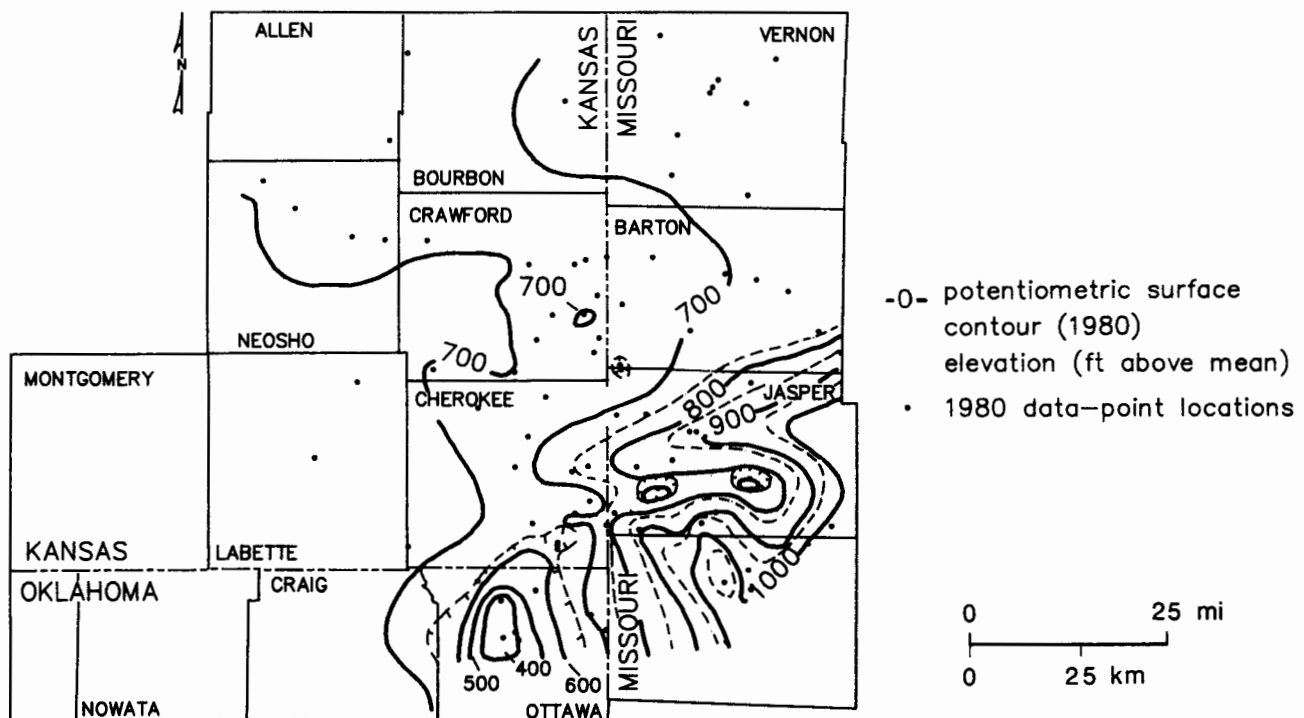


FIGURE 5—COMPOSITE POTENTIOMETRIC SURFACE MAP OF LOWER PALEOZOIC AQUIFERS IN TRI-STATE REGION.

Hydraulic connection between aquifers

Leakage of ground water downward from aquifers in the Mississippian rocks to the Cambrian–Ordovician is possible where the Northview and Chattanooga shales are thin or absent and where greater hydraulic head exists in the Mississippian aquifer than in the Cambrian–Ordovician aquifer (Reed and others, 1955; Feder and others, 1969). Fractures further enhance the possibility of downward leakage in these aquifers. Interconnection of aquifers does occur in 32 wells in the study area where the open bore-hole portion of the well includes Mississippian and Cambrian–Ordovician rocks. Hydraulic-head data from Spruill (1984) for the Mississippian in the Joplin, Missouri, and Miami, Oklahoma, areas indicate that substantial hydraulic-head differences exist between the Mississippian and Cambrian–Ordovician aquifers in these areas. Some recharge may be occurring in western Jasper County, Missouri, where the static water levels of two water wells have apparently risen since they were drilled. Additionally, geochemical evidence from this study and Feder and others (1969) indicate that aquifers in the Cambrian–Ordovician rocks are receiving significant amounts of recharge from the overlying Mississippian in southwest Missouri and northeast Oklahoma. This is discussed further in the ground-water chemical-quality section of this report.

Effects of well development

The ground-water resources of the Cambrian–Ordovician aquifers in the Tri-State region have been used extensively in the area for water supply since the early 1900's. One result of this development has been a lowering of the static water levels in wells completed in the aquifer systems throughout the area (Reed and others, 1955; Stramel, 1957). Where the rate of water withdrawal from the Cambrian–Ordovician aquifer has been relatively low, the decline in static water level is generally less than 50 ft (15 m). Static water-level declines in excess of 450 ft (135 m) have occurred in the area north of Miami, Oklahoma, and declines of 150 ft (45 m) have occurred southeast of Pittsburg, Kansas, and in northwestern Jasper County, Missouri. In these areas the rate of ground-water withdrawal has been substantial (approximately 4 Mgal/d in the Miami, Oklahoma, area in 1980) since the early 1900's. The static water-level declines in wells in the Joplin area have not been as extensive because sufficient recharge from the Mississippian may be able to partially overcome the effects of ground-water withdrawals from the Cambrian–Ordovician, and the total amount of water withdrawn from the aquifer by wells has been small relative to other parts of the Tri-State region.

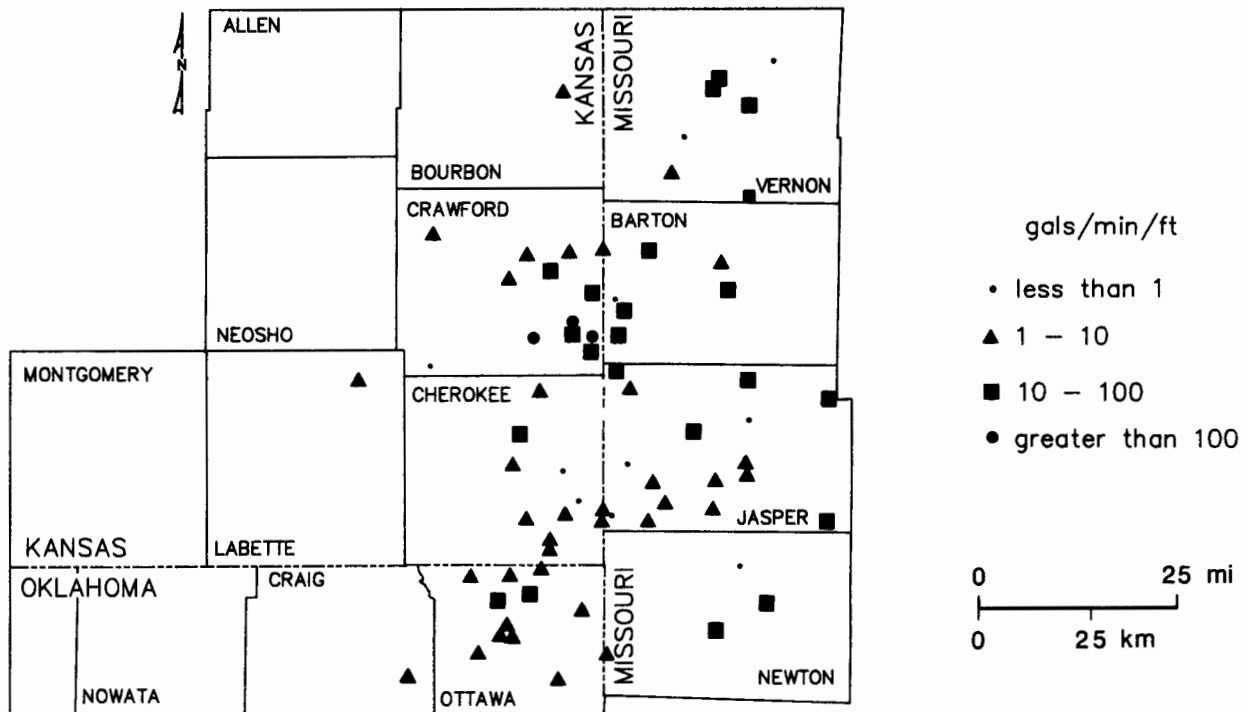


FIGURE 6—SPECIFIC-CAPACITY VARIATION REPORTED FOR WELLS COMPLETED IN LOWER PALEOZOIC AQUIFERS IN TRI-STATE REGION.

Chemical quality of ground waters from the lower Paleozoic aquifers

Sampling sites

Water samples from 119 wells were collected during this investigation from domestic, municipal, industrial, oil-field water supply, and oil-producing wells penetrating the lower Paleozoic aquifers in the study area. Of these wells, only two are thought to be open to part of the Pennsylvanian System; seven open only to the Mississippian System; 78 of the wells open to the Cambrian-Ordovician; and 32 to portions of the Mississippian and Cambrian-Ordovician units present. All the wells in the freshwater part of the aquifers were sampled more than once during 1979-1980. The chemical-quality data from the fall 1980 sampling are used as the basis for maps of this report and most of the discussion here. Well locations and aquifer units contributing water are indicated on fig. 7 for all sites used in preparation of the chemical-quality maps. The oil-producing wells and most of the oil-field water-supply wells were sampled only once during 1980-81. Restricted distribution of sampling sites in Kansas and limited information for the Pennsylvanian and Mississippian aquifer systems placed some constraints on the interpretation of water quality in the ground-water systems of the Tri-State region.

Ground-water quality

Feder (1979) noted marked variations in ground-water chemical quality and yields for wells in the Pennsylvanian, Mississippian, and Cambrian-Ordovician aquifer systems

of southwestern Missouri, ranging from greater than 1,000 mg/L dissolved solids and 50 gpm (6.4 ft³/min) for Pennsylvanian wells to less than 300 mg/L dissolved solids and 100-500 gpm (13-64 ft³/min) for Cambrian-Ordovician wells. Macfarlane and others (1981) and Hathaway and Macfarlane (1980) found that water quality changes rapidly and deteriorates markedly in a westward direction in the Tri-State region of Kansas, Missouri, and Oklahoma.

Water-type classifications used in this report are based on percent milliequivalent contributions of the various chemical species to total number of milliequivalents of cations and anions. Classifications for all sampling sites in the study area are represented by the modified Piper diagram found in fig. 8, which suggests a general transition from Ca-HCO₃ or Ca-Mg-HCO₃ type waters (southeast portion of the study area) to Na-Cl type waters (west-northwest portions of the study area). This simple picture is complicated by: 1) the occurrence of Na-HCO₃ type waters (Crawford County, Kansas, and Barton County, Missouri); 2) the presence of a number of wells open to Mississippian and Cambrian-Ordovician units whose water chemistries fall in the transition region between Ca-HCO₃ and Na-Cl type waters; 3) marked variations in water chemistries of wells of similar construction within a given well field; and 4) significant fluctuation in water chemistries noted at some wells open to Mississippian and Cambrian-Ordovician units.

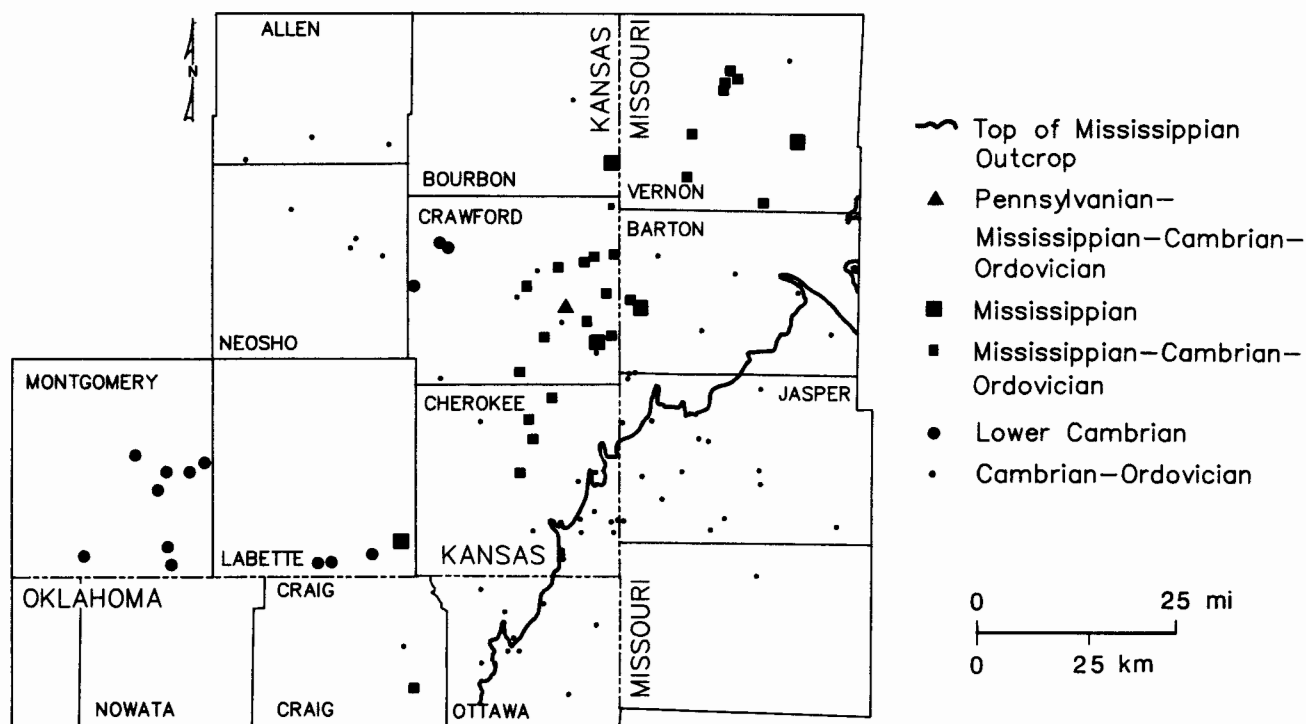


FIGURE 7—AQUIFER UNITS CONTRIBUTING GROUND WATERS TO WELLS SAMPLED IN STUDY AREA.

Pennsylvanian aquifers

Water-quality data obtained by Darr (1978) for Pennsylvanian wells in Bates County in southwestern Missouri indicate that Na-Cl type waters are the dominant classification in the region just northeast of the present study area. Total dissolved-solids concentrations in these waters ranged from about 800 to 7,100 mg/L, and sulfide concentrations ranged from less than 0.1 to 30 mg/L. From an application of factor analysis to chemical-quality data for Missouri ground waters, Feder (1979) concluded that Pennsylvanian wells in Cass and Johnson counties of western Missouri exhibit a high loading from a Na-HCO₃-Cl type end-member water. Total dissolved solids in these waters ranged from approximately 330 to 1,100 mg/L, with accompanying sulfide levels in the range of less than 0.1 to 8.5 mg/L.

The Pennsylvanian strata in the area covered by the present study, as well as in studies of Darr (1978) and Feder (1979), are generally considered to represent an unconfined aquifer system. The influence of abandoned open-pit and underground coal workings upon ground-water quantity and quality within the study area is largely unknown due to the lack of a premining-era ground-water-quality data base. These features are known to influence locally the quality of surface waters.

Two wells sampled during the present study are open to Pennsylvanian units. One is in NESWNW sec. 1, T. 27 S., R. 25 E., southeast Bourbon County, Kansas, and is believed to be completed in the lower part of the Pennsylvanian section. The water is a Na-Cl type with a dissolved-solids content of approximately 1,100 mg/L and about 3.5 mg/L sulfide. The second well located in NESWNE sec. 1, T. 30 S., R. 24 E., is open from the Pennsylvanian to the

Cambrian-Ordovician. The relative amounts of ground water contributed by the different stratigraphic units to the discharge of the well are unknown. The water from this second well exhibits some variability in its classification but is predominately a Na-HCO₃ type. The dissolved solids level is approximately 650 mg/L. Sulfide values ranged from 8 to 20 mg/L through the duration of the study. The relatively low dissolved-solids level indicates that Pennsylvanian aquifers are not the major contributor of the water produced at this location.

Mississippian aquifers

The Mississippian wells sampled by Feder (1979) are located in the central portion of the Springfield plateau region of southwestern Missouri. This is the outcrop area for limestones of Mississippian age and probably serves as a general recharge area for the Mississippian aquifers. Dissolved solids in waters from these wells ranges from 125 to 404 mg/L and sulfide levels from less than 0.1 to 0.2 mg/L. Factor analysis indicated that the chemistry of waters from Mississippian wells in this part of the unconfined aquifer system reflects the influx of precipitation. Data from Darr's (1978) study indicate a general deterioration in water quality for Mississippian wells northwest of the Springfield plateau area in regions where Pennsylvanian-age units overlay the aquifer. Here the waters fall into a Na-Cl or Na-HCO₃ classification. Approximately one-third of the wells investigated exhibited a Na-HCO₃ classification. Total dissolved-solids contents range from approximately 500 to 7,300 mg/L and sulfide levels from less than 0.1 to 42 mg/L.

Abandoned lead-zinc mines of northeast Oklahoma and southeast Kansas locally serve as reservoirs for ground

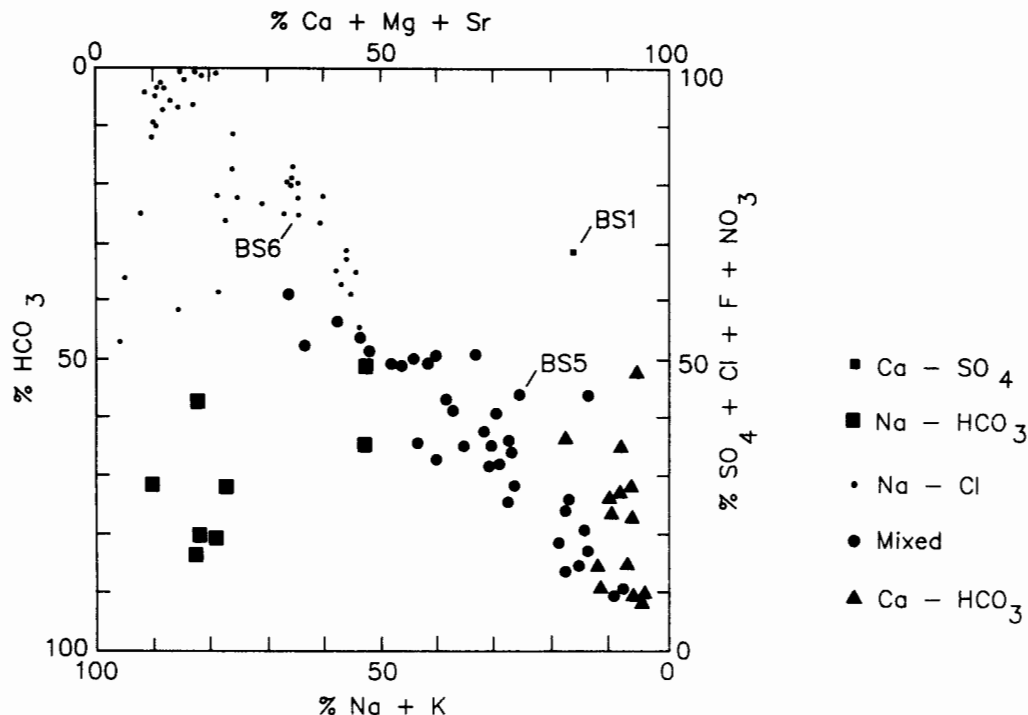


FIGURE 8—MODIFIED PIPER DIAGRAM FOR WATER SAMPLES COLLECTED FROM WELLS IN LOWER PALEOZOIC AQUIFERS IN TRI-STATE REGION. Percentages represent contributions to the mg/L of cations and anions. BS1, 5, and 6 represent water samples from Baxter Springs wells 1, 5, and 6.

and surface water within the Mississippian strata. The mine workings possibly also act as access routes for ground-water movement downward into the Cambrian–Ordovician system where intervening confining units, the Northview and the Chattanooga shales, are missing or are of limited thickness. Playton and Davis (1977) noted that water within the mine shafts was generally stratified with specific conductance, temperature, sulfate, and dissolved-solids and heavy-metal loads increasing with depth. The pH of these waters usually decreases with depth into the mine. Thus, an influx of water from the old mining area would seem to have an undesirable influence upon local ground-water quality.

Well logs indicate that a number of the wells sampled in Vernon County (Missouri) and eastern Crawford and north-central Cherokee counties (Kansas) are open to portions of the Lower Mississippian as well as to strata in the Cambrian–Ordovician system (see fig. 7). These wells tend to fall within a general transition zone found in the Cambrian–Ordovician system (fig. 9). The western boundary of this zone was set at a chloride concentration of 2,500 mg/L, approximately 5% of the maximum value determined for oil-field brines collected during this study. The greater depth and aquifer thicknesses intercepted by oil-field water-supply wells in Neosho, Allen, and Crawford counties, Kansas, relative to that of the oil wells of Montgomery and Labette counties, Kansas, lend uncertainty to the placement of this boundary. The eastern limit coincides with the exposed Mississippian–Pennsylvanian boundary.

Maps based on a composite of water-quality data for all wells sampled during this study indicate a gradation from fresh, Ca-HCO₃ type waters in southwest Missouri to saline, Na-Cl type waters within the transition zone in southeast Kansas. In northeast Oklahoma, low dissolved-

solids Na-Cl type waters were found just west of the Mississippian outcrop (figs. 10 and 11).

Sulfide concentrations greater than 0.2 mg/L, indicating the presence of reducing conditions, were encountered west of the Mississippian outcrop (fig. 12). The pattern of boron values (fig. 13) corresponded well to the defined brine, transition, and freshwater zones of fig. 9, suggesting its use as a salinity indicator for this region. Other water-quality parameters such as chloride, strontium, and radium-226 (to be discussed later) also exhibited concentration gradations similar to that noted for total dissolved solids.

Na-HCO₃ type waters were found in Mississippian and some of the multiaquifer wells in Vernon and Barton counties (Missouri) and Crawford County (Kansas). Excess amounts of HCO₃, relative to the Ca and Mg contents of the waters, were noted in a number of other wells open to Mississippian and Cambrian–Ordovician aquifers in the region, corresponding to the quality transition zone extending from Craig County (Oklahoma) through Labette, Cherokee, Crawford, and Bourbon counties (Kansas). However, not all wells which were thought to be open to Mississippian units exhibited excess HCO₃. Multiaquifer municipal wells at Mindenmines and Sheldon (fig. 14) in southwest Missouri showed considerable variation in water chemistry over the 2-yr period of this study (table 2). This suggested variable contributions to the output of these wells from the different aquifer sources over a period of time. Data presented by Darr (1978) for a 10-yr timespan also showed similar variations in water quality at those two locations. The origin of the Na-HCO₃ type waters is not understood but may lie in complex ion-exchange dissolution reactions between invading freshwaters from the Springfield plateau area and interbedded marine shales and limestones. The

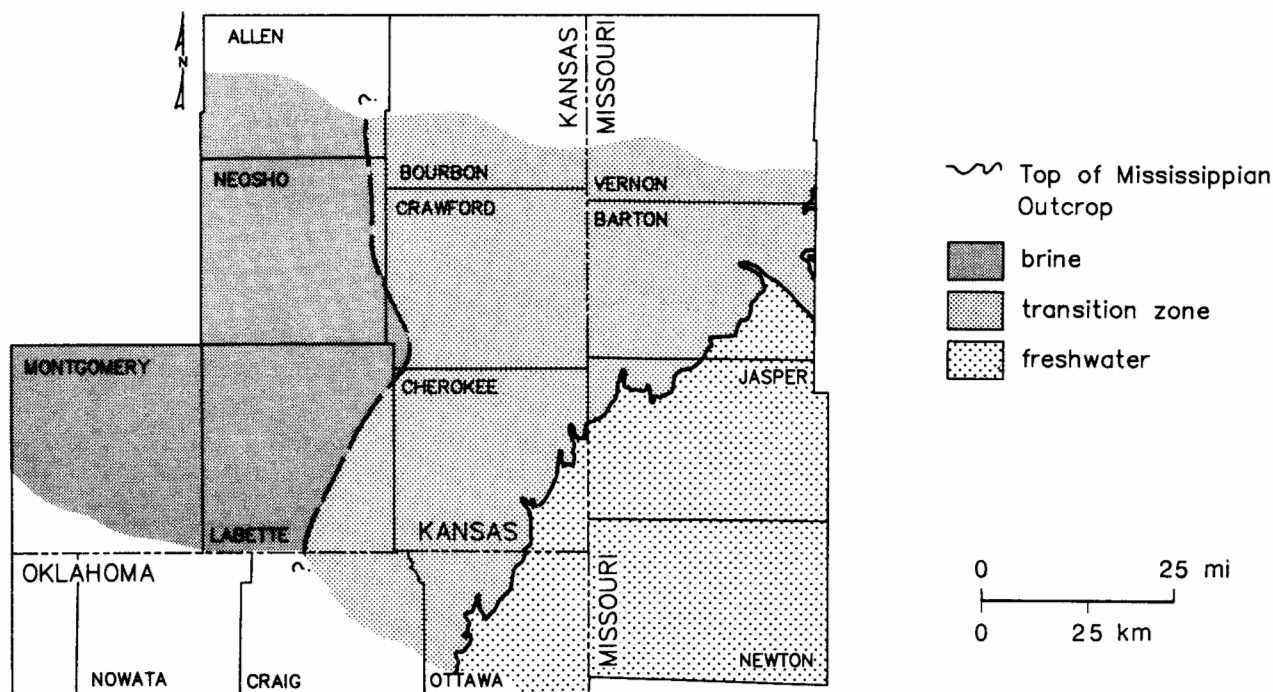


FIGURE 9—GENERALIZED REPRESENTATION OF TRANSITION ZONE IN CAMBRIAN–ORDOVICIAN AQUIFER; SOLID LINES REPRESENT PENNSYLVANIAN–MISSISSIPPIAN BOUNDARY OUTCROP AND DASHED LINE IS THE 2,500 MG/L ISOCHLOR.

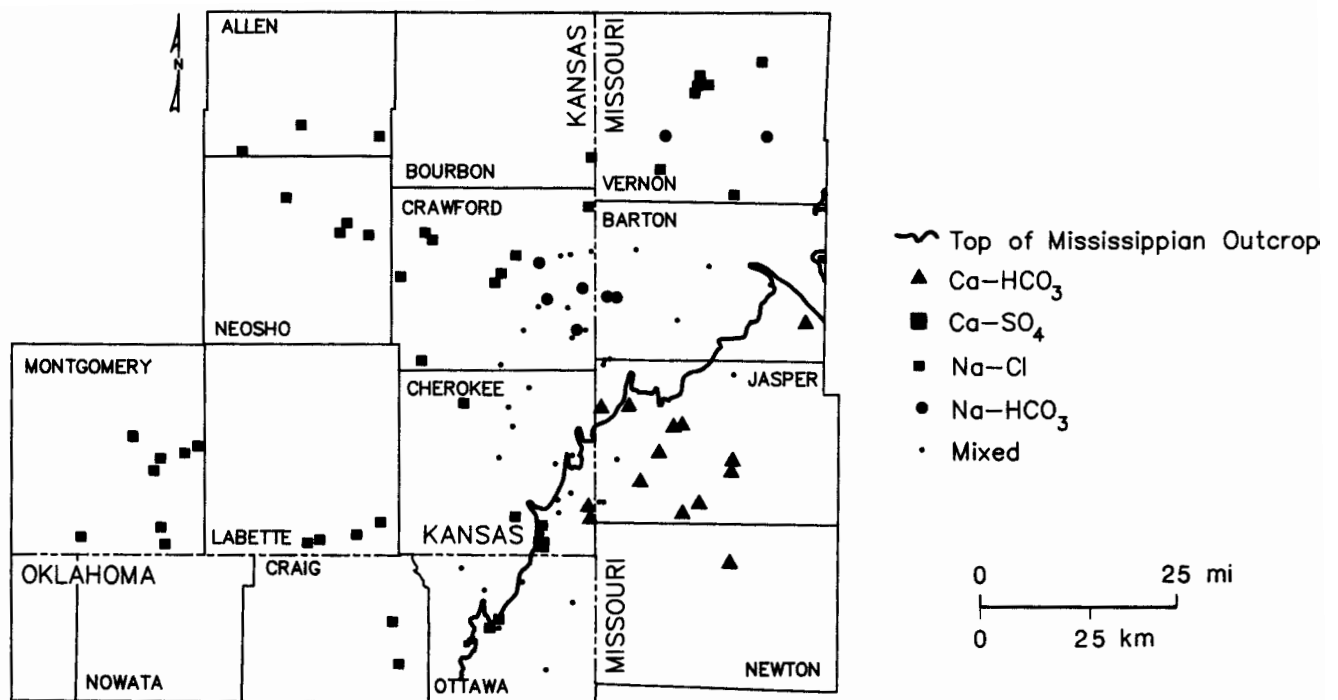


FIGURE 10—CLASSIFICATION OF GROUND WATERS FROM LOWER PALEOZOIC AQUIFERS BASED ON DOMINANT CATION AND ANION PRESENT.

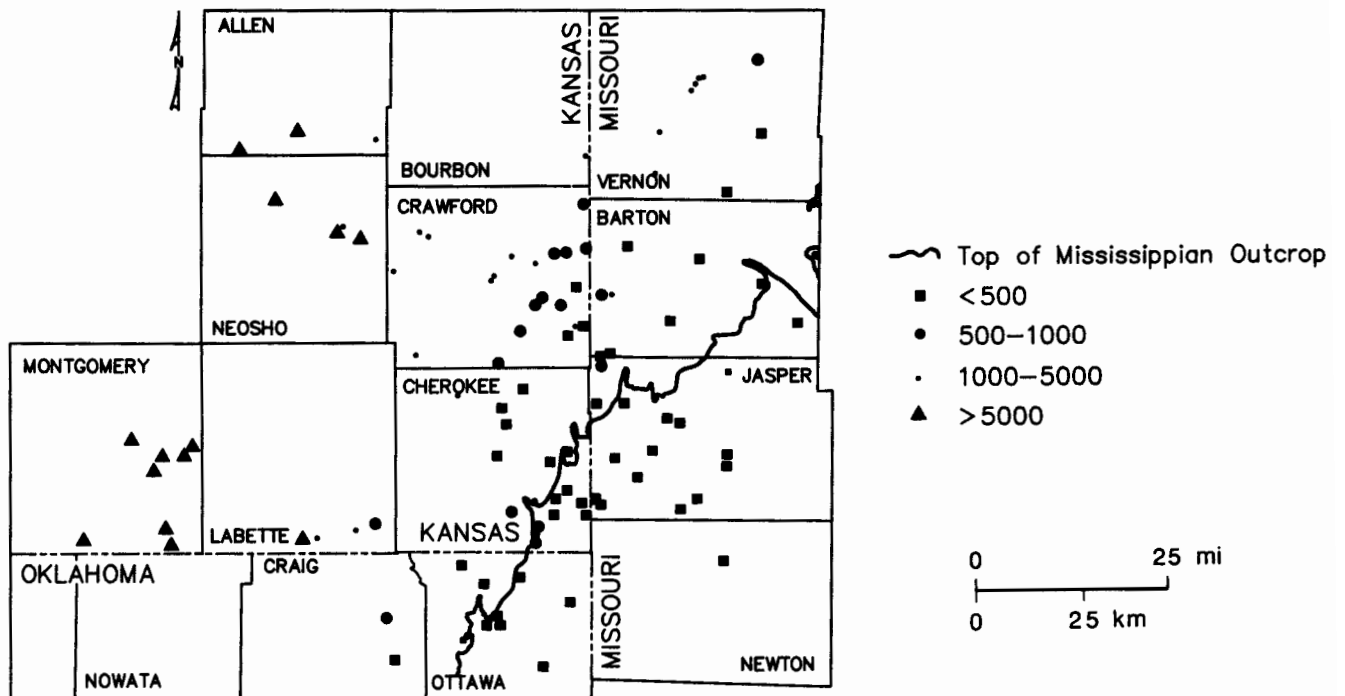


FIGURE 11—CALCULATED TOTAL DISSOLVED SOLIDS (PPM) OF GROUND-WATER SAMPLES FROM LOWER PALEOZOIC AQUIFERS, TRI-STATE REGION.

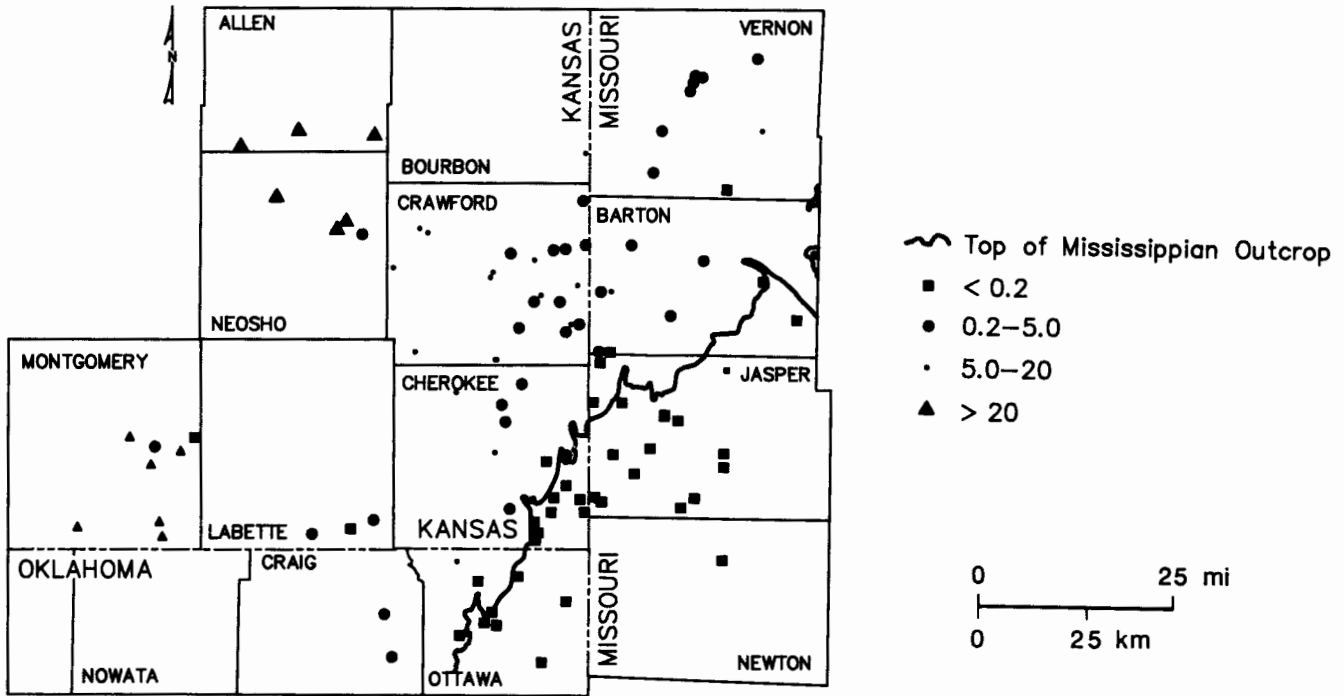


FIGURE 12—SULFIDE CONCENTRATIONS IN GROUND WATERS FROM LOWER PALEOZOIC AQUIFERS IN TRI-STATE REGION.

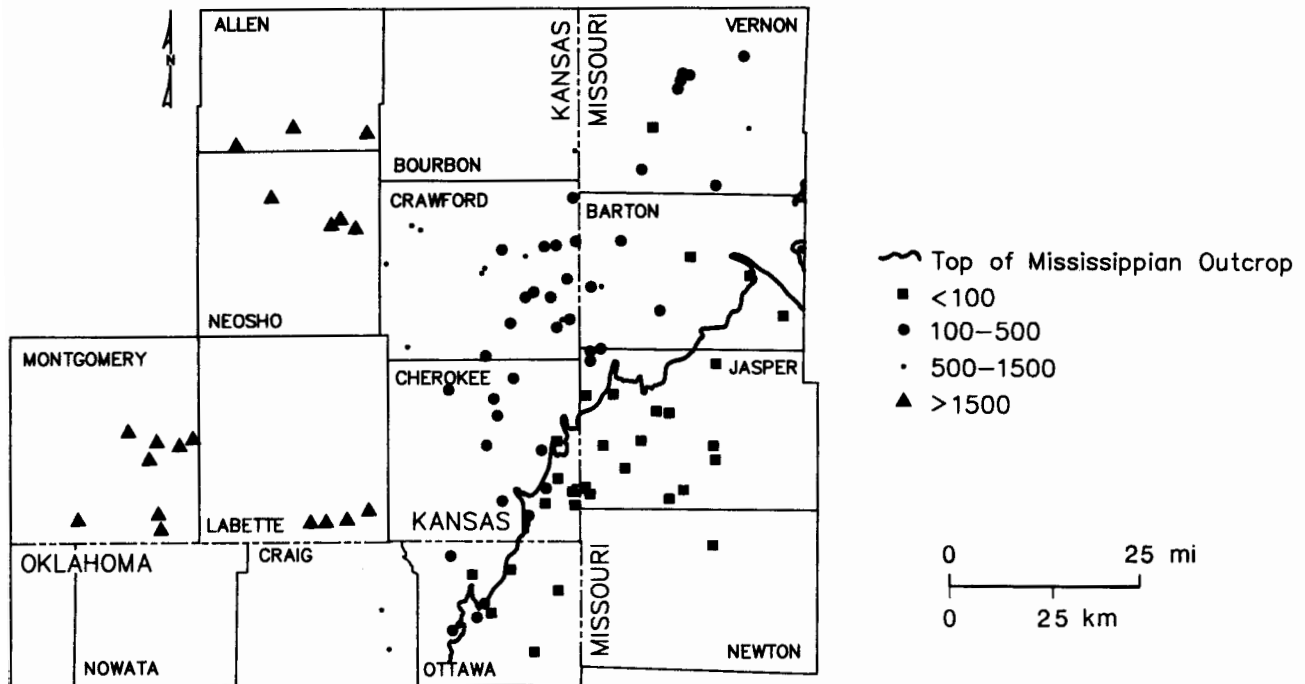


FIGURE 13—BORON CONCENTRATIONS IN GROUND WATERS FROM LOWER PALEOZOIC AQUIFERS IN TRI-STATE REGION.

occurrence of these waters may reflect the products of biological activity on carbonaceous materials within the strata.

The reason for wells in the transition zone being open to Lower Mississippian units is unclear at present. A number of these wells were formerly used in coal-processing operations, and lack of good stratigraphic control or a simple desire for water quantity may have been factors in the placement of well casings in this area.

Sulfide levels in the five Mississippian wells located in the confined portion of the aquifer sampled during the present study had a range of 4.0–13 mg/L. This indicates a reducing environment within that part of the aquifer system. Sulfate levels in the same five wells vary from 16 to 201 mg/L, suggesting that waters from some of these wells may not be in a state of chemical equilibrium but rather represent mixtures of waters of varying chemistries which have been produced by pumpage of the wells. Sulfide levels of less than 0.1 mg/L were found at the two Mississippian well sites located in unconfined portions of the system.

Intrinsic features of the aquifer system such as faults, folding, solution channels, fractures, and areas of silicification may serve to isolate and interconnect water-bearing zones having varied ground-water chemistries. Wells open to Mississippian and Cambrian–Ordovician units exhibit sulfide levels of less than 0.2–8.0 mg/L and sulfate levels of 8–128 mg/L. Here also the higher sulfate and sulfide levels may be found together suggesting a mixing of waters from different sources, but generally this coexistence indicates the presence of a reducing environment.

Ordovician and Cambrian aquifers

In southwest Missouri, northeast Oklahoma, and southeast Kansas, the dolomites and sandstones of Ordovician and Cambrian age serve as important sources of freshwater. Westward into Kansas, these units become saline and supply waters for oil-field water-flooding operations and then become sources for oil and oil-brine production.

Harvey (1980) noted that at West Plains in south-central Missouri, wells into exposed Cambrian–Ordovician units are 1,300–1,500 ft deep and have 950–1,000 ft of casing that is pressure-grouted in place. Yet water from the wells often is turbid after rainstorms. Solution channels in the overlying limestone are clearly making possible the rapid movement of water from the surface down to the Cambrian–Ordovician system at this location. Westward, the dominant constituents in ground water from the Cambrian–Ordovician aquifer system in the region of the Springfield plateau of southwest Missouri are Ca, Mg, and HCO_3 . In areas with dolomitic source rocks, the Ca/Mg ratio, based on milliequivalents per liter, is nearly 1.0. Ratios of 2.0–3.0 for some wells cemented through Mississippian-limestone sequences suggest that slow leakage through exposed limestone units to the underlying Cambrian–Ordovician system is taking place.

Feder's (1979) study of Missouri waters suggests that two end-member water types may be contributing to water quality of Cambrian–Ordovician units in Dade, Barton, Jasper, Newton, and Lawrence counties. One end member

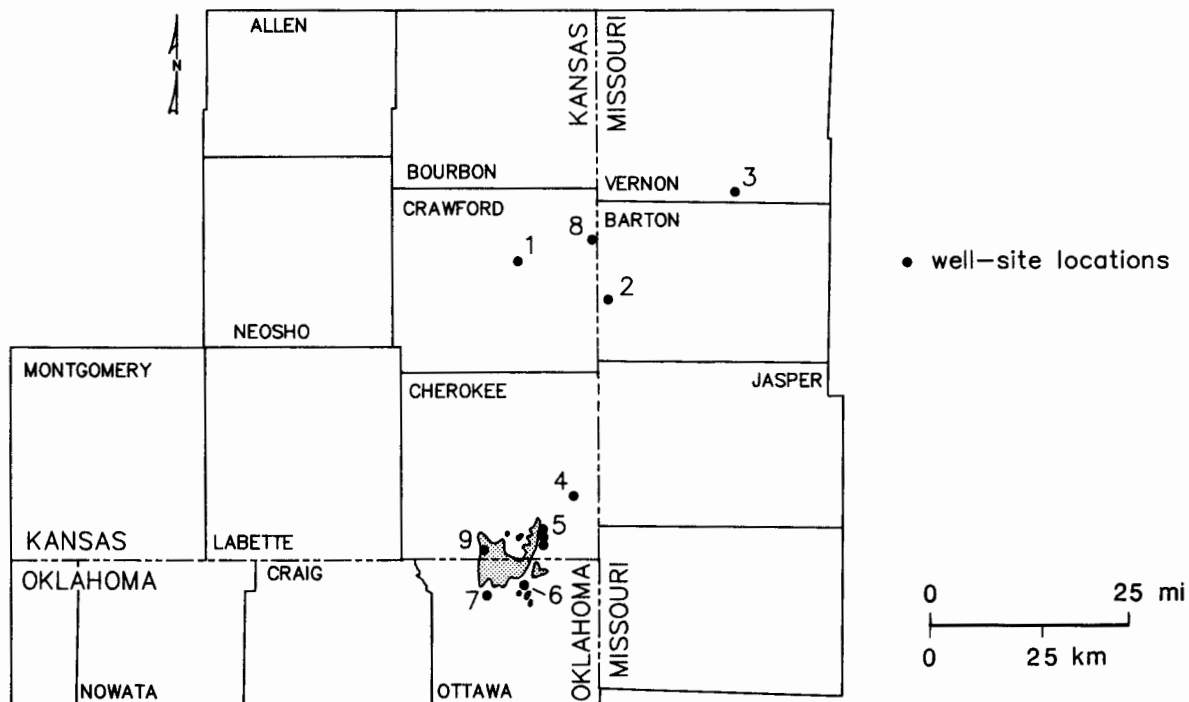


FIGURE 14—GEOGRAPHIC LOCATION OF WELL SITES AND PICHER MINING FIELD IN TRI-STATE REGION: Crawford Rural Water District #7, well #1 (1); Mindenmines, Missouri, city well (2); Sheldon, Missouri, city well #2 (3); Gulf Oil Chemical Corporation well (4); Baxter Springs, Kansas, city wells (5); Quapaw, Oklahoma, city wells (6); Commerce, Oklahoma, city well #3 (7); Clemons Coal, well #1 (8); and Picher mining field (9).

is enriched in Ca, Mg, and HCO₃, and the other represents recharging precipitation. Dissolved-solids levels in waters from this aquifer system ranged from 160 to 459 mg/L and sulfide levels from less than 0.1 to 1.4 mg/L. Northward into Vernon County, Missouri, data from Darr (1978) showed a Na-Cl type classification for a Cambrian-Ordovician well indicating a transition in water chemistry northward from the Ca-Mg-HCO₃ type waters. Dissolved solids and sulfide levels at this well site were 1,022 mg/L and 3.1 mg/L, respectively.

Cambrian-Ordovician wells in Missouri sampled during the present study exhibited a general transition northward from a Ca-HCO₃ classification in Newton and Jasper counties, to a Ca-Mg-HCO₃ to Ca-Mg-Na-HCO₃ classification (shown as mixed in fig. 10) in Barton County, and a Na-Cl classification in Vernon County. Dissolved-solids levels in the HCO₃ type waters ranged from approximately 150 to 525 mg/L. The dissolved-solids level was 824 mg/L in the Na-Cl type water. Westward into Kansas and Oklahoma, the water chemistry of the Cambrian-Ordovician system exhibited a gradation to Na-Cl type waters in Crawford and Cherokee counties, Kansas, and Ottawa County, Oklahoma (fig. 10). This transition was accompanied by a marked increase westward in the dissolved-solids contents of the waters (fig. 11). Macfarlane and others (1981) suggested that chemistries of water samples from Cambrian-Ordovician wells within the Tri-State area can be approximated by mixing different amounts of two general end-member waters, a Ca-Mg-HCO₃ freshwater and a Na-Cl brine.

Milliequivalent per liter (meq/L) Ca/Mg ratios for ground-water samples from the Cambrian-Ordovician aquifer collected during this study typically have values in the range of 1.0-2.0. Three wells in central Jasper County, Missouri, are exceptions with Ca/Mg values near 3, suggesting a greater influence of waters in contact with exposed Mississippian limestones in the area. Ground waters from Cambrian-Ordovician wells generally do not contain HCO₃ in excess of that necessary to satisfy their corresponding Ca and Mg contents. Brines from two oil wells in southern Labette County, Kansas, are exceptions with HCO₃ excesses greater than 6 meq/L. This suggests the possibility of Na-HCO₃ type water influx from the Mississippian aquifer at these sites. In this area the Northview and Chattanooga shales only have a combined thickness of approximately 20 ft (6 m).

Sulfide levels did not exceed 0.2 mg/L for wells east of the Mississippian outcrop. Westward from the outcrop zone, sulfide levels increased to approximately 100 mg/L in oil-field brines of Montgomery County, Kansas. The reducing environment in the Cambrian-Ordovician aquifer, as designated by the presence of sulfide levels greater than 0.2 mg/L, seems to coincide very well with the similar conditions found in the overlying confined Mississippian-aquifer system. Nitrate levels in excess of 2.0 mg/L were not observed for any well where the sulfide level was greater than 0.2 mg/L, again substantiating the presence of a reducing environment in parts of the Mississippian and Cambrian-Ordovician systems within the study area. Sulfate concentrations in waters from Cambrian-Ordovician wells were observed to be low (less than or equal to 20 mg/L), generally in areas east of the Mississippian outcrop, to increase to levels of approximately 20-125 mg/L in the freshwater-brine transition zone, and to decrease again to levels of less than or equal to 20 mg/L in brines from the western portion of the study area. The simultaneous occurrence of sulfide levels of 3-100 mg/L and sulfate levels of 75-1,100 mg/L in many waters from Cambrian-Ordovician wells located west of the Mississippian outcrop suggested that a state of chemical equilibrium may not exist in these samples. Sulfate originally present may be incompletely reduced, or a source within the stratigraphic column may be leaking sulfate to the aquifer system faster than it can be reduced. Otherwise pumpage of the wells may simply produce a disequilibrium blend from waters with different chemistries. Within the brine portion of the aquifer, barium levels tended to vary directly with changes in the sulfide content of the waters. Similarly, Gilkeson and others (1983) found that high barium levels occurred in ground water from confined portions of the Cambrian-Ordovician system in northeastern Illinois where dissolved sulfate was depleted through anaerobic microbial reactions.

Areal displays of ground-water chemical-quality data such as those shown in figs. 10-12 may give the impression that quality only varies laterally. However, the complex nature of the carbonate and sandstone units which make up the Cambrian-Ordovician aquifer system and the regional structural fabric almost insure that chemical-quality variations will exist in the vertical profile of the system as well. General information on vertical changes with depth in chemical quality in the Cambrian-Ordovician aquifer system is available for few sites within the study area. The

TABLE 2—SHORT-TERM CHEMICAL-QUALITY CHANGES ASSOCIATED WITH TWO MULTIAQUIFER WELLS FROM STUDY AREA.

Date	HCO ₃ (mg/L)	Cl (mg/L)	Specific conductance (μ mho at 25°)	Water type
Sheldon, Missouri				
4/17/79	215	133	780	Na-mix.
9/25/79	314	102	870	Na-HCO ₃
5/14/80	210	136	810	Na-Cl
10/8/80	509	36	920	Na-HCO ₃
Mindenmines, Missouri				
4/18/79	327	53	700	Na-HCO ₃
9/25/79	744	39	1,530	Na-HCO ₃
5/12/80	522	54	945	Na-HCO ₃
10/7/80	327	—	700	—

Jayhawk Ordnance well, now located on the Gulf Oil plant site (fig. 14) in southeastern Cherokee County, Kansas, was completed January 1942. Abernathy (1943) presents chemical-quality data for water samples taken from different formation levels during the drilling of the well. These samples were obtained using a bailer and thus may only represent composites from the various units penetrated. The data do suggest a general but erratic increase in chloride and total dissolved-solids levels with depth in the Cambrian-Ordovician system. Chloride data printed on a log dated 1938 for the Clemens Coal Co. well #1 in northeastern Crawford County, Kansas (fig. 14), suggest a decrease in chloride levels with depth in the Cambrian-Ordovician system down into the Roubidoux Formation. Thus, no simple picture of vertical variation in water quality seems to exist within the Tri-State area for the Cambrian-Ordovician aquifer system. Deterioration of quality with depth in the more saline portions of the aquifer in the western half of the study area might be expected.

On a local scale, lateral variations in water quality may be very complex within the Cambrian-Ordovician system. This is best exemplified by the city well field at Baxter Springs, Kansas (fig. 14). Well #5 is about 0.3 mi (0.5 km) north of well #1, and well #6 is about 0.3 mi (0.5 km) north of well #5. All three wells were completed to approximately the same depth and have similar well construction. Samples collected between April 1979 and October 1980 showed well #1 produced a Ca-SO₄ type water with dissolved solids of 480-705 mg/L, well #5 produced a mixed cation-HCO₃ type water with dissolved solids of 240-305 mg/L, and well #6 produced a Na-Cl type water with dissolved solids of 420-605 mg/L. Changes in the dissolved-solids levels at these three wells were reflected in fluctuations of Cl and SO₄ contents of the waters, suggesting that prolonged pumpage of any of the three wells may have induced noticeable changes in water quality. During a 24-hr pump test at well #1 in May 1979, the specific conductance was observed to drop from 1,065 μ mho/cm to 930 μ mho/cm while water temperature and pH remained constant.

Pumpage at Crawford County Rural Water District #7, well #1 (fig. 14), has induced an increase in the sodium and chloride content of the water produced at that site. Between 1972 and 1980, Na levels increased from approximately 270 to 315 mg/L and Cl levels rose 460-525 mg/L. Water from this well remained a Na-Cl type throughout that period of time. Based on the response of water quality to pumpage in the Baxter Springs well field and at Crawford County RWD #7, well #1, an eastward movement of saline waters toward pumping centers is occurring or seems to be a possibility for Cambrian-Ordovician wells located within the region of the eastern edge of the water-quality transition zone.

Local ground-water chemistry, regional transitions in water quality, and changes induced by pumpage may be controlled to a large extent by the complex subsurface geologic structure associated with the Tri-State area. Fig. 5 provides a general picture of water movement for the Cambrian-Ordovician system within the study area. Seemingly, structural features such as the Pittsburg anticline in Kansas and Chesapeake fault in Missouri (fig. 3) should influence water movement, and thus water quality, in the

study area. The presence of the Bourbon arch in Kansas and Missouri may serve as a general barrier in the northern portion of the study area to separate Na-Cl type saline waters to the north of the structure from HCO₃ type freshwaters moving to the north and west from the Ozark uplift.

The low dissolved-solids Na-Cl type waters encountered in northeast Oklahoma indicate dilution of the Cambrian-Ordovician brines by vertical leakage with little flushing or displacement of Na-Cl type waters westward from the Mississippian outcrop. However, lead-zinc mining operations in the Picher field have exposed mineralized zones in the Mississippian to oxidizing conditions which favor conversion of sulfide to sulfate. Sulfate concentrations in the Cambrian-Ordovician aquifer at Quapaw wells #2 and #3 and Commerce well #3 (fig. 14) are elevated relative to the areal background value of about 15 mg/L. Also, the sulfate concentration at these sites increased during the time of this study (table 3). This suggests a local vertical recharge to the Cambrian-Ordovician system, which is enhanced by past mining activities and substantial hydraulic-head differences between the Mississippian and Cambrian-Ordovician aquifer systems.

Distribution of selected members of uranium-238 and thorium-232 decay chains in waters of lower Paleozoic aquifers of Tri-State area

The radioactive isotopes thorium-232, uranium-235, and uranium-238, with half-lives of 1.41×10^{10} yr, 7.04×10^8 yr, and 4.47×10^9 yr, respectively, are long-lived parent isotopes of naturally occurring radioactive-decay chains which are of importance in the areas of geochemistry and environmental health. All three chains undergo a series of alpha and beta decay processes that terminate with the formation of stable lead isotopes. The natural uranium-238/uranium-235 atomic abundance ratio is 137.5/1 and the thorium/uranium mass ratios for whole igneous rocks are approximately 3.5-4.0 (Rogers and Adams, 1978).

Certain members of the thorium-232 and uranium-238 decay chains have received interest in the areas of

TABLE 3—SULFATE CONCENTRATIONS FOR SELECTED WELLS AT QUAPAW AND COMMERCE, OKLAHOMA, APRIL 1979-MAY 1980.

Well	Date	SO ₄ (mg/L)
Quapaw #3	5/80	212
	4/79	44
	9/79	57
Quapaw #2	5/80	70
	9/79	34
	5/80	42
Commerce #3		

hydrology (Osmond and Cowart, 1976; Osmond, 1980; King and others, 1982; Krishnaswami and others, 1982; Gilkeson and others, 1983) and human health (Radioactivity Subcommittee-NAS, 1977; Hess and others, 1979). Fig. 15 depicts partial decay chains for these two parent isotopes.

The radioactivity of an unstable isotope is defined as

$$A = N\lambda = 0.693 (N/t_{1/2})$$

where A is the activity in disintegrations per unit time, N is the number of atoms of the isotope in the system, λ is the decay constant for the isotope, and $t_{1/2}$ is the isotopic half-life. The units used in this report to express the content of many of the radioactive elements are picocuries per liter (pCi/L). A curie is defined as that quantity of a radionuclide in which the number of disintegrations/sec is 3.7×10^{10} . A picocurie (pCi) is equal to 1×10^{-12} curies or 2.22 disintegrations/min. In a closed system the activity of a radioactive daughter (A_d) equals that of the radioactive parent (A_p) if a state of secular equilibrium exists. This state is possible if

$$\lambda_p \ll \lambda_d (t_{1/2(p)} \gg t_{1/2(d)})$$

and the system has reached sufficient maturity. However, at or near the earth's surface the activity ratio A_d/A_p often has a value other than 1.00, indicating that disequilibrium exists within the decay series.

Uranium, thorium, radium, and radon tend to fractionate in the hydrogeological environment because of differences in chemical behavior. Uranium is mobilized in an oxidizing aqueous environment through interactions of carbonate, sulfate, or phosphate ions with hexavalent uranium which produce soluble complex species. In reducing environments, represented in this study by ground waters containing sulfide ions, uranium is reduced to the relatively immobile tetravalent state and precipitated within the aquifer system. Mobility of tetravalent thorium is very

limited under almost all near-surface hydrogeochemical environments. Under oxidizing ground-water conditions the solubility of divalent radium seems to be controlled largely by adsorption-desorption processes with the aquifer materials. Radium levels of these waters are generally well below those expected from solubility considerations based on the relatively insoluble RaSO_4 . Gilkeson and others (1983) have suggested that co-precipitation of radium in the deposition of BaSO_4 may be an important control upon radium concentrations in ground waters. Under reducing conditions where sulfate ions are converted to sulfide ions, and with increasing salinity of the ground-water, radium is desorbed and remobilized. Marikos (1981) noted that in Missouri, elevated radium-226 levels from the uranium-238 decay chain may be associated with high dissolved solids in ground water and the existence of surface or subsurface faults. On the other hand, anomalously high radium-228 and radon-222 activities from the thorium-232 decay chain were found in samples from heavily faulted areas.

Activities of radium-226 in ground waters from the Tri-State area in excess of the present maximum contaminant level of 5 pCi/L for radium, as set by U.S. Environmental Protection Agency (EPA), have been reported. Scott and Barker (1962) in a survey of data for uranium and radium in ground waters of the United States for 1954-57 list a value of 8.9 pCi/L of radium-226 for the old well at Girard, Kansas (Crawford County). Hobart (1976) cites a mean value of 11.2 pCi/L for radium-226, based on monthly samplings in 1975, for the Afton, Oklahoma (Ottawa County), water-supply system. A direct correlation between radium-226 and total dissolved solids was observed for this site. Spiker and others (1979) reported that in 1977 and 1978, seven of the 28 public-water supplies sampled in Cherokee and Crawford counties had radium-226 levels which at times exceeded a 5 pCi/L

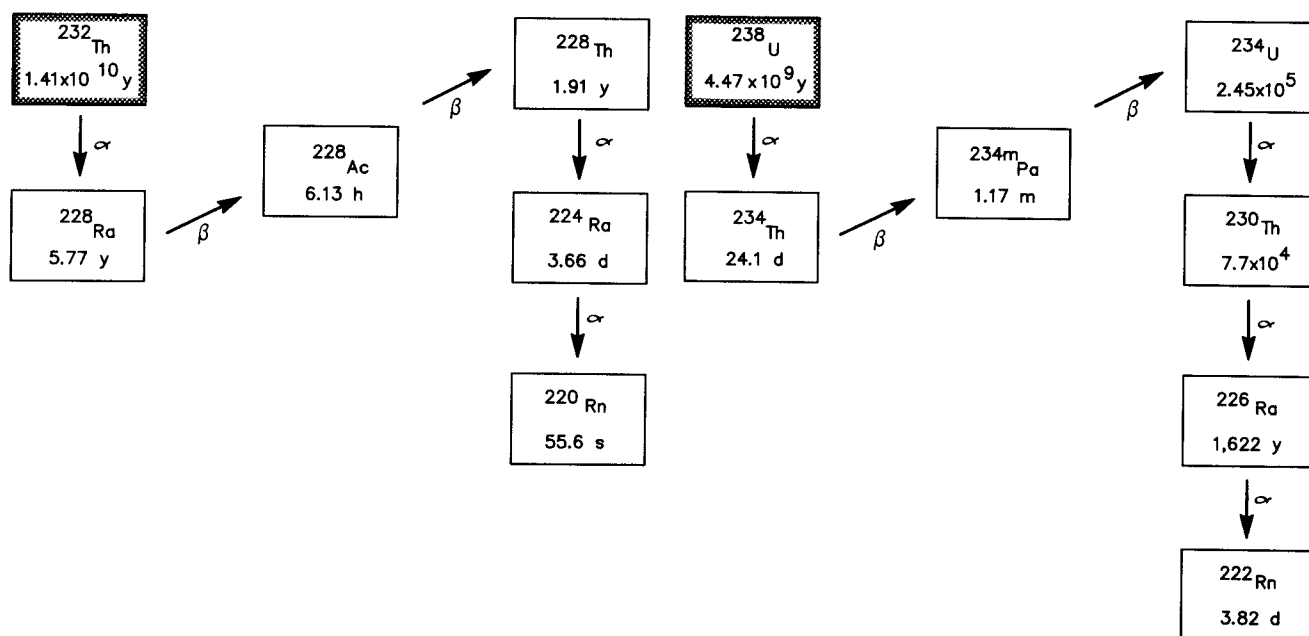


FIGURE 15—PARTIAL RADIOACTIVE-DECAY CHAINS FOR THORIUM-232 AND URANIUM-238 SHOWING HALF-LIVES IN YEARS (Y), DAYS (D), OR HOURS (H) AND MODES, α — OR β — DECAY.

level. They also found that high radium-226 levels tended to correlate with increased chloride contents of the waters.

From 1979 through 1981, water samples were collected for radionuclide analyses at 80 sites in the study area to obtain more detailed information regarding radium-226 in ground waters. Activities of radium-226 were determined in samples from all sites. Total uranium and uranium-234/uranium-238 activity-ratio measurements were made on samples from 35 sites. In addition, values of radium-228 activity were determined for samples from eight sites in the western half of the study area (Montgomery, Neosho, Allen, and Crawford counties in Kansas) which represent Cambrian-Ordovician oil wells or oil-field water-supply wells.

Fig. 16 is an areal display of radium-226 data collected during the course of this investigation. Activities of radium-226 within the freshwater portion of the study area are generally less than 2 pCi/L, levels within the chemical-quality transition zone range from less than 2-9 pCi/L, and radium-226 levels in wells from the brine portion of the study area range upward to 1,600 pCi/L. Overall, radium-226 values greater than 2 pCi/L tend to be associated with the presence of reducing conditions and increased concentrations of dissolved solids. Spiker and others (1979) have suggested that Kansas public-supply wells located within the region of the transition zone in Cherokee and Crawford counties may exhibit elevated radium levels as a result of downward leakage of water from Mississippian units. However, radium-226 values in samples from the three wells in the Mississippian aquifer range only from 0.8 to 3.6 pCi/L. These waters would not be capable of producing the elevated levels noted.

Fluctuations in radium-226 activity with time in samples of water from two multiaquifer wells located within the transition zone were evaluated by analysis of ten

samples collected on approximately a monthly basis from April 1979 to April 1980 at two sites. Average values of 2.2 ± 0.2 pCi/L for Mindenmines, Missouri (Mississippian-Cambrian-Ordovician well), and 7.2 ± 0.5 pCi/L for Crawford County Rural Water District #7, well #1 (uppermost Lower Ordovician well), Kansas, indicated limited variation in the radium-226 levels for these types of wells. This is in contrast to wide fluctuations in basic water chemistry noted at the Mindenmines well (see table 2) and only small fluctuations at the rural-water-district well during the same period of time.

The three Cambrian-Ordovician wells of the Baxter Springs, Kansas, municipal well field seem to be located just inside the freshwater, non-reducing side of the freshwater transition-zone boundary (figs. 14 and 9). Radium-226 values of 1.8, 2.3, and 12 pCi/L were observed for samples collected in 1980 from wells #1, #5, and #6, respectively. This trend in the radium level does not correlate with total dissolved-solids contents of the waters (701, 303, and 605 mg/L, respectively) but does vary inversely with sulfate (315, 58, and 22 mg/L, respectively). Additionally, the highest radium level found in well #6 is associated with a Na-Cl type water and a chloride value which is about five times greater than the levels found at wells #1 and #5. This suggests a pumpage-induced eastward movement of saline water toward well #6; local hydrologic conditions producing a back flushing through sediments containing precipitated uranium at sites near or within the transition zone may be very important in determining radium-226 values encountered in waters produced by individual wells.

The direct relationship between radium-226 values greater than 2 pCi/L and sulfide levels greater than 0.2 mg/L depicted in fig. 16 suggests that the increase in radium-226 activities from the freshwater side into the

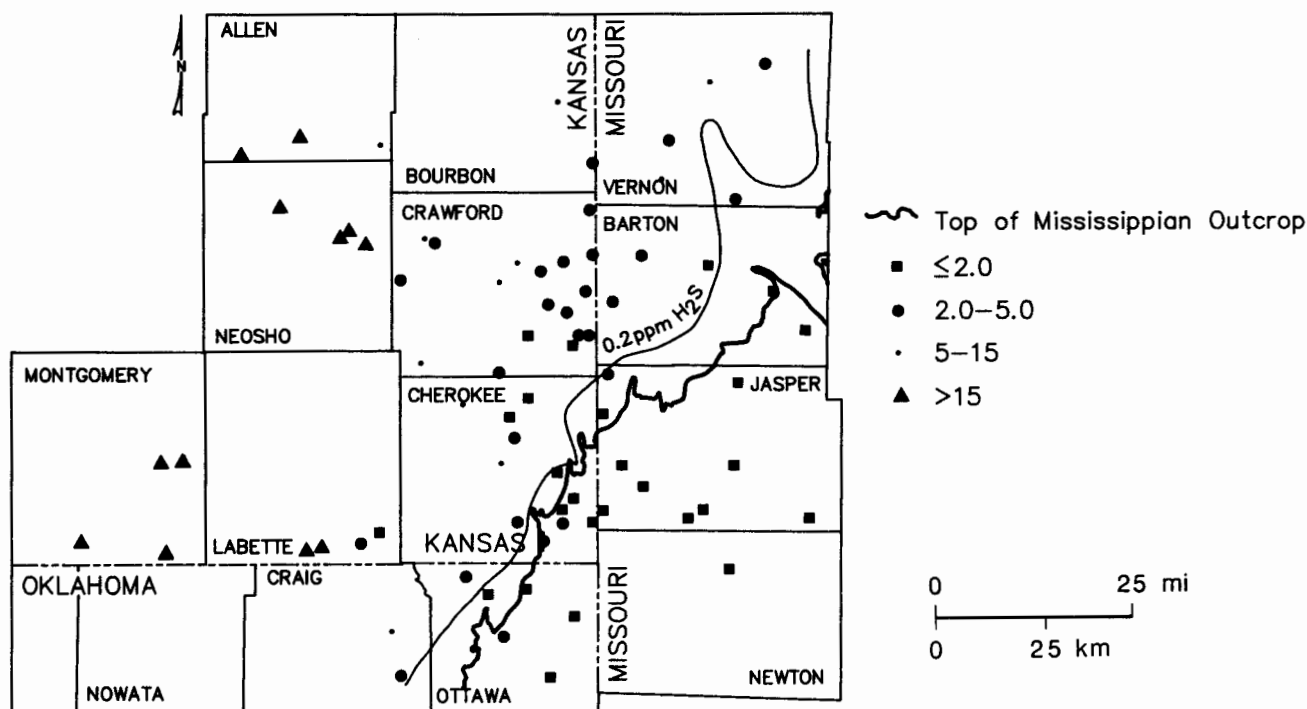


FIGURE 16—RADIUM-226 DISTRIBUTION IN GROUND WATERS FROM LOWER PALEOZOIC AQUIFERS IN TRI-STATE REGION.

transition zone may reflect long-term cumulative effects of the reduction and deposition of uranium carried by invading freshwaters from the southeastern portion of the study area. Variations in the concentrations of sulfide, total dissolved solids, and uranium-238 decay-chain radionuclide data for selected Cambrian-Ordovician wells are summarized in figs. 17 and 18.

These two figures (17 and 18) show that the concentration of uranium declines and radium-226 activities begin to increase near the eastern boundary of the transition zone as freshwaters encounter sulfide-bearing waters of the transition zone. Radium-226 activities in the two traverses vary directly with concentrations of sulfide and total dissolved solids. The sulfide concentration reported at site A may be too low due to sampling difficulties and subsequent loss of H₂S. The uranium-234/uranium-238 activity ratios exhibit relatively little variation and are anomalously high (7-11) from the freshwater portion of the study area westward and northwestward far into the transition zone. Szabo (1982) found similar uranium-activity ratios in springs of the Pomme de Terre Valley of southwestern Missouri. In the more saline regions of the study area west of the transition zone, the uranium-234/uranium-238 activity ratios range from 1.5 to 4.0. The differing ranges of uranium-activity ratios suggest two different sources of uranium in ground waters of the study area and the possible eastward migration in recent geologic time of the reducing environment. Deposition of uranium with a high activity ratio along the eastern edge of the transition zone would enhance the potential for radium-226 production. This conclusion is consistent with the observation that radium-226/uranium-234 activity ratios are near equilibrium with values of about 1.0 in the freshwaters but become greater than 1.0 as sulfide levels become greater than 0.2 mg/L (Hathaway and Macfarlane,

1980). However, the high radium-226 levels and low uranium-activity ratios found in ground waters west of the transition zone indicate that a different source for radium-226 probably exists in the western portion of the study area.

Radium-228, unlike radium-226, is not expected to migrate very far within a slow-moving, confined-aquifer system because of its relatively short half-life. Radium-226/radium-228 activity ratios of 0.7-0.9 are to be expected in hydrogeologic systems at equilibrium with materials containing crustal thorium/uranium mass ratios of 3.5-4.5. Radium-228 activities in southeastern Allen and northwestern Crawford counties in Kansas are in the range of 2.0-3.0 pCi/L, and radium-226/radium-228 activity ratios at the corresponding well locations are in the 2.4-2.6 range. To the southwest in Montgomery County, Kansas, the radium-228 levels rise to values of 20-74 pCi/L, and the radium-226/radium-228 activity ratio increases to values of 11-13. Gilkeson and others (1983) found in Illinois that confined sandstone aquifers of the Cambrian-Ordovician system contribute waters with the highest radium concentrations. They also noted that high radium-226 activities were related to the presence of highly mineralized ground water, but that radium-228 activities seem to be unrelated to the ionic strength of the solution. Feldspar grains within the matrix of the aquifer are suggested as the source for radium-228. The limited data, poor spatial distribution, and lack of information regarding uranium/thorium ratios in materials from the Precambrian basement or Cambrian-Ordovician system make it difficult at present to evaluate the significance of the radium-228 data to an understanding of the hydrogeochemistry of the Tri-State area. Another major problem in the interpretation of radium activity in the lower Paleozoic aquifers of the study

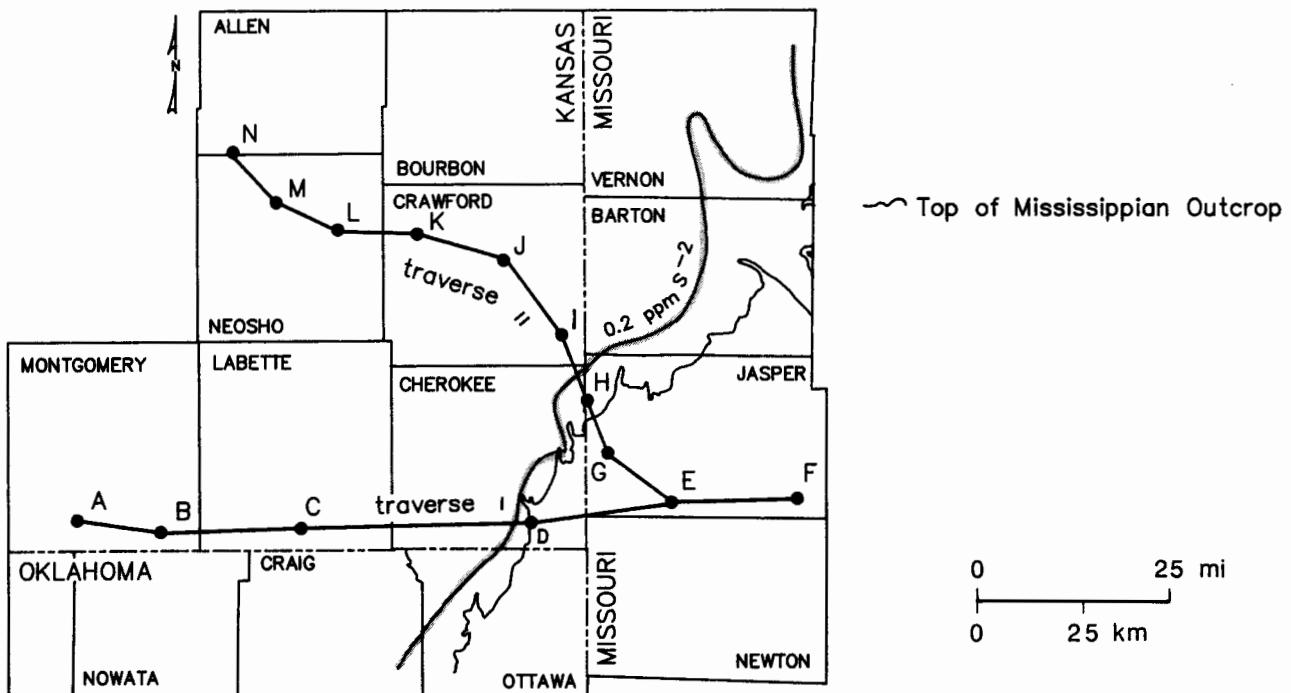


FIGURE 17—LOCATION OF WELLS ALONG TWO TRAVERSE LINES SAMPLED FOR SELECTED RADIONUCLIDES.

area is the lack of specific knowledge of the precise source of the sampled water. The limited availability of well-construction information for the older wells, coupled with

long, open bore-hole sections in most of the wells, prohibits precise definition of water sources for most of the wells.

Summary and conclusions

Ground water is available throughout the lower Paleozoic stratigraphic section in varying amounts depending on the lithology of the aquifer and the development of secondary permeability in the carbonate rocks. The rocks that comprise the framework of these aquifers show evidence that they have undergone changes induced by solution and tectonic activity 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 ground water are available from the undifferentiated Mississippian rocks as compared with Cambrian-Ordovician strata. Typical well yields to be expected from the Mississippian range from 10 to 100 gpm (1.3 to 13.4 ft³/min), whereas typical well yields from the Cambrian-Ordovician are in the range of 100-750 gpm (13.4-100 ft³/min).

Ground water flows through these aquifers in a westerly direction in the Tri-State area away from recharge areas in the Ozark region of southern Missouri where the Lower Paleozoic rocks crop out. Locally the movement of ground water in these aquifers is influenced by pumping centers. Ground-water withdrawal from pumping wells has produced large cones of depression in the Miami, Oklahoma-Baxter Springs, Kansas, and in the Pittsburg, Kansas, areas. In some areas static water-level declines in excess of 450 ft (135 m) have been recorded since pumping began. Static water-level declines are generally less than 50 ft (15 m) over most of the area.

Ground-water chemical quality in the lower Paleozoic aquifers varies widely across the region reflecting a change from fresh to saline conditions. The mixing of fresh and saline waters is regionally a simple process but may be more complex locally due to chemical interactions and the influence of geologic structure. Ground waters from the confined portion of the Mississippian aquifer were Na-Cl or Na-HCO₃ type and contained sulfide; samples from the unconfined portion were a Ca-HCO₃ type water. The ground waters in the freshwater portion of the Cambrian-Ordovician aquifer generally fell into a Ca-HCO₃ classification. Ground water from the saline portion of the aquifer was sodium-chloride brines which may contain up to 100 mg/L sulfide. Chloride and total dissolved-solids levels increased in a westerly direction across a wide northeast-southwest-trending chemical-quality transition zone separating the fresh and saline portions of the Cambrian-Ordovician aquifer system. Waters in the Cambrian-Ordovician system westward of the Mississippian outcrop contained sulfide concentrations greater than 0.2 mg/L, as was noted for the overlying confined Mississippian system. The presence of sulfide in the aquifers indicated a reducing hydrogeochemical environment.

Some changes in ground-water chemical quality with time were documented during this study. A number of the multiaquifer wells showed significant changes in ground-water chemical quality during the sampling period. Na-HCO₃ type waters from Mississippian aquifers seem to

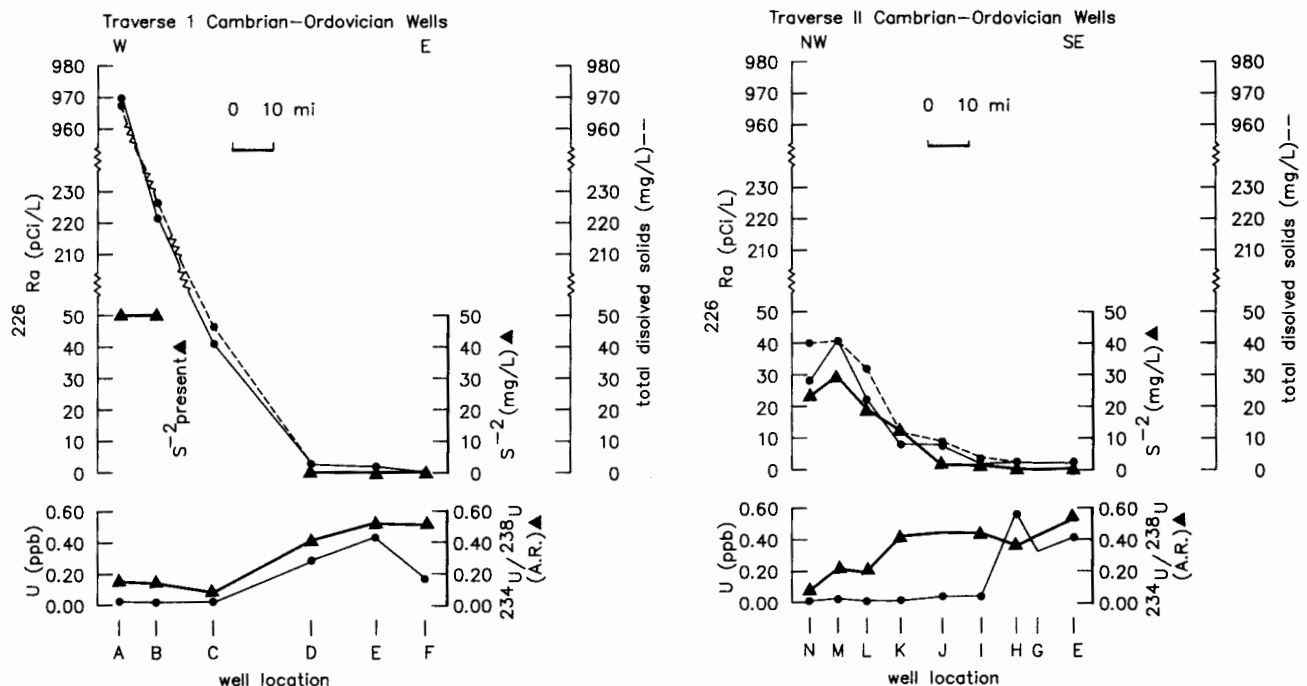


FIGURE 18—RADIUM-226 ACTIVITY, URANIUM CONCENTRATION, URANIUM-234/URANIUM-238 ACTIVITY RATIO, TOTAL DISSOLVED SOLIDS, AND SULFIDE CONCENTRATION VARIATIONS ALONG TWO TRAVERSES ACROSS TRI-STATE REGION SHOWN IN FIG. 16.

make significant and variable contributions to the total water chemistry of several wells open to both the Mississippian and Cambrian–Ordovician aquifer systems. These findings confirm the results of previous investigations in the area. Ground-water chemical-quality changes over time also were noted for two Cambrian–Ordovician wells in the study area.

The distribution of radium-226, uranium, and uranium-234/uranium-238 activity ratios in waters from the lower Paleozoic aquifers is consistent with the freshwater-transition zone and saline hydrogeochemical partitioning of the aquifer. The freshwater portion generally represents an oxidizing environment; whereas, the transition zone and saline portion, with sulfide-bearing waters, are reducing environments. Radium-226 activity is generally less than 2 pCi/L and uranium-activity ratios are anomalously high in the freshwater portion of the aquifer. In the eastern portion of the transition zone, the uranium-activity ratios remain

anomalously high and the radium-226 activity ranges from 2 to 9 pCi/L. In the saline portion of the aquifer, uranium-activity ratios decrease and radium-226 activity ranges upward to 1,600 pCi/L in some of the oil-field brines. Uranium concentrations in the freshwater region are more than two orders of magnitude higher than they are in the saline portion of the Cambrian–Ordovician aquifer. Radium-226 activities range from 0.8 to 3.6 pCi/L for a series of samples collected from wells open only to the Mississippian. These findings suggest that the source of radium-226 in the Cambrian–Ordovician aquifers is not from water leakage from the Mississippian. Furthermore, an eastward movement of the reducing environment in recent geologic time is suggested from the distributions of the various radionuclide data. The distribution of radium-228 is difficult to interpret because of the small number of sample sites and their location.

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Appendices

APPENDIX 1

Listing of the stratigraphic data points; all depths, thicknesses, and elevations are in units of feet, surface = at the surface.

Well location	Surface elevation	Total depth	Depth to top of Mississippian	Combined thickness, Northview, Compton, Chattanooga shales	Depth to top of Ordovician
Allen County, Kansas					
24S-18E-26	995?	2,180?	1,040	—	1,268
24S-21E-34aaa	1,060	1,407	822	103	1,125
26S-21E-29daa	1,057	1,640	864	88	1,238
26S-18E-34cca	930	1,500	1,021	—	1,268 ?
Bourbon County, Kansas					
24S-25E-20acc	860	1,053	428	98	848
25S-24E-36aac	912	1,400	455	105	620
26S-24E-6bdd	825	1,508	450	—	700
26S-24E-16dca	933	2,403	490	80	915
26S-25E-8ccb	932	—	—	—	800
27S-25E-1caa	846	1,010	300	30	750
Cherokee County, Kansas					
31S-22E-30add	860	1,862	245	12	444
32S-23E-5ddd	894	1,014	348	15	725
32S-23E-6daa	910	1,284	380	15	700
32S-24E-29bbb	910	1,100	210	25	545
32S-25E-24caa	872	955	—	5	430
32S-25E-31aaa	892	564	105	15	450
32S-25E-35dbc	885	327	170	5	325
33S-21E-13caa	810	1,927	404	5	763
33S-23E-13aba	890	1,778	207	0	560
33S-23E-17dcb	897	1,862	310	0	685
33S-25E-9ddc	880	1,016	—	6	426
33S-25E-18daa	870	900	76	12	382
34S-24E-17dcd	854	1,050	160	10	520
34S-24E-29cbc	846	1,005	surface	3	368
34S-24E-36caa	832	1,094	surface	5	385
34S-24E-36bba	820	1,175	surface	0	350
34S-25E-3cdc	812	304	surface	0	257
34S-25E-4aac	854	897	surface	10	315
34S-25E-8cbc	850	920	surface	5	331
34S-25E-13bbb	896	870	surface	10	260
34S-25E-13ccc	955	1,260	surface	10	335
34S-25E-13ccc	960	1,177	surface	2	312
35S-23E-5dcc	830	1,053	—	10	520
35S-23E-11cab	841	1,685	120	10	437
35S-23E-12aad	859	1,660	439	10	817
35S-23E-12aa	865	693	308	0	675
35S-23E-14aab	840	1,798	155	10	500
35S-24E-7cdc	850	1,195	—	10	490
35S-24E-10aca	863	950	—	0	455
35S-24E-10aac	850	1,125	—	3	435

Well location	Surface elevation	Total depth	Depth to top of Mississippian	Combined thickness, Northview, Compton, Chattanooga shales	Depth to top of Ordovician
Crawford County, Kansas					
28S-22E-8bca	965	1,123	709	25	1,057
28S-22E-20ccd	907	1,015	615	27	916
28S-22E-27cad	945	1,005	598	—	910
28S-22E-28bcc	920	964	640	31	940
28S-23E-10bdd	1,005	951	572	41	901
28S-23E-22bdb	995	1,401	550	63	933
28S-24E-1add	885	912	340	50	620
28S-25E-20bdd	911	1,862	350	60	725
28S-25E-24ccc	907	939	250	80	585
29S-21E-10bba	915	1,044	422	29	987
29S-21E-14ddd	942	1,095	—	33	1,013
29S-23E-24acd1	990	900	444	16	742
29S-23E-24acd2	990	1,186	465	40?	775
29S-24E-5ddc	970	1,012	437	52	802
29S-24E-11daa	996	1,145	435	25?	815
29S-25E-4dda	908	986	348	20	725
29S-25E-5cdd	1,020	1,177	455	45	815
29S-25E-22add	962	938	310	—	710
29S-25E-26cbc	982	940	300	45	685
30S-22E-7bdb	885	1,000	500	20	925
30S-22E-19ccc	928	930	536	22	867
30S-22E-20bbb	924	955	560	19	890
30S-22E-30add	905	895	497	11	830
30S-22E-31cbb	890	912	502	19	851
30S-23E-8caa	920	910	480	25	838
30S-24E-2ddd	947	1,113	385	50	665
30S-24E-21ada	915	1,165	360	35	720
30S-25E-10acc	938	990	350	32	727
30S-25E-19ddc	940	1,233	240	45	600
30S-25E-20abd	939	1,400	219	38	560
30S-25E-23ccd	925	1,045	105	40	430
30S-25E-28daa	905	1,050	145	35	500
31S-21E-1daa	890	913	495	16	830
31S-22E-6ddc	893	890	500	15	835
31S-22E-7bbb	895	910	488	17	836
31S-22E-8ddc	920	1,307	490	20	835
31S-22E-23cbd	860	1,036	356	7	697
31S-22E-30add	860	1,862	245	12	444
31S-24E-18dbd	927	950	354	20	728
Labette County, Kansas					
31S-17E-11acc	885	1,265	964	29	1,255
31S-20E-23cbd	905	1,100	587	17	905
31S-20E-22cca	933	1,810	662	10	910
31S-21E-17daa	856	1,892	500	31	844
32S-17E-23dad	840	1,277	942	38	1,261
32S-17E-36cdd	910	1,346	991	46	1,334
32S-18E-18dbc	800	1,233	912	53	1,227
32S-19E-22abb	905	1,430	755	25	1,045
32S-21E-6cdd	870	896	560	17	866
33S-17E-1bbb	894	1,350	991	32	1,314
33S-17E-7ada	780	1,665	894	43	1,231
33S-18E-7aad	840	1,665	893	36	1,320
33S-18E-7cab	810	1,801	882	49	1,250
33S-18E-36cbb	860	1,163	818	31	1,163
33S-19E-11aab	918	1,269	756	24	1,113
33S-19E-17cdb	890	1,106	744	42	1,100
33S-20E-17cdc	895	1,013	660	23	984
34S-17E-36bbb	764	1,229	825	67	1,217
34S-18E-35adc	940	1,145	792	40	1,141
34S-20E-9aca	880	918	552	26	916
34S-20E-36ddb	935	845	490	25	845

Well location	Surface elevation	Total depth	Depth to top of Mississippian	Combined thickness, Northview, Compton, Chattanooga shales	Depth to top of Ordovician
Labette County, Kansas					
34S-21E-35cbb	810	1,248	410	—	720
35S-19E-1bdb	905	1,351	—	40	948
35S-20E-6baa	907	968	602	35	966
Montgomery County, Kansas					
31S-14E-5cdd	960	1,775	1,445	35	1,735
31S-14E-18abc	925	2,202	1,399	40	1,746
31S-14E-23bbb	909	1,802	1,404	24	1,724
31S-14E-26ccb	916	1,746	1,396	—	1,702
31S-14E-27ccd	895	1,860	1,424	46	1,752
31S-14E-31bdd	910	1,769	1,416	32	1,735
31S-15E-3dac	880	1,466	1,200	30	1,446
31S-15E-9abd	871	1,535	1,192	—	1,522
31S-15E-10aac	853	1,381	1,097	21	1,372
31S-15E-10aad	848	1,383	1,098	17	1,370
31S-15E-12aab	949	1,580	1,266	24	1,543
31S-15E-21cdc	870	1,811	1,210	35	1,525
31S-15E-21cab	824	1,448	1,144	34	1,445
31S-15E-21cdb	838	1,462	1,151	35	1,460
31S-16E-11cdd	919	1,876	1,135	11	1,444
31S-16E-12bda	870	2,358	1,122	—	1,416
31S-16E-19ddc	830	1,383	1,063	19	1,369
31S-17E-11acc	885	1,265	964	29	1,258
31S-17E-19ccc	940	1,478	1,001	30	1,280
32S-14E-8cdb	845	1,753	1,425	40	1,735
32S-14E-23baa	823	2,487	1,334	30	1,640
32S-14E-28dcb	850	1,616	1,354	24	1,616
32S-14E-30caa	845	1,762	1,436	34	1,722
32S-14E-33acb	885	1,830	1,411	28	1,678
32S-14E-33dbb	934	1,837	1,439	—	1,701
32S-15E-5bcc	815	1,599	1,271	27	1,599
32S-15E-21bac	808	1,590	1,225	36	1,572
32S-15E-34acd	800	1,856	1,185	37	1,545
32S-17E-4cbb	830	1,183	846	43	1,183
32S-17E-20adc	872	1,322	994	27	1,319
32S-17E-29bac	840	1,340	1,010	36	1,322
33S-14E-21add	890	1,810	1,442	42	1,736
33S-14E-25ccd	925	1,760	1,430	51	1,724
33S-15E-2add	810	2,102	1,555	50	1,934
33S-15E-7ccc	855	2,555	1,360	39	1,695
33S-15E-25acc	856	1,975	1,335	49	1,670
33S-15E-32bcd	785	2,555	1,360	37	1,695
33S-16E-1acc	860	1,450	1,102	42	1,450
33S-16E-2abc	750	1,360	1,012	64	1,360
33S-16E-3dcb	820	1,467	1,080	53	67(?)
33S-16E-5acb	795	1,354	1,012	32	1,323
33S-16E-11dda	750	1,280	945	57	1,277
33S-16E-12cca	860	1,336	998	69	1,334
33S-16E-23bdb	823	1,400	1,046	53	1,381
33S-17E-3cbd	790	1,227	900	38	1,225
33S-17E-4dbb1	770	1,513	889	44	1,157
33S-17E-4dbb2	770	1,562	829	42	1,159
33S-17E-8ddb	768	1,268	920	48	1,262
33S-17E-33aba	750	2,160	850	—	1,205
33S-17E-33abd	750	—	922	42	1,277
34S-14E-5ddb	830	2,212	1,477	11	1,750
34S-16E-34acc	743	2,427	1,050	65	1,367
35S-13E-11dca	731	2,837	1,531	51	1,862

Well location	Surface elevation	Total depth	Depth to top of Mississippian	Combined thickness, Northview, Compton, Chattanooga shales	Depth to top of Ordovician
Neosho County, Kansas					
28S-19E-4bbd	895	1,448	869	40	1,140
28S-20E-22ccc	900	2,004	695	40	1,005
28S-21E-29abc	890	1,460	712	—	960
29S-18E-18aaa	1,005	1,154	800	50	1,147
29S-20E-13ddc	890	1,010	670	28	975
29S-21E-10bbb	915	1,044	422	29	1,037
30S-18E-34cbd	953	2,240	993	15	1,295
30S-19E-20ccc	946	1,250	940	38	1,248
30S-21E-30bbd	850	794	592	22	922
Barton County, Missouri					
30N-33W-1ccc	888	1,810	28	—	395
31N-29W-20aab	1,148	900	surface	47	245
31N-29W-26cdd	1,060	893	surface	58	348
31N-29W-35cab	1,063	1,100	surface	56	342
31N-32W-6cbc	964	1,050	155	40	520
31N-32W-21cbc	950	1,100	141	40	490
31N-32W-22aaa	1,000	900	—	55	505
31N-32W-30dca	924	696	100	30	495
31N-32W-30dcb	910	1,125	110	—	495
31N-33W-5bbd	966	910	250	50	635
31N-33W-20acc	955	1,055	210	48	588
31N-33W-30dad	950	1,100	225	41	620
32N-30W-27add	1,040	940	82	55	415
32N-30W-29dbb	975	981	150	60	560
32N-31W-17aaa	996	900	137	75	485
32N-31W-28cac	961	1,020	157	57	550
32N-32W-33ccc	997	1,450	185	50	525
32N-33W-2aca	904	817	160	65	480
32N-33W-2acd	902	825	165	55	470
Jasper County, Missouri					
27N-29W-8cad	1,172	1,258	surface	20	390
27N-29W-17bbc	1,180	1,059	surface	25	400
27N-30W-8dcc	1,079	1,262	surface	15	365
27N-31W-15bbc	1,124	815	surface	12	342
27N-32W-1bbc	980	1,402	surface	10	285
27N-32W-3cbc	1,077	935	surface	—	350
27N-32W-3ccb	1,086	500	surface	8	412
27N-32W-10bdd	1,067	1,228	surface	20	330
27N-34W-2bdd	930	1,415	surface	3	255
27N-34W-2bcc	920	1,500	surface	3	262
27N-34W-12caa	1,007	920	surface	0	255
27N-31W-3caa	955	1,854	surface	17	385
28N-31W-5caa	1,007	1,250	surface	15	425
28N-31W-10ddd	1,038	745	surface	5	395
28N-32W-2cac	1,020	1,520	surface	15	400
28N-32W-13acb	980	1,230	surface	10	380
28N-32W-28dbd	1,075	—	surface	15	425
28N-32W-34aca	1,042	944	surface	1	350
28N-32W-36bac	1,028	1,402	surface	10	335
28N-33W-5ccd	913	1,502	surface	15	380
28N-33W-13aaa	971	1,470	surface	5	405
28N-33W-13dda	979	930	surface	15	390
28N-33W-15dcd	970	925	surface	10	380
28N-33W-36bac	960	1,200	surface	10	315
28N-33W-34bdd	1,008	896	—	10	290
29N-31W-11ccc	1,011	958	surface	20	435
29N-32W-15bdb	965	1,100	surface	20	400
29N-33W-4ccc	872	1,225	15	25	360
29N-33W-36dac	975	1,335	surface	5	394
29N-34W-2ddc	900	925	80	20	450
30N-29W-27daa	1,040	1,240	surface	24	419
30N-30W-35dcc	1,022	415	surface	42	382

Well location	Surface elevation	Total depth	Depth to top of Mississippian	Combined thickness, Northview, Compton, Chattanooga shales	Depth to top of Ordovician
Jasper County, Missouri					
30N-31W-24ccc	948	1,505	surface	25	350
30N-33W-17cca	961	970	95	30	430
30N-33W-17bab	936	1,035	130	35	525
30N-33W-17cba	955	1,000	98	25	430
30N-33W-17bda	942	942	98	30	445
30N-33W-28dca	913	590	35	25	385
Newton County, Missouri					
24N-32W-4ccd	1,190	1,450	surface	45	400
24N-34W-8aaa	846	1,260	surface	26	266
25N-32W-13dab	1,008	1,200	surface	10	195
25N-32W-13ddd	997	1,180	surface	10	185
25N-34W-35aaa	1,004	1,435	surface	20	385
25N-34W-35dbc	978	1,279	surface	21	386
25N-34W-35dab	882	822	surface	25	270
26N-31W-7ddb	1,070	852	surface	10	365
26N-31W-10bbb	1,180	1,250	surface	35	290
26N-32W-6bac	1,033	905	surface	5	325
26N-32W-35cbc	1,126	465	surface	20	400
26N-33W-6cac	1,082	700	surface	—	305
26N-33W-9bbd	1,135	464	surface	10	345
26N-33W-32dcd	1,128	378	surface	25	370
26N-33W-ccd	1,132	370	surface	5	360
26N-33W-34ccc	1,163	400	surface	5	385
27N-33W-3ddd	996	1,300	surface	10	380
27N-33W-34daa	915	710	surface	0	100
Vernon County, Missouri					
34N-31W-23dad	917	920	200	112	650
34N-31W-35acc	922	930	165	85	600
34N-31W-35aad	922	930	180	79	604
34N-31W-35abd	915	850	180	89	611
34N-32W-5ada	868	785	210	120	650
34N-32W-20baa	910	853	245	98	670
35N-31W-5caa	864	1,100	135	80	515
35N-31W-5bad	842	1,095	110	78	492
35N-31W-13aab	889	1,050	185	80	575
35N-31W-22bbc	835	530	104	—	515
36N-30W-15bcc	855	840	220	75	620
36N-31W-21aac	816	1,100	135	65	525
36N-31W-33bbc	846	1,100	—	80	530
36N-32W-6aad	795	1,520	200	95	575
36N-33W-22add	810	775	130	80	612
36N-33W-22baa	769	875	—	95	684
Craig County, Oklahoma					
27N-21E-20ddc	830	1,043	245	35	625
29N-18E-18aaa	950	1,170	800	55	1,150
Ottawa County, Oklahoma					
26N-22E-15ddd	805	1,110	surface	45	415
26N-23E-9abb	825	1,250	surface	37	410
27N-22E-1ccc	820	1,426	55	18	490
27N-23E-7bdb	850	1,055	surface	35	460
27N-24E-8bdb	850	1,030	surface	37	397
27N-24E-28cad	774	1,225	surface	33	300
27N-25E-9abd	850	1,247	surface	26	276
28N-22E-1bdd	825	1,250	100	12	490
28N-22E-1add	797	650	surface	0	415
28N-22E-8dac	792	350	175	0	not present
28N-22E-24cad	798	1,055	surface	7	442
28N-22E-24dab	795	1,060	surface	30	460
28N-22E-24aab	788	1,235	surface	15	470
28N-22E-24bcb	765	1,200	surface	7	457
28N-22E-24ada	798	1,060	surface	7	442

Well location	Surface elevation	Total depth	Depth to top of Mississippian	Combined thick- ness, Northview, Compton, Chatta- nooga shales	Depth to top of Ordovician
Ottawa County, Oklahoma					
28N-22E-24bda	792	1,465	surface	15	465
28N-23E-6abc	815	1,440	—	15	495
28N-23E-24ddb	850	1,035	surface	10	425
28N-23E-28bbb	800	1,535	surface	6	451
28N-23E-33baa	830	1,525	surface	35	440
28N-24E-13abb	960	1,165	surface	12	405
29N-22E-21ddd	825	1,205	145	1	526
29N-22E-25acc	835	1,229	—	5	470
29N-23E-13ddc1	850	1,115	—	6	455
29N-23E-13ddc2	822	1,260	100	—	450
29N-23E-18dbd	840	1,176	—	0	370
29N-23E-19dcc	833	1,765	110	—	443
29N-23E-19abb	838	1,645	75	—	370
29N-23E-20dbc	832	1,690	70	10	420
29N-23E-21dcd	825	1,040	—	5	385
29N-23E-26ddc	840	1,115	—	—	390
29N-23E-31bdc	834	1,385	—	10	490
29N-23E-31bcd	835	1,505	—	10	495
29N-23E-32bac	785	1,356	surface	25	450

APPENDIX 2

Listing of the static water level and specific-capacity data for wells visited during study; all depths and elevations are in units of feet, values of specific capacity are in gallons per minute per ft (gal/min/ft), C-O = Cambrian-Ordovician aquifer, and M = Mississippian aquifer.

Well location	Surface elevation	Aquifer	Depth to water	Date measured	Reported static-water-level altitude	Specific capacity
Barton County, Missouri						
31N-29W-20aab	1,148	C-O	395	5/80	—	—
31N-29W-35cab	1,063	C-O	196	5/79	—	—
31N-32W-22aaa	1,000	C-O	296	5/80	—	—
31N-33W-5bbd	966	M,C-O	281	5/80	—	1.56
32N-30W-24aaa	930	C-O	222	1978	—	—
32N-30W-27add	1,040	C-O	328	5/80	—	—
32N-31W-17aaa	996	C-O	298	5/80	—	5.47
32N-33W-2aca	904	C-O	217	5/80	—	17.60
Jasper County, Missouri						
27N-29W-8cad	1,172	C-O	147	5/79	—	11.60
27N-32W-10caa	1,067	C-O	90	5/80	—	1.09
27N-32W-1bbb	—	C-O	—	6/83	949	1.91
27N-33W-17dab	—	C-O	—	6/66	895	—
27N-34W-2bcc	920	C-O	167	5/80	—	—
27N-34W-2bdd	930	C-O	147	5/80	—	0.47
28N-31W-10ddd	1,038	C-O	378	5/80	—	2.60
28N-33W-24aac	994	C-O	339	5/79	—	2.50
28N-33W-5ccd	913	C-O	109	5/80	—	0.62
29N-32W-16bbb	965	C-O(?)	93	5/80	—	—
29N-32W-15bdb	965	C-O	81	5/80	—	14.44
29N-33W-36baa	975	C-O	148	5/79	—	—
29N-33W-4ccc	875	C-O	147	5/80	—	—
29N-34W-2dda	902	C-O	196	5/80	—	—
30N-31W-28ccc	948	C-O	111	5/80	—	17.04
30N-33W-17cba	940	C-O	347	5/80	—	—
30N-33W-17baa	925	C-O	271	5/80	—	39.47
30N-33W-17cba	965	C-O	339	5/80	—	—
Newton County, Missouri						
25N-31W-19ccc	—	—	—	6/60	974	32.00
26N-31W-10bbb	1,180	C-O	174	5/80	—	0.35
26N-31W-7ddd	—	C-O	—	6/66	1,070	—
26N-31W-22bcc	—	C-O	—	6/66	997	—
Vernon County, Missouri						
34N-31W-35aad	922	M,C-O	204	5/80	—	36.50
34N-32W-5ada	868	M,C-O	705	5/80	—	0.79
34N-32W-20baa	910	M,C-O	203	5/80	—	5.29
35N-31W-5bad	842	M,C-O	121	5/80	—	23.61
35N-31W-5caa	864	M,C-O	149	5/80	—	—
35N-31W-13	—	M,C-O	—	7/78	718	43.75
36N-30W-15bcc	855	C-O	134	5/80	—	0.34
36N-31W-33bbc	846	M,C-O	127	5/80	—	39.23
37N-32W-31	—	C-O	—	6/83	719	—
Craig County, Oklahoma						
27N-21E-20ddc	830	M,C-O	123	1/72	—	2.63
28N-21E-29cbd	851	C-O	168	5/80	—	—
Ottawa County, Oklahoma						
28N-23E-6bbc	812	C-O	468	5/80	—	11.67
28N-23E-28bbb	800	C-O	468	9/80	—	2.06
28N-23E-30acc	770	C-O	436	5/80	—	—
28N-23E-33baa	830	C-O	467	9/80	—	3.47
28N-23E-35bdd	—	C-O	—	—	582	23.33
28N-24E-13abb	960	C-O	271	5/80	—	7.95
28N-25E-20caa	—	C-O	—	11/78	699	—
29N-22E-21ddd	825	C-O	162	5/80	—	10.00

Well location	Surface elevation	Aquifer	Depth to water	Date measured	Reported static-water-level altitude	Specific capacity
Bourbon County, Kansas						
24S-21E-34aac	1,060	C-O	370	6/81	—	—
25S-24E-36aac	912	C-O	208	9/79	—	14.00
Cherokee County, Kansas						
31S-24E-34bac	923	M,C-O	229	5/80	—	4.67
32S-23E-6daa	910	C-O	229	5/80	—	—
32S-24E-29bbb	910	M,C-O	219	5/80	—	15.14
33S-23E-13abb	910	M,C-O	222	9/79	—	8.33
33S-25E-9dda	880	C-O	92	5/80	—	—
33S-25E-18daa	870	C-O	157	5/80	—	0.63
34S-24E-17dcd	854	C-O	183	5/80	—	4.00
34S-24E-36caa	832	C-O	221	5/80	—	—
34S-24E-36bba	820	C-O	607	9/79	—	7.27
34S-25E-4aac	854	C-O	229	9/79	—	0.47
34S-25E-8cbc	847	C-O	119	5/80	—	6.21
34S-25E-23aad	960	C-O	220	5/80	—	7.48
Crawford County, Kansas						
28S-22E-20acd1	907	C-O	217	5/80	—	1.71
29S-23E-29acd2	990	C-O	298	5/80	—	7.50
29S-24E-5ddc	970	C-O	277	5/80	—	5.00
29S-25E-1bbc	915	M,C-O ?	224	5/80	—	—
29S-25E-4ddc	908	M,C-O	218	5/80	—	—
29S-25E-5ddc	1,020	M,C-O	329	5/80	—	3.50
29S-25E-26cbc	951	M,C-O	253	5/80	—	32.00
30S-24E-2ddd	947	C-O	270	7/80	—	—
30S-24E-28aaa	927	M,C-O	240	5/80	—	108.00
30S-25E-23ccd	925	M,C-O	252	5/80	—	111.00
30S-25E-28daa	905	C-O	242	9/79	—	47.87
31S-22E-8ddc	920	C-O	222	5/80	—	0.45
31S-24E-18dbd	927	M,C-O	231	5/80	—	—
Labette County, Kansas						
31S-20E-23cbd	905	C-O	—	12/41	729	4.35
33S-19E-11aab	918	C-O	—	1940	728	—
34S-21E-35cbb	810	C-O	—	1942	719	—
Neosho County, Kansas						
26S-18E-34cca	930	C-O	264	6/81	—	—
26S-21S-2baa	1,075	C-O	380	6/81	—	—
27S-18E-14dca	980	C-O	290	6/81	—	—
28S-20E-22ddd	900	M,C-O	234	6/81	—	—
28S-20E-23bdb	914	C-O	219	6/81	—	—
28S-21E-29abc	890	C-O	210	6/81	—	—
28S-22E-27bca	945	C-O	265	6/81	—	—

APPENDIX 3

Listing of the ground-water chemical-quality data from wells tested in Tri-State area during this study.

Well name/ location	Date sampled	Specific conductance, umho @25°C				pH	Temp °C	TDS2 ppm	Total S-7, ppm	KANSAS														U3 ppb	234U/ 238U34	
		Aquifer unit	1,320	7.60	20.1					724	4.5	Ca, ppm	Mg, ppm	Na, K, ppm	Sr, ppm	HCO ₃ , ppm	SO ₄ , ppm	Cl, ppm	F, NO ₃ , ppm	Fe ppb	Mn ppb	B ppb	Li ppb			Ba ppb
Arcadia #2	5/12/80	M,O-C	1,320	7.60	20.1	724	4.5	65	27	166	7.8	1.38	296	53	247	0.8	0.3	52	4.4	314	138	77	3.4	—	—	
28S-25E-1bbd																										
Arma #2	5/12/80	M,O-C	1,360	7.55	25.7	757	4.0	68	28	175	7.3	1.32	357	63	228	1.0	0.2	14	3.6	293	144	90	4.5	—	—	
29S-25E-5cdd																										
Baxter Springs #1	5/13/80	O-C	900	7.20	19.5	701	<0.1	128	43	44	3.8	0.38	222	315	47	0.2	0.0	525	16	88	40	35	1.7	0.493	7.48	
34S-24E-36cdd																										
Baxter Springs #5	5/13/80	O-C	530	7.60	20.0	303	<0.1	43	24	32	2.8	0.33	185	58	42	0.3	0.0	162	5.3	68	32	29	2.3	0.280	8.30	
34S-24E-36caa																										
Baxter Springs #6	5/13/80	O-C	1,140	7.60	20.0	605	<0.1	41	21	155	5.3	0.86	170	22	266	0.6	0.0	23	2.9	246	99	62	12.0	0.350	7.10	
34S-24E-36bba																										
Capaldo #1	5/13/80	P,M,O-C	1,900	7.50	21.0	651	20	62	29	136	7.9	1.43	361	92	133	0.8	0.9	75	4.5	270	144	103	4.8	—	—	
30S-24E-1aca																										
Cherokee West	5/13/80	M,O-C	932	7.45	23.2	548	6.5	68	33	85	6.2	1.26	344	96	78	0.9	0.3	26	2.0	218	114	60	3.2	—	—	
30S-24E-18fbd																										
Cherokee County																										
RWD 1, #1	5/13/80	O-C	465	7.55	18.8	275	<0.1	46	24	19	3.5	0.68	236	50	5.5	0.7	0.0	66	3.0	109	45	72	1.5	0.54	6.80	
33S-25E-18daa																										
Cherokee County																										
RWD 1, #2	5/13/80	O-C	520	7.55	19.0	307	0.2	50	28	21	3.8	0.67	259	50	16	0.5	0.0	147	4.5	80	58	62	—	—	—	
33S-25E-9daa																										
Cherokee County																										
RWD 2	5/13/80	O-C	875	7.75	18.8	484	<0.1	33	15	127	4.0	0.56	198	48	148	0.8	0.0	83	3.1	316	74	94	1.2	—	—	
34S-25E-8cbc																										
Cherokee County																										
RWD 3	5/13/80	O-C	544	7.70	21.0	544	2.0	46	24	122	6.4	1.20	195	38	200	0.9	0.0	40	2.7	294	100	125	3.1	—	—	
34S-24E-17dec																										
Cherokee County																										
RWD 4	5/12/80	M,O-C	393	7.75	24.2	393	4.0	50	26	56	5.2	1.10	283	57	47	1.0	0.2	154	3.3	209	84	75	4.1	—	—	
32S-24E-29bbb																										
Bill's Coal Co.,																										
Chetopa	5/14/80	M	1,660	7.70	23.0	905	4.0	6.8	3.7	354	8.3	0.24	457	16	272	9.5	0.2	887	11	197	328	37	0.8	—	—	
34S-21E-28cbb																										
Columus #6	5/12/80	M,O-C	845	7.60	23.0	495	8.0	53	29	86	6.7	1.46	375	79	52	1.4	0.6	13	0.7	388	111	108	5.5	—	—	
33S-23E-13baa																										
Crawford County																										
RWD 1	5/12/80	M,O-C	698	7.80	24.0	390	6.0	37	19	85	3.9	0.56	284	19	75	0.6	0.3	274	2.2	174	48	154	3.5	—	—	
29S-25E-26cbb																										
Crawford County																										
RWD 2	5/13/80	M,O-C	2,150	7.65	23.1	1,313	7.0	20	15	488	11	1.06	1,061	33	220	2.4	0.6	166	5.8	574	252	143	4.5	—	—	
29S-24E-11daa																										
Crawford County																										
RWD 3	5/12/80	M,O-C	1,180	7.50	23.9	634	4.0	63	27	138	5.9	1.05	323	47	182	0.8	0.2	73	3.5	222	109	115	—	—	—	
29S-25E-4ada																										
Crawford County																										
RWD 4	5/12/80	M,O-C	1,050	7.45	24.4	591	4.0	70	34	96	7.1	1.31	318	92	123	0.8	0.2	34	6.7	209	122	50	1.8	0.041	8.84	
30S-24E-28aaa																										
Crawford County																										
RWD 5	5/14/80	M,O-C	632	7.75	20.9	365	4.0	46	22	62	3.8	0.56	275	26	58	0.6	0.3	9.3	1.2	146	58	336	4.7	—	—	
30S-25E-23ccd																										
Crawford County																										
RWD 7, #1	5/13/80	C-O	2,320	7.5	25.6	1,260	4.0	97	48	303	12	2.32	310	110	524	0.9	0.4	89	6.4	434	265	60	7.5	.053	9.10	
29S-24E-5ddc																										
Crawford County																										
RWD 7, #2	10/7/80	C-O	1,190	7.45	24.0	625	3.0	71	32	111	8.9	1.37	341	87	135	0.7	0.4	18	<3	245	141	56	—	—	—	
30S-24E-24ddd																										

Well name/ location	Date sampled	Specific conductance,				pH	Temp °C	TDS2 ppm	Total S ²⁻ , ppm	Ca, ppm	Mg, ppm	Na, ppm	K, ppm	Sr, ppm	HCO ₃ , ppm	SO ₄ , ppm	Cl, ppm	F, NO ₃ , ppm	Fe ppb	Mn ppb	B ppb	Li ppb	Ba ppb	226Ra3 pCi/L	U3 ppb	234U/ 238U34
		umbho @25°C	unit	°C	ppm																					
KANSAS																										
Roberts, OFWS	4/81	C-O	14,600	7.0	—	8,048	30	195	97	2,770	37	25	4,680	<10	8,600	43	—	—	—	—	—	—	—	—	—	
26S-19E-23abb	4/81	C-O	69,400	—	25.2	45,127	4	1,470	788	14,400	158	197	27,900	<5	27,000	1,600	0.026	1.95	—	—	—	—	—	—	—	
33S-16E-12ccd	4/81	C-O	2,535	7.55	21.5	—	1.5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	
Fort Scott	3/80	C-O	2,150	—	—	1,170	0.0	13	6	455	9	0.4	436	5	2,000	2.5	0.010	1.68	—	—	—	—	—	—	—	
25S-24E-36aac	3/80	C-O	12,400	—	—	6,942	pres.	120	77	2,484	24	10	3,844	7	2,400	2,000	40	0.013	1.46	—	—	—	—	—		
Chetopa, OW	4/80	C-O	4,700	—	21.9	2,580	3.5	40	21	964	12	2	1,235	3	2,900	500	0.100	2.08	—	—	—	—	—	—		
34S-20E-36adc	4/80	C-O	30,200	—	19.5	18,600	—	408	160	6,378	88	16	10,670	10	7,400	3,000	—	—	—	—	—	—	—	—		
Wickertle, OW	4/80	C-O	58,500	—	29	37,200	80	1,220	440	12,540	174	41	22,420	150	8,800	1,000	—	—	—	—	—	—	—	—		
33S-17E-36bb	4/80	C-O	73,200	—	—	47,600	90	16,691	701	15,380	186	113	28,230	119	7,400	1,300	—	—	—	—	—	—	—	—		
Wooldridge, OW	9/27/79	C-O	725	7.20	18.0	498	<0.1	123	22	10	1.3	0.18	8.7	0.1	1,884	16	19	—	—	—	—	—	—	—		
Independence, OW	5/12/80	C-O	400	7.80	20.5	246	<0.1	52	18	9.8	24	0.29	0.5	0.6	3,069	7.8	47	25	100	1.5	0.584	7.24	—	—		
33S-16E-5adb	5/15/80	C-O	740	7.55	21.0	458	<0.1	71	32	51	4.5	0.57	46	0.6	0.0	51	5.3	129	70	63	—	—	—	—		
Alpha-Powell #1	5/15/80	C-O	700	7.35	21.0	464	0.6	73	32	51	4.7	0.57	42	0.6	0.0	763	11	123	70	55	4.0	—	—	—		
29N-34W-2bbd	5/15/80	C-O	840	7.40	20.5	527	<0.1	82	32	65	4.7	0.57	80	0.6	0.0	50	6.5	124	63	60	—	—	—	—		
EmpDisElec #1	5/12/80	C-O	295	7.80	19.0	161	<0.1	29	17	6.1	1.4	0.12	2.5	0.2	0.0	74	0.3	24	11	134	0.8	—	—	—		
30N-33W-17cha	5/12/80	C-O	400	7.75	20.5	221	0.3	32	18	26	2.2	0.28	28	0.3	0.0	74	1.1	86	25	160	1.2	—	—	—		
EmpDisElec #4	5/12/80	C-O	545	7.60	22.0	332	0.7	42	22	52	3.4	0.55	72	0.4	0.0	406	7.0	134	43	40	—	—	—	—		
30N-33W-17cdb	4/17/79	C-O	272	7.95	20.0	149	<0.1	30	15	3.1	0.7	0.09	2.5	0.1	0.1	43	3.9	13	5.9	149	1.1	—	—	—		
BartonCo PWS#1	5/12/80	M,C-O	2,050	7.60	20.5	1,163	4.0	73	37	310	10	1.99	495	1.0	0.2	77	2.5	475	213	107	5.8	—	—	—		
Well #1	5/15/80	C-O	371	7.65	19.4	216	<0.1	40	18	13	2.2	0.16	8.5	0.3	0.0	181	5.1	46	24	112	1.5	0.335	8.72	—		
Well #3	5/14/870	C-O	661	7.45	19.2	457	<0.1	102	21	33	2.5	0.29	42	0.2	4.7	14	2.6	78	24	110	1.8	—	—	—		
31N-29W-17aab	5/14/80	C-O	400	7.75	19.8	226	<0.1	46	19	11	1.4	0.13	12	0.2	0.0	20	4.9	23	9.6	94	—	—	—	—		
Bronaugh #3	5/14/80	C-O	312	7.70	19.2	205	<0.1	44	19	4.1	1.6	0.09	1.5	0.1	0.0	44	3.1	10	9.2	70	0.9	—	—	—		
34N-32W-20baa	5/15/80	C-O	331	7.65	18.0	189	<0.1	39	18	3.7	1.4	0.09	2.0	0.1	0.0	15	3.9	11	11	151	0.9	0.416	10.37	—		
Carl Jct #3	5/14/80	M	745	8.15	17.0	447	7.5	14	8.1	150	6.4	0.56	26	2.2	0.4	74	0.4	602	106	122	—	—	—	—		
28N-33W-5cdc	5/14/80	C-O	337	7.60	20.0	191	<0.1	32	18	14	1.9	0.19	8.5	0.3	0.0	9.6	0.4	58	22	97	1.6	—	—	—		
Carriage #7	5/14/80	C-O	396	7.60	18.0	234	<0.1	46	19	8.5	2.1	0.21	1.5	0.3	0.0	142	9.3	27	20	65	—	—	—	—		
Carriage #10	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
28N-31W-10ddd	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
Diamond #1	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
26N-31W-3cab	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
28N-31W-4bad	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
28N-31W-10ddd	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
Duenweg #2	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
27N-32W-10caa	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
Hansen, Shdstm	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
Jasper #2	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
35N-30W-34cdd	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
30N-31W-24ccc	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
JasperCo PWS#2	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
Well #1	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		
30N-33W-4ccb	5/14/80	C-O	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		

Well name/ location	Date sampled	Specific conductance, Aquifer unit @25°C	pH	Temp °C	TDS2 ppm	Total S ²⁻ , ppm	Ca, ppm	Mg, ppm	Na, ppm	K, ppm	Sr, ppm	HCO ₃ , ppm	SO ₄ , ppm	Cl, ppm	F, NO ₃ , ppm	Fe ppb	Mn ppb	B ppb	Li ppb	Ra ppb	226Ra3 pCi/L	U3 ppb	238U34	
MISSOURI																								
AtlasPowder #6 27N-32W-1bbd	5/15/80	C-O	382	7.95	19.0	222	<0.1	47	16	6.4	1.5	0.11	177	49	3.5	0.2	0.9	17	3.5	21	12	104	1.5	—
FarmChemCorp, west well, Joplin 27N-34W-2bcc	5/15/80	C-O	320	8.00	22.6	179	<0.1	32	17	10	1.7	0.33	170	18	6.5	0.4	0.0	137	3.5	52	22	126	—	—
FarmChemCorp, east well, Joplin 27N-34W-2bcd	4/20/79	C-O	318	8.15	22.3	177	<0.1	48	19	8.7	2.5	0.30	185	65	1.7	0.3	0.0	885	28	27	22	104	1.7	0.270
Kelsey, Mind. 31N-33W-4abb	5/12/80	M	1,400	7.65	19.5	1,117	7.0	39	31	351	8.3	1.42	871	201	44	2.6	0.6	25	5.0	679	183	106	—	—
Liberal #2 32N-33W-2acd	5/12/80	C-O	700	7.60	20.0	426	3.0	44	23	84	4.3	0.78	240	25	116	0.6	0.0	55	2.0	175	67	97	2.4	—
Mindemines #1 32N-33W-5bbb	5/12/80	M,C-O	850	7.80	22.0	613	3.5	25	13	205	5.1	0.57	552	27	54	1.8	0.4	64	2.5	405	124	116	2.3	—
VermontCo PWS#1 Well 1 34N-32W-5aad	5/14/80	M,C-O	1,990	7.85	19.0	1,264	5.0	39	21	391	11	1.35	730	41	288	2.5	0.3	6.8	0.6	746	204	99	4.4	—
MoPubServ Nevada #3 35N-31W-5caa	5/13/80	M,C-O	2,050	7.55	19.5	1,273	3.0	82	44	337	12	2.24	271	74	578	0.9	0.0	68	3.9	477	204	82	—	—
MoPubServ Nevada #4 35N-31W-5bad	5/13/80	M,C-O	2,100	7.55	19.5	1,278	4.0	85	45	330	12	2.23	272	73	586	0.9	0.0	45	3.3	490	246	82	—	—
NevStHosp #1 36N-31W-32aad	5/13/80	M,C-O	1,900	7.55	19.5	1,291	3.0	84	45	336	12	2.32	270	83	585	0.9	0.4	529	7.0	490	242	77	—	—
NevStHosp #4 36N-31W-33bbd	5/13/80	M,C-O	2,000	7.55	18.5	1,237	4.0	80	43	323	11	2.21	268	70	565	0.8	0.3	241	6.8	478	278	76	7.3	—
Oronogo #3 29N-32W-31caa	5/15/80	C-O	361	7.70	19.8	216	<0.1	43	18	11	1.8	0.14	215	20	6.5	0.3	0.0	96	7.0	37	18	138	—	—
Purcell #1 29N-32W-9ccb	5/14/80	C-O	487	7.70	17.5	293	<0.1	76	16	7.1	1.4	0.19	250	54	3.0	0.2	2.5	5,500	18	33	16	140	—	—
Sheldon #2 34N-31W-35aad	5/14/80	M,C-O	800	7.50	18.0	431	<0.1	40	20	96	4.1	0.76	210	20	136	0.7	0.0	243	3.2	206	72	142	2.1	—
Snyder, Webb City 28N-33W-14cbb	5/15/80	M	428	7.25	15.0	238	<0.1	81	2.5	3.7	0.5	0.10	213	44	1.0	0.1	0.0	166	28	7.4	8.9	153	—	—
Walker #1 36N-30W-15bcc	5/13/80	C-O	1,500	7.60	19.5	824	2.5	67	29	203	7.7	1.43	241	41	346	0.6	0.0	51	2.5	344	150	117	2.6	—
Webb City #11 28N-33W-24aac	5/15/80	C-O	261	7.80	18.9	149	<0.1	30	13	4.0	1.2	0.12	146	15	3.5	0.2	0.2	379	7.1	18	14	136	1.0	0.325
OKLAHOMA																								
Blue Jacket #1 27N-21E-20dcc	5/12/80	M,C-O	1,020	8.15	23.8	465	0.9	20	8.9	144	4.9	0.59	194	13	164	4.0	0.3	268	3.8	836	172	78	2.7	—
Commerce #3 28N-23E-6bac	5/13/80	C-O	545	7.60	21.0	289	0.1	40	18	39	2.2	0.49	153	42	62	0.4	0.0	190	4.4	81	38	51	0.8	—
Miami #5 28N-23E-32bab	5/13/80	C-O	710	7.95	20.0	377	0.1	31	16	89	2.9	0.70	143	14	142	0.6	0.0	348	6.9	130	53	32	2.2	—
Miami #6 28N-23E-33baa	5/13/80	C-O	469	7.85	20.0	258	0.1	31	15	45	2.0	0.44	142	14	70	0.5	0.0	70	2.3	96	40	23	—	—
Miami #7 28N-23E-28bbb	5/13/80	C-O	664	7.95	20.5	363	<0.1	33	15	78	2.6	0.60	142	13	140	0.4	0.2	20	3.1	135	52	43	3.7	—
OttawaCo RWD1 27N-24E-28cda	5/14/80	C-O	261	7.90	19.2	163	<0.1	29	12	12	1.4	0.21	151	14	9.5	0.4	0.2	318	5.0	66	23	18	0.5	—
OttawaCo RWD2 27N-22E-1ccc	5/12/80	C-O	680	7.90	22.2	361	<0.1	32	16	82	3.1	0.76	151	14	128	0.7	0.0	49	2.4	170	69	71	—	—
OttawaCo RWD3 28N-24E-13aba	5/14/80	C-O	275	7.90	20.0	158	<0.1	30	17	5.2	0.8	0.07	164	9.9	4.0	0.1	0.0	44	6.1	14	6.4	13	0.5	—

Well name/ location	Date sampled	Specific conductance, Aquifer unit @25°C	pH	Temp °C	TDS2 ppm	Total S ²⁻ , ppm	Ca, ppm	Mg, ppm	Na, ppm	K, ppm	Sr, ppm	HCO ₃ , ppm	SO ₄ , ppm	Cl, ppm	F, NO ₃ , ppm	Fe ppb	Mn ppb	B ppb	Li ppb	Ba ppb	226Ra3 pCi/L	U3 ppb	234U/ 238U34
OttawaCo RWD7	10/7/80	C-O	8.20	19.0	321	9.0	23	11	80	3.9	0.81	168	8.0	99	1.8	0.5	4,600	19	437	125	34	—	—
29N-22E-21ddd Ouapaw #2	5/12/80	C-O	7.60	19.8	260	<0.1	45	22	14	1.9	0.23	155	70	20	0.2	0.0	21	6.6	42	21	32	1.0	—
29N-23E-35bdd Welch #1 28N-21E-29ebd	5/12/80	C-O	7.80	24.8	951	4.0	45	21	286	9.7	1.55	182	22	464	2.6	0.0	33	2.2	904	202	160	5.1	—

1 Aquifer units: P, Pennsylvanian; M, Mississippian; O-C or C-O, Cambrian-Ordovician.

2 Calculated TDS value retains one-half of the HCO₃ value.

3 Samples for radium-226, uranium, and uranium-234/uranium-238 activity-ratio determinations were collected separately and at different times from the date shown.

4 Activity ratio.

5 OWFS, oil-field water-supply well.

6 OW, oil well.

