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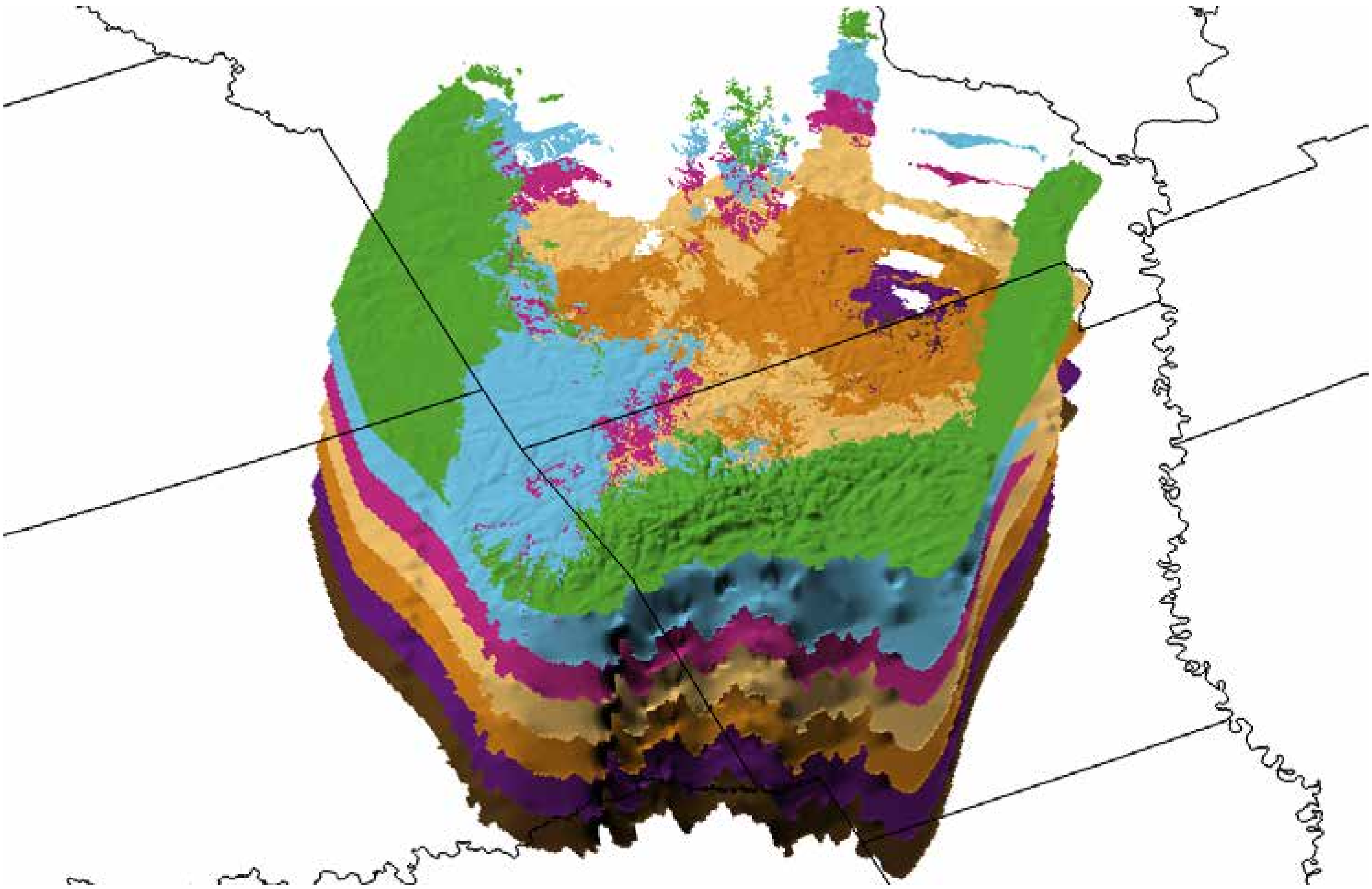
Altitudes and Thicknesses of Hydrogeologic Units of the Ozark Plateaus Aquifer System in Arkansas, Kansas, Missouri, and Oklahoma



Scientific Investigations Report 2016–5130

U.S. Department of the Interior
U.S. Geological Survey

Front cover, Hydrogeologic unit surfaces from the report displayed in a three-dimensional view with vertical exaggeration. Created by Brian R. Clark, Lower Mississippi-Gulf Water Science Center.

Back cover, Artistic concept of transition from well borehole data to a three-dimensional gridded hydrogeologic unit surface. Created by Brian R. Clark, Lower Mississippi-Gulf Water Science Center.

Altitudes and Thicknesses of Hydrogeologic Units of the Ozark Plateaus Aquifer System in Arkansas, Kansas, Missouri, and Oklahoma

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U.S. Department of the Interior
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U.S. Geological Survey
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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88)].

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)].

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

DEM	Digital Elevation Model
GIS	Geographic information system
TIN	Triangulated irregular network
USGS	U.S. Geological Survey

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Abstract

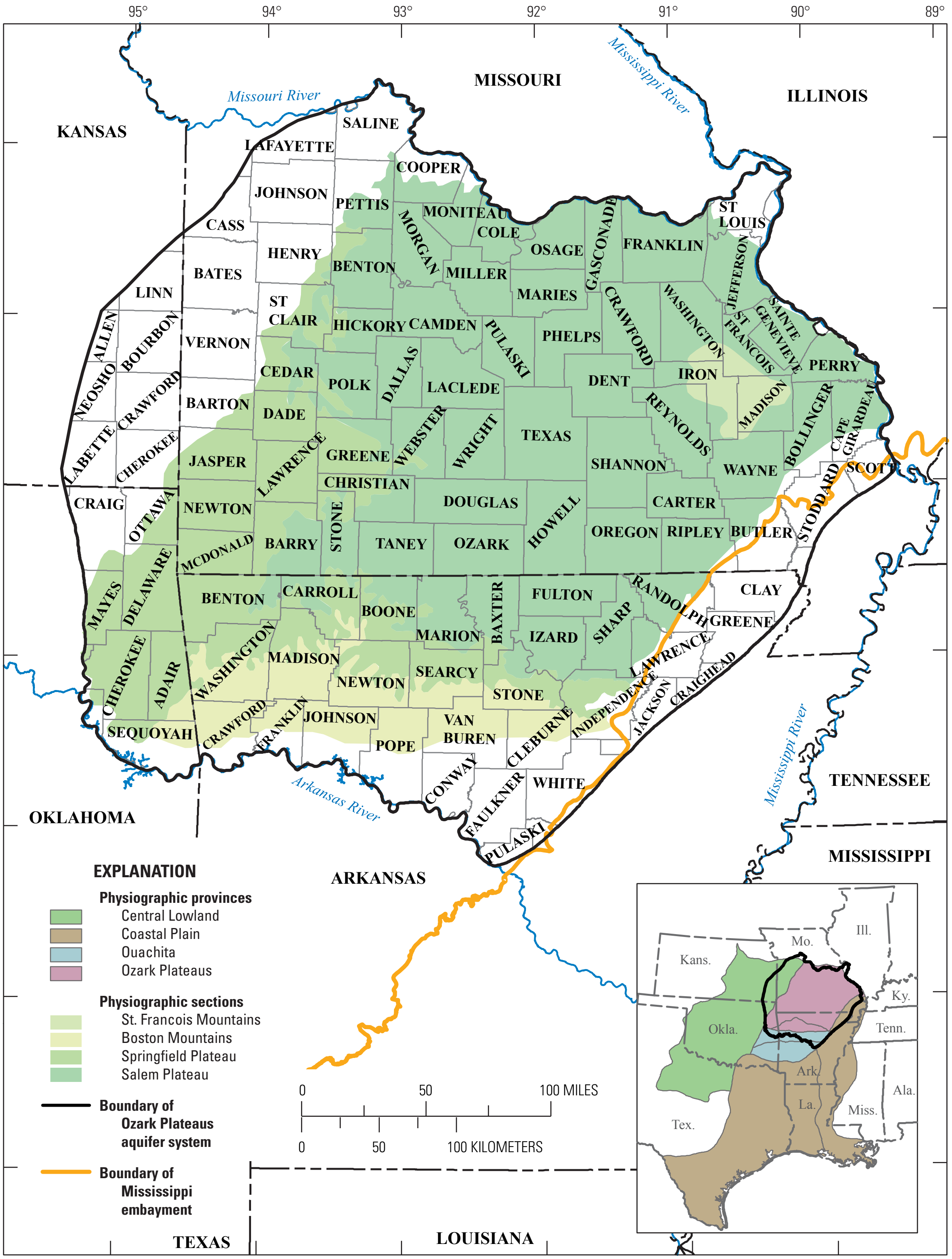
A hydrogeologic framework was constructed to represent the altitudes and thicknesses of hydrogeologic units within the Ozark Plateaus aquifer system as part of a regional groundwater-flow model supported by the U.S. Geological Survey Water Availability and Use Science Program. The Ozark Plateaus aquifer system study area is nearly 70,000 square miles and includes parts of Arkansas, Kansas, Missouri, and Oklahoma. Nine hydrogeologic units were selected for delineation within the aquifer system and include the Western Interior Plains confining system, the Springfield Plateau aquifer, the Ozark confining unit, the Ozark aquifer, which was divided into the upper, middle, and lower Ozark aquifers to better capture the spatial variation in the hydrologic properties, the St. Francois confining unit, the St. Francois aquifer, and the basement confining unit. Geophysical and well-cutting logs, along with lithologic descriptions by well drillers, were compiled and interpreted to create hydrologic altitudes for each unit. The final compiled dataset included more than 23,000 individual altitude points (excluding synthetic points) representing the nine hydrogeologic units within the Ozark Plateaus aquifer system.

Introduction

Refined knowledge of the altitudes and thicknesses of the hydrogeologic units within the framework of the Ozark Plateaus aquifer system (hereinafter referred to as the "Ozark system") is essential for planning and management of the regional groundwater resource. Quantitative analysis of groundwater storage and movement, including numerical modeling of the system, requires accurate thicknesses for the calculation of transmissivity and storage volumes. The confined or unconfined condition of each aquifer is determined by comparing the altitude of each hydrogeologic unit with the corresponding water level. Additionally, regulatory agencies utilize the framework in determining casing requirements for public-supply wells. The U.S. Geological Survey's (USGS) Water Availability and Use Science Program is supporting several large-scale regional studies of groundwater availability in major aquifer systems across the United States to provide information to managers and the public about how water resources respond to natural and anthropogenic stresses.

The Ozark Plateaus aquifer system groundwater availability study began in 2013 as a 4-year effort to evaluate the groundwater availability in the Ozark system. The data and analysis provided in this report are one component of a broader analysis and modeling study of the groundwater resources of the Ozark system. The study area covers nearly 70,000 square miles (mi^2) in parts of Arkansas, Kansas, Missouri, and Oklahoma (fig. 1). As a part of the study, a hydrogeologic framework was constructed to represent the altitudes and thicknesses of selected hydrogeologic units within the Ozark system. The hydrogeologic units are distinguished by rocks with similar hydrologic properties, which usually coincide with formation boundaries and can span several geologic-time systems. The hydrogeologic framework, which includes hydrogeologic units from land surface to the top of the basement confining unit, will be included in a groundwater flow model that is being developed to evaluate groundwater availability (U.S. Geological Survey, 2015).

This study refines the results of several previous investigations that evaluated the hydrogeologic framework of the Ozark system. The Central Midwest Regional Aquifer-System Analysis (CM–RASA) study was one of the first to investigate the hydrogeology of the complete Ozark Plateaus physiographic province and adjacent areas (Jorgensen and Signor, 1981). Imes (1990a–g) presented a series of map reports detailing the major aquifers and confining units in the Ozark Plateaus aquifer system. Smith and Imes (1991) provided a correlation of regional hydrogeologic units to geological formations in southern Missouri. Imes and Emmett (1994) identified the major hydrologic units in the Ozark system. The correlation and identification of hydrogeologic units from these previous studies formed the basis for delineating the hydrogeologic units presented in this report for the entire Ozark system. The current hydrogeologic framework refines previous information by including the most



Base from the U.S. Geological Survey digital data, 2000, 100,000
Alber Equal-Area Conic USGS projection
Standard parallels 29.5 and 45.5
Central meridian -96.0
North American Datum 1983

Physiographic regions modified from Fenneman, 1938; Fenneman and Johnson,1946; Adamski and others, 1995

Figure 1. The study area and physiographic sections and provinces of the Ozark Plateaus aquifer system.

current data available to improve the spatial resolution of each hydrogeologic unit within the Ozark system. Numerical interpolation allows almost any contour value desired, whereas many previous regional frameworks were based on hand-contoured geologic surfaces that were limited by scale to contour intervals of 100 feet (ft) or more. Because of the additional data and improved technologies, select hydrogeologic units were further divided vertically to better represent lithologic changes within regional aquifer units.

Purpose and Scope

This report presents a (1) summary description of regional geology and (2) a three-dimensional hydrogeologic framework composed of continuous grids representing the altitudes and thicknesses for the major hydrogeologic units identified within the Ozark system. Nine hydrogeologic units were selected for delineation within the Ozark system and include from youngest to oldest the (1) Western Interior Plains confining system, (2) Springfield Plateau aquifer, (3) the Ozark confining unit, (4) the upper Ozark aquifer, (5) the middle Ozark aquifer, (6) the lower Ozark aquifer, (7) the St. Francois confining unit, (8) the St. Francois aquifer, and (9) the basement confining unit (figs. 2 and 3). The scope of this effort included the compilation and interpretation of hydrogeologic altitudes from drillers' logs, geophysical logs, lithologic logs, and borehole data from previous investigations. The final compiled dataset included more than 23,000 individual altitude points (excluding synthetic points) representing the nine hydrogeologic units (fig. 4). This report provides a description of the characteristics for each hydrogeologic unit and the methods used to develop the altitudes and thicknesses of the three-dimensional hydrogeologic framework included in the Ozark system groundwater availability project.

Description of Study Area

The Ozark system study area (70,000 mi^2) includes parts of Arkansas, Kansas, Missouri, and Oklahoma and is bounded by the Missouri River to the north, the Mississippi River and the Mississippi embayment to the east, the Arkansas River to the south, and a broad and gentle regional topographic low extending from northeastern Oklahoma north to the Missouri River on the west (fig. 1). The study area includes the entire Ozark Plateaus physiographic province and small parts of the Ouachita, Central Lowland, and Coastal Plain physiographic provinces (Fenneman, 1938; Fenneman and Johnson, 1946). The study area is largely covered by the Ozark Plateaus physiographic province, often referred to as the Ozark Mountains, which is composed mainly of sedimentary rocks that dip away from an underlying structural dome centered around a core of igneous rocks referred to as the St. Francois Mountains in southeastern Missouri. Within the Ozark Plateaus physiographic province, the sedimentary rocks form three distinct physiographic sections: the Springfield Plateau, the Salem Plateau, and the Boston Mountains (Fenneman, 1938; Fenneman and Johnson, 1946; fig. 1).

The Ozark system study area is a diverse environment with wide ranges in topography, geology, and hydrologic influences and controls. The land-surface altitudes for the Ozark system range from near 200 ft within the Mississippi embayment to just over 2,500 ft in the Boston Mountains. The land cover within the study area is primarily forest, pasture, and cropland; land use includes row-crop production, logging, poultry, cattle and swine production, and mining (Adamski and others, 1995). The Ozark system has previously been divided into five primary hydrogeologic units: the Springfield Plateau aquifer, the Ozark confining unit, the Ozark aquifer, the St. Francois confining unit, and the St. Francois aquifer. These units are bounded by the overlying Western Interior Plains confining system and the underlying basement confining unit (Imes and Emmett, 1994; Czarnecki and others, 2009). This report further divides the Ozark aquifer into three additional hydrogeologic units, the upper, middle, and lower Ozark aquifers, to better represent the properties of the Ozark aquifer, which can affect movement and availability of water (fig. 2). The Springfield Plateau aquifer, the upper, middle, and lower Ozark aquifers, and the St. Francois aquifer, provide freshwater to domestic users, municipalities, industries, and for agricultural use.

Methods

The hydrogeologic framework represents a continuous grid of altitude values for surfaces that define the vertical limits and thicknesses of each of the nine hydrogeologic units (thickness was not calculated for the basement confining unit). Information about the geologic formations beneath land surface can be sparse and often is isolated to discrete borehole locations. The drilled borehole often results from water or energy exploration, and a description or log of the borehole's attributes is collected through various methods.

Borehole data were compiled from various sources, including but not limited to, geophysical, lithologic, driller description, and well-cutting logs. The borehole data included information about the drilling, construction, and physical characteristics of the borehole and were used to correlate the lithology (rock characteristics) between boreholes. The borehole data were obtained from a variety of sources including USGS Water Science Centers in Arkansas, Kansas, Missouri, and Oklahoma; the USGS National Water Information System (NWIS; U.S. Geological Survey, 2013); the Arkansas Oil and Gas Commission; the Arkansas Geological Survey; the Kansas Geological Survey; and the Missouri Department of Natural Resources.

Era	System	Southeastern Missouri	Southwestern Missouri	Southeastern Kansas	Northeastern Oklahoma	Northern Arkansas	Aquifers and confining units described in the report: Hydrogeologic unit	Aquifers and confining units described in the report: Hydrogeologic system
PALEOZOIC	Pennsylvanian	Pleasanton Formation[1] Marmaton Group[1] Cherokee Group[1]	Kansas City Group Pleasanton Formation Marmaton Group Cherokee Group	Kansas City Group Pleasanton Formation Marmaton Group Cherokee Group	Marmaton Group Cabaniss Group Krebs Group Atoka Formation Bloyd Shale Hale Formation	McAlester Formation Hartshorne Sandstone Atoka Formation Bloyd Shale Hale Formation		Western Interior Plains confining system[2]
	Mississippian	Vienna Limestone[1,4] Tar Springs Sandstone[1,4] Glen Dean Limestone[1,4] Hardinsburg Sandstone[1,4] Golconda Formation[1,4] Cypress Formation[1,4] Paint Creek Formation[1] Yankeetown Sandstone[1] Renault Formation[1,4] Aux Vases Sandstone[1]	Fayetteville Shale Batesville Sandstone Hindsville Limestone Carterville Formation		Pitkin Limestone Fayetteville Shale Batesville Sandstone Hindsville Limestone	Pitkin Limestone Fayetteville Shale Batesville Sandstone		
		Ste. Genevieve Limestone[3] St. Louis Limestone[3] Salem Formation[3] Warsaw Limestone[3] Keokuk Limestone[3] Burlington Limestone[3] Fern Glen Limestone[3]	St. Louis Limestone Salem Formation Warsaw Limestone Keokuk Limestone Burlington Limestone Elsey Formation Reeds Spring Formation Pierson Formation[4]	St. Louis Limestone Salem Limestone Warsaw Limestone Keokuk Limestone Burlington Limestone Fern Glen Limestone	Moorefield Formation Keokuk Limestone[4] Boone Formation Reeds Spring Member St. Joe Limestone Member	Moorefield Formation Boone Formation Reeds Spring Member St. Joe Limestone Member	Springfield Plateau aquifer	Ozark Plateaus aquifer system[5]
		Chouteau Limestone Hannibal Shale Bachelor Formation[4]	Northview Shale Sedalia Limestone Compton Limestone	Chouteau Limestone	Northview Shale[6] Compton Limestone[6]		Ozark confining unit	
	Devonian	Bushberg Sandstone Glen Park Limestone Chattanooga Shale	Chattanooga Shale	Chattanooga Shale	Woodford Chert Chattanooga Shale	Chattanooga Shale		
		St. Laurent Limestone Grand Tower Limestone Clear Creek Chert[4] Little Saline Limestone Bailey Limestone	Callaway Formation[4] Fortune Formation[4]		Sallisaw Formation Frisco Limestone	Clifty Limestone Penters Chert	Ozark aquifer: Upper	
	Silurian	Bainbridge Limestone Sexton Creek Limestone[4]			St. Clair Limestone	Lafferty Limestone St. Clair Limestone Brassfield Limestone		

Figure 2. Stratigraphic column showing generalized correlation of Paleozoic units and regional hydrogeologic units of the Ozark Plateaus aquifer system.

Era	System	Southeastern Missouri	Southwestern Missouri	Southeastern Kansas	Northeastern Oklahoma	Northern Arkansas	Aquifers and confining units described in the report: Hydrogeologic unit	Aquifers and confining units described in the report: Hydrogeologic system
PALEOZOIC							Ozark aquifer: Upper	Ozark Plateaus aquifer system[5]
	Ordovician	Girardeau Limestone Orchard Creek Shale Thebes Sandstone Maquoketa Shale						
		Cape Limestone[4] Kimmswick Limestone Decorah Formation Plattin Limestone Rock Levee Formation[4] Joachim Dolomite Dutchtown Formation[4] St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite	Kimmswick Limestone Plattin Limestone Joachim Dolomite St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite	Powell Dolomite	Sylvan Shale Fernvale Limestone Viola Limestone Fite Limestone Tyner Formation Burgen Sandstone Undefined units equivalent to the Smithville Formation[6] Powell Dolomite	Cason Shale Fernvale Limestone Kimmswick Limestone Plattin Limestone Joachim Dolomite St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite		
		Cotter Dolomite Jefferson City Dolomite	Cotter Dolomite Jefferson City Dolomite	Cotter Dolomite Jefferson City Dolomite	Cotter Dolomite Jefferson City Dolomite	Cotter Dolomite Jefferson City Dolomite	Ozark aquifer: Middle	
		Roubidoux Formation Gasconade Dolomite Van Buren Formation[4] Gunter Sandstone Member[4]	Roubidoux Formation Gasconade Dolomite Gunter Sandstone Member[4]	Roubidoux Formation Gasconade Dolomite Van Buren Formation[4] Gunter Sandstone Member[4]	Roubidoux Formation Gasconade Dolomite Van Buren Formation[4] Gunter Sandstone Member[4]	Roubidoux Formation Gasconade Dolomite Van Buren Formation[4] Gunter Sandstone Member[4]	Ozark aquifer: Lower	
	Cambrian	Eminence Dolomite Potosi Dolomite	Eminence Dolomite Potosi Dolomite	Eminence Dolomite Potosi Dolomite[6]	Eminence Dolomite Potosi Dolomite[6]	Eminence Dolomite Undefined units equivalent to the Potosi Dolomite[6]		
		Doe Run Formation Derby Formation Davis Formation	Doe Run Formation Derby Formation Davis Formation	Undefined units equivalent to the Doe Run Formation[6] Derby Formation[6] Davis Formation	Undefined units equivalent to the Doe Run Formation[6] Derby Formation[6] Davis Formation[6]	Undefined units equivalent to the Doe Run Dolomite[6] Derby Formation[6] Davis Formation	St. Francois confining unit	
		Bonneterre Formation[6] Reagan Sandstone[4] Lamotte Sandstone	Bonneterre Dolomite Reagan Sandstone[4] Lamotte Sandstone	Bonneterre Dolomite[6] Reagan Sandstone Lamotte Sandstone	Undefined units equivalent to the Bonneterre Dolomite[6] Reagan Sandstone[6] Lamotte Sandstone	Bonneterre Dolomite Undefined units equivalent to the Reagan Sandstone[6] Lamotte Sandstone	St. Francois aquifer	
		PRECAMBRIAN IGNEOUS AND METAMORPHIC ROCKS					Basement confining unit	

[1]Geologic unit in southeastern Missouri that is stratigraphically equivalent to geologic units in the Western Interior Plains confining system but not part of the confining system.

[2]The Western Interior Plains confining system also includes younger sediments west of the study area.

[3]Geologic unit in southeastern Missouri that is stratigraphically equivalent to geologic units in the Springfield Plateau aquifer but not part of the aquifer.

[4]Unit follows usage of the State geologic agencies.

[5]The Western Interior Plains aquifer system deeply buried in the western part of the study area included, where permeable carbonate rocks in the subsurface are equivalents of the aquifers of the Ozark Plateaus aquifer system (Miller and Appel, 1997).

[6]Unit follows usage from Imes and Emmett, 1994.

Figure 2. Stratigraphic column showing generalized correlation of Paleozoic units and regional hydrogeologic units of the Ozark Plateaus aquifer system.—Continued

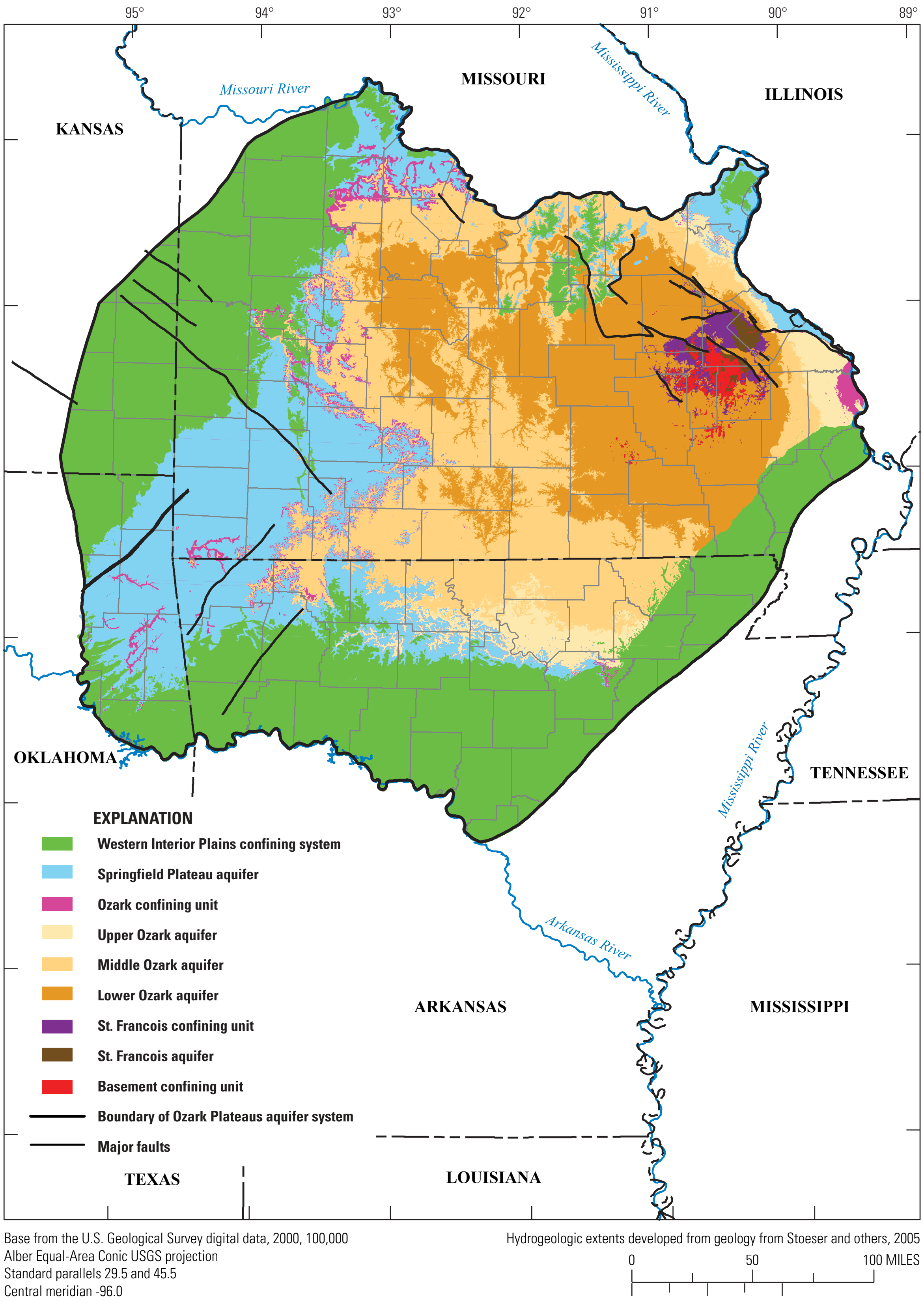


Figure 3. Surficial geology and structural features of the Ozark Plateaus aquifer system.

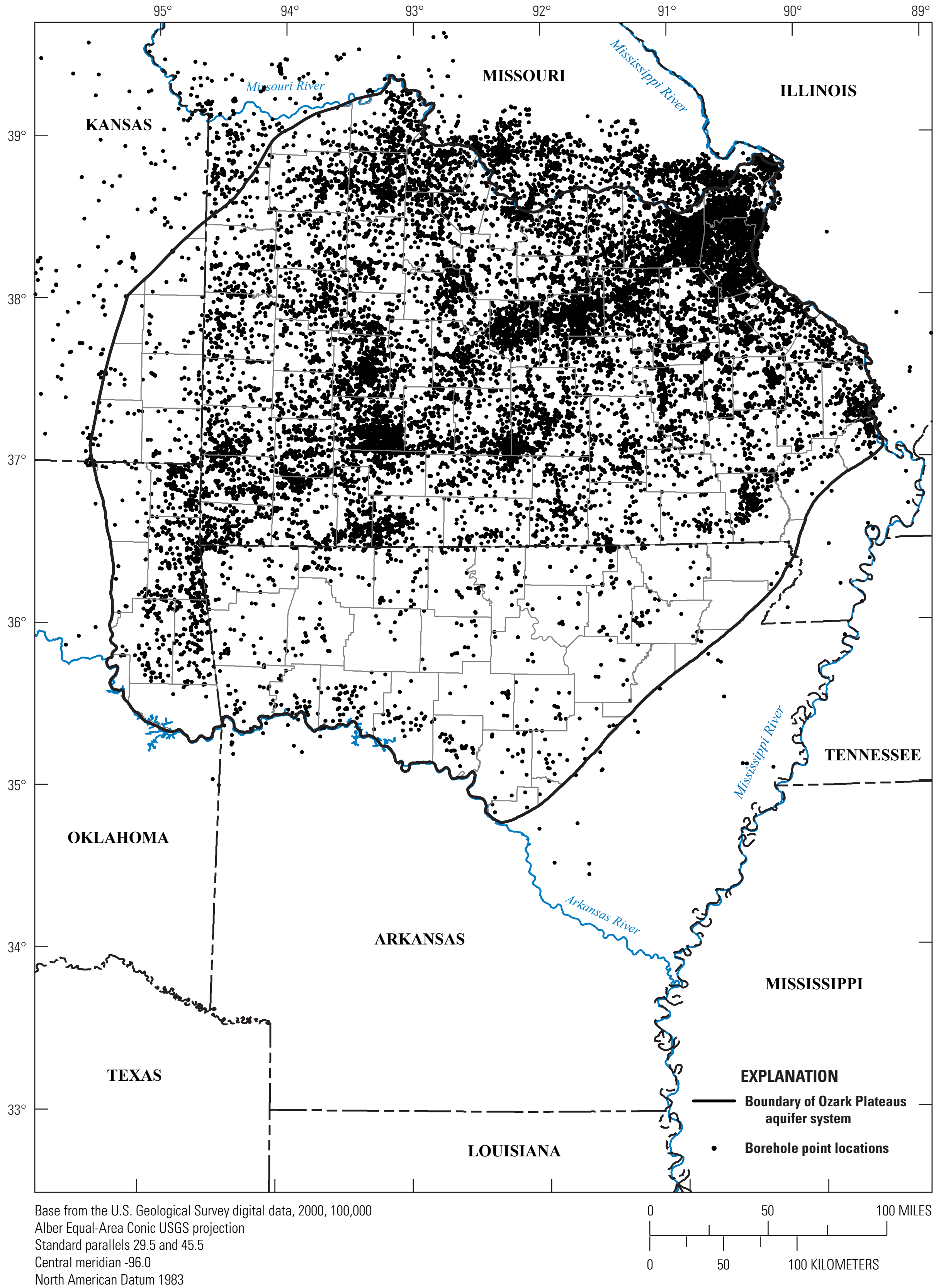


Figure 4. Borehole locations relating to the Ozark Plateaus aquifer system.

The borehole data were checked for completeness, digitized, and assigned spatial coordinates when applicable. The available information varied greatly among the type of data sources. Borehole data either directly provided altitude data for a hydrogeologic unit or the collected information required further interpretation. Lithologic logs provided depth, thickness, and altitude information about the geologic formation penetrated by a borehole, which can be related to the specific hydrogeologic unit of interest. A major source of lithologic information for Missouri was obtained from interpreting geologic formation altitudes using cuttings collected by drillers (Imes and Emmett, 1994). Hydrogeologic unit altitudes were interpreted using geophysical logs of boreholes that consisted of normal-resistivity, spontaneous potential, natural-gamma, induction, and density logs.

The vertical datum of a borehole log is essential for the interpretation of the altitude of hydrogeologic units. Geophysical, lithologic, and driller log vertical datum information was used to aid in the location of the borehole; the final log vertical datum was derived from 10-meter (m) Digital Elevation Model (DEM) data (U.S. Geological Survey, 2014). If the vertical datum reported on the log varied by more than 10 percent from the vertical datum derived from the DEM, the log was not included. Once log compilation and interpretation were completed, the data points representing altitudes for the nine hydrogeologic units were imported into a geographic information system (GIS; Esri, 2010) for further analysis as described below.

The altitude values at each data point were interpolated onto a regular grid of 200-m cells to create a three-dimensional hydrogeologic surface of each unit. The top of the uppermost unit, the Western Interior Plains confining system, was assumed to be land surface based on a 10-m DEM (U.S. Geological Survey, 2014) in all areas outside of the Coastal Plain. The interpolation method for creation of each hydrogeologic surface within a GIS included several steps. To avoid the intersection of surfaces, particularly in areas of thin or absent hydrogeologic units, a uniform spacing of synthetic points was created to better constrain the interpolation for each of the hydrogeologic units. The synthetic points were placed on a regular grid of 36 mi^2, extending beyond the boundaries of the study area to encompass approximately 110,000 total mi^2. Synthetic data values were derived from a regional average of adjacent altitude data points or interpolated thickness derived from nearby known altitudes. Each surface was created using a triangulated irregular network (TIN; Esri, 2010).The TIN was then converted to a grid using the natural neighbor interpolation (Esri, 2010) method and extrapolated data in areas where spatial data gaps existed. To avoid local interpolation errors, additional points and altitude information were added to the synthetic dataset as needed in areas of sparse data in an iterative process. Each hydrogeologic surface was constrained to land surface in the outcrop areas, and outcrop altitudes were taken from a 10-m DEM (U.S. Geological Survey, 2014). Outcrop and subcrop extents were determined from published State geologic maps (Stoeser and others, 2005) and from geophysical-log interpretations.

Statistics were calculated to provide various metrics of model fit based on the difference between the altitude on the geophysical logs and the altitude of the interpolated hydrogeologic surface, commonly known as residuals. These statistics include the minimum, maximum, mean, and root mean square error (RMSE) of the residuals for all data values that are within the study area and within the subcrop area of each respective hydrogeologic unit. The RMSE, in feet, is determined using the equation:

$$\sqrt{\left(h_o - h_s\right)^2} / n$$

where

h_s is simulated hydraulic head, in feet
h_0 is observed hydraulic head, in feet, and
n is number of observations

In general, limitations of data interpolation included areas of sparse data, poorly defined borehole vertical datum, unknown exact extent of each hydrogeologic unit in subcrop, interpolation limitations from sparse altitude data, and values averaged over the 200-m cell grid spacing. Thickness grids for eight hydrogeologic units were created using a GIS to calculate the difference between the altitude of the top of the unit and the altitude of the top of the underlying unit. Maximum, minimum, mean, and median thicknesses are provided for the hydrogeologic units.

For the purposes of this report, the current hydrogeologic framework altitude and thickness grids are considered to be version 1.0. A version number is used to track future updates of the interpretation of the hydrogeologic unit as more data are acquired and the overall understanding of the subsurface changes. Additionally, the term “aquifer” indicates a unit is porous and permeable and therefore, a viable, water-yielding unit (Alley and others, 1999). The term “confining unit” indicates that a unit is of low porosity and permeability and restricts vertical flow from one aquifer unit to another and provides pressure confinement to underlying units. The determination of whether a particular geologic formation or sequence is designated as an aquifer or confining unit is scale and need dependent. In general, a confining unit may contain a locally important groundwater source, while acting regionally as a confining unit. While the designated aquifers vary spatially (horizontally and vertically) in hydraulic properties acting to impede and confine flow in some areas or at some horizons, it was beyond the scope of this report to delineate these differences. Hydrogeologic units were defined on a regional-scale basis to support study objectives.

Characteristics, Altitudes, and Thicknesses of the Hydrogeologic Framework

Evaluation of the hydrogeologic framework was completed by comparing each interpreted altitude grid with the individual altitude points. Residuals were calculated for each hydrogeologic unit, excluding the Western Interior Plains confining unit (because of the use of the DEM), by subtracting an altitude point value from a corresponding altitude grid value. Residuals were not calculated in outcrop areas because altitude values represent the DEM. Residuals help to describe the fit of each grid compared to the data. Each altitude grid had an overall residual mean difference from 0 to -9 ft (table 1). Maximum and minimum residual differences generally were located in subcrop areas where sparse altitude points provided limited interpolation control (such as steeply dipping units and near the southern boundary of the study area). In general, the highest interpreted altitudes coincided with land-surface altitudes located within the outcrop areas of each unit. Minimum interpreted altitudes occurred in the southern part of the study area where each unit dips steeply downward. A detailed discussion of altitude and thickness statistics and altitude point residuals for each hydrogeologic unit is included in the following sections. Hydrogeologic unit and unit extent datasets are downloadable in several formats including American Standard Code for Information Interchange (ASCII) grids, binary raster grids, shapefiles from the USGS ScienceBase catalog (Westerman and others, 2016), and the Web page for the USGS Ozark Plateaus Groundwater Availability Study (U.S. Geological Survey, 2015).

Western Interior Plains Confining System

The Western Interior Plains confining system overlies the Mississippian-age rocks included in the Ozark system and the Western Interior Plains aquifer system (fig. 3). The Western Interior Plains confining system is the uppermost major hydrogeologic unit consisting of a thick sequence of Mississippian and Pennsylvanian-aged sedimentary rocks of low permeability. Facies and lithologic differences as well as differing mapping histories have resulted in different stratigraphic assignments in the four States (fig. 2). The Western Interior Plains confining system overlies the Springfield Plateau aquifer and is exposed at the surface in the northwestern and southern parts of the study area, capping the Ozark system (fig. 3). This confining unit is missing (either from erosion or not having been deposited) in the rest of the study area and in the Mississippi embayment except for isolated remnants. The topography of the surface is characterized by gently rolling hills and broad alluvial valleys.

The altitude of the top of the Western Interior Plains confining system represents the land surface with altitudes ranging from near 200 ft to over 2,500 ft and was developed from a DEM (U.S. Geological Survey, 2014; fig. 5), and the median altitude was 818 ft (table 2). The mean interpreted thickness of the Western Interior Plains confining system was 1,420 ft; the median was 542 ft (table 2). As with all the units, the interpreted thickest sections of the Western Interior Plains

Table 1. Residual summary statistics for the interpretation of the hydrogeologic units in subcrop and within the Ozark Plateaus aquifer system.

[Count refers to the number of data points used in the statistical calculations of altitude; minimum and maximum differences are those measured between the unit correlation altitudes on the geophysical logs and the altitudes of the interpolated digital hydrogeologic surfaces; mean differences (correlation altitude on the geophysical logs minus interpolated digital hydrogeologic surface altitude) is the average difference between the unit correlation altitudes on the geophysical logs and the altitudes of the interpolated digital hydrogeologic surfaces at the location of the geophysical log control point; root mean squared error is the square root of the mean of the square of all of the differences between the unit correlation altitudes on the geophysical logs and the altitudes of the interpolated digital hydrogeologic surfaces; --, no value; negative altitudes are below the North American Vertical Datum of 1988]

Hydrogeologic unit	Count	Minimum difference in subcrop (feet)	Maximum difference in subcrop (feet)	Mean difference in subcrop (feet)	Root mean square error in subcrop (feet)
Western Interior Plains confining system	--[1]	--[1]	--[1]	--[1]	--[1]
Springfield Plateau aquifer	1,169	-413	113	-2	23
Ozark confining unit	3,813	-227	257	-0	14
Upper Ozark aquifer	1,303	-277	308	-1	25
Middle Ozark aquifer	4,143	-211	171	-0	15
Lower Ozark aquifer	5,030	-275	135	-1	15
St. Francois confining unit	1,019	-185	103	-2	20
St. Francois aquifer	1,120	-413	472	-5	40
Basement confining unit	416	-320	359	-9	47

[1]Values for the hydrogeologic unit are land-surface altitudes and therefore no statistics were completed.

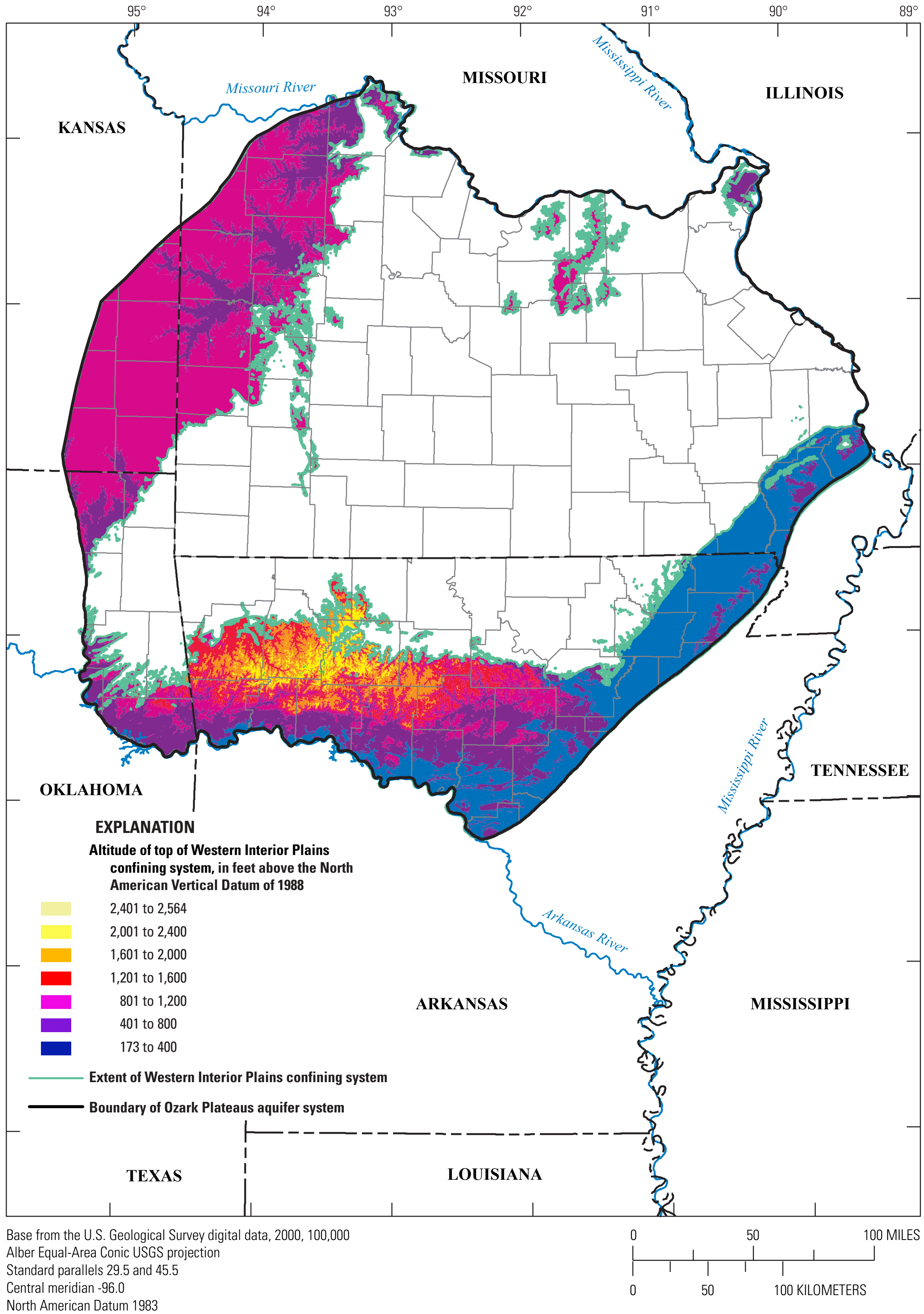


Figure 5. Altitude of the top of the Western Interior Plains confining system within the Ozark Plateaus aquifer system.

Table 2. Summary statistics for the interpreted hydrogeologic units within the Ozark Plateaus aquifer system.

[--, no value; NAVD 88, North American Vertical Datum of 1988]

Hydrogeologic unit	Mean altitude (feet above NAVD 88)	Median altitude (feet above NAVD 88)	Mean depth below land surface (feet)	Median depth below land surface (feet)	Minimum thickness (feet)	Maximum thickness (feet)	Mean thickness (feet)	Median thickness (feet)
Western Interior Plains confining system	809	818	--[1]	--[1]	<1	11,392	1,420	542
Springfield Plateau aquifer	-84	631	1,024	216	<1	1,840	227	237
Ozark confining unit	-268	448	1,207	437	<1	1,609	59	42
Upper Ozark aquifer	-841	255	1,686	648	<1	1,999	649	590
Middle Ozark aquifer	-224	446	1,106	390	<1	2,197	504	416
Lower Ozark aquifer	-429	222	1,309	672	<1	2,687	1,006	885
St. Francois confining unit	-1,420	-581	2,301	1,502	<1	973	235	228
St. Francois aquifer	-1,646	-755	2,526	1,698	<1	1,196	316	291
Basement confining unit	-1,939	-1,005	2,820	1,996	--[1]	--[1]	--[1]	--[1]

[1]Thickness values were not calculated for this hydrogeologic unit.

confining system were located in the southern sections of the Ozark system where the units tend to thicken and dip steeply. The interpreted thinnest sections of the Western Interior Plains confining system were located along the inner extent boundary where the unit has eroded (fig. 6). The thickness of the Western Interior Plains confining system generally increases to the west and south.

Springfield Plateau Aquifer

The Springfield Plateau aquifer is the uppermost hydrogeologic unit in the Ozark system and overlies the Ozark confining unit except in small areas where the Ozark confining unit is absent and then the aquifer is hydraulically connected with the Ozark aquifer. The Springfield Plateau aquifer generally dips gently away from the St. Francois Mountains at the center of the Ozark uplift (Imes and Emmett, 1994). The aquifer is exposed at the surface and generally unconfined in a large part of northwestern Arkansas, southeastern Kansas, southwestern Missouri, and northeastern Oklahoma (fig. 1) and is overlain and confined where the Western Interior Plains confining system is present in much of the northwestern and southern parts of the study area (fig. 3).

In Arkansas, the Boone Formation, which contains the Reeds Spring and St. Joe Limestone Members, composes the Springfield Plateau aquifer (fig. 2). The Boone Formation is a gray, fine- to coarse-grained, fossiliferous limestone with interbedded chert layers. The St. Joe Limestone Member of the Boone Formation is a gray or pink fine-grained limestone. Solution channels and other karst features are well developed in the St. Joe Limestone Member. Persistent chert layers within the Boone Formation can create perched aquifers (Renken, 1998). Springs are common where the Boone Formation is exposed in Arkansas (Hudson and others, 2011).

In southeastern Kansas and southern Missouri, the Burlington and Keokuk Limestones (fig. 2) make up most of the aquifer. Both are medium to coarsely crystalline bedded limestones with variable but commonly abundant gray chert. Solution channels and other karst features are well developed in the upper part of the formation. Overlying formations may also contain bedded shale (Frick, 1980).

In northeastern Oklahoma, the Springfield Plateau aquifer is composed of the Moorefield Formation, the Keokuk Limestone, and the Boone Formation (fig. 2). The Moorefield Formation varies in lithology from limestone to siltstone and shale and is not very permeable. The Keokuk Limestone and the Boone Formation are lithologically similar to the Keokuk and Burlington Limestones in southwestern Missouri, but karst features are not as well developed. The Keokuk Limestone and the Reeds Spring Member of the Boone Formation have substantial chert content that increases from west to east (Imes and Emmett, 1994). The Boone Formation is a coarsely crystalline limestone with interbedded chert, which increases from west to east. The Boone Formation can be present as a highly fractured limestone with dissolution occurring along fractures, resulting in increased secondary porosity (Imes, 1989).

The median interpreted depth below land surface for the Springfield Plateau aquifer was 216 ft (table 2), and the median altitude was 631 ft (fig. 7; table 2). The mean interpreted thickness of the Springfield Plateau aquifer was 227 ft, and the median was 237 ft (fig. 8; table 2). A total of 1,169 Springfield Plateau aquifer altitude points were used to statistically compare to the interpolated surface for goodness of fit (table 1).

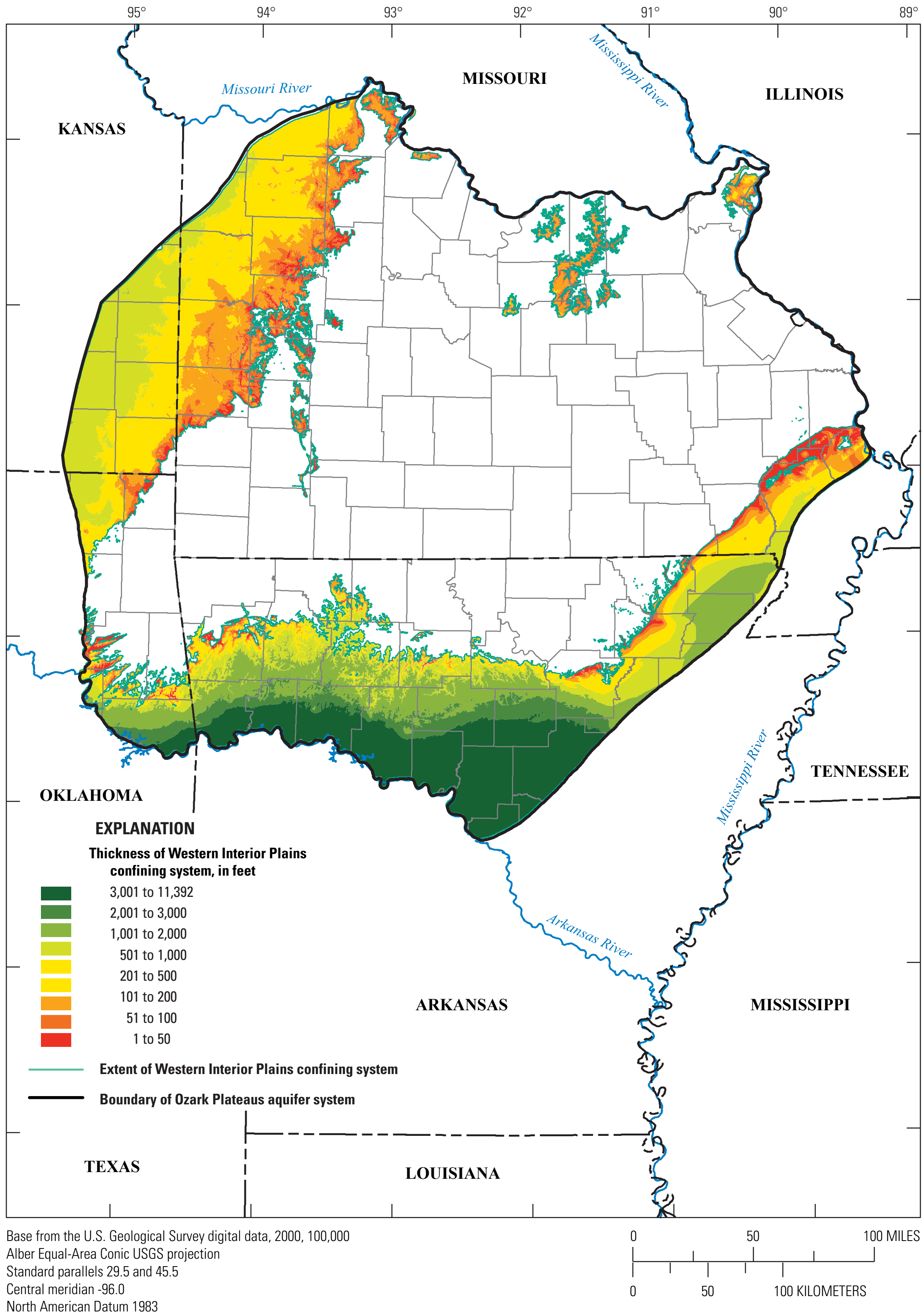


Figure 6. Thickness of the Western Interior Plains confining system within the Ozark Plateaus aquifer system.

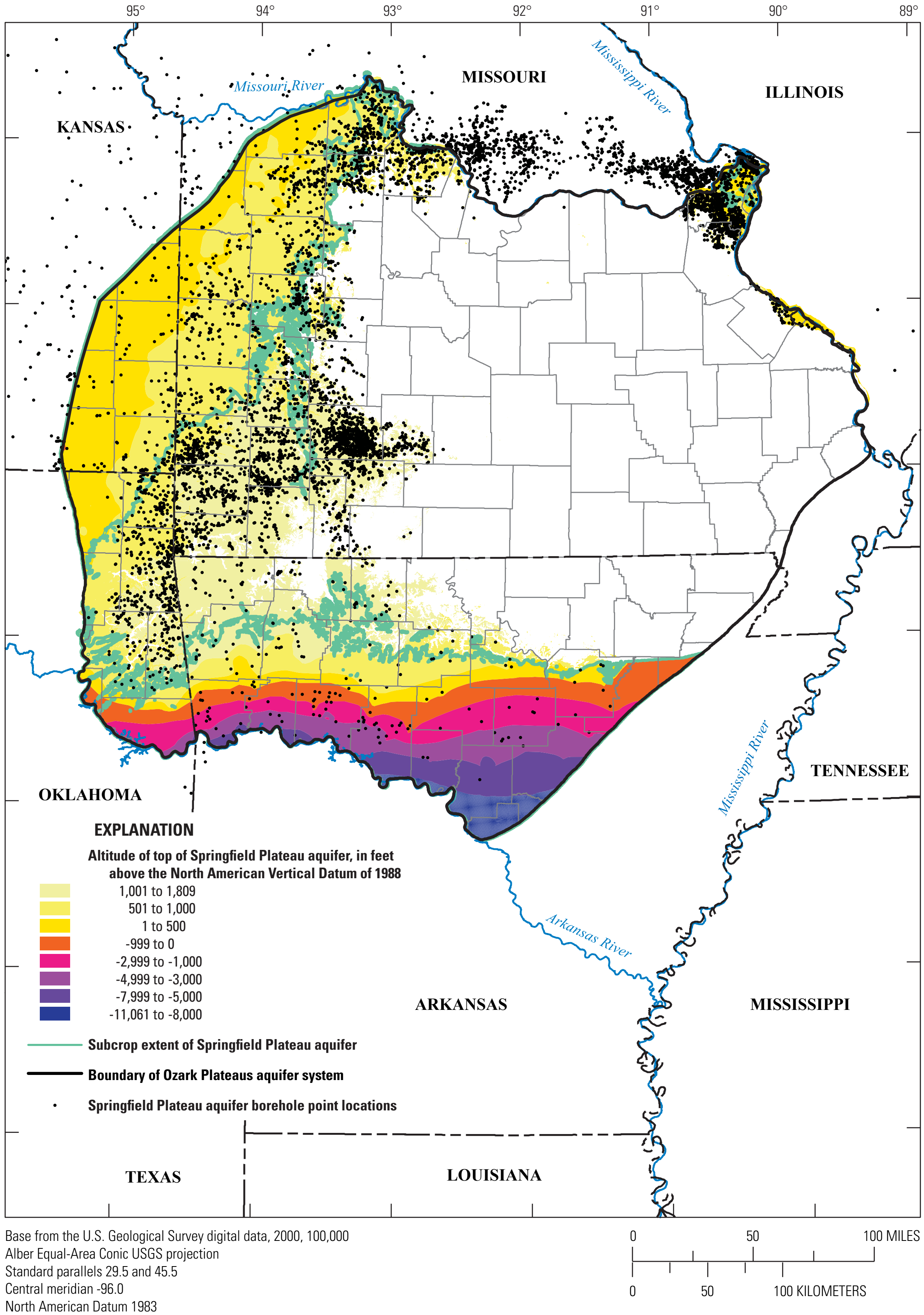


Figure 7. Altitude of the top of the Springfield Plateau aquifer within the Ozark Plateaus aquifer system.

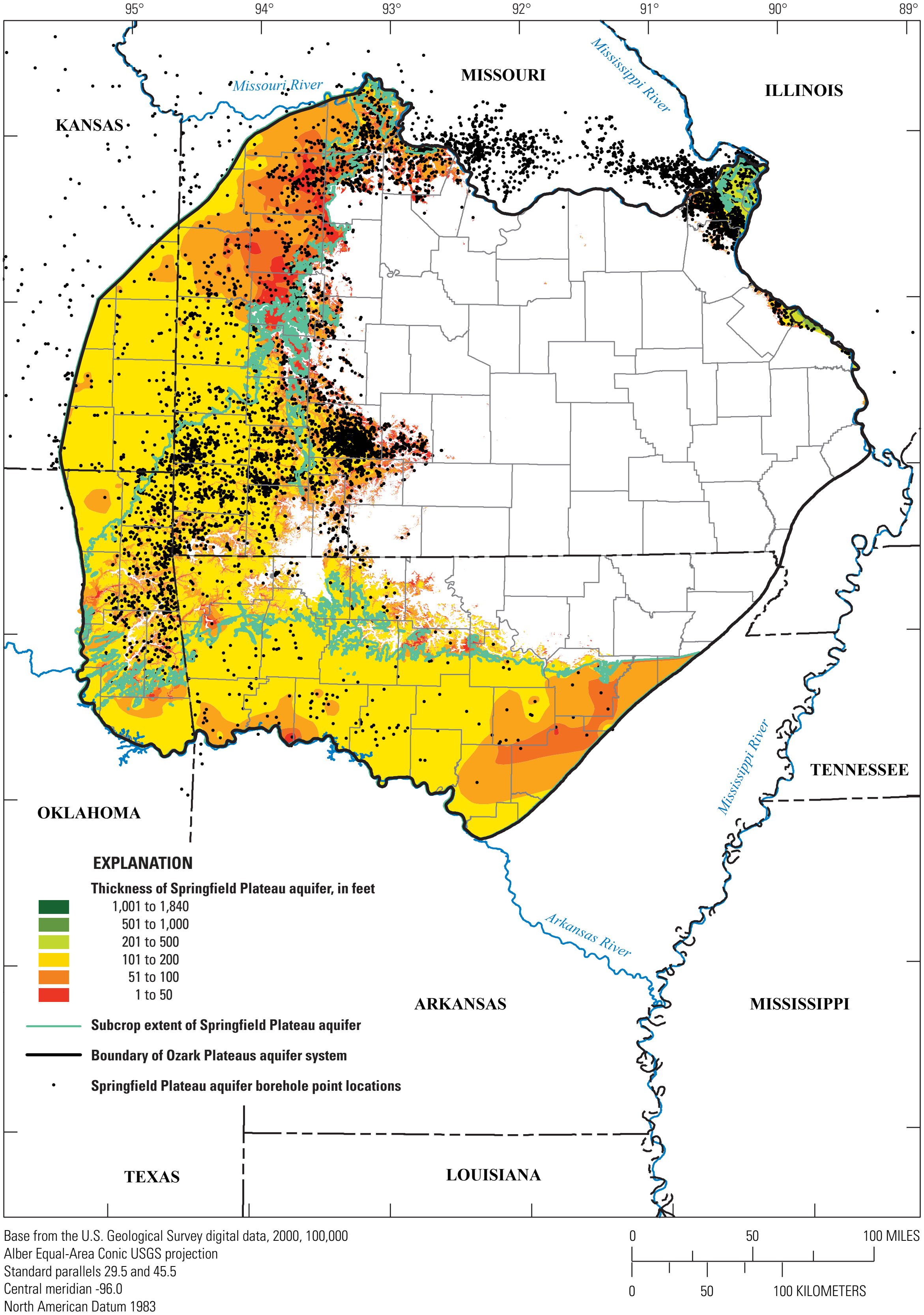


Figure 8. Thickness of the Springfield Plateau aquifer within the Ozark Plateaus aquifer system.

Ozark Confining Unit

The Ozark confining unit is a regionally important unit because it lies between the Springfield Plateau and the Ozark aquifers and impedes groundwater flow between the two aquifer units (fig. 3). The important geologic formations that constitute the confining unit vary across the study area. The confining unit comprises Mississippian-, Devonian-, Silurian-, and Upper Ordovician-age cherts, limestones, sandstones, and shales (fig. 2). In the northern part of the study area, the predominant rock strata are limestones with some shale. There are isolated areas in the northern extent of the Ozark confining system where there is no shale. Shale content reaches 100 percent in the southern part of the study area, in most of Arkansas and Oklahoma, and in the southern counties of Missouri where the confining unit is dominantly represented by the Chattanooga Shale (Imes and Emmet, 1994). However, the Ozark confining unit may be thin or absent in parts of the study area (Imes and Emmet, 1994). The Ozark confining unit thins in a band that trends southeast to northwest across the study area from Newton and Jasper Counties, Missouri, to Labette County, Kansas (Macfarlane and Hathaway, 1987). In eastern Kansas and western Missouri, the confining unit dips gently to the west (fig. 9). The unit dips more sharply along the western and southern limits of the Ozark system in Arkansas and Oklahoma.

The median interpreted depth below land surface for the Ozark confining unit was 437 ft (table 2), and the median altitude was 448 ft (fig. 9; table 2).The Ozark confining unit was the thinnest hydrogeologic unit in the Ozark system with a mean interpreted thickness of 59 ft and a median interpreted thickness of 42 ft (table 2). The Ozark confining unit is thin, less than 50 ft for much of the Ozark system, but does thicken to more than 100 ft in northern Missouri and parts of Kansas (fig. 10). The interpreted thickness for the Ozark confining unit across much of Arkansas was 20 to 40 ft. A total of 3,813 Ozark confining unit altitude points were used to statistically compare to the interpolated surface for goodness of fit (table 1).

Ozark Aquifer

The Ozark aquifer is the primary groundwater source in the study area. The Ozark aquifer is exposed in southern Missouri and northern Arkansas (fig. 3), is faulted and fractured, and is heavily dissected by surface drainage (McCracken, 1964). Except where the Ozark aquifer is exposed or where the Ozark confining unit is missing, the aquifer is overlain by the Ozark confining unit and overlies the St. Francois confining unit. The Ozark aquifer is in direct hydraulic connection with the overlying Springfield Plateau aquifer in some isolated places where the Ozark confining unit is missing. The Ozark aquifer generally dips away from the St. Francois Mountains at the center of the Ozark uplift and dips steeply to the south in central Arkansas.

Upper Ozark Aquifer

The upper Ozark aquifer is composed of Devonian-, Silurian-, and Late Ordovician-age limestones, sandstones, shales, and dolomites (fig. 2). Groundwater is primarily produced from the limestones, dolomites, and sandstones of the upper Ozark aquifer. The dominant water bearing formations are the St. Peter Sandstone and the Everton Formation (Imes and Emmet, 1994; fig. 2). The St. Peter Sandstone is generally a massive bedded sandstone with some interbedded shale, limestone, or dolomites. The Everton Formation varies considerably in lithology at different locations across the study area, being variously represented by sandy dolomite, sandstone, and limestone, or interbedded units of multiple lithologies. The Burgen Sandstone of northeastern Oklahoma correlates with the St. Peter Sandstone and exhibits similar lithology (Huffman, 1958).

The upper Ozark aquifer is present across much of the Salem Plateau, is exposed to the east, north, and south, of the Ozark uplift, and is exposed in some deeply incised streams and on uplifted fault blocks within the Springfield Plateau. The upper Ozark aquifer is unconfined where it is exposed across the Salem Plateau and confined where present in the subsurface in the Springfield Plateau and Boston Mountain sections. Karst development is less pronounced in the upper Ozark aquifer, and primary porosity, permeability, and yield tend to be lower in the upper Ozark aquifer than in the lower Ozark aquifer.

The median interpreted depth below land surface for the upper Ozark aquifer was 648 ft (table 2), and the median altitude was 255 ft (fig. 11; table 2).The mean and median interpreted thicknesses of the upper Ozark aquifer were 649 and 590 ft, respectively (table 2). The interpreted thickness of the upper Ozark aquifer was several hundred feet in Arkansas, but the unit thins considerably to 50 ft or less into Kansas and parts of Missouri (fig. 12). A total of 1,303 upper Ozark aquifer altitude points were used to statistically compare to the interpolated surface for goodness of fit (table 1).

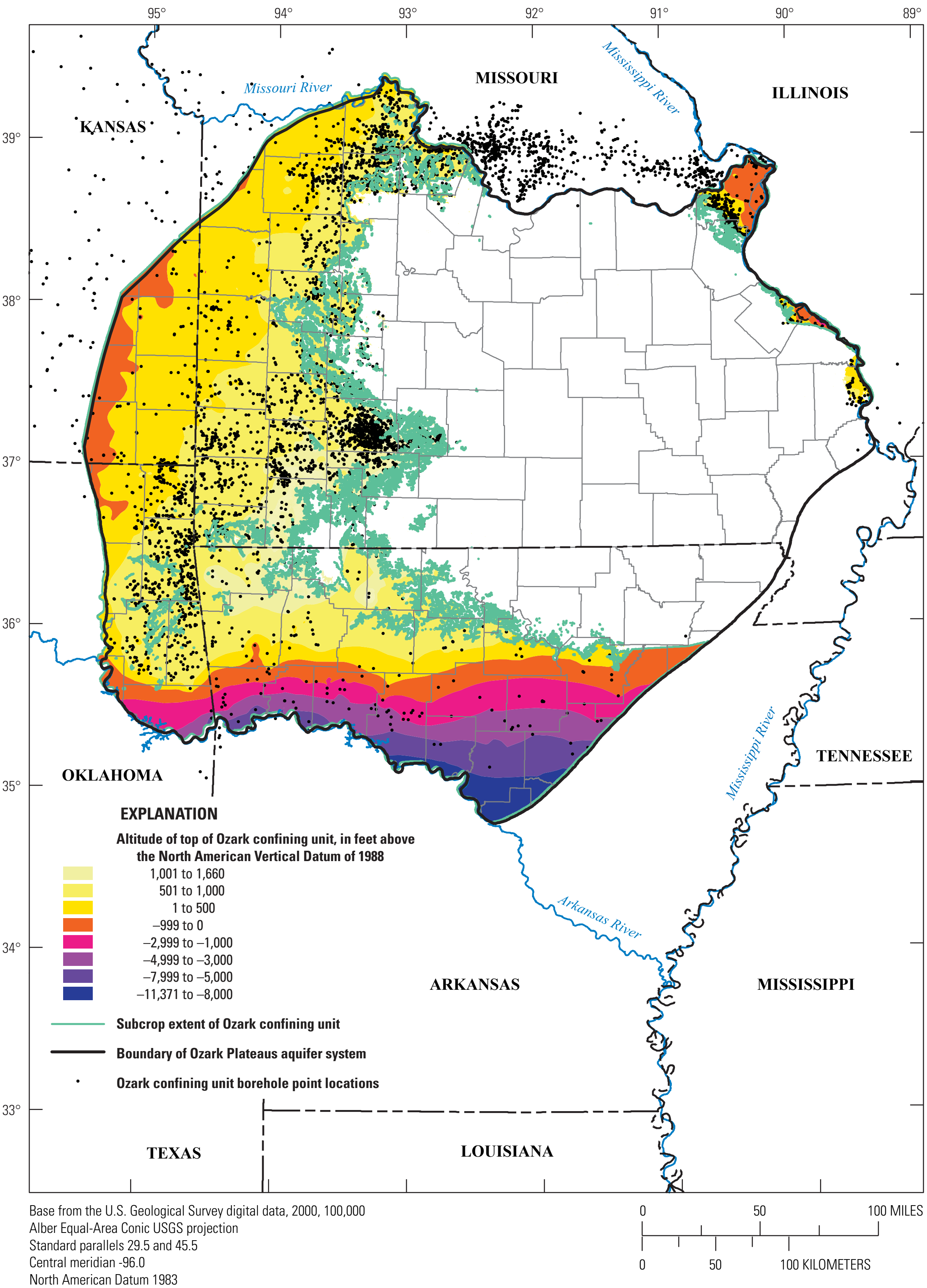


Figure 9. Altitude of the top of the Ozark confining unit within the Ozark Plateaus aquifer system.

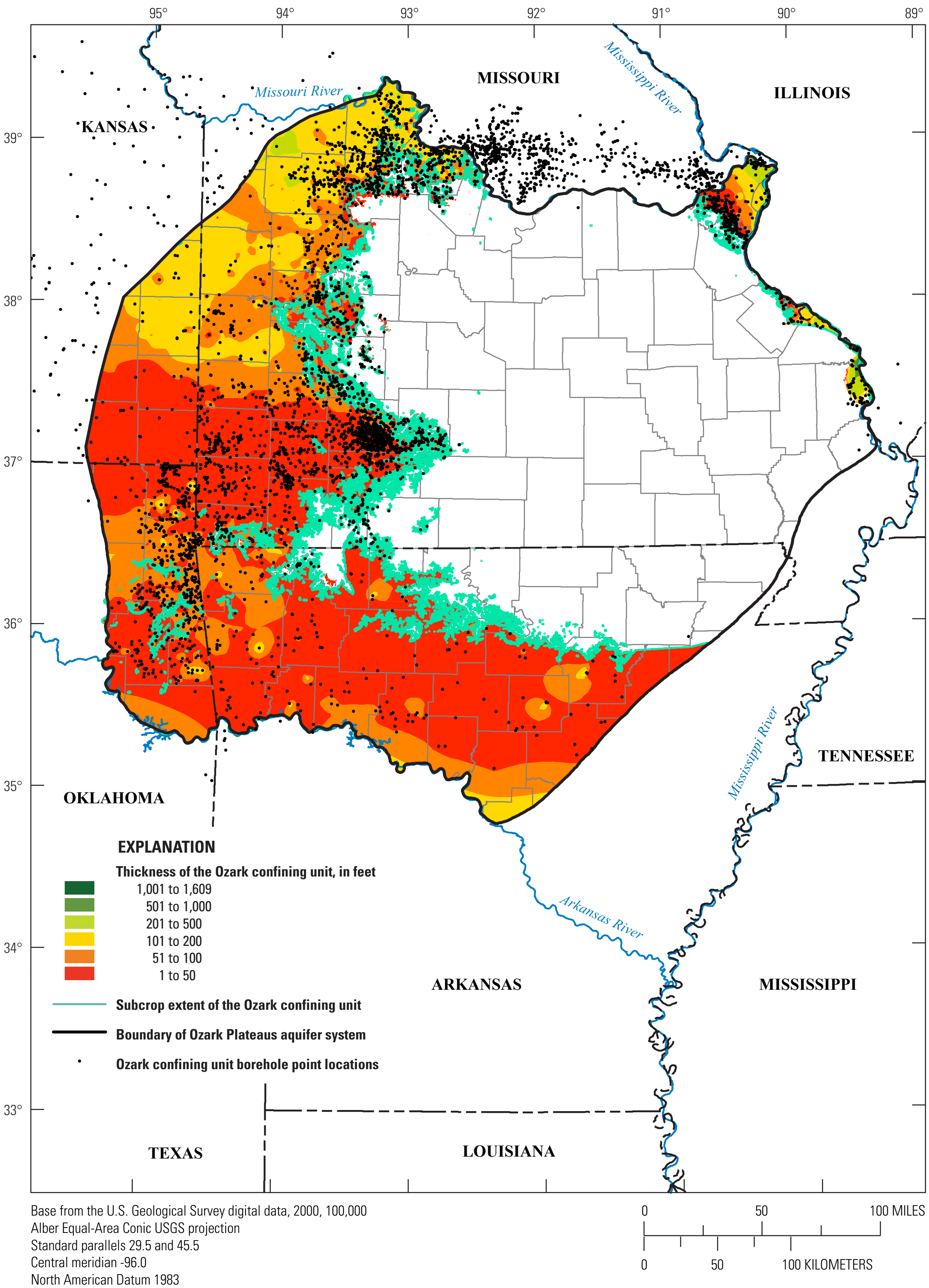


Figure 10. Thickness of the Ozark confining unit within the Ozark Plateaus aquifer system.

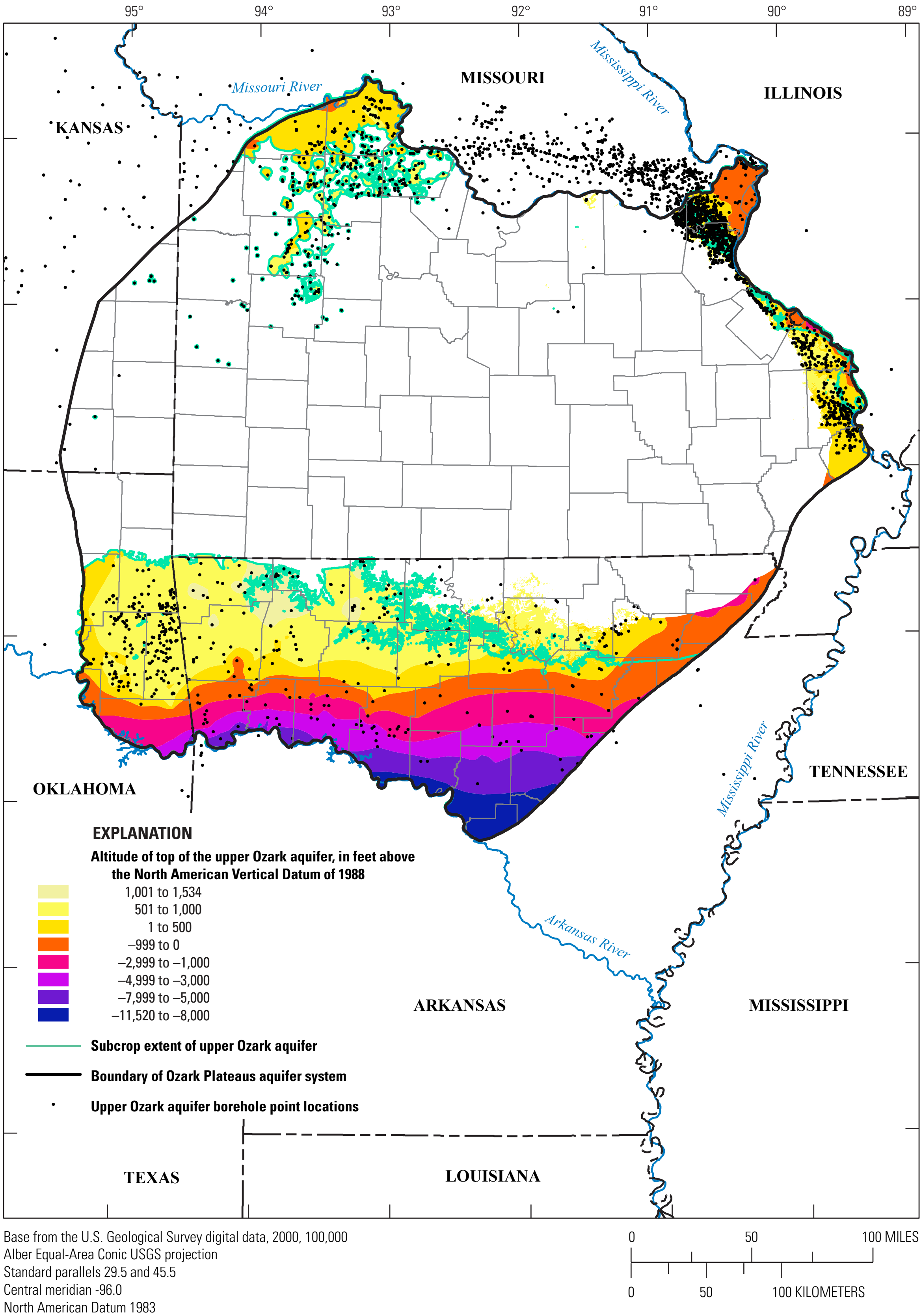


Figure 11. Altitude of the top of the upper Ozark aquifer within the Ozark Plateaus aquifer system.

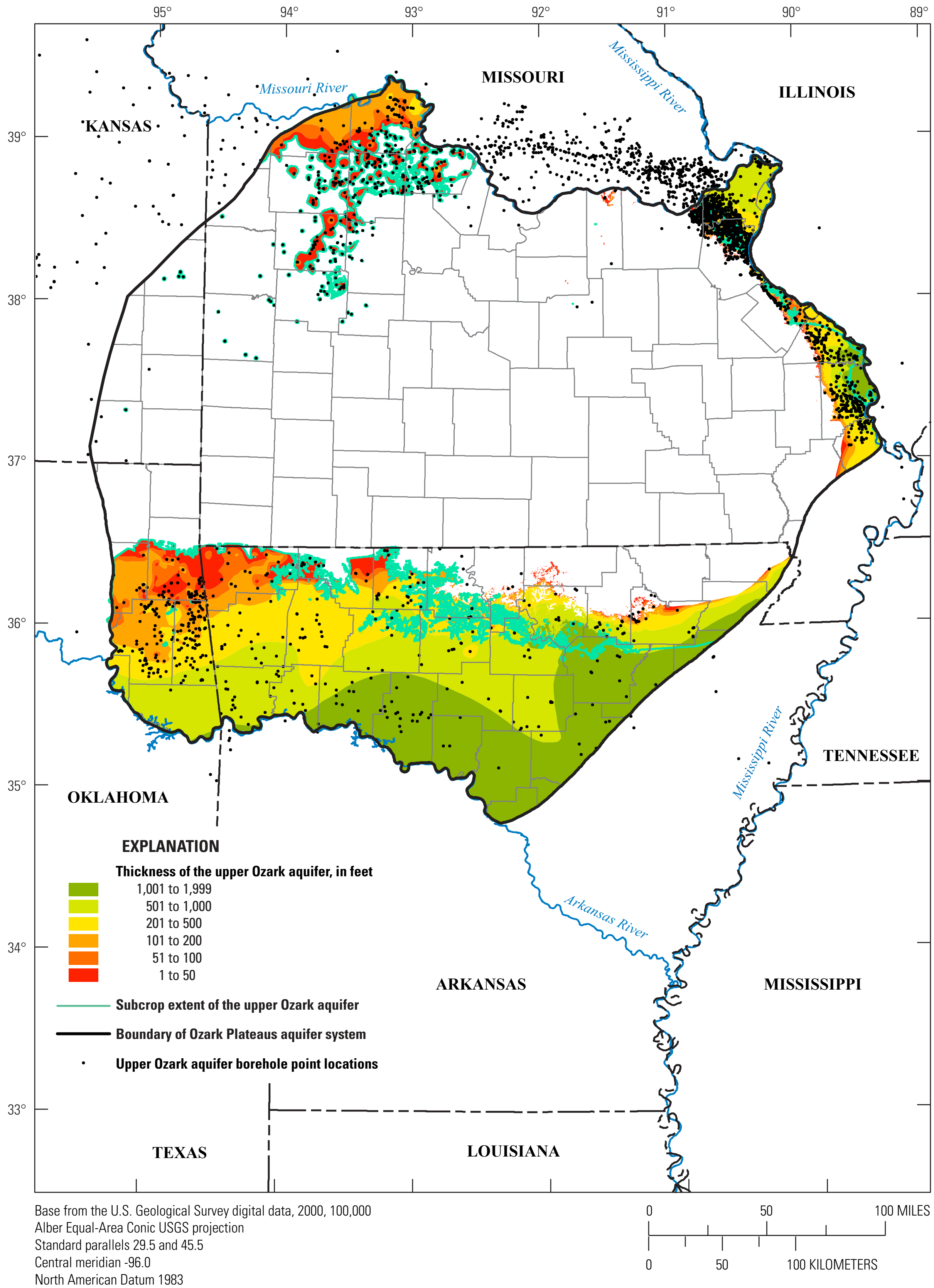


Figure 12. Thickness of the upper Ozark aquifer within the Ozark Plateaus aquifer system.

Middle Ozark Aquifer

The middle Ozark aquifer is composed of the Ordovician-age Cotter Dolomite and Jefferson City Dolomite of light- to dark-tan, fine- to medium-grained dolomite with chert and some thin beds of sandstone and shale. These two formations are indistinguishable in parts of the study area (McFarland, 1998). The hydraulic characteristics contrast markedly with bounding units and as such may impede the flow of water into the underlying lower Ozark aquifer. The middle Ozark aquifer yields water in quantities sufficient for domestic supply and livestock watering but it does not serve as a regionally important aquifer. For high yields, wells are commonly open to both the middle and lower Ozark aquifer.

The median interpreted depth below land surface for the middle Ozark aquifer was 390 ft (table 2) , and the median altitude was 446 ft (fig. 13; table 2).The mean interpreted thickness of the middle Ozark aquifer was 504 ft, and the median was 416 ft (table 2). The thickest interpreted sections of the middle Ozark aquifer were within an east to west trending band in northern Arkansas where values range from 500 to more than a 1,000 ft in thickness (fig. 14). A total of 4,143 middle Ozark aquifer altitude points were used to statistically compare to the interpolated surface for goodness of fit (table 1).

Lower Ozark Aquifer

The lower Ozark aquifer is the major water producing hydrogeologic unit in the study area (Kresse and others, 2014). This area has one of the greatest densities of first-magnitude springs (average flow that exceeds 100 cubic feet per second; Meinzer, 1927) in the United States (Vineyard and Feder, 1974).

The lower Ozark aquifer is composed of Early Ordovician- and Late Cambrian-age limestones, dolomites, sandstones, and shales (fig. 2). The lower Ozark aquifer is exposed and unconfined within the central and eastern area of the Salem Plateau (fig. 3). The dominant hydrogeologic units include the Roubidoux Formation, Gasconade Dolomite, the Gunter Sandstone Member of the Van Buren Formation, the Eminence Dolomite, and the Potosi Dolomite. The Roubidoux Formation is primarily composed of dolomite, sandstone, and chert (Caplan, 1960; Howe and Koenig, 1961; Imes and Emmet, 1994; Adamski and others, 1995). The water-bearing sandstones consist of discontinuous beds of white to light-gray quartz (Snyder, 1976; MacDonald and others, 1977). The Gasconade Dolomite and Van Buren Formation are composed primarily of light-colored dolomite containing chert, and both typically are undifferentiated in Arkansas and parts of Missouri. The Gunter Sandstone Member is mainly composed of white to light-gray quartz sandstone and dolomite. In the southern parts of the study area, the Eminence and Potosi Dolomites generally are undifferentiated (Caplan, 1960; McCracken, 1964).

The median interpreted depth below land surface for the lower Ozark aquifer was 672 ft (table 2), and the median altitude was 222 ft (fig. 15; table 2). The mean interpreted thickness of the lower Ozark aquifer was 1,006 ft, and the median was 885 ft (table 2). Beginning near the Mississippi embayment along the southeastern part of the Ozark system, interpreted thickness values are greater than 2,000 ft, and the unit continues to be 800 ft thick or more into most of Missouri (fig. 16). The lower Ozark aquifer is considered the most important part of the Ozark system because of the distribution, accessibility, thickness, and hydrologic properties of the aquifer. A total of 5,030 lower Ozark aquifer altitude points were used to statistically compare to the interpolated surface for goodness of fit (table 1).

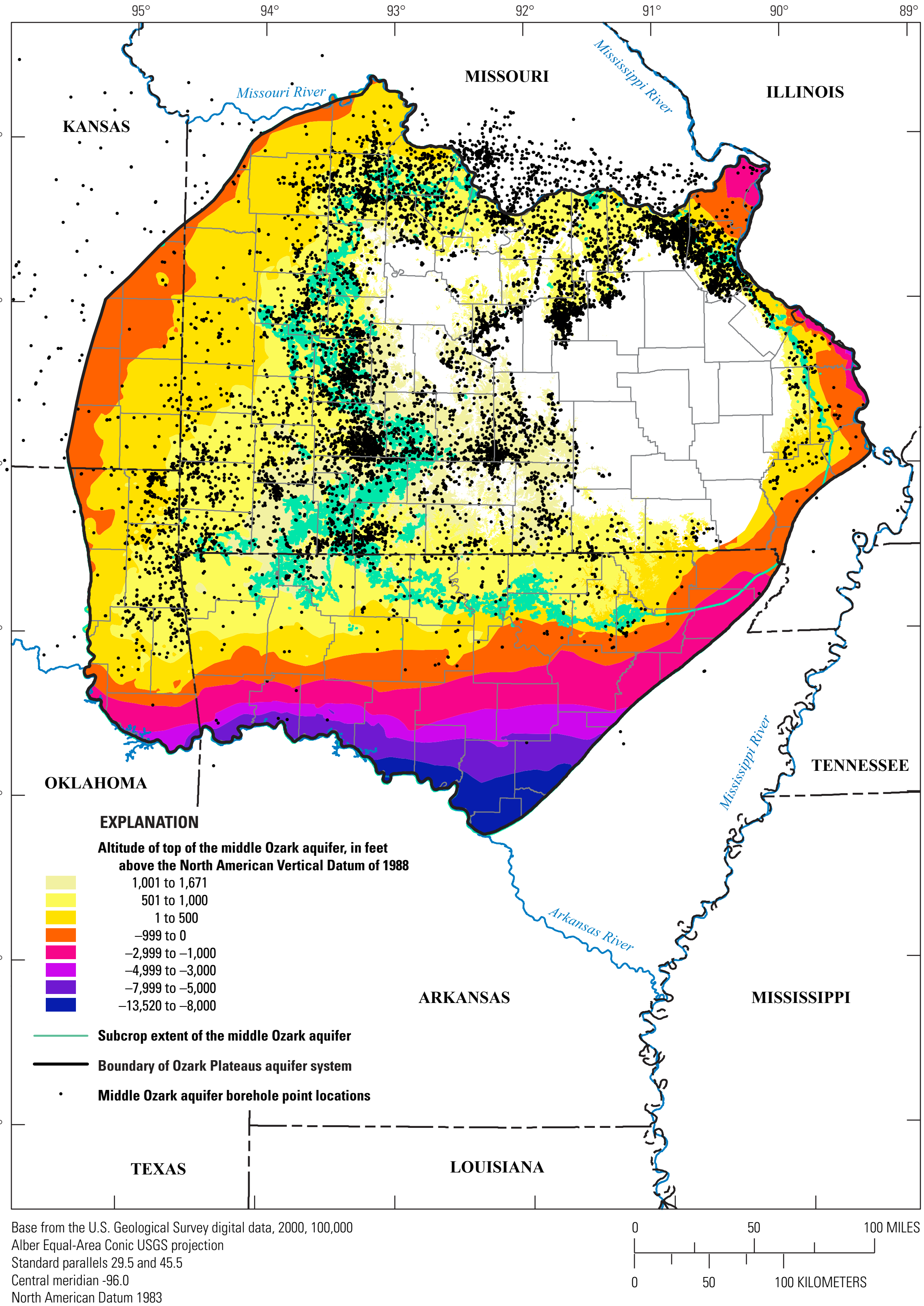


Figure 13. Altitude of the top of the middle Ozark aquifer within the Ozark Plateaus aquifer system.

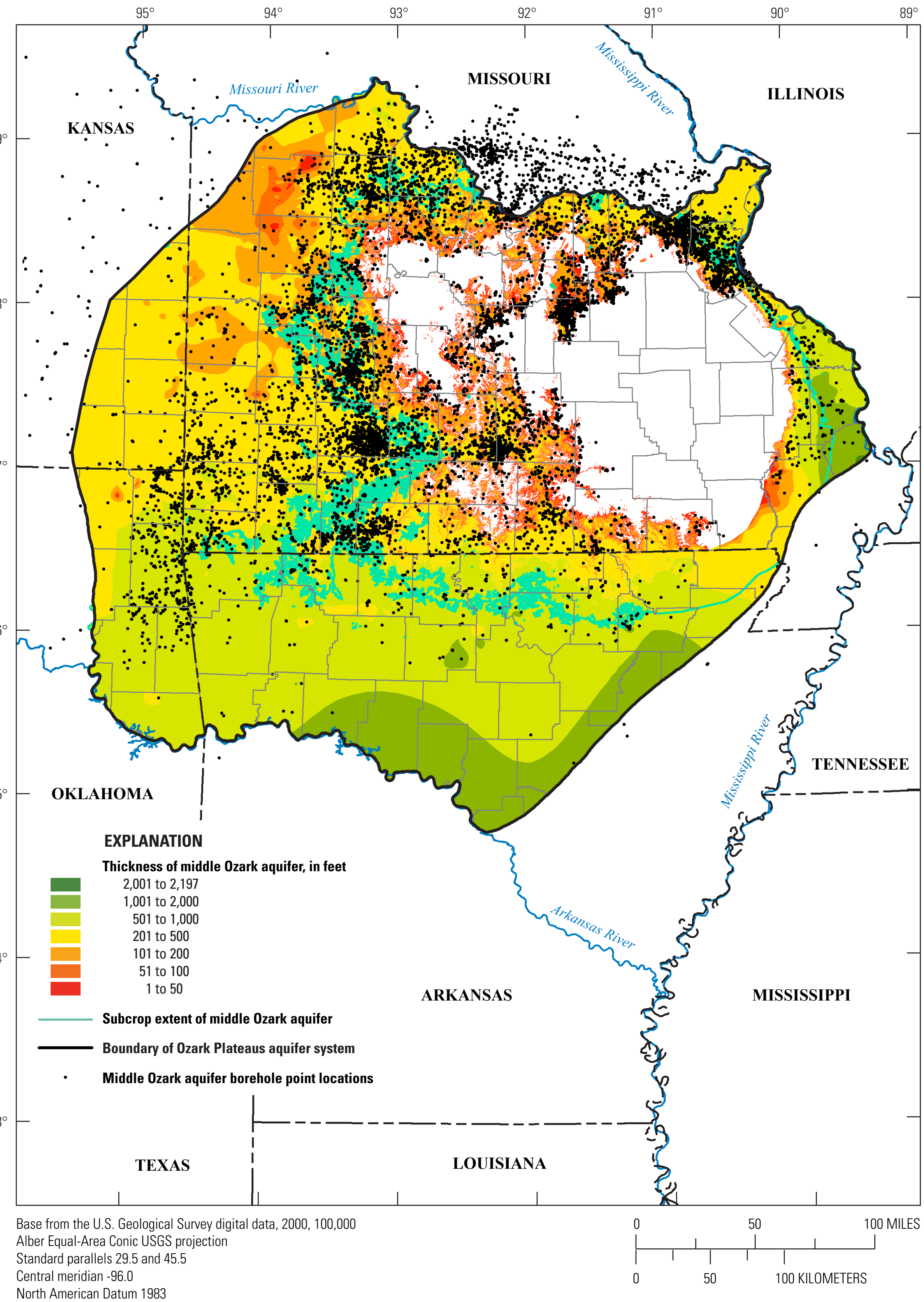


Figure 14. Thickness of the middle Ozark aquifer within the Ozark Plateaus aquifer system.

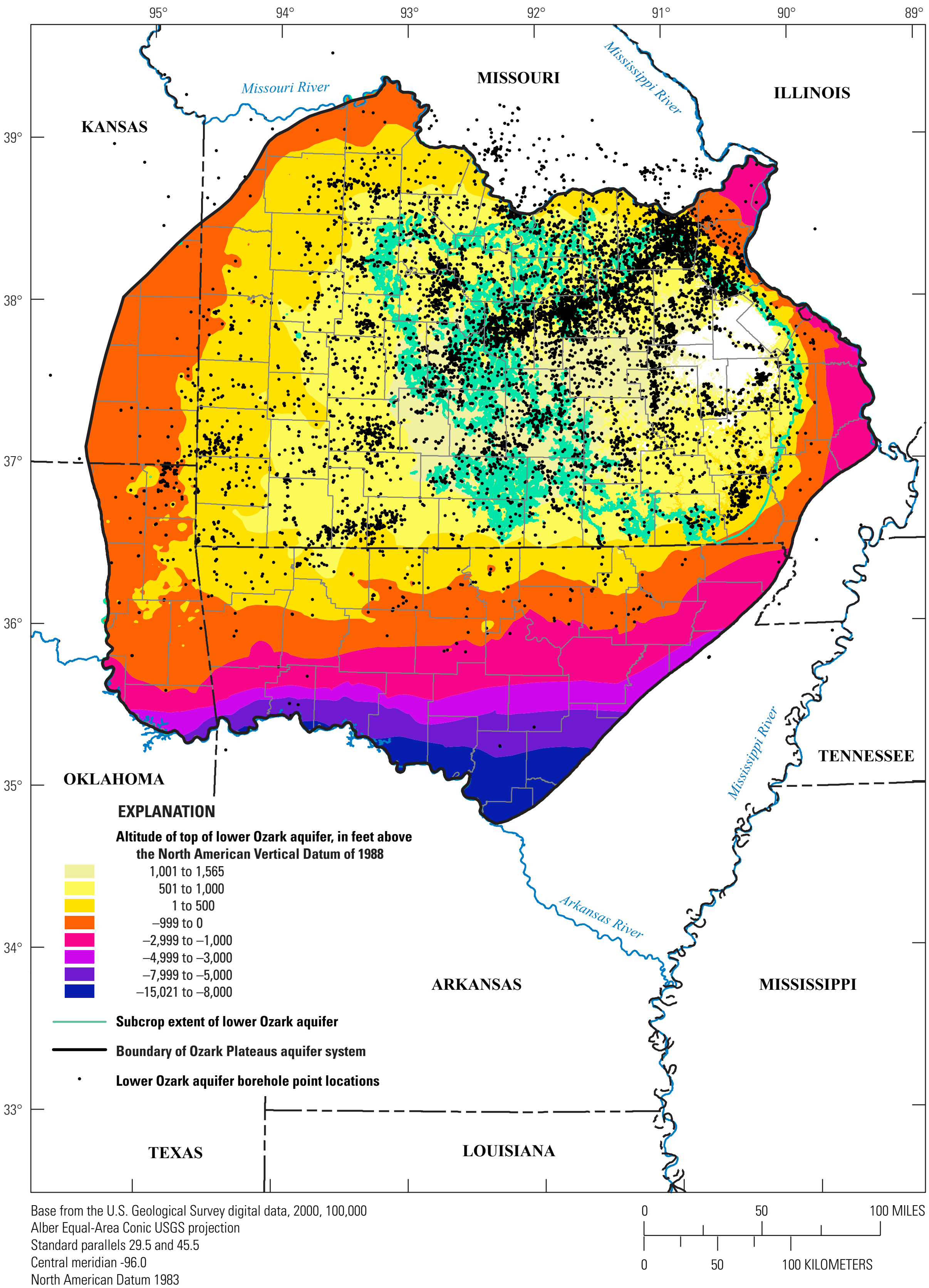


Figure 15. Altitude of the top of the lower Ozark aquifer within the Ozark Plateaus aquifer system.

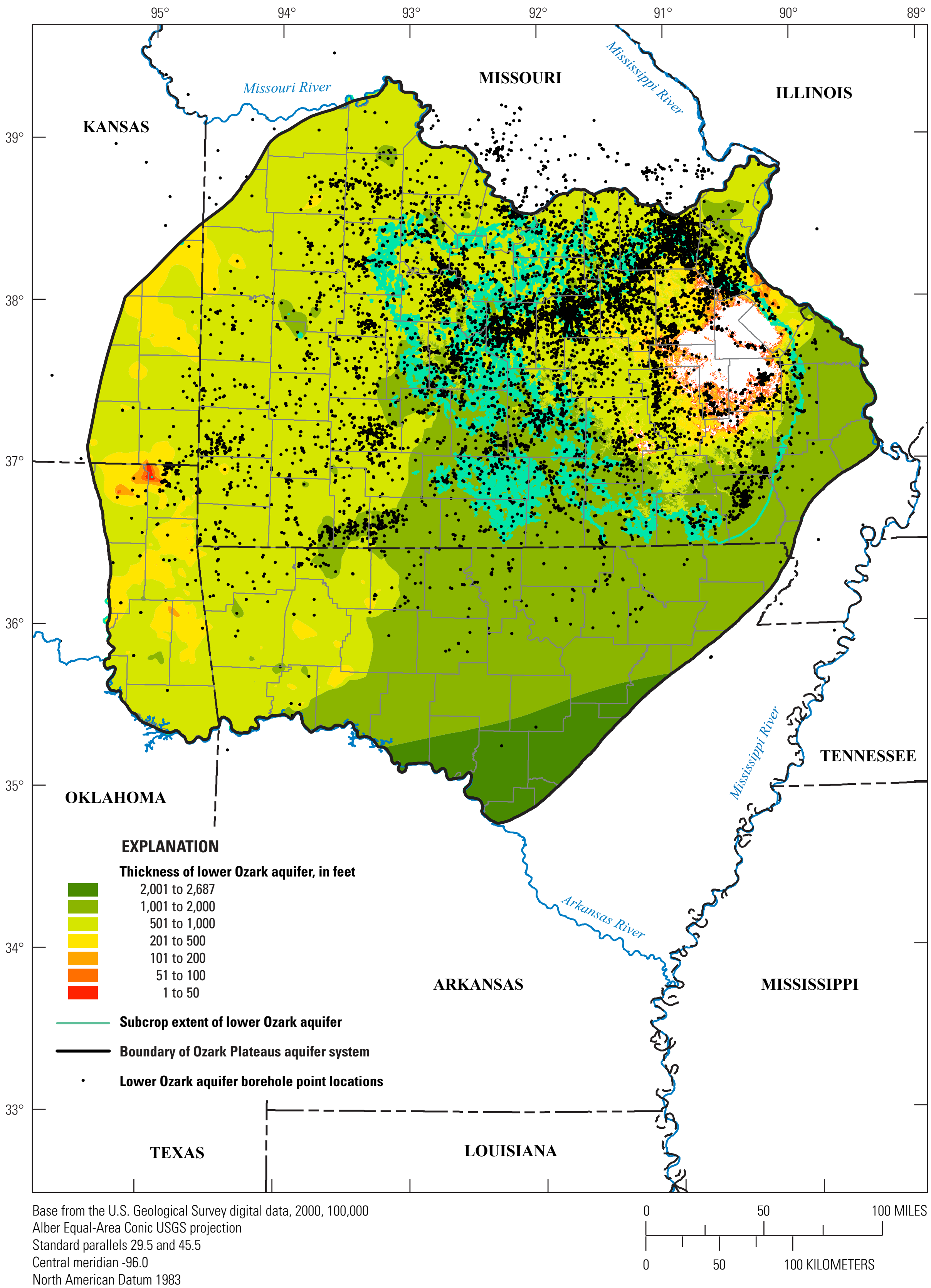


Figure 16. Thickness of the lower Ozark aquifer within the Ozark Plateaus aquifer system.

St. Francois Confining Unit

The St. Francois confining unit hydraulically separates the overlying lower Ozark aquifer from the underlying St. Francois aquifer. The confining unit is exposed around the Ozark uplift and is absent where it has been removed by erosion in the St. Francois Mountains; the confining unit also is thin or absent in the subsurface in isolated areas of western Missouri, northeastern Oklahoma, and northwestern Arkansas (Imes and Emmet, 1994). The unit consists of the Late Cambrian-age Doe Run Formation, Derby Formation, and Davis Formation. This confining unit is composed of intervals of relatively low permeability shale, siltstone, dolomite, and limestone.

The median interpreted depth below land surface for the St. Francois confining unit was 1,502 ft (table 2), and the median altitude was -581 ft (fig. 17; table 2). The mean interpreted thickness of the St. Francois confining unit was 235 ft, and the median was 228 ft (table 2). Interpreted thickness values indicate that the St. Francois confining unit is less than 100 ft in large parts of Oklahoma, Kansas, and along the western parts of both Arkansas and Missouri (fig. 18). For large parts of Missouri, the interpreted thickness is 200 ft or greater. In the southernmost part of the Ozark system and along the Mississippi River in Missouri, the interpreted thickness values increase to over 900 ft. A total of 1,019 St. Francois confining unit altitude points were used to statistically compare to the interpolated surface for goodness of fit (table 1).

St. Francois Aquifer

The St. Francois aquifer overlies the basement confining unit and is overlain by the St. Francois confining unit. The aquifer is composed of Upper Cambrian-age dolomite and sandstone from the Bonneterre Formation (also called the Bonneterre Dolomite or undefined units equivalent to the Bonneterre Dolomite depending on State), Reagan Sandstone, and Lamotte Sandstone. The St. Francois aquifer is exposed in the St. Francois Mountains near the center of the Ozark uplift (fig. 3). The St. Francois aquifer is not an important source of groundwater over much of the study area, but it is locally important in the St. Francois Mountains area.

The median interpreted depth below land surface for the St. Francois aquifer was 1,698 ft (table 2), and the median altitude was –755 ft (fig. 19; table 2). The mean interpreted thickness of the St. Francois aquifer was 316 ft, and the median was 291 ft (table 2). The unit dips away from the Ozark uplift in all directions and dips steeply in the southern part of the study area (fig. 19). The interpreted thicknesses for the St. Francois aquifer are thinnest in the western part of the Ozark system and through the north-central section of Arkansas but increases in thickness in Missouri and along the eastern boundary of the Ozark system (fig. 20). A total of 1,120 St. Francois aquifer altitude points were used to statistically compare to the interpolated surface for goodness of fit (table 1).

Basement Confining Unit

The basement confining unit underlies the St. Francois aquifer and is considered the base of the aquifer system. The unit primarily consists of Precambrian-age rhyolite-granite sequences and metamorphic rocks that are nearly impermeable. The unit forms the structural base for which subsequent sedimentary units are overlain, and, therefore, affects the presence, thickness, and structure of the overlying units. The basement confining unit is exposed on structural highs at the St. Francois Mountains in southeastern Missouri and at small areas in southwestern Missouri (fig. 3).

The median interpreted depth below land surface for the basement confining unit was 1,996 ft (table 2), and the median altitude was -1,005 ft (fig. 21; table 2). The altitude of the top of the basement confining unit declines sharply to the south and southeast. A total of 416 basement confining unit altitude points were used to statistically compare to the interpolated surface for goodness of fit (table 1).

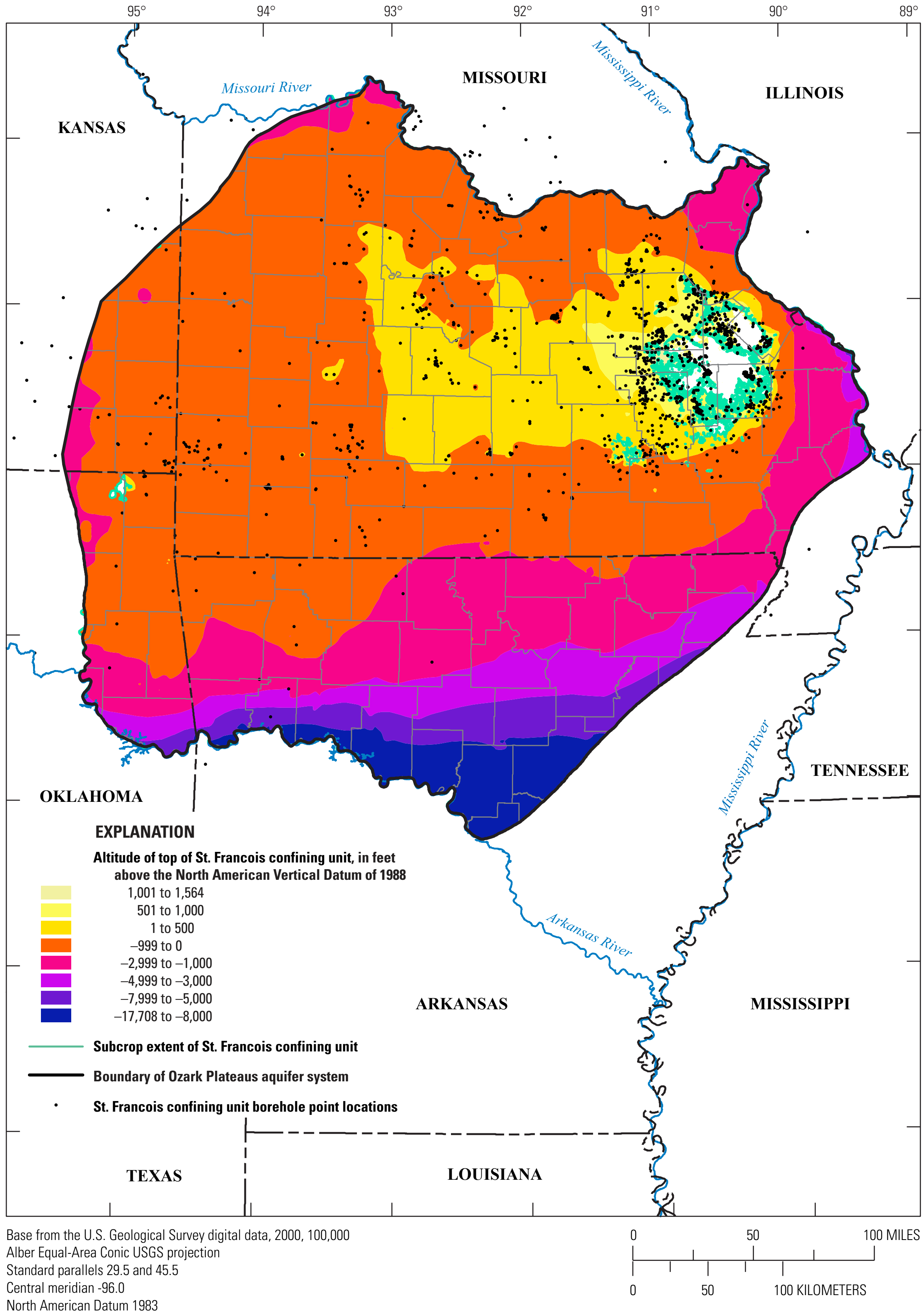


Figure 17. Altitude of the top of the St. Francois confining unit within the Ozark Plateaus aquifer system.

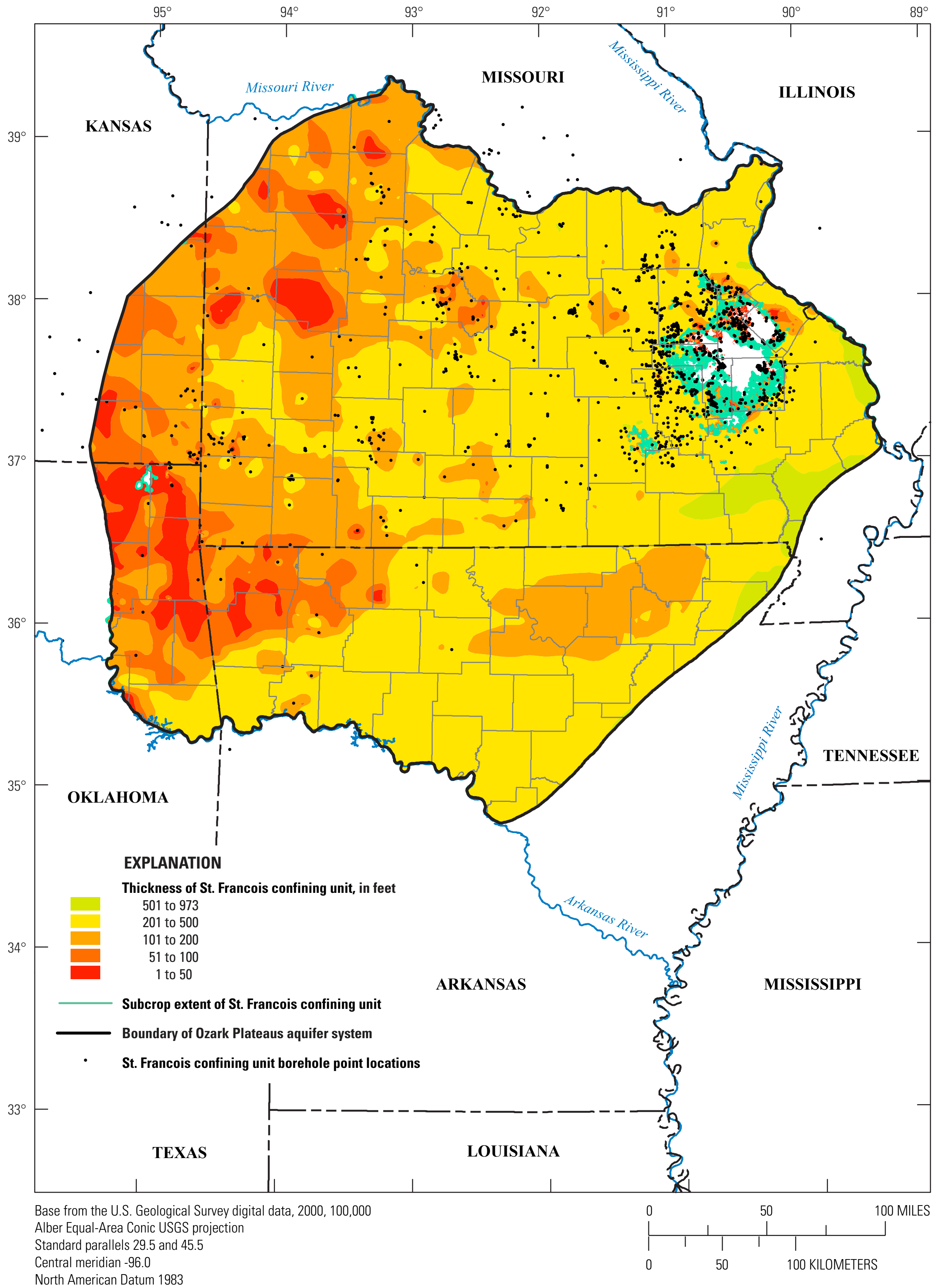


Figure 18. Thickness of the St. Francois confining unit within the Ozark Plateaus aquifer system.

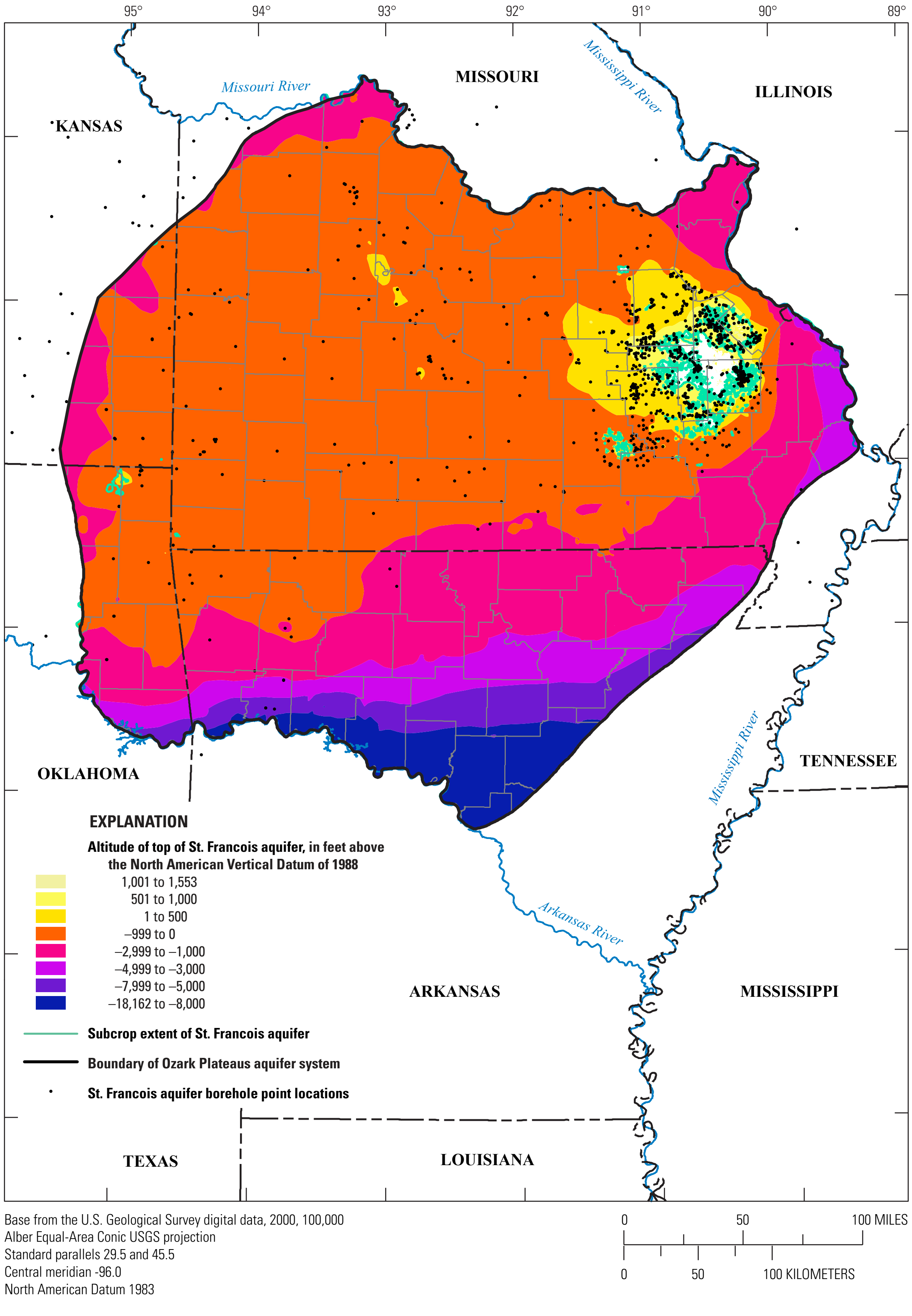


Figure 19. Altitude of the top of the St. Francois aquifer within the Ozark Plateaus aquifer system.

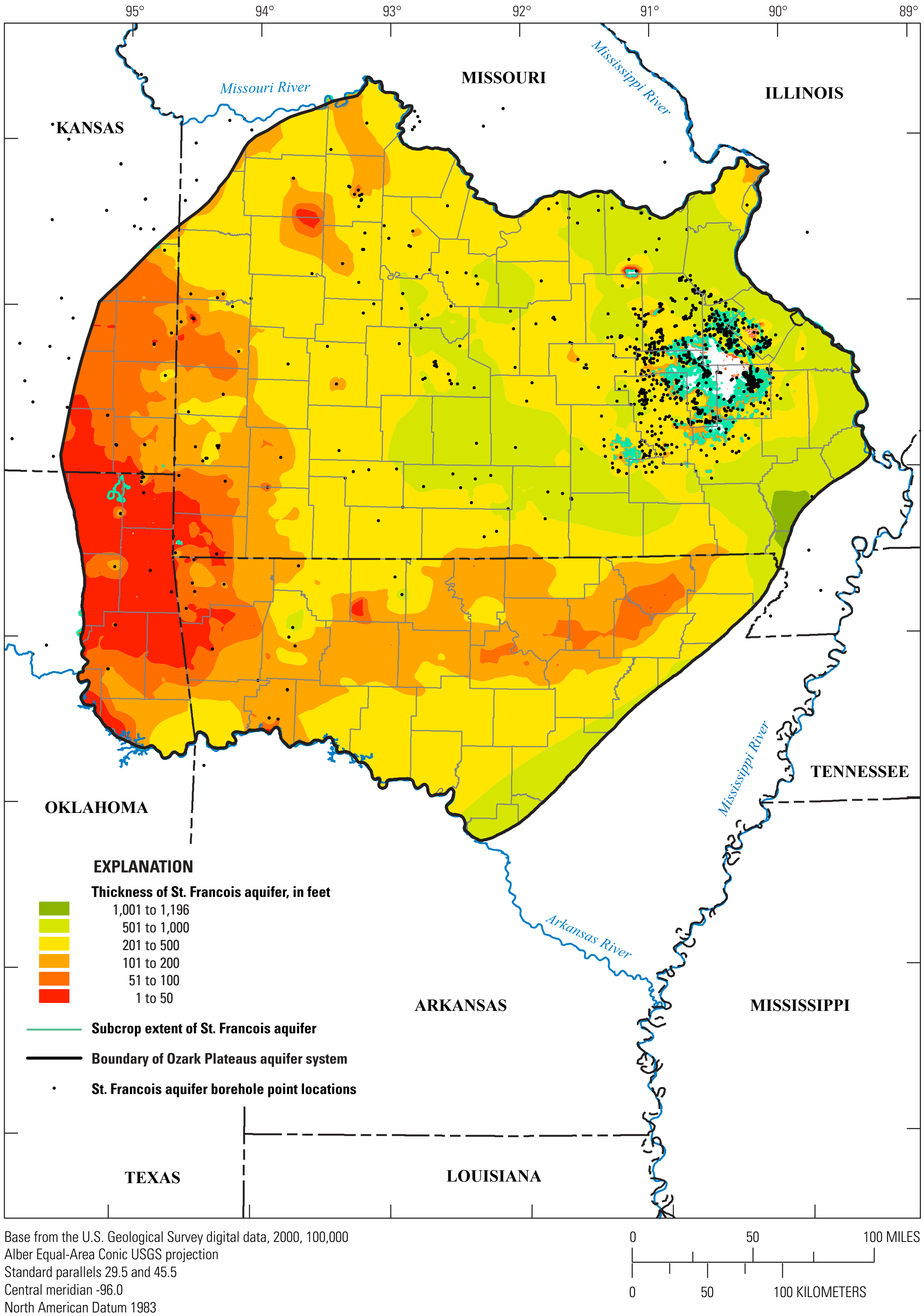


Figure 20. Thickness of the St. Francois aquifer within the Ozark Plateaus aquifer system.

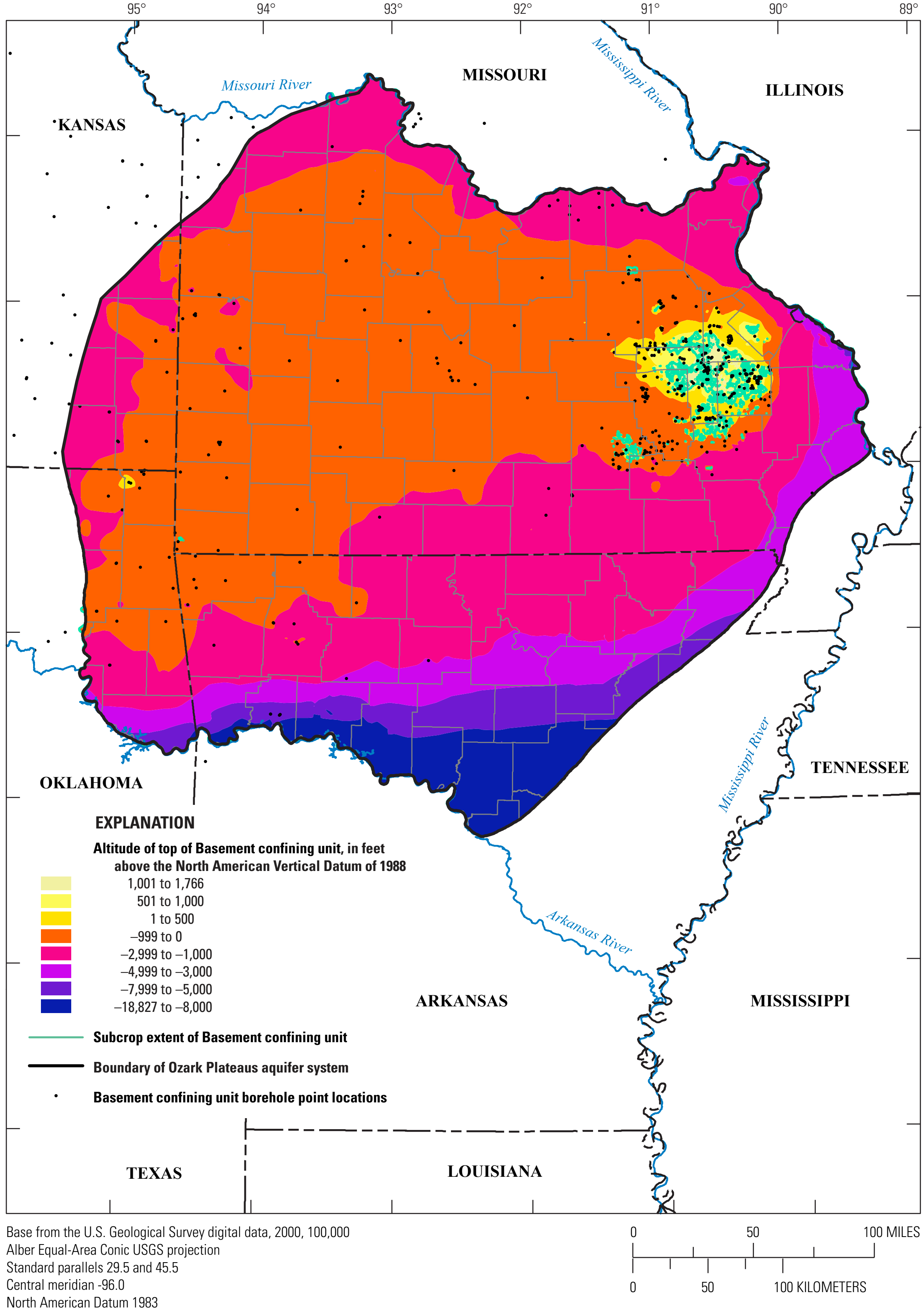


Figure 21. Altitude of the top of the basement confining unit within the Ozark Plateaus aquifer system.

Summary

A hydrogeologic framework for the Ozark Plateaus aquifer system was developed that represents a continuous altitude grid for surfaces defining boundaries and thicknesses of eight hydrogeologic units and the upper boundary of a ninth unit. The Western Interior Plains confining system was assumed to be present at or near land surface and had a median thickness of 542 ft. The Springfield Plateau aquifer had a median depth below land surface of 216 ft and median thickness of 237 ft. The Ozark confining unit had a median depth below land surface of 437 ft and median thickness of 42 ft. The upper Ozark aquifer had a median depth below land surface of 648 ft and median thickness of 590 ft. The middle Ozark aquifer had a median depth below land surface of 390 ft and median thickness of 416 ft. The lower Ozark aquifer, the major water producing hydrogeologic unit in the Ozark Plateaus aquifer system, had a median depth below land surface of 672 ft and median thickness of 885 ft. The St. Francois confining unit had a median depth below land surface of 1,502 ft and median thickness of 228 ft. The St. Francois aquifer had a median depth below land surface of 1,698 ft and median thickness of 291 ft. The basement confining unit had a median depth below land surface of 1,996 ft. The hydrogeologic framework will serve as a stand-alone reference for potential future refinements and investigations within the Ozark Plateaus aquifer system where the geometry of the hydrogeologic units is necessary.

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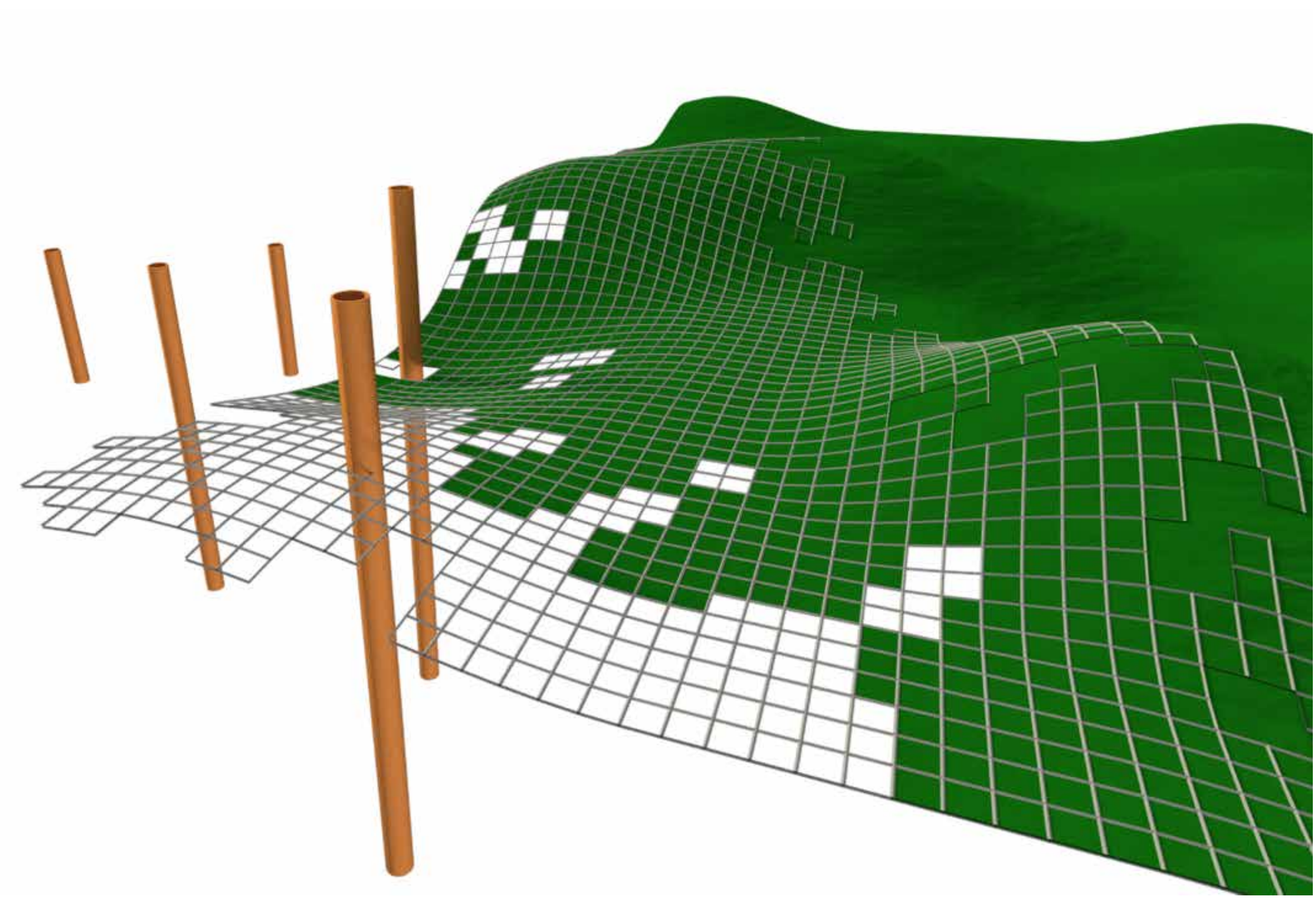

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